

Preparation and Characterization of Aluminum Nitride Nanorod Arrays via Chemical Vapor Deposition

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We developed a novel method using chemical vapor deposition (CVD) for the growth of AlN nanorod arrays. The method adopted the basic principle from the epitaxial growth by using the two-stage CVD, in which an AlN film was first deposited and subsequently the arrays of AlN nanorods were grown on the top of the film. The process can be reached by the careful controls on the nucleation concentrations of gaseous AlN sources during the deposition. The as-grown arrays of AlN nanorods are well-crystallized and oriented along *c*-axis direction. Our method of the controlled two-stage growth has provided a new route for the preparations of the arrays of other III-V semiconductor nanorods.

Growth GaN thin films by MBE with ammonia on Al₂O₃ (0001)

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Using of ammonia as a source of nitrogen in molecular beam epitaxy of thin films of III-V groups nitrides (MBE with ammonia) combine in to themselves advantages of MOCVD systems (large growth rates, high perfection of growing layers) and MBE installations (absence of "memories" systems on components III groups, low cost of experiments, opportunity of in-situ research of growth processes). It makes to perspective use MBE with ammonia at manufacturing small sets of complex multilayer structures on a basis of III-V groups nitrides. The influence of conditions of growth process at MBE with ammonia on the properties of GaN layers is still insufficiently investigated. Already the available experimental data do not cover all range of growth conditions. Besides because of complexity of exact measurement of the growth temperature, there is a problem of carry of experimental results from the one to the other installations.

In the submitted work the research of influence of growth conditions - temperature of growth and pressure of ammonia – on electrophysical and optical properties of GaN layers, grown on substrates Al₂O₃ (0001) is presented. The experiments were carried out on the installation Riber-CBE 32P. The Ga and Al flow was formed by usual crucible sources. Sapphire (0001) substrates were used. For the control of the growth parameters and the structural property of a GaN surface in situ were used high energy electron diffractometry and optical reflectometry. The temperature of growth was determined under the indications infra-red pyrometry and by thermocouple. GaN/Al₂O₃ samples also has been characterized ex situ by double crystal XRD, cross-section high-resolution transmission electron microscopy, atomic force microscopy, spectral ellipsometry, photoluminescence and measurements of effect of a Hall are resulted.

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The influence of nucleation stages on polarity of GaN films growing on Al₂O₃(0001) by MBE with ammonia

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The polarity is a key parameter for growth of high-quality GaN films affecting on impurities incorporation, morphology and crystalline perfection of growing layers. The polarity of epitaxial GaN films on (0001) sapphires substrates is assigned at the stage of nucleation. Therefore information about polarity of a nucleated GaN film can help in choice of conditions of subsequent growth.

A polarity of GaN crystal along <0001> arises from absence of the center of inversion symmetry in a wurzite-type GaN. It determines a sufficient difference between the properties of GaN (0001) and GaN(000-1) surfaces. Besides, different growth conditions are necessary to produce perfect GaN films on the (0001) and (000-1) surfaces. The dependence of polarity from nucleation stage conditions is not well understood up to date. There are some contradictions in the literature: the low-temperature AlN nucleation layer on the sapphire substrate can results in N-polarity or Ga-polarity. Therefore, the information concerning the polarity of growing film available just after the nucleation stage is very important for the choice of conditions of subsequent growth. During MBE with ammonia the polarity of GaN film can be determined on observation by RHEED of surface structures typical for Ga- and N-face. It allows to define GaN films polarity at the initial stages of growth. In the present work the sequence of operations for obtaining of a smooth surface, appropriate for observation of surface structures of GaN films, after growth only 20-30 nm of a buffer layer is disclosed. The effects of the nitridation and the nucleation stages on the growing film polarity are investigated by using this technique.

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Indium-rich Nano-clusters in InGaN Thin Films and InGaN/GaN Quantum Wells

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With optical studies, it has been shown that different doping conditions, including different doping layers, in InGaN/GaN quantum-well (QW) structures lead to different nano-structures and hence different optical characteristics. In particular, due to the large lattice mismatch between InN and GaN, indium-rich clusters are usually formed in such a QW structure through spinodal decomposition. In some situations, quantum-dot-like nano-structures can be observed. With different silicon doping conditions, the clustering structures are different. In this paper, we report the results of material analysis and optical characterization of the nano-structures in InGaN thin films and InGaN/GaN QWs. We compare the samples of different average indium contents, different doping layers (including un-doped, well-doped, and barrier-doped), and different doping concentrations. Generally speaking, compared with the un-doped sample, well doping can usually increase the cluster density within the QWs. Barrier doping leads to the strongest clustering behavior, resulting in island-by-island structures. Therefore, carrier localization is expected to be the strongest for the highest radiative efficiency in the barrier-doped samples. In other words, the QW structures are essentially preserved in the un-doped and well-doped samples. However, in the barrier-doped samples the QW characteristics basically disappear. Also, the clustering phenomena are normally stronger in the samples of higher average indium contents. Based on the SSA images, we calculate the average indium contents in the well layers of different samples. It is found that the un-doped samples tend to have lower average indium contents, compared with well- and barrier-doped samples, assuming that other growth conditions are the same. This trend can be interpreted as the different indium incorporation efficiencies under different doping and hence strain conditions.

MOVPE growth of AlN/AlGaN heterostructures with high Al content

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Heterostructures on the base of AlGaN layers with high Al content are required for fabrication of emitters and detectors in UV range. We report on growth of such heterostructures by MOVPE technique and discuss the appearing problems.

The growth run has been realized in updated EPIQUIP growth system with a gas foil rotation of one 2-inch (0001) sapphire substrate. The growth rate, the position and thickness of the QW and roughness of the samples have been controlled by in situ multiwavelength reflectometry. The deposition was carried out at low pressure (30-60 mbar) and temperatures 1000-1050⁰C. First we deposited AlN buffer layer with thickness 50 - 200 nm, then a AlGaN layer or AlN/AlGaN multi-quantum well structure. X-ray diffraction data showed that the buffer layers grown without using the low-temperature nucleation have the best crystal quality. At low pressure we have not observed the homogeneous reaction between ammonia and metalloorganic compounds of Ga and Al, which results in appearing of parasitic white deposition on cool parts of the reactor. We have grown the thick samples with mirror like surfaces, the growth rates of AlN and AlGaN being 0.5 and 1,0 Å/sec respectively. The emission intensity of heterostructures with 40% content of Al was investigated using forth harmonic of Nd: YAG laser. At higher Al content we studied cathodoluminescence spectra. In best samples near band edge lines were dominated ones at room temperature spectra.

One of the problems with deposition of AlGaN with high Al content (destruction of graphite susceptor) was overcome using original low temperature deposition of SiC from methylsilane directly in the reactor. SiC stop up the surface pores and this made the susceptor high gas-proof. Deposition of SiC layer results in the increase of the susceptor work period and improve of the grown structure quality.

A set grown heterostructures were testing as solar-blind (250-290 nm) emitters and detectors.

Modeling of III-nitride Chemical Vapor Deposition

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Nowadays, Chemical Vapor Deposition (CVD) has become the major industrial technology for large scale manufacturing of a diverse range of semiconductor devices. In particular, Metal-Organic Vapor Phase Epitaxy (MOVPE) is used for the fabrication of semiconductor lasers and high-brightness Light Emitting Diodes (LED) that are of primary importance for optoelectronic applications. Chloride Vapor Phase Epitaxy (ChVPE) of GaN is a promising technique for growth of thick and quasi-bulk GaN epilayers. ChVPE combines high crystal growth rates with a low defectiveness, which makes it very attractive for industrial production of GaN substrates for III-nitride heterostructures.

A growing need to increase throughput, increase wafer size, reduce non-uniformity and cut down cost necessitates optimization of the deposition process in today's commercial reactors with respect to controllability of the growth. Practical achievement of these goals by trial-and-error method may be extremely time-consuming and expensive due to a variety of aspects that should be taken into consideration, working out a reliable set of operating parameters. Among them, one can note the formation of low and moderate temperature parasitic deposits on the reactor walls and constructive elements, limiting the process reproducibility. Enhanced temperatures commonly used to grow high quality III-nitrides activate a chemical mechanism that is not pronounced during the growth of arsenides and phosphides: desorption of volatile group-III species from the growth surface. Formation of complex molecules and particles in the gas-phase is known to be one of the key problems in growing of III-nitride compounds. This process results in material losses and lowers the precursor utilization efficiency. Poor intermixing of the precursors that results in thickness and quality non-uniformities of the epilayers is another problem specific primarily for ChVPE reactors.

The use of numerical modeling to study these processes can be considered as an effective alternative to the experimental procedure. A detailed simulation of transport phenomena in combination with advanced models of gas-phase kinetics and surface chemistry is a powerful tool for an analysis and optimization of the deposition process. The aim of the present contribution is to highlight some crucial points of the MOVPE and ChVPE technologies and to suggest explanations of different effects observed experimentally. We will present numerous examples on simulation of CVD processes for various materials systems and reactor types. From the results of modeling and analysis of experimental data, conclusions will be made on physical-chemical mechanisms underlying the observed trends in III-nitride CVD.

Technology of III-nitride materials and devices

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This presentation contains results of the investigations which were carried out at Ioffe Institute in the area of the technology of MOCVD growth of III-N compounds. Areas of the activity of Ioffe group are: development of growth methods of nanostructures in the system InGaN-AlGaIn-GaN such as short-period SL, quantum wells and quantum dots and nanostructure based LED, LD and HEMT structures.

For the fabrication of LED for solid state lighting development of the technology of the growth of structures, which allow passing current with high density and having high temperature stability of the parameters of emission is required. Applying of the nanostructures as active region of LD and LED leads to the possibility to realize following advantages: keep wavelength emission at lower average In content in the structure; small shift of the emission at increase of excitation; suppression of the carrier transport in the InGaIn layers due to 3D localization.

This paper represents the results of the investigations of the structural and optical properties of the InGaIn/GaN quantum dots formed during deposition of the ultrathin InGaIn layers in a GaIn matrix and device structures containing quantum dots in an active region of LEDs and LDs.

Formation of self-organized GaN dots on $\text{Al}_{0.11}\text{Ga}_{0.89}\text{N}$ by alternating supply of source precursors

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Self-organized GaN dot structure is successfully grown on a slightly lattice-mismatched $\text{Al}_{0.11}\text{Ga}_{0.89}\text{N}$ epilayer using flow-rate modulation epitaxy (FME) growth technique. From the variation of dot density with growth temperature, we can find the GaN dot growth here is controlled predominately by the surface diffusion of Ga adatoms for substrate temperatures below 915°C and by re-evaporation at higher temperatures. Because of the special alternating gas supply feature in FME, during the Ga source step it is the Ga metal depositing on the underlying $\text{Al}_{0.11}\text{Ga}_{0.89}\text{N}$ layer. Due to the large lattice mismatch 41.8% between Ga metal (4.15\AA) and $\text{Al}_{0.11}\text{Ga}_{0.89}\text{N}$ (3.18\AA). We believe the GaN dot growth in our study is mainly through the Volmer-Weber growth mode, not the commonly used the Stranski-Krastanow growth mode.

The thermodynamic model of nucleation mechanism at heteroepitaxial growth of GaN on sapphire

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There is a very great interest in our time for heterostructures on the basis of GaN. The GaN is perspective material to receive the optoelectronics and high frequency devices with unique characteristics. MOVPE is the main method for their fabrication on alien substrates. The thermodynamic model of nucleations GaN has been made.

The differences between physics and crystals characteristics of substrate and layer is determine energy barrier at nucleation. On the Gibbs ideas the equations for 2D and 3D nucleuses can be write in such form: $E_2 = \pi(V)^{4/3}(2\sigma_1 + \sigma_2 - \sigma_3)^2 / 2F$ and $E_3 = \pi(V)^2(2\sigma_1 + \sigma_2 - \sigma_3)^3 / 3F^2$, where $\sigma_{1, 2, 3}$ – free surface energy of GaN, heterojunction GaN/Al₂O₃, Al₂O₃ respectively; V – molles volume of crystal substance; F – thermodynamic supersaturation.

For the growth rate of nucleation can be write $I_i = I_i^0 \exp(-E_i/kT)$. I^0 connected with adsorbability of surface. The qualitative analysis has been carried out for realistic supersaturation at MOVPE.

For example the heteroepitaxial deposition with high velocity is energy advantage at high supersaturation and 3D –nucleation. The supersaturation in system is necessary definite change after coalescence and transitions 3D-2D. It is not easy in really process. However 3D-2D energy gap can be decrease with decreasing free surface energy of substrate by means of creator atomic layers AlN on Al₂O₃(0001). It is achieve by means of nitridation Al₂O₃ or deposition thin AlN on Al₂O₃ before epitaxyal growth GaN. In this case, the nucleation of GaN can to come to other mechanism.

This points have been confirmed at the research of nucleation GaN on Al₂O₃(0001) and quest optimum condition of it using MOCVD vertical reactor (D-180) with difference inlet TMGa and NH₃. The level FWHM-XRD 0.06-0.08° has been achieved at nitridation (60 sec.), obtaining atomic layers Al before nucleation layer Al_{0.05}Ga_{0.95}N (25-30 nm) and using Al_{0.15}Ga_{0.85}N(20A°)-GaN(20A°) – superlattice at initial stage high temperature growth.

Optical studies of InN and InGaN alloys

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We present the results of a systematic study of interband photoluminescence (PL) and absorption spectra, on hexagonal InN with different electron concentrations grown by MBE techniques on (0001) sapphire substrates [1]. The PL spectra were measured both at room and cryogenic temperatures; a set of lasers for the PL excitation in the energy range from 2.41 down to 0.81 eV was used. The lineshape dependence on the carrier concentration, temperature, excitation power and excitation energy has been investigated. The experimental findings were fitted and interpreted in the frame of a model that takes into account the Urbach tails of the conduction and valence bands and the acceptor states. Calculations of PL and absorption spectra have shown that the band gap of InN in the limit of zero temperature and zero electron concentration is close to 0.665-0.670 eV and the band gap shrinkage from zero to room temperature $E_g(0)-E_g(300)$ is 55-60 meV.

Resonant Raman scattering together with the absorption and PL studies was used to investigate the band gap of $\text{In}_x\text{Ga}_{1-x}\text{N}$ ($0.15 < x < 0.95$) alloys. Similar to InN, all $\text{In}_x\text{Ga}_{1-x}\text{N}$ alloy samples were found to have the PL bands due to recombination of free carriers and photoexcited holes. A considerable broadening of PL bands in alloys as compared with those in InN indicates essentially higher concentration of free carriers in $\text{In}_x\text{Ga}_{1-x}\text{N}$ samples. Several lines of Ar^+ and Kr^+ lasers in the range from 2.71 to 1.83 eV were used in Raman experiments. A strong resonant behavior of Raman scattering from LO-phonons in $\text{In}_x\text{Ga}_{1-x}\text{N}$ alloys at excitation near the interband absorption threshold was observed for the first time. A quasi-elastic approach has been developed to describe the resonant Raman cross sectional profile in the presence of a Burstein-Moss shift of the interband optical transitions. It has been shown that a simultaneous study of absorption, photoluminescence, and Raman spectra provides reliable information about the band gap, band gap bowing, and free carrier concentration of alloys. A value of 2.5 eV for the band gap bowing parameter obtained earlier in our studies of these alloys has been confirmed [2].

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Surface-plasmon-related effects in non-stoichiometrical InN

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Among III-nitrides, InN is a unique material which tends to stoichiometry violation during growth and precipitation of metallic nano-clusters. The phenomenon influence dramatically optical properties and seeming fundamental parameters of the compounds [1,2]. Plasmon-related resonances and coupling phenomena are possible within metal-enriched regions and near their surface. These effects complicate a study of the compound, however they make InN perspective for a set of important applications like efficient infrared light emitting and terahertz generation.

The main consequences of the non-stoichiometry are estimated using the approximation of the empirical nearest-neighbor tight binding theory. It is demonstrated that due to the strong difference in atomic orbital energies of nitrogen and indium, the 5-10% excess of atoms can significantly shift the InN optical gap as compared with a stoichiometrical value, with $N/In < 1$ and $N/In > 1$ corresponding to the lower and higher energy shifts, respectively. Good agreement with the experimental data is found for material with the optical gap above 1.2-1.3 eV. The reasons of the strong dispersion for the narrow-gap materials are discussed. It is also demonstrated that the non-stoichiometry can result in variation of electron effective masses in the 0.07-0.14 range and the high-frequency dielectric constant in the 6.7-10 range, which is well consistent with experimental data. Besides, the non-stoichiometry is likely a crucial reason of the high electron concentration in InN. The contribution of the latter, relevant to the Burstein-Moss effect, is analyzed.

Photoluminescence (PL) in InN demonstrates some unusual characteristics, such as a weak dependence on temperature and pressure, along with high resistance to irradiation. Our previous studies had shown that the emission is strongly enhanced in a vicinity of metallic indium nano-clusters, spontaneously formed within InN layers during growth [2]. The paper reports the results of studies of the state-of-art InN films without obvious massive metallic inclusions. Complicated nature of infrared luminescence and absorption in such films is revealed by comparative studies including thermally detected optical absorption, PL excitation and selective PL spectroscopy. Extremely sharp near-edge absorption peak, polarization and angular dependences of PL are suggestive of influence of surface plasmons on optical properties of narrow-gap InN. This phenomenon can enhance PL intensity and its radiation stability. The location of such plasmonic excitations, either in indium nano-clusters or in other metal-like regions, is discussed.

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One-dimensional nanoworld of group-III (Al, In, and Ga) nitrides – What makes them distinct from their film counterparts?

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I will present our work on the one-dimensional (1D) nanostructures such as nanowires, nanorods, nanobelts, nanocables and nanotips of Group-III (Al, Ga, In)-Nitrides. Such types of nanostructures are gaining considerable attention because of their highly anisotropic morphology and the natural confinement of electrons, holes and photons in these materials. Therefore, it is of value not only for academic interest but also for future technological development to fabricate the 1D nanostructures and investigate their properties that might be distinctive from their bulk or thin film counterparts. Briefly, these 1D nanostructures are single crystals of high quality in that their high-resolution transmission electron microscopic (HRTEM) images show nearly defect-free structures and their band edge emissions, as measured in photoluminescence (PL) peaks, are quite sharp and show very weak PL quenching in comparison to their counterparts in films. For instance, the InN nanobelts exhibit a PL peak position at ~ 0.76 eV with a full-width-half-maximum (FWHM) of 14 meV and the core-shell type InN@GaN nanocables have a PL FWHM of only 7 meV, the sharpest reported to date. Cathodoluminescence (CL) corroborated with HRTEM studies reveal that, upon ion implantation, these 1D nanostructures show enhanced dynamic annealing. Meanwhile, a hexagonal-to-cubic phase transformation in GaN nanowires, irradiated at a medium level of self-ion, has also been observed. Finally, a few examples of devices based on these 1D nanostructures including single-wire GaN and InN field-effect-transistors, AlN nanotips arrayed field-emission-diode and aligned GaN nanobridges super-photoconductors have been fabricated. The I-V characteristics of these devices and their implications will be discussed.

(The present work is in collaboration with the following five groups led by Kuei-Hsien Chen, Chia-Chun Chen, Chia-Fu Chen, Yang-Feng Chen and Gou-Chung Chi.)

Plasma-assisted and ammonia-based MBE growth of InN on sapphire

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The paper gives an overview of recent activity in molecular beam epitaxial (MBE) growth and characterization of InN epilayers on sapphire (0001), using plasma activation (PA) of N₂ gas and ammonia decomposition on growth surface. Thermodynamic consideration of InN growth by PA MBE in comparison with that of GaN is presented, explaining an extremely narrow range of growth parameters available for indium-droplet-free high-temperature deposition of InN. Importance of employing a proper nucleation layer for improving structural quality, residual stress accumulation in epitaxial InN films is addressed. Rigid limitations for InN growth parameters in ammonia-based MBE are shown to results from comparison of the input active nitrogen flux due to the ammonia decomposition, that reduces steeply with the growth temperature decrease below 550°C, and the output N flux due to the InN decomposition, that increases strongly at the temperature above 530°C.

The main impact is on the interplay between growth conditions and properties of InN epilayers grown by PA MBE atop a 0.7 micron-GaN(000-1) buffer layers on c-Al₂O₃ substrates. Growth monitoring using a reflection high energy electron diffraction (RHEED) and an optical laser reflectometry ($\lambda=660\text{nm}$) enables one to characterize *in-situ* the smoothness and sharpness of growth surfaces and interfaces on a scale from several monolayers to ~100nm, as well as to define growth rates and complex refractive indexes in the InN/GaN/Al₂O₃ system. The growth conditions (buffers, substrate temperature and In/N flux ratio) necessary to obtain the atomically smooth InN surface and continuous sharp InN/GaN interface are discussed. Optical properties in the IR-wavelength range and electrical properties of the InN epilayers having different stoichiometry are reported.

Commensurately Matched InN/AlN Heterojunction: Structure, Optical Properties, and Applications

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Because of their wide bandgaps, chemical stability, mechanical strength, and superior transport properties (high electron mobility, large electron drift velocity, and high breakdown voltage), group-III nitride heterostructures are promising materials for high-frequency, high-speed, and high-power electronic devices. To realize such applications, it is important to be able to grow group-III nitride heterostructures with high crystalline quality, atomically abrupt interfaces, and large band offsets. The heterojunction formed between InN and AlN is very interesting because of a huge bandgap difference (0.7 eV vs. 6.2 eV) and superior electron transport properties in InN. However, the large differences in lattice parameters (~12% for InN grown on AlN) and the lack of III-nitride substrates pose daunting challenges for growing high-quality InN/AlN heterostructures. We report here the growth and properties of commensurately matched InN/AlN heterojunction on Si(111) substrate by plasma-assisted molecular-beam epitaxy (PAMBE). By using the technique of *in situ* reflection high-energy electron diffraction (RHEED), we found that the pseudomorphic to commensurate lattice transition occurs within the first monolayer growth of InN on AlN. As a result, InN/AlN heterojunction can be made perfectly commensurate at the atomic level. Furthermore, very large heterojunction band offset and type-I band alignment were confirmed by X-ray photoelectron spectroscopy. Due to the excellent structural and electronic properties, we propose that the InN/AlN heterojunction technology can provide a platform for future device applications and for new functionality.

Developments of High Efficiency InGaN-Based Light-Emitting Diodes

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1. Introduction

The quest for environment friendly and energy saving technologies has propelled the advancement of light-emitting diodes (LEDs) for solid-state lighting. High efficiency LEDs, especially GaN-based white light LEDs, become the subject of intensive research worldwide. There have been various technologies tackling different aspects of the luminous properties of GaN-based LED proposed in the past few years. Increasing external quantum efficiency is naturally one of the most popular topics. Based on the same techniques for GaAs-based LEDs, GaN LEDs with improved efficiency were also demonstrated by surface roughening, chip shaping, microcavity formation, wafer bonding, and substrate patterning. However, the internal efficiency of GaN-based LEDs decreases markedly as the emission wavelength moves to ultraviolet (UV) range, i.e. 400 nm and shorter, where can be used to pump RGB phosphors for lighting purpose. This reduction of the internal quantum efficiency is believed to be associated with material-dependent luminescence mechanism. Besides, the performance of the Ni/Au semi-transparent conductive layer used in conventional LEDs is also wavelength-dependent and becomes an issue for high power UV LEDs. In this talk, we will present the results of our recent work on these issues, which are essential to achieve high efficiency UV LEDs.

2. Luminescence Properties

The luminescence efficiency of InGaN/GaN quantum well decreases with decreasing InN mole fraction when the emission wavelength is tuned toward ultraviolet range. This was attributed to two fundamental reasons, i.e. less localized effect due to less InGaN composition fluctuation and less carrier confinement due to lower band discontinuity. Although our recent study on 410 nm InGaN/GaN multi-quantum wells shows that bandedge emission indeed dominates over localized states at high current levels, it seems that growth parameter and material quality make a difference. To probe further on this topic, we characterize LEDs ($300 \times 300 \mu\text{m}^2$) in 400 nm and 470 nm, which correspond to different InN mole fractions in quantum wells. Tests on the electroluminescence (EL) integrated intensity of the 400 nm LED driven at various currents shows that the light output starts to saturate or degrade at a point depending on duty cycle of the driving current. The 470 nm device exhibits the same behavior. It can be concluded that thermal effect instead of carrier overflow effect dominates the luminescence efficiency at high current levels since this point moves to higher current levels when the duty cycle is decreased. More detailed characteristics can be observed from the external quantum efficiency at different current densities. It can be seen that before the thermal effect sets in, the dependence of external quantum efficiency on current density is different for these two devices. It might be related to the carrier confinement, defect density, and localized states in the active region. The implication of this result is twofold. One is the dominant luminescence mechanism for low and high In content quantum wells might be different. The other one is epilayer structure must be optimized for certain chip size and current density with adequate heat dissipation when designing large area LEDs for high flux output.

3. Chip processing

Due to the limited conductivity of p-type cap layer and n-type buffer layer in typical GaN-based LEDs, current crowding effect becomes significant as the chip size is increased.

Semitransparent ohmic contacts, such as Ni/Au, Pd/Au, and indium tin oxide (ITO), have been widely used to alleviate this problem. However, the reliability and transmittance of these contacts degrade when they are applied to high power large area UV LEDs. We proposed a p-side down tunneling junction LED structure for this reason. External quantum efficiency as high as 17 % was achieved without using any transparent contact layer. Although current crowding effect still exists in this device, it can be minimized by optimizing the growth and design of the n-type cap and bottom layers. Nonetheless, flip-chip scheme seems to be the most promising approach for high power LEDs. This approach is even more desirable for UV LEDs lighting source since better light extraction and heat dissipation can be achieved this way. A reflective p-type ohmic contact is therefore necessary for flip-chip LED. We have developed an Al-based reflective ohmic contact with about 75 % reflectivity at both 370 and 400 nm. It should be noted that proper layout design is still necessary to ensure uniform current spreading through the n-type layer.

4. Summary

We review recent work on the developments of InGaN-based LEDs regarding material characteristics and chip processing, which are essential to realize high power LEDs for solid-state lighting.

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Research and Development of GaN/AlGaN based High Frequency Transistors

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Design, processing technology of device fabrication, and characterization of the sub-0,25 μm – AlGaN/GaN-HEMT's grown by MOCVD on the sapphire substrates are presented. In the device fabrication we focused on optimization of the rapid thermal annealing of the Ohmic contacts, as well as on the optimization of the reactive ion etching gate recess, by using ECR-plasma system, and on the Ar-plasma etching of the mesa regions. Impact of Si₃N₄-passivation on the electron transport properties in the heterostructure and on the device characteristics has also been analysed. Additionally, we have investigated the insulating gate AlGaN/GaN-FET's, fabricated by incorporation of the thin Si₃N₄-dielectric layer under the gate electrode between the gate and the semiconductor. The multifinger device chips with the total gate width of 2mm were designed, fabricated and investigated. Static and dynamic characteristics of these devices in the frequency range at 12GHz are presented.

AlGaN based UV Metal-Semiconductor-Metal PhotodetectorsP.I.Kuznetzova and *S.V.Averine**

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Gallium Nitride and related ternary compounds has generated much interest for optoelectronic short wavelength device applications. We report on the growth, fabrication, characterization and analysis of high-speed AlGaN/GaN ultraviolet metal-semiconductor-metal (MSM) photodetectors.

We have elaborated the MOCVD growth technology of AlN, Al_xGa_{1-x}N layers with large Al content and MQW structures on their base. The growth run has been produced with a gas foil rotation on 2-inch (001) sapphire substrate at 1000-1050⁰C and under low pressure without the use of low-temperature nucleation. The growth rate and roughness of the samples and their thickness have been controlled in situ by multiwavelength reflectometry.

We have fabricated AlGaN based heterostructures of different thickness and alternation of active layers. We measured photoluminescence and transmission spectra as well as X-ray diffraction. These data confirm high degree of crystal perfection. Then the UV MSM-photodetectors have been fabricated and studied. The MSM-photodetector is a planar device consisting of two fork-shaped interdigitated contacts oppositely laying on the semiconductor surface. For our samples the diode fingers were defined by optical lithography and formed by evaporation and subsequent lift-off process of Ni and Mo. The finger width and spacing both are 2.8 μm and square active areas equal to 90x90 μm². Detectors demonstrate low dark current and high current responsivity in the range of 250-300 nm. The absence of low-temperature nucleation on a sample with AlN buffer layer results in smaller dark current (0.4 nA at 30 V bias) and larger UV/visible rejection. The dark current is qualified by simple thermionic emission below ~30 V after that the current is strongly dominated by significant tunneling component due to the Schottky barrier lowering at high fields. We have deduced a barrier height of 1.1 eV for Ni-AlGaN contacts and 1,4 eV for the sample with Mo-AlGaN contacts. The junction ideality coefficient is in the range of 1.1-1.24 demonstrating a good quality of the Schottky barriers in the AlGaN MSM-interdigitated contact system.

Two-dimensional self-consistent time-dependent simulation technique has been used to investigate electron-hole transport in the active region of GaN-based MSM-photodiodes and to analyse their high-speed response at different levels of optical illumination. Charge accumulation and screening of the dark electric field at high excitation levels gives rise to impulse response distortion and reduced bandwidth and efficiency. Some ways to improve the high-speed response are analysed. It is shown that GaN-based MSM-detectors have considerable advantages over the GaAs and InGaAs based devices in their ability to detect high energy levels of optical radiation without saturation and distortions. Analysis shows that the MSM-diode geometry can be optimized to provide the largest signal for the required speed of detector response.

GaN Technology and Applications in Taiwan

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GaN technologies in Taiwan are growing rapidly since 2000. Currently, there are over 100 GaN MOCVD reactors in Taiwan producing epitaxial wafers for LEDs. The LED revenue of Taiwan has reached \$4.75B or a 21.0% worldwide share in 2003 and ranked the second in the world. The technology development is currently driving toward improving the efficiency and reducing the cost of GaN light emitting devices for lighting applications.

Growth and Investigation of *n*-GaN/*p*-SiC heterojunction diodes

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In this work we report on the investigation of electrical characteristics of n-GaN/p-SiC heterojunction diode. The GaN epitaxial layer for this study was grown by hydride vapor phase epitaxy (HVPE) on commercial SiC substrate. The GaN layer was deposited directly on the SiC substrate without any buffer layer. The substrate was p-type 6H-SiC wafer with a doping level of $7.8 \times 10^{17} \text{ cm}^{-3}$. The GaN was undoped, with an unintentional doping causing a carrier concentration in the 10^{17} cm^{-3} region and the aluminum mole fraction was around 0.15. The thickness of n-GaN layer is about 0.8 microns. To investigate the electrical characteristics of the n-p heterojunction, mesastructures of 100, 200 and 1500 microns in diameter were fabricated by reactive ion etching. Ni ohmic contact was formed by vacuum thermal evaporation on the n-GaN layer and Ti/Al/Ni was used as a backside contact to p-SiC substrate. The diodes were characterized by current–voltage (I-V) and capacitance-voltage (C-V) measurements at room temperature.

The C-V measurements of GaN/SiC pn heterojunctions were done at frequencies of 1 kHz and 10 kHz and a $1/C^2$ vs. V plot linear dependence was observed for reverse bias up to 12V. The cut-off voltage was about 2.24 V at 1 kHz and about 2.28 at 10 kHz. This value is close to the built-in potential for n-GaN/p-SiC heterojunctions that have been reported in the literature. The I-V characteristics of the investigated samples exhibited a clear diode behavior.

The reverse voltage depends on diode area, increases with area decreasing and reach about 60 V for smallest diode area. Forward I-V characteristics at high current are non-linear and forward voltage drop also depends on diode area. At small forward current range ($10^{-9} - 3 \times 10^{-8}$ A) the current varies nearly exponentially with voltage: $I = I_0 \exp(qU/(nkT))$ and characterized by ideality coefficient *n* about 2.5 (curve 1) or 2 (curve 3). The *n* value higher than 2 is a sign of tunnel mechanism of the forward current.

Multi-layer AlN/Al_xGa_{1-x}N/GaN/Al_yGa_{1-y}N heterostructures grown by ammonia MBE for power microwave transistors

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III-Nitride based field effect transistors are known as the most suitable for X-band power amplifiers. We report on technology issues and DC-parameters of HFETs based on multilayer AlN/AlGa_xN/GaN/AlGa_yN heterostructures (MHS), grown by molecular beam epitaxy using ammonia. As compared with widely explored classic HEMT-like GaN/AlGa_xN heterostructures, this approach provides more efficient carriers confinement, excellent breakdown voltages and additional opportunities in device design, including back-doping etc.

Important, that due to high Al content in our MHS, substrate temperatures should be higher than usual and growth sequence should be respectively modified. By using adequate equipment (SemiTEq’s specialized MBE system EPN-3) and replacing classic thin nucleation layers with 0,2 μm-thick AlN grown at 1100°C, crystal quality and surface morphology of GaN-based heterostructures were essentially improved.

These AlN quasi-templates demonstrate streaky 2×2 RHEED pattern, step-like surface with root-mean-square (rms) roughness of few Å and ideally suit to initiate heterostructure growth. To improve crystal quality of GaN channel and to smooth GaN/AlGa_xN interface, intermediate Al_xGa_{1-x}N layers of average Al content $x \approx 0,5$ as well as strained superlattices (SLS) with graded Al content were used. As a result, undoped 1 μm-thick GaN layers demonstrate ω-scan (0002) reflex of 350” wide, and rms roughness of 15 Å.

In MHS intended for power transistors 1400 Å-thick GaN, capped with 250 Å Al_{0,3}Ga_{0,7}N, was grown. Both und- and modulation doped upper barriers were used. In such a structures 2DEG is formed with RT mobilities as high as 1450, 1350 and 1000 cm²/V·s for electron sheet concentrations 1,3·10¹³, 1,6·10¹³ and 2,0·10¹³ cm⁻² respectively. C-V profiling have confirmed excellent electron confinement in 2DEG, with background electron concentration in buffer layer in the mid of 10¹⁴ cm⁻³.

Test HFETs with 1×20 μm gates were processed, using RIE for mesa-isolation and electron beam evaporated metallizations. Drain current densities 1,0-1,2 A/mm and extrinsic transconductance of 180 mS/mm demonstrated are comparable to the best ones obtained on traditional HEMT-like devices.

Optical studies on the polarization fields and localization states in InGaN alloys

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The InGaN alloys have attracted much attention for the fabrication of green/blue light emitting diodes (LED), and laser diodes. This alloy possesses peculiar properties, such as polarization fields and localization states, which will affect the intensity and life time of light emission. In this talk we will present the studies of polarization field on InGaN quantum well (QW) diode structure by electroreflectance (electroabsorption). The polarization field induced quantum confined Stark effect on the QW will be demonstrated. The strength of polarization field in InGaN/GaN QW is found to be 2 MV/cm. While the polarization field is reduced to 0.21 MV/cm as the QW barrier layer (GaN) is replaced by the AlInGaN. This polarization field reduction is due to the contribution of spontaneous polarization in the quaternary barrier. We also present a photoluminescence (PL) studies on In rich InGaN epitaxy film. The PL measurements were performed at the temperatures ranging from 10K to 700K. The S-shape energy shift and anomalous linewidth (FWHM) were observed from the temperature dependent PL spectra. We explain this behavior as the evidence of localized states which might arise from the compositional fluctuation of InGaN alloy.

Modeling of III-nitride advanced semiconductor devices

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Due to direct bandgaps ranged from 0.7 to 6.2 eV, high breakdown voltage, and other unique physical properties, group-III nitrides have recently become basic materials for visible/ultra-violet (UV) optoelectronic and high-power electronic devices. However, the progress in the fabrication technology of these devices has leaved far behind a detailed understanding of their operation, generally invoking analogies with conventional III-V heterostructures. This is largely because of non-ordinary physical properties of nitride semiconductors, like spontaneous electric polarization, strong piezoeffect, extremely low efficiency of acceptor activation, and a high dislocation density inherent in epitaxial materials. In particular, huge polarization charges induced at the structure interfaces affect dramatically the device band diagram; III-nitride light-emitting diodes (LEDs) are known to operate effectively despite a high density of threading dislocations, etc. All these specific features hamper an intuitive design of the III-nitride devices. Thus, additional efforts are necessary to clarify physical aspects of the device operation.

This paper reviews recent developments in the bandgap engineering of advanced III-nitride devices in terms of numerical modeling. The focus is made on visible/UV LEDs and high-electron mobility transistors (HEMTs). The specificity of nitride materials is taken into account, including the polarization issues and dislocation effects on the device performance.

The carrier confinement, injection and recombination of non-equilibrium electrons and holes, light emission, I-V characteristic, and the internal quantum efficiency (IQE) of a number of LEDs with a single-quantum-well or a multiple-quantum-well active region are considered in detail. Special attention is paid to effects of the lateral current spreading in LED chips on their performance. We will also discuss new trends in design of LEDs on low-dislocation substrates, allowing a considerable improvement of their IQE. The technological factors, like indium surface segregation, are shown to affect remarkable the LED characteristics. The theoretical predictions are compared with available observations.

Recently ZnO/MgZnO and hybrid ZnO/AlGa_N LEDs have been suggested as promising UV light sources. In the paper, we discuss specific features of operation of these devices, related to a type-II band alignment and a particular distribution of the polarization charges at the structure interfaces. The use of such hybrid heterostructures provides additional freedom degree for bandgap engineering of advanced optoelectronic devices.

Both conventional single-heterostructure and double-heterostructure HEMTs are compared and factors limiting their performance are discussed. We consider two-dimensional electron and hole gas formation as a function of bias, the carrier transport in the channel, and the output static characteristics of the transistors, including transconductance. New types of device exploiting distributed polarization doping in the graded-composition materials are examined as well. The simulation results are compared with experimental data.

Finally, we will consider the importance of modeling for research and development of advanced III-nitride devices. Modern trends in the software design and availability of the specialized packages are discussed.