Feedback Control of a Quantum Dot Cavity-QED System — FRANZ SCHULZE, ALEXANDER CARMELE, AND ANDREAS KNORR — Institut für Theoretische Physik, Technische Universität Berlin, Germany

We investigate externally pumped quantum dots embedded in a nanocavity within an equation-of-motion approach.[1] In the limit of many emitters and photons the standard cluster expansion scheme is a well-known factorization procedure to investigate quantum light emission.[2] A possible way of stabilizing this emission and its statistical properties is a time delayed self-feedback as it is described classically by the Lang-Kobayashi model.[3] Here, we discuss the transition from the classical [4] to the quantum mechanical model and present first steps towards a fully quantized feedback description.

modified Förster model taking into account the concentration quenching as well as the dimensionality of the nanostructures. To check the general validity of this model, nanostructures of diverse morphology were doped with two different luminescence centers, namely Terbium and Manganese with concentrations of 4% and 4% by ion implantation. The PL transition of the internal \( \text{Tb}^{3+} (4f^6) \) and the \( \text{Mn}^{2+} (3d^5) \) transitions were measured over four orders of magnitude.

For wires as well as for belts an enhancement of the effective dimensionality could be observed for increasing Mn concentration at 10K. Measurements at room temperature indicate, however, again a reduction of the effective dimensionality, due to the enhanced transfer probability inside the sublevels of the luminescence centers. Temperature treatment and ion irradiation were used to incorporate additional defects for a thorough investigation of the energy transfer influenced by nonradiative killer centers.

**HL 25.8 Mon 16:00 Poster D**

**Investigation of Parametrizations for the Valence Band Structure of GaN** — **Felix Schwarz, Steve Lenk, and Erich Rungen** — Institut für Physik und Institut für Mikro- und Nanotechnologien, Technische Universität Ilmenau, 98693 Ilmenau, Germany

We calculate the dielectric function of hexagonal GaN including the A-, B-, and C-excitons using a multi-valence band formalism. The importance of excitons for the interpretation of reflectance spectroscopy or GaN was emphasized by several experimental groups, but only recently theoretical calculations were presented. We obtain the dielectric function from a numerical solution of an initial-value problem [2] via an exponential split-operator method, taking into account the full 6x6 valence band structures of several parametrizations calculated by other groups. We present the complex dielectric function as well as the dispersion of the effective dimensionality, due to the enhanced transfer probability inside the sublevels of the luminescence centers. Temperature and ion irradiation were used to incorporate additional defects for a thorough investigation of the energy transfer influenced by nonradiative killer centers.


**HL 25.9 Mon 16:00 Poster D**

**Optical second harmonic spectroscopy of GaAs excitons in crossed electric and magnetic fields** — **David Brunne**, Marco Lafrentz, Victor Pavlov, Roman Pihrev, Dmitri Yakovlev, and Manfred Bayer — Experimentelle Physik 2, TU Dortmund, D-44221 Dortmund, Germany — Ioffe Physical-Technical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia

Optical second harmonic generation is a powerful tool to investigate exciton resonances in semiconductors. Recent measurements on GaAs in an external magnetic field have revealed a rich spectrum of magnetic excitons related to carrier Landau levels with numbers up to eight. In the present work we extend this research by additional application of an electric field, which modifies considerably the spectrum of magnetic excitons detected via second harmonic generation (SHG). Electric and magnetic fields are applied perpendicular to each other and to the (001) crystal axis of a GaAs sample. In the absence of these fields SHG intensity is zero as the nonlinear process is forbidden in the electric-dipole approximation. Polarization characteristics are analyzed. We discuss the rich spectrum of magnetic excitons which stems from the complex energy and spin structure of the valence band.

**HL 25.10 Mon 16:00 Poster D**

**Long-range transport of indirect excitons by moving strain dots in a GaAs double quantum wells** — **Snezana Lazic, Rudolf Hey, and Paulo Santos** — Paul-Drude-Institut für Festkörperelektronik, Hausvogteiplatz 5-7, 10117 Berlin, Germany

We report on the acoustic transport of spatially indirect (inter-well) excitons in a GaAs/AlGaAs double quantum well. The photo-excited excitons are trapped within an array of moving strain dots with a spatial periodicity of a few \( \mu \text{m} \). These dynamic potential dots are formed by interfering two surface acoustic waves (SAWs) propagating along orthogonal non-piezoelectric crystallographic directions. The trapping mechanism relies on a dynamic type-I modulation of the band edges via the deformation potential interaction. The exciton lifetime is voltage-tunable via the top semi-transparent gate and is substantially longer than the SAW period. We show that such system offers a controllable way for artificially producing cold exciton gases for the investigation of quantum collective effects.

Using spectrally and spatially resolved low-temperature photoluminescence measurements, we have observed the formation of a luminescence ring around the laser illumination spot, which is discussed in terms of thermalization of long-living indirect excitons. Under acoustic excitation, we demonstrate the long-range transport (of the order of 100 \( \mu \text{m} \)) followed by recombination at the inter-well exciton transition energy. These experiments allow us to determine the distribution of indirect excitons as well as to probe the exciton-exciton interactions within the dot array.

**HL 25.11 Mon 16:00 Poster D**

**Photoluminescence line shape features of carbon delta-doped GaAs heterostructures** — **Jürgen Schuster**, Tan Yang Ko, Edwin Batke, Dirk Reuter, and Andreas Wiecek — Physikalisches Institut der Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany — Lehrstuhl für Angewandte Festkörperphysik, Ruhr-Universität Bochum, Universitätstrasse 150, D-44780 Bochum, Germany

The PL line shape features of quasi two-dimensional electron gas (2DEG) in setback delta doped GaAs heterostructure at liquid helium temperature are studied. The sample with two different excitation energies, below and above the band gap of AlGaAs. The whole density of states of 2DEG can be directly visible due to the relaxation of k-selection rule. We observed clearly the ground and the first excited 2D subbands. A simple fit to the line shape including broadening demonstrated that there is an exponential low-energy tail along with the usual subband model. The separation of the subband bottom energies, the quasi Fermi-energy, the electron temperature and the integrated strengths, enabling an accurate determination of the subband populations and the transition probability. A self-consistent calculation of subband properties including the potential contribution of the delta doping reproduces the subband separations and recombination intensities well. The dependence of excitation intensity, temperature and magnetic field strength on the PL line shape is studied.

**HL 25.12 Mon 16:00 Poster D**

**Near-field scanning optical microscopy of infrared emitting semiconductor nanostructures** — **Alexander Semchenkov, Uri Givan, Oussama Moutanabbir, Vadim Talalaev, and Peter Werner** — Max Planck Institute of Microstructure Physics, Weinberg 2, D-06120 Halle (Saale), Germany — Centre for Innovation Competence SiLi-nano, Martin-Luther-University, Karl-Freiheer-von-Fritsche-Str. 3, 06120 Halle, Germany

The fabrication of low-dimensional semiconductor materials with controlled variation of structural parameters in nanometer scale is fascinating activity in the quantum nano research. These structures are interesting for study the fundamental physical properties and possibilities of their application in advanced optoelectronic devices as well. Optical spectroscopy is one of the most powerful tools for investigation of electronic and optical properties of low-dimensional semiconductor nanostructures which are determined by quantum-mechanical confinement of electronic wave functions. Using near-field scanning optical microscopy (NSOM) allows one to study these properties of single nanostructures with sub-wavelength spatial resolution.

In this work we address abilities of our NSOM technique to perform space resolved experiments at low temperature. We will report on results of a near-field optical study of semiconductor nanostructures, e.g. single Si nanowires and InGaAs nanoclusters. The combination of NSOM data with TEM, SEM, and Raman spectroscopy opens the possibility to get complete information about properties of low-dimensional nanostructures.

**HL 25.13 Mon 16:00 Poster D**

**Direct determination of piezoelectric coefficients for GaN by AFM** — **Uwe Röder**, Frank Lips, Martin Feinberg, Ferdinand Scholz, and Klaus Thonke — Institute of Quantum Matter / Semiconductor Physics Group, Ulm University — Institut für Experimentelle Physik, Otto-von-Guericke-Universität Magdeburg

For the piezoelectric coefficients of GaN a broad range can be found in literature (\( d_{31} = 2...4 \text{ pm/V} \); \( d_{33} = 2.9...3.3 \text{ pm/V} \)). Mostly, these parameters have been determined from polycrystalline thin layers. We present here data obtained on thick semi-insulating Fe doped GaN lay-
ers grown by HVPE. By applying AC voltages with varying amplitude and frequency to top and bottom contacts, and measuring the elongation of the thick GaN layer with an AFM tip in contact mode and lock-in technique to record the phase-correlated periodic change of the quadrature diode signal, we get a direct measure of the piezoelectric constant $d_{33}$. We obtain a value of $d_{33} = (2.2 \pm 0.3) \text{pm/V}. \quad$ Similar to $d_{15}$, this could be obtained by recording the shear displacement. Effects of mechanical sample resonances etc. have to be carefully avoided.

**HL 25.14 Mon 16:00 Poster D**

Low voltage spatially resolved cathodoluminescence measurements on nitride semiconductors — •Matthias Höcker1, Ingo Tischer1, Robert A.R. Lüte2, Ferdinand Scholz2, and Klaus Thönke1

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Cathodoluminescence (CL) measurements with very low acceleration voltages can drastically improve spatial resolution. For low electron energies of 500 – 2000 eV and small working distances of 2 – 4 mm in the scanning electron microscope, we achieve a spatial resolution down to the diffusion length of the generated excitons. We demonstrate the application of low voltage CL measurements to InGaN quantum wells, and compare the results to Monte Carlo simulations.

**HL 25.15 Mon 16:00 Poster D**

Untersuchung von InGaN-basierten Quantenpunktsystemen mittels STEM Z-Kontrast — •Alexander Wörpel1, Thorsten Mirhata1, Christian Tessarek1, Timo Aschenbrenner1, Detlef Hommel1, and Andreas Rosemauer1

1AG Elektronenmikroskopie, Institut für Festkörperphysik, Universität Bremen, Deutschland

InGaN-basierte (Laser-)Dioden emittieren im blauen bis grünen Spektralbereich. Die Verwendung von Quantenpunkten (QPe) in der aktivten Schicht verbessert die Effizienz und ermöglicht neue Anwendungen wie z.B. Einzelphotonenemitter.

Es werden InGaN/InN-Strukturen untersucht, die mittels MOVPE unter Verwendung komplexer Temperaturprofile gewachsen wurden. Die spinodale und binodale Entmischung wird als treibende Kraft für die Bildung von InGaN-Quantenpunkten auf spinodalem und binodalem Niveau. Wir stellen Ergebnisse von Experimenten und Simulationen vor, die den Einfluss der Materialeigenschaften auf die Quantenpunktstruktur und -aussendichte verdeutlichen.

**HL 25.16 Mon 16:00 Poster D**

Photoluminescence of cubic AlGaN layers — •Florian Horrich1, Sarah Osterburger1, Maria Fátima Romero1, Martin Feneberg1, Thorsten Schupp1, Christian Metzke1, Donat J. As2, and Rüdiger Goldhahn1

1Otto-von-Guericke University Magdeburg, Germany 2University Paderborn, Department Physik, Paderborn, Germany

Thin cubic AlGaN layers grown by molecular beam epitaxy were investigated by photoluminescence (PL) at variable temperatures. The energy width of the PL peak was measured from 100 K to 300 K and found to be constant up to 250 K. The results were compared to the predictions of different theories and models. A good agreement was found for the model of Shockley-Read-Hall recombination.

**HL 25.17 Mon 16:00 Poster D**

Ultraviolet photoluminescence spectroscopy of homo- and heteroepitaxially grown AlN — •Christoph Reich1, Viola Küllner2, Arne Knauber2, Martin Feneberg1, Jessica Schlegel2, Markus Weeres2, Rüdiger Goldhahn1, and Michael Kneissl2

1Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstr. 36, 10623 Berlin, Germany 2Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Str. 4, 04129 Berlin, Germany

InGaN-based quantum dots (QD) on various substrates were investigated by photoluminescence (PL) and cathodoluminescence (CL). The PL spectrum of InGaN on GaN shows a peak at 3.4 eV, which is attributed to the emission of excitons confined in the InGaN quantum dots. The CL spectrum shows a peak at 3.6 eV, which is attributed to the emission of excitons confined in the GaN quantum dots.

**HL 25.18 Mon 16:00 Poster D**

Effect of growth parameters and annealing on the p-doping of GaN:Mg — •Gunnar Kusch, Martin Frentrup, Tim Kolbe, Tim Wernicke, Markus Pristovsek, and Michael Kneissl

Technische Universität Berlin, Institut für Festkörperphysik, Hardenbergstr. 36, 10623 Berlin, Germany

One of the key challenges limiting the output power of group-III nitride light emitting diodes (LEDs) and laser diodes is the p-doping of (Al)GaN with magnesium (Mg). During growth of GaN:Mg by metalorganic vapor phase epitaxy compensating defects are incorporated such as nitrogen vacancies, Mg-H-N complexes and inversion domains. The high activation energy is a further obstacle for effective p-doping with hole concentrations $> 1 \times 10^{17} \text{ cm}^{-3}$. We have investigated Mg incorporation in GaN in the range of $10^{17}$ to $10^{19} \text{ cm}^{-3}$ as well as excitation and the influence of activation on LEDs. Variation of the Mg/III ratio showed a strong influence on the hole concentration. The lower limit is given by the n-type background doping below a II/III ratio of 15 $\times 10^{-2}$ and the upper limit by compensating defects above a II/III ratio of 25 $\times 10^{-3}$.

**HL 25.19 Mon 16:00 Poster D**

Optimization of the internal and external quantum efficiency of high In content GaInN LED structures — •Fedor Alexei Ketzer1, Holger Jönen, Ailun Zhao, Heiko Bremers, Uwe Rossow, and Andreas Hangleiter

1Institut für Angewandte Physik, TU Braunschweig

We investigate high indium content GaInN based light emitting diodes grown via low pressure MOVPE. The efficiency of such structures is rather small due to the high indium content. In order to improve the efficiency we study the growth of the p-doped GaN layer and rapid thermal annealing (RTA), needed to activate the p-dopants (Mg). Due to the high thermal load these processes influence the quantum well (QW) and therefore the external quantum efficiency (EQE). These influences appear to raise with higher indium content.

For this purpose the IQE before and after RTA is compared with the external quantum efficiency (EQE). Also conditions during RTA and growth of the layers following the QW were modified to examine changes in emission spectra and efficiency. The IQE was determined by temperature dependent photoluminescence and the EQE was determined by electroluminescence. With these results the growth conditions of the active region and their following layers can be optimized for high internal and external quantum efficiencies.

**HL 25.20 Mon 16:00 Poster D**

MBE growth and characterization of group III/N quantum dots on various substrates — •Andreas Kraus, Heiko Bremers, Uwe Rossow, and Andreas Hangleiter

1Institut für Angewandte Physik, TU Braunschweig

Devices based on quantum dots are expected to overcome some of the limitations of quantum well based structures opening the way to applications such as laser diodes and single photon sources. Our experiments include RF MBE (Riber 32) grown self-organized group III/N dots using Stranski-Krastanov (SK) growth mode under metal rich conditions. Various templates including InGaN were used with sapphire material.
and SiC as substrates. Afterwards the dots were capped, allowing studies of the optical properties.

In situ RHEED reveals a dotty pattern indicating 3D island formation and therefore 5K growth mode. AFM characterization of the samples hints at rough surface morphology with dot-like features. Structural properties were investigated with XRDC. Concerning the AIN buffer layer XRDE revealed an improvement for optimized growth conditions. The optical properties were investigated using a UV photoluminescence setup. We discuss PL studies of the samples as well as the optimization of dot formation via adjusted growth conditions.

HL 25.21 Mon 16:00 Poster D Investigation of the incorporation of Mg as p-dopant in GaN grown by metal modulated epitaxy

Investigation of the incorporation of Mg as p-dopant in GaN grown by metal modulated epitaxy (MME) which was reported in the literature to strongly increase the doping level up to 4×10^{19} cm^{-3}. During MME the metal shutters (Ga, Mg) are periodically opened and closed while the N-shutter remains constantly open. This method is used to optimize the incorporation of Mg into the structure while preserving a smooth surface. The growth takes place under metal-rich conditions and is monitored in situ by RHEED. The substrate temperature is 550°C. AFM investigations reveal RMS values of 1.9 nm. The surface shows holes with a depth of about 30 nm in between them RMS values of 0.7 nm indicate an atomically flat surface. Hall effect measurements were performed to determine the doping level. Charge carrier densities up to 1.6×10^{19} cm^{-3} are achieved, which remain almost constant over a temperature range between 50 - 400 K. Activation energies of 10 - 12meV as well as mobilities around 10^6 cm^2/Vs indicate electronic conductivity.

HL 25.22 Mon 16:00 Poster D Implantation studies on silicon doped group-III nitride semiconductors

 Ronnie Simon1, Reinier Vianden2, and Klaus Köhler3

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2Fraunhofer Institut für angewandte Festkörperphysik, Freiburg

Silicon doped GaN layers grown by low-pressure metal-organic vapor–phase epitaxy with Si concentrations ranging from 2×10^{12} to 2×10^{18} atoms/cm^3 were investigated by means of the perturbed angular correlation (PAC) technique applied to implanted ^111In(Cd). An undoped GaN film is used as a reference. The Si-atoms replace Ga-atoms in the lattice and silicon, being a group-IV element, acts as a donor on the Ga-site and contributes one extra electron to the conduction band. Hall effect measurements confirmed that the free charge carrier density is essentially increased and of the order of the silicon concentration. PAC investigations of the annealing behavior after implantation of the ^111In probes shows that best recovery is achieved after annealing at 1200°C. GaN films more stable at high temperatures. Further, it was found that the temperature dependence of the electric field strength is reduced by increasing Si concentrations.

HL 25.23 Mon 16:00 Poster D External oxidation of GaN studied by Perturbed Angular Correlations

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A sample of 2 µm GaN was heated in air at 1273 K in steps of 5 min for 80 min. During this treatment, external oxidation of the sample occurred. After each oxidation step, perturbed angular correlation measurements were performed at room temperature. The growth of the oxide will be discussed.

β-Ga2O3 can be used for transparent conductors or electronic devices. Thin films were already achieved with external oxidation, but the feasibility of these films for UV photonics due to high oxidation rate of the sample occurred. After each oxidation step, perturbed angular correlation measurements were performed at room temperature. The growth of the oxide will be discussed.

Based on the hyperfine interaction between the intermediate state of a probe nucleus undergoing a g–g–cascade and an electric field gradient (EFG) generated by the electronic conditions in the sample. The strong dependence of the EFG to its origin makes PAC ideal for studies on the nanoscale.

Weng et al., IEEE Sensors Journal, 11, 999 (2011)

HL 25.24 Mon 16:00 Poster D Electrochemical characterization of Si- and Mg-doped GaN nanowire electrodes

Jens Wallys1, Florian Furtmayer2, Jörg Trubert2, Vladimir Schäfer2, Jörg Schömann1, and Martin Eckhoff3

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Recent progress in the field of GaN nanowire (NW) growth, in particular the possibility to realize both p- and n-type doping, suggest their use as novel electrodes for chemical and biological sensors or in the field of photovoltaics. However, the knowledge about their electrochemical properties and the influence of doping is still very limited.

We investigated ensembles of undoped, Si-doped and Mg-doped GaN NWs with different doping concentrations and average diameters grown on Si (111) substrates by plasma assisted molecular beam epitaxy (PMBE). The samples were analyzed using bias dependent electrochemical impedance spectroscopy (EIS) and electrochemical impedance measurements (EIS) in the frequency range between 10^{-4} and 10^{4} Hz under physiological electrolyte conditions. By fitting the results to an equivalent circuit model the electronic properties of GaN NW ensembles could be extracted. According to these results a classification of the NWs into conducting and depleted ones is suggested and verified by cyclic voltamograms in the presence of a redox couple and correlated to scanning electron microscope images.

HL 25.25 Mon 16:00 Poster D Investigation of efficiency of blue and green GaN based LEDs

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GaN based light-emitting diodes (LEDs) have been attracting much attention due to their promising and wide application in display and lighting during the past decades. Since blue light is of special interest in their performance, there still remain many technical challenges impeding further applications of LEDs, an important one of which is the efficiency droop. The efficiency droop includes two aspects: one is the efficiency decreasing with increasing injection current and another is the decrease with longer wavelength. We grow blue and green LEDs on sapphire substrate along c-direction by MOVPE. As we are mainly interested in effects related to the internal efficiency, simple on-wafer processing is used, providing small but fairly well-known extraction efficiency. The samples were characterized by electroluminescence. We investigated the series resistance, external quantum efficiency (EQE), efficiency droop and peak emission wavelength of our samples. We observe that, generally, LEDs showing strong efficiency droop also show a strong injection blue shift. We discuss the implications on the possible droop mechanism.

HL 25.26 Mon 16:00 Poster D Current-injection and carrier confinement in InAlGaN ultraviolet light emitting diodes

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Ultraviolet (UV) light emitting diodes (LEDs) have attracted great interest in recent years because of their potential applications in photonic and sensor technology. However the external quantum efficiency (EQE) of these LEDs is only in low percentage range. One of the key challenges to improve the EQE is the carrier injection in to the active region. Therefore, an optimisation of the electron blocking layer (EBL) is very important to prevent an electron leakage into the p-layers of the LED with a simultaneous unhindered hole injection. In this work we have investigated 320 nm LEDs with different donor type EBLs. The devices were grown by metalorganic vapour phase epitaxy on (001) sapphire substrates. A combination of electroluminescence measurements and simulations of the LED heterostructure were performed to investigate the carrier injection in to the active region of the LEDs. We will compare LEDs with AlGaN EBLs with an aluminum content between 37 and 84 % and show that the highest EQE is obtained for LEDs with an Al_{0.45}Ga_{0.55}N EBL. This is in a good agreement with our simulation results. The temperature effect on the performance of LEDs with different EBLs is investigated by tempera-
ture dependent electroluminescence measurements which shows a clear influence of the temperature on the electron leakage current of the UV LEDs.

**Performance Enhancement of InAlN/AlN GaN-HEMTs by using In-Situ SiN Passivation for High Temperature Applications** — Alexander Alexewicz¹, Paul Marko¹, Mohammed Alomari², Hannes Behmenburg³, Christoph Giesen³, Michael Heuken², Dionyz Pogany¹, Erhard Kohn², and Gottfried Strasser¹

1 TU Wien — 2 Universität Ulm — 3 AIXTRON SE, Herzogenrath — 4 RWTH Aachen

We present InAlGaN/AlN GaN high electron mobility transistors (HEMTs) with an optimized MOCVD-grown (metal organic chemical vapor deposition) SiN passivation, compared to the standard PECVD (plasma enhanced CVD)-SiN. Passivating the devices effectively reduces electronically active surface states, which can deteriorate the device performance drastically. In this work, GaN HEMTs are processed on SiC substrate with MOCVD-SiN passivation layers of different thicknesses (5 nm, 30 nm, no passivation). SiN is grown in the same run (in-situ) as the InAlGaN/AlN/GaN heterostructure, before the actual processing of the device, what enhances the interface quality by avoiding surface contamination before deposition of the passivation. The non-passivated devices show a maximum drain current of 0.8 A/mm in DC and 0.5 A/mm in pulsed mode at a gate voltage of 3 V. The 5 nm and 30 nm passivated devices exhibit an improvement of these values by 25 % and 50 % in DC, and 80 % and 140 % in pulsed mode, as well as a strongly reduced electron trapping related current collapse. Due to the better interface quality, this kind of passivation has great potential for high temperature device applications.