**Progress Report** DOE/ER/45604--T1

DOE Award No: DE-FG03-96ER45604
Period Covered: 04/01/97 - 05/31/98
Project Title: Optical and Electrical Properties of III-V Nitride Wide Bandgap Semiconductors
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## I. Summary of Progress

The objectives of this project were to investigate the optical and electrical properties of III-nitride wide bandgap semiconductors (GaN, InGaN, AlGaN) and quantum wells, to understand the fundamental optical transitions and impurity properties of these materials, to study the physics components of GaN-based devices, and to provide input for new approaches toward the improvement of materials quality and the optimization of device design. We were the first group to employ transport measurement techniques on the persistent photoconductivity (PPC) state to study the impurity properties of III-nitrides. We were also one of the few research groups in the world to employ picosecond **time-resolved** photoluminescence (PL) measurement technique to study mechanisms of optical transitions, LED emission, and lasing in GaN materials. During this funding period, we have investigated a variety of GaN samples and structures grown by MBE as well as by MOCVD. We have also made a significant progress in MOCVD GaN materials growth. Our accomplishments are summarized below:

1. *Effects of Deep Level Impurities in the AlGaN/GaN Heterostructures*

Photocurrent (PC) transient characteristics of an AlGaN/GaN heterostructure have been studied. We observed that the PC transients of the AlGaN/GaN heterostructure depended strongly on its history (initial conditions). Under a pulsed laser excitation, the PC responsivity, dark current level, and decay time constant all increase progressively with the number of successive excitation pulses and eventually saturate at constant values after about 30 pulsed laser exposures. Our results demonstrated that the observed PC transient characteristics are directly correlated with the effect of PPC caused by deep level impurities in the AlGaN barrier layer and can have a significant effect on the performance of UV photodetectors and transistors based on AlGaN/GaN heterostructures, including sensitivity, noise property, dark level, and response speed. The PC transient measurement also provides an effective method for investigating the deep level impurities in GaN materials.

2. *Materials Characterization of III-Nitride Alloys*

$In_xGa_{1-x}N$/GaN multiple quantum well (MQW) system is distinctively different from the better understood MQW systems such as GaAs/AlGaAs from the sense that the wells are formed by an alloy material. In additional to the well known effect of interface roughness in MQWs, alloy disorder in InGaN wells is expected to have a strong influence on their optical properties. Knowledge concerning the parameters which describe the degrees of interface roughness and alloy disorder in the InGaN/GaN MQW system is crucial for the improvement of the materials quality as well as to the device design. However, when both types of disorders are simultaneously present in the same system, direct methods for determining these parameters do not exist currently. Most recently, we have developed a method for determining the alloy disorder parameter and interface roughness parameter in $In_xGa_{1-x}N$/GaN MQWs, which can be applied to other MQW systems with wells being alloy materials. The method is based on fitting the low temperature PL emission

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roughness parameter in $In_xGa_{1-x}N$/GaN MQWs, which can be applied to other MQW systems with wells being alloy materials. The method is based on fitting the low temperature PL emission spectra to a formula derived by our group.

3. *Optical Studies of III-Nitride Epilayers and Quantum Wells*

i. Determination of optimum quantum well structures: Effects of well thickness and Si doping on the electronic properties of GaN/AlGaN and InGaN/GaN MQWs have been investigated. Our results have yielded that (i) the optical transitions in nominally undoped MQWs with narrow well thicknesses ($L_W < 40$ Å) are blue shifted with respect to the GaN epilayer due to quantum confinement, whereas no such blue shift is evident for the MQWs with well thicknesses larger than 40 Å, (ii) the exciton recombination lifetimes in MQWs of narrow well thicknesses increases linearly with temperature up to 60° K, which is a hallmark of radiative recombination in MQWs, and iii) Si-doping significantly improves the quality of MQWs of large well thicknesses ($L_W > 40$ Å).

ii. Origin of room temperature intrinsic transitions in GaN: We have investigated the mechanism of room temperature intrinsic transitions in high quality III-nitride epilayers. We found that the spontaneous emission peak position shifts toward the lower emission energies with excitation intensity, $I_{exc}$. More importantly, the red shift follows exactly the expression, $\Delta E \propto -I_{exc}^{1/3}$. This observation can only be explained by the energy bandgap renormalization due to free carrier screening and gives direct evidence for the band-to-band (or free electron - free hole) transition at room temperature. The immediate consequence of this result is that the electron-hole plasma is most likely responsible for lasing in nitride lasers because the band-to-band transition is the most dominant transition in high quality epilayers at room temperature. This conclusion is also consistent with our previous results on the surface emission properties of an InGaN epilayer grown on GaN under strong optical excitation. In InGaN/GaN heterostructure, the photoreflectance effect (reduction of index of refraction under high rate of carrier injection) was observed due to the formation of an electron-hole plasma state.

4. *Fabrication and Optical Studies of III-Nitride Microdisk Arrays*

We have fabricated the III-nitride microdisks by dry etching from GaN/AlGaN and InGaN/GaN multiple quantum well (MQW) structures. The optical properties of these microdisks have been studied. With respect to the original MQWs, strong enhancement of the emission intensity and lifetime of the intrinsic transitions and resonant optical modes have been observed in these microdisks. The intrinsic transition is excitonic at low temperatures and band-to-band at room temperature and exhibits an approximate 10-fold increase in both recombination lifetime and quantum efficiency upon formation of microdisks. This result implies a bright future for III-nitride micro-size optoelectronic devices, including microcavity lasers and vertical cavity surface emitting lasers (VCSELs).

5. *Materials Growth by MOCVD*

We have made rapid progress in GaN materials growth by MOCVD. As grown GaN films grown by our MOCVD system emit only the intrinsic free-exciton transitions with the room temperature electron concentration and mobility of $2 \times 10^{17}$ $cm^3$ and 470 $cm^2/Vs$. They can be doped n-type with Si and p-type with Mg. We have fabricated the first GaN n-i-p-i superlattice in our MOCVD system, which is design for the studies of Si and Mg impurity properties and their associated optical properties in GaN. We are working on further improvements in p-type doping by Mg and the growth of AlGaN alloys.

## II. Contributions to Education and Human Resources

Two graduate students are supported in part (half-time) by this project. They have acquired knowledge concerning optical and electrical properties of III-nitride wide bandgap semiconductors and basic techniques of materials characterization. Furthermore, they are also learning semiconductor materials growth by MOCVD. We believe that the DoE supported research project is able to train our graduate students to compete successfully in today's challenging technological world.

## III. Technology Transfer

We are collaborating very closely with many research groups working on III-nitride materials growth and device processing, including Sandia National Laboratory, National Renewable Energy Laboratory, Rockwell Science Center, Honeywell Technology Center, APA Optics, Prof. H. Morkoc (University of Illinois), and Prof. S. M. Bedair (North Carolina State University). As we hoped, our time-resolved PL results have provided them with valuable information for optimizing material growth conditions as well as device design.

## IV. List of Publications

We have disseminated our research results through publications in scientific journals. During the funding period (9/96 - current), we have published a total of 22 papers on GaN (15 papers marked with * sign have acknowledged the DoE support):


1. J. Z. Li, J. Y. Lin, and H. X. Jiang, "Nature of Mg Impurities in GaN," Appl. Phys. Lett., 69, 1474 (1996).
2. M. Smith, G. D. Chen, J. Y. Lin, H. X. Jiang, M. Asif Khan, and Q. Chen, "Time-Resolved Photoluminescence Studies of InGaN Epilayers," Appl. Phys. Lett., 69, 2837 (1996).
3. M. Smith, J. Y. Lin, and H. X. Jiang, "Optical Transitions in GaN/$Al_xGa_{1-x}N$ Multiple Quantum Wells Grown by Molecular Beam Epitaxy," Appl. Phys. Lett., 69, 2453 (1996).

*4. H. X. Jiang, J. Y. Lin, M. Asif Khan, Q. Chen, and J. W. Yang, "Surface Emission of $In_xGa_{1-x}N$ Epilayers Under Strong Optical Excitation," Appl. Phys. Lett. 70, 984 (1997).

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6. C. J. Sun, M. Zubair Anwar, Q. Chen, J. W. Yang, M. Asif Khan, M. S. Shur, A. D. Bykhovski, Z. Liliental-Weber, C. Kisielowski, M. Smith, J. Y. Lin, and H. X. Jiang, "Quantum Shift of Band-Edge Stimulated Emission in InGaN-GaN Multiple Quantum Well Light-Emitting Diodes," Appl. Phys. Lett. 70, 2978 (1997).

*7. M. Smith, J. Y. Lin, H. X. Jiang, A. Khan, Q. Chen, A. Salvador, A. Borchkarev, and H.Morkoc,"Exciton-Phonon Interactions in InGaN/GaN and GaN/AlGaN Multiple Quantum Wells," Appl. Phys. Lett. 70, 2882 (1997).

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*10. K. C. Zeng, J. Y. Lin, H. X. Jiang, A. Salvador, G. Popovici, H. Tang, W. Kim, and H. Morkoc, "Effects of Well Thickness and Si-Doping on the Optical Properties of

GaN/AlGaN Multiple Quantum Wells," Appl. Phys. Lett. 71, 1368 (1997).

*11. R. Mair, K. C. Zeng, J. Y. Lin, H. X. Jiang, B. Zhang, L. Dai, H. Tang, W. Kim, A. Botchkarevand, and H. Morkoc, "Optical Properties of GaN/AlGaN Multiple Quantum Well Micro-disks," Appl. Phys. Lett. 71, 2898 (1997).

*12. J. Z. Li, J. Y. Lin, H. X. Jiang, M. Asif Khan, and Q. Chen, "Two-Dimensional Electron Gas in AlGaN/GaN Heterostructure," J. Vac. & Sci. Tech. B15, 1117 (1997).

13. K. C. Zeng, M. Smith, J. Y. Lin, H. X. Jiang, J. C. Robert, E. L. Piner, F. G. McIntosh, S.M. Bedair, and J. Zavada, "Optical Transitions in InGaN/AlGaN Single Quantum Wells," J.Vac. & Sci. Tech. B15, 1139 (1997).

14. M. Smith, J. Y. Lin, H. X. Jiang, M. Khan, Q. Chen, A. Salvador, A. Borchkarev, and H. Morkoc, "Optical Transitions and Recombination Lifetimes in GaN and InGaN Epilayers, and InGaN/GaN and GaN/AlGaN Multiple Quantum Wells," Symposium Proceedings of Materials Research Society, Vol 449, 829 (1997).

*15. J. Z. Li, J. Y. Lin, H. X. Jiang, M. Khan, Q. Chen, A. Salvador, A. Borchkarev, and H. Morkoc, "Persistent Photoconductivity in p-Type GaN Epilayers and n-type AlGaN/GaN Heterostructures," Symposium Proceedings of Materials Research Society, Vol. 449, 537 (1997).

16. M. Smith, K. C. Zeng, J. Y. Lin, and H. X. Jiang, "Effects of Well Thickness on the Light Emission Properties in InGaN/GaN and GaN/AlGaN Multiple Quantum Wells," 1997 Digest of the LEOS Summer Topical Meeting on GaN Materials, Processing, and Devices, p31.

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*19. R. Mair, K. C. Zeng, J. Y. Lin, H. X. Jiang, B. Zhang, L. Dai, H. Tang, W. Kim, A. Botchkarevand, H. Morkoc, and M. Asif Khan, "Photoluminescence Properties of GaN/AlGaN Multiple Quantum Well Micro-disks," Symposium Proceedings of Materials Research Society, 482, 649 (1998).

*20. K. C. Zeng, M. Smith, J. Y. Lin, H. X. Jiang, H. Morkoc, and M. Asif Khan, "Optical Transitions and Dynamic Processes in III-Nitride Epilayers and Multiple Quantum Wells," Proceeding of the 24th International Symposium on Compound Semiconductors, 1997, in press.

*21. H. X. Jiang and J. Y. Lin, "Dynamics of Fundamental Optical transitions in GaN," Proceeding of Society of Photo-Optical Instrumentation Engineers (SPIE) Optoelectronics 1998 (invited), Vol 3277, 108 (1998).

*22. J. Z. Li, J. Y. Lin, H. X. Jiang, and M. A. Khan, "Effects of Persistent Photoconductivity on the Characteristic Performance of an AlGaN/GaN Heterostructure Ultraviolet Detector." Appl. Phys. Lett., June 1998, in press.

## V. **Other Support Obtained During the Funding Period**

"Streak Camera Instrumentation for Study Picosecond Optical Transitions and Carrier Dynamics in GaN," H. X. Jiang (P.I.) & J. Y. Lin, DoD, $147,142, 4/97- 3/98.

## Summary of Future Research

The specific goals for the next funding period are:

1. *Properties of $Al_xGa_{1-x}N$ Alloys*

Defect levels and formation energies, doping properties, and surface terminations, which are strong functions of the alloy composition, are not well understood for III-nitride alloys. Nevertheless, all nitride based devices must take advantage of quantum well and heterojunction structures such as GaN/AlGaN and InGaN/GaN and the tunability of the bandgap in the alloys, from InN (1.9 eV) to GaN (3.4 eV) and to AlN (6.2 eV). Additionally, due to the large band offset between AlGaN and GaN, the system of the two-dimensional electron gas (2DEG) in the AlGaN/GaN heterojunctions represents a novel structure for investigating fundamental physical properties, including piezoelectric effect, electronic transition between different sub-bands near the hetero-interface, and 2-D carrier scattering mechanisms.

We plan to investigate the transport properties of AlGaN as a function of the AlN composition. The native donor and Si donor activation energies and their associated deep level impurity properties will be studied. The critical AlN composition at which donors undergo a shallow-deep transition will be determined. The electron concentration and mobility as functions of AlN composition will be measured. The transport properties of the 2DEG system in the AlGaN/GaN heterostructures will be studied by varying the AlGaN layer thickness, the GaN space layer thickness, the AlN composition, and the doping concentration in the AlGaN barrier layer. From these studies, the electron mobilities in different quantum states near the interface and scattering mechanisms will be determined.

2. *Doping Properties*

Impurity doping in GaN remains one of the most important issues to be investigated. GaN and AlGaN n-i-p-i superlattices provides a unique system for investigating the properties of doped impurities and their related transitions in nitrides. We propose a systematic study of the effects that influence the optical and transport properties of these materials. Layer thicknesses, doping concentrations in the n- and p-type layers, alloy composition in AlGaN, and post-growth treatment conditions will be varied for the n-i-p-i structures. Issues to be addressed include n- and p-type doping in AlGaN alloys, defect energy levels, self-compensation, and the formation of deep level impurities.

3. *Optical Properties of III-Nitride Multiple Quantum Wells and Microstructures*

Recently, great successes toward stable and robust III-nitride lasers have been reported. The anticipated success of these edge-emission lasers is encouraging for the study of alternative laser geometries which offer several benefits over the edge-emitter. For instance, the microdisk cavity laser offers benefits over edge-emitters including the ability to create arrays of individually controllable lasers on a single chip, laser production without cleaving or edge-polishing, enhanced quantum efficiency, and a greatly reduced lasing threshold. Most recently, we have observed a large enhancement of the intrinsic transition lifetime and quantum efficiency relative to the as-grown MQW structure for the GaN/AlGaN MQW microdisks.

Our objective here is to develop a knowledge base for future optoelectronic devices based on III-nitrides, in particular for UV/blue microcavity lasers and VCSELs. We plan to focus on several key issues in the understanding of the III-nitride materials, which include (a) effects of

reduced volume and optical confinement on the optical emission properties and carrier dynamics in microcavities, (b) the variation of index of refraction with injection carrier density under high carrier injection rate, and (c) carrier dynamics and carrier-photon interactions in artificially constructed microcavities. In particular, we will investigate the optical properties of microdisks with sizes comparable to the emitted photon wavelengths, in which a strong coupling between carriers and photons (or excitons and photons) and new optical transition modes are expected. Coupled Maxwell equations and Poisson equation for these geometries will be studied to get a better understanding of possible optical modes in the disks. The results of our studies on carrier dynamics in these microcavities can provide essential information on the development of suitable material quality and device structure for many applications, in particular for blue/UV microcavity lasers and VCSELs.

In order to achieve these goals, an integrated effort is necessary to develop innovative approaches to synthesize high quality materials and to study the fundamental physics of III-nitride materials and microstructures. At the present, each of us receives support for 1/2 graduate student and 1/2 month summer salary from this project. We hope the level of support from this project can be increased to 1 graduate student and 1 month summer salary for each of us. We have summarized the proposed budget for the fiscal year of 1999 as follows:

*Proposed Budget Summary for Period 9/1/98 - 8/31/99*
Grant No: DE-FG03-96ER45604

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|---|---|---|---|
| 1. | Salaries and Fringe Benefits<br>(2 graduate students +<br>1 month summer salary for P.I.s) | | $ 54,150 |
| 2. | Travel | | $ 6,000 |
| 3. | Materials & Supplies | | $ 10,000 |
| 5. | Indirect Cost (47% of 1-3) | | $ 32,970 |
| | | Total | $ 103,120 |