Late News and Addendum

15th International Conference on Metal Organic Vapor Phase Epitaxy:
Posters I
Regency Ballroom

P1.31 Growth and Characterization of npn Heterojunction Bipolar Transistors with $In_xGa_{1-x}N$ Bases: *Zachary Meyer Lochner*[1]; Hee Jin Kim[1]; Suk Choi[1]; Yi-Che Lee[1]; Yun Zhang[1]; Jae-Hyun Ryou[1]; Shyh-Chiang Shen[1]; Russell D. Dupuis[1]; Georgia Institute of Technology[1]

The device operation of InGaN/GaN Heterojunction Bipolar Transistors (HBTs) grown by metalorganic chemical vapor deposition is examined. InGaN is used in the p-type base layer for npn III-nitride HBTs due to its higher p-type incorporation efficiency, as well as its lower bandgap energy relative to that of GaN, resulting in reduced base contact and sheet resistance. However, the strain induced at the InGaN-GaN interfaces by abrupt base-collector (BC) and base-emitter (BE) junctions leads to material defects, such as dislocations and V-defects, which hinder device performance. Therefore, a structure with graded BC and BE junctions has been developed to improve the crystal quality at each interface, and enhance the current gain. This study compares structures with two different Indium concentrations for the base, 3% and 5%, each employing the graded junction design. Using atomic force microscopy, a higher defect density was observed in the $In_{0.05}Ga_{0.95}N$ sample than the $In_{0.03}Ga_{0.97}N$ counterpart. This is attributed to the larger strain conditions in the former, even with the graded junctions. The effects of these defects are reflected in the device performance. If we consider the band offset between the InGaN base and GaN layer, HBTs with p $In_{0.05}Ga_{0.95}N$ base are expected to show higher current gain than HBTs with p-$In_{0.03}Ga_{0.97}N$ base. However, typical current gains for HBTs with a p-$In_{0.03}Ga_{0.97}N$ base were found to be around 82, and the current gains for HBTs with a p-$In_{0.05}Ga_{0.95}N$ base were around 35. It is supposed that the higher defect density compromises the benefits of the smaller bandgap. Several other device configurations have also been considered in order to improve performance, including a single quantum well and superlattice base structure. It is theorized that the quantum confinement will aid lateral carrier transport within the base.

P1.32 Improved Light Output Power of Ingan/Gan Based Light-Emitting Diodes Using Silica Nanospheres on Patterned Sapphire Substrate: *Nam Han*[1]; Hyung-Gu Kim[1]; Hee-Yun Kim[1]; Hyun-Kyu Kim[1]; Ji-Hye Kang[1]; Jae-Hyung Ryu[1]; Young-Jae Park[1]; Min Han[1]; Mi-So Lee[1]; Beo-Deul Ryu[1]; Chang-Hee Hong[1]; Chonbuk National University[1]

We demonstrate the growth of GaN-based light-emitting diodes (LEDs) with high light output power and high crystal quality through the use of silica nano-spheres on a wet-etched patterned sapphire substrate (PSS). Before arraying the silica nano-spheres, a 100-nm thick SiO2 layer was deposited on a c-plane sapphire substrate by plasma-enhanced chemical vapor deposition which then defined by standard photolithography to serve as the reverse hole pattern wet-etch mask. To obtain a clean and oxide-free surface, we etched the reverse hole wet-etch mask with H2SO4:H3PO4 (3:1) solution for 2 min at 270 °C. After the etching process, a colloidal silica spheres solution was dropped onto the reverse PSS and we were carried out a spin coating method that the thin layers of colloidal silica sphere was deposited by employing spin coates. The spin speed and spinning time were 1100 rpm, 10 sec and 4000 rpm, 5 sec for the first and the second step, respectively. After the spin coating process, we grew InGaN/GaN based epilayers on silica nanospheres coated PSS using metal organic chemical vapor deposition (MOCVD). Adopting the silica nanospheres coated PSS, the light output power of the LEDs was improved 1.5times higher than that of LEDs on flat spphire substrate. In addition, the reduction of full width at half maximum (FWHM) in the ω-scan rocking curves for the (0002) and (10-12) planes of GaN on silica nanosphers PSS suggests on improvement in the crystal quality.

P1.33 Catalyst-Free Inp Nanowires Induced by Oxidized Submonolayer Gas on Inp: *J. Yuan*[1]; Hao Wang[1]; P. J. van Veldhoven[1]; R. Notzel[1]; Eindhoven University of Technology[1]

Catalyst-free InP nanowire formation is observed by metal organic vapor phase epitaxy (MOVPE) on InP (100) templates containing near surface oxidized GaAs and InAs layers with submonolayer (sub-ML) coverage. Template formation is as follows: After growth of an InP buffer layer on InP (100) substrate, 0.05 ML GaAs and 0.1 ML InAs is grown, followed by 15 nm InP. The structure is then removed from the MOVPE reactor and oxidized in an Oxygen plasma stripper at 300 W for 10 minutes and etched in phosphoric acid. This typical cleaning step is repeated twice. Then the structure is returned into the MOVPE reactor and nominally 250 nm InP is grown at 500 °C. Surprisingly InP nanowires form. The typical length of the nanowires is several micrometers and the diameter can be as small as 100 nm. No nanowires form in the absence of the GaAs and InAs layers and without the oxidation step. Hence, we propose that the two-dimensional GaAs and InAs ML islands formed in the sub-ML layer act as nanoscale masks after oxidation to induce nanowire formation in a form of nano scale selective area growth. The Ga and As oxides are not removed at 500 °C. Moreover, the oxidized GaAs and InAs islands are stable during heat up in contrast to metal catalyst islands. All nanowires are oriented along the [111] B direction. Importantly, nanowires also form on deep-etched (111) B facets to produce vertical arrangements. Further experiments will elucidate the influence of the GaAs coverage and ML island size on the nanowire dimensions and density.

P2.28 MOVPE of a Metal-Cavity Surface-Emitting Laser Operating CW at Room-Temperature: *Tim David Germann*[1]; Udo W. Pohl[1]; Dieter Bimberg[1]; Chien-Yao Lu[2]; Shu-Wei Chang[2]; Shun Lien Chuang[2]; Technische Universität Berlin[1]; University of Illinois at Urbana-Champaign[2]

Miniaturized ultrafast lasers are key elements for large-scale integration of digital photonic circuits. To realize microsize devices novel concepts based on metal/dielectric waveguides using surface plasmon modes have been proposed. Metal cavities enable smallest mode volume with fast photon relaxation, low-power operation, and efficient thermal management. Thus, large current densities and high modulation frequencies become possible. Recently the feasibility and fundamental theory of such devices were reported [1, 2]. Here we present details of growth, fabrication, and operation of the first substrate-free metal-cavity surface-emitting laser operating continuous wave (CW) at room temperature. Our devices were grown by metalorganic vapor phase epitaxy using partly alternative precursors. The structures include top to bottom GaAs:Zn and $Al_{0.2}Ga_{0.8}As$:Zn contact and cladding layers respectively, 14 GaAs quantum wells separated by $Al_{0.2}Ga_{0.8}As$ barriers, an AlGaAs graded interface (17.5 pairs) distributed Bragg reflector with optimized doping scheme, and an InGaP:Si window layer as etch stop for substrate removal. The processing of the devices includes the metallization of the etched mesa surface and flip bonding on a silicon wafer [3]. Subsequent substrate removal allows emission from the bottom of the epitaxial structure. The final device has a 2 µm diameter and a 2.5 µm height. Electrically pumped operation proves lasing at 868 nm with a CW threshold of 1.66 mA at 300 K. The linewidth yields a quality factor of 580 for the cavity. This value agrees quantitatively with results of our transfer matrix simulation. The very high characteristic temperature of 323 K is attributed to the broadband metallic top-mirror. In conclusion, the design, simulation, growth, and implementation of room temperature CW metal-cavity surface-emitting lasers are demonstrated. Cross-talk free integration in existing processes becomes possible by substrate-free mounting on silicon realized here.

P2.29 Inp Substrate Evaluation by MOVPE Growth of Lattice Matched Epilayers: *Jeff Cederberg*[1]; Darrell Alliman[1]; Mark Overberg[1]; Sandia National Laboratories[1]

InP substrates are the starting point for a wide variety of infrared devices. The surface morphology and growth-related features produced during epitaxy depends critically on the starting substrate. We have evaluated (100)-oriented InP wafers from three different vendors by growing thick (5 µm), lattice-matched epilayers of GaInAs, AlInAs, and InP and evaluating the surfaces produced with differential interference contrast microscopy (DICM) and atomic force microscopy (AFM). The impact of small, intentional misorientations was considered. S-doped wafers were evaluated for two cases. The growths were performed in a Veeco D125 chamber with methyl-substituted metal-organics and hydrides as source materials. All growths were performed at 660°C and 60 Torr total pressure. Wafers with near singular (100) orientations produce inferior surfaces in general. For AlInAs epitaxy, pyramidal pits form. Mound defects are found for GaInAs and InP epitaxy. We speculate that these defects are associated with threading dislocation termination at surface. The root mean square (RMS) roughness between the macroscopic features is low, 0.2 to 0.4 nm. The effect of small miscuts (0.2 degree) toward the (111)A, (110), and (111)B were considered for wafers from one vendor. Vicinal substrates improve the epitaxial surface for InP dramatically reducing the density of macroscopic defects while maintaining the low RMS roughness over large regions (625 square micrometers). GaInAs and AlInAs epitaxy forms ripples along the miscut direction, with RMS roughness around 2 nm for AlInAs and 0.4 nm for GaInAs. The wavelength and amplitude of the ripples increase as the AlInAs thickness increases. Differences in adatom mobility may drive the instability leading to the observed ripples. S-doped wafers from two vendors were considered for near singular (100) and for misorientations of 0.2 degree toward the (110). We found that the mound defects observed for InP and GaInAs layers on Fe-doped singular surfaces were absent for singular S-doped wafers. When AlInAs films were grown on S-doped wafers lower pit densities were obtained. These observations support the speculation that dislocation termination are the source of the macroscopic defects, as the dislocation density is approximately an order magnitude lower for S-doped InP due to impurity hardening effects.

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P2.30 Quantum Dots Coupled to a Parabolic Quantum Well Structure for Infrared Photodetectors: Growth, Characterization and Applications: *Maurcio Pamplona Pires[1]*; Germano M Penello[1]; Rudy M. S. Kawabata[2]; Deborah Alvarenga[3]; Karl Unterrainer[4]; Paulo Sergio S Guimarães[3]; Patricia L Souza[2]; UFRJ[1]; PUC-Rio[2]; UFMG[3]; TU Wien[4]

The investigation of novel structures for infrared photodetection is of paramount importance when one considers the wide variety of applications: environment protection, health treatments, security and astronomy to name a few. Even though quantum dot infrared photodetectors (QDIP) should, in principle, outperform the ones based on quantum wells, there still remain challenges to overcome some of the drawbacks. The poor control on dot size, density and shape makes the design and production of QDIPs for operation at specific wavelengths difficult. One approach to bypass such difficulty is to couple the quantum dot to a quantum well. Varying the quantum well parameters allows for an easier wavelength tuning. In this work we propose a novel heterostructure where the quantum dot layer is inserted in a parabolic shaped quantum well. The investigated structures consist of InAs quantum dots embedded in an InGaAlAs parabolic quantum well lattice matched to the InP substrate, where the quaternary Al concentration was dynamically varied between 0 and 20% during growth. Photoluminescence and X-ray measurements were used to control the layers real composition. Samples with four different thicknesses of the parabolic quantum well were grown and investigated by Fourier transform spectroscopy. Theoretical calculations were performed to determine the optical transitions involved and the results fully agree with the experimental observations. Without optimizing the structures, strong photocurrent around 6 microns was detected for temperatures as high as 140 K, indicating a potential for high temperature operation. Additionally, an interesting current reversal effect, where one measures photocurrent of different sign for different wavelengths but same bias and temperature conditions, is observed. Such effect can be used to discriminate simultaneous radiation of two different wavelengths.

P2.31 Impact of Substrate Orientation on Facet Stabilization Characteristics of III-Nitrides Nanostructures: *Shadi Shahedipour-Sandvik[1]*; Vibhu Jindal[2]; State University of New York-Albany[1]; SEMATECH[2]

The emphasis on development of AlInGaN nanostructures is continuously increasing for applications in optoelectronic devices such as light emitting devices, sensors, and detector. Template-confined selective area growth (SAG) technique is one of the processes that can generate well-defined nanostructures with controllable size, morphology, and position. Under non-equilibrium growth conditions such as those used in MOCVD of III-nitrides, crystal morphology of such nanostructures is strongly affected by the growth kinetics and substrate crystal orientation. The shape of the resulting structure is determined by slow growing facets, and can be modeled using the Kinetic Wulff construction model. We have extensively studied facet stabilization in SAG of GaN nanostructures as a function of growth parameters such as temperature, precursor flow rates, and growth time. To better understand the dependency of facet growth rate and stabilization on growth parameters and crystallographic orientation we've employed templates with various mask openings, namely a combination of square, rectangle, hexagon, octagon, star shape, and ring pattern. We have found that interfacial strain due to lattice mismatch between the substrate (surface) and the growing structures substantially influence the final morphology and faceting of nanostructures. In a separate set of experiments, we studied the effect of substrate crystallographic orientation and mask opening on faceting of nanostructures. For these experiments we chose a-plane and c-plane GaN as substrate and varied the size of the mask opening between 30nm and 3 µm. While stabilization of (1-101) planes result in the commonly observed hexagonal pyramids in c-direction, arrow headed shapes were observed for nanostructures grown in a-crystallographic direction. Facet stabilization and final shape of nanostructures will be discussed with respect to the stability and growth rates of various planes and their dependency on growth conditions. In addition, growth of selective area ternary alloys such as AlGaN and InGaN were also performed. Facet stabilization in III-nitride ternary is shown to vary from that of binary GaN. For example, relatively higher growth rates of (1-101) planes in growth of InGaN nanostructures resulted in flower shape as opposed to more stable (1-101) planes in GaN growth that leads to hexagonal pyramidal shape.

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P2.32 Surface of Epitaxial Gan on Chemical-Mechanically Polished Gan (0001) Substrate: *Li Huang*[1]; Fang Liu[1]; Robert F. Davis[1]; Carnegie Mellon University[1]

Determination of the growth mechanism(s), defect generation and microstructure that evolve during progressive epitaxy of monolayers of III-nitride films on chemo-mechanically polished surfaces of GaN (0001) substrates having a dislocation density of 5E7 cm-2 is important for determination and comparison of the efficacy of these substrates for increased performance of opto- and micro-electronic devices relative to similar devices grown on sapphire and SiC. Establishment of process conditions that result in step-flow growth rather than re-nucleation and coalescence of islands on the terraces of the GaN substrates is necessary to prevent generation of new dislocations in the subsequently grown active regions of the devices. In this study, a MOVPE-based process route was developed to achieve homoepitaxial deposition of GaN films via step-flow growth on GaN (0001) substrates having < 1 degree off-cut. The individual surfaces of 0, 1, 2, 5 and 10 nm thick GaN films were evaluated ex-situ using atomic force microscopy (AFM). Steps and terraces were the only features; three-dimensional GaN islands were not present. The presence of very low angle GaN grain boundaries in the GaN substrates was manifest in variations in terrace width and step orientation observed across the films. This process also mitigated generation of additional dislocations. Details of the optimum MOVPE process route will be presented in tandem with companion AFM and TEM micrographs of the films and substrate/film interfaces.

P2.33 Growth of High Quality Ingan/Gan LED Structures On (111) Si Substrates with Internal Quantum Efficiency Exceeding 50%: JaeWon Lee[1]; Jun-Youn Kim[1]; Youngjo Tak[1]; Hyunggi Hong[1]; Suhee Chae[1]; Bokki Min[1]; Hyungsu Jeong[1]; Jong-Ryeol Kim[1]; Jinwoo Yoo[1]; Youngsoo Park[1]; [1]Samsung

We have successfully grown InGaN/GaN LED structures on (111) Si substrates with internal quantum efficiency (IQE) exceeding 50%, which was estimated by the integrated PL intensity ratio from 10 K to room temperature. The LED structure includes 3.5-um-thick Si-doped n-GaN layer, 3 periods of InGaN/GaN electron emissive layers, 5 periods of InGaN/GaN multiple quantum wells having the peak wavelength of 430 nm, Al0.15Ga0.85N electron blocking layer and p-GaN layer. To reduce the TDD of n-GaN layer on (111) Si substrate, a couple of step-graded AlGaN buffer layers separated by GaN/AlN inter-layers was proposed. We observed remarkable reduction of the TDD at the interface between the last AlGaN and n-GaN layer from cross-sectional transmission electron microscope images. The threading dislocation density (TDD) of n-GaN layer was 6E8cm-2. For comparison, we also measured the TDD of a 2 um-thick GaN film grown on the conventional single AlN and step-graded AlGaN buffer layer pair, and the TDD was 2E9cm-2. The newly proposed structure does not generate any additional tensile stress caused by low angle grain boundary coalescence in the conventional structures. This structure seems to be very useful to overcome stress related problems while keeping a low TDD in the GaN films on Si (111) substrate.

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12:00 p.m.

First c-Plane Green InGaN-Laser Operating Pulsed at 531.7nm and CW at 524nm: *Adrian Avramescu*[1]; Teresa Lermer[1]; Jens Müller[1]; Christoph Eichler[1]; Georg Bruederl[1]; Stephan Lutgen[1]; Uwe Strauss[1]; Osram Opto-Semiconductors[1]

Development of longer wavelength laser diodes in the nitride compound semiconductor system has proved to be difficult in comparison to ultra-violet laser diodes that are now common in blu-ray drives. Also, the commercial motivation of developing such laser diodes emitting in the true-blue (440-460 nm) and true-green (515-530 nm) spectral range was totally different from the storage market being mainly fueled by visualization applications such as rgb-laser projection. After the commercial introduction of true blue laser diodes by a couple of companies, a lot of effort was focused on developing diodes in the green spectral region with research based on GaN substrates in the polar, non- and different semi-polar orientations. We report about true-green laser diodes emitting up to 531.7nm, which are grown on c-plane GaN substrates in a polar direction.
One of the challenges for such lasers is the epitaxial growth of the complex laser structures with quantum wells that have a high Indium content above 30% while maintaining a good crystal quality. The density of non radiative centers in the active layers emitting in the true-green spectral range was very large and it required a significant reduction. As a result, test laser with laser operation up to 531nm will be demonstrated in pulse mode. In a next step, we also drastically improved the performance of ridge waveguide lasers diodes in continuous wave operating up to 50mW optical output power at 524nm. The combination of low laser threshold of 97mA, operating voltage of 7.1V and slope efficiency of ~330mW/A was crucial for improving the laser diodes wall plug efficiency up to 2.3% at 50mW output power. The continuous improvements of the true-green nitride-based green lasers will bring these devices closer to commercial deployment in small laser projectors.

Addendum: Cancellations

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P2.4, Influence of Reactor Pressure on the Phase Stability of Indium- Rich In1-xGaxN Epilayers

P2.26, The Characterization of p-GaAs/i-InGaAsN/n-GaAs Hetero-Junction Solar Cell with Various DMHy Flow Rates