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Characteristic of InGaN/GaN Laser Diode Grown by a Multi-Wafer MOCVD System

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InGaN/GaN multi-quantum well (MQW) laser diodes (LDs) were grown on c-plane sapphire substrates using a multi-wafer MOCVD system. The threshold current for pulsed lasing was 1.6 A for a gain-guided laser diode with a stripe of 10 × 800 μm². The threshold current density was 20.3 kA cm^{-2} and the threshold voltage was 16.5 V. The optical power ratio of transverse electric mode to transverse magnetic mode was found to be greater than 50. The characteristic temperature measured from the plot of threshold current versus measurement temperature was between 130 and 150K.

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Structural and Optical Properties of GaN Laterally Overgrown on Si(111) by Metalorganic Chemical Vapor Deposition Using an AlN Buffer Layer

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Lateral epitaxial overgrowth (LEO) on Si(111) substrates using an AlN buffer layer is demonstrated and characterized using scanning electron microscopy, atomic force microscopy, transmission electron microscopy, x-ray diffraction, photoluminescence spectroscopy, and cathodoluminescence imaging. The ⟨1$\bar{1}$00⟩-oriented LEO GaN stripes grown on silicon substrates are shown to have similar structural properties as LEO GaN grown on GaN/Al_2O_3 substrates: the surface topography is characterized by continuous crystallographic steps rather than by steps terminated by screw-component threading dislocations; the density of threading dislocations is $<10^6$ cm^{-2}; the LEO regions exhibit crystallographic tilt (0.7–4.7°) relative to the seed region. The AlN buffer thickness affects the stripe morphology and, in turn, the microstructure of the LEO GaN. The issues of chemical compability and thermal expansion mismatch are discussed.

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A GaN/4H-SiC Heterojunction Bipolar Transistor with Operation up to 300°C

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We report on the fabrication and characterization of GaN/4H-SiC n-p-n heterojunction bipolar transistors (HBTs). The device structure consists of an n-SiC collector, p-SiC base, and selectively grown n-GaN emitter. The HBTs were grown using metalorganic chemical vapor deposition on SiC substrates. Selective GaN growth through a SiO_2 mask was used to avoid damage that would be caused by reactive ion etching. In this report, we demonstrate common base transistor operation with a modest dc current gain of 15 at room temperature and 3 at 300°C.

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Novel Approach to Simulation of Group-III Nitrides Growth by MOVPE

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Recent studies revealed specific features of chemical processes occurring on the surface of growing group-III nitrides - extremely low sticking probability of molecular nitrogen, low sticking coefficient and incomplete decomposition of ammonia frequently used as the nitrogen precursor. These features (kinetic by nature) result in the growth process going on under conditions remarkably deviated from the gas-solid heterogeneous equilibrium. In this paper we propose a novel approach to modeling of group-III nitride growth by MOVPE taking into account these features. In the model the sticking/evaporation coefficients of N_2 and NH_3 extracted from independent experiments are used allowing adequate description of the kinetic effects. The model is applied to analysis of growth of binary (GaN) and ternary (InGaN) compounds in a horizontal tube reactor. The growth rate and the solid phase composition are predicted theoretically and compared with available experimental data. The modeling results reveal lower ammonia decomposition ratio on the surface of the crystal as compared to thermodynamic expectations. The developed model can be used for optimization of growth process conditions.

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Modeling of InGaN MOVPE in AIX 200 Reactor and AIX 2000 HT Planetary Reactor

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Multiwafer Planetary Reactor is a promising system for large-scale production of heterostructures for LED's based on III-group nitrides. Analysis of chemical processes occurring in the reactor allows one to get insight into specific mechanisms governing growth of nitride based heterostructures. In the present paper results of modeling analysis of MOVPE of $In_xGa_{1-x}N$ layers in AIX-200 Reactor and AIX 2000 HT Planetary Reactor are reported. The model used for MOVPE process analysis accounts for gas flow, heat transfer, and multicomponent mass transport along with gas phase and surface chemical reactions. Results of the modeling analysis of In transport and incorporation into the solid phase are compared with experimental data. It is shown that the model predicts reasonably well the In incorporation during MOVPE of InGaN under In/(In+Ga) ratio in the gas phase less than 20%.

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The Growth Rate Evolution versus Substrate Temperature and V/III Ratio During GaN MBE Using Ammonia

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The growth rate evolution versus V/III ratio and substrate temperature was studied by means of optical reflectivity during MBE of GaN layers using NH_3 as nitrogen source. The GaN desorption becomes observable at temperatures above 800°C and causes the reduction of growth rate accompanied with the surface roughening at temperatures above 850–870°C. Unlike GaAs, which evaporates in accordance with the action mass law, the desorption rate of GaN is found to be almost independent of V/III ratio within the N-rich growth conditions. The activation energy for GaN desorption during the growth is found to be (3.2±0.1) eV. This value is very close to the activation energy for free evaporation. At V/III ratio values exceeding 200 the GaN growth rate reduction caused by violation of the molecular flow regime is observed. The Mg-doped samples grown under these extreme conditions tend to have improved acceptor activation and thus p-type conductivity.

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Photoluminescence Measurements on GaN/AlGaN Modulation Doped Quantum Wells

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Photoluminescence spectra were measured for 100 Å wurtzite GaN AlGaN modulation doped quantum wells. Three well-resolved peaks originate from the quantum well. The theoretically calculated confinement energies have been compared to the experimental energy positions and found to be in good agreement with the data, assuming that the piezoelectric field is largely screened by the electron gas. The highest energy transition may originate from the Fermi edge, consistent with the temperature dependence of the photoluminescence. Decay times for the different transitions indicate that the photoexcited holes are localized.

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Growth and Device Performance of GaN Schottky Rectifiers

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Undoped, 4 µm thick GaN layers grown by Metal Organic Chemical Vapor Deposition were used for fabrication of high stand off voltage (356 V) Schottky diode rectifiers. The figure of merit V_{RB}^2/R_{ON}, where V_{RB} is the reverse breakdown voltage and R_{ON} is the on-resistance, was ~ 4.53 MW-cm^{-2} at 25°C. The reverse breakdown voltage displayed a negative temperature coefficient, due to an increase in carrier concentration with increasing temperature. Secondary Ion Mass Spectrometry measurements showed that Si and O were the most predominant electrically active impurities present in the GaN.

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Visible-Blind UV Digital Camera Based On a 32 × 32 Array of GaN/AlGaN *p-i-n* Photodiodes

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A visible-blind UV camera based on a 32 × 32 array of backside-illuminated GaN/AlGaN p-i-n photodiodes has been successfully demonstrated. Each of the 1024 photodiodes in the array consists of a base n-type layer of AlGaN (~20%) onto which an undoped GaN layer followed by a p-type GaN layer is deposited by metallorganic vapor phase epitaxy. Double-side polished sapphire wafers are used as transparent substrates. Standard photolithographic, etching, and metallization procedures were employed to obtain fully-processed devices. The photodiode array was hybridized to a silicon readout integrated circuit using In bump bonds. Output from the UV camera was recorded at room temperature at a frame rate of 30 Hz. This new type of visible-blind digital camera is sensitive to radiation from 320 nm to 365 nm in the UV spectral region.

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Synthesis and Growth of Gallium Nitride by the Chemical Vapor Reaction Process (CVRP)

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A new process for synthesis and bulk crystal growth of GaN is described. GaN single crystal c-plane platelets up to 9 mm by 2 mm by 100 µm thick have been grown by the Chemical Vapor Reaction Process (CVRP). The reaction between gallium and a nitrogen precursor is produced by sublimation of solid ammonium chloride in a carrier gas, which passes over gallium at a temperature of approximately 900°C at near atmospheric pressures. Growth rates for the platelets were 25–100 µm/hr in the hexagonal plane. Seeded growth in the c-direction was also accomplished by re-growth on previously grown c-plane platelets. The crystals were characterized by X-ray diffractometry, atomic force microscopy, secondary ion mass spectrometry, inert gas fusion, and room temperature Hall effect and resistivity measurements.

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Optical Phonons and Free-Carrier Effects in MOVPE-Grown $Al_xGa_{1-x}N$ measured by Infrared Ellipsometry

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We report on the application of infrared spectroscopic ellipsometry (IR-SE)

for wavenumbers from 333 cm^{-1} to 1200 cm^{-1} as a novel approach to non-destructive optical characterization of free-carrier and optical phonon properties of group III-nitride heterostructures. Undoped α-GaN, α-AlN, α- $Al_xGa_{1-x}N$ (x = 0.17, 0.28, 0.5), and *n*-type silicon (Si) doped α-GaN layers were grown by metal-organic vapor phase epitaxy (MOVPE) on *c*-plane sapphire (α-Al_2O_3). The four-parameter semi-quantum (FPSQ) dielectric lattice-dispersion model and the Drude model for free-carrier response are employed for analysis of the IR-SE data. Model calculations for the ordinary ($\epsilon\perp$) and extraordinary ($\epsilon\|$) dielectric functions of the heterostructure components provide sensitivity to IR-active phonon frequencies and free-carrier parameters. We observe that the α-$Al_xGa_{1-x}N$ layers are unintentionally doped with a back ground free-carrier concentration of 1-4 10^{18} cm^{-3}. The ternary compounds reveal a two-mode behavior in $\epsilon\perp$, whereas a one-mode behavior is sufficient to explain the optical response for $\epsilon\|$. We further provide a precise set of model parameters for calculation of the sapphire infrared dielectric functions which are prerequisites for analysis of infrared spectra of III-nitride heterostructures grown on α-Al_2O_3.

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Electric Field Distribution in Strained p-i-n GaN/InGaN Multiple Quantum Well Structures

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The presence of piezoelectric fields within *p-i-n* GaN/InGaN multiple quantum well structures is discussed. Time integrated and time-resolved photoluminescence measurements and theoretical calculations of the effect of these fields is presented. Furthermore, a description of how these fields influence the carrier dynamics and a discussion of how the piezoelectric field effects the design of GaN/InGaN devices is presented.

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New Buffer Sublayers with Crystal Structure of Cubic Syngony for Growing the Heteroepitaxial Films of Nitride Compounds of Type $A^{III}B^{V}$ on Sapphire Substrates

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We propose the use of a buffer sublayer made of materials with crystal structure of cubic syngony to eliminate 30° in-plane rotation of (0001) heteroepitaxial wurtzite type $A^{III}B^{V}$ nitride films with respect to the (0001) or (11$\bar{2}$0) working surface of the sapphire substrate. In these cases, the lattice parameter mismatch between the sapphire substrate surface and the semiconductor film is much smaller, and the cleavage planes of the sapphire and the semiconductor films with wurtzite structure forming the active region of a heterolaser are parallel. It is shown experimentally that using, for instance, Nb on (0001) Al_2O_3 or NbN on (11$\bar{2}$0) Al_2O_3, allows the elimination of the 30° in-plane rotation of the (0001)AlN film with respect to the (0001) or (11$\bar{2}$0) working surface of the sapphire substrate .

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Strain Relaxation in GaN Layers Grown on Porous GaN Sublayers

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We have studied epitaxial GaN layers grown by hydride vapor phase epitaxy (HVPE) on porous GaN sublayers formed on SiC substrates. It was shown that these layers can be grown with good surface morphology and high crystalline quality. X-ray, Raman and photoluminescent (PL) measurements showed that the stress in the layers grown on porous GaN was reduced to 0.1–0.2 GPa, while the stress in the layers grown directly on 6H-SiC substrates remains at its usual level of about 1 GPa. Thus, we have shown that growth on porous GaN sublayer is a promising method for fabrication of high quality epitaxial layers of GaN with low strain values.

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Photoluminescence, Magnetospectroscopy, and Resonant Electronic Raman Studies of Heteroepitaxial Gallium Nitride

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Optical spectroscopy, including low- and room-temperature photoluminescence (PL), reflectance, PL measurements in high magnetic fields up to 12 T, and resonantly enhanced electronic Raman scattering (RERS) in zero and high magnetic field, has been used to investigate exciton and impurity states and surface recombination in high quality heteroepitaxial GaN grown on sapphire and SiC. Theoretical finite-difference calculations of the donor states as a function of magnetic field have been carried out for comparison, including the effects of anisotropy in the effective mass and dielectric constant. Up to six residual donor species are observed in material grown by hydride vapor phase epitaxy (HVPE) and metalorganic chemical vapor deposition (MOCVD) from their $n = 2$ and $n = 3$ two-electron satellites observed in PL and by RERS. The donor-related nature of the relevant transitions is confirmed from their magnetic field dependence, and the spectral resolution is improved at high fields. The Si donor level is determined to have a binding energy of about 21 meV from observation of its two-electron satellite in lightly Si-doped HVPE material. The free exciton binding energy is shown to be about 26.4 meV, independent of strain, based on observations of the $n = 2$ free exciton. The room-temperature band-edge PL peak is confirmed to be free excitonic in nature, based on its linewidth and on comparison with simple reflectance measurements. Reflectance from the edge of a thick HVPE layer shows clear evidence of *A*, *B*, and *C* excitons obeying the relevant selection rules at both low and room temperature. Surface chemical treatments are shown to have substantial effects on room-temperature PL efficiency. Passivation with ammonium or sodium sulfide solutions, in particular, yields increases in PL efficiency by a factor of five to seven over air-exposed surfaces. The passivation effect is stable in air, lasting at least one month.

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Radiative Recombination in $In_{0.15}Ga_{0.85}N$/GaN Multiple Quantum Well Structures

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We present a study of the radiative recombination in $In_{0.15}Ga_{0.85}N$/GaN multiple quantum well samples, where the conditions of growth of the InGaN quantum layers were varied in terms of growth temperature (< 800°C) and donor doping. The photoluminescence peak position varies strongly (over a range as large as 0.3 eV) with delay time after pulsed excitation, but also with donor doping and with excitation intensity. The peak position is mainly determined by the Stark effect induced by the piezoelectric field. In addition potential fluctuations, originating from segregation effects in the InGaN material, from interface roughness, and the strain fluctuations related to these phenomena, play an important role, and largely determine the width of the emission. These potential fluctuations may be as large as 0.2 eV in the present samples, and appear to be important for all studied growth temperatures for the InGaN layers. Screening effects from donor electrons and excited electron-hole pairs are important, and account for a large part of the spectral shift with donor doping (an upward shift of the photoluminescence peak up to 0.2 eV is observed for a Si donor density of 2×10^{18} cm^{-3} in the well), with excitation intensity and with delay time after pulsed excitation (also shifts up to 0.2 eV). We suggest a two-dimensional model for electron- and donor screening in this case, which is in reasonable agreement with the observed data, if rather strong localization potentials of short range (of the order 100 Å) are present. The possibility that excitons as well as shallow donors are impact ionized by electrons in the rather strong lateral potential fluctuations present at this In composition is discussed.

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