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$ScAlMgO_4$: An Oxide Substrate for GaN Epitaxy

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We report the use of $ScAlMgO_4$ as a substrate for the epitaxial growth of wurzitic GaN. The low misfit (+1.8%) allows coherent epitaxy of GaN, as observed by RHEED. The congruent melting of $ScAlMgO_4$ makes Czochralski growth possible, suggesting that large, high quality substrates can be realized. Boules about 17 mm in diameter are reported. We have used nitrogen-plasma molecular beam epitaxy to grow GaN epitaxial films onto $ScAlMgO_4$ substrates. Band-gap photoluminescence has been observed from some of these films, depending primarily on the deposition conditions. A 3×3 superstructure has been observed by RHEED on the GaN surfaces. Structural analysis by x-ray diffraction indicates very good in-plane alignment of the GaN films. We also report thermal expansion measurements for $ScAlMgO_4$.

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Free Excitons in GaN

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Optical spectra on free exciton properties for GaN are presented and discussed, in particular the influence of epitaxial strain and temperature. The exciton-phonon coupling is also manifested via the temperature dependence of the LO phonon replicas of the free exciton.

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Study of GaN Films Grown by Metalorganic Chemical Vapour Deposition

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In this paper GaN films are examined, which are grown on basal plane (0001) sapphire substrates. Growth is performed in a novel type of vertical rotating disk reactor. The effects of several growth parameters on the film quality are discussed. The results on *n*-type doping of GaN with SiH_4 are presented. The GaN layers were evaluated by surface morphology studies, DC X-ray diffraction, electrical and optical characterisation.

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Research on GaN MODFETs

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Initial results on 0.25 μm gate MODFETs have yielded $f_t = 21.4$ GHz and $f_{max} = 77.5$ GHz. These devices have characteristics that agree with the gradual channel model dominated by the electron mobility. The AlGaN/GaN structure, grown on sapphire substrates, are polycrystalline, and thus yield low mobility (<100 cm^2/Vs) at low electron sheet density. Using a simple model, design optimization predicts electron sheet density values of 7.3×10^{12} cm^{-2} in thin, 3 nm quantum wells for single-sided doping with 5 nm spacer for use in future high frequency $Al_{0.4}Ga_{0.6}N/In_{0.25}Ga_{0.75}N/GaN$ MODFETs with gate lengths of 0.10 μm. Double sided doping with 5 nm spacers would yield a sheet density of 1.4×10^{13} cm^{-2} in such 3 nm quantum wells.

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Surface Morphology of as Grown and Annealed Bulk GaN Crystals

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GaN single crystals have been grown from Ga solution. The crystals grow in the form of platelets with their basal plane perpendicular to the *c*-axis. The two opposite crystal surfaces are not equivalent since one is N- and the other Ga-terminated. Atomic force microscopy has been applied to study surface morphology on both surfaces. It was found that one side is atomically flat. The other side consists of pyramid-like structures about 25 nm in size.

The influence of annealing in an $NH_3 + H_2$ atmosphere in the temperature range from 600°C to 900°C was investigated. Depending on crystal face the results were drastically different. It was found that on the rough

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side, annealing yields an atomically flat surface with terraces of monolayer height. The size of the terraces depends on the temperature of the annealing. On the originally flat side the surface becomes rougher after annealing. The transformation of surface morphology begins at temperatures below 700°C. Preliminary results of annealing in a hydrogen atmosphere are also reported. These findings are crucial for the understanding and development of GaN homoepitaxy.

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The Morphology and Cathodoluminescence of GaN Thin Films

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In this paper we compare gallium nitride (GaN) films grown by molecular beam epitaxy on sapphire (Al_2O_3), gallium arsenide (GaAs (111)B) and lithium gallate ($LiGaO_2$) substrates. Atomic force microscopy, scanning electron microscopy, cathodoluminescence imaging and cathodoluminescence spectroscopy are used to characterise the films. From growth runs carried out to date, GaN films on GaAs substrates exhibit the best surface uniformity and the cleanest luminescence.

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Yellow Band and Deep Levels in Undoped MOVPE GaN.

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Undoped layers of GaN grown by MOVPE on sapphire substrates have been characterized by photoluminescence, photocapacitance and photoinduced current transient spectroscopy (PICTS). Photocapacitance reveals in all samples two specific signatures at photon energies of 1 eV and 2.5 eV. The photocapacitance decrease observed at 1 eV seems to be due to an electron capture process from the valence band, whereas the capacitance increase at 2.5 eV is related to an electron emission process. The fact that the capacitance step at 1 eV is only seen after photoionization at energies above 2.5 eV, and the observed correlation between its amplitude and the photoluminescence intensity of the "yellow band," lead us to conclude that both transitions are linked to the same trap, which is also suggested to be responsible for the yellow band. The position of this trap, at 2.5 eV below the conduction band, is confirmed by PICTS measurements, that show a hole thermal emission activation energy of 0.9 eV at 350 K.

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Growth, Doping and Characterization of $Al_xGa_{1-x}N$ Thin Film Alloys on 6H-SiC(0001) Substrates

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Thin films of $Al_xGa_{1-x}N$ ($0.05 \leq x \leq 0.96$) having smooth surfaces were deposited directly on both vicinal and on-axis 6H-SiC(0001) substrates. Cross-sectional TEM of $Al_{0.13}Ga_{0.87}N$ revealed stacking faults near the SiC/Nitride alloy interface and numerous threading dislocations. EDX, AES, and RBS were used to determine the compositions, which were paired with their respective CL near band-edge emission energies. A negative bowing parameter was determined. The CL emission energies were similar to the bandgap energies obtained by SE. FE-AES of the initial growth of $Al_{0.2}Ga_{0.8}N$ revealed an aluminum rich layer near the interface. N-type (silicon) doping was achieved for $Al_xGa_{1-x}N$ for $0.12 \leq x \leq 0.42$. $Al_{0.2}Ga_{0.8}N$/GaN superlattices were fabricated with coherent interfaces. Additionally, HEMT structures using an AlN/GaN/AlN buffer structure were fabricated.

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Optical Detection of Electron Nuclear Double Resonance on the Residual Donor in GaN

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Optically detected electron nuclear double resonance (ODENDOR) was measured in the 2.2 eV "yellow" luminescence band associated with the residual donor in *n*-type undoped GaN. The ODENDOR lines are due to gallium and show a quadrupole splitting which can be described with an axial tensor. The quadrupole parameter was estimated to be $q(^{69}Ga) = 1/2\ Q_{zz} = 0.22$ MHz. A hyperfine interaction for ^{69}Ga of about 0.3 MHz for the isotropic and of about 0.15 MHz for the anisotropic part was estimated from the width of the ODENDOR lines. It is tentatively suggested that a Ga interstitial is the residual donor.

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Growth and Doping of AlGaN Alloys by ECR-Assisted MBE

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We report the growth of $Al_xGa_{1-x}N$ alloys on (0001) sapphire by the method of Electron Cyclotron Resonance-assisted Molecular Beam Epitaxy (ECR-MBE). The films were doped *n*-type with silicon at carrier concentration levels from 10^{16} to 10^{19} cm^{-3}. SEM studies reveal smooth surface morphology consistent with the observed 3×4 surface reconstruction in the RHEED pattern. Independent determination of the Al-concentration and the lattice constant of the alloys shows that Vegard's rule is obeyed in the pseudo-binary GaN-AlN system. The bandgap of the alloys, determined by transmission and photoluminescence measurements, was found to depend linearly on Al-concentration.

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Luminescence Spectra of Superbright Blue and Green InGaN/AlGaN/GaN Light-Emitting Diodes

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Electroluminescence spectra of superbright blue and green LEDs based on epitaxial $In_xGa_{1-x}N/Al_yGa_{1-y}N$/GaN heterostructures with thin quantum well active layers [1] were studied at currents $J = 0.01$-20 mA. Spectral maxima of blue and green LEDs are max = 2.58-2.75 eV and max = 2.38–2.45 eV, dependent on the active layer In content. The low energy tails of the spectra are exponential with the parameter $E_0 = 42$–50 meV almost independent of the temperature. The high energy tails of the spectra are exponential with a temperature dependent parameter $E_1 = 20$–40 meV. Both parameters (E_0, E_1) are current independent at $J > 0.5$ mA. The spectral band can be described by taking into account quantum size effects, impurities and electron-phonon interactions in active layers. A structure in the spectra was detected which can be described by the influence of light interference in the GaN layer on the sapphire substrate. Light intensity was

a linear function of the drive current over the interval $J = 1-20$ mA, and was slightly temperature dependent. In the blue LEDs, the efficiency fall off at low currents ($J < 0.7$ mA) had a $I \sim J^{4\text{-}5}$ dependence at room temperature. The green LEDs showed no such dependence. The influence of tunnel effects on the efficiency at low currents is discussed. Tunnel radiation spectra with maxima moving with the voltage were detected at low currents in III-N structures.

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Growth Rate Reduction of GaN Due to Ga Surface Accumulation

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GaN(0001) has been grown on $Al_2O_3(0001)$ by molecular beam epitaxy where NH_3 was used as the nitrogen precursor. Desorption mass spectroscopy and reflection high energy electron diffraction (RHEED) were used to monitor the relationship between growth rate and the incident fluxes during growth. Excess surface Ga decreases the GaN formation rate when the substrate temperature is too low or the Ga flux is too high. A simple rate equation is used to describe the observed behavior.

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Photoluminescence Study on GaN Homoepitaxial Layers Grown by Molecular Beam Epitaxy

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GaN epitaxial layers on GaN single crystals were grown using molecular beam epitaxy with an NH_3 source. The deposited layers were examined by high resolution x-ray diffraction and photoluminescence (PL) spectroscopy. We observed strong and extremely narrow (half-widths of 0.5 meV) lines related to the bound excitons. In the higher energy range we observed three strong lines. Two of them are commonly attributed to free exciton transitions A (3.4785 eV) and B (3.483 eV). Their energetic positions are characteristic of strain-free GaN material.

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Bandgap Variation at the Isostructural Phase Transformation of Wurtzite InN

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The pressure variation of the bandgap, at the isostructural phase transition of wurtzite InN, is determined theoretically, using the first-principles total-energy pseudopotential method. It is found that the bandgap (as well as the structural parameters) exhibit three different types of behavior in three regions of pressure. Optical experiments at low temperatures could then be employed to directly identify the two different wurtzite phases of InN.

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