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Time-Resolved Photoluminescence Studies of InGaN/GaN Multiple Quantum Wells

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We report both cw and time resolved optical investigations performed on an InGaN/GaN multiple quantum well grown by MOVPE on ⟨0001⟩-oriented sapphire substrate. At low temperature we find a strong "blue" luminescence band, of which energy position corresponds well with the wavelength of stimulated emission when excited with a nitrogen laser. We show that this PL band appears systematically red-shifted with respect to the QWs features, which supports a standard picture of fluctuations of the indium composition. Coming to the time-resolved data, we find at low temperature at least two "blue" band components which are both associated with long decay times (up to 4–5 ns at 8 K). The decay time is temperature dependent and, when raising the temperature, the recombination rate increases. At room temperature, we reach typical values in the range ~100 to 500 ps.

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Theoretical Studies of Hydrogen Passivated Substitutional Magnesium Acceptor in Wurzite GaN

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Infrared measurements on wurzite GaN codoped with Mg and H reveal strong absorption at 3125 cm^{-1}. Theoretical work provides strong evidence for the H being antibonding to N. We have performed an *ab-initio* study of Mg-H complexes in wurzite GaN, using the Local Density Approximation on a large H-terminated cluster $MgHGa_{25}N_{26}H_{42}$. We have investigated the physical properties of three neutral configurations along the c direction. In all configurations Mg sits in a gallium substitutional site. H is then located in the Mg-N bond centre (BC), in the antibonding site on nitrogen side (AB_N) or in the antibonding position on magnesium side (AB_{Mg}). We found the lowest total energy configuration is hydrogen in the antibonding on the nitrogen site. The stretch mode in this configuration is calculated at 3277 cm^{-1} which agrees with experiment and previous LDA calculations and we predict an unreported infra red active wag mode at 1311 cm^{-1}. The exp erimental isotopic shift with D is well reproduced. The BC and AB_{Mg} configurations are 0.5 and 3.7 eV higher, producing local modes at 3645 and 2144 cm^{-1}, respectively. No wag modes appear for the BC and AB_{Mg} configurations.

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Temperature Behaviour of the Yellow Emission in GaN

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Even in good quality undoped GaN samples, as assessed by the intense excitonic emission, the yellow band is present. This band has been attributed either to a shallow donor to deep double donor pair recombination, to a deep donor to a shallow acceptor or to a shallow donor and a deep state. However, its origin is not yet clear. We present data on time resolved spectroscopy compared with steady state results. These results indicate that there is no difference in band shape between steady state and time resolved spectra at all temperatures. However, in some samples there is an increase in intensity of the yellow band. It is concluded that besides a fast emission, due to prompt excitation of the centre, an indirect path from a trap 13.7 meV below the shallow donor is responsible for the long component of the decay and the intensity increase. An emission with a lifetime of ca. 300 ms is also present with a maximum at 2.35 eV.

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p-Doping of GaN by MOVPE

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Mg has been widely used as p-doping species despite its intrinsic difficulties. It is nowadays well established that during the growth process of Mg doped GaN, atomic H is generated from the decomposition of NH_3 and Mg-H complexes are formed in the layer. This has been for instance shown by the occurrence of LO mode in IR absorption, and by the observation of the Mg-H local vibration modes. This H passivation limits the electrical activity of Mg, therefore an activation process is required to get full activation of the Mg atoms. In the present study, bismethylcyclopentadienyl magnesium [$(MeCp)_2Mg$]

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was used as precursor. However, this precursor reacts in the gas phase with NH_3 to produce tiny solid particles as evidenced by a very bright diffuse emission visible along the laser beam used for reflectometry measurements. This simplest obvious product would be $[(MeCp)Mg(NH_2)]_m$ ($m \geq 2$). To limit this drawback, Ga and Mg precursor lines have been separated. With proper in situ heat treatment, doping densities up to 1.5×10^{18} cm^{-3} have been obtained. PL spectra of lightly Mg doped samples (10^{16} cm^{-3}) are dominated by shallow donor-acceptor pairs whereas for higher doping densities (10^{18} cm^{-3}), the luminescence is dominated by a broad band in the 2.7–2.9 eV range. GaN LEDs were fabricated from Si doped (n-type) and Mg-doped (p-type) GaN, these LEDs emit in the blue-UV range.
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Electron Beam Pumped MQW InGaN/GaN Laser
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E-beam pumped lasers are attractive for Laser Cathode Ray Tubes (LCRT) in projection displays and a variety of applications typically associated with optically pumped lasers. For the first time an InGaN/GaN multiple quantum well (MQW) inplane laser pumped by surface normal pulse and scanning electron beams was demonstrated. Pumping at room temperature (RT) and 80 K showed peak stimulated emission wavelengths of 402 and 409 nm with a full width half maximum (FWHM) of 0.6 nm and 1.2 nm, respectively. The threshold electron beam current densities have been estimated as 60 A/cm^2 for 35 keV electron energy at 80 K using scanning e-beam pumping and 200–300 A/cm^2 at RT using pulsed e-beam pumping with a maximum electron energy of 150 keV. At 80 K, light output of 150 mW was measured out of one facet at an e-beam current of 1.7 mA.
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Physical Properties of Bulk GaN Crystals Grown by HVPE
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Free standing GaN platelets were fabricated by hydride vapor phase epitaxy (HVPE). The platelets having a current maximum size of $7 \times 6 \times 0.1$ mm^3 were obtained by HVPE growth of ~100 μm thick GaN layers on SiC substrates and subsequent removal of the substrates by reactive ion etching (RIE). Surface of the GaN platelets was characterized by reflectance high energy election diffraction (RHEED), and Auger electron spectroscopy (AES). Crystal structure and optical properties of the platelets were studied by x-ray diffraction and photoluminescence (PL), respectively. Raman spectroscopy was also applied for material characterization. Residual strain was detected in the crystals. The stress was eliminated by high temperature anneal.
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Raman Study of $Ga_{1-x}Al_xN$ Solid Solutions
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Long wavelength optical phonons of $Al_xGa_{1-x}N$ solid solutions have been identified in the whole compositional range by Raman spectroscopy. The frequencies of A_1 and E_1 polar phonons increase continuously with x from one-member crystal to the other. A generalization of the dielectric model of Hon and Faust is used to treat the coupling of the longitudinal optic (LO) mode. This approach accounts for the observed frequencies and confirms the so-called one-mode behaviour of polar LO phonons. Moreover, a signature of the coupling of a discrete mode (tentatively associated to silent $q = 0$ B_1 mode) with an unidentified continuum has been obtained.
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Characteristics of Indium-Gallium-Nitride Multiple-Quantum-Well Blue Laser Diodes Grown by MOCVD
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Room temperature (RT) pulsed operation of blue (420 nm) nitride based multi-quantum well (MQW) laser diodes grown on c-plane sapphire substrates with lifetimes exceeding 6 hours have been demonstrated. Threshold current densities as low as 12.7 kA/cm^2 were observed for 10×1200 μm lasers with uncoated reactive ion etched (RIE) facets. The emission is strongly TE polarized and has a sharp transition in the far field pattern above threshold.
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Surface Treatment and Layer Structure in 2H-GaN Grown on the (0001)Si Surface of 6H-SiC by MBE
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Heteroepitaxy of hexagonal symmetry materials is more complicated than in the more usual case of cubic systems. In the growth of layers on the (0001) surfaces, the misfit dislocations always exhibit a screw component that leads to rotation of the epilayer in a 3 dimensional growth mode. The size of the islands will depend on many factors among which the substrate surface treatment, prior to growth, may be a predominant one. In this work, a comparative study is carried out for samples grown on plasma treated samples, with and without additional substrate annealing prior to epitaxy. It is found that the defect density can be brought below 10^9 cm^{-2}, which is better than one order of magnitude in comparison to the layers grown on sapphire substrates. On top of the annealed substrates, the island growth is not obvious. Whereas, misorientations as large as a few degrees can be measured inside the layers on top of nonannealed substrates, justifying the occurrence of high densities of threading dislocations.
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Raman Characterization of the Optical Phonons in $Al_xGa_{1-x}N$ Layers Grown by MBE and MOCVD
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We present the results of Raman measurements performed on $Al_xGa_{1-x}N$ layers grown by MBE and MOCVD. The films were deposited on (0001) c-sapphire substrates, and the aluminum content covered the whole composition range for x from 0 (GaN) to 1 (AlN). It is shown that the energies of both A_1(TO) and A_1(LO) phonon modes smoothly increase with increas-

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ing x, indicating a one-mode behavior. The E_2 phonon mode, however, presents a different behavior. Its energy increases very slowly with aluminum content and, for x ≈ 0.4, a new phonon mode shows up which is shifted to higher energies by 50 cm^{-1}. This new line leads to the E_2 AlN mode for increasing aluminum content. The linewidths and intensities of these modes strongly depend on composition. These results are compared with recent theoretical calculations. Finally, the Raman selection rules in the MBE and MOCVD samples are compared and conclusions about the quality of the layers are drawn.
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GaN Based LEDs With Different Recombination Zones
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GaN based homo- and heterotype LEDs have been fabricated and characterized which emit in the blue and ultra-violet part of the spectral range. Complete epitaxial LED layer sequences with different recombination zones have been grown using MOVPE as well as MBE. Subsequent to the material growth, chemically-assisted ion-beam etching and contact metallization are utilized to achieve full LED devices. MBE-grown homotype LEDs reveal a peak in the output light spectrum at a wavelength of 372 nm with a linewidth being as narrow as 12 nm. GaN/InGaN LEDs grown by MOVPE show visible single peak emission with linewidths of 23 nm. The optical output power as measured in a calibrated Ulbricht sphere is in the 1 μW regime.
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The Role of Gaseous Species in Group-III Nitride Growth
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A quasi-thermodynamic model accounting for kinetics of molecular nitrogen evaporation is applied to simulate the growth of binary and ternary group-III nitrides using atomic group-III elements and molecular ammonia as the sources. The values of the molecular nitrogen evaporation coefficients from the surface of GaN and AlN necessary for the simulation are extracted from experiments on free evaporation of the crystals in vacuum, while for InN only estimates are available. The growth process of AlN and InN is studied by analyzing the composition of the desorbed vapor species that are thought to influence the native defect formation in group-III nitrides. Different channels of desorption from the surfaces of group-III nitrides (related either to group-III atoms or to their hydrides) are compared. Specific features of the growth processes under the metal-rich and N-rich conditions are analyzed. The developed approach is extended to study the growth of the ternary compounds GaInN and AlGaN. The growth rate of ternary compounds versus temperature shows a two-drop behavior corresponding to the rapid increase of the respective group-III atom desorption. The effect is accompanied by a corresponding stepwise change in the solid phase composition. Factors retarding the growth of ternary compounds—the miscibility gap related to internal strain accumulated in the solid phase due to the lattice mismatch of binary constituents, and the extra liquid phase formation during growth—are discussed with respect to GaInN.
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Characteristics of an Electron Cyclotron Resonance Plasma Source for the Production of Active Nitrogen Species in III-V Nitride Epitaxy
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A simple analysis is provided to determine the characteristics of an electron cyclotron resonance (ECR) plasma source for the generation of active nitrogen species in the molecular beam epitaxy of III-V nitrides. The effects of reactor geometry, pressure, power, and flow rate on the dissociation efficiency and ion flux are presented. Pulsing the input power is proposed to reduce the ion flux.
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http://nsr.mij.mrs.org/3/1/
GaInN/GaN Multi-Quantum Well Laser Diodes Grown by Low-Pressure Metalorganic Chemical Vapor Deposition
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We report the growth, fabrication and characterization of GaInN/GaN multi-quantum well lasers grown on (00·1) sapphire substrates by low pressure metalorganic chemical vapor deposition. The threshold current density of a 1800 μm long cavity length laser was 1.4 kA/cm^2 with a threshold voltage of 25 V. These lasers exhibited series resistances of 13 and 14 Ω at 300 and 79 K, respectively.
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Electron Overflow to the AlGaN p-Cladding Layer in InGaN/GaN/AlGaN MQW Laser Diodes
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Current flow through an InGaN/GaN/AlGaN multi-quantum well (MQW) laser diode is simulated. We found that electron overflow to the AlGaN p-cladding layer is very large, which prevents the current injection into the MQW layers. We clarified that the electron overflow occurs easily in nitride lasers because of three intrinsic reasons; poor hole injection due to the small hole mobility and thermal velocity, the small conduction band offset for InGaN/GaN, and the high threshold carrier density. We show that the Al composition and the p-doping of the AlGaN p-cladding layer is of critical importance to obtain laser oscillation by current injection.
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Atomic Force Microscopy Observation of Threading Dislocation Density Reduction in Lateral Epitaxial Overgrowth of Gallium Nitride by MOCVD
H. Marchand, J.P. Ibbetson, P.T. Fini, P. Kozodoy, S. Keller, S. DenBaars, J.S. Speck, and U.K. Mishra
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Extended defect reduction at the surface of GaN grown by lateral epitaxial overgrowth (LEO) on large-area GaN/Al_2O_3 wafers by low pressure MOCVD is demonstrated by atomic force microscopy. The overgrown GaN has a rectangular cross section with smooth (0001) and {11$\bar{2}$0} facets. The density of mixed character threading dislocations at the surface of the LEO GaN is reduced by at least 3–4 orders of magnitude from that

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of bulk GaN. Dislocation-free GaN surfaces exhibit an anisotropic step structure that is attributed to the orientation dependence of the dangling bond density at the step edges.

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Effect of Internal Absorption on Cathodoluminescence from GaN

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We have studied optical properties of GaN grown on sapphire by metalorganic chemical vapor deposition in the near band-edge energy range by cathodoluminescence. A large shift of the band-edge luminescence to lower energies is induced by increasing the beam energy. The free exciton position shifts about 20 meV when the beam energy is increased from 5 keV to 25 keV at room-temperature. The effect is explained by internal absorption caused by an exponential absorption tail at the band-edge. An Urbach parameter of about 30 to 40 meV for the exponential band-tail in our samples is estimated by comparing experimental with simulated spectra.

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New Plasma Chemistries for Etching GaN and InN: BI_3 and BBr_3

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Smooth, anisotropic etching of InN and GaN is obtained in BI_3- or BBr_3-based Inductively Coupled Plasmas. Etch selectivities of 100:1 were achieved for InN over both GaN and AlN in the BI_3 mixtures, while for BBr_3 discharges values of 100:1 for InN over AlN and 25:1 for InN over GaN were measured. The etched surface morphologies of InN and GaN with both mixtures are similar or better than those of control samples.

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Study of the Epitaxial Lateral Overgrowth (ELO) Process for GaN on Sapphire Using Scanning Electron Microscopy and Monochromatic Cathodoluminescence

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Growth of GaN by MOVPE on mismatched substrates such as sapphire or SiC produces a columnar material consisting of many hexagonal grains ~1 μm across. In contrast, the epitaxial-lateral-overgrowth (ELO) process creates a new material–single-crystal GaN. We have studied the ELO process using GaN/sapphire layers patterned with SiO_2 stripes. SEM images show that the (0001) GaN surface remains very flat as the ELO progresses. Cathodoluminescence images at 590 nm reveal spotty yellow-green emission from the columnar GaN as it emerges from the window areas. Very bright 590 nm emission occurs as the ELO process begins. We associate this deep-level cathodoluminescence with the strain field that accompanies the conversion of columnar GaN into single-crystal GaN via the ELO process. As the ELO process continues across the SiO_2 stripes, the 590 nm emission disappears and is replaced with pure band edge cathodoluminescence at 365 nm which is maintained until coalescence of adjacent ELO layers occurs near the centers of the SiO_2 stripes.

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Fabrication and Characterization of GaN/AlGaN Ultraviolet-Band Heterojunction Photodiodes

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Results from MOCVD grown n-$Al_{0.1}Ga_{0.9}N$/i-GaN/p-GaN UV photodetectors on sapphire substrates are presented. The devices show peak responsivities near 0.2 A/W for wavelengths between 352 nm and 362 nm, and responsivities of less than 10^{-3} A/W for wavelengths longer than 375 nm and shorter than 342 nm. The data is explained in terms of a simple device model.

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