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Public Health and Environmental Benefits of Adopting Lead-Free Solders	*Oladele A. Ogunseitan*	After more than 7,000 years of widespread use, lead is fi guratively sinking in contemporary industrial ecology and global societal commerce. But, despite the long research history of documenting the detrimental impacts of lead use, and of legislative initiatives to phase lead out of various products and processes, the United States currently has no federal mandate comparable to the European Union's "restriction of the use of certain hazardous substances in electrical andelectronic equipment" banning the saleof new electrical and electronic equipment containing specifi ed levels of six major toxic materials, including lead. Without a strong environmental agenda leaning toward preventive strategies, concerns about demonstrated public health effects often prove to be strong motivators of U.S. materials use policy. This article assesses various ways in which universal adoption of lead-free solders, coupled with additional material restrictions, may have tangible benefits for public health and the environment,and how these benefi ts may help secure true innovation in material selection and product design for the environment.	*JOM: July 2007*	pp. 12-17	Read the Full Paper
Lead-Free Solders: Reliability and Other Issues a Year after the Legislation	*Srinivas Chada*	Commentary	*JOM: July 2007*	pp. 19	Read the Full Paper
The Development of the COST 531 Lead-Free Solders Thermodynamic Database	*A. Kroupa, A.T. Dinsdale, A. Watson, J. Vrestal, J. Vízdal, and A. Zemanova*	The methods for modeling the thermodynamic properties of multicomponent systems are described in this article. The rules for creating a consistent database for muticomponent systems are described in general terms and documented in relation to the thermodynamic database for lead-free solders, developed within the scope of European Cooperation in the Field of Scientific and Technical Research Action 531. New assessments and reassessments of the Bi-Sn-Zn, Cu-Ni-Sn, and Ag-Cu-Sn systems are shown as examples illustrating the application of the database for the modeling of lead-free solder materials.	*JOM: July 2007*	pp. 20-25	Read the Full Paper
The Effects of Additives to SnAgCu Alloys on Microstructure and Drop Impact Reliability of Solder Joints	*Weiping Liu and Ning-Cheng Lee*	The impact reliability of solder joints in electronic packages is critical to the lifetime of electronic products, especially those portable devices using area array packages such as ball-grid array (BGA) and chip-scale packages (CSP). Currently, SnAgCu (SAC) solders are most widely used for lead-free applications. However, BGA and CSP solder joints using SAC alloys are fragile and prone to premature interfacial failure, especially under shock loading. To further enhance impact reliability, a family of SAC alloys doped with a small amount of additives such as Mn, Ce, Ti, Bi, and Y was developed. The effects of doping elements on drop test performance, creep resistance, and microstructure of the solder joints were investigated, and the solder joints made with the modifi ed alloys exhibited significantly higher impact reliability.	*JOM: July 2007*	pp. 26-31	Read the Full Paper

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Electrical Measurement of a Lead-Free Solder Assembly after Environmental Tests by SEM Internal Probing	*T.I. Shih, Y.C. Lin, J.G. Duh, Tom Hsu, and W.S. Wu*	In this study, electrical characterization for lead-free materials in bump technology was developed and joint assemblies were thermally treated under temperature cycling tests. Measurements of sheet resistivity and contact resistance of intermetallic compounds (IMCs) in solder joints were conducted. Quantitative analysis and elemental redistribution of IMCs were obtained by fi eld-emission electron probe microanalyzer. A scanning-electron microscopy internal probing system was introduced to evaluate electrical characteristics in IMCs after thermal treatments. To determine resistivity of IMCs, a novel method incorporating SELA-EM2 and a focused ion beam was developed to prepare the joint sample.	*JOM: July 2007*	pp. 32-37	Read the Full Paper
Observations of Nucleation Catalysis Effects during Solidification of SnAgCuX Solder Joints	*I.E. Anderson, J. Walleser, and J.L. Harringa*	While modification of a strong (high Cu) Sn-Ag-Cu (SAC) solder alloy with a substitutional alloy addition (X=Co, Fe, Zn, and Ni) for Cu has been demonstrated to enhance solder joint strength and 2.8 ductility after aging at 150ºC for 1,000 h, control of the as-solidifi ed SAC+X solder joint microstructure is also needed to inhibit undercooling and nucleation of brittle pro-eutectic phases (e.g., Ag_3Sn). Figure 1. The composition region that closely surrounds the calculated ternary eutectic composition of Sn-3.7Ag-0.9Cu (wt.%), as seen from the calculated liquidus surface.10 The indicated points on the diagram cor-respond to two common commercial SAC solder alloys, Sn-3.9Ag-0.6Cu and Sn-3.0Ag-0.5Cu, as well as two experimental compositions, Sn-3.6Ag-1.0Cu and Sn-3.5Ag-0.95Cu (shown at the intersection of two iso-composition lines). Bulk undercooling measurements of SAC+X alloys and microstructural analysis of SAC+X solder joints were used to rank the effectiveness and con-sistency of low-level (X $<$ 0.15 wt.%) substitutional additions to a base SAC composition, Sn-3.5Ag-0.95Cu (wt.%).	*JOM: July 2007*	pp. 38-43	Read the Full Paper
Phase Transformation and Microstructural Evolution in Solder Joints	*Sinn-wen Chen, Chao-hong Wang, Shih-kang Lin, Chen-nan Chiu, and Chih-chi Chen*	Soldering is the most important of joining technologies and there are numerous solder joints in modern electronic products.The phases and microstructures of solder joints are critical to their properties.Various remarkable phenomena caused by phase transformation and microstructural evolution in solder joints have been reported. The phenomena include ripening, layer detachment, liquation, cruciform pattern formation, solid-state amorphization, alternating layer formation, shift of reaction paths, and the effects of electromigration.	*JOM: January 2007*	pp. 39-43	Read the Full Paper
Low-Temperature Sintering with Nano-Silver Paste in Die-Attached Interconnection	*Tao Wang, Xu Chen, Guo-Quan Lu and Guang-Yin Lei*	Traditional materials used in chip-level interconnections are not compatible with the high-temperature operation of wide-bandgap high-power semiconductor devices; therefore, this paper studies sintered nano-silver as a novel interconnect material mounting semiconductor devices onto metallized substrates. A low-temperature sintering process was employed in the preparation of a sintered nano-silver die-attachment. The physical mechanisms in volatilization and burnout of the added organic components employed in nano-silver paste were analyzed primarily by thermal gravimetric analysis (TGA) to obtain a reasonable temperature-controlling profile. The shear strength of sintered nano-silver joints was investigated, and the evolution of microstructure in the nano-silver paste sintering process was observed using a scanning electron microscope (SEM) in this process. The effects of sintering temperature, heating rate, and holding time during the sintering process were analyzed according to the densification mechanism. The microstructural observations and shear strength tests showed that a sintering temperature of 285°C, heating rate of	*Journal of Electronic Materials: October 2007*	pp. 1333-1340	Acquire this Paper
Solid-State Reactions between Cu(Ni) Alloys and Sn	*Vesa Vuorinen, Tomi Laurila, Toni Mattila, Erkki Heikinheimo and Jorma K. Kivilahti*	Solid-state interfacial reactions between Sn and Cu(Ni) alloys have been investigated at the temperature of 125°C. The following results were obtained. Firstly, the addition of 0.1 at.% Ni to Cu decreased the total thickness of the intermetallic compound (IMC) layer to about half of that observed in the binary Cu/Sn diffusion couple; the Ni addition decreased especially the thickness of Cu_3Sn. Secondly, the addition of 1 to 2.5 at.% Ni to Cu further decreased the thickness of Cu_3Sn, increased that of Cu_6Sn_5 (compared to that in the binary Cu/Sn couple) and produced significant amount of voids at the Cu/Cu_3Sn interface. Thirdly, the addition of 5 at.% Ni to Cu increased the total thickness of the IMC layer to about two times that observed in the binary Cu/Sn diffusion couple and made the Cu_3Sn disappear. Fourthly, in contrast to the previous case, the addition of 10 at.% Ni to Cu decreased the total IMC (Cu_6Sn_5) thickness again close to that of the Cu/Sn couple. With this Ni content no voids were detected. The results are rationalized with the help of the thermodynamics of the Sn-Cu-Ni system as well as with kinetic considerations.	*Journal of Electronic Materials: October 2007*	pp. 1355-1362	Acquire this Paper

Interfacial Reactions between Eutectic SnZn Solder and Bulk or Thin-Film Cu Substrates	*Chih-ming Chen and Chih-hao Chen*	Interfacial reactions between eutectic SnZn solder and bulk or thin-film Cu substrates are investigated and compared. The thicknesses of bulk and thin-film Cu substrates are 0.5 mm and 4,000 Å, respectively. Different dominant reaction products and interfacial microstructures are observed in these two types of interfacial reactions. In the bulk Cu type, the Cu5Zn8 phase is the dominant reaction product under reflow and solid-state annealing. However, the CuZn5 phase becomes the dominant reaction product in the thin-film Cu type. The Cu5Zn8 phase in the bulk Cu type remains as a uniform microstructure after reflow. After solid-state annealing, however, the Cu5Zn8 phase fractures and the Cu6Sn5 and Cu3Sn phases are formed at the Cu5Zn8/Cu interface. The CuZn5 phase in the thin-film Cu type ripens after reflow and the phase morphology is transformed from a uniform layer into separated scallops. In situ observation of the interfacial microstructure after solid-state annealing reveals that prominent deformation occurs in the solder region close to the interface in the bulk Cu type. While in the thin-film Cu type, the CuZn5 grain is ext	*Journal of Electronic Materials: October 2007*	pp. 1363-1371	Acquire this Paper
Current-Induced Phase Partitioning in Eutectic Indium-Tin Pb-Free Solder Interconnect	*John P. Daghfal and J. K. Shang*	Structural changes from high-density electric currents were examined in a eutectic In-Sn/Cu interconnect. Under electrical loading, Sn and In migrated in opposite directions, creating a partition of the Sn- and In-rich phases between the anode and the cathode. At the anode, a net gain of Sn atoms resulted in the formation of massive, columnar hillocks on the surface, but a net loss of In led to dissolution and disappearance of the In-rich intermetallic layer. At the cathode, the exodus of Sn left valleys adjacent to the In-rich regions on the surface, while the amount of the In-rich phase grew, due to the net influx of In at the expense of the In-rich intermetallic layer.	*Journal of Electronic Materials: October 2007*	pp. 1372-1377	Acquire this Paper
The Hillock Formation in a Cu/Sn-9Zn/Cu Lamella upon Current Stressing	*Shih-Ming Kuo and Kwang-Lung Lin*	The electromigration (EM) that occurs in a Cu/Sn-9Zn/Cu lamella was investigated for hillock formation at room temperature with a current density of 103 A/cm2 for up to 230 h. Hillocks and cavities grew in the middle of the bulk solder and at the cathode, respectively. The formation of hillocks was ascribed to a compressive stress resulting from the diffusion of Sn atoms driven by electromigration and Cu-Zn compound formation.	*Journal of Electronic Materials: October 2007*	pp. 1378-1382	Acquire this Paper
Cross-Interaction of Interfacial Reactions in Ni (Au/Ni/Cu)-SnAg-Cu Solder Joints during Reflow Soldering and Thermal Aging : Erratum	*H.T. Chen, C.Q. Wang, C. Yan, M.Y. Li and Y. Huang*	Interfacial reactions in Ni-SnAg-Cu and Au/Ni/Cu-SnAg-Cu solder joints were investigated to understand the coupling effect between different pads during soldering and thermal aging processes. Scanning electron microscopy (SEM) was used to characterize the microstructures and phases. The element distributions in the joints were identified using the x-ray mapping technique. The thickness variation of intermetallic compounds (IMCs) with aging time was also measured. The results showed that interfacial reactions were not only affected by the compositions of solders and the local metallizations but the remote pads as well. The Au surface finish had an effect on the growth of IMCs at the interfaces. No redeposition of (Au, Ni)Sn4 was found in the Au/Ni/Cu-SnAg-Cu solder joint. The effect of Cu on the formation of IMCs and redeposition of (Au, Ni)Sn4 was also discussed.	*Journal of Electronic Materials: October 2007*	p. 1405	Acquire this Paper
Damage Produced in Solder Alloys during Thermal Cycling	*X.W. Liu and W.J. Plumbridge*	The anisotropy of tin is associated with significant variations in its coefficient of thermal expansion and elastic modulus, with crystallographic direction. Under pure thermal cycling (with no externally applied stress or strain), substantial strains, in excess of 100%, may develop locally, and for very small structures, such as soldered interconnections comprising a few grains, structural integrity may be adversely affected. To examine this possibility, freestanding samples of tin, Sn-3.5wt.%Ag, Sn-0.5wt.%Cu, and Sn-3.8wt.%Ag-0.7wt.%Cu, have been subjected to thermal cycling. Temperature cycles from 30°C to 125°C or from −40°C to 55°C initially caused surface cracking, with openings up to several tens of microns after 3,000 cycles. Subsequently, the surface cracks grew into the interior of the specimens, with the maximum penetration ranging from a few microns after 100 cycles to more than 200 μm after 3,000 cycles. The cracks initiated from damage accumulated along grain boundaries. For the same temperature range, less damage resulted after the lower maximum (or mean) temperature cycle, and there appears to be a thermally activated com	*Journal of Electronic Materials: September 2007*	pp. 1111-1120	Acquire this Paper

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Interfacial Reactions in Sn-0.7wt.%Cu/Ni-V Couples at 250°C	*Sinn-wen Chen and Chih-chi Chen*	The Delco process is a major flip chip under-bump metallurgy process and its contact is soldered with the Ni-7wt.%V substrate; there are, however, only a few studies on the interfacial reactions between solders and Ni-V alloys. This study examines the interfacial reactions of the Sn-0.7wt.%Cu alloy with the Ni-7wt.%V, Ni-5wt.%V, and Ni-3wt.%V substrates at 250°C. It is found that the interfacial reactions between Sn-0.7wt.%Cu and Ni-V alloys are different from those between Sn-0.7wt.%Cu and pure Ni. In addition to the formation of the Cu_6Sn_5 phase, a new Sn-rich phase, denoted the Q phase, is found in the Ni-V substrate couples. Nucleation of the Ni_3Sn_4 phase is at a much earlier stage and the rates of consumption of Ni are much higher in Ni-V substrate couples than in Ni substrate couples. Knowledge of these different reactions is important for proper assessment of the flip chip products.	*Journal of Electronic Materials: September 2007*	pp. 1121-1128	Acquire this Paper
Effect of Interfacial Reactions on the Reliability of Lead-Free Assemblies after Board Level Drop Tests	*Yanghua Xia, Chuanyan Lu and Xiaoming Xie*	The reliability of lead-free electronic assemblies after board level drop tests was investigated. Thin small outline package (TSOP) components with 42 FeNi alloy leads were reflow soldered on FR4 printed circuit boards (PCBs) with Sn3.0Ag0.5Cu (wt%) solder. The effects of different PCB finishes [organic solderability preservative (OSP) and electroless nickel immersion gold (ENIG)], multiple reflow (once and three times), and isothermal aging (500 h at 125°C after one time reflow) were studied. The ENIG finish showed better performance than its OSP counterparts. With the OSP finish, solder joints reflowed three times showed obvious improvement compared to those of the sample reflowed once, while aging led to apparent degradation. The results showed that intermetallic compound (IMC) types, IMC microstructure and solder microstructure compete with each other, all playing very important roles in the solder joint lifetime. The results also showed that it is important to specify adequate conditions for a given reliability assessment program, to allow meaningful comparison between results of different investigators.	*Journal of Electronic Materials: September 2007*	pp. 1129-1136	Acquire this Paper
Morphology and Pull Strength of Sn-Ag(-Co) Solder Joint with Copper Pad	*Hiroshi Nishikawa, Akira Komatsu and Tadashi Takemoto*	In order to clarify the effect of the addition of Co to the Sn-Ag solder, the formation and growth of an intermetallic compound (IMC) at the interface between Sn-Ag(-Co) solders and a Cu pad were investigated, and the joint strength of the solder with a Cu pad was also evaluated by a bump pull test. Binary Sn-3.5mass%Ag solder was used as the basic solder, and Sn-3.5mass%Ag-xCo solders (x = 0.1 mass%, 0.3 mass%, and 0.5 mass%) were specially prepared as Co-added solders. For the reflow process, specimens were heated in a radiation furnace at 523 K for 60 s. For the aging process, some specimens were then heat-treated in an oil bath at 423 K for 168 h, 504 h, and 1008 h. The results show that the addition of Co to the Sn-Ag solder strongly affected the formation and growth of the IMC at the interface. The results of the pull test clearly show that all solders had similar pull strengths, regardless of the Co addition, although the IMC morphology at the interface of the Sn-Ag-Co solder was quite different from that of the binary Sn-3.5Ag solder.	*Journal of Electronic Materials: September 2007*	pp. 1137-1143	Acquire this Paper
Electromigration in the Flip Chip Solder Joint of Sn-8Zn-3Bi on Copper Pads	*W.H. Lin, Albert T. Wu, S.Z. Lin, T.H. Chuang and K.N. Tu*	Electromigration in Sn-8Zn-3Bi flip chip solder bumps on Cu pads has been studied at 120°C with an average current density of 4×10^3 A/cm^2 and 4.5×10^4 A/cm^2. Due to the polarity effect, the thickness of the intermetallic compound Cu-Zn (γ-phase) formed at the anode is much greater than that at the cathode. The solder joint fails after 117 h of stressing at 4.5×10^4 A/cm^2, and void formation at the cathode can clearly be seen after polishing. However, it is the melting at the edge of the bump that causes the solder joint to fail. A simulation of the current density distribution indicates that the current density is not distributed uniformly, and current crowding occurs inside the bump. The results indicate that the increase of current density associated with Joule heating has affected melting and enhanced damage in the solder joint during electromigration.	*Journal of Electronic Materials: July 2007*	pp. 753-759	Acquire this Paper
Effects of Copper Doping on Microstructural Evolution in Eutectic SnBi Solder Stripes under Annealing and Current Stressing	*Chih-Ming Chen, Chih-Chieh Huang, Chien-Neng Liao and Kuen-Ming Liou*	Effects of Cu doping on the microstructural evolution in the eutectic SnBi solder stripes under annealing and current stressing were investigated. Coarsening of the Bi grains was observed in the eutectic SnBi solder upon annealing at 85°C. Doping of 1 wt.% Cu could significantly reduce the grain coarsening rate from 2.8 to 0.5 μm^3/h. In addition to grain coarsening, mass accumulation of Bi at the anode and solder depletion at the cathode of the eutectic SnBi solder stripe stressed by a current of 1.3×10^4 A/cm^2 at 85°C were also observed. Doping of 1 wt.% Cu could also reduce the grain coarsening of the solder under current stressing; however, it resulted in an enhancement of the electromigration effect. Accumulation of Bi at the anode and the solder depletion at the cathode became more severe in the Cu-doped solder stripe.	*Journal of Electronic Materials: July 2007*	pp. 760-765	Acquire this Paper

Properties of Sn3.8Ag0.7Cu Solder Alloy with Trace Rare Earth Element Y Additions	*H. Hao, J. Tian, Y.W. Shi, Y.P. Lei and Z.D. Xia*	In the current research, trace rare earth (RE) element Y was incorporated into a promising lead-free solder, Sn3.8Ag0.7Cu, in an effort to improve the comprehensive properties of Sn3.8Ag0.7Cu solder. The range of Y content in Sn3.8Ag0.7Cu solder alloys varied from 0 wt.% to 1.0 wt.%. As an illustration of the advantage of Y doping, the melting temperature, wettability, mechanical properties, and microstructures of Sn3.8Ag0.7CuY solder were studied. Trace Y additions had little influence on the melting behavior, but the solder showed better wettability and mechanical properties, as well as finer microstructures, than found in Y-free Sn3.8Ag0.7Cu solder. The Sn3.8Ag0.7Cu0.15Y solder alloy exhibited the best comprehensive properties compared to other solders with different Y content. Furthermore, interfacial and microstructural studies were conducted on Sn3.8Ag0.7Cu0.15Y solder alloys, and notable changes in microstructure were found compared to the Y-free alloy. The thickness of an intermetallic compound layer (IML) was decreased during soldering, and the growth of the IML was suppressed during aging.	*Journal of Electronic Materials: July 2007*	pp. 766-774	Acquire this Paper
Cross-Interaction of Interfacial Reactions in Ni (Au/Ni/Cu)-SnAg-Cu Solder Joints during Reflow Soldering and Thermal Aging : Erratum	*H.T. Chen, C.Q. Wang, C. Yan, M.Y. Li and Y. Huang*	Interfacial reactions in Ni-SnAg-Cu and Au/Ni/Cu-SnAg-Cu solder joints were investigated to understand the coupling effect between different pads during soldering and thermal aging processes. Scanning electron microscopy (SEM) was used to characterize the microstructures and phases. The element distributions in the joints were identified using the x-ray mapping technique. The thickness variation of intermetallic compounds (IMCs) with aging time was also measured. The results showed that interfacial reactions were not only affected by the compositions of solders and the local metallizations but the remote pads as well. The Au surface finish had an effect on the growth of IMCs at the interfaces. No redeposition of (Au, Ni)Sn4 was found in the Au/Ni/Cu-SnAg-Cu solder joint. The effect of Cu on the formation of IMCs and redeposition of (Au, Ni)Sn4 was also discussed.	*Journal of Electronic Materials: January 2007*	pp. 26-32	Acquire this Paper
	Nik Chawla, Srinivas Chada, Sung K. Kang, C. Robert Kao, Kwang -Lung Lin, Jim Lucas and Laura Turbini	Without Abstract	*Journal of Electronic Materials: December 2006*	pp. 2073	Acquire this Paper
The effect of Ag content on the formation of Ag3Sn plates in Sn-Ag-Cu lead-free solder	*Huann-Wu Chiang, Kenndy Chang and Jun-Yuan Chen*	The formation of Ag3Sn plates in the Sn-Ag-Cu lead-free solder joints for two different Ag content solder balls was investigated in wafer level chip scale packages (WLCSPs). After an appropriate surface mount technology reflow process on a printed circuit board, samples were subjected to 150°C high-temperature storage (HTS), 1,000 h aging, or 1,000 cycles thermal cycling test (TCT). Sequentially, the cross-sectional analysis was scrutinized using a scanning electron microscope/energy dispersive spectrometer (SEM/EDX) to observe the metallurgical evolution of the amount of the Ag3Sn plates at the interface and the solder bulk itself. Pull and shear tests were also performed on samples. It was found that the interfacial intermetallic compound (IMC) thickness, the overall IMC area, and the numbers of Ag3Sn plates increase with increasing HTS and TCT cycles. The amount of large Ag3Sn plates found in the Sn-4.0Ag-0.5 Cu solder balls is much greater than that found in the Sn-2.6Ag-0.5Cu solder balls; however, no significant difference was found in the joint strength between two different Ag content solder joints.	*Journal of Electronic Materials: December 2006*	pp. 2074-2080	Acquire this Paper
Morphology and growth pattern transition of intermetallic compounds between Cu and Sn-3.5Ag containing a small amount of additives	*Feng Gao, Tadashi Takemoto and Hiroshi Nishikawa*	The morphology and grain growth pattern of intermetallic compounds (IMCs) formed between the Cu substrate and Sn-3.5Ag solder doped with a small amount of additive (0.1 mass%), say, Ni or Co, was investigated. After soldering, a duplex structure due to the additive discontinuity at the (Cu, Ni)6Sn5 and (Cu, Co)6Sn5 region was detected. That is, the outer area of the (Cu, Ni)6Sn5 and (Cu, Co)6Sn5 region on the solder side contained much higher Ni or Co additive concentration than the inner area on the Cu side. The faceted-shape IMCs were observed at the outer area, while the rounded-shape were identified at the inner area of (Cu, Ni)6Sn5 and (Cu, Co)6Sn5. Based on the thermodynamic calculation, the higher solubility of additive at the outer area will enhance the enthalpy change during interfacial reaction and lead to the larger Jackson's parameter; thus, the faceted IMC morphology was formed. Moreover, the abnormal grain growth (AGG) at the outer area of (Cu, Ni)6Sn5 and (Cu, Co)6Sn5 was demonstrated from the IMC grain size distribution, while the normal grain growth pattern was suggested for the inner area of the IMC region.	*Journal of Electronic Materials: December 2006*	pp. 2081-2087	Acquire this Paper

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Microstructure and mechanical behavior of novel rare earth-containing Pb-Free solders	*M. A. Dudek, R. S. Sidhu, N. Chawla and M. Renavikar*	Sn-rich solders have been shown to have superior mechanical properties when compared to the Pb-Sn system. Much work remains to be done in developing these materials for electronic packaging. In this paper, we report on the microstructure and mechanical properties of La-containing Sn-3.9Ag-0.7Cu alloys. The addition of small amounts of La (up to 0.5 wt.%) to Sn-Ag-Cu refined the microstructure by decreasing the length and spacing of the Sn dendrites and decreased the thickness of the Cu6Sn5 intermetallic layer at the Cu/solder interface. As a result of the change in the microstructure, Sn-Ag-Cu alloys with La additions exhibited a small decrease in ultimate shear strength but significantly higher elongations compared with Sn-Ag-Cu. The influence of LaSn3 intermetallics on microstructural refinement and damage evolution in these novel solders is discussed. Our results have profound implications for improving the mechanical shock resistance of Pb-free solders.	*Journal of Electronic Materials: December 2006*	2088-2097	Acquire this Paper
Effect of reflow and thermal aging on the microstructure and microhardness of Sn-3.7Ag-xBi solder alloys	*M. He and V. L. Acoff*	This work investigates the effect of reflow and the thermal aging process on the microstructural evolution and microhardness of five types of Sn-Ag based lead-free solder alloys: Sn-3.7Ag, Sn-3.7Ag-1Bi, Sn-3.7Ag-2Bi, Sn-3.7Ag-3Bi, and Sn-3.7Ag-4Bi. The microhardness and microstructure of the solders for different cooling rates after reflow at 250°C and different thermal aging durations at 150°C for air-cooled samples have been studied. The effect of Bi is discussed based on the experimental results. It was found that the microhardness increases with increasing Bi addition to Sn-3.7Ag solder regardless of reflow or thermal aging process. Scanning electron microscopy images show the formation of Ag3Sn particles, Sn-rich phases, and precipitation of Bi-rich phases in different solders. The increase of microhardness with Bi addition is due to the solution strengthening and precipitation strengthening provided by Bi in the solder. The trend of decrease in microhardness with increasing duration of thermal aging was observed.	*Journal of Electronic Materials: December 2006*	2098-2106	Acquire this Paper
Nanoindentation on SnAgCu lead-free solder joints and analysis	*Luhua Xu and John H. L. Pang*	The lead-free SnAgCu (SAC) solder joint on copper pad with organic solderability preservative (Cu-OSP) and electroless nickel and immersion gold (ENIG) subjected to thermal testing leads to intermetallic growth. It causes corresponding reliability concerns at the interface. Nanoindentation characterization on SnAgCu solder alloy, intermetallic compounds (IMCs), and the substrates subjected to thermal aging is reported. The modulus and hardness of thin IMC layers were measured by nanoindentation continuous stiffness measurement (CSM) from planar IMC surface. When SAC/Ni(Au) solder joints were subject to thermal aging, the Young's modulus of the NiCuSn IMC at the SAC/ENIG specimen changed from 207 GPa to 146 GPa with different aging times up to 500 h. The hardness decreased from 10.0 GPa to 7.3 GPa. For the SAC/Cu-OSP reaction couple, the Young's modulus of Cu6Sn5 stayed constant at 97.0 GPa and hardness about 5.7 GPa. Electron-probe microanalysis (EPMA) was used to thermal aging. The creep....	*Journal of Electronic Materials: December 2006*	2107-2115	Acquire this Paper
Electromigration effect on intermetallic growth and Youngâ€™s modulus in SAC solder joint	*Luhua Xu, John H. L. Pang, Fei Ren and K. N. Tu*	Solid-state intermetallic compound (IMC) growth behavior plays and important role in solder joint reliability of electronic packaging assemblies. The directional impact of electromigration (EM) on the growth of interfacial IMCs in Ni/SAC/Ni, Cu/SAC/Ni single BGA ball solder joint, and fine pitch ball-grid-array (FPBGA) at the anode and cathode sides is reported in this study. When the solder joint was subjected to a current density of 5,000 A/cm2 at 125°C or 150°C, IMC layer growth on the anode interface was faster than that on the cathode interface, and both were faster than isothermal aging due to the Joule heating effect. The EM affects the IMC growth rate, as well as the composition and mechanical properties. The Young's modulus and hardness were measured by the nanoindentation continuous stiffness measurement (CSM) from planar IMC surfaces after EM exposure. Different values were observed at the anode and cathode. The energy-dispersive x-ray (EDX) line scan analysis was conducted at the interface from the cathode to anode to study the presence of species; Ni was found in the anode IMC at SAC/Cu in the Ni/SAC/Cu joint, but not detec	*Journal of Electronic Materials: December 2006*	2116-2125	Acquire this Paper
Effect of phosphorus content on Cu/Ni-P/Sn-3.5Ag solder joint strength after multiple reflows	*Zhong Chen, Aditya Kumar and M. Mona*	Electroless Ni-P layers with three different P contents (6.1 wt.%, 8.8 wt.%, and 12.3wt.%) were deposited on copper (Cu) substrates. Multilayered samples of Sn-3.5Ag/Ni-P/Cu stack were prepared and subjected to multiple reflows at 250°C. A tensile test was performed to investigate the effect of P content on the solder joint strength. The low P samples exhibited the highest joint strength after multiple reflows, while the strength of medium and high P samples decreased more rapidly. From interfacial analysis, the Ni3Sn4 intermetallic compound (IMC) formed at the interface of low P sample was found to be more stable, while the one of medium and high P samples spalled into the molten solder. The IMC spallation sped up the consumption of electroless Ni-P, leading to the large formation of Cu-Sn IMCs. Fractographic and microstructural analyses showed that the degradation in solder joint strength was due to the formation of layers of voids and growth of Cu-Sn IMCs between the solder and the Cu substrate.	*Journal of Electronic Materials: December 2006*	2126-2134	Acquire this Paper

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Morphology of intermetallic compounds formed between lead-free Sn-Zn based solders and Cu substrates	*Chia-Wei Huang and Kwang-Lung Lin*	The morphologies of intermetallic compounds formed between Sn-Zn based solders and Cu substrates were investigated in this study. The investigated solders were Sn-9Zn, Sn-8.55Zn-0.45Al, and Sn-8.55Zn-0.45Al-0.5Ag. The experimental results indicated that the Sn-9Zn solder formed Cu5Zn8 and CuZn5 compounds on the Cu substrate, while the Al-containing solders formed the Al4.2Cu3.2Zn0.7 compound. The addition of Ag to the Sn-8.55Zn-0.45Al solder resulted in the formation of the AgZn3 compound at the interface between the Al4.2Cu3.2Zn0.7 compound and the solder. Furthermore, it was found that the cooling rate of the specimen after soldering had an effect on the quantity of AgZn3 compound formed at the interface. The AgZn3 compound formed with an air-cooling condition exhibited a rougher surface and larger size than with a water-quenched condition. It was believed that the formation of the AgZn3 compound at the interface occurs through heterogenous nucleation during solidification.	*Journal of Electronic Materials: December 2006*	2135-2141	Acquire this Paper
Thickness determination of ultrathin oxide films and its application in magnetic tunnel junctions	*J. Joshua Yang, Chengxiang Ji, Ying Yang, Y. Austin Chang, Feng X. Liu, Bharat B. Pant and Allan E. Schultz*	In this study we propose a method for utilizing x-ray photoelectron spectroscopy (XPS), a surface sensitive technique, coupled with a wedge-shaped sample to determine the thickness of an ultrathin aluminum oxide tunnel barrier layer (~2 nm) in a magnetic tunnel junction (MTJ). The uncertainty of the measured thickness is analyzed and the factors affecting the accuracy of this measurement are discussed as well as the advantages over the use of high-resolution transmission electron microscopy. Using this approach, we were able to quickly optimize the thickness of an aluminum oxide layer in a fabricated MTJ, yielding a high magnetoresistance ratio. In addition to XPS, one can also use Auger electron spectroscopy to determine the thickness of the oxidized tunnel barrier layer. This method can also be applied to other tunnel barrier materials such as the nitrides	*Journal of Electronic Materials: December 2006*	2142-2146	Acquire this Paper
Effect of surface finish on the failure mechanisms of flip-chip solder joints under electromigration	*Y. L. Lin, Y. S. Lai, C. M. Tsai and C. R. Kao*	Two substrate surface finishes, Au/Ni and organic solderable preservative (OSP), were used to study the effect of the surface finish on the reliability of flip-chip solder joints under electromigration at 150°C ambient temperature. The solder used was eutectic PbSn, and the applied current density was 5×103 A/cm2 at the contact window of the chip. The under bump metallurgy (UBM) on the chip was sputtered Cu/Ni. It was found that the mean-time-to-failure (MTTF) of the OSP joints was six times better than that of the Au/Ni joints (3080 h vs. 500 h). Microstructure examinations uncovered that the combined effect of current crowding and the accompanying local Joule heating accelerated the local Ni UBM consumption near the point of electron entrance. Once Ni was depleted at a certain region, this region became nonconductive, and the flow of the electrons was diverted to the neighboring region. This neighboring region then became the place where electrons entered the joint, and the local Ni UBM consumption was accelerated. This process repeated itself, and the Ni-depleted region extended further on, creating an ever-larger nonconductive region. The solder joint e	*Journal of Electronic Materials: December 2006*	2147-2153	Acquire this Paper
Microstructural characteristics and vibration fracture properties of Sn-Ag-Cu-TM (TM=Co, Ni, and Zn) alloys	*Jenn-Ming Song, Chi-Feng Huang*	This study investigated microstructure thermal behavior, and mechanical properties of Sn-3.3Ag-0.5Cu alloys (SAC) with the addition of transition metals (TM, Ni, Co, and Zn). Results show that alloying with TM elements was able to reduce the degree of undercooling and strengthen SAC alloys. Among these elements, only Zn can raise the ductility. CoSn and Cu-Ni-Sn intermetallics appeared, respectively, in the Co-containing and Ni-containing samples while coarse Sn dendrites and a large area of eutectic phases could be observed in the specimens with Zn. These microstructural changes led to an inferior vibration fracture resistance under resonant vibration with a constant pull force	*Journal of Electronic Materials: December 2006*	2154-2163	Acquire this Paper
Diffusion behavior of Cu in Cu/electroless Ni and Cu/electroless Ni/Sn-37Pb solder joints in flip chip technology	*Yu-Ching Hsu and Jenq-Gong Duh*	For Cu pads used as under bump metallization (UBM) in flip chip technology, the diffusion behavior of Cu in the metallization layer is an important issue. In this study, isothermal interdiffusion experiments were performed at 240°C for different times with solid-solid and liquid-solid diffusion couples assembled in Cu/electroless-Ni (Ni-10 wt.% P) and Cu/electroless Ni (Ni-10 wt.% P)/ Sn-37Pb joints. The diffusion structure and concentration profiles were examined by scanning electron microscopy and electron microprobe analysis. The interdiffusion fluxes of Cu, Ni and P were calculated from the concentration profiles with the aid of Matano plane evaluation. The values of JCu, JNi, and JP decreased with increasing annealing time. The average effective interdiffusion coefficients on the order of 10−14 cm2/s were also evaluated within the diffusion zone. The amounts of	*Journal of Electronic Materials: December 2006*	2164-2171	Acquire this Paper
Cathodoluminescence study of micro-crack-induced stress relief for AlN films on Si(111)	*G. Sarusi, O. Moshe, S. Khatsevich, D. H. Rich, J. Salzman, B. Meyler, M. Shandalov and Y. Golan*	Spatially, spectrally, and depth-resolved cathodoluminescence (CL) measurements were performed for high-quality thin AlN films grown on Si(111). Cl spectra exhibited a sharp peak at 5.960 eV, corresponding to the near-band-edge excitonic emission of AlN. Depth-resolved CL analysis showed that deep level oxygen and carbon impurities are localized primarily at the AlN/Si interface and AlN outer surface. Monochromatic CL imaging of the near-band-edge emission exhibits a spotty pattern, which corresponds to high concentrations of threading dislocations and thermally induced microcracks in the thin layers. We have examined relief of the thermal stress in close proximity to single microcracks and intersecting microcracks. Local CL spectra acquired with a focused e-beam show blue-shifts as large as ~82 meV in the AlN near-band edge excitonic peaks, reflecting defect-induced reductions in the biaxial thermal stress, which has a maximum value of ~47 kbar.	*Journal of Electronic Materials: December 2006*	L15-L19	Acquire this Paper

Recent TMS Articles: Lead-Free Solders

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Title	Authors	Summary	Source	Pages	Link
Lead-Free Implementation: Reliability, Alloy Development, and New Technology	*Srinivas Chada*	In light of new government regulations, many electronic product manufacturers are making haste to implement lead-free solders and to market reliable 'green' products. Thus, in response to growing interest and want of technical information on lead-free solders, the Electronic Packaging and Interconnection Materials Committee of the TMS Electronic, Magnetic & Photonic Materials Division organized a series of successful symposia on lead-free and lead-bearing solders over the past few years. This commentary introduces four papers from the recent Lead-Free Implementation: Reliability, Alloy Development, and New Technology symposium held at the 2006 TMS Annual Meeting in San Antonio, Texas.	*JOM: June 2006*	p. 56	Read the Full Paper
Novel Rare-Earth-Containing Lead-Free Solders with Enhanced Ductility	*M.A. Dudek, R.S. Sidhu, and N. Chawla*	Several lead-free material systems are available as replacements for traditional lead-based solders in microelectronic packaging, including near-eutectic combinations of tin-rich alloys. Although these materials have superior mechanical properties as compared to the Pb-Sn system, much work remains in developing these materials for electronic packaging. Small additions of rare-earth elements have been shown to refine the microstructure of several lead-free solder systems, thus improving their mechanical properties. This study investigated the effect of the addition of lanthanum on the melting behavior, microstructure, and shear strength of an Sn-3.9Ag-0.7Cu alloy. The influence of LaSn3 intermetallics on microstructural refinement and damage evolution in these novel solders is discussed.	*JOM: June 2006*	pp. 57-62	Read the Full Paper
A Synchrotron Radiation X-Ray Microdiffraction Study on Orientation Relationships between a Cu6Sn5 and Cu Substrate in Solder Joints	*J.O. Suh, K.N. Tu, and N. Tamura*	The orientation distribution of Cu6Sn5 scallops and its relationship with the orientation of copper substrate was studied using synchrotron-radiation based micro-x-ray diffraction. Laue spots were obtained both from the Cu6Sn5 and copper at the same time. From the Laue patterns, orientation distribution maps of the Cu6Sn5 and copper were obtained. The orientation of the Cu6Sn5 scallops had a strong dependence on that of copper. The [001] direction of Cu6Sn5 is always parallel to the [110] of copper, and either the (110) or the (010) plane of Cu6Sn5 is parallel to the (001) plane of copper. It was also found that the scallops of Cu6Sn5 gradually gain texture in the early stage of reflow, but lose the texture after a long reflow.	*JOM: June 2006*	pp. 63-66	Read the Full Paper
The Material Optimization and Reliability Characterization of an Indium-Solder Thermal Interface Material for CPU Packaging	*Carl Deppisch, Thomas Fitzgerald, Arun Raman, Fay Hua, Charles Zhang, Pilin Liu, and Mikel Miller*	Developing new thermal interface materials (TIMs) is a key activity to meeting package thermal performance requirements for future generations of microprocessors. Indium solder is capable of demonstrating end-of-line performance to meet current technology targets due to its inherent high thermal conductivity. However, improving its reliability performance, particularly in temperature cycling, is a challenge. This study describes the failure mechanisms and reliability performance of indium solder TIM as a function of integrated heat spreader metallization thickness, TIM bond line thickness, and die size. Also studeied were the steps taken to improve its temperature cycle performance. Analyses were performed using thermal resistance measurements, scanning-electron microscopy, scanning-acoustic microscopy, and transmission-electron microscopy to characterize the solder TIM thermal performance, interfacial microstructure, and failure mechanisms.	*JOM: June 2006*	pp. 67-74	Read the Full Paper
The Root Cause of Black Pad Failure of Solder Joints with Electroless Ni/Immersion Gold Plating	*Kejun Zeng, Roger Stierman, Don Abbott, and Masood Murtuza*	This paper reports on a study of the reaction of solder with the electroless-nickel with immersion gold (ENIG) plating system, and the resulting interfacial structures. A focused-ion beam (FIB) was used to polish the cross sections to reveal details of the microstructure of the ENIG-plated pad with and without soldering. High-speed pull testing of solder joints was performed to expose the pad surface. Results of scanning-electron microscopy/energy-dispersive x-ray analysis of the cross sections and fractured pad surfaces support the suggestion that black pad is the result of galvanic hyper-corrosion of the plated electroless nickel by the gold plating bath. Criteria are proposed for diagnosing black pad of ENIG plating.	*JOM: June 2006*	pp. 75-79	Read the Full Paper
Wettability of Electroplated Ni-P in Under Bump Metallurgy with Sn-Ag-Cu Solder	*Yung-Chi Lin, Jenq-Gong Duh, and Bi-Shiou Chiou*	Nickel plating has been used as the under bump metallurgy (UBM) in the microelectronics industry. In this study, the electroplating process was demonstrated to be a good alternative approach to produce the Ni-P layer as UBM. The wettability of several commercial solder pastes, such as Sn-3.5Ag, Sn- 37Pb, and Sn-3Ag-0.5Cu solder, on electroplated Ni-P with various phosphorous contents (7 wt.%, 10 wt.%, and 13 wt.%) was investigated. The role of phosphorus in the wettability was probed. The surface morphology and surface roughness in electroplated Ni-P was observed with the aid of both field emission scanning electron microscope (SEM) and atomic force microscope (AFM). The correlation between wettability and phosphorus contents in electroplated Ni-P was evaluated. As the phosphorous contents increased, the surface morphology of the Ni-P deposit was smoother and surface roughness of Ni-P became smaller. The improvement of surface morphology and surface roughness enhanced the wettability of electroplated Ni-P. The interfacial reaction between lead-free solder and electroplating Ni-P UBM was also investigated.	*Journal of Electronic Materials: January 2006*	pp. 7-14	Acquire this Paper

Recent TMS Articles: Lead-Free Solders

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Title	Authors	Abstract	Journal	Pages	Link
Effects of Bi and Pb on Oxidation in Humidity for Low-Temperature Lead-Free Solder Systems	*Keun-Soo Kim, Toshinori Matsuura, and Katsuaki Suganuma*	The oxidation behavior of various Sn-Zn(-Bi) alloys during 60°C/90% and 85°C/85% relative humidity (RH) exposure were investigated by microstructure observation and x-ray diffraction analysis. The mechanical property of the joints of resistor chips (1608R) with two kinds of terminations, Sn and Sn-10Pb, soldered on a printed circuit board with Sn-Zn(-Bi) were evaluated by a shear test. The heat/humidity exposure of Sn-Zn alloys promotes segregation into the grain boundary accompanying oxidation of Zn resulting in the ZnO formation. This segregation induces serious degradation of alloys and Sn whisker growth. Heat/humidity exposure of 85°C/85%RH seriously decreases the shear strength of the surface mounted chip joints, especially Sn-Zn-Bi solder, due to the formation of ZnO at the interface between the solder and the reaction layer. The presence of Bi or Pb in Sn-Zn alloys enhances the diffusion, resulting in severe degradation at 85°C/85%RH exposure. In contrast, the exposure at 60°C/90%RH does not influence the joint strength for up to 1000 h. Under this condition, the oxidation of Zn only reaches a few microns in dep	*Journal of Electronic Materials: January 2006*	pp. 41-47	Acquire this Paper
Microstructure Evolution of Gold-Tin Eutectic Solder on Cu and Ni Substrates	*J.Y. Tsai, C.W. Chang, C.E. Ho, Y.L. Lin, and C.R. Kao*	The microstructures of the eutectic Au20Sn (wt.%) solder that developed on the Cu and Ni substrates were studied. The Sn/Au/Ni sandwich structure (2.5/3.75/2 µm) and the Sn/Au/Ni sandwich structure (1.83/2.74/5.8 µm) were deposited on Si wafers first. The overall composition of the Au and the Sn layers in these sandwich structures corresponded to the Au20Sn binary eutectic. The microstructures of the Au20Sn solder on the Cu and Ni substrates could be controlled by using different bonding conditions. When the bonding condition was 290°C for 2 min, the microstructure of Au20Sn/Cu and Au20Sn/Ni was a two-phase (Au5Sn and AuSn) eutectic microstructure. When the bonding condition was 240°C for 2 min, the AuSn/Au5Sn/Cu and AuSn/Au5Sn/Ni layered microstructure formed. After bonding, the Au20Sn/Cu and Au20Sn/Ni diffusion couples were subjected to aging at 240°C. The thermal stability of Au20Sn/Ni was better than that of Au20Sn/Cu. Moreover, less Ni was consumed compared to that of Cu. This indicates that Ni is a more effective diffusion barrier material for the Au20Sn solder.	*Journal of Electronic Materials: January 2006*	pp. 65-71	Acquire this Paper
Microstructure, Solderability, and Growth of Intermetallic Compounds of Sn-Ag-Cu RE Lead-Free Solder Alloys	*C.M.T. Law, C.M.L. Wu, D.Q. Yu, L. Wang, and J.K.L. Lai*	The near-eutectic Sn-3.5 wt.% Ag-0.7 wt.% Cu (Sn-3.5Ag-0.7Cu) alloy was doped with rare earth (RE) elements of primarily Ce and La of 0.05–0.25 wt.% to form Sn-3.5Ag-0.7Cu-xRE solder alloys. The aim of this research was to investigate the effect of the addition of RE elements on the microstructure and solderability of this alloy. Sn-3.5Ag-0.7Cu-xRE solders were soldered on copper coupons. The thickness of the intermetallic layer (IML) formed between the solder and Cu substrate just after soldering, as well as after thermal aging at 170°C up to 1000 h, was investigated. It was found that, due to the addition of the RE elements, the size of the Sn grains was reduced. In particular, the addition of 0.1wt.%RE to the Sn-3.5Ag-0.7Cu solder improved the wetting behavior. Besides, the IML growth during thermal aging was inhibited.	*Journal of Electronic Materials: January 2006*	pp. 89-93	Acquire this Paper
Suppression of Void Coalescence in Thermal Aging of Tin-Silver-Copper-X Solder Joints	*I.E. Anderson and J.L. Harringa*	Addressing the potential for drop impact failure of Pb-free interconnects, the shear ductility after extensive aging of Sn-Ag-Cu (SAC) solders has been improved radically by Co or Fe modifications. Several other SAC + X candidates (X = Mn, Ni, Ge, Ti, Si, Cr, and Zn) now have been tested. Solder joint microstructures and shear strength results show that new SAC + X alloys also suppress void formation and coalescence at the Cu (substrate)/Cu3Sn interface (and embrittlement) after aging at 150°C for up to 1,000 h. Microprobe measurements of 1,000 h aged samples suggest that Cu substitution by X is usually accentuated in the intermetallic layers, consistent with X = Co and Fe results.	*Journal of Electronic Materials: January 2006*	pp. 94-106	Acquire this Paper
A Quantitative Evaluation of Time-Indepenent and Time-Dependent Deformations of Lead-Free and Lead-Containing Solder Alloys	*Ken-Ichi Ohguchi, Katsuhiko Sasaki, and Masahiro Ishibashi*	A method to separate plasticity and creep is discussed for a quantitative evaluation of the plastic, transient creep, and steady-state creep deformations of solder alloys. The method of separation employs an elasto-plastic-creep constitutive model comprised of the sum of the plastic, transient creep, and steady-state creep deformations. The plastic deformation is expressed by the Ramberg–Osgood law, the steady-state creep deformation by Garofalo's creep law, and the transient creep deformation by a model proposed here. A method to estimate the material constants in the elasto-plastic-creep constitutive model is also proposed. The method of separation of the various deformations is applied to the deformation of the lead-free solder alloy Sn/3Ag/0.5Cu and the lead-containing solder alloy Sn/37Pb to compare the differences in the plastic, transient creep, and steady-state creep deformations. The method of separation provides a powerful tool to select the optimum lead-free solder alloys for solder joints of electronic devices.	*Journal of Electronic Materials: January 2006*	pp. 132-139	Acquire this Paper

Title	Authors	Abstract	Journal	Pages	Link
Morphology and Growth Kinetics of Intermetallic Compounds in Solid-State Interfacial Reaction of Electroless Ni-P with Sn-Based Lead-Free Solders	*M.L. Huang, T. Loeher, D. Manessis, L. Boettcher, A. Ostmann, and H. Reichl*	A comparative study of solid/solid interfacial reactions of electroless Ni-P (15 at.% P) with lead-free solders, Sn-0.7Cu, Sn-3.5Ag, Sn-3.8Ag-0.7Cu, and pure Sn, was carried out by performing thermal aging at 150°C up to 1000 h. For pure Sn and Sn-3.5Ag solder, three distinctive layers, Ni3Sn4, SnNiP, and Ni3P, were observed in between the solder and electroless Ni-P; while for Sn-0.7Cu and Sn-3.8Ag-0.7Cu solders, two distinctive layers, (CuNi)6Sn5 and Ni3P, were observed. The differences in morphology and growth kinetics of the intermetallic compounds (IMCs) at the interfaces between electroless Ni-P and lead-free solders were investigated, as well as the growth kinetics of the P-enriched layers underneath the interfacial IMC layers. With increasing aging time, the coarsening of interfacial Ni3Sn4 IMC grains for pure Sn and Sn-3.5Ag solder was significantly greater than that of the interfacial (CuNi)6Sn5 IMC grains for Sn-0.7Cu and Sn-3.8Ag-0.7Cu solders. Furthermore, the Ni content in interfacial (CuNi)6Sn5 phase slightly increased during aging. A small addition of Cu (0.7 wt.%) resulted in differences in the type, morphology, and growth k	*Journal of Electronic Materials: January 2006*	pp. 181-188	Acquire this Paper
Lead Contamination of a Transient Liquid-Phase-Processed Sn-Bi Lead-Free Solder Paste	*M. Whitney and S.F. Corbin*	The influence of Pb contamination on the solidification behavior of a transient liquid-phase powder-processed Sn-Bi solder paste has been studied using differential scanning calorimetry. The development of low-temperature ternary reactions was found to be very sensitive to both the Pb and Bi content of the solder. Solders with high Bi content favored the formation of the ternary eutectic reaction. Solders with high Pb contents favored the formation of a ternary peritectic reaction. These results agree very well with solidification predictions present in the literature for ternary Sn-Bi-Pb alloys. In particular, the dependence of ternary reactions on composition is due to a change in solidification path. Alloy compositions which mark the transition from one path to the next were identified.	*Journal of Electronic Materials: February 2006*	pp. 284-291	Acquire this Paper
Effects of Strain Ratio and Tensile Hold Time on Low-Cycle Fatigue of Lead-Free Sn-3.5Ag-0.5Cu Solder	*Chih-Kuang Lin and Chun-Ming Huang*	Low-cycle fatigue (LCF) behavior of a lead-free Sn-3.5Ag-0.5Cu solder alloy was investigated at various combinations of strain ratio (R = –1, 0, and 0.5) and tensile hold time (0, 10, and 100 sec). Results showed that the LCF life of the given solder, at each given combination of testing conditions, could be individually described by a Coffin-Manson relationship. An increase of strain ratio from R = –1 to 0 and to 0.5 would cause a significant reduction of LCF life due to a mean strain effect instead of mean stress effect. LCF life was also markedly reduced when the hold time at tensile peak strain was increased from 0 to 100 sec, as a result of additional creep damage generated during LCF loading. With consideration of the effects of strain ratio and tensile hold time, a unified LCF lifetime model was proposed and did an excellent job in describing the LCF lives for all given testing conditions.	*Journal of Electronic Materials: February 2006*	pp. 292-301	Acquire this Paper
Cross-Interaction Between Au and Cu in Au/Sn/Cu Ternary Diffusion Couples	*C.W. Chang, Q.P. Lee, C.E. Ho, and C.R. Kao*	Both Au and Cu are so-called fast diffusers in Sn, and can diffuse very long distances in Sn in a relatively short time. In this study, the cross-interaction between Au and Cu across a layer of Sn was investigated through the use of the Au/Sn/Cu ternary diffusion couples. A 7-μm Au layer and a 100-μm Sn layer were electroplated over Cu foils to produce the Au/Sn/Cu diffusion couples. Aging at 200°C revealed that cross-interaction could occur in as short a time as 10 min. Evidence of this cross-interaction included the formation of (Cu1–xAux)6Sn5 on the Au side of the diffusion couples as well as on the Cu side. The reaction products on the Au side included the Au-Sn binary compounds. Between the Au-Sn compounds and the Sn was (Cu1–xAux)6Sn5. The reaction products on the Cu side initially was only (Cu1–xAux)6Sn5, but a layer of Au-free Cu3Sn eventually formed between (Cu1–xAux)6Sn5 and Cu. A detailed atomic flux analysis showed that the Cu flux through the Sn layer was about 2–3 times higher than the Au flux at any moment. The results of this study show that the cross-interaction of Au and Cu in solders is extremely rapid, and cannot be ignor	*Journal of Electronic Materials: February 2006*	pp. 366-371	Acquire this Paper
Influence of Ni Concentration and NI3Sn4 Nanoparticles on Morphology of Sn-Ag-Ni Solders by Mechanical Alloying	*Hsiang-Yi Lee and Jenq-Gong Duh*	The mechanical alloying (MA) process was employed as an alternative method to produce the lead-free solder pastes of Sn-3.5Ag-xNi (x = 0.1, 0.5, 1.0, 1.5, and 2.0) in this study. When the Ni concentration was low (x = 0.1, 0.5), MA particles agglomerated to a flat ingot with particle sizes >100 μm. For higher Ni concentration (x = 1.0, 1.5, and 2.0), MA particles turned into fragments with particle sizes <100 μm. The particle size of the solders appeared to be dependent on the Ni concentration. To reduce the particle size of SnAgNi alloys with low Ni concentration, Ni3Sn4 nanoparticles were doped into Sn and Ag powders to derive a Ni3Sn4-doped solder. For the Ni3Sn4-doped solder, the particle size was smaller than that doped by the pure Ni. The distinction of milling mechanism between Ni3Sn4-doped solder and the pure Ni-doped solder by MA process was probed and discussed. In addition, differential scanning calorimetry (DSC) results ensured its feasibility in applying the solder material in the reflow process. Wettability tests between solders and Cu substrate also revealed that the wetting angles for Ni3Sn4-doped solder with low Ni concentr	*Journal of Electronic Materials: March 2006*	pp. 494-503	Acquire this Paper

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Title	Authors	Abstract	Journal	Pages	Link
Microstructure and Mechanical Properties Evolution of Intermetallics between Cu and Sn-3.5Ag Solder Doped by Ni-Co Additives	*F. Gao, T. Takemoto, H. Nishikawa, and A. Komatsu*	The evolution of intermetallic compounds (IMCs) generated between Sn-3.5Ag solder doped by additive couples (namely, 0.2mass%Co and 0.1mass%Ni) and Cu substrate was characterized. After soldering, the additive couples, Co-Ni, were all detected at the intermetallic region. The microstructure of intermetallic was identified as (Cu, Ni, Co)6Sn5 by electron probe microanalysis (EPMA) and x-ray diffraction (XRD). However, the morphology of (Cu, Ni, Co)6Sn5 was converted to columnar like and was not as dense as the typical scallop-like Cu6Sn5. A duplex structure of (Cu, Ni, Co)6Sn5, namely, two distinct regions bearing different concentrations of Ni and Co, was observed. Much higher Ni and Co concentrations were probed in the outer intermetallic region adjacent to the solder matrix, while lower concentration at the inner region was verified. After aging, the intermetallic (Cu, Ni, Co)6Sn5 tended to be dense, while the growth rate was depressed at the early stage. In addition, the Cu3Sn phase was not detected after aging at 110°C, while it appeared at 130°C and 150°C for 504 h. Using the nanoindentation technique, some mechanical properties of	*Journal of Electronic Materials: May 2006*	pp. 905-911	Acquire this Paper
A Study of Electrically Conductive Adhesives as a Manufacturing Solder Alternative	*F.M. Coughlan and H.J. Lewis*	Soldering processes using tin/lead solder are standard interconnection technologies for electronic manufacturing. These processes are currently under threat from the Waste Electrical and Electronic Equipment and the Restriction of Hazardous Substances (RoHS) environmental directives, issued by the European Union in 2000. These directives explain that solder is to be free from lead by 2006, as lead has been recognized by the European Union as an environmentally harmful material. One solder alternative that has been investigated by the electronics industry is the area of electrically conductive adhesives (ECAs). This paper outlines the electrical and mechanical analysis of two isotropic conductive adhesives where the main properties of joint resistance and adhesive strength were examined before and after different environmental treatments. Joint resistance was measured with a four-probe tester and adhesive strength was examined with the use of shear testing. Crosssectional and scanning electron microscopy analyses were used to determine problems such as oxidation and moisture absorption that may have an affect	*Journal of Electronic Materials: May 2006*	pp. 912-921	Acquire this Paper
Effect of Zn Content on the Vibration Fracture Behavior of Sn-Zn and Sn-Zn-Bi Solders	*Jenn-Ming Song, Truan-Sheng Lui, Yea-Luen Chang, and Li-Hui Chen*	This study investigated the microstructure and vibration properties of Sn-Zn and Sn-Zn-Bi alloys with different Zn contents. Experimental results show that the hypoeutectic Sn-Zn-Bi alloy (with a Zn content of 5 wt.%) has the poorest damping capacity and the lowest critical vibration cycles to failure due to a hardening effect by Bi and intergranular fracturing. On the other hand, since the Zn/Sn interfaces at which internal friction may occur during vibration contribute to the dissipation of vibration energy, the hypereutectic Sn-13Zn samples with numerous massive primary Zn needles possess superior damping capacity and vibration life under constant vibration force conditions.	*Journal of Electronic Materials: May 2006*	pp. 929-936	Acquire this Paper
Reliability of Adhesion Strength of the Sn-9Zn-1.5Ag-0.5Bi/Cu during Isothermal Aging	*Chih-Yao Liu, Moo-Chin Wang, and Min-Hsiung Hon*	The reliability of adhesion strength of the Sn-9Zn-1.5Ag-0.5Bi/Cu during isothermal aging has been investigated. Due to the growth and decomposition of the intermetallic compound (IMC), the adhesion strength varies with aging at 150°C from 100, 400, and 700–1,000 h as wetted at 250°C for 60 sec. The IMC layers are determined at the Sn-9Zn-1.5Ag-0.5Bi/Cu interface by an x-ray diffractometer (XRD), an optical microscope (OM), a scanning electron microscope (SEM), an energy-dispersive spectroscope (EDS), and a transmission electron microscope (TEM). The adhesion strength has been investigated by the pull-off test. The results show that the Cu6Sn5, Cu5Zn8, and Ag3Sn IMCs are identified at the Sn-9Zn-1.5Ag-0.5Bi/Cu interface as aging. The adhesion strengths are 12.44 ± 0.58, 8.57 ± 0.43, 5.50 ± 0.78, 4.32 ± 0.78, and 3.32 ± 0.43 MPa for aging times of 0 h, 100 h, 400 h, 700 h, and 1,000 h, respectively.	*Journal of Electronic Materials: May 2006*	pp. 966-971	Acquire this Paper
Dissolution Behavior of Cu and Ag Substrates in Molten Solders	*Po-Yi Yeh, Jenn-Ming Song, and Kwang-Lung Lin*	This study investigated the dissolution behavior of Cu and Ag substrates in molten Sn, Sn-3.5Ag, Sn-4.0Ag-0.5Cu, Sn-8.6Zn and Sn-8.55Zn-0.5Ag-0.1Al-0.5Ga lead-free solders as well as in Sn-37Pb solder for comparison at 300, 350, and 400°C. Results show that Sn-Zn alloys have a substantially lower dissolution rate of both Cu and Ag substrates than the other solders. Differences in interfacial intermetallic compounds formed during reaction and the morphology of these compounds strongly affected the substrate dissolution behavior. Soldering temperature and the corresponding solubility limit of the substrate elements in the liquid solder also played important roles in the interfacial morphology and dissolution rate of substrate.	*Journal of Electronic Materials: May 2006*	pp. 978-987	Acquire this Paper
Reliability Testing of WLCSP Lead-Free Solder Joints	*Huann-Wu Chiang, Jun-Yuan Chen, Ming-Chuan Chen, Jeffrey C.B. Lee, and Gary Shiau*	The interfacial reactions of solder joints between Sn-4Ag-0.5Cu solder ball and a couple of presoldered pastes (Sn-7Zn-Al(30ppm) and Sn-3Ag-0.5Cu) were investigated in wafer-level chip-scale package (WLCSP). After appropriate surface mount technology reflow processes on printed circuit boards with a Cu/OSP (organic solderability preservative) surface finish, samples were subjected to 150°C high-temperature storage (HTS) for 1,000 h of aging or 1,000 cycles of a thermal cycling test (TCT). Sequentially, cross-section analysis is scrutinized by scanning electron microscopy/energy dispersive spectrometry and energy probe microanalysis to observe metallurgical evolution in the interface and solder buck itself. It was found that the degradation of the joint shear strength after TCT is more pronounced than that of the shear strength after HTS. Fracture surface analyses of the shear tests show that the degradation of the joint strength for HTS is solely due to the influence of the interfacial IMC grain growth, while the shear strength degradation for TCT is mainly due to the coefficient thermal expansion mismatch from the thermal cy	*Journal of Electronic Materials: May 2006*	pp. 1032-1040	Acquire this Paper

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Mechanical Properties of Intermetallic Compounds on Lead-Free Solder by Moire Techniques	*Iting Tsai, Enboa Wu, S.F. Yen, and T.H. Chuang*	In this paper, methods for determining elastic moduli and coefficients of thermal expansion (CTE) of intermetallic compounds (IMC) formed at the interfaces between lead-free solder and metal substrates are presented. For the determination of elastic moduli, two kinds of lead-free solder—SnZn and Sn—were used; the metal substrates were copper and nickel. Nanoindentation techniques were adopted to determine the elastic moduli of Cu33.5Zn66.6, Cu3Sn, Cu6Sn5, and Ni3Sn4. Results for Cu33.5Zn66.6 are new to the literature, and others values are in good agreement with those presented in the literature. On the other hand, for CTE determination, two moiré techniques, namely reflection moiré and shadow moiré, were developed to measure the deformation of IMC/metal composite structures subjected to thermal loading. Finite-element analyses using ANSYS were then performed as a convolutional process, and the genetic search algorithm was used to optimally obtain the CTE of IMC. The CTE of Cu33.5Zn66.6 was found to be approximate to that of copper, and the CTE of Cu3Sn was 10% larger. This method is also applicable to on-wafer films....	*Journal of Electronic Materials: May 2006*	pp. 1059-1066	Acquire this Paper
Comparative Study of Microstructures and Properties of Three Valuable SnAgCuRE Lead-Free Solder Alloys	*Weimin Xiao, Yaowu Shi, Yongping Lei, Zhidong Xia, and Fu Guo*	Lead-free solders with excellent material properties and low cost are essential for the electronics industry. It has been proved that mechanical properties of SnAgCu alloys can be remarkably improved with a minute addition of rare earth (RE) elements. For comparison and optimization, three valuable solder candidates, Sn3.8Ag0.7Cu0.05RE, Sn3Ag0.5Cu0.05RE, and Sn2.9Ag1.2-Cu0.05RE, were chosen due to the excellent properties of their own SnAgCu basic alloys. Wetting properties, melting temperature, bulk tensile properties, and joint tensile and shear properties were investigated. In addition, the microstructures of solder joints were observed and the effects of microstructure on mechanical properties were analyzed. Experimental results indicated that the tensile and shear strengths of solder joints were decreased from Sn3.8Ag0.7Cu0.05RE, Sn2.9Ag1.2Cu0.05RE, to Sn3Ag0.5Cu0.05RE, in order. Such difference in mechanical properties could be attributed to the influence of slightly coarse or strong Cu6Sn5 scallops in the reaction layer as well as superior eutectic network and large volume percentage of large primary intermetallic	*Journal of Electronic Materials: May 2006*	pp. 1095-1103	Acquire this Paper
Interfacial Reaction between Sn-0.7Cu (-Ni) Solder and Cu Substrates	*Hiroshi Nishikawa, Jin Yu Piao, and Tadashi Takemoto*	The interfacial reaction between Sn-0.7mass%Cu-(Ni) solders and a Cu substrate was investigated to reveal the effect of the addition of Ni to Sn-Cu solder on the formation of intermetallic compounds (IMCs). Sn-0.7Cu-xNi solders (x = 0, 0.05, 0.1, 0.2 mass%) were prepared. For the reflow process, specimens were heated in a radiation furnace at 523 K for 60 sec, 300 sec, and 720 sec to estimate the interfacial reaction between the molten solder and Cu substrate. Then, for the aging process, some specimens were heat-treated in an oil bath at 423 K for 168 h and 504 h. The cross sections of soldered specimens were observed to measure the dissolution thickness of the Cu substrate and the thickness of the IMC and to investigate the microstructures of IMC. The results showed that, just after the reflow process, the dissolution thickness of the Cu substrate increased with the increase of Ni content in the Sn-0.7Cu-xNi solder and the thickness of the IMC between the solder and Cu substrate was the minimum in the Sn-0.7Cu-0.05Ni solder. After the aging process, the IMC grew with the increase of aging time. In the case of 0.05% Ni, the IMC thickn	*Journal of Electronic Materials: May 2006*	pp. 1127-1132	Acquire this Paper
Lead-Free Solder Reinforced with Multiwalled Carbon Nanotubes	*S.M.L. Nai, J. Wei, and M. Gupta*	In this study, varying weight percentages of multiwalled carbon nanotubes were successfully incorporated into 95.8Sn-3.5Ag-0.7Cu solder to synthesize novel lead-free composite solders. The composite solders were synthesized using a powder metallurgy route consisting of blending, compaction, sintering, and extrusion. The extruded materials were then characterized for their physical, thermal, and mechanical properties. With the addition of increasing weight percentage of carbon nanotubes, the composite solders experienced a corresponding decrease in density values and an improvement in wetting properties. The melting temperatures of the composite solders were found to be unchanged with additions of carbon nanotubes. However, improvements in the mechanical properties, in terms of microhardness and tensile properties, were observed with increasing weight percentages of carbon nanotubes.	*Journal of Electronic Materials: July 2006*	pp. 1518-1522	Acquire this Paper
Effect of Flux on the Wetting Characteristics of SnAg, SnCu.SnAgBi, and SnAgCu Lead-Free Solders on Copper Substrates	*Maria F. Arenas, Min He, and Viola L. Acoff*	The effect of flux on the wetting characteristics of four lead-free solders, Sn-3.5Ag, Sn-0.7Cu, Sn-3.5Ag-4.8Bi, and Sn-3.8Ag-0.7Cu (wt.%), on copper substrates have been studied at 240, 260, and 280°C. The fluxes investigated were rosin (R), mildly activated rosin (RMA), and activated rosin (RA). The wetting tests were conducted using the sessile-drop method. Results showed that fluxes significantly affect the wetting properties of the solders. Contact angles ranging from 10° to 30° for RMA, 20° to 30° for RA, and 5° to 60° for R were obtained. The effect of temperature on contact angle depended on the type of flux used. The contact angle decreased with increasing temperature; however, in some cases the contact angle was independent of temperature. The Sn-3.5Ag-4.8Bi exhibited the lowest contact angles indicating improved wettability with addition of bismuth. The microstructure of the solder/copper interface was analyzed by scanning electron microscopy.	*Journal of Electronic Materials: July 2006*	pp. 1530-1536	Acquire this Paper

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Intermetallic Growth Kinetics for Sn-Ag, Sn-Cu, and Sn-Ag-Cu Lead-Free Solders on Cu, Ni, and Fe-42Ni Substrates	*N. Dariavach, P. Callahan, J. Liang, and R. Fournelle*	Soldering with the lead-free tin-base alloys requires substantially higher temperatures (~235–250°C) than those (213–223°C) required for the current tin-lead solders, and the rates for intermetallic compound (IMC) growth and substrate dissolution are known to be significantly greater for these alloys. In this study, the IMC growth kinetics for Sn-3.7Ag, Sn-0.7Cu, and Sn-3.8Ag-0.7Cu solders on Cu substrates and for Sn-3.8Ag-0.7Cu solder with three different substrates (Cu, Ni, and Fe-42Ni) are investigated. For all three solders on Cu, a thick scalloped layer of η phase (Cu6Sn5) and a thin layer of ε phase (Cu3Sn) were observed to form, with the growth of the layers being fastest for the Sn-3.8Ag-0.7Cu alloy and slowest for the Sn-3.7Ag alloy. For the Sn-3.8Ag-0.7Cu solder on Ni, only a relatively uniform thick layer of η phase (Cu,Ni)6Sn5 growing faster than that on the Cu substrate was found to form. IMC growth in both cases appears to be controlled by grain-boundary diffusion through the IMC layer. For the Fe-42Ni substrate with the Sn-3.8Ag-0.7Cu, only a very thin layer of (Fe,Ni)Sn2 was observed to develop.	*Journal of Electronic Materials: July 2006*	pp. 1581-1592	Acquire this Paper
Microstructure, Creep Properties, and Failure Mechanism of SnAgCu Solder Joints	*Janne J. Sundelin, Sami T. Nurmi, Toivo K. Lepistö, and Eero O. Ristolainen*	The effect of microstructure on the creep properties and the failure mechanism of SnAgCu solder joints was studied. Single overlap shear specimens made of FR-4 printed circuit boards (PCBs) with organic solderability preservative (OSP), NiAu, and immersion Sn surface finish were reflow-soldered with hypoeutectic, eutectic, and hypereutectic SnAgCu solder paste. Creep tests of the solder joints were performed at 85°C and 105°C under constant load. The effect of microstructure on the creep behavior of the joints was studied by examining the fracture surfaces and cross-sectional samples of the tested joints. Results show that the intermetallic compound at the interface between the PCB and solder affects the fracture behavior of SnAgCu solder joints, thus creating a significant difference in the creep properties of solder joints on different surface finishes. Composition of SnAgCu solder was also found to affect the creep properties of the joints.	*Journal of Electronic Materials: July 2006*	pp. 1600-1606	Acquire this Paper
Optimal Phosphorous Content Selection for the Soldering Reaction of Ni-P Under Bump Metallication with Sn-Ag-Cu Solder	*Yung-Chi Lin and Jenq-Gong Duh*	Nickel plating has been used as the under bump metallization (UBM) in the microelectronics industry. The electroplated Ni-P UBM with different phosphorous contents (7 wt.%, 10 wt.%, and 13 wt.%) was used to evaluate the interfacial reaction between Ni-P UBM and Sn-3Ag-0.5Cu solder paste during multiple reflow. (Cu,Ni)6Sn5 intermetallic compounds (IMC) formed in the SnAgCu solder/Ni-P UBM interface after the first reflow. For three times reflow, (Ni,Cu)3Sn4 IMC formed, while (Cu,Ni)6Sn5 IMC spalled into the solder matrix. With further increasing cycles of reflow, the Ni-Sn-P layer formed between (Ni,Cu)3Sn4 IMC and Ni-P UBM for Ni-10wt.%P and Ni-13wt.%P UBM. However, almost no Ni-Sn-P layer was revealed for the Ni-7wt.%P UBM even after ten cycles of reflow. In consideration of the wettability of Ni-P UBM, the interfacial reaction of SnAgCu/Ni-P, and dissolution of Ni-P UBM, the optimal phosphorous selection in Ni-P UBM was proposed and also discussed.	*Journal of Electronic Materials: August 2006*	pp. 1665-1671	Acquire this Paper
Strengthening Effects of ZrO2 Nanoparticles on the Microstructure and Microhardness of Sn-3.5Ag Lead-Free Solder	*J. Shen, Y.C. Liu, Y.J. Han, Y.M. Tian, and H.X. Gao*	A ZrO2 nanoparticle strengthened lead-free Sn-3.5Ag-ZrO2 solder was prepared by mechanically stirring ZrO2 nanoparticles into the molten melt of eutectic Sn-3.5Ag alloy. The influence of ZrO2 nanoparticles on the eutectic solidification process, in particular, the formation of Ag3Sn intermetallic compounds (IMCs) and the associated microstructure that forms and microhardness of Sn-3.5Ag solder, was systematically investigated. The addition of ZrO2 nanoparticles significantly refined the size of Ag3Sn IMCs due to the strong adsorption effect of the ZrO2 nanoparticles. The refined Ag3Sn IMCs increase the Vicker's microhardness of the prepared Sn-3.5Ag-ZrO2 solder, which corresponds well with the prediction of the classic theory of dispersion strengthening.	*Journal of Electronic Materials: August 2006*	pp. 1672-1679	Acquire this Paper
Effect of Small Additions of Alloying Elements on the Properties of Sn-Zn Eutectic Alloy	*X. Chen, M. Li, X.X. Ren, A.M. Hu, and D.L. Mao*	Sn-Zn alloys have been considered for use as lead-free solders. Their poor wetting and oxidation resistance properties are the main obstacles that prevent them from becoming commercially viable solders. The effects of alloying elements, such as lanthanum, titanium, aluminum, and chromium, on oxidation resistance, wetting properties, and tensile properties of eutectic Sn-Zn solder are described herein. Results show the addition of alloying Ti, Al, and Cr can improve the oxidation resistance of Sn-9Zn solder. La, Ti, and Cr do not have much effect on the wetting properties, whereas Al worsens the wetting. Differential scanning calorimetry investigations reveal the solidus temperature of these solders to be ~200°C. Addition of Cr improves ductility while maintaining tensile strength.	*Journal of Electronic Materials: September 2006*	pp. 1734-1739	Acquire this Paper
Role of Shape-memory Alloy Reinforcements on Strain Evolution in Lead-free Solder Joints	*I. Dutta, D. Pan, S. Ma, B.S. Majumdar, and S. Harris*	Microelectronic solder joints are exposed to aggressive thermomechanical cycling (TMC) during service, resulting in strain localization near solder/bond-pad interfaces, which eventually leads to low-cycle fatigue (LCF) failure of the joint. In order to mitigate these strain concentrations, a "smart solder" reinforced with a martensitic NiTi-based shape-memory alloy (SMA) has been proposed before. In the present work, the role of NiTi particles on strain evolution in composite solders was studied using a combination of experimental and numerical means. Finite element modeling showed that NiTi pariculate reinforcements can reduce inelastic strain levels in the solder via shape recovery associated with the B19′ → B2 transformation. In situ TMC studies in the scanning electron microscope (SEM), in conjunction with strain analysis via digital image correlation (DIC), showed evidence of reverse deformation in the solder commensurate with the NiTi phase transformation, demonstrating the conceptual viability of the smart solder approach.	*Journal of Electronic Materials: October 2006*	pp. 1902-1913	Acquire this Paper

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Effects of Solder Alloy Constitutive Relationships on Impact Force Responses of Package-level Solder Joints Under Ball Impact Test	*Chang-Lin Yeh and Yi-Shao Lai*	The ball impact test was developed as a package-level measure for the board-level drop reliability of solder joints in the sense that it leads to fracturing of solder joints around intermetallics, similar to that from a board-level drop test. We investigated numerically the effects of constitutive relationships of solder alloy on transient structural responses of a single package-level solder joint subjected to ball impact testing. This study focused on the characteristics of the ascending part of the impact force profile. According to the piecewise linear stress-strain curve obtained for the Sn-4Ag-0.5Cu solder alloy, parametric studies were performed by varying either segmental moduli or characteristic stresses of the curve at fixed ratios, with regard to the lack of available rate-dependent material properties of solder alloys.	*Journal of Electronic Materials: October 2006*	pp. 1892-1901	Acquire this Paper
Effect of Cu Additives on Sn Whisker Formation of Sn(Cu) Finishes	*H.J. Kao, W.C. Wu, S.T. Tsai, and C.Y. Liu*	Sn whisker formation on Sn(Cu) finishes has been studied. (1) With respect to the thickness effect, we found that Sn whisker density for pure Sn and Sn0.7Cu finishes has a linear relationship with the finish thickness. The safety thickness for Sn and Sn0.7Cu finishes is about 10 μm and 20 μm, respectively. (2) With respect to the alloying effect, we found that Sn whisker formation could be retarded by increasing Cu content in the Sn(Cu) finishes. We conclude that the Cu additives could reduce the two major driving forces of the Sn whisker formation, i.e., metal underlayer dissolution and thermal stress. The Cu additives self-formed a Cu-Sn compound barrier layer, which effectively prevents the reaction and dissolution with the metal underlayer. On the other hand, the Cu additives precipitated out as Cu-Sn compound in the Sn(Cu) finish layer, which is believed to be the reason for smaller values of the coefficient of thermal expansion (CTE) for Sn(Cu) alloys. The smaller CTE values results in a lower thermal stress level in the Sn(Cu) finishes.	*Journal of Electronic Materials: October 2006*	pp. 1885-1891	Acquire this Paper
Effect of Thermal Cycling on the Growth of Intermetallic Compounds at the Sn-Zn-Bi-In-P Lead-Free Solder/Cu Interface	*Guohai Chen, Xiaoyan Li, and Jusheng Ma*	The low-temperature Sn-9Zn-1.5Bi-0.5In-0.01P lead-free solder alloy is used to investigate the intermetallic compounds (IMCs) formed between solder and Cu substrates during thermal cycling. Metallographic observation, scanning electron microscopy, transmission electron microscopy, and electron diffraction analysis are used to study the IMCs. The γ-Cu5Zn8 IMC is found at the Sn-9Zn-1.5Bi-0.5In-0.01P/Cu interface. The IMC grows slowly during thermal cycling. The fatigue life of the Sn-9Zn-1.5Bi-0.5In-0.01P solder joint is longer than that of Pb-Sn eutectic solder joint because the IMC thickness of the latter is much greater than that of the former. Thermodynamic and diffusivity calculations can explain the formation of γ-Cu5Zn8 instead of Cu-Sn IMCs. The growth of IMC layer is caused by the diffusion of Cu and Zn elements. The diffusion coefficient of Zn in the Cu5Zn8 layer is determined to be 1.10 × 10–12 cm2/sec. A Zn-rich layer is found at the interface, which can prevent the formation of the more brittle Cu-Sn IMCs, slow down the growth of the IMC layer, and consequently enhance the fatigue life of the solder joint.	*Journal of Electronic Materials: October 2006*	pp. 1873-1878]	Acquire this Paper
Metallurgical Reactions in Composite 90Pb10Sn/Lead-Free Solder Joints and Their Effect on Reliability of LTCC/PWB Assembly	*O. Nousiainen, J. Putaala, T. Kangasvieri, R. Rautioaho, and J. Vähäkangas*	Use of 90Pb10Sn solder as a noncollapsible sphere material with 95.5Sn 4Ag0.5Cu and SnInAgCu lead-free solders is investigated. Practical reflow conditions led to strong Pb dissolution into liquid solder, resulting in >20 at.% Pb content in the original lead-free solders. The failure mechanism of the test joints is solder cracking due to thermal fatigue, but the characteristic lifetime of 90Pb10Sn/SnInAgCu joints is almost double that of 90Pb10Sn/95.5Sn4Ag0.5Cu in a thermal cycling test (TCT) over the temperature range from –40°C to 125°C. It is predicted that this is mainly a consequence of the better fatigue resistance of the SnPbInAgCu alloy compared with the SnPbAgCu alloy. Indium accelerates the growth of the intermetallic compound (IMC) layer at the low temperature co-fired ceramic (LTCC) metallization/solder interface and causes coarsening of IMC particles during the TCT, but these phenomena do not have a major effect on the creep/fatigue endurance of the test joints.	*Journal of Electronic Materials: October 2006*	pp. 1857-1865	Acquire this Paper
Interfacial Reaction between Sn-Bi Alloy and Ni Substrate	*J. Wang, H.S. Liu, L.B. Liu, and Z.P. Jin*	Interfacial reactions between Sn-Bi alloys of different compositions and Ni substrates at 423 K for different durations were investigated. Only one interfacial phase, Ni3Sn4, was detected despite the existence of several other intermetallic compounds (IMCs) in Ni-Sn and Ni-Bi binary systems. This observation (only Ni3Sn4 was formed at the interface) was explained as a combination of the driving force for formation of the IMC and diffusion of Ni. The change of Ni3Sn4 layer thickness as a function of annealing time, which obeys a parabolic rule, was further confirmed. The thickness of Ni3Sn4 was also found to decrease with increasing Bi content in the Sn-Bi alloy.	*Journal of Electronic Materials: October 2006*	pp. 1842-1747	Acquire this Paper
Effect of Reaction Time on Mechanical Strength of the Interface Formed between the Sn-Zn (-Bi) Solder and the Au/Ni/Cu Bond Pad	*Ahmed Sharif and Y.C. Chan*	In this work, the shear strengths and the interfacial reactions of Sn-9Zn, Sn-8Zn-1Bi, and Sn-8Zn-3Bi (wt.%) solders with Au/Ni/Cu ball grid array (BGA) pad metallization were systematically investigated after extended reflows. Zncontaining Pb-free solder alloys were kept in molten condition (240°C) on the Au/electrolytic Ni/Cu bond pads for different time periods ranging from 1 min. to 60 min. to render the ultimate interfacial reaction and to observe the consecutive shear strength. After the shear test, fracture surfaces were investigated by scanning electron microscopy equipped with an energy dispersive x-ray spectrometer. Cross-sectional studies of the interfaces were also conducted to correlate with the fracture surfaces. The solder ball shear load for all the solders during extended reflow increased with the increase of reflow time up to a certain stage and then decreased. It was found that the formation of thick Ni-Zn intermetallic compound (IMC) layers at the solder interface of the Au/ electrolytic Ni/Cu bond pad with Sn-Zn(-Bi) alloys deteriorated the mechanical strength of the joints.	*Journal of Electronic Materials: October 2006*	pp. 1812-1817	Acquire this Paper

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Electrical Characteristics for Sn-Ag-Cu Solder Bump with Ti/Ni/Cu Under-Bump Metallization after Temperature Cycling Tests	*T.I. Shi, Y.C. Lin, J.G. Duh, and Tom Hsu*	Lead-free solder bumps have been widely used in current flip-chip technology (FCT) due to environmental issues. Solder joints after temperature cycling tests were employed to investigate the interfacial reaction between the Ti/Ni/Cu under-bump metallization and Sn-Ag-Cu solders. The interfacial morphology and quantitative analysis of the intermetallic compounds (IMCs) were obtained by electron probe microanalysis (EPMA) and field emission electron probe microanalysis (FE-EPMA). Various types of IMCs such as (Cu1–x,Agx)6Sn5, (Cu1–y,Agy)3Sn, and (Ag1–z,Cuz)3Sn were observed. In addition to conventional I-V measurements by a special sample preparation technique, a scanning electron microscope (SEM) internal probing system was introduced to evaluate the electrical characteristics in the IMCs after various test conditions. The electrical data would be correlated to microstructural evolution due to the interfacial reaction between the solder and under-bump metallurgy (UBM). This study demonstrated the successful employment of an internal nanoprobing approach, which would help further understanding of the electrical behavior within an	*Journal of Electronic Materials: October 2006*	pp. 1773-1780	Acquire this Paper
Kinetics of $AuSn_4$ Migration in Lead-Free Solders	*C.W. Chang, C.E. Ho, S.C. Yang, and C.R. Kao*	The relatively fast diffusion of Au atoms in eutectic PbSn matrix is considered one of the contributing factors to the Au embrittlement problem. In this study, we further investigated the Au embrittlement problem in high-Sn solders. Experimentally, Sn3.5Ag (wt.%) spheres with 500-µm diameter were soldered over the Au/Ni soldering pads. It was found that some of the AuSn4 needles that formed after reflow inside the solder migrated back to the solder/pad interface during thermal aging. However, the migration kinetics in high-Sn solders was slower compared to that in eutectic PbSn. The difference in migration kinetics of AuSn4 in eutectic PbSn and SnAg was ascribed to the difference in the magnitudes of the Au flux and the Ni flux. In eutectic PbSn, the Au flux was much greater than that of the Ni flux, and the Au and Ni flux were in the same order of magnitude in eutectic SnAg. The relative magnitude of the Au and Ni flux changed in eutectic PbSn and SnAg because the homologous temperatures of PbSn and SnAg were different.	*Journal of Electronic Materials: November 2006*	pp. 1948-1954	Acquire this Paper
Numerical Prediction of Fraction of Eutectic Phase in Sn-Ag-Cu Soldering Using the Phase-Field Method	*Machiko Ode, Minoru Ueshima, Taichi Abe, Hideyuki Murakami, and Hidehiro Onodera*	A combination of macroscale solidification simulation and phase-field calculation is employed to predict the volume fraction of the eutectic phase in Sn-4.0 mass%Ag-XCu solder alloys (X = 0.5–1.1 mass%). The solidification simulation incorporates the cooling rate in the phase-field simulation. We assume the residual liquid solidifies as eutectic phase when the driving force for the nucleation of Cu_6Sn_5 amounts to a critical value, which is determined based on the experimental data. Though the calculation results depend on the experimental data, the obtained fractions are about 40% for 0.5 mass%Cu and more than 90% for 1.1 mass%Cu alloy, which shows good agreement with the experimental data.	*Journal of Electronic Materials: November 2006*	pp. 1969-1974	Acquire this Paper
In-Situ Electromigration Study on Sn-Ag-Cu Solder Joint by Digital Image Speckle Analysis [	*Luhua Xu and John H.L. Pang*	The phenomenon of electromigration in Pb-free Sn-Ag-Cu solder joint specimens subject to high current density was characterized. Digital image speckle analysis (DISA) was used to measure the in-situ microdeformation and strain of cross-sectioned solder joints, which are subject to electromigration with a current density of 5 × 103 A/cm2 under an ambient temperature of 150°C. After a 120 h electromigration test, a higher strain near large voids was detected near preexisting voids in the solder joints. The current-crowding effect on strain formation was characterized, as it was found that the strain is high near the interface, while in the middle of the solder bump, the strain is low and could be neglected. Nanoindentation markers were used to form dummy voids to study the effect of preexisting voids. The Sn atomic flux and its effect on formation of electromigration strain are discussed.	*Journal of Electronic Materials: November 2006*	pp. 1993-1999	Acquire this Paper
The Effect of Ag Content on the Formation of Ag_3Sn Plates in Sn-Ag-Cu Lead-Free Solder	*H.-W. Chiang, K. Chang, and J.-Y. Chen*	The formation of Ag3Sn plates in the Sn-Ag-Cu lead-free solder joints for two different Ag content solder balls was investigated in wafer level chip scale packages (WLCSPs). After an appropriate surface mount technology reflow process on a printed circuit board, samples were subjected to 150°C hightemperature storage (HTS), 1,000 h aging, or 1,000 cycles thermal cycling test (TCT). Sequentially, the cross-sectional analysis was scrutinized using a scanning electron microscope/energy dispersive spectrometer (SEM/EDX) to observe the metallurgical evolution of the amount of the Ag3Sn plates at the interface and the solder bulk itself. Pull and shear tests were also performed on samples. It was found that the interfacial intermetallic compound (IMC) thickness, the overall IMC area, and the numbers of Ag3Sn plates increase with increasing HTS and TCT cycles. The amount of large Ag3Sn plates found in the Sn-4.0Ag-0.5Cu solder balls is much greater than that found in the Sn-2.6Ag-0.5Cu solder balls; however, no significant difference was found in the joint strength between two different Ag content solder joints.	*Journal of Electronic Materials: December 2006*	pp. 2074-2080	Acquire this Paper

Title	Authors	Abstract	Journal	Pages	Link
Morphology and Growth Pattern Transition of Intermetallic Compounds between Cu and Sn-3.5Ag Containing a Small Amount of Additives	*Feng Gao, Tadashi Takemoto, and Hiorshi Nishikawa*	The morphology and grain growth pattern of intermetallic compounds (IMCs) formed between the Cu substrate and Sn-3.5Ag solder doped with a small amount of additive (0.1 mass%), say, Ni or Co, was investigated. After soldering, a duplex structure due to the additive discontinuity at the (Cu, Ni)6Sn5 and (Cu, Co)6Sn5 region was detected. That is, the outer area of the (Cu, Ni)6Sn5 and (Cu, Co)6Sn5 region on the solder side contained much higher Ni or Co additive concentration than the inner area on the Cu side. The faceted-shape IMCs were observed at the outer area, while the rounded-shape were identified at the inner area of (Cu, Ni)6Sn5 and (Cu, Co)6Sn5. Based on the thermodynamic calculation, the higher solubility of additive at the outer area will enhance the enthalpy change during interfacial reaction and lead to the larger Jackson's parameter; thus, the faceted IMC morphology was formed. Moreover, the abnormal grain growth (AGG) at the outer area of (Cu, Ni)6Sn5 and (Cu, Co)6Sn5 was demonstrated from the IMC grain size distribution, while the normal grain growth pattern was suggested for the inner area of the IMC region.	*Journal of Electronic Materials: December 2006*	pp. 2081-2087	Acquire this Paper
Microstructure and Mechanical Behavior of Novel Rare Earth-Containing Pb-Free Solders	*M.A. Dudek, R.S. Sidhu, N. Chawla, and M. Renavikar*	Sn-rich solders have been shown to have superior mechanical properties when compared to the Pb-Sn system. Much work remains to be done in developing these materials for electronic packaging. In this paper, we report on the microstructure and mechanical properties of La-containing Sn-3.9Ag-0.7Cu alloys. The addition of small amounts of La (up to 0.5 wt.%) to Sn-Ag-Cu refined the microstructure by decreasing the length and spacing of the Sn dendrites and decreased the thickness of the Cu6Sn5 intermetallic layer at the Cu/solder interface. As a result of the change in the microstructure, Sn-Ag-Cu alloys with La additions exhibited a small decrease in ultimate shear strength but significantly higher elongations compared with Sn-Ag-Cu. The influence of LaSn3 intermetallics on microstructural refinement and damage evolution in these novel solders is discussed. Our results have profound implications for improving the mechanical shock resistance of Pb-free solders.	*Journal of Electronic Materials: December 2006*	pp. 2088-2097	Acquire this Paper
Effect of Reflow and Thermal Aging on the Microsctructure and Microhardness of Sn-3.7Ag-xBi Solder Alloys	*M. He and V.L. Acoff*	This work investigates the effect of reflow and the thermal aging process on the microstructural evolution and microhardness of five types of Sn-Ag based lead-free solder alloys: Sn-3.7Ag, Sn-3.7Ag-1Bi, Sn-3.7Ag-2Bi, Sn-3.7Ag-3Bi, and Sn-3.7Ag-4Bi. The microhardness and microstructure of the solders for different cooling rates after reflow at 250°C and different thermal aging durations at 150°C for air-cooled samples have been studied. The effect of Bi is discussed based on the experimental results. It was found that the microhardness increases with increasing Bi addition to Sn-3.7Ag solder regardless of reflow or thermal aging process. Scanning electron microscopy images show the formation of Ag_3Sn particles, Sn-rich phases, and precipitation of Bi-rich phases in different solders. The increase of microhardness with Bi addition is due to the solution strengthening and precipitation strengthening provided by Bi in the solder. The trend of decrease in microhardness with increasing duration of thermal aging was observed.	*Journal of Electronic Materials: December 2006*	pp. 2098-2106	Acquire this Paper
Nanoindentation on SnAgCu Lead-Free Solder Joints and Analysis	*Luhua Xu and John H.L. Pang*	The lead-free SnAgCu (SAC) solder joint on copper pad with organic solderability preservative (Cu-OSP) and electroless nickel and immersion gold (ENIG) subjected to thermal testing leads to intermetallic growth. It causes corresponding reliability concerns at the interface. Nanoindentation characterization on SnAgCu solder alloy, intermetallic compounds (IMCs), and the substrates subjected to thermal aging is reported. The modulus and hardness of thin IMC layers were measured by nanoindentation continuous stiffness measurement (CSM) from planar IMC surface. When SAC/Ni(Au) solder joints were subject to thermal aging, the Young's modulus of the NiCuSn IMC at the SAC/ENIG specimen changed from 207 GPa to 146 GPa with different aging times up to 500 h. The hardness decreased from 10.0 GPa to 7.3 GPa. For the SAC/Cu-OSP reaction couple, the Young's modulus of Cu6Sn5 stayed constant at 97.0 GPa and hardness about 5.7 GPa. Electron-probe microanalysis (EPMA) was used to characterize the evolution of composition for NiCuSn ternary IMC during thermal aging. The creep effect on the measured result was analyzed wh	*Journal of Electronic Materials: December 2006*	pp. 2107-2116	Acquire this Paper
Electromigration Effect on Intermetallic Growth and Young's Modulus in SAC Solder Joint	*Luhua Xu, J.H.L. Pang, F. Ren, and K.N. Tu*	Solid-state intermetallic compound (IMC) growth behavior plays an important role in solder joint reliability of electronic packaging assemblies. The directional impact of electromigration (EM) on the growth of interfacial IMCs in Ni/SAC/Ni, Cu/SAC/Ni single BGA ball solder joint, and fine pitch ball-grid-array (FPBGA) at the anode and cathode sides is reported in this study. When the solder joint was subjected to a current density of 5,000 A/cm2 at 125°C or 150°C, IMC layer growth on the anode interface was faster than that on the cathode interface, and both were faster than isothermal aging due to the Joule heating effect. The EM affects the IMC growth rate, as well as the composition and mechanical properties. The Young's modulus and hardness were measured by the nanoindentation continuous stiffness measurement (CSM) from planar IMC surfaces after EM exposure..	*Journal of Electronic Materials: December 2006*	pp. 2116-2125	Acquire this Paper

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Effect of Phosphorus Content on Cu/Ni-P/Sn-3.5Ag Solder Joint Strength after Multiple Reflow	*Zhong Chen, Aditya Kumar, and M. Mona*	Electroless Ni-P layers with three different P contents (6.1 wt.%, 8.8 wt.%, and 12.3 wt.%) were deposited on copper (Cu) substrates. Multilayered samples of Sn-3.5Ag/Ni-P/Cu stack were prepared and subjected to multiple reflows at 250°C. A tensile test was performed to investigate the effect of P content on the solder joint strength. The low P samples exhibited the highest joint strength after multiple reflows, while the strength of medium and high P samples decreased more rapidly. From interfacial analysis, the Ni3Sn4 intermetallic compound (IMC) formed at the interface of low P sample was found to be more stable, while the one of medium and high P samples spalled into the molten solder. The IMC spallation sped up the consumption of electroless Ni-P, leading to the large formation of Cu-Sn IMCs. Fractographic and microstructural analyses showed that the degradation in solder joint strength was due to the formation of layers of voids and growth of Cu-Sn IMCs between the solder and the Cu substrate.	*Journal of Electronic Materials: December 2006*	pp. 2126-2134	Acquire this Paper
Morphology of Intermetallic Compounds Formed between Lead-Free Sn-Zn Based Solders and Cu Substrate	*Chia-Wei Huang and Kwang-Lung Lin*	The morphologies of intermetallic compounds formed between Sn-Zn based solders and Cu substrates were investigated in this study. The investigated solders were Sn-9Zn, Sn-8.55Zn-0.45Al, and Sn-8.55Zn-0.45Al-0.5Ag. The experimental results indicated that the Sn-9Zn solder formed Cu5Zn8 and CuZn5 compounds on the Cu substrate, while the Al-containing solders formed the Al4.2Cu3.2Zn0.7 compound. The addition of Ag to the Sn-8.55Zn-0.45Al solder resulted in the formation of the AgZn3 compound at the interface between the Al4.2Cu3.2Zn0.7 compound and the solder. Furthermore, it was found that the cooling rate of the specimen after soldering had an effect on the quantity of AgZn3 compound formed at the interface. The AgZn3 compound formed with an air-cooling condition exhibited a rougher surface and larger size than with a water-quenched condition. It was believed that the formation of the AgZn3 compound at the interface occurs through heterogeneous nucleation during solidification.	*Journal of Electronic Materials: December 2006*	pp. 2135-2141	Acquire this Paper
Microstructural Analysis of Lead-Free Solder Alloys	*Vineet Kumar, Zhigang Zak Fang, Jin Liang, and Nader Dariavach*	Among the many issues related to the performance of lead-free solder alloys, the dependence of their mechanical properties on the microstructure and the stability of the microstructure stability are some of the most important issues. A comprehensive understanding of the process-microstructure-property relationships is essential. Toward that goal, a microtextural analysis is performed using orientation imaging microscopy (OIM) for alloy Sn-3.8Ag-0.7Cu (wt pct) processed at four different temperatures. Sn-3.8Ag-0.7Cu is one of the most promising lead-free solder alloys that has shown superior mechanical properties to other candidate lead-free solder alloys. However, a comprehensive understanding of their microstructure and the dependence of microstructure on processing conditions are still lacking. In the present work, a detailed microstructure characterization with respect to phase compositions, grain size and size distributions, texture, and orientation relationships between various phases are performed. The measured microstructural features are correlated with the soldering temperatures.	*Metallurgical & Materials Transactions A: August 2006*	pp. 2505-2514	Acquire this Paper
Solid-Liquid Reactions: The Effect of Cu Content on Sn-Ag-Cu Interconnects	*Henry Y. Lu, Haluk Balkan, and K.Y. Simon Ng*	The impact of copper content on the Sn-Ag-y%Cu (Ag = constant = 3.5; y = 0.0, 0.5, 1.0, and 2.0) interconnects was investigated in this study. The copper content and solid-liquid (S-L) reactions were used as inputs, and the outputs were the interfacial microstructure evolution and joint macro-performance. Surface microetching microscopy, cross-section microscopy, energy-dispersive x-ray analysis, shear test, and differential scanning calorimetry were used in the studies. It was discovered that as-soldered Sn-Ag-y% Cu interconnects could have different interfacial microstructures depending on copper content; no Ag3Sn plates were observed for any alloy groups. After the S-L reactions, Ag3Sn plates occurred for all groups. The magnitude of the Ag3Sn plate growth depended on copper content. This and other effects of copper content on Sn-Ag-Cu interconnects are discussed in this article.	*JOM: June 2005*	pp. 30-35	Read the Full Paper
Solidification Shrinkage Defects in Electronic Solders	*Girish S. Wable, Srinivas Chada, Bryan Neal, and Raymond A. Fournelle*	Alloys that undergo solidification over a wide range of temperatures generally exhibit a difference in the contraction behavior of the ensuing solid and liquid phases. Furthermore, dissolution of substrate metals during process reflow can lead to shifts in phase composition, additional primary phases, and volumetric contraction artifacts. The extent and frequency of surface roughness, shrinkage voids, fillet lifting, and hot tearing seen in lead-free solders are different than for eutectic tin lead solder. Shrinkage effects have been reported in Sn/Pb, Sn/Pb/Ag, Sn/Ag/Cu, and Sn/Cu/Ni solders for various components, but few studies have examined their impact on solder joint reliability. Nevertheless, they warrant proper identification due to the shift toward lead-free solders. This article is a review of the effects of shrinkage in Sn-Pb and lead-free solders as well as a discussion of some of the factors that contribute to their formation.	*JOM: June 2005*	pp. 38-42	Read the Full Paper
The Orientation Imaging Microscopy of Lead-Free Sn-Ag Solder Joints	*A.U. Telang and T.R. Bieler*	Orientation imaging microscopy was used to identify solidification microstructures and early stages of damage evolution in tin-silver eutectic solder joints on copper and nickel substrates after aging, creep, and thermomechanical fatigue. A visco-plastic self-consistent plasticity model was able to simulate texture changes when work hardening occurred at higher strain rates, but not with lower rates, where grain boundary sliding dominated the deformation and slip occurred predominantly on one or two slip systems that could be predicted using a Schmid (Sachs) analysis.	*JOM: June 2005*	pp. 44-49	Read the Full Paper

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The Oxidation of Lead-Free Sn Alloys by Electrochemical Reduction Analysis	*Sungil Cho, Jin Yu, Sung K. Kang, and Da-Yuan Shih*	The oxidation of pure tin and Sn-0.7Cu, Sn-3.5Ag, Sn-1Zn, and Sn-9Zn alloys at 150°C was investigated. Both the chemical nature and the amount of oxides were characterized using electrochemical reduction analysis by measuring the electrolytic reduction potential and total transferred electrical charges. X-ray photoelectron spectroscopy was also conducted to support the results of reduction analysis. The effect of copper, silver, and zinc addition on surface oxidation of tin alloys is reported. For tin, Sn-0.7Cu, and Sn-3.5Ag, SnO grew first and then the mixture of SnO and SnO2 was found. SnO2 grew predominantly during long-time aging. For zinc-containing tin alloys, both ZnO and SnO2 were formed. Zinc promotes the formation of SnO2.	*JOM: June 2005*	pp. 50-52	Read the Full Paper
Comparative Study of Interfacial Reactions of Sn-Ag-Cu and Sn-Ag Solders on Cu Pads during Reflow Soldering	*Ahmed Sharif and Y.C. Chan*	The interfacial reaction in soldering is a crucial subject for the solder-joint integrity and reliability in electronic packaging technology. However, electronic industries are moving toward lead-free alloys because of environmental concerns. This drive has highlighted the fact that the industry has not yet arrived at a decision for lead-free solders. Among the lead-free alloys, Sn-3.5Ag and Sn-3.5Ag-0.5Cu are the two potential candidates. Here, detailed microstructural studies were carried out to compare the interfacial reaction of Sn-3.5Ag and Sn-3.5Ag-0.5Cu solder with a ball grid array (BGA) Cu substrate for different reflow times. The Cu dissolution from the substrate was observed for different soldering temperatures ranging from 230°C to 250°C, and the dissolution was found to increase with time and temperature. Dissolution of Cu in the Sn-3.5Ag solder is so fast that, at 240°C, 12 µm of the Cu substrate is fully consumed within 5 min. Much less dissolution is observed for the Sn-3.5Ag-0.5Cu solder. In respect to such high dissolution, there is no significant difference observed in the intermetallic compound (IMC) thickness at the interface for both solder alloys. A simp	*Journal of Electronic Materials: January 2005*	pp. 46-52	Acquire this Paper
Cyclic Softening of the Sn-3.8Ag-0.7Cu Lead-Free Solder Alloy with Equiaxed Grain Structure	*Qiu-Lian Zeng, Zhong-Guang Wang, Ai-Ping Xian, and J.K. Shang*	Low-cycle fatigue behavior of the Sn-Ag-Cu ternary-eutectic alloy was investigated under a fully reversed loading condition. The solder alloy exhibited cyclic softening early in the fatigue life and continued to soften as the number of fatigue cycles increased. Following cyclic loading, numerous microcracks were found in the microstructure. Most of the microcracks were located along the grain boundaries in the areas with finer grains. The areal density of the microcracks increased with both strain amplitude and cycle number. By combining percolation theory with microcracking analysis, the cycle-dependent softening behavior was shown to result from accumulation of microcrack density with fatigue cycles.	*Journal of Electronic Materials: January 2005*	pp. 62-67	Acquire this Paper
Thermosonic Bonding of Lead-Free Solder with Metal Bump for Flip-Chip Bonding	*Jihye Lee, Jung H. Kim, and Choong D. Yoo*	While extensive research on the lead-free solder has been conducted, the high melting temperature of the lead-free solder has detrimental effects on the packages. Thermosonic bonding between metal bumps and lead-free solder using the longitudinal ultrasonic is investigated through numerical analysis and experiments for low-temperature soldering. The results of numerical calculation and measured viscoelastic properties show that a substantial amount of heat is generated in the solder bump due to viscoelastic heating. When the Au bump is thermosonically bonded to the lead-free solder bump (Sn-3%Ag-0.5%Cu), the entire Au bump is dissolved rapidly into the solder within 1 sec, which is caused by the scrubbing action of the ultrasonic. More reliable solder joints are obtained using the Cu/Ni/Au bump, which can be applied to flip-chip bonding.	*Journal of Electronic Materials: January 2005*	pp. 96-102	Acquire this Paper
Microstructural Development of Sn-Ag-Cu Solder Joints	*Andreas R. Fix, Gabriel A. López, Ingo Brauer, Wolfgang Nüchter, and Eric J. Mittemeijer*	The effects of Cu as pad material and of the metallization of pad (with Sn) and component (with Ni) on the evolving microstructure of lead-free solder joints were studied. A solder paste with composition 95.5wt.%Sn-4.0wt.%Ag-0.5wt.%Cu was used. Partial dissolution of the Cu substrate led to a change in the overall composition of the solder, which caused a precipitation morphology different from the one expected regarding the initial composition. Kinetics of growth of the Cu6Sn5 phase, as particles in the bulk of the solder and as a reaction layer adjacent to the Cu pad, was studied in the temperature range 125ndash;175°C.	*Journal of Electronic Materials: February 2005*	pp. 137-142	Acquire this Paper
Controlling the Microstructures from the Gold-Tin Reaction	*J.Y. Tsai, C.W. Chang, Y.C. Shieh, Y.C. Hu, and C.R. Kao*	The microstructures from the reaction between Au and Sn under different conditions were studied. A Sn/Au/Ni sandwich structure (2.5/3.752 µm) was deposited over the Si wafer. The overall composition of the Au and Sn layers corresponded to the Au20Sn binary eutectic (wt.%). When the reaction condition was 290°C for 2 min, the microstructure produced was a typical two-phase (Au5Sn and AuSn) eutectic microstructure over Ni. In contrast, when the reaction condition was 240°C for 2 min, a AuSn/Au5Sn/Ni layered microstructure was produced. In both microstructures, a small amount of Ni was dissolved in Au5Sn and AuSn. When the AuSn/Au5Sn/Ni layered structure was subjected to aging at 240°C, the AuSn layer gradually exchanged its position with the Au5Sn layer and eventually formed an Au5Sn/AuSn/Ni three-layer structure in less than 9 h. The driving force for Au5Sn and AuSn to exchange their positions is for the AuSn phase to seek more Ni. The dominant diffusing species for the AuSn and Au5Sn has also been identified to be Au and Sn, respectively.	*Journal of Electronic Materials: February 2005*	pp. 182-187	Acquire this Paper

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Title	Authors	Abstract	Journal	Pages	Link
Creep Deformation of Sn-3.5Ag-xCu and Sn-3.5Ag-xBi Solder Joints	*S.W. Shin and Jin Yu*	Creep properties of lead-free Sn-3.5Ag-based alloys with varying amounts of Cu or Bi were studied by single lap-shear test. Solder balls with five different compositions of Cu (0 wt.%, 0.75 wt.%, 1.5 wt.%) and Bi (2.5 wt.%, 7.5 wt.%) were reflowed on Cu. The Cu-containing alloy had a lower creep rate than the Bi-containing alloy. The Sn-3.5Ag alloy showed the lowest creep rate on Cu, implying that the Cu element already dissolved in the Sn-3.5Ag alloy during reflow. The Cu-containing alloy was strengthened by dispersed small precipitates of Cu6Sn5. As the Cu content increased up to 1.5 wt.%, the Cu6Sn5 coarsened and platelike Ag3Sn intermetallics were found, which deteriorated the creep resistance.	*Journal of Electronic Materials: February 2005*	pp. 188-195	Acquire this Paper
Tensile Creep and Microstructural Characterization of Bulk Sn3.9Ag0.6Cu Lead-Free Solder	*Qiang Xiao and William D. Armstrong*	The microstructural and creep behavior of bulk 63SnPb37 and the Pb-free solder alloy Sn3.9Ag0.6Cu are reported and compared. The Sn3.9Ag0.6Cu alloy showed much lower absolute creep rates than 63SnPb37. The size and distribution of the intermetallic compound (IMC) coarsened with increasing creep temperature. A number of coarsened precipitates of Cu6Sn5 segregate around β-Sn grain boundaries. After creep at 80°C and 115°C. the β-Sn particles in the Sn3.9Ag0.6Cu alloy are strongly aligned at approximately 45° to the uniaxial tension, parallel to the maximum shear-stress planes. The power-law-defined stress exponent significantly increases with increasing stress in both the 63Sn37Pb and Sn3.9Ag0.6Cu alloys; therefore, the Dorn model is unsuitable for these materials over large stress and temperature ranges. Both sets of experimental data were successfully fit with the present power-law stress-dependent energy-barrier model and the Garofalo model. However, the application of the present power-law stress-dependent energy model resulted in a significantly lower estimated variance as compared to the Garofalo model.	*Journal of Electronic Materials: February 2005*	pp. 196-211	Acquire this Paper
Effect of Rare Earth Element Addition on the Microstructure of Sn-Ag-Cu solder Joint	*Bo Li, Yaowu Shi, Yongping Lei, Fu Guo, Zhidong Xia, and Bin Zong*	The effects of minimal rare earth (RE) element additions on the microstructure of Sn-Ag-Cu solder joint, especially the intermetallic compounds (IMCs), were investigated. The range of RE content in Sn-Ag-Cu alloys varied from 0 wt.% to 0.25 wt.%. Experimental results showed that IMCs could be dramatically repressed with the appropriate addition of RE, resulting in a fine microstructure. However, there existed an effective range for the RE addition. The best RE content was found to be 0.1 wt.% in the current study. In addition to the typical morphology of Ag3Sn and Cu6Sn5 IMCs, other types of IMCs that have irregular morphology and uncertain constituents were also observed. The IMCs with large plate shape mainly contained Ag and Sn, but the content of Ag was much lower than that of Ag3Sn. The cross sections of Cu6Sn5 IMCs whiskers showed various morphologies. Furthermore, some eutectic-like structures, including lamellar-, rod-, and needle-like phases, were observed. The morphology of eutectic-like structure was related to the RE content in solder alloys. When the content of RE is 0.1 wt.%, the needle-like phase was dominant, while the lan	*Journal of Electronic Materials: March 2005*	pp. 217-224	Acquire this Paper
Microstructure and Mechanical Properties Predicted by Indentation Testing of Lead-Free Solders	*T. Ogawa, R. Kaga, and T. Ohsawa*	Microstructure and mechanical properties were investigated for ten systems of lead-free solders compared with the eutectic Sn-Pb solder. Mechanical properties including elastic, plastic, and creep deformations were predicted by indentation testing. This method was established based on the elastic-plastic-creep finite-element method (FEM). The predicted mechanical properties were obtained for the temperatures ranging between –20°C and 160°C.	*Journal of Electronic Materials: March 2005*	pp. 311-317	Acquire this Paper
The Anomalous Microstructural, Tensile, and Aging Response of Thin-Case Sn3.9Ag0.6Cu Lead-Free Solder	*Qiang Xiao, Luu Nguyen, and William D. Armstrong*	In this study, bulk and thin-cast samples were produced with an identical Sn3.9Ag0.6Cu composition. The thin-cast material exhibited a much finer as-quenched microstructure than the bulk material with the intermetallic compound (IMC) phase restricted to a thin network. Both the bulk and thin-cast materials continually softened during room-temperature aging, while both materials initially softened and then subsequently hardened when aged at 120°C and 180°C. The thin-cast material was in all cases significantly softer than the bulk material, and responded to aging as if it were bulk material aged at a higher temperature. These results have significant implications for the elevated temperature application of Sn3.9Ag0.6Cu.	*Journal of Electronic Materials: May 2005*	pp. 617-624	Acquire this Paper
Interfacial Reactions of Cu-Containing Lead-Free Solders with Au/NiP Metallization	*M.N. Islam and Y.C. Chan*	Cu-containing solder alloys have been used to identify their interfacial reactions with electroless NiP. As-reflowed, AuSn4 intermetallic compounds (IMCs) are formed in the Sn-Cu and Sn-Ag-Cu solders, but in the cases of Sn-Ag-Cu-In, In-Sn-Au IMCs are formed and are uniformly distributed in the solder. Different types of IMCs such as high-Cu (>30 at.%), medium-Cu (30–15 at.%), and low-Cu (<15 at.%) containing IMCs are formed at the interface. High-Cu and medium-Cu containing ternary intermetallic compounds (TIMCs) are found in the Sn-Cu and Sn-Ag-Cu solder joints, respectively. Medium-Cu containing quaternary intermetallic compounds (QIMCs) are found in the Sn-Ag-Cu-In joints. Initially, TIMCs and QIMCs have higher growth rates, resulting in the entrapment of some Pb-rich phase in the high-Cu containing TIMCs and some In-Sn-Au phase in the QIMCs. High-Cu containing TIMCs have a lower growth rate and consume less of the NiP layer. The spalling of medium-Cu containing TIMCs in the Sn-Ag-Cu solder increases both the growth rate of TIMCs and the consumption rate of the NiP layer. Low-Cu containing QIMCs in the Sn-Ag-Cu	*Journal of Electronic Materials: May 2005*	pp. 662-669	Acquire this Paper

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Influence of Flux on Wetting Behavior of Lead-Free Solder Balls during the Infrared-Reflow Process	*Cho-Liang Chung, Kyoung-Sik Moon, and C.P. Wong*	The effects of two different fluxes (A6 and B6) on the wetting performance of Sn-3.5Ag-0.5Cu lead-free solder balls were investigated during the reflow process. Solder ball wetting behavior in real time via an optical microscope coupled with a video recorder during the reflow process was studied. The leadfree solder balls started to melt and wet at 210°C by using A6, which is 8°C lower than the melting point (218°C) of the solder material used. The wetting performance of the lead-free solder ball was dramatically enhanced by using A6. The wettability test indicated that the height of the solder ball after the reflow process with flux A6 was significantly lower than that with B6. It was found that strong fluxing capability caused these phenomena.	*Journal of Electronic Materials: July 2005*	pp. 994-1001	Acquire this Paper
Room-Temperature Indentation Creep of Lead-Free Sn-5%Sb Solder Alloy	*A.R. Geranmayeh and R. Mahmudi*	Creep behavior of the lead-free Sn-5%Sb solder alloy was studied by long-time Vickers indentation testing at room temperature. Four different conditions of the material were examined. These were unhomogenized cast (UC), homogenized cast (HC), unhomogenized wrought (UW), and homogenized wrought (HW) conditions. Based on the steady-state power-law creep relationship, the stress exponents were determined through different methods of analysis, and in all cases, the calculated exponents were in good agreement. The stress exponent values of about 5 and 12, depending on the processing route of the material, are very close to those determined by room-temperature conventional creep testing of the same material reported in the literature. For the HW condition, the n value of about 5 together with a very fine grain size of 4.5 µm and a high volume fraction of second-phase particles of 8.6% may suggest that dislocation climb is the creep mechanism. For all other conditions with different grain sizes and second-phase volume fractions, however, the high n value of 12 implies that the operative creep mechanism is dislocation creep, whi	*Journal of Electronic Materials: July 2005*	pp. 1002-1009	Acquire this Paper
High-Temperature Variable Melting Point Sn-Sb Lead-Free Solder Paste Using Transient Liquid-Phase Powder Processing	*S.F. Corbin*	During this investigation, a high-temperature, variable melting point (VMP) Sn-Sb solder paste was developed. The solder was created by mixing pure Sn and Sb powders together with a flux to form a paste. The proper choice of flux composition and Sn powder size resulted in a Sn-10wt.%Sb solder paste that had an initial melting point of 232°C and solder ball formation at peak temperatures as low as 241°C. This represents a significant reduction in the process temperature that would normally be required for a prealloyed solder with a melting point of 250°C. When this solder paste is reheated, significant remelting does not take place until a temperature above 241°C is reached. In this way, the solder exhibits a VMP. Experiments indicate that this VMP behavior is due to isothermal solidification (or freezing) at the solder temperature owing to the partial transient liquid-phase (TLP) behavior of the solder powder paste.	*Journal of Electronic Materials: July 2005*	pp. 1016-1025	Acquire this Paper
Anomalously High Tensile Creep Rates fron Thin Cast Sn3.9Ag0.6Cu Lead-Free Solder	*Qiang Xiao, Luu Nguyen, and Wm. D. Armstrong*	The present paper compares the creep and microstructural changes during creep behavior of bulk and thin cast forms of Sn3.9Ag0.6Cu. The processing parameters of the thin cast material were selected to result in a very fine microstructure analogous to what occurs in very small size solder electronic interconnections. We found that the thin cast material is less creep resistant than the bulk material. A comparison of Ag element maps between as-crept bulk and thin cast material shows that the relevant climb process occurs in a very different environment in the bulk material as compared to the thin cast material. In the bulk material, the relevant climb process occurs within a finely dispersed intermetallic compound (IMC) eutectic, which covers broad areas within the material. In the thin cast material, the relevant climb process occurs primarily in the beta-Sn grains that continuously surround isolated, coarse IMC particles. This resulted in the activation energy of the bulk material being larger than that for the thin cast material. Finally, it is important to note that the strength deficiency of the thin cast material is persistent—once the material is cast in thin cast for	*Journal of Electronic Materials: July 2005*	pp. 1065-1075	Acquire this Paper
Lead-Free Interconnect Technique by Using Variable Frequency Microwave	*Kyoung-Sik Moon, Yi Li, Jianwen Xu, and C.P. Wong*	A novel lead-free interconnect technique using variable frequency microwave (VFM) was investigated. The lead-free solder interconnection between the component chips and the metal pads through VFM was first demonstrated. Comparison between the microstructures of the lead-free solder joints on Cu and Sn surfaces formed by a conventional thermal reflow process and VFM was conducted. The VFM heating technique successfully created the lead-free solder/Cu and Sn joints through their intermetallic compounds (IMCs), while maintaining the substrate temperature as low as 210°C.	*Journal of Electronic Materials: July 2005*	pp. 1081-1088	Acquire this Paper
Wetting and Reaction of Sn-2.8Ag-0.5Cu-1.0Bi Solder with Cu and Ni Substrates	*M.J. Rizvi, Y.C. Chan, C. Bailey, H. Lu, M.N. Islam, and B.Y. Wu*	The wettability of newly developed Sn-2.8Ag-0.5Cu-1.0Bi lead-free solder on Cu and Ni substrates was assessed through the wetting balance tests. The wettability assessment parameters such as contact angle (θc) and maximum wetting force (Fw) were documented for three solder bath temperatures with three commercial fluxes, namely, no-clean (NC), nonactivated (R), and watersoluble organic acid flux (WS). It was found that the lead-free Sn-2.8Ag-0.5Cu-1.0Bi solder exhibited less wetting force, i.e., poorer wettability, than the conventional Sn-37Pb solder for all flux types and solder bath temperatures. The wettability of Sn-2.8Ag-0.5Cu-1.0Bi lead-free solder on Cu substrate was much higher than that on Ni substrate. Nonwetting for Sn-2.8Ag-0.5Cu-1.0Bi and Sn-Pb solders on Ni substrate occurred when R-type flux was used. A model was built and simulations were performed for the wetting balance test. The simulation results were found very close to the experimental results. It was also observed that larger values of immersion depth resulted in a decrease of the wetting force and corresponding meniscus height, whereas the increase	*Journal of Electronic Materials: August 2005*	pp. 1115-1122	Acquire this Paper

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Interfacial Reactions and Compound Formation on Sn-Ag-Cu Solders by Mechanical Alloying on Electroless Ni-P/Cu Under Bump Metallization	*Szu-Tsung Kao and Jenq-Gong Duh*	Electroless Ni-P under bump metallization (UBM) has been widely used in electronic interconnections due to the good diffusion barrier between Cu and solder. In this study, the mechanical alloying (MA) process was applied to produce the SnAgCu lead-free solder pastes. Solder joints after annealing at 240°C for 15 min were employed to investigate the evolution of interfacial reaction between electroless Ni-P/Cu UBM and SnAgCu solder with various Cu concentrations ranging from 0.2 to 1.0 wt.%. After detailed quantitative analysis with an electron probe microanalyzer, the effect of Cu content on the formation of intermetallic compounds (IMCs) at SnAgCu solder/electroless Ni-P interface was evaluated. When the Cu concentration in the solder was 0.2 wt.%, only one (Ni, Cu)3Sn4 layer was observed at the solder/electroless Ni-P interface. As the Cu content increased to 0.5 wt.%, (Cu, Ni)6Sn5 formed along with (Ni, Cu)3Sn4. However, only one (Cu, Ni)6Sn5 layer was revealed, if the Cu content was up to 1 wt.%. With the aid of microstructure evolution, quantitative analysis, and elemental distribution by x-ray color mapping, the	*Journal of Electronic Materials: August 2005*	pp. 1129-1134	Acquire this Paper
Primary Solidification Phases of the Sn-Rich Sn-Ag-Cu-Ni Quaternary System	*Cheng-An Chang, Sinn-Wen Chen, Chen-Nan Chiu, and Yu-Chih Huang*	The eutectic and near-eutectic Sn-Ag-Cu solders are the most promising lead-free solders, and nickel is frequently used as the barrier layer material. Nickel dissolves into the molten Sn-Ag-Ni alloy during the soldering process, and the ternary solder becomes a Sn-Ag-Cu-Ni quaternary melt near the nickel substrate. Liquidus projection is the projection of the liquidus trough and it delineates the boundaries of various primary solidification phases. Information of liquidus projection is helpful for understanding the alloys' solidification behavior. This study prepared the Sn-Ag-Cu-Ni alloys of various compositions at the Sn-rich corner. The alloys were melted at higher temperatures and solidified in air. The solidified alloys were metallographically examined to determine the phases formed, especially the primary solidification phases. No ternary or quaternary compounds were found. The knowledge of the primary solidification phases, phase formation sequences, and reaction temperatures determined in this study were put together with all of the available liquidus projections of the constituent ternary systems to determine the primary solidification phases of the qu	*Journal of Electronic Materials: August 2005*	pp. 1135-1142	Acquire this Paper
Local Creep in SnAg3.8Cu0.7 Lead-Free Solder	*Pascal P. Jud, Guenter Grossmann, Urs Sennhauser, and Peter J. Uggowitzer*	In this study, local creep of lead-free solder SnAg3.8Cu0.7 has been investigated for the first time by using surface markers prepared by focused ion beam (FIB). The test setup was optimized with respect to the applied shear stresses. Two different microstructures have been investigated at 30°C, 50°C, and 80°C, respectively. A high sensitivity of the steady-state creep rate to the microstructure has been demonstrated. The shear deformation was observed to be inhomogeneous and concentrated in specific areas. Local dislocation bands dominate the solder deformation.	*Journal of Electronic Materials: September 2005*	pp. 1206-1214	Acquire this Paper
Role of Ag in the Formation of Interfacial Intermetallic Phases in Sn-Zn Soldering	*Jenn-Ming Song, Pei-Chi Liu, Chia-Ling Shih, and Kwang-Lung Lin*	This study explored the effect of Ag as the substrate or alloying element of solders on the interfacial reaction in Sn-Zn soldering. Results show that instead of Ag-Sn compounds, χ-AgZn and γ-Ag5Zn8 form at the Sn-Zn/Ag interface. The addition of Ag in Sn-Zn solders leads to the precipitation of ε-AgZn3 from the liquid solder on preformed interfacial intermetallics. The morphology of this additional AgZn3 is closely related to the solidification process of Ag-Zn intermetallics and the under intermetallic layer.	*Journal of Electronic Materials: September 2005*	pp. 1249-1254	Acquire this Paper
A Parametric Approach for Assessment of Thermomechanical Performance of Sn-Based Solder Joints	*K.N. Subramanian*	Thermomechanical fatigue (TMF) behavior of tin-based solder joints depends on several material-, process-, and service-related parameters. Although several focused studies have been conducted on such solder joints, incorporation of the roles of the above parameters and their relative importance for a comprehensive assessment of TMF behavior has not materialized so far due to the complexities involved. This paper suggests a simple parametric approach for the lifetime/reliability prediction of Sn-based solder joints incorporating findings from studies related to material and service issues.	*Journal of Electronic Materials: October 2005*	pp. 1313-1317	Acquire this Paper
Scanning Electron Microscope In-Situ Investigation of Fracture Behavior in 95.6Sn3.5Ag Lead-Free Solder	*Ying Ding, Chunqing Wang, and Mingyu Li*	In-situ tensile tests of as-cast 96.5Sn3.5Ag eutectic solder were performed under the scanning electron microscope (SEM) using different strain rates at room temperature, and various crack initiation and propagation behavior was observed on the specimen surface. It was found that, due to the existence of Ag3Sn intermetallic particles and the special microstructure of β-Sn phases in Sn3.5Ag solder, grain boundary sliding (GBS) was no longer the dominant mechanism for this Pb-free solder. In the lower strain rate regime, accompanied by partial intragranular cracks, intergranular fracture along the grain boundaries in Sn-Ag eutectic structure or along the interphase boundaries between Sn-rich dendrites and Sn-Ag eutectic phases occurred primarily for the Sn3.5Ag solder in the early tensile stage. However, significant plastic deformation was observed in large areas for the specimens tested at higher strain rates, and cracks propagated in a transgranular manner across the Sn dendrites and Sn-Ag eutectic structure.	*Journal of Electronic Materials: October 2005*	pp. 1324-1335	Acquire this Paper

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Processing and Creep Properties of Sn-Cu Composite Solders with Small Amounts of Nanosized Ag Reinforcement Additions	*F. Tai, F. Guo, Z.D. Xia, Y.P. Lei, Y.F. Yan, J.P. Liu, and Y.W. Shi*	In this research, nanosized Ag reinforcement particles were incorporated by mechanical means into a promising lead-free solder, Sn-0.7Cu, in an effort to improve the comprehensive property of the Sn-0.7Cu solder. Wettability, mechanical performance, and creep-rupture life tests were conducted to study the difference between Sn-0.7Cu solder and its composite solder with different Ag reinforcement volume fractions. Experimental results indicated that the composite solders and their joints showed better wettability and mechanical properties, as well as longer creep-rupture lives, than Sn-0.7Cu solder. The composite solder with 1vol.%Ag reinforcement addition exhibited the best comprehensive property as compared to the composite solders with other reinforcement volume fractions. Systematic creep-rupture life tests were conducted on the 1vol.%Ag-reinforced Sn-0.7Cu-based composite solder joints. Significant enhancement of the creep-rupture lives were found in the composite solder joints under different stress and temperature combinations as compared to the Sn-0.7Cu solder joint. Ductile rupture surfaces were exhibited in most of the broken	*Journal of Electronic Materials: November 2005*	pp. 1357-1362	Acquire this Paper
Lead-Free Solder Materials: Experimental Enthalpies of Mixing of Liquid Ag-In-Pd-Sn Alloys	*Christoph Luef, Hans Flandorfer, and Herbert Ipser*	The partial and integral enthalpies of mixing of liquid Ag-In-Sn and Ag-In-Pd-Sn alloys were determined at 900 °C by a drop calorimetric technique using a Calvet-type microcalorimeter. The binary interaction parameters of Ag-In and the ternary interaction parameters of Ag-In-Pd and Ag-In-Sn were fitted based on both literature data and the authors' measurements employing the Redlich–Kister–Muggiano model for substitutional solutions. Furthermore, it was investigated whether additional quaternary interactions have to be taken into account for the description of the enthalpy of mixing in the Ag-In-Pd-Sn system.	*Metallurgical & Materials Transactions A: May 2005*	pp. 1273-1277	Acquire this Paper
Effects of Cu, Bi, and In on Microstructure and Tensile Properties of Sn-Ag-X(Cu, Bi, In) Solders	*M.L. Huang and L. Wang*	Effects of minor additions of Cu, Bi, and In on microstructure, melting temperature, and tensile properties of Sn-Ag–based lead-free solders were investigated. It was found that the intermetallic compounds (IMCs) Ag2In and Cu6Sn5 are formed in In- and Cu-containing solders, respectively. At low concentration, Bi dissolved in the Sn matrix and tended to precipitate pure Bi particles at the solubility limit of 4 wt pct Bi. The formation of large Ag3Sn precipitates from the solder matrix was suppressed when alloying bismuth into the Sn-Ag alloy. The Bi addition resulted in a significant linear increase of the ultimate tensile strength (UTS) of solders, which is attributed to a solid-solution hardening mechanism. Solder strengthening due to In and Cu is less pronounced and attributed to a dispersion strengthening mechanism. The additions of Cu, Bi, and In all depressed the melting temperatures of Sn-Ag–based solders; however, In is the most effective one.	*Metallurgical & Materials Transactions A: June 2005*	pp. 1439-1446	Acquire this Paper
Directional Solidification in a AgCuSn Eutectic Alloy	*Robert J. Schaefer and Daniel J. Lewis*	An experimental study of microstructures in a directionally solidified, near-eutectic Ag-Cu-Sn alloy has been completed. This material is an important candidate for use as a lead-free solder, and the studies show the origin and velocity dependence of some of the microstructures seen in solder joints. Quantitative stereology and microstructural observation were completed for directional solidification experiments where the sample was moved through a gradient furnace at velocities between 0.826 and 500 µm/s.	*Metallurgical & Materials Transactions A: October 2005*	pp. 2775-2783	Acquire this Paper
Thermal Properties and Interfacial Reaction between the Sn-9Zn-xAg Lead-Free Solders and Cu Substrate	*Tao-Chih Chang, Moo-Chin Wang, and Min-Hsing Hon*	The thermal properties and interfacial reaction between the Sn-9Zn-xAg lead-free solders and Cu substrate, such as solidus and liquidus temperatures, heat of fusion, intermetallic compounds, and adhesion strength, have been investigated. Two endothermic peaks appear in the DSC curve when the Ag content in the Sn-9Zn-xAg solder alloy is above 1.5 wt pct. The solidus temperatures of the Sn-9Zn-xAg solder alloys are around 197 °C, but the liquidus temperatures decrease from 225.3 °C to 221.7 °C and 223.6 °C with increasing the Ag content in the solder alloy from 1.5 to 2.5 and 3.5 wt pct, respectively. Three intermetallic compounds, namely, Cu6Sn5, Cu5Zn8, and Ag3Sn are observed at the Sn-9Zn-xAg/Cu interface. The Cu5Zn8 is formed close to the Cu substrate, Ag3Sn is adjacent to it, and Cu6Sn5 is nearest the Sn-9Zn-1.5Ag solder alloys. A bi-structural Cu6Sn5 layer with hexagonal η-Cu6Sn5 and monoclinic η′-Cu6Sn5 is found at the Sn-9Zn-1.5Ag/Cu interface due to Ag dissolution. A maximum adhesion strength of 10.7 ± 0.8 MPa is obtained at the Sn-9Zn-2.5Ag/Cu interface as soldered at 250 °C for 30 seconds.	*Metallurgical & Materials Transactions A: November 2005*	pp. 3019-3029	Acquire this Paper
The Observation and Simulation of Sn-Ag-Cu Solder Solidification in Chip-Scale Packaging	*Keun-Soo Kim, Katsuaki Suganuma, Jong-Min Kim, and Chi-Won Hwang*	The formation of solidification defects in lead-free soldering is greatly infl uenced by material factors as well as the design of circuit assemblies. To establish ideal processing conditions and design concepts for sound soldering structures, defect formation in Sn-Ag-Cu for various types of circuit assemblies must be understood. In this study, the solidification process of Sn-3Ag-0.5Cu solder balls on circuit boards for a chip-scale package was examined primarily by using an in-situ solidification observation system with the aid of the solidification simulation. Microstructural observations were also carried out on soldered joints to support those observations and simulations. The experimental results correlate with the simulation results.	*JOM: June 2004*	pp. 39-43	Read the Full Paper

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Title	Authors	Abstract	Source	Pages	Link
Sn-Ag-Cu and Sn-Cu Solders: Interfacial Reactions with Platinum	*Tae Hyun Kim and Young-Ho Kim*	The interfacial reaction and intermetallic formation at the interface between tin solders containing a small amount of copper with platinum were investigated in this study. Sn-0.7Cu and Sn-1.7Cu solders were reacted with platinum by dipping Pt/Ti/Si specimens into the molten solder at 260°C. Sn-3.8Ag-0.7Cu solder was reacted with platinum by reflowing solder paste on a Pt/Ti/Si substrate at 250°C. $PtSn_4$ intermetallic formed in all specimens while Cu_6Sn_5 interfacial intermetallic was not observed at the solder/platinum interfaces in any specimens. A parabolic relationship existed between the thickness of the Pt-Sn intermetallic and reaction time, which indicates the intermetallic formation in the solder/platinum interface is diffusion controlled.	*JOM: June 2004*	pp. 45-49	Read the Full Paper
Effects of Different Printed-Circuit-Board Surface Finishes on the Formation and Growth of Intermetallics at Thermomechanically Fatigued, Small Outline J Leads/Sn-Ag-Cu Interfaces	*Pei-Lin Wu,Meng-Kuang Huang,Chiapyng Lee,and Shyh-Rong Tzan*	The effects of printed-circuit-board (PCB) surface finish and thermomechanical fatigue (TMF) on the formation and growth of intermetallic compounds (IMCs) between small outline J (SOJ) leads and Sn-3.0Ag-0.5Cu solder were investigated.The thickness of the IMC layer formed initially at the as-soldered SOJ/Sn-Ag-Cu interface over a Ni/Au PCB surface finish was about 1.7 times of that over the organic solderability preservative (OSP) PCB surface finish. The parabolic TMF-cycle dependence clearly suggests that the growth processes are controlled primarily by solid-state diffusion.The diffusion coefficient for the growth of the total IMC layer at the SOJ/Sn-Ag-Cu interface over the Ni/Au PCB surface finish is the same as that over the OSP PCB surface finish, and thus,the total IMC layer at the SOJ/Sn-Ag-Cu interface over the Ni/Au PCB surface finish is thicker than that over the OSP PCB surface finish. Using the Cu-Ni-Sn ternary isotherm, the anomalous phenomenon that the presence of Ni retards the growth of the Cu_3Sn layer while increasing theinitial growth of the Cu_6Sn_5 layer can be addressed.	*Journal of Electronic Materials: March 2004*	pp. 157-161	Acquire this Paper
Reactive Interdiffusion between a Lead-Free Solder and Ti/Ni/Ag Thin-Film Metallizations	*G. Ghosh*	The reactive interdiffusion between a Sn-3.0wt.%Ag-0.7wt.%Cu solder and thin-film Ti/Ni/Ag metallizations on two semiconductor devices, a diode and ametal-oxide-semiconductor field-effect transistor (MOSFET), and a Au-layer on the substrates are studied. Comprehensive microanalytical techniques, scanning electron microscopy, transmission electron microscopy (TEM), and analytical electron microscopy (AEM) are employed to identify the interdiffusion processes during fabrication and service of the devices. During the reflow process of both diode and MOSFET devices, (1) the Ag layer dissolves in the liquid solder; (2) two intermetallics, $(Ni,Cu)_3Sn_4$and $(Cu,Ni)_6Sn_5$, form near the back metal/solder interface; and (3) the Au metallization in the substrate side dissolves in the liquid solder, resulting in precipitation of the $(Au,Ni,Cu)Sn_4$ intermetallic during solidification. During solid-state aging of both diode and MOSFET solder joints at 125°C and 200°C, the following atomic transport processes occur: (1) interdiffusion of Cu, Ni, and Sn, leading to the growth of a (Ni,Cu)3Sn>SUB>4 layer until the Ni layer is completely consumed; (2) interdiffusion of Au, Cu, Ni, a	*Journal of Electronic Materials: March 2004*	pp. 229-240	Acquire this Paper
Low-Cycle Fatigue Characteristics of Sn-Based Solder Joints	*K.O. Lee, Jin Yu, T.S. Park, and S.B. Lee*	Low-cycle, lap-shear fatigue behavior of Sn-based, Pb-free solder alloys, Sn-3.5Ag,Sn-3.5Ag-Cu, Sn-3.5Ag-Bi, nd Sn-0.7Cu, were studied at room temperature using specimens with printed circuit board (PCB)/solder/PCB structure under total displacement of ±10 μm, 12 μm, 15 μm, and 20 μm.The fatigue lives of various solder joint materials, defined as 50% load drop, were correlated with the fracture paths and analyzed using the Coffin?Manson relation, Morrow's plastic-energy dissipation model, and Solomon's load-drop parameter. The Sn-3.5Ag,Sn-0.7Cu eutectics, and Sn-3.5Ag-Cu ternary alloys showed the same level of fatigue resistance, while Bi-containing alloys showed substantially worse fatigue properties. Cross-sectional fractography revealed cracks initiated at the solder wedge near the solder mask and subsequently propagated into the solder matrix in the former group of alloys, in contrast with the crack propagation along the solder/under bump metallurgy (UBM) interfaces in the Sn-3.5Ag-Bi alloys. Inferior fatigue resistance of Bi-containing alloys was ascribed to high matrix hardness, high stiffness, possible Bi segregation to the	*Journal of Electronic Materials: April 2004*	pp. 249-258	Acquire this Paper
Development of a Novel Adaptive Lead-Free Solder Containing Reinforcements Displaying the Shape-Memory Effect	*I. Dutta, B.S. Majumdar, D. Pan, W.S. Horton, W. Wright, and Z.X. Wang*	Microelectronic solder joints are typically exposed to aggressive thermomechanical cycling (TMC) conditions during service.During TMC,strain localization occurs near solder/bond pad interfaces,where large,inelastic-shear strains accumulate,eventually causing low-cycle fatigue (LCF) failure of the joint. In this study, a novel methodology to mitigate the effects of strain localization within the joint is discussed, wherein the solder alloy is reinforced with a martensitic NiTi-based, shape-memory alloy (SMA). In this scheme, the SMA reinforcement deforms in shear concurrently with the solder during TMC and, subsequently, undergoes martensite-to-austenite (M A) transformation, placing the solder matrix next to the reinforcements in reverse shear. This is purported to reduce inelastic-strain localization within the solder and, thus, enhance joint life. In this paper, we present results of thermal-mechanical loading experiments conducted on a monolithic 95.5Sn-3.8Ag-0.7Cu solder, a Cu/Cu_6Sn_5 particle-reinforced solder, and NiTi-solder, single-fiber composites (SFCs) to elucidate the impact of the shape-memory effect on the overall joint behavior.	*Journal of Electronic Materials: April 2004*	pp. 258-270	Acquire this Paper

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Effect of Silver Content on the Shear Fatigue Properties of Sn-Ag-Cu Flip-Chip Interconnects	*Yoshiharu Kariya et al.*	The mechanical shear fatigue test has been performed to study the effect of silver content on the fatigue properties of Sn-xAg-0.5Cu (x = 1, 2, 3, and 4) for flip-chip interconnections. The strength of the solder alloy increases with increasing silver content, preventing shear plastic deformation of the solder bump. The flip-chip joints made using higher silver content solder, such as 3%Ag and 4%Ag, exhibit longer fatigue life for all conditions. The fatigue ductility of the solder decreases with an increase in the silver content. The fatigue endurance of 1%Ag solder is superior to other solders over the plastic strain range of 3%, even though the strength of the solder is the lowest in the solders tested. Based on this study, the 3Ag solder may exhibit good fatigue performance for all conditions, and the 1Ag solder is optimum for severe strain conditions.	*Journal of Electronic Materials: April 2004*	pp. 321-328	Acquire this Paper
Low-Cycle Fatigue Prediction Model for Pb-Free Solder 96.5Sn-3.5Ag	*C. Kanchanomai and Y. Mutoh*	Low-cycle fatigue (LCF) data of Sn-Ag eutectic solder (96.5Sn-3.5Ag) under various temperatures and frequencies has been described using three different prediction models, i.e., Coffin-Manson model, Smith-Watson-Topper (SWT) model, and Morrow energy model. The LCF behavior represented by the present prediction models showed temperature and frequency dependences, i.e., the fatigue ductility coefficient increased with increasing frequency and decreasing temperature. In order to better correlate the LCF data, a flow stress and/or frequency-dependent modifications were introduced to the Coffin-Manson and Morrow energy models. The frequency-modified Coffin-Manson model could not describe the influence of temperature on LCF behavior, while the flow stress?modified frequency-modified Morrow energy model, into which the metallurgical response (flow stress and frequency) was introduced to account for the effect of temperature and frequency on LCF behavior, gave reasonable predictions of LCF data under various temperatures and frequencies.	*Journal of Electronic Materials: April 2004*	pp. 329-333	Acquire this Paper
Thermodynamic Assessment of the Sn-Co Lead-Free Solder System	*Libin Liu, Cristina Andersson, and Johan Liu*	The Sn-Co-Cu eutectic alloy can be a less expensive alternative for the Sn-Ag-Cu alloy. In order to find the eutectic solder composition of the Sn-Co-Cu system, the Sn-Co binary system has been thoroughly assessed with the calculation of phase diagram (CALPHAD) method. The liquid phase, the FCC and HCP Co-rich solidsolution, and the BCT Sn-rich solid solution have been described by the Redlich–Kister model. The Hillert–Jarl–Inden model has been used to describe the magnetic contributions to Gibbs energy in FCC and HCP. The CoSn2, CoSn, Co3Sn2_β, and Co3Sn2_α phases have been treated as stoichiometric phases. Aseries of thermodynamic parameters have been obtained. The calculated phase diagram and thermodynamic properties are in good agreement with the experimental data. The obtained thermodynamic data was used to extrapolate the ternary Sn-Co-Cu phase diagram. The composition of the Sn-rich eutectic point of the Sn-Co-Cu system was found to be 224°C, 0.4% Co, and 0.7% Cu.	*Journal of Electronic Materials: September 2004*	pp. 935-939	Acquire this Paper
Residual Stress and Interfacial Reaction of the Electroplate Ni-Cu Alloy Under Bump Metallurgy in the Flip-Chip Solder Joint	*S.-H. Kim, J.-Y. Kim, J. Yu, and T.Y. Lee*	Pure Ni, the Ni-Cu alloy, and pure Cu layers as the under bump metallurgy (UBM) for a flip-chip solder joint were deposited by electrolytic plating. For the pure Ni layer, residual stress can be controlled by adding a wetting agent and decreasing current density, and it is always under tensile stress. The Ni-Cu alloys of different Cu compositions from 20wt.%Cu to 100wt.%Cu were deposited with varying current density in a single bath. The residual stress was a strong function of current density and Cu composition. Decreasing current density and increasing Cu content simultaneously causes the residual stress of the metal layers to sharply decrease. For the pure Cu layer, the stress is compressive. The Cu layer acts as a cushion layer for the UBM. The residual stress of the UBM strongly depends on the fraction of the Cu cushion layer. Interfacial reaction of the UBM with Sn-3.5 wt.% Ag was studied. As the Cu contents of Ni-Cu alloys increased, the dissolution rate increased. Several different intermetallic compounds (IMCs) were found. The lattice constants of alloys and the IMC increase with increasing Cu contents because the larger Cu atoms substitute for t	*Journal of Electronic Materials: September 2004*	pp. 948-957	Acquire this Paper
Constitutive Relations on Creep for SnAgCuRE Lead-Free Solder Joints	*Zhigang Chen, Yaowu Shi, and Zhidong Xia*	Taking the most promising substitute of the Sn-3.8Ag-0.7Cu solder as the research base, investigations were made to explore the effect of rare earths (REs) on the creep performance of the Sn-3.8Ag-0.7Cu solder joints. The SnAgCu-0.1RE solde with the longest creep-rupture life was selected for subsequent research. Creep strain tests were conducted on Sn-3.8Ag-0.7Cu and SnAgCu-0.1RE solder joints in the intermediate temperature range from 298 K to 398 K, corresponding to the homologous temperatures η = 0.606, 0.687, 0.748, and 0.809 and η = 0.602, 0.683, 0.743, and 0.804, respectively, to acquire the relevant creep parameters, such as stress exponent and activation energy, which characterize the creep mechanisms. The final creep constitutive equations for Sn-3.8Ag-0.7Cu and SnAgCu-0.1RE solder joints were established, demonstrating the dependence of steady-state creep rate on stress and temperature....	*Journal of Electronic Materials: September 2004*	pp. 964-971	Acquire this Paper

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Study of Immersion Silver and Tin Printed-Circuit-Board Sruface Finishes in Lead-Free Solder Applications	*Minna Arra, Dongkai Shangguan, Dongji Xie, Janne Sundelin, Toivo Lepistö, and Eero Ristolainen*	The wetting of I-Ag (immersion silver) and I-Sn (immersion tin) printed-circuit-board (PCB) finishes by Sn/Ag/Cu and eutectic Sn/Pb solders was studied in this work with Ni/Au (electroless nickel/immersion gold) and organic solderability preservative (OSP) finishes as baselines. Wetting tests were performed on fresh boards and boards subjected to different preconditioning treatments that simulated the effects of aging, storage, and multiple reflow cycles. When the boards are fresh, the wetting of the I-Sn and Ni/Au finishes is better than that on the I-Ag and OSP finishes. However, after the preconditioning treatments, the wetting of the I-Sn finish degrades the fastest, whereas the wetting of the I-Ag and OSPfinishes degrade less through the different preconditioning treatments. The wetting of the Ni/Au finish remains excellent through all the preconditioning treatments. The chemical and microstructural changes in the finishes during aging treatments were evaluated using electron spectroscopy chemical analysis (ESCA), x-ray diffractometry (XRD), and cross-sectioning followed by scanning electron microscopy (SEM). The results indicate that a single lead-free reflow c	*Journal of Electronic Materials: September 2004*	pp. 977-990	Acquire this Paper
Interfacial Reaction between Multicomponent Lead-Free Solders and Ag, Cu, Ni, and Pd Substrates	*G. Ghosh*	The interfacial reaction between two prototype multicomponent lead-free solders, Sn-3.4Ag-1Bi-0.7Cu-4In and Sn-3.4Ag-3Bi-0.7Cu-4In (mass%), and Ag, Cu, Ni, and Pd substrates are studied at 250°C and 150°C. The microstructural characterization of the solder bumps is carried out by scanning electron microscopy (SEM) coupled with energy dispersive x-ray analysis. Ambient temperature, isotropic elastic properties (bulk, shear, and Young's moduli and Poisson's ratio) of these solders along with eutectic Sn-Ag, Sn-Bi, and Sn-Zn solders are measured. The isotropic elastic moduli of multicomponent solders are very similar to the eutectic Sn-Ag solder. The measured solubility of the base metal in liquid solders at 250°C agrees very well with the solubility limits reported in assessed Sn-X (X Ag, Cu, Ni, Pd) phase diagrams. The measured contact angles were generally less than 15° on Cu and Pd substrates, while they were between 25° and 30° on Ag and Ni substrates. The observed intermediate phases in Ag/solder couples were Ag3 Sn after reflow at 250°C and Ag3Sn and ζ (Ag-Sn) after solid-state aging at 150°C. In Cu/solder and Ni/solder	*Journal of Electronic Materials: October 2004*	pp. 1080-1091	Acquire this Paper
Influence of Cu Additionto Interface Microstructure betweem Sn-Ag Solder and Au/Ni-6P Plating	*Chi-Won Hwang, Katsuaki Suganuma, Masayuki Kiso, and Shigeo Hashimoto*	The formation and growth of intermetallics at the interface between Sn-Ag-(Cu) alloy balls and Au/Ni-6P plating were experimentally examined as a function of soldering period. Joint strengths were also evaluated by a ball pull test. For the joint with Sn-3.5Ag, the primary reaction product of Ni3Sn4 exhibits growth and shrinkage in thickness repeatedly with a passage of reaction time up to 30 min, while the Ni3SnP reaction layer monotonously increases its thickness without fluctuation. In the cases of the joints with Cu bearing solder, Sn-3Ag-0.5Cu and Sn-3.5Ag-0.8Cu, a single η-(Cu,Ni)6Sn5 interface layer grows by fast Cu segregation from liquid solder to the interface layer on soldering. For all the soldered joints, a P-rich layer appears at the surface region of a Ni-6P plating layer by Ni depletion to form those intermetallic compounds at interfaces. The growth rate of a P-rich layer for Sn-3.5Ag is faster by about 4–8 times than those of the Sn-Ag-Cu. The presence of Cu in solder enhances the formation of the Cu6Sn5 intermetallic layer at the interface resulting in prevention of Ni diffusion to liquid solder. For all the soldered joints, coarsened reaction interfaces de	*Journal of Electronic Materials: October 2004*	pp. 1200-1209	Acquire this Paper
Intermetallic Growth Studies on Sn-Ag-Cu Lead-Free Solder Joints	*John H.L. Pang, Luhua Xu, X.Q. Shi, W. Zhou, and S.L. Ngoh*	Solid-state intermetallic compound (IMC) growth behavior plays an important role in solder joint reliability of electronic packaging assemblies. The morphology and growth of interfacial IMC compounds between 95.5Sn-3.8Ag-0.7Cu Pb-free solders and nickel/gold (Ni/Au) surface finish on BGA solder joint specimen is reported. Digital imaging techniques were employed in the measurement of the average IMC growth thickness. The IMC growth behavior subjected to isothermal aging exposure at 125°C, thermal cycling (TC), and thermal shock (TS) with upper soak temperatures of 125°C are compared. An equivalent isothermal aging time is proposed for comparison of IMC layer growth data. It was noted that IMC layer growth under thermal cycling and thermal shock aging gives an acceleration factor of 1.4 and 2.3 based on the equivalent isothermal aging time.	*Journal of Electronic Materials: October 2004*	pp. 1219-1226	Acquire this Paper
The Effect of Microstructural and Geometrical Features on the Reliability of Ultrafine Flip Chip Microsolder Joints	*Zhiheng Huang, Paul P. Conway, Changqing Liu, and Rachel C. Thomson*	A thermodynamic approach was used to investigate solder alloy systems containing Sn, Ag, Sb, and Pb, during both equilibrium and Scheil cooling conditions. The modeled microstructure was used to explore recent experimental results and to establish the microstructure-property relationships in microsolder joints. This approach is shown to be very useful in the transition from Pb-Sn to lead-free solders by enabling the consideration of contamination by a small amount of Pb. Molten solder interacts with the under bump metallization or print circuitboard (PCB) metallization to form intermetallic compounds (IMCs). A truncated sphere structure was used to predict the solder joint geometry, and a two-dimensional finite-element (FE) method was adopted to investigate the kinetics of the dissolution of Au during the reflow process. The dissolution of Au into different volumes of solder material for three sizes of joints has been studied. In the modeling of the dissolution kinetics, the Nernst?Brunner equation is found to have poor validity for these calculations because of the dramatic change in the microscopic geometry and boundary conditions fo	*Journal of Electronic Materials: October 2004*	pp. 1227-1235	Acquire this Paper

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Title	Authors	Abstract	Journal	Pages	Link
Molecular Dynamics Study on the Coalescence of Cu Nanoparticles and Their Deposition on hte Cu Substrate	*Hai Dong, Kyoung-Sik Moon, and C.P. Wong*	Molecular dynamics (MD) simulation was conducted to investigate the coalescence of Cu nanoparticles and their deposition on a Cu substrate at various temperatures from 400 K to 1,000 K using the embedded atom method (EAM). The x-z plane projection, spreading index, coalescence index,and pair-correlation distribution were analyzed to gain more insight into the sintering process. Simulation results showed that even at a low temperature of 400 K, metal spheres can be collapsed and deposited on the substrate. Yet higher temperatures were helpful in enhancing the degree of collapsing and deposition.	*Journal of Electronic Materials: November 2004*	pp. 1326-1330	Acquire this Paper
Foreword	*Srinivas Chada, Laura J. Turbini, Sung K. Kang, Kwang-Lung Lin, Michael R. Notis, and Jin Yu*	Featuring 23 papers presented at the symposium Lead-Free Solders and Processing Issues Relevant to Microelectronic Packaging sponsored by the TMS Electronic, Magnetic, & Photonic Materials Division's Electronic Packaging and Interconnections Materials Committee. This symposium was held as part of the 2004 TMS Annual Meeting in Charlotte, North Carolina, 14–18 March 2004.	*Journal of Electronic Materials: December 2004*	p. 1411	Acquire this Paper
Grain-Boundary Character and Grain Growth in Bulk Tin and Bulk Lead-Free Solder Alloys	*A.U. Telang, T.R. Bieler, J.P. Lucas, K.N. Subramanian, L.P. Lehman, Y. Xing, and E.J. Cotts*	Grain-boundary deformation is the primary failure mode observed in solder joints. Understanding the effects of alloy composition variations and cooling rates on microstructural stability and deformation processes will allow development of improved joints. The effects of these variables on grain-boundary character were investigated in a pure-tin ingot and a reflowed sample; ingots of Sn-3.5wt.%Ag and Sn-3.8wt.%Ag-0.7wt.%Cu; and solder balls with 1.63-wt.% or 3-wt.% Ag. The microstructure was characterized using orientation imaging microscopy (OIM). After aging (150°C for 200 h), the fine-grained polycrystalline microstructure in both pure-tin specimens grew considerably, revealing preferred misorientations and ledge formation at grain boundaries. Aging of the alloy ingots showed only slight grain growth caused by precipitate pinning. The solder balls showed similar phenomena. The role of alloying elements, cooling rate, and the anisotropy of the coefficient of thermal expansion (CTE) in tin on microstructural evolution, grain-boundary character, and properties of solder joints are discussed.	*Journal of Electronic Materials: December 2004*	pp. 1412-1423	Acquire this Paper
Cross-Interaction of Under-Bump Metallurgy and Surface Finish in Flip-Chip Solder Joints	*C.M. Tsai,W.C. Luo, C.W. Chang, Y.C. Shieh, and C.R. Kao*	The cross-interaction of the under-bump metallurgy (UBM)/solder interface and the solder/surface-finish interface in flip-chip solder joints was investigated. In this study, the UBM on the chip side was a single layer of Cu (8.5 µm), and the surface finish on the substrate side was a 0.2-µm Au layer over 5-µm Ni. It was shown that, after two reflows, the Ni layer of the surface finish had been covered with (Cu1–xNix)6Sn5. This shows that the effect of cross-interaction of the two interfaces is important even during the reflow stage. During subsequent solidstate aging at 115°C, 135°C, and 155°C, the formation of ((Cu1–xNix)6Sn5 over the Ni layer was found to have the effect of reducing the Ni consumption rate. At the same time, the Cu consumption rate of the UBM was accelerated. The results of this study show that the selection of the UBM and the surface finish has to be considered together because the cross-interaction of the two interfaces plays an important role.	*Journal of Electronic Materials: December 2004*	pp. 1424-1428	Acquire this Paper
Growth of Sn and Intermetallic Compounds in Sn-Ag-Cu Solder	*L.P. Lehman, S.N. Athavale, T.Z. Fullem, A.C. Giamis, R.K. Kinyanjui, M. Lowenstein, K. Mather, R. Patel, D. Rae, J.Wang, Y. Xing, L. Zavalij, P. Borgesen, and E.J. Cotts*	The microstructure of the Sn-Ag-Cu solder is examined by optical microscopy and scanning electron microscopy (SEM) for various compositions near the ternary eutectic for different cooling rates from the solder melt. Focus is on the size and orientation of Sn grains as indicated by cross-polarized, light optical microscopy, and pole figures from x-ray diffraction.We find that both composition and cooling rate have strong influences on Sn grain size, with Sn grain size increasing an order of magnitude as Cu concentration increases from 0% to 1.1%. Cyclic growth twinning, with twinning angles near 60°, is observed in Sn-Ag-Cu alloys near the composition Sn-3.9Ag-0.6Cu.	*Journal of Electronic Materials: December 2004*	pp. 1429-1439	Acquire this Paper
The Application of Lead-Free Solder to Optical Fiber Packaging	*S. Ou, G. Xu, Y. Xu, and K.N. Tu*	To achieve precise, hermetic, and reliable optoelectronic packaging, we studied a novel technology for bonding fibers to v-grooved chips by metallic soldering. Multilayered metallization of Ti/Au, Ti/Cu/Au, or Ti/Ni/Au has been prepared to improve the poor bonding nature of solder on oxide surface. The eutectic 43Sn57Bi (wt.%) alloy, having a melting point of 139°C, was selected to bond the fibers to v-grooved chips. The alignment and adhesion tests result show that the precision packaging by soldering has a satisfied reliability in the range of working temperature from –40°C to 85°C. The metallic solder bonding is hermetic, and hence, it can isolate the optical device from ambient environment.	*Journal of Electronic Materials: December 2004*	pp. 1440-1444	Acquire this Paper
Effect of Cu Concentration on Morphology of Sn-Ag-Cu Solders by Mechanical Alloying	*Szu-Tsung Kao and Jenq-Gong Duh*	The mechanical alloying (MA) process is considered an alternative approach to produce solder materials. In this study, the effect of Cu concentration in the ternary Sn-3.5Ag-xCu (x = 0.2, 0.7, and 1) solder by MA was investigated. The (Cu,Sn) solid solution was precipitated as the Cu6Sn5 intermetallic compound (IMC), which was distributed nonuniformly through the microstructure. The Cu6Sn5 IMC, which was present in the SnAgCu solder with high Cu composition, causes the as-milled MA particle to fracture to a smaller size. Appreciable distinction on morphology of as-milled MA powders with different Cu content was revealed. When the Cu concentration was low (x = 0.2), MA particle aggregated to a spherical ingot with large particle size. For higher Cu concentration (x = 0.7 and x = 1), the MA particle turned to flakes with smaller particle size. The distinction of the milling mechanism of Sn-3.5Ag-xCu (x = 0.2, 0.7, and 1) solder by the MA process was discussed. An effective approach was developed to reduce the particle size of the SnAgCu solder from....	*Journal of Electronic Materials: December 2004*	pp. 1445-1451	Acquire this Paper

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Contact Angle Measurements of Sn-Ag and Sn-Cu Lead-Free Solders on Copper Substrates	*Mario F. Arenas and Viola L. Acoff*	In this study, the contact angles of four lead-free solders, namely, Sn-3.5Ag, Sn-3.5Ag-4.8Bi, Sn-3.8Ag-0.7Cu, and Sn-0.7Cu (wt.%), were measured on copper substrates at different temperatures. Measurements were performed using the sessile-drop method. Contact angles ranging from 30° to 40° after wetting under vacuum with no fluxes and between 10° and 30° with rosin mildly activated (RMA) and rosin activated (RA) fluxes were obtained. The Sn-3.5Ag-4.8Bi exhibited the lowest contact angles, indicating improved wettability with the addition of bismuth. For all soldering alloys, lower contact angles were observed using RMA flux. Intermetallics formed at the solder/Cu interface were identified as Cu6Sn5 adjacent to the solder and Cu3Sn adjacent to the copper substrate. The Cu3Sn intermetallic phase was generally not observed when RMA flux was used. The effect of temperature on contact angle was dependent on the type of flux used.	*Journal of Electronic Materials: December 2004*	pp. 1452-1458	Acquire this Paper
Morphology and Kinetic Study of the Interfacial Reaction between the Sn-3.5Ag Solder and Electroless Ni-P Metallization	*Zhong Chen, Min He, and Guojun Qi*	This work summarizes the interfacial reaction between lead-free solder Sn-3.5Ag and electrolessly plated Ni-P metallization in terms of morphology and growth kinetics of the intermetallic compounds (IMC). Comparison with pure Ni metallization is made in order to clarify the role of P in the solder reaction. During reflow, the IMCs formed with the Ni-P under-bump metallization (UBM) exist in chunky crystal blocks and small crystal agglomerates, while the ones with the sputtered Ni UBM exhibit uniformly scallop grains with faceted surfaces. The IMC thickness increases with reflow time following approximately a t1/3 power law for both systems. The IMC growth rate is higher with the Ni-P UBM than the Ni UBM. The thickness of the Ni3Sn4 layer increases linearly with the square root of thermal aging time, indicating that the growth of the IMCs is a diffusion-controlled process. The activation energy for Ni3Sn4 growth in solid-state reaction is found to be 110 kJ/mol and 91 kJ/mol for the Ni-P and sputtered Ni UBMs, respectively. Kirkendall voids are detected inside the Ni3P layer in the Sn-3.5Ag/Ni-P system. No such voids are found in the Sn-3.5Ag/Ni system.	*Journal of Electronic Materials: December 2004*	pp. 1465-1472	Acquire this Paper
Creep Behavior of ther Ternary 95.5Sn3.9Ag-0.6Cu Solder: Part II—Aged Condition	*P.T. Vianco, J.A. Rejent, and A.C. Kilgo*	Compression creep tests were performed on the 95.5Sn-3.9Ag-0.6Cu (wt.%) solder. The specimens were aged prior to testing at 125°C, 24 h or 150°C, 24 h. Applied stresses were 2.40 MPa. Test temperatures were –25°C to 160°C. The 125°C, 24-h aging treatment caused the formation of coarsened Ag3Sn particle boundaries within the larger ternary-eutectic regions. The 150°C, 24-h aging treatment resulted in contiguous Ag3Sn boundaries in the ternary-eutectic regions as well as a general coarsening of Ag3Sn particles. The 125°C, 24-h aging treatment had only a small effect on the strain-time curves vis-a-vis the as-cast condition. Negative creep was observed at 75°C for time periods >105 sec and stresses of 3–10 MPa. The creep kinetics exhibited a sinh term (stress) exponent, p, of 5.3 ± 0.6 and an apparent-activation energy, ΔH, of 49 ± 5 kJ/mol when data from all test temperatures were included. A good data correlation was observed over the [–25–125°C] temperature regime. Steady-state creep kinetics exhibited a greater variability in the [125–160°C] regime because of the simultaneous coarsening of Ag3Sn particles. Th	*Journal of Electronic Materials: December 2004*	pp. 1473-1484	Acquire this Paper
Elevated Temperature Aging of Solder Joints Based on Sn-Ag-Cu: Effects on Joint Microstructure and Shear Strength	*I.E. Anderson and J.L. Harringa*	The shear strength behavior and microstructural effects after aging for 100 h and 1,000 h at 150°C are reported for near-eutectic Sn-Ag-Cu (SAC) solder joints (joining to Cu) made from Sn-3.5Ag (wt.%) and a set of SAC alloys (including Co- and Fe-modified SAC alloys). All joints in the as-soldered and 100-h aged condition experienced shear failure in a ductile manner by either uniform shear of the solder matrix (in the strongest solders) or by a more localized shear of the solder matrix adjacent to the Cu6Sn5 interfacial layer, consistent with other observations. After 1,000 h of aging, a level of embrittlement of the Cu3Sn/Cu interface can be detected in some solder joints made with all of the SAC alloys and with Sn-3.5Ag, which can lead to partial debonding during shear testing. However, only ductile failure was observed in all solder joints made from the Co- and Fe-modified SAC alloys after aging for 1,000 h. Thus, the strategy of modifying a strong (high Cu content) SAC solder alloy with a substitutional alloy addition for Cu seems to be effective for producing a solder joint that retains both strength and ductility for extended isothermal aging at high t	*Journal of Electronic Materials: December 2004*	pp. 1485-1496	Acquire this Paper
Accelerated Thermal Fatigue of Lead-Free Solder Joints as a Function of Reflow Cooling Rate	*Y. Qi, A.R. Zbrzezny, M. Agia, R. Lam, H.R. Ghorbani, P. Snugovsky, D.D. Perovic, and J.K. Spelt*	Leadless chip resistor (LCR) assemblies were manufactured using both traditional tin-lead (Sn37Pb) and lead-free (Sn3.8Ag0.7Cu) solders. The leadfree test vehicles were assembled using three different cooling rates: 1.6°C/sec, 3.8°C/sec, and 6.8°C/sec. They were then exposed to accelerated thermalcycling (ATC) tests between 0°C and 100°C with a 10–14°C/min ramp rate and a 5-min dwell time. The test results indicated that these lead-free solder joints had better creep-fatigue performance than the tin-lead solder joints. The LCR built with the medium cooling rate showed the longest fatigue life compared with the resistors built with the normal cooling rate of 1.6°C/sec and the higher cooling rate 6.8°C/sec. The number of cycles to failure was significantly correlated to the void defect rate. Failure analyses were done using crosssectioning methods and scanning electron microscopy (SEM). Finite-element models were built to analyze the inelastic, equivalent strain range in solder joints subjected to thermal-cycling conditions with different degrees of solder wetting. The results indicated that poor wetting increases strains throughout the joi	*Journal of Electronic Materials: December 2004*	pp. 1497-1506	Acquire this Paper

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Effects of Load and Thermal Conditions on Pb-Free Solder Joint Reliability	*J. Liang, S. Downes, N. Dariavach, D. Shangguan, and S.M. Heinrich*	Reliability of lead-free solder joints has been a hot topic widely debated in the electronic industry. Most published data indicate that a change to lead-free soldering has the potential benefit of more reliable solder joints than the current Sn-Pb eutectic solder joints. However, in reality many mechanical, metallurgical, thermal, and environmental factors affect the service reliability of solder joints. This paper tries to shed some light on the effects of mechanical loading and thermal conditions on solder joint reliability. These conditions are determined not only by external environments but also by the solder alloy itself and the joint geometry. Analyses with first principles are carried out on solder joints of both areal array and peripheral packages. Effects on fatigue life of solder joint geometry, thermal and mechanical characteristics of components and substrate materials, and application conditions are discussed. The analysis helps explain why lead-free solder joints may not be more reliable in certain application conditions than the current Sn-Pb eutectic solder joints.	*Journal of Electronic Materials: December 2004*	pp. 1507-1515	Acquire this Paper
Ceramics Bonding Using Solder Glass Frit	*Z. Sun, D. Pan, J. Wei, and C.K. Wong*	Ceramics bonding is becoming an important technology and has found wide applications in different engineering and electronic industries. In this paper, furnace bonding of ceramics using solder glass frit was investigated with emphasis on the effects of surface treatment and bonding conditions on bonding strength. Alumina (Al_2O_3) sheet and SCHOTT solder glass G017-393 were used as the base and brazing filler materials, respectively. Chemical surface treatments using various acids were tested. The results reveal the effects of spreading and voids on bonding strength. An optimum bonding strength can be produced by an appropriate combination of bonded glass-frit density and spreading area. Bonding strength is not only related to surface-contact angle but also surface roughness. The study shows that high-quality ceramics bonding or sealing can be achieved with the application of appropriate bonding conditions.	*Journal of Electronic Materials: December 2004*	pp. 1516-1523	Acquire this Paper
Intermetallic Phase Detection in Lead-Free Solders Using Synchrotron X-ray Diffraction	*Gavin J. Jackson, Hua Lu, Raj Durairaj, Nick Hoo, Chris Bailey, Ndy N. Ekere, and Jon Wright*	The high-intensity, high-resolution x-ray source at the European Synchrotron Radiation Facility (ESRF) has been used in x-ray diffraction (XRD) experiments to detect intermetallic compounds (IMCs) in lead-free solder bumps. The IMCs found in 95.5Sn3.8Ag0.7Cu solder bumps on Cu pads with electroplated-nickel immersion-gold (ENIG) surface finish are consistent with results based on traditional destructive methods. Moreover, after positive identification of the IMCs from the diffraction data, spatial distribution plots over the entire bump were obtained. These spatial distributions for selected intermetallic phases display the layer thickness and confirm the locations of the IMCs. For isothermally aged solder samples, results have shown that much thicker layers of IMCs have grown from the pad interface into the bulk of the solder. Additionally, the XRD technique has also been used in a temperature-resolved mode to observe the formation of IMCs, in situ, during the solidification of the solder joint. The results demonstrate that the XRD technique is very attractive as it allows for nondestructive investigations to be performed on expensive state-of-the-art	*Journal of Electronic Materials: December 2004*	pp. 1524-1529	Acquire this Paper
Effect of Cooling Rate on Growth of the Intermetallic Compound and Fracture Mode of Near-Eutectic Sn-Ag-Cu/Cu Pad: Before and After Aging	*Sang Won Jeong, Jong Hoon Kim, and Hyuck Mo Lee*	Several near-eutectic solders of (1) Sn-3.5Ag, (2) Sn-3.0Ag-0.7Cu, (3) Sn-3.0Ag-1.5Cu, (4) Sn-3.7Ag-0.9Cu, and (5) Sn-6.0Ag-0.5Cu (in wt.% unless specified otherwise) were cooled at different rates after reflow soldering on the Cu pad above 250°C for 60 sec. Three different media of cooling were used to control cooling rates: fast water quenching, medium cooling on an aluminum block, and slow cooling in furnace. Both the solder composition and cooling rate after reflow have a significant effect on the intermetallic compound (IMC) thickness (mainly Cu_6Sn_5). Under fixed cooling condition, alloys (1), (3), and (5) revealed larger IMC thicknesses than that of alloys (2) and (4). Slow cooling produced an IMC buildup of thicker than 10 μm, while medium and fast cooling produced a thickness of thinner than 5 μm. The inverse relationship between IMC thickness and shear strength was confirmed. All the fast- and medium-cooled joints revealed a ductile mode (fracture surface was composed of the β-Sn phase), while the slow-cooled joints were fractured in a brittle mode (fracture surface was composed of Cu_6Sn_5 and Cu_3Sn phases). The effect of isotherma	*Journal of Electronic Materials: December 2004*	pp. 1530-1544	Acquire this Paper
Quantitative Metallography of β-Sn Dendrites in Sn-3.8Ag-0.7Cu Ball Grid Array Solder Balls via Electron Backscatter Diffraction and Polarized Light Microscopy	*A. LaLonde, D. Emelander, J. Jeannette, C. Larson,W. Rietz, D. Swenson, and D.W. Henderson*	Electron backscatter diffraction and polarized light microscopy have been used to quantify the number of crystallographically independent â-Sn dendrites present in near-eutectic, ball grid array Sn-Ag-Cu (SAC) solder balls as a function of cooling rate (0.35–3.0°C/s). Based on these data, it is estimated that a single 900-μm-diameter solder ball contains on average eight individual β-Sn dendrites, independent of cooling rate. Specific orientation relationships were also found to be prevalent between neighboring â-Sn dendrites. These results confirm and expand upon recent research, and further emphasize the probable anisotropic nature of SAC solder joints.	*Journal of Electronic Materials: December 2004*	pp. 1545-1549	Acquire this Paper
Interfacial Reaction Study on a Solder Joint with Sn-4Ag-0.5Cu Solder Ball and Sn-7Zn-Al (30 ppm) Solder Paste in a Lead-Free Wafer Level Chip Scale Package	*Huann-Wu Chiang, Jun-Yuan Chen, Jeffrey C. B. Lee, and S.M. Li*	The interfacial reactions of solder joints between the Sn-4Ag-0.5Cu solder ball and the Sn-7Zn-Al (30 ppm) presoldered paste were investigated in a wafer level chip scale package (WLCSP). After appropriate surface mount technology (SMT) reflow process on the printed circuit board (PCB) with organic solderability preservative (Cu/OSP) and Cu/Ni/Au surface finish, samples were subjected to 150°C high-temperature storage (HTS), 1,000 h aging. Sequentially, the cross-sectional analysis is scrutinized using a scanning electron microscope (SEM)/energy-dispersive spectrometer (EDS) and energy probe microanalysis (EPMA) to observe the metallurgical evolution in the interface and solder buck itself. It was found that Zn-enriched intermetallic compounds (IMCs) without Sn were formed and migrated from the presolder paste region into the solder after reflow and 150°C HTS test.	*Journal of Electronic Materials: December 2004*	pp. 1550-1556	Acquire this Paper

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Intermetallic Compounds and Adhesion Strength between the Sn-9Zn-1.5Ag-0.5Bi Lead-Free Solder and Unfluxed Cu Substrate	*C.-Y. Liu, M.-C. Wang, and M.-H. Hon*	The intermetallic compounds (IMCs) formed at the interface between the Sn-9Zn-1.5Ag-0.5Bi lead-free solder alloy and unfluxed Cu substrate have been investigated by x-ray diffraction, optical microscopy, scanning electron microscopy (SEM), and energy-dispersive spectrometry (EDS). The melting point and melting range of the Sn-9Zn-1.5Ag-0.5Bi solder alloy are determined as 195.9°C and 10°C, respectively, by differential scanning calorimetry (DSC). Cu_6Sn_5 and Cu_5Zn_8 IMCs are formed between the Sn-9Zn-1.5Ag-0.5Bi/unfluxed Cu substrate wetted at 250°C for 10 sec. The interfacial adhesion strength changes from 10.27 ± 0.68 MPa to 8.58 ± 0.59 MPa when soldering time varies from 10 sec to 30 sec at 250°C.	*Journal of Electronic Materials: December 2004*	pp. 1557-1560	Acquire this Paper
The Effect of Isothermal Aging on the Thickness of Intermetallic Compound Layer Growth between Low Melting Point Solders and Ni-Plated Cu Substrate	*Dae-Gon Kim and Seung-Boo Jung*	The growth kinetics of the intermetallic compound (IMC) layer formed between two low melting point solders and electrolytic Ni/Cu substrate by solid-state isothermal aging were examined. The solders were 100 In and In-48Sn. A quantitative analysis of the IMC layer thickness as a function of aging time and aging temperature was performed. Experimental results showed that the IMCs, such as $In_{27}Ni_{10}$ and $Ni_3(In, Sn)_4$, were observed for different solders. Additionally, the growth rate of these IMCs increased with the aging temperature and time. The layer growth of the IMC in the couples of indium solder alloy/electrolytic Ni system satisfied the parabolic law at a given temperature range. As a whole, because the values of the time exponent (n) are approximately 0.5, the layer growth of the IMC was mainly controlled by the diffusion mechanism over the temperature range studied. The apparent activation energies for IMC growth were 60.03 kJ/mol for $In_{27}Ni_{10}$ and 72.84 kJ/mol for $Ni_3(In, Sn)_4$.	*Journal of Electronic Materials: December 2004*	pp. 1561-1566	Acquire this Paper
Effects of Cooling Rate on Creep Behavior of a Sn-3.5Ag Alloy	*F. Ochoa, X. Deng, and N. Chawla*	The effect of cooling rate on microstructure and creep behavior of bulk, eutectic Sn-3.5Ag solders was studied. The cooling rate is an important processing variable that significantly affects the microstructure of the solder and therefore determines its mechanical behavior. Controlled cooling rates were obtained by cooling specimens in different media: water, air, and furnace, which resulted in cooling rates of 24°C/s, 0.5°C/s, and 0.08°C/s, respectively. The cooling rate decreased the secondary dendrite arm size and the spacing of the Sn-rich phase, as well as the morphology of Ag_3Sn. The Sn-dendrite arm size and spacing were smaller at fast cooling rates, while slower cooling rates yielded a nearly eutectic microstructure. The morphology of Ag_3Sn also changed from relatively spherical, at faster cooling rates, to needlelike for slower cooling. The effect of cooling rate on creep behavior was studied at 25°C, 60°C, 95°C, and 120°C. Faster cooling rates were found to increase the creep strength of the solder due to the refinement of the solder microstructure. Stress exponents, n, indicated that dislocation climb was the controlling mechanism. .	*Journal of Electronic Materials: December 2004*	pp. 1596-1607	Acquire this Paper
Electromigration Effects upon Interfacial Reactions	*Sinn-wen Chen and Chih-ming Chen*	At the joints in microelectronic products, electric currents pass through interfaces of dissimilar materials. At these joints, atomic fluxes are driven by both the compositional gradients and electromigration effects. Although interfacial reactions at these joints appear to be affected by both of the driving forces, most often only compositional gradients are investigated when interfacial reactions are concerned. This study examines the effects of electromigration upon interfacial reactions together with the effects of compositional gradients, primarily in lead-free solder joints. It is found that electromigration significantly affects intermetallic compound growth in various systems. Growth rates of the intermetallic compounds are either enhanced or retarded depending upon the diffusion directions of the primary moving species and those of the applied electric currents. This study demonstrates that electromigration effect is an important factor in the interfacial reactions at the joints with the passage of electric currents.	*JOM: February 2003*	pp. 62-67	Acquire this Paper
Lead-Free Solders and Processing Issues in Microelectronics	*Raymond A. Fournelle*	During the 2003 TMS Annual Meeting in San Diego, California, a technical symposium on Pb-Free Solders and Processing Issues Relevant to Microelectronic Packaging, presented various aspects of lead-free solder R&D. Of the papers presented, four were chosen for this issue of JOM to provide an update on the issues, especially on the characterization of mechanical properties, solidification behavior, and intermetallics. This commentary introduces the lead-free solder articles.	*JOM: June 2003*	p. 49	Read the Full Paper
The Compression Stress-Strain Behavior of Sn-Ag-Cu Solder	*Paul T. Vianco, Jerome A. Rejent, and Joseph J. Martin*	The yield-stress behavior was investigated for the 95.5Sn-4.3Ag-0.2Cu (wt.%), 95.5Sn-3.9Ag-0.6Cu, and 95.5Sn-3.8Ag-0.7Cu ternary lead-free solders using the compression stressstrain test technique. Cylindrical specimens were evaluated in the as-cast or aged (125°C, 24 h) condition. The tests were performed at ?25°C, 25°C, 75°C, 125°C, and 160°C using strain rates of 4.2 × 105s1 or 8.3 × 104s1. Specially designed Sn-Ag-0.6Cu samples were fabricated to compare the yield stress of the dendritic microstructure versus that of the equiaxed microstructure that occurs in this alloy.	*JOM: June 2003*	pp. 50-55	Read the Full Paper
Effects of Cooling Rates on Microstructure and Mechanical Behavior of Sn-3.5Ag Solder	*F. Ochoa, J.J. Williams, and N. Chawla*	The microstructure, tensile, and creep behavior of bulk Sn-3.5Ag solder were studied as a function of cooling rate. Controlled cooling rates were obtained by cooling specimens in different media: water, air, or furnace. The cooling rate signifi cantly affected secondary dendrite arm size and spacing of the tin-rich phase, as well as the morphology of Ag_3Sn. Ag_3Sn was relatively spherical at the fastest cooling rate and had a needlelike morphology at the slowest cooling rate. Both the yield strength in tension and creep resistance of Sn-3.5Ag solder increased with increasing cooling rate while the strain-to-failure decreased. In this study, the mechanical behavior was correlated with the observed microstructure, creep-stress exponents, and fracture behavior, in order to understand the underlying damage mechanisms.	*JOM: June 2003*	pp. 56-60	Read the Full Paper

Recent TMS Articles: Lead-Free Solders

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Title	Authors	Abstract	Source	Pages	Link
Ag3Sn Plate Formation in the Solidification of Near-Ternary	*Sung K. Kang, Won Kyoung Choi, Da-Yuan Shih, Donald W. Henderson, Timothy Gosselin, Amit Sarkhel, Charles, Goldsmith, and Karl J. Puttlitz*	Near-ternary eutectic Sn-Ag-Cu alloys are leading lead-free candidate solders for various applications. These alloys yield three phases upon solidification: b-Sn, Ag3Sn, and Cu6Sn5. Large, plate-like, pro-eutectic Ag3Sn structures can grow rapidly within the liquid phase, potentially adversely affecting the mechanical behavior and reducing the fatigue life of solder joints. This article reports on the formation of such plates in Sn-Ag-Cu solder balls and joints and demonstrates how large Ag3Sn plate formation can be minimized.	*JOM: June 2003*	pp. 61-65	Read the Full Paper
Measuring the Mechanical Properties of Pb-Free Solder and Sn-Based Intermetallics by Nanoindentation	*R. R. Chromik, R.P. Vinci, S.L. Allen, and M.R. Notis*	The technique of nanoindentation coupled with an atomic force microscope has been used to measure mechanical properties of Cu-Sn and Ag-Sn intermetallics at length scales similar to those observed in real solder joints. This article describes the experiment and discusses the results in terms of the effect of intermetallics on the reliability of microelectronic packages. The results show that, despite their high hardness, the intermetallics deform plastically without cracking at the small loads and length scales of nanoindentation testing.	*JOM: June 2003*	pp. 66-69	Read the Full Paper
The Use of Phase Diagrams and Thermodynamic Databases for Electronic Materials	*X.J. Liu, K. Oikawa, I. Ohnuma, R. Kainuma, and K. Ishida*	Phase diagrams and a thermodynamic database constructed by the Calculation of Phase Diagrams approach offer powerful tools for alloy design and materials development. This article presents recent progress on the thermodynamic database for microsolders and copper-based alloys, which is useful for the development of lead-free solders and prediction of interfacial phenomena between solders and the copper substrate in electronic packaging technology. In addition, examples of phase diagram applications are presented to facilitate the development of Co-Cr-based magnetic recording media in hard disks and new ferromagnetic shape-memory alloys.	*JOM: December 2003*	pp. 53-59	Read the Full Paper
Microstructural Effect on the Creep Strength of a Sn-3.5%Ag Solder Alloy	*Kepeng Wu, Noboru Wade, Jie Cui, and Kazuya Miyahara*	The effect of microstructure obtained by rapid or slow solidification and cooling of a Sn-3.5%Ag lead-free solder alloy on the creep strength has been investigated. The rapidly cooled alloy showed that the microstructure consisted of the primarily crystallized Sn phase and the quasi-eutectic phase, where fine Ag3Sn particles dispersed in the Sn matrix. In the slowly cooled alloy, large platelets of Ag3Sn were formed sparsely in the Sn matrix. A difference of about 2.5 orders of magnitude in the cooling rate translates to about 1.5 orders of magnitude in the creep-rupture time. Accordingly, fine particle dispersion of Ag3Sn is considered to be very beneficial for the restraining of creep deformation, that is, for the decreasing of creep rate of the Sn-3.5%Ag alloy, compared with the effect of large platelets of Ag3Sn sparsely formed in the Sn matrix.	*Journal of Electronic Materials: January 2003*	pp. 5-8	Acquire this Paper
The Wettability and Microstructure of Sn-Zn-RE Alloys	*C.M.L. Wu, C.M.T. Law, D.Q. Yu, and L. Wang*	Rare earth (RE) elements with concentrations of 0.05 wt.% and 0.1 wt.% of primarily Ce and La were added to the Sn-9Zn eutectic alloy to produce Sn-9Zn- RE alloys. A small amount of rodlike Zn-rich phases, which decreases in amount as the RE content increases, is distributed in the Sn matrix under slow cooling. The microstructure is refined with RE additions, and particulateshaped Sn-RE compounds begin to appear when the RE content reaches 0.1 wt.%. There is no change in the liquidus temperature after RE additions. Of the rosin-activated (RA), rosin mildly activated (RMA), rosin-nonactivated (R), and volatile organic compounds (VOC)-free types of fluxes used for the wetting balance tests in ambient air at 245°C, 260°C, and 290°C, only the RA flux can provide wetting. The addition of RE elements or the increase in soldering temperature reduces the wetting angle and increases the wetting force. The microhardness of the Sn-Zn-RE alloy system was found to be higher than that of Sn-9Zn.	*Journal of Electronic Materials: February 2003*	pp. 63-69	Acquire this Paper
A Constitutive Model for Creep of Lead-Free Solders Undergoing Strain-Enhanced Microstructural Coarsening: A First Report	*I. Dutta*	Lead-free solder joints in microelectronic applications frequently have microstructures comprising a dispersion of intermetallic particles in a Sn matrix. During thermomechanical cycling (TMC) of the solder joint, these particles undergo strain-enhanced coarsening, resulting in a continuously evolving, creep behavior. Because the extent of coarsening is dependent on the stress/strain state, which is dependent on the location within a joint, it is important that creep models used in joint-life prediction incorporate these effects. Here, an approach for incorporating the effect of in-situ second-phase particle coarsening in a dislocation-creep model applicable to lead-free solder alloys is proposed. The formulation, which can be expressed in a closed analytic form following some simplifications, incorporates the effects of both static- and strain-enhanced coarsening and accounts for the effects of inelastic-strain history and hydrostatic constraint. Predictions of coarsening based on the model agreed reasonably well with experimentally observed trends. Because of its simplicity, the microstructurally adaptive creep model proposed here can be easily inc	*Journal of Electronic Materials: April 2003*	pp. 201-207	Acquire this Paper
Lead-Free Sn-Ag and Sn-Ag-Bi Solder Powders Prepared by Mechanical Alloying	*H.L. Lai and J.G. Duh*	A mechanical alloying (MA) process was used to produce lead-free solder pastes of Sn-3.5Ag and the Sn-3.5Ag-4Bi system. Because of the high energy induced by repeated fracturing and welding, the grinding media played an important role during the MA process. A ceramic container was used to provide stronger impact force, which could induce phase transformation better than a Teflon container. In addition, it was found that 1-cm balls could fracture Bi particles and promote their dissolution into the Sn matrix. On the contrary, the milling process tended to achieve homogeneous mixing when using 3-mm balls. The MA powders, after milling with 3-mm balls, showed a small endothermic peak from the differential scanning calorimetry (DSC) profile at around 138°C, which was the eutectic temperature of Sn-Bi. The melting points of the MA powders in the ceramic container were measured to be 221°C and 203°C, respectively, for Sn-3.5Ag and Sn-3.5Ag-4Bi from the DSC curves. The reduced melting point ensured the complete melting during reflow with a peak temperature of 240°C. The formation of Ag3Sn was also observed from the x-ray diffraction pea	*Journal of Electronic Materials: April 2003*	pp. 215-220	Acquire this Paper

Recent TMS Articles: Lead-Free Solders

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Title	Authors	Abstract	Journal	Pages	Link
Properties of Lead-Free Solder SnAgCu Containing Minute Amounts of Rare Earth	*Zhigang Chen, Yaowu Shi, Zhidong Xia, and Yanfu Yan*	Because of excellent wetting and mechanical properties, SnAgCu solder alloys have been regarded as the most promising Pb-free substitutes for the SnPb solder. The Sn-3.8Ag-0.7Cu solder has garnered attention because of its creep resistance. However, under the drives of increasingly finer pitch design and severe service conditions, novel lead-free solders with higher creep performance may be needed. Adding a surface-active element to an alloy is an effective way to improve the high-temperature performance of the solder. The present work focuses on the effect of rare earth (RE) on the physical properties, spreading property, and mechanical properties of SnAgCu solder. Results show that the creep-rupture life of SnAgCu solder joints at room temperature could be notably increased by adding a minute amount of RE, up to 7 times more than that of SnAgCu solder joints when containing 1.0wt.%RE. The differential scanning calorimetry (DSC) curves indicated that the melting temperature of SnAgCu solder with RE increased a little, and no lower melting-temperature, eutectic endothermal peak appears on the DSC curve.	*Journal of Electronic Materials: April 2003*	pp. 235-243	Acquire this Paper
Foreword	*Michael A. Capano and Stephen J. Pearton*	Creep-rupture properties of lead-free Sn-3.5Ag?based alloys with varying amount of Cu were investigated using rolled and heat-treated dog-bone-shaped specimens. Nominal compositions of added copper were 0 wt.%, 0.5 wt.%, 0.75 wt.%, 1.0 wt.%, and 1.5 wt.%. During creep tests, the matrix hardness dropped significantly, and the minimum strain rates (min) were lowest for the 0.75Cu specimens. The stress exponents (n) of min were usually around 4, with the exception of the 0.5Cu and 0.75Cu alloys, which showed somewhat higher values of n. Fractographic analyses revealed typical creep rupture by the nucleation and growth of cavities in the matrix except the 1.5Cu specimens, which showed cavity nucleation at brittle Cu6Sn5 particles.	*Journal of Electronic Materials: May 2003*	p. 287	Acquire this Paper
Predicting Tensile Properties of the Bulk 96.5Sn-3.5Ag Lead-Free Solder	*Yi-Wen Cheng and Thomas A. Siewert*	Equations are presented for predicting tensile properties as functions of temperature and strain rate for the bulk-eutectic 96.5Sn-3.5Ag lead-free solder. At 25°C, we obtained 49.0 GPa for Young's modulus based on acoustic measurements, which is higher than most of those measured by tensile tests that are subject to viscoelastic creep; 23.1 MPa and 26.3 MPa for yield stress and ultimate tensile strength (UTS) of specimens that are cast, annealed, and aged at a strain rate of 2.0 × 10–4 s–1; 48.7% for total elongation, which is larger than most of the reported values. The presence of "initial defects" in the specimens, such as porosity and void, might cause the reduction in measured total elongations.	*Journal of Electronic Materials: June 2003*	pp. 535-540	Acquire this Paper
Creep Rupture of Lead-Free Sn-3.5Ag-Cu Solders	*D.K. Joo, Jin Yu, and S.W. Shin*	Creep-rupture properties of lead-free Sn-3.5Ag?based alloys with varying amount of Cu were investigated using rolled and heat-treated dog-bone-shaped specimens. Nominal compositions of added copper were 0 wt.%, 0.5 wt.%, 0.75 wt.%, 1.0 wt.%, and 1.5 wt.%. During creep tests, the matrix hardness dropped significantly, and the minimum strain rates (min) were lowest for the 0.75Cu specimens. The stress exponents (n) of min were usually around 4, with the exception of the 0.5Cu and 0.75Cu alloys, which showed somewhat higher values of n. Fractographic analyses revealed typical creep rupture by the nucleation and growth of cavities in the matrix except the 1.5Cu specimens, which showed cavity nucleation at brittle Cu6Sn5 particles.	*Journal of Electronic Materials: June 2003*	pp. 541-547	Acquire this Paper
Interfacial Microstructure Evolution in Pb-Free Solder Systems	*K.Y. Lee and M. Li*	The Sn-3.5Ag and Sn-3.0Ag-0.5Cu ball-grid-array solder balls bonded onto Ni/Au metallization exhibited different interfacial morphology after both wetting and solid-state reactions. In contrast to the eutectic-SnPb solder system, both Pb-free systems showed higher solder-ball shear strength after annealing. Reprecipitation of Au as (Au,Ni)Sn4 at the interface, as shown in the eutectic-SnPb solder system, was not observed in both Pb-free solder systems. Instead, Ni3Sn4 and Cu-Sn-Ni-Au intermetallic compounds (IMCs) were found in the SnAg and SnAgCu systems, respectively. In the SnAgCu system, a thick, acicular-Cu-Sn-Ni IMC formed after wetting, but a faceted-Cu-Sn-Ni-Au phase was found with longer annealing. The growth of this interfacial phase in the Sn-3.0Ag-0.5Cu solder system was also slightly inhibited by the addition of Cu, with a formation energy of about 200 kJ/mol.	*Journal of Electronic Materials: August 2003*	pp. 906-912	Acquire this Paper
The Microstructures and Mechanical Properties of the Sn-Zn-Ag-Al-Ga Solder Alloys—The Effect of Ga	*Kang-I Chen and Kwang-Lung Lin*	The microstructures and mechanical properties of Sn-8.55Zn-0.5Ag-0.45Al-yGa (wt.%) lead-free solders were investigated. The y content of the solders investigated was 0.5?3.0 wt.%. The results indicate that Ga exhibits prominent influence in the microstructure as well as mechanical properties of the solders. By increasing Ga, the fraction of the Sn/Zn eutectic region decreases and the Sn-matrix region increases. An increase in the Ga content from 0.5 wt.% to 2.0 wt.% enhances the tensile strength while degrading the ductility. The mechanical properties and differential scanning calorimetry (DSC) behavior have been compared with that of the 63Sn-37Pb solder. Gallium lowers the melting point of the Sn-8.55Zn-0.5Ag-0.45Al-yGa solders. The Sn-8.55Zn-0.5Ag-0.45Al-0.5Ga solders exhibit greater tensile strength and better ductility than the 63Sn-37Pb solder.	*Journal of Electronic Materials: October 2003*	pp. 1111-1116	Acquire this Paper

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Title	Authors	Abstract	Journal	Pages	Link
A Study on the Reaction between Cu and Sn3.5Ag Solder Doped with Small AMounts of Ni	*J.Y Tsai, Y.C. Hu, C.M. Tsai, and C.R. Kao*	The reaction between Cu and the Sn-Ag solders doped with different amounts of Ni is studied. Four different solders with the Ag concentration fixed at 3.5 wt.% and Ni concentrations varied between 0.0 wt.% and 1.0 wt.% are used. In contrast to the reaction between Ni and the Sn-Ag solders doped with different amounts of Cu, the type of intermetallic compound formed does not depend on the Ni concentration. The compound Cu6Sn5 forms for all the Ni concentrations used. For the Ni-doped solders, the Cu6Sn5 phase contains a small amount of Ni. The compound Cu3Sn appears subsequently between Cu6Sn5and Cu as the reaction time increases. The addition of Ni has the effect of substantially increasing the amount of intermetallic compound at the interface. The addition of Ni also produces two distinct Cu6Sn5 regions at the interface. The outer region contains more Ni, and the inner region contains less Ni. This study also finds that, during solid-state aging, the growth of Cu3Sn becomes slower when Ni is added to the solder. The findings of this study are rationalized using the Cu-Ni-Sn isotherm.	*Journal of Electronic Materials: November 2003*	pp. 1203-1208	Acquire this Paper
Intermetallic Growth between Lead-Free Solders and Palladium	*Gaurav Sharma, C.M. Eichfeld, and S.E. Mohney*	Intermetallic growth between Pd and the lead-free solders Sn-Ag and Sn-Ag-Cu has been studied. Diffusion couples were prepared by reflowing the solders on Pd and then aging the couples at 156°C, 175°C, 195°C, and 210°C. At thehigher temperatures of 175°C, 195°C, and 210°C, PdSn4 made up most of the layer that grew between the solders and the Pd, although small regions of second phases were always found in the PdSn4 matrix, and it was sometimes possible to identify discontinuous regions of PdSn3 next to the Pd. The thickness of the intermetallic layer increased with the square root of time, consistent with diffusion-controlled growth. In couples annealed at 156°C, themorphology of the PdSn3 phase and growth kinetics differed depending on thecomposition of the solder.	*Journal of Electronic Materials: November 2003*	pp. 1209-1213	Acquire this Paper
Interfaces in Lead-Free Soldering	*Chi-Won Hwang, Keun-Soo Kim, and Katsuaki Suganuma*	Structural integrity of circuits is greatly dependent on interfacial microstructure. In this paper, the status of the current understanding of various interfaces appearing in lead-free soldering is reviewed, and recent data on interfaces in electronic interconnections, primarily analyzed by transmission electron microscopy (TEM), is presented. The compound Cu6Sn5 is formed, as localized precipitates attach to the interface of a Cu substrate with Sn plating, even in an as-received condition. After long-time exposure at room temperature, it grows into a Cu6Sn5 layer along the interface. When the temperature is raised slightly or Sn in a plating layer is consumed by the reaction, a Cu3Sn layer cangrow between a Cu6Sn5 layer and a Cu substrate. In soldering, most Sn alloys involving pure Sn, Sn-Ag, or their ternary alloys form two intermetallic compounds, e.g., Cu6Sn5 and Cu3Sn, on a Cu substrate, with the former much thicker than the latter. The Ni plating forms Ni3Sn4/Ni3Sn2 double layers at the interface with Sn alloys in soldering with the latter layer very much thinner. In contrast, Fe-42Ni alloy forms (Fe,Ni)Sn2 double layers by the reacti	*Journal of Electronic Materials: November 2003*	pp. 1249-1256	Acquire this Paper
Effects of Intermetallic Morphology at the Metallic Particle/Solder Interface on Mechanical Properties of Sn-Ag-Based Solder Joints	*H. Rhee, F. Guo, J.G. Lee, K.C. Chen, and K.N. Subramanian*	Mechanical incorporation of metallic particles in the Sn-Ag-based solder resulted in various intermetallic compound (IMC) morphologies around these particles during reflow. Unlike with the Ni particles, the IMCs formed around Cu and Ag particles are relatively insensitive to reflow profiles employed. The IMC formed around the Ni particles ranges from "sunflower" morphology to "blocky" morphology with increasing time and temperature above liquidus during the heating part of the reflow profile. Mechanical properties, such as simple shear strength and creep behavior, of these composite solders were affected by the IMC morphologies in the composite solders investigated. Sunflower-shaped IMC formed around an Ni particles resulted in higher simple shear strength and better creep properties.	*Journal of Electronic Materials: November 2003*	pp. 1257-1264	Acquire this Paper
Electromigration Studies of Flip Chip Sn95/Sb5 Solder Bumps on Cr/Cr-Cu/Cu Under-Bump Metallization	*T.L. Shao, K.C. Lin, and Chih Chen*	The electromigration-induced failure of Sn95/Sb5 flip chip solder bumps was investigated. The failure of the joints was found at the cathode/chip side after current stressing with a density of 1 × 104 A/cm2at 150°C for 13 sec. The growth of intermetallic compounds (IMCs) was observed at the anode side after current stressing. Voids were found near the current crowding area in the cathode/chip side, and the (Cu,Ni)6Sn5 IMC at the cathode/chip end was transformed into the Sn phase. The failure mechanism for Sn95/Sb5 flip chip solder joint is proposed in this paper.	*Journal of Electronic Materials: November 2003*	pp. 1278-1283	Acquire this Paper
Mechanical Properties and Intermetallic Compound Formation at the SnNi and Sn-0.7 wt.%Cu/Ni Joints	*Sinn-Wen Chen, Shou-Wei Lee, and Ming-Chuen Yip*	The Ni/Sn/Ni and Ni/Sn-0.7wt.%Cu/Ni couples are reacted at 200°C for various lengths of time. The tensile strengths of these annealed specimens are determined at room temperature. In addition, the interfacial reactions and fracture surfaces of the specimens are examined as well. These properties are important for the evaluation of the usage of Sn-0.7wt.%Cu lead-free solders,which has been not available in the literature. Only the Ni3Sn4 phase isformed at the Sn/Ni interface, but both the Cu6Sn5and Ni3Sn4 phases areformed at the Sn-0.7wt.%Cu/Ni interface. The thickness of the intermetallic compound layers grows, while the joint strength decreases with longer reaction time. With a 1-h reaction at 200°C, the fracture surface is in the solder matrix for both of the two kinds of couples. Shifting toward the compound layer with longer reaction time, the fracture surface is in the Ni3Sn4 layer in the Sn/Ni couple and is at the interface between the Cu6Sn5 and Ni3Sn4 in theSn-0.7wt.%Cu/Ni after reacting at 200°C for 240 h.	*Journal of Electronic Materials: November 2003*	pp. 1284-1289	Acquire this Paper

Title	Authors	Abstract	Journal	Pages	Link
Phase Equilibria Studies of Sn-Ag-Cu Eutectic Solder Using Differential Cooling of An-3.8Ag-0.7Cu Alloys	*Jae-Yong Park, Choong-Un Kim, Ted Carper, and Viswanadham Puligandla*	This paper is a study of the phase equilibria of the Sn-3.8Ag-0.7Cu alloy investigated by a differential cooling method. The difficulty in assessing phase equilibria of the Sn-Ag-Cu (SAC) system because of the insufficient resolution of conventional characterization techniques is solved by inducing preferential growth of a solid phase in a melt by holding the alloy at the solid-liquid phase-equilibrium field. Application of the technique to Sn-3.8Ag-0.7Cu with varying holding temperatures yielded results that the alloy is slightly off eutectic composition. The phase-formation sequence of the alloy during solidification wasfound to be Ag3Sn, β-Sn, and finally the ternary eutectic microstructure.	*Journal of Electronic Materials: November 2003*	pp. 1297-1302	Acquire this Paper
Foreword	*James P. Lucas, Srini Chada, Sung K. Kang, C. Robert Kao, Kwang-Lung Lin, Jud Ready, and Jin Yu*	This special issue includes some of the papers presented at the Lead-Free Solders and Processing Issues Relevant to Microelectronic Packaging" symposium held in San Diego, California on March 3-5, 2003 as part of the 2003 TMS Annual Meeting.	*Journal of Electronic Materials: December 2003*	p. 1359	Acquire this Paper
Packaging of Nanostructured Microelectromechanical Systems Microtriode Devices	*L.H. Chen and S. Jin*	Combining the world of microelectromechanical systems (MEMS) with that of nano can lead to new devices with unique or advanced functionalities. Carbon nanotubes are fascinating new nanomaterials with many interesting physical, chemical, and electronic properties and potential new applications. We have incorporated nanotubes into the MEMS structure as patterned, cold-cathode field emitters to create on-chip, miniature vacuum tubes of microtriodes that can be useful for high-frequency microwave communications. Proper bonding and assembly processes were essential in providing reliable electrical connections and improved amplification performances.	*Journal of Electronic Materials: December 2003*	pp. 1360-1365	Acquire this Paper
Rare-Earth-Enabled Universal Solders for Microelectromechanical Systems and Optical Packaging	*Sungho Jin*	In packaging of microelectromechanical systems (MEMS), optical, and electronic devices, there is a need to directly bond a wide variety of inorganic materials, such as oxides, nitrides, and semiconductors. Such applications involve hermetic-sealing components, three-dimensional MEMS assembly components as well as active semiconductor or optical components, dielectric layers, diffusion barriers, waveguides, and heat sinks. These materials are known to be very difficult to wet and bond with low melting-point solders. New Sn-Ag- or Au-Sn-based universal solders doped with a small amount of rare-earth (RE) elements have been developed, which now allow direct and powerful bonding onto the surfaces of various MEMS, optical, or electronic device materials. The microstructure, interface properties, and mechanical behavior of the bonds as well as the potential packaging applications of these new solder materials for MEMS and optical fiber devices are described. Various packaging-related structural, thermal, or electrical issues in MEMS are also discussed.	*Journal of Electronic Materials: December 2003*	pp. 1366-1370	Acquire this Paper
Temperature and Duration Effects on Microstructure Evolution during Copper Wafer Bonding	*K.N. Chen, A. Fan, C.S. Tan, and R. Reif*	Interfacial morphologies during Cu wafer bonding at bonding temperatures of 300?400°C for 30 min followed by an optional 30-min or 60-min nitrogen anneal were investigated by means of transmission electron microscopy (TEM). Results showed that increased bonding temperature or increased annealing duration improved the bonding quality. Wafers bonded at 400°C for 30 min followed by nitrogen annealing at 400°C for 30 min, and wafers bonded at 350°C for 30 min followed by nitrogen annealing at 350°C for 60 min achieve the same excellent bonding quality	*Journal of Electronic Materials: December 2003*	pp. 1371-1374	Acquire this Paper
Mechanical Properties of Intermetallic Compounds Associated with Pb-Free Solder Joints Using Nanoindentation	*J.P. Lucas, H. Rhee, F. Guo, and K.N. Subramanian*	Mechanical properties of intermetallic compound (IMC) phases in Pb-free solder joints were obtained using nanoindentation testing (NIT). The elastic modulus and hardness were determined for IMC phases associated with insitu FeSn particle reinforced and mechanically added, Cu particle-reinforced, composite solder joints. The IMC layers that formed around Cu particle reinforcement and at the Cu substrate/solder matrix interface were probed with NIT. Moduli and hardness values obtained by NIT revealed were noticeably higher for Cu-rich Cu3Sn than those of Cu6Sn5. The Ag3Sn platelets that formed during reflow were also examined for eutectic Sn-Ag solder column joints. The indentation modulus of Ag3Sn platelets was significantly lower than that of FeSn, SnCuNi, and CuSn IMCs. Indentation creep properties were assessed in localized microstructure regions of the as-cast, eutectic Sn-Ag solder. The stress exponent, n, associated with secondary creep differed widely depending on the microstructure feature probed by the indenter tip.	*Journal of Electronic Materials: December 2003*	pp. 1375-1383	Acquire this Paper
Isothermal Aging of Near-Eutectic Sn-Ag-Cu Solder Alloys and Its Effect on Electrical Resistivity	*B.A. Cook, I.E. Anderson, J.L. Harringa, and S.K. Kang*	Solder joints were prepared from seven eutectic and near-eutectic Sn-based compositions and characterized for electrical resistivity after 100 h and 1,000 h of isothermal aging at 423 K. The solder joint samples were prepared by hand soldering to copper substrates, and the post-heat treatment resistivity was measured at room temperature in a specially designed, four-point probe fixture. Compositions tested included Sn-3.5Ag, Sn-3.7Ag-0.9Cu, Sn-3.0Ag- 0.5Cu, Sn-3.6Ag-1.0Cu, and Sn-3.9Ag-0.6Cu. In addition, the effect of a minor addition of a fourth element, designed to improve high-temperature shear strength, was also evaluated in the compositions Sn-3.7Ag-0.6Cu-0.3Co and Sn-3.7Ag-0.7Cu-0.2Fe. The observed changes in electrical resistivity are discussed in terms of microstructural coarsening, diffusional transport from the substrate, and nucleation of precipitate phases.	*Journal of Electronic Materials: December 2003*	pp. 1384-1391	Acquire this Paper

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Creep and Rupture Behavior of Cu Wire/Lead-Free Solder-Alloy Joint Specimen	*Kepeng Wu, Makoto Aoyama, Noboru Wade, Jie Cui, Shinji Yamada, and Kazuya Miyahara*	Creep and rupture behavior of Cu wire/lead-free solder-alloy joint specimens have been investigated using Sn-3.5% Ag and Sn-0.5% Cu alloys. A Sn-37% Pb solder alloy is also used as a reference material. The present authors have fabricated a creep-rupture testing machine for Cu wire/solder-alloy joint specimens, performed creep and rupture tests at 303 K and 403 K, analyzed the characteristics of the creep and rupture behavior, and compared these to test specimens cut from the same alloy ingots. It is also found that the rupture strength of the joint specimens is related to the rupture strength of the alloys.	*Journal of Electronic Materials: December 2003*	pp. 1392-1397	Acquire this Paper
The Constitutive Creep Equation for a Eutectic Sn-Ag Alloy Using the Modified Theta-Projection Concept	*Yoshiharu Kariya, Masahisa Otsuka, and William J. Plumbridge*	Creep data for a eutectic tin-silver alloy at temperatures between 298 K and 398 K have been analyzed using the modified theta-projection concept, instead of the steady-state creep constitutive equation in the following formula: ecr = A {1 - exp(-at)} + B {exp(at) - 1}, where A, B, and a are constants to be experimentally determined. The equation describes well the creep curves of the eutectic tin-silver alloy up to the tertiary stage. All constants exhibited power law relationships with the applied stress. The rate constant, a, has a high stress exponent, which is attributed to dispersion strengthening. The rate constant a and the strain factor B only showed temperature dependence, while the strain factor A was independent of temperature. The activation energy for a was 65 kJ/mol at high stresses and 90 kJ/mol at low stresses. The energies suggest that the dislocation pipe diffusion and the lattice diffusion are predominant at high stresses and low stresses, respectively.	*Journal of Electronic Materials: December 2003*	pp. 1398-1402	Acquire this Paper
Influence of Initial Morphology and Thickness of Cu6Sn5 and Cu3Sn Intermetallics on Growth and Evolution during Thermal Aging of Sn-Ag Solder/Cu Joints	*X. Deng, G. Piotrowski, J.J. Williams, and N. Chawla*	Intermetallic-layer formation and growth in Pb-free solder joints, during solder reflow or subsequent aging, has a significant effect on the thermal and mechanical behavior of solder joints. In this study, the influence of initial intermetallic morphology on growth rate, and kinetics were examined in a Sn-3.5Ag solder reflowed on Cu. The initial morphology of the intermetallic was tailered by cooling in water, air, or furnace conditions. Solder aging was conducted at 100°C, 140°C, and 175°C and aged for 0-1,000 h. Cooling rate, aging temperature, and aging time played an important role on microstructure evolution and growth kinetics of Cu6Sn5 (h) and Cu3Sn (e) intermetallic layers. Prior to aging, faster cooling rates resulted in a relatively planar Cu6Sn5 layer, while a nodular Cu6Sn5 morphology was present for slower cooling. Intermetallic-growth rate measurements after aging at various times, indicated a mixed growth mechanism of grain-boundary and bulk diffusion. These mechanisms are discussed in terms of the initial intermetallic thickness and morphology controlled by cooling rate, diffusion kinetics, and the competition between Cu6Sn5 and Cu3Sn growth.	*Journal of Electronic Materials: December 2003*	pp. 1403-1413	Acquire this Paper
Effects of Cooling Rate on the Microstructure and Tensile Behavior of a Sn-3.5wt.%Ag Solder	*FF. Ochoa, J.J. Williams, and N. Chawla*	The tensile behavior and microstructure of bulk, Sn-3.5Ag solders as a function of cooling rate were studied. Cooling rate is an important processing parameter that affects the microstructure of the solder and, therefore, significantly influences mechanical behavior. Controlled cooling rates were obtained by cooling specimens in different media: water, air, and furnace. Cooling rate significantly affected secondary dendrite-arm size and spacing of the Sn-rich phase, as well as the aspect ratio of Ag3Sn. The Sn-rich dendrite-arm size and spacing were smaller for water-cooled specimens than for air-cooled specimens. Furnace cooling yielded a nearly eutectic microstructure because the cooling rate approached equilibrium cooling. The morphology of Ag3Sn also changed from spherical, at a fast cooling rate, to a needlelike morphology for slower cooling. The changes in the microstructure induced by the cooling rate significantly affected the mechanical behavior of the solder. Yield strength was found to increase with increasing cooling rate, although ultimate tensile strength and strain-to-failure seemed unaffected by cooling rate. Cooling rate did not seem to affect `	*Journal of Electronic Materials: December 2003*	pp. 1414-1420	Acquire this Paper
Lead-Free Ceramic Ball Grid Array: Thermomechanical Fatigue Reliability	*Mukta Farooq, Charles Goldsmith, Ray Jackson, and Gregory Martin*	Flip-chip carriers have become the preferred solution for high-performance, application-specific integrated circuit and microprocessor devices. Typically, these are packaged in organic or ceramic ball grid array (BGA) packages, which cover a wide range of package input/output (I/O) capabilities required for high-performance devices, typically, between 300 to more than 1,600 I/O. Recently, there has been a move toward Pb-free solders as replacement alloys for standard, eutectic Sn/Pb and other Pb-based BGAs. The leading solder that has emerged from various Pb-free solder evaluations by industry and academic consortia is the Sn/Ag/Cu (SAC) alloy. One of the primary issues with changing solders is the reliability of the joints when these are subjected to thermomechanical fatigue (TMF). This evaluation has previously been conducted on SAC ceramic ball grid array (CBGA) assemblies in a 1.27-mm pitch. However, with the need to shrink the I/O pitch to accommodate higher wiring density, it has become increasingly important to conduct TMF reliability assessments in a 1-mm pitch format. This paper describes such an evaluation conducted u	*Journal of Electronic Materials: December 2003*	pp. 1421-1425	Acquire this Paper

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Effect of Microelements Addition on the Interfacial Reaction between Sn-Ag-Cu Solders and the Cu Substrate	*Chiang-Ming Chuang and Kwang-Lung Lin*	Three kinds of Sn-Ag-based lead-free solders, Sn-3.5Ag-0.7Cu, Sn-3.5Ag-0.5Cu- 0.07Ni-0.01Ge, and Sn-3.5Ag-0.07Ni (in wt.%), were selected to explore the effect of microelements (Ni and Ge) on the interfacial reaction between the solder and the Cu substrate. The thickness of the interfacial intermetallics formed with the Sn-3.5Ag-0.5Cu-0.07Ni-0.01Ge and Sn-3.5Ag-0.07Ni solders is several times that of the Sn-3.5Ag-0.7Cu solder. The added microelements converted the feature of interfacial intermetallics from pebble shape to worm shape. However, the results of x-ray diffraction (XRD) analysis suggest that the interfacial intermetallics formed with both solders have the same crystal structure. The results of energy dispersive spectroscopy (EDS) analysis show that the major interfacial intermetallic formed with the Sn-3.5Ag-0.7Cu solder is Cu6Sn5, while it is (Cux,Ni1–x)6Sn5 with Sn-3.5Ag-0.5Cu-0.07Ni- 0.01Ge. Ni influences the interfacial intermetallics and plays the influential role on the difference of interfacial reaction rate between liquid solder and solid Cu and the morphology of interfacial intermetallics. Additionally, the growth kinetics of the interf	*Journal of Electronic Materials: December 2003*	pp. 1426-1431	Acquire this Paper
Effects of Mechanical Deformation and Annealing on the Microstructure and Hardness of Pb-Free Solders	*Paul Lauro, Sung K. Kang, Won Kyoung Choi, and Da-Yuan Shih*	The microstructure property relations of several Pb-free solders are investigated to understand the microstructural changes during thermal and mechanical processes of Pb-free solders. The Pb-free solder alloys investigated include pure Sn, Sn-0.7% Cu, Sn-3.5% Ag, and Sn-3.8% Ag-0.7% Cu (in weight percent). To reproduce a typical microstructure observed in solder joints, the cooling rate, ingot size, and reflow conditions of cast alloys were carefully controlled. The cast-alloy pellets are subjected to compressive deformation up to 50% and annealing at 150°C for 48 h. The microstructure of Pb-free solders is evaluated as a function of alloy composition, plastic deformation, and annealing. The changes in mechanical property are measured by a microhardness test. The work hardening in Sn-based alloys is found to increase as the amount of alloying elements and/or deformation increases. The changes in microhardness upon deformation and annealing are correlated with the microstructural changes, such as recrystallization or grain growth, in Pb-free solder alloys.	*Journal of Electronic Materials: December 2003*	pp. 1432-1440	Acquire this Paper
Thickening Kinetics of Interfacial Cu6Sn5 and Cu3Sn Layers during Reaction of Liquid Tin with Solid Copper	*Robert A. Gagliano and Morris E. Fine*	Thickening behavior of interfacial h (Cu6Sn5) phase and e (Cu3Sn) phase intermetallic layers was investigated in liquid tin/solid copper reaction couples over reaction times from 30 sec to over 4,000 min and temperatures from 250°C to 325°C. A scanning electron microscope (SEM) was used to quantify the interfacial microstructure at each processing condition. The h developed with a scalloped morphology, while the e always grew as a somewhat undulated planar layer in phase with the h. The thickness of each phase was quantitatively evaluated from SEM micrographs using imaging software. Thickening kinetics of the e and h compounds were modeled using time- and temperaturedependent empirical power-law equations. From the model, values for the kinetic exponent, rate constant, and activation energy were established for each intermetallic layer. Measured values for the kinetic exponents and activation energies suggest that thickening of the h is controlled by a grain-boundary diffusion mechanism, and growth of the e occurs by solid-state diffusion, probably grain-boundary diffusion.	*Journal of Electronic Materials: December 2003*	pp. 1441-1447	Acquire this Paper
Microstructure Characterization of Sn-Ag Solder Joints between Stud Bumps and Metal Pads	*Mu-Seob Shin and Young-Ho Kim*	The microstructure of the flip-chip solder joints fabricated using stud bumps and Pb-free solder was characterized. The Au or Cu stud bumps formed on Al pads on Si die were aligned to corresponding metal pads in the substrate, which was printed with Sn-3.5Ag paste. Joints were fabricated by reflowing the solder paste. In the solder joints fabricated using Au stud bumps, Au-Sn intermetallics spread over the whole joints, and the solder remained randomly island-shaped. The d-AuSn, e-AuSn2, and h-AuSn4 intermetallic compounds formed sequentially from the Au stud bump. The microstructure of the solder joints did not change significantly even after multiple reflows. The AuSn4 was the main phase after reflow because of the fast dissolution of Au. In the solder joints fabricated using Cu stud bumps, the scallop-type Cu6Sn5 intermetallic was formed only at the Cu interface, and the solder was the main phase. The difference in the microstructure of the solder joints with Au and Cu stud bumps resulted from the dissolution-rate difference of Au and Cu into the solder.	*Journal of Electronic Materials: December 2003*	pp. 1448-1454	Acquire this Paper
Comparisons of Experimental and Computed Crystal Rotations Caused by Slip in Crept and Thermomechanically Fatigued Dual-Shear Eutectic Sn-Ag Solder Joints	*A.U. Telang, T.R. Bieler, D.E. Mason, and K.N. Subramanian*	Single shear-lap specimens having a solder joint area of 1 mm2 and nominally 100-mm thickness on copper substrates were crept at 85°C and compared to dual shear-lap specimens with copper and nickel interfaces that were thermomechanically cycled from -15°C to 150°C to mimic the solder-joint deformation history of surface-mount components. Electron microscopy revealed surface cracks in some grain boundaries in the creep specimen and shear bands and other surface relief features on the originally polished surfaces after 100 cycles with short times at high temperature and long times at cold temperature. Orientation imaging microscopy (OIM) studies of various regions of these specimens were used to determine how the microstructure and crystallographic orientations evolved with creep or thermomechanical cycling. These results are compared to ascertain how strain path, the anisotropy of Sn, and various slip systems could account for crack nucleation and ultimate failure of the solder joint in surfacemount components.	*Journal of Electronic Materials: December 2003*	pp. 1455-1462	Acquire this Paper

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Compound Formation for Electroplated Ni and Electroless Ni in the Under-Bump Metallurgy with Sn-58Bi Solder during Aging	*Bi-Lian Young, Jenq-Gong Duh, and Guh-Yaw Jang*	The Ni-based under-bump metallurgies (UBMs) are of interest because they have a slower reaction rate with Sn-rich solders compared to Cu-based UBMs. In this study, several UBM schemes using Ni as the diffusion barrier are investigated. Joints of Sn-58Bi/Au/electroless nickel (EN)/Cu/Al2O3 and Sn-58Bi/Au/electroplated nickel/Cu/Al2O3 were aged at 110°C and 130°C for 1?25 days to study the interfacial reaction and microstructural evolution. The Sn-Bi solder reacts with the Ni-based multimetallization and forms the ternary Sn-Ni-Bi intermetallic compound (IMC) during aging at 110°C. Compositions of ternary IMC were (78-80)at.%Sn-(12-16)at.%Ni-(5-8)at.%Bi in joints of Sn-58Bi/Au/Ni-5.5wt.%P/Cu, Sn-58Bi/Au/Ni-12wt.%P/Cu, and Sn-58Bi/Au/Ni/Cu. Elevated aging at 130°C accelerates the IMC growth rate and results in the formation of (Ni,Cu)3Sn4 and (Cu,Ni)6Sn5 adjacent to the ternary Sn-Ni-Bi IMC for the Sn-58Bi/Au/Ni-12wt.%P/Cu and Sn-58Bi/Au/Ni/Cu joints, respectively. The Cu content in the (Cu,Ni)6Sn5 IMC is six times that in (Ni,Cu)3Sn4. Electroplated Ni fails to prevent Cu diffusion toward the Ni/solder interface as compare	*Journal of Electronic Materials: December 2003*	pp. 1463-1473	Acquire this Paper
Influence of Au Addition on the Phase Equilibria of Near-Eutectic Sn-3.8Ag-0.7Cu Pb-Free Solder Alloy	*Jae-Yong Park, Rajendra Kabade, Choong-Un Kim, Ted Carper, Steven Dunford, and Viswanadham Puligandla*	This paper illustrates the influence of Au addition on the phase equilibria of Sn-Ag-Cu (SAC) near-eutectic alloys and on the interface reaction with the Cu substrate. From the thermal and microstructural characterization of Sn-3.8Ag-0.7Cu alloys containing various amounts of Au, it is found that the Au promotes the formation of a quaternary-eutectic reaction at 204.5°C ± 0.3°C. The equilibrium phases in the quaternary-eutectic microstructure are found to be AuSn4, Ag3Sn, bSn, and Cu6Sn5. While the addition of Au to Sn-3.8Ag-0.7Cu alloys is also found to increase liquidus temperature and the temperature ranges of the phase equilibria field for primary phases, such influences from Au are found to be less pronounced when the alloys were reacted with the Cu substrate. Because of the formation of the Au-Cu-Sn-ternary interface intermetallic, it is found that a majority of Au added to the solder is drained from the melt. The drainage of Au reduces the impact of Au on the phase equilibria of the solder alloys in the joint. It is further found that the involvement of Au in the interface reaction results in a change of the interface phase morphology fro	*Journal of Electronic Materials: December 2003*	pp. 1474-1482	Acquire this Paper
Developments in Lead-Free Solders and Soldering Technology	*Sung K. Kang*	At the 2002 TMS Annual Meeting in Seattle, Washington, a technical symposium on "Pb-Free Solders and Materials Issues in Microelectronic Packaging" provided a successful forum to present and discuss recent findings on various aspects of lead-free solder R&D. Papers presented dealt with fundamental studies, microstructure, alloy development, interfacial reactions, mechanical properties, physical metallurgy, solder joint reliability of lead-free solders, and solder joints. Of the papers presented, four will be published in this issue of JOM to provide an update on our current understanding of the issues, especially microstructure-property relations and reliability-related problems of creep deformation, interfacial reactions, and electromigration.	*JOM: June 2002*	p. 25	Read the Full Paper
Sn-Ag-Cu Solders and Solder Joints: Alloy Development, Microstructure, and Properties	*I.E. Anderson, B.A. Cook, J.L. Harringa, and R.L. Terpstra*	Slow cooling of Sn-Ag-Cu and Sn-Ag-Cu-X (X = Fe, Co) solder-joint specimens made by hand soldering simulated reflow in surface-mount assembly to achieve similar as-solidified joint microstructures for realistic shear-strength testing, using Sn-3.5Ag (wt.%) as a baseline. Minor substitutions of either cobalt or iron for copper in Sn-3.7Ag-0.9Cu refined the joint matrix microstructure, modified the Cu6Sn5 intermetallic phase at the copper substrate/solder interface, and increased the shear strength. At elevated (150°C) temperature, no significant difference in shear strength was found in all of the alloys studied. Ambient temperature shear strength was reduced by large-scale tin dendrites in the joint microstructure,	*JOM: June 2002*	pp. 26-29	Read the Full Paper
The Creep Properties of Lead-Free Solder Joints	*H.G. Song, J.W.Morris, Jr., and F. Hua*	This paper describes the creep behavior of three tin-rich solders that have become candidates for use in lead-free solder joints: Sn-3.5Ag, Sn-3Ag-0.5Cu, and Sn-0.7Cu. The three solders show the same general behavior when tested in thin joints between copper and Ni/Au metallized pads at temperatures between 60°C and 130°C. Their steady-state creep rates are separated into two regimes with different stress exponents. The low-stress exponents range from ~3–6, while the high-stress exponents are anomalously high (7–12). Strikingly, the high-stress exponent has a strong temperature dependence near room temperature, increasing significantly as the temperature drops from 95°C to 60°C. The anomalous creep behavior of the solders appears to be due to the dominant tin constituent. Research on creep in bulk samples of pure tin suggests that the anomalous temperature dependence of the stress exponent may show a change in the dominant mechanism of creep. Whatever its source, it has the consequ ence that conventional constitutive relations for steady-state creep must be used with caution in treating tin-rich solder joints, and qualifi	*JOM: June 2002*	pp. 30-32	Read the Full Paper
Electromigration in Solder Joints and Solder Lines	*H. Gan, W.J. Choi, G. Xu, and K.N. Tu*	Electromigration may affect the reliability of flip-chip solder joints. Eutectic solder is a two-phase alloy, so its electromigration behavior is different from that in aluminum or copper interconnects. In addition, a flip-chip solder joint has a built-in current-crowding configuration to enhance electromigration failure. To better understand electromigration in SnPb and lead-free solder alloys, the authors prepared solder lines in v-grooves etched on Si (001). This article discusses the results of those tests and compares the electromigration failure modes of eutectic SnPb and SnAgCu flip-chip solder joints along with the mean-time-to-failure.	*JOM: June 2002*	pp. 34-37	Read the Full Paper

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Aspects of the Structural Evolution of Lead-Free Solder Joints	*A. Zribi, R. Kinyanjui, P. Borgesen, L. Zavalij, and E.J. Cotts*	Studies of the formation of intermetallic compounds at some lead-free solder/metallization interfaces are briefly reviewed in this article. SnAgCu/Ni and SnAgCu/Cu interfaces are examined in particular. It has been found that (Cu,Ni)6Sn5 forms at SnAgCu/Ni interfaces until copper is depleted from the solder matrix. This article also contrasts the formation of (Au,Ni)Sn4 and related compounds in PbSn/Ni solder joints and lead-free solder joints.	*JOM: June 2002*	pp. 38-40	Read the Full Paper
Phase Diagrams for Lead-Free Solder Alloys	*Ursula R. Kattner*	The need for new, improved solder alloys and a better understanding of reactions during the soldering process grows steadily as the need for smaller and more reliable electronic products increases. Information obtained from phase equilibria data and thermodynamic calculations has proven to be an important tool in the design and understanding of new lead-free solder alloys. A wide range of candidate alloys can be rapidly evaluated for proper freezing ranges, susceptibility to contamination effects, and reactions with substrate materials before the expensive process of preparing and testing candidate alloys is initiated.	*JOM: December 2002*	pp. 45-51	Read the Full Paper
The Chemical Modeling of Electronic Materials and Interconnections [	*J.K. Kivilahti*	Thermodynamic and kinetic modeling, together with careful experimental work, is of great help for developing new electronic materials such as lead-free solders, their compatible metallizations and diffusion-barrier layers, as well as joining and bonding processes for advanced electronics manufacturing. When combined, these modeling techniques lead to a rationalization of the trial-and-error methods employed in the electronics industry, limiting experimentation and, thus, reducing significantly time-to-market of new products. This modeling provides useful information on the stabilities of phases (microstructures), driving forces for chemical reactions, and growth rates of reaction products occurring in interconnections or thin-film structures during processing, testing, and in long-term use of electronic devices. This is especially important when manufacturing advanced lead-free electronics where solder joint volumes are decreasing while the number of dissimilar reactive materials is increasing markedly. Therefore, a new concept of local nominal composition was introduced and applied together with the relevant ternary and multicomponent phas	*JOM: December 2002*	pp. 52-57	Read the Full Paper
Joint Shape, Microstructure, and Shear Strength of Lead-Free Solder Joints with Different Component Terminations	*Shawkret Ahat, Huang Weidong, Sheng Mei, and Luo Le*	The joint shape, microstructure, and shear strength of 95Sn5Sb solder joints with components with different terminal metallizations (AgPd and Ni/AgPd) were investigated and compared to 62Sn36Pb2Ag solder. The rapid reaction between SnSb solder and AgPd leads to the solder not spreading entirely on the Cu pad but agglomerating on the component termination. The shear strength of the SnSb/AgPd solder joint is very low and fracture occurs at the original interface of the AgPd/ceramic. The Ni layer in the SnSb/Ni/AgPd joint effectively avoids interdiffusion between the AgPd and the solder so that a high-strength solder joint with an ideal shape is achieved. However, the terminations of the components have little effect on the shape and the shear strength of the SnPbAg solder joint. Fracture occurs in the SnPbAg solder after shear testing to failure.	*Journal of Electronic Materials: February 2002*	pp. 136-141	Acquire this Paper
Low-Cycle Fatigue Behavior and Mechanisms of a Lead-Free Solder 96.5Sn/3.5Ag	*Chaosuan Kanchanomai, Yukio Miyashita, and Yoshiharu Mutoh*	Low-cycle fatigue tests of as-cast Sn-Ag eutectic solder (96.5Sn/3.5Ag) were performed using a noncontact strain controlled system at 20°C. The fatigue behavior followed the Coffin-Manson equation with a fatigue-ductility exponent of 0.76. Without local deformation and stress concentration at contact points between the extensometer and the specimen surface in strain-controlled fatigue tests, crack initiation and propagation behavior was observed on the specimen surface using a replication technique. After failure, the longitudinal cross sections were also examined using scanning electron microscopy (SEM). Microcracks initiated from steps at the boundary between the Sn-dendrite and the Sn-Ag eutectic structure and cavities along the boundaries especially around the Ag3Sn particles. Stage II crack propagated in mixed manner with intergranular cracks along the Sn-dendrite boundaries and transgranular cracks through the Sn-dendrites and the Sn-Ag eutectic structure. Propagation of stage II cracks could be expressed by the relation of $dac/dN = 4.7 \times 10^{-11}[\Delta J]^{1.5}$, where ac is the average crack length and ΔJ is the J-int	*Journal of Electronic Materials: February 2002*	pp. 142-151	Acquire this Paper
Interfacial Reactions in In-Sn/Ni Couples and Phase Equilibria of the In-Sn-Ni System	*Ching-Yu Huang and Sinn-Wen Chen*	The In-Sn-Ni alloys of various compositions were prepared and annealed at 160°C and 240°C. No ternary compounds were found; however, most of the binary compounds had extensive ternary solubility. There was a continuous solid solution between the Ni3Sn phase and Ni3In phase. The Sn-In/Ni couples, made of Sn-In alloys with various compositions, were reacted at 160°C and 240°C and formed only one compound for all the Sn-In alloys/Ni couples reacted up to 8 h. At 240°C, Ni28In72 phase formed in the couples made with pure indium, In-10at.%Sn and In-11at.%Sn alloys, while Ni3Sn4 phase formed in the couples made of alloys with compositions varied from pure Sn to In-12at.%Sn. At 160°C, except in the In/Ni couple, Ni3Sn4 formed by interfacial reaction.	*Journal of Electronic Materials: February 2002*	pp. 152-160	Acquire this Paper

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Determination of the Eutectic Structure in the Ag-Cu-Sn System	*Daniel Lewis, Sarah Allen, Michael Notis, and Adam Scotch*	A search for lead-free solder alloys has produced an alloy in the Ag-Cu-Sn system. This alloy is of great importance to the soldering community, and proper determination of structure, processing, and properties will be significant. In the present study, tin-rich alloys were fabricated to better determine the much-debated morphology of secondary and tertiary phases in the eutectic structure. A deep etching procedure was used to reveal the growth structure of monovariant "eutectic-like" reactions as well as the ternary eutectic reaction. Scanning electron microscopy (SEM) and electron-probe microanalysis (EPMA) verified the three-phase nature of the eutectic. The rodlike eutectic structure in this system is consistent with the more simplified volume fraction and surface energy models that have been presented in the literature.	*Journal of Electronic Materials: February 2002*	pp. 161-167	Acquire this Paper
Microstructural Characterization of Damage in Thermomechanically Fatigued Sn-Ag Based Solder Joints	*S. Choi, J.G. Lee, K.N. Subramanian, J.P. Lucas and T.R. Bieler*	Sn-Ag based solder joints of 100-µm thickness were thermomechanically fatigued between −15°C and +150°C with a ramp rate of 25°C/min for the heating segment and 7°C/min for the cooling segment. The hold times were 20 min at high temperature extreme and 300 min at the low temperature extreme. Surface damage accumulation predominantly consisted of shear banding, surface relief due to Sn-grain extrusion, grain boundary sliding, and grain decohesion usually near the solder/substrate interface. Small alloy additions were found to affect the extent of this surface damage accumulation.	*Journal of Electronic Materials: April 2002*	pp. 292-297	Acquire this Paper
Creep Behavior of Eutectic Sn-Cu Lead-Free Solder Alloy	*C.M.L. Wu and M.L. Huang*	Tensile creep behavior of precipitation-strengthened, tin-based eutectic Sn-0.7Cu alloy was investigated at three temperatures ranging from 303-393 K. The steady-state creep rates cover six orders of magnitude (10−3 − 10−8 s−1) under the stress range of σ/E = 10−4 − 10−3. The initial microstructure reveals that the intermetallic compound Cu6Sn5 is finely dispersed in the matrix of β-Sn. By incorporating a threshold stress, σth, into the analysis, the creep data of eutectic Sn-Cu at all temperatures can be fitted by a single straight line with a slope of 7 after normalizing the steady-state creep rate and the effective stress, indicating that the creep rates are controlled by the dislocation-pipe diffusion in the tin matrix. So the steady-state creep rate, &OV0580;, can be expressed as where QC is the activation energy for creep, G is the temperature-dependent shear modulus, b is the Burgers vector, R is the universal gas constant, T is the temperature, σ is the applied stress, A is a material-dependent constant, and , in which σOB is the Orowan bowing stress, and kR is the relaxation factor.	*Journal of Electronic Materials: May 2002*	pp. 442-448	Acquire this Paper
Low-Cycle Fatigue Behavior of Sn-Ag, Sn-Ag-Cu, and Sn-Ag-Cu-Bi Lead-Free Solders	*Chaosuan Kanchanomai, Yukio Miyashita, and Yoshiharu Mutoh*	Low-cycle fatigue (LCF) tests on as-cast Sn-3.5Ag, Sn-3Ag-0.5Cu, Sn-3Ag-0.5Cu-1Bi, and Sn-3Ag-0.5Cu-3Bi solders was carried out using a noncontact strain-controlled system at 20°C with a constant frequency of 0.1 Hz. The addition of Cu does not significantly affect the fatigue life of eutectic Sn-Ag solder. However, the fatigue life was significantly reduced with the addition of Bi. The LCF behavior of all solders followed the Coffin-Manson relationship. The fatigue life of the present solders is dominated by the fracture ductility and can be described by the ductility-modified Coffin-Manson's relationship. Steps at the boundaries of dendrite phases were the initiation sites for microcracks for Sn-3.5Ag, Sn-3Ag-0.5Cu, and Sn-3Ag-0.5Cu-1Bi solders, while for Sn-3Ag-0.5Cu-3Bi solder, cracks initiated along both the dendrite boundaries and subgrain boundaries in the dendrite phases. The linking of these cracks and the propagation of cracks inside the specimen occurred both transgranularly through eutectic ph ases and intergranularly along dendrite boundaries or subgrain boundaries.	*Journal of Electronic Materials: May 2002*	pp. 456-465	Acquire this Paper
Effect of Cu Concentration on the Reactions between Sn-Ag-Cu Solders and Ni	*C.E. Ho, R.Y. Tsai, Y.L. Lin, and C.R. Kao*	The reaction between the Sn-Ag-Cu solders and Ni at 250°C for 10 min and 25 h was studied. Nine different Sn-Ag-Cu solders, with the Ag concentration fixed at 3.9 wt.% and Cu concentrations varied between 0.0-3.0 wt.%, were used. When the reaction time was 10 min, the reactions strongly depended on the Cu concentration. At low-Cu concentrations (0.2 wt.%), only a continuous (Ni1−xCux)3Sn4 layer formed at the interface. When the Cu concentration increased to 0.4 wt.%, a continuous (Ni1−xCux)3Sn4 layer and a small amount of discontinuous (Cu1−yNiy)6Sn5 particles formed at the interface. When the Cu concentration increased to 0.5 wt.%, the amount of (Cu1−yNiy)6Sn5 increased and (Cu1−yNiy)6Sn5 became a continuous layer. Beneath this (Cu1−yNiy)6Sn5 layer was a very thin but continuous layer of (Ni1−xCux)3Sn4. At higher Cu concentrations (0.6-3.0 wt.%), (Ni1−xCux)3Sn4 disappeared, and only (Cu1−yNiy)6Sn5 was present. The reactions at 25 h also depended strongly on the Cu concentration, proving that the strong concentration dependence was not a transient phenomenon limited to a short reaction time. The findings of this study were rationalized using the....	*Journal of Electronic Materials: June 2002*	pp. 584-590	Acquire this Paper
The Microstructures and Mechanical Properties of the Sn-Zn-Ag-Al-Ga Solder Alloys—the Effect of Ag	*Kang-I. Chen and Kwang-Lung Lin*	The microstructures and mechanical properties of Sn-8.55Zn-xAg-0.45 Al-0.5Ga (wt.%) lead-free solders were investigated. The x content of the solders investigated were 0.5-3.0 wt.%. The results indicate that Ag plays an important role not only in the structure but also in the mechanically properties. The mechanical properties and differential scanning calorimetry (DSC) behavior has been compared with that of 63Sn-37Pb solder. Small additions of Ag decreased the melting point of the Sn-8.55Zn-xAg-0.45Al-0.5Ga solders while maintaining the same strength and ductility as the 63Sn-37Pb solder.	*Journal of Electronic Materials: August 2002*	pp. 861-867	Acquire this Paper

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Title	Authors	Abstract	Source	Pages	Link
Fatigue Crack-Growth Behavior of Sn-Ag-Cu and Sn-Ag-Cu-Bi Lead-Free Solders	*J. Zhao, Y. Mutoh, Y. Miyashita, and S. L. Mannan*	Fatigue crack-growth behavior and mechanical properties of Sn-3Ag-0.5Cu, Sn-3Ag-0.5Cu-1Bi, and Sn-3Ag-0.5Cu-3Bi solders have been investigated at room temperature (20°C). The tensile strength and hardness of the solders increased with increasing Bi content. However, the yield strengths of Sn-3Ag-0.5Cu-1Bi and Sn-3Ag-0.5Cu-3Bi solders were nearly similar, but the 3Bi solder exhibited the lowest ductility. Fatigue crack-growth behavior of the solders was dominantly cycle dependent in the range of stress ratios from 0.1-0.7 at a frequency of 10 Hz, except for the Sn-3Ag-0.5Cu solder tested at a stress ratio of 0.7. Mixed intergranular/transgranular crack propagation was observed for the Sn-3Ag-0.5Cu solder tested at the stress ratio of 0.7, indicating the importance of creep in crack growth. The Sn-3Ag-0.5Cu-1Bi and Sn-3Ag-0.5Cu-3Bi solders had higher resistance to time-dependent crack growth, resulting from the strengthening effect of the Bi constituent. It appears that the addition of Bi above a certain concentration is harmful to the mechanical properties of Sn-3Ag-0.5Cu.	*Journal of Electronic Materials: August 2002*	pp. 879-886	Acquire this Paper
The Properties of Sn-9Zn Lead-Free Solder Alloys Doped with Trace Rare Earth Elements	*C.M. L. Wu, D. Q. Yu, C.M. T. Law, and L. Wang*	The Sn-Zn alloys have been considered as lead-free solders. It is well known that their poor properties of wetting and oxidation resistance are the main problems to prevent them from becoming commercially viable solders. In this paper, trace rare earth (RE) elements of mainly Ce and La have been used as alloying elements into the Sn-9Zn alloy. The results indicated that with the RE addition the originally coarse β-Sn grains in the microstructure of the alloy were refined. The tensile strength significantly increased with only a slight decrease in ductility. The surface tension was decreased, resulting in great improvement in wetting properties with rosin-based active flux.	*Journal of Electronic Materials: September 2002*	pp. 921-927	Acquire this Paper
The Thermal Property of Lead-Free Sn-8.55Zn-1Ag-XAl Solder Alloys and Their Wetting Interaction with Cu	*Shou Chang Cheng and Kwang Lung Lin*	The wetting behaviors between the quaternary Sn-8.55Zn-1Ag-XAl solder alloys and Cu have been investigated with the wetting balance method. The Al contents, x, of the quaternary solder alloys investigated were 0.01-0.45 wt.%. The results of differential scanning calorimeter (DSC) analysis indicate that the solders exhibit a solid-liquid coexisting range of about 7-10°C. The solidus temperature of the quaternary Sn-8.55Zn-1Ag-XAl solder alloys is about 198.2°C, while the liquidus temperatures are 205-207°C. The experimental results showed that the wettability of the Sn-8.55Zn-1Ag-XAl solder alloys is improved by the addition of Al. The mean maximum wetting force of the solders with Cu is within 0.75-1.18 mN and the mean wetting time is around 1.0-1.1 sec, better than the ~1.3 sec of eutectic Sn-9Zn and Sn-8.55Zn-1Ag solder alloys. The addition of Al also depresses the formation of ε-Ag-Zn compounds at the interface between Sn-8.55Zn-1Ag-XAl solders and copper.	*Journal of Electronic Materials: September 2002*	pp. 940-945	Acquire this Paper
Evaluation of the Mechanical Properties of a Ternary Sn-20In-2.8Ag Solder	*M.S. Yeh*	The Sn-20In-2.8Ag solder alloy is a potential lead-free solder for replacing the traditional Sn-Pb solders. In this study, the mechanical properties of the bulk material are reported by tensile test at various strain rates and temperatures. The Sn-20In-2.8Ag solder possessed a solidus and liquidus between 170.8°C and 195.5°C. The ultimate tensile strength (UTS) and elongation were 59.3 MPa and 50.2% at a strain rate of 10-3 s-1 at room temperature. Moreover, the UTS of this alloy decreased, but its elongation increased, with increasing testing temperature. Stress exponents of Sn-20In-2.8Ag alloy varied from 6.5 at room temperature to 4 at 100°C, and the activation energy for creep was 51.0 kJ/mol at the higher temperature range from 50°C to 100°C. The typical intergranular creep fracture mode was observed in Sn-20In-2.8Ag solder during tensile creep deformation.	*Journal of Electronic Materials: September 2002*	pp. 953-956	Acquire this Paper
Recent Progress in Pb-free Solders and Soldering Technologies	*Sung K. Kang*	To meet environmental goals as well as to improve performance, investigation is ongoing into the best substitute for lead solders in consumer electronic products. This commentary introduces five papers on lead-free solders and soldering technologies.	*JOM: June 2001*	p. 16	Read the Full Paper
High Temperature Lead-free Solder for Microelectronics	*Frank R. Gayle, Gary Becka, Jerry Badgett, Gordon Whitten, Tsung-Yu Pan, Angela Grusd, Brian Bauer, Rick Lathrop, Jim Slattery, Iver Anderson, Jim Foley, Alan Gickler, Duane Napp, John Mather, and Chris Olson*	This paper reports results of a four-year industrial consortium effort to develop lead-free solders for high-temperature applications (up to 160°C). Work included preliminary evaluations of 32 tin-based alloys, a screening of the thermomechanical fatigue performance of 13 promising alloys, and a full manufacturability and fatigue testing of the seven most promising of those alloys, namely Sn-3.5Ag, Sn-4Ag-1Cu, Sn-4Ag-0.5Cu, Sn-2.5Ag-0.8Cu-0.5Sb, Sn-4.6Ag-1.6Cu-1Sb-1Bi, Sn-3.3Ag-1Cu-3.3Bi, and Sn-3.5Ag-1.5In (compositions in weight percent). Eight different components were used on the reliability test vehicle, and the alloys were compared through Weibull analysis. In addition, the same seven experimental alloys were tested with ball grid array packages cycled up to 100°C or 125°C. All the lead-free alloys performed well, but those containing bismuth showed especially outstanding performance. In general, the ternary and higher alloys performed as well or better than the industry standard tin-silver eutectic, suggesting that solders other....	*JOM: June 2001*	pp. 17-21	Read the Full Paper

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Creep Properties of Sn-Ag Solder Joints Containing Intermetallic Particles	*S. Choi, J.G. Lee, F. Guo, T.R. Bieler, K.N. Subramanian, and J.P. Lucas*	The creep behavior of the eutectic tin-silver joints and tin-silver composite solder joints containing 20 vol.% of Cu6Sn5, Ni3Sn4, and FeSn2 intermetallic reinforcements introduced by in-situ methods was investigated. These creep tests were carried out using single shear lap solder joints at room temperature, 85°C, and 125°C. The creep resistance was similar in magnitude for all alloys, and with increasing temperature, the stress exponents decreased in a manner consistent with power-law breakdown behavior. The FeSn2 intermetallic reinforced composite solder was found to be the most creep-resistant alloy at room temperature. Creep failure was observed to occur within the solder matrix in all these solder joints. Although a detailed analysis of the processes involved was difficult because of smearing of the features in the fracture surface, there were indications of grain-boundary separation, ductile fracture, and interfacial separation.	*JOM: June 2001*	pp. 22-26	Read the Full Paper
Pb-Free Solders for Flip-Chip Interconnects	*D.R. Frear, J.W. Jang, J.K. Lin, and C. Zhang*	A variety of lead-free solder alloys were studied for use as flip-chip interconnects including Sn-3.5Ag, Sn-0.7Cu, Sn-3.8Ag-0.7Cu, and eutectic Sn-37Pb as a baseline. The reaction behavior and reliability of these solders were determined in a flip-chip configuration using a variety of under-bump metallurgies (TiW/Cu, electrolytic nickel, and electroless Ni-P/Au). The solder microstructure and intermetallic reaction products and kinetics were determined. The Sn-0.7Cu solder has a large grain structure and the Sn-3.5Ag and Sn-3.8Ag-0.7Cu have a fine lamellar two-phase structure of tin and Ag3Sn. The intermetallic compounds were similar for all the lead-free alloys. On Ni, Ni3Sn4 formed and on copper, Cu6Sn5 Cu3Sn formed. During reflow, the intermetallic growth rate was faster for the lead-free alloys, compared to eutectic tin-lead. In solid-state aging, however, the interfacial intermetallic compounds grew faster with the tin-lead solder than for the lead-free alloys. The reliability tests performed included shear strength and thermomechanical fatigue. The lower strength Sn-0.7Cu alloy also had the best thermomechanical fatigue behavior. Failures occurred nea	*JOM: June 2001*	pp. 28-32, 38	Read the Full Paper
Growth of [eta] Phase Scallops and Whiskers in Liquid Tin-Solid Copper Reaction Couples	*Robert A. Gagliano and Morris E. Fine*	In the microelectronics industry, many solder junctions rely upon reaction between a copper substrate and a molten tin-based alloy. For the tin/copper system, interfacial continuity is afforded by the formation of the h (Cu6Sn5) and ε (Cu3Sn) phase intermetallic compounds. The h grows in a scalloped morphology along the tin interface with whiskers emanating from their tops. This article quantitatively describes the unusual growth behavior of the h phase scallops and whiskers formed during reaction of liquid tin with a solid copper substrate.	*JOM: June 2001*	pp. 33-38	Read the Full Paper
Tin Pest in Sn-0.5 wt.% Cu Lead-free Solder	*Yoshiharu Kariya, Naomi Williams, Colin Gagg, and William Plumbridge*	Tin pest (the product of the allotropic transformation of β-tin into α-tin at temperatures below 286 K) has been observed in a Sn-0.5 wt.% Cu solder alloy. Some 40 percent of the specimen surface was transformed into gray tin after aging at 255K for 1.5 years, and after 1.8 years, the proportion increased to about 70 percent. The degree of transformation in work-hardened areas is much higher than in other areas, suggesting residual stress might provide an additional driving force for the transformation into α-tin. The allotropic change results in a 26 percent increase in volume, and cracks are initiated to accommodate the changes in volume. Results indicate that tin pest could lead to total disintegration of micro-electronic solder joints. The tin-copper eutectic system may become a prominent lead-free.	*JOM: June 2001*	pp. 39-41	Read the Full Paper
Wettability of Electroless Ni in the Under Bump Metallurgy with Lead-Free Solder	*Bi-Lian Young, Jenq-Gong Duh, and Bi-Shiou Chiou*	This study investigates the wettability of several lead-free solders, including Sn, Sn-Ag, and Sn-Bi, on electroless Ni (EN) with various phosphorus contents. The role of phosphorus on solder wettability is studied. Microstructure evolution in the lead-free solder/EN joint is investigated with the aid of electron probe microanalyzer (EPMA) to relate metallurgical reactions between the solder and the EN. The Sn solder exhibits better wettability on EN, while the Sn-Bi solder has a larger contact angle. Wettability degrades as the phosphorus content in EN decreases. The dependence of wetting angle on the phosphorous content can be attributed to the surface roughness and density of EN, along with the interfacial reaction between the solders and EN. An EPMA analysis reveals the presence of a Sn-Bi-Ni-P solid solution at the interface of solder/EN joints due to the interdiffusion of major constituent Ni and Sn. The interaction zone of the solid solution increases with increasing temperature. Wettability of Pb-free solders on EN degrades with the presence of NiO due to oxidation or the existence of Ni3P due to precipitation after annealing. For an adequate w	*Journal of Electronic Materials: May 2001*	pp. 543-553	Acquire this Paper
Ethylene Glycol Ether-Free Solder Paste Development	*Bill Lytle,Treliant Fang, Li Li, and Charles Zhang*	There are growing concerns in the electronics industry for not only finding alternatives to lead but also other potentially hazardous materials as well. This paper summarizes the development of ethylene glycol ether (EGE)-free solder flux for the formulation of lead-free solder pastes. Replacing the toxic components in the flux was only the first challenge, the criteria of commercially proven pastes also had to be met. Both commercial and in-house solder paste formulations were evaluated for printability, reflow, wetting, flux residue removal, and solder void characteristics. Two critical issues, solder bump voids and flux residue removal, were identified and associated with the high temperature reflow of Pb-free pastes. These issues were not effectively improved by the existing commercial EGE-free solder pastes. New solder paste formulations were developed utilizing alternative chemistry than those found in traditional solder paste fluxes. These pastes, some of which are also water soluble, reduced void frequency and size by more than 4x as compared to vendors' pastes. Solder bump height uniformity of 135 ± 4 μm within each die was cons	*Journal of Electronic Materials: August 2001*	pp. 1035-1041	Acquire this Paper

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Foreword	*Sung K. Kang, Hareesh Mavoori, Srinivas Chada, C. Robert Kao, and Ronald W. Smith*	This special issue contains a selection of papers presented at the technical symposium on "Lead-Free Solder Materials and Soldering Technologies", sponsored by The Minerals, Metals & Materials Society's Electronic, Magnetic & Photonic Materials Division, and the Electronic Packaging and Interconnections Materials Committee. This symposium was held as part of the 2001 TMS Annual Meeting in New Orleans, Louisiana, 11-15 February 2001.	*Journal of Electronic Materials: September 2001*	p. 1049	Acquire this Paper
Processing and Aging Characteristics of Eutectic Sn-3.5Ag Solder Reinforced with Mechanically Incorporated Ni Particles	*F. Guo, J. Lee, S. Choi, J.P. Lucas, T.R. Bieler, and K.N. Subramanian*	Composite solders offer improved properties compared to non-composite solders. Ni reinforced composite solder was prepared by mechanically dispersing 15 vol.% of Ni particles into eutectic Sn-3.5Ag solder paste. The average size of the Ni particle reinforcements was approximately 5 microns. The morphology, size and distribution of the reinforcing phase were characterized metallographically. Solid-state isothermal aging study was performed on small realistic size solder joints to study the formation and growth of the intermetallic (IM) layers at Ni reinforcement/solder and Cu substrate/solder interfaces. Effects of reflow on microstructure and solderability were studied using Cu substrates. Regarding solderability, the wetting angle of multiple reflowed Ni reinforced composite solder was compared to the solder matrix alloy, eutectic Sn-3.5Ag. General findings of this study revealed that Ni particle reinforced composite solder has comparable wetting characteristics to eutectic Sn-3.5Ag solder. Significant IM layers growth was observed in the Ni composite solder joint under isothermal aging at 150°C. Microstructural evolution was insignificant wl	*Journal of Electronic Materials: September 2001*	pp. 1073-1082	Acquire this Paper
Use of Thermodynamic Data to Calculate Surface Tension and Viscosity of Sn-Based Soldering Alloy Systems	*Jong Ho Lee and Dong Nyung Lee*	A thermodynamic database for the Pb-free soldering alloy systems, which include Sn, Ag, Cu, Bi, and In, has been made using the CALPHAD method. The resulting thermodynamic properties of the Sn-based binary alloy systems were used to determine the surface tensions and viscosities. The surface tensions were calculated using Butler's monolayer model and the viscosities by Hirai's and Seetharaman's models. Butler's model was also used to determine the surface active element. The results for binary systems were extended to the Sn-based ternary systems (Sn-Ag-Cu, Sn-Ag-Bi). The surface tensions of commercial eutectic Sn-Pb and Sn-Pb-Ag solder alloys were measured by the sessile drop method. The measured values and other researchers' results were compared with the calculated data.	*Journal of Electronic Materials: September 2001*	pp. 1112-1119	Acquire this Paper
Interfacial Reactions in the Sn-Ag/Au Couples	*Sinn-Wen Chen and Yee-Wen Yen*	Ag-Sn alloys are one of the most promising lead-free solders. Their reactions with Au substrates have been examined by using the reaction couple technique. Sn-3.5wt.%Ag/Au and Sn-25wt.%Ag/Au couples have been prepared and reacted at 120, 150, 180 and 200°C for various lengths of time. Three phases, δ-AuSn, ε2-AuSn2, and η-AuSn4, are found in all the couples. The thickness of the reaction layers increases with higher temperatures and longer reaction time, and their growth rates are described by using the parabolic law. Arrhenius equation is used to describe the temperature dependence of the growth rates. The activation energy of the growth of the intermetallic layers in both kinds of the reaction couples is similar and is determined to be 76.74 KJ/mole. Based on the reaction path knowledge and interfacial morphology, it is concluded that Sn is the fastest diffusion species in the couples.	*Journal of Electronic Materials: September 2001*	pp. 1133-1137	Acquire this Paper
Reflow Soldering and Isothermal Solid-State Aging of Sn-Ag Eutectic Solder on Au/Ni Surface Finish	*C.M. Liu, C.E. Ho, W.T. Chen, and C.R. Kao*	The reaction between the eutectic Sn-3.5Ag solder and the Au/Ni surface finish during reflow as well as during isothermal aging was studied. The Au layer was electroplated and had a thickness of one µm. The peak reflow temperature was fixed at 250°C while the reflow time was varied between 10 sec and one h. Samples that went through 90 sec reflow time were then subjected to 160°C isothermal aging for up to 875 h. It was found that during reflow the Au layer reacted very quickly with the solder to form AuSn4. One µm of Au layer was consumed in less than 10 sec. As the aging time increased, AuSn4 grains began to separate themselves from the Ni layer at the roots of the grains and started to fall into the solder. When the reflow time reached 30 sec, all the Au intermetallic had left the interface, and Ni3Sn4 started to form at the interface. The Ni3Sn4 growth rate followed linear kinetics initially (<240 sec), but the growth rate slowed down afterward. During the isothermal aging, only a small amount of (AuxNi1-x)Sn4 resettled back to the interface, and a continuous (Au0.45Ni0.55)Sn4 layer did not form at the interface, unlike the case for the Sn-37Pb so	*Journal of Electronic Materials: September 2001*	pp. 1152-1156	Acquire this Paper
The Creep of Lead-Free Solders at Elevated Temperatures	*W.J. Plumbridge, C.R. Gagg, and S. Peters*	Full implementation of the new generation of lead-free solders requires a detailed knowledge and understanding of their mechanical behavior. This paper reports an investigation of the creep behavior of three lead-free alloys: Sn-0.5Cu, Sn-3.5Ag, and Sn-3.8Ag-0.7Cu, at 75°C, and compares their response to that of Sn-37Pb at the same temperature. In terms of stress and time to rupture, the Sn-0.5Cu alloy behaves similarly to the eutectic Sn-Pb over the range of rupture lives considered (up to ~1000 h). The silver-containing alloys exhibit much greater creep resistance, typically a hundred fold and a thousand fold for the binary and ternary, respectively. These alloys are less ductile but their creep strains to failure are generally above ten percent. Their minimum creep rates are at least 100 times slower. When testing at the same homologous temperature (0.76), the silver-containing alloys retain the substantial superiority. The relationship between applied steady-state (or minimum) creep rate behavior is best described by a power law equation, although the steady state domain generally occupies less than 30 percent of life. The microstructural	*Journal of Electronic Materials: September 2001*	pp. 1178-1183	Acquire this Paper

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Constitutive and Damage Model for a Lead-Free Solder	*Shengmin Wen, Leon M. Keer, and Hareesh Mavoori*	A unified creep plasticity theory with damage is presented for a lead-free solder. The damage is caused by microcracking both inside grains and along grain boundaries and increases with cyclic loading and creep. The Mura theory of microcrack nucleation was used to model the microcrack formation, while the percolation theory was used to characterize the damage such microcracking caused to the mechanical performance of the solder. The model is materials science based and is capable of application to solder joints of different sizes. It is also cast within the framework of phenomenological damage mechanics and is therefore convenient for implementation into commercially available computational software package. The theory was used to model isothermal experimental data for a eutectic solder 96.5Sn-3.5Ag, and good agreement was achieved.	*Journal of Electronic Materials: September 2001*	pp. 1190-1196	Acquire this Paper
Stress Relaxation Behavior of Composite and Eutectic Sn-Ag Solder Joints	*S.G. Jadhav, T.R. Bieler, K.N. Subramanian, and J.P. Lucas*	Stress relaxation experiments were carried out at 25°C and 150°C on 96.5Sn-3.5Ag eutectic solder and Sn-Ag composite solder joints (Sn-Ag eutectic solder with 20 vol.% Cu6Sn5 reinforcements incorporated by in-situ methods). The magnitude of the stress drop during relaxation depends primarily upon the plastic shear strain imposed prior to the stress relaxation process. For sequential stress relaxation experiments that include unloading, the stress drop is nearly independent of the accumulated plastic shear strain. However, for sequential stress relaxation that does not include unloading, the stress relaxation is more dependent upon the cumulative plastic shear strain history. The stress in single shear lap joints does not relax to zero stress, as is observed in stress relaxation of bulk tension specimens, even at 150°C. Creep strain rates extracted from the relaxation data were much lower with smaller pre-strains in both eutectic Sn-Ag and composite solder joints. The stress exponent values (n) calculated from the stress relaxation test data ranged from 7 to 15 for both eutectic and composite solder joints, which were consistent with conventional cr	*Journal of Electronic Materials: September 2001*	pp. 1197-1205	Acquire this Paper
Application of Asymmetrical Four Point Bend Shear Test to Solder Joints	*O. Unal, I.E. Anderson, J.L. Harringa, R.L. Terpstra, B.A. Cook and J.C. Foley*	The asymmetrical four-point bend shear (AFPB) test method was used to measure the shear strength and creep properties through the stress relaxation experiments using three different Pb-free solder joint compositions in an as-solidified condition. Since it was difficult to shear the uniform specimens and the local bending usually occurs at the inner loading points, the notches were introduced at the joint line to preferentially weaken this region. The stress analysis by finite element modeling showed that the straight notches transform the parabolic shear stress distribution in the uniform specimen into a relatively uniform shear distribution along the bond line in the notched specimens. Therefore, the shear strength results from the notched specimens are expected to be much more accurate. Experiments showed that both the Sn-3.6Ag-1Cu (wt.%) and Sn-3.6Ag-1Cu-0.45Co joints have superior strength and creep properties as compared to the Sn-3.5Ag joint. However, there was no statistical difference between the shear strength of the Sn-3.6Ag-1Cu and Sn-3.6Ag-1Cu-0.45Co joints. Moreover, the difference between the creep resistance of these two typ	*Journal of Electronic Materials: September 2001*	pp. 1206-1213	Acquire this Paper
Fabrication of 0.95Sn-0.05Au Solder Micro-Bumps for Flip-Chip Bonding	*Takao Ishii, Shinji Aoyama, and Masami Tokumitsu*	This letter describes the successful fabrication of a 0.95Sn-0.05Au solder micro-bump on a compound semiconductor wafer by reflowing of multi-layer metal film. Since the inherent interdiffusion in Au-Sn phases results in the alloying of multi-layer films, the composition of mirco-bump is well controlled by the thickness of constituent metal films. The micro-bumps melt at about 220°C, which is close to the lowest eutectic temperature in a Au-Sn system. Solder bonding using 0.95Sn-0.05Au micro-bump is a very useful technique for the flip-chip bonding of compound semiconductor devices.	*Journal of Electronic Materials: June 2001*	pp. L25-L27	Acquire this Paper
Dispersion Strengthening for Dimensional Stability in Low-Melting-Point Solders	*H. Mavoori and S. Jin*	An improved solder structure with an ultrafine grain size of ~200-500 nm and significantly enhanced mechanical properties has been created by incorporating nanosized, nonreacting, noncoarsening oxide dispersoids into solder alloys. These solders display up to three orders of magnitude reduction in the steady-state creep rate, 4-5 times higher tensile strength at low strain rates, and improved ductility under high-strain-rate deformation. With a dispersion of TiO2 particles, the Pb-Sn eutectic solder with a low-melting point of 183°C can be made more creep resistant than the Au-20Sn eutectic solder with a much higher melting point of 278°C. This technique can be extended to other solder systems, such as the emerging lead-free solder alloys, and used to achieve enhanced dimensional stability.	*JOM: June 2000*	pp. 30-32	Acquire this Paper
The Adhesion Strength of a Lead-Free Solder Hot-Dipped on Copper Substrate	*Shan-Pu Yu, Nin-Hsiung Hon, and Moo-Chin Wang*	Eutectic Sn-Zn-Al solder alloy was used [composition: 91Sn-9(5Al-Zn)] to investigate the effects of dipping parameters such as the temperature, rate and time dipping on the adhesion strength between solder and substrate using dimethylammonium chloride (DMAHCl) flux. The optimum conditions for the highest adhesion strength(about 8 MPa) were determined as dipping at 350°C, and a rate of 10.8 ~11.8 mm/s for 5 ~7.5 min. A poor solder coating was obtained as dipped at 250°C. Some defects by non-wetting were found as dipped at a slow rate (slower than 8.2 mm/s). Quite different from the most tin-based solders for copper substrate, g-Cu5Zn8 intermetallic compound particles were found by x-ray diffraction (XRD) analysis at the interface of solder and substrate as dipped at 300°C after pull-off test by etching out the unreacted solder layer. The morphology of the intermetallic compound formed was observed by scanning electron microscopy (SEM). The elements of Al (near Cu), Zn (near Sn) are enriched at the interface of solder and copper substrate as determined by the line scanning and mapping analysis.	*Journal of Electronic Materials: February 2000*	pp. 237-243	Acquire this Paper

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Title	Authors	Abstract	Journal	Pages	Link
Creep Phenomena in Lead-Free Solders	*V.I. Igoshev and J.I. Kleiman*	A critical review of data on microstructure and creep process activation energy values for a number of lead-free solder alloys like Sn-Ag; Sn-Bi; Sn-In was conducted. The review revealed a scatter in experimental data, which could not be explained by the dislocation creep mechanism only, even after the published data was corrected for Young's modulus temperature dependence. An analysis of the data implies that possible origin of such a scatter is nucleation, accumulation and further growth of such internal defects as pores and microcracks during creep. It is shown that these processes may affect the measured steady-state creep rates, and may be one of the major reasons for the observed scatter in experimental data, and, therefore, must be taken into consideration in lead-free solder alloys' creep studies.	*Journal of Electronic Materials: February 2000*	pp. 244-250	Acquire this Paper
Developing a Lead-Free Solder Alloy Sn-Bi-Ag-Cu by Mechanical Alloying	*C.M.L. Wu, M.L. Huang, J.K.L. Lai, and Y.C. Chan*	A new lead free alloy, Sn-6Bi-2Ag-0.5Cu, has been developed by mechanical alloying and has great potential as a lead-free solder system. Initial trials on the manufacture of solder joints with this alloy revealed that a high quality bond with copper could be formed. Its melting range of 193.87°C to 209.88°C is slightly higher than that of eutectic tin-lead solder. Examination of the microstructure of the as-soldered joints revealed that it mainly consists of small bismuth (1 μm to 2 μm) and Ag3Sn (1 μm) particles finely dispersed in a nearly pure tin matrix with a small amount of h-Cu6Sn5 particles. The Cu-Sn intermetallic compound (IMC) layer formed at solder-copper interface is the h-Cu6Sn5 phase with grain size of 2 μm. The shear strength of the solder joint is higher than that of Sn-37Pb or Sn-3.5Ag. Under shear loading, fracture occurred at IMC layer-solder interface as well as in the bulk of solder.	*Journal of Electronic Materials: August 2000*	pp. 1015-1020	Acquire this Paper
Microstructural Evolution of a Lead-Free Solder Alloy Sn-Bi-Ag-Cu Prepared by Mechanical Alloying during Thermal Shock and Aging	*M.L. Huang, C.M.L. Wu, J.K.L. Lai, and Y.C. Chan*	In a previous study, a lead-free solder, Sn-6Bi-2Ag-0.5Cu, was developed by mechanical alloying. The alloy shows great potential as a lead-free solder system. In the present work, the microstructural evolution during thermal shock and aging was examined. In the as-soldered joints small bismuth (1 μm to 2 μm) and Ag3Sn (1 μm) particles were finely dispersed in a nearly pure tin matrix with a small amount of h-Cu6Sn5 phase in the bulk of solder. During thermal shock and aging microstructural evolution occurred with Cu-Sn intermetallic compound (IMC) layer growth at interface, bismuth phase coarsening and Ag3Sn phase coarsening. The microstructure of the solder appeared to be stable at high temperature. The shear strength of the present solder joint is higher than that of Sn-37Pb and Sn-3.5Ag solders. Shear failure occurred Cu-Sn IMC layer-solder interface and in the bulk of solder.	*Journal of Electronic Materials: August 2000*	pp. 1021-1026	Acquire this Paper
Experimental and Thermodynamic Assessment of Sn-Ag-Cu Solder Alloys	*K.-W. Moon, W.J. Boettinger, U.R. Kattner, F.S. Biancaniello, and C.A. Handwerker*	Sn-rich alloys in the Sn-Ag-Cu system are being studied for their potential as Pb-free solders. Thus, the location of the ternary eutectic involving L, (Sn), Ag3Sn and Cu6Sn5 phases is of critical interest. Phase diagram data in the Sn-rich corner of the Sn-Ag-Cu system are measured. The ternary eutectic is confirmed to be at a composition of 3.5 wt.% Ag, 0.9 wt.% Cu at a temperature of 217.2 ± 0.2°C (2σ). A thermodynamic calculation of the Sn-rich part of the diagram from the three constituent binary systems and the available ternary data using the CALPHAD method is conducted. The best fit to the experimental data is 3.66 wt.% Ag and 0.91 wt.% Cu at a temperature of 216.3°C. Using the thermodynamic description to obtain the enthalpy-temperature relation, the DTA signal is simulated and used to explain the difficulty of liquidus measurements in these alloys.	*Journal of Electronic Materials: October 2000*	pp. 1122-1136	Acquire this Paper
Flux Development for Lead-Free Solders Containing Zinc	*S. Vaynman and M.E. Fine*	New lead-free solders containing zinc are promising candidates to replace near-eutectic tin-lead solders because the solders melt at lower temperatures than Sn-Ag-base solders. They also possess good mechanical and fatigue properties and are less expensive. However, the contact angle on copper for Sn-Zn solders is high when fluxes used for Sn-Pb solders are utilized. A novel approach for flux development to improve wetting of copper surfaces by tin-zinc eutectic solder was developed: tin containing organic compounds, which decomposes at soldering temperatures and produces metallic tin on surfaces to be soldered was added to several specially formulated fluxes. This process improves wetting of copper surfaces by molten tin-zinc eutectic solder. Fluxes were developed that give a contact angle as low as 20°.	*Journal of Electronic Materials: October 2000*	pp. 1160-1163	Acquire this Paper
Reactions of Lead Free Solders with CuNi Metallizations	*T.M. Korhonen, P. Su, S.J. Hong, M.A. Korhonen, and C.Y. Li*	We have done experimental research on the dissolution rate and intermetallic growth on Cu, Ni, and CuNi-alloy substrates as a function of time and Cu/Ni ratio of the substrate. Reactions that occur when CuNi metallizations are soldered with lead-free solders were investigated. The experiments were performed using Sn-3.5Ag and Sn-3.8Ag-0.7Cu solders and different CuNi alloys. To determine the rate of dissolution of the substrate material into the solder, CuNi foils of different concentrations were immersed in Sn-3.5Ag and Sn-3.8Ag-0.7Cu solder baths for soldering times ranging from 15 sec to 5 min at 250°C. In addition, reflows of solder balls were made on top of bulk substrates to study the reaction when there is a practically infinite amount of CuNi available compared to the amount of solder. Thin film experiments were also done, where Ni containing under bump metallizations (UBMs) were fabricated and reflowed with eutectic SnAg solder balls. The nickel slows down the dissolution of the UBM into the solder and the formation of intermetallics during reflow compared to Cu metallizations. The solder/UBM interfaces were analyzed with SEM to	*Journal of Electronic Materials: October 2000*	pp. 1194-1199	Acquire this Paper

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Title	Authors	Abstract	Journal	Pages	Link
Cu Substrate Dissolution in Eutectic Sn-Ag Solder and Its Effect on Microstructure	*S. Chada, R. A. Fournelle, W. Laub and D. Shangguan*	The dissolution of Cu into molten Sn-3.8at.%Ag (Sn-3.5wt.%Ag) solder and its effect on microstructure were studied by light microscopy, scanning microscopy, and x-ray microanalysis. X-ray microanalysis of the average Cu content of samples soldered under various conditions showed that the amount of Cu dissolved during soldering increased with increasing soldering temperature and time and that the rate of dissolution could be described by a Nernst-Brunner equation. Microstructurally it was found that the volume fractions of primary β(Sn) dendrites and η-phase dendrites increase with increasing soldering temperature and time. The microstructural changes can be explained using Sn-Ag-Cu phase equilibrium data. A numerical method was developed for calculating the amount of Cu dissolved under non-isothermal conditions, which describes dissolution reasonably well.	*Journal of Electronic Materials: October 2000*	pp. 1214-1221	Acquire this Paper
Effects of Solder Reflow on Wettability, Microstructure, and Mechanical Properties	*F. Guo, S. Choi, J.P. Lucas, and K.N. Subramanian*	Solder joints used in electronic applications undergo reflow operations. Such operations can affect the solderability, interface intermetallic layer formation and the resultant solder joint microstructure. These in turn can affect the overall mechanical behavior of such joints. In this study the effects of reflow on solderability and mechanical properties were studied. Nanoindentation testing (NIT) was used to obtain mechanical properties from the non-reflow (as-melted) and multiple reflowed solder materials. These studies were carried out with eutectic Sn-3.5Ag solders, with or without mechanically added Cu or Ag reinforcements, using Cu substrates. Microstructural analysis was carried out on solder joints made with the same solders using copper substrate.	*Journal of Electronic Materials: October 2000*	pp. 1241-1248	Acquire this Paper
Thermomechanical Fatigue Behavior in Sn-Ag Solder Joints	*T. S. Choi, K. N. Subramanian, J. P. Lucas*	Microstructural studies of thermomechanically fatigued actual electronic components consisting of metallized alumina substrate and tinned copper lead, soldered with Sn-Ag or 95.5Ag/4Ag/0.5Cu solder were carried out with an optical microscope and environmental scanning electron microscope (ESEM). Damage characterization was made on samples that underwent 250 and 1000 thermal shock cycles between -40°C and 125°C, with a 20 min hold time at each extreme. Surface roughening and grain boundary cracking were evident even in samples thermally cycled for 250 times. The cracks were found to originate on the free surface of the solder joint. With increased thermal cycles these cracks grew by grain boundary decohesion. The crack that will affect the integrity of the solder joint was found to originate from the free surface of the solder very near the alumina substrate and progress towards and continue along the solder region adjacent to the Ag3Sn intermetallic layer formed with the metallized alumina substrate. Re-examination of these thermally fatigued samples that were stored at room temperature after ten months revealed the effec	*Journal of Electronic Materials: October 2000*	pp. 1249-57	Acquire this Paper
Analysis of Ring and Plug Shear Strengths for Comparison of Lead-Free Solders	*J.C. Foley, A.Gickler, F.H. Leprovost, and D. Brown*	The drive to replace the use of toxic lead metal and its alloys has spurred the development of many new lead-free solder alloys. Moreover, current leaded solders lack shear strength, resistance to creep and to thermal-mechanical fatigue. Solder that exhibits enhancements of these properties and retains solderability is crucial in applications where the solder joints are subjected to thermal cycling, severe vibrations, and temperatures of up to 125°C. Modified ring and plug joints were made with 18 selected lead-free solders and three well characterized lead-containing solders. Analysis of the results provides a guide for the design of additional testing.	*Journal of Electronic Materials: October 2000*	pp. 1258-1263	Acquire this Paper
Materials Issues in Area-Array Microelectronic Packaging	*D.R. Frear*	The important issues in advanced area-array electronic packaging for semiconductor devices are materials driven. Some of the processing-driven materials issues include the effect of introducing a silicon device interface with copper pads and a low-κ dielectric, the effect of decreasing pitch and feature size on the package interconnects, the development and implementation of organic substrates, and advanced underfills for fine-pitch flip-chip applications. From a materials reliability aspect, important materials issues include enhanced solder interconnect reliability, α-particle-induced soft errors, and the introduction of lead-free solder alloys.	*JOM: March 1999*	pp. 22-27	Read the Full Paper
The Microstructures of the Sn-Zn-Al Solder Alloys	*Kwang-Lung Lin, Li-Hsiang Wen, and Tzy-Pin Liu*	The microstructures of the Sn-Zn-Al lead-free solders have been investigated using scanning electron microscopy. The Al and Zn contents of the solders investigated were 0.45%~4.5% and 8.55%~85.5%, respectively. The solders were prepared from the Zn-5Al master alloy and Sn. The precipitates formed in these solders were analyzed for their compositions with energy dispersive spectroscopy. The eutectic temperature and the transition temperatures of these solders upon cooling were identified with cooling curves as well as with differential scanning calorimetry.	*Journal of Electronic Materials: March 1998*	pp. 97-105	Acquire this Paper
Thermodynamics of the Sn-In-Ag Solder System	*T.-M. Korhonen and J.K. Kivilahti*	The lead-free solder system Sn-In-Ag was studied both experimentally and by thermodynamic modeling. Thermodynamic descriptions for the phases in Ag-In and In-Sn binary systems were optimized taking into account the available thermodynamic and phase equilibria data. They were combined with the previously assessed Ag-Sn binary system to get a complete thermodynamic description of the Sn-In-Ag system. The thermodynamic functions obtained are used to model the solidifying behavior of the alloys with diagrams of the relative amount of phases (microstructures) as a function of temperature and the effect of diffusional segregation on the solidification path. The solidification of alloys of different compositions and its relevance to the microstructure and mechanical properties of the solidified solder are discussed. In the experimental research, alloys of different compositions were heat treated and analyzed by differential scanning calorimetry (DSC), optical microscopy, and scanning electron microscopy/electron probe microanalysis techniques. Ternary alloys were annealed at 250°C to gain information about the location of the phase boundarie	*Journal of Electronic Materials: March 1998*	pp. 149-158	Acquire this Paper

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Effect of Bismuth on the Isothermal Fatigue Properties of Sn-3.5mass%Ag Solder Alloy	*Yoshiharu Kariya and Masahisa Otsuka*	Sn-3.5mass%Ag eutectic solder is selected as a candidate base alloy for replacing the eutectic Sn-Pb, and the effect of bismuth (2, 5, 10mass%) on the fatigue life of bulk Sn-3.5mass%Ag eutectic at room temperature has been studied over the total strain range from 0.3 to 3 percent in tension-tension mode. Fatigue life is defined as the number of cycles at which the load decreases to a half of the initial value. The fatigue life dramatically decreases with increasing contents of bismuth and adding this element over 2% makes fatigue life shorter than that of tin-lead eutectic alloy. Tensile strength of the alloy significantly increases with an increase in bismuth contents due to solid solution hardening (<5%Bi) or dispersion strengthning of fine bismuth particles, while ductility of this system dramatically decreases with increasing bismuth contents. Fatigue life of these alloys depends on ductility obtained by tensile test. The fatigue life of Bi containing Sn-3.5%Ag alloys can be described by, $(\Delta \varepsilon p/2D)$. $Nf0.59 = 0.66$ where Nf is fatigue life defined by number of cycles to one-half load reduction, $\Delta \varepsilon p$ is the plastic strain range for initial cycles, D is the ductility as measurec	*Journal of Electronic Materials: July 1998*	pp. 866-870	Acquire this Paper
Thermodynamic Prediction of Interface Phases at Cu/Solder Joints	*Hyuck Mo Lee, Seung Wook Yoon, and Byeong-Joo Lee*	A thermodynamic method to predict the intermetallic compound which forms first at the substrate/solder interface during the soldering process has been suggested through calculations of metastable phase equilibria between the substrate and the liquid solder and by comparison of the driving forces of formation of individual intermetallic compound phases. It has been applied to the interfacial reaction between Cu substrate and Sn-Ag, Sn-Zn eutectic solders. The prediction from thermodynamic calculations was in good agreement with observed experimental results. The solid-state growth behavior of compound phases formed at the interface of Cu/Sn-Zn and Cu/Sn-Ag eutectic solder joints was explained and a schematic diffusion path suggested through calculated ternary phase diagrams.	*Journal of Electronic Materials: November 1998*	pp. 1161-1166	Acquire this Paper
Thermodynamic Database for Phase Diagrams in Micro-Soldering Alloys	*I. Ohnuma, X.J. Liu, H. Ohtani, and K. Ishida*	A thermodynamic database for the calculation of phase diagrams in micro-soldering alloy systems, which include the elements Pb, Bi, Sn, Sb, Cu, Ag, and Zn has been developed using the CALPHAD method. The various thermodynamic parameters for describing the Gibbs energies of the different constituent phases have been evaluated by optimizing experimental data on phase boundary compositions and thermochemical properties such as activity, heat of mixing and enthalpy of formation. The resulting database provides the means whereby the liquidus and solidus surfaces, isothermal and vertical section diagrams, phase percentages and the mole fraction of the phase constitutions etc., in multi-component soldering alloys can be readily calculated. Related information such as the surface tension and viscosity of the liquid phase can also be predicted, thus rendering the database as a valuable tool for developing leadbearing and lead-free solders.	*Journal of Electronic Materials: November 1999*	pp. 1164-1171	Acquire this Paper