REPORT DOCUMENTATION PAGE

AFRL-SR-AR-TR-03-

0372

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1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 2003	Final Technical (10/15/99-11/30/02)

4. TITLE AND SUBTITLE

"Uncooled RF Electronics for Airborne Radar"

5. FUNDING NUMBERS

F49620-00-1-0143

6. AUTHOR(S)

Dr. Umesh K. Mishra

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Department of Electrical & Computer Engineering
University of California
Santa Barbara, CA 93106-9560

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFOSR/PK
Attn: Wendy Veon
4015 Wilson Blvd., Rm. 713
Arlington, VA 22203-1954

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Improvements to the AlGaN/GaN HEMT device technology was studied at the epitaxial level by MOCVD, aimed at enhancing efficiency and linearity. A number of projects were performed under the program, including reducing the contact resistance, introducing a type of contacts that permits very short access regions, introducing hot electron launching into the channel, and double channel structures. Basic research in support of these projects was also performed, including studies of non-planar selective area growth, polarization effects in AlGaN/GaN heterostructures, and doping of GaN with Fe and oxygen.

14. SUBJECT TERMS

AlGaN, GaN, HEMTs, MOCVD

15. NUMBER OF PAGES 13

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Abstract

Improvements to the AlGaN/GaN HEMT device technology was studied at the epitaxial level by MOCVD, aimed at enhancing efficiency and linearity. A number of projects were performed under the program, including reducing the contact resistance, introducing a type of contacts that permits very short access regions, introducing hot electron launching into the channel, and double channel structures. Basic research in support of these projects was also performed, including studies of non-planar selective area growth, polarization effects in AlGaN/GaN heterostructures, and doping of GaN with Fe and oxygen.

1. INTRODUCTION

Under the program for uncooled RF power electronics *efficiency* was identified as one of the key parameters to optimize. The device technology under study was the AlGaN/GaN HEMT, which has demonstrated record power densities at microwave operation, but also exhibits several efficiency-lowering features: a large knee voltage, a 'soft' knee, and early onset of gain compression. While several mechanisms have been proposed to explain these features, we believe they are directly or indirectly related to the low-field source-gate region, where the low electron mobility is causing current choking in the on-state of the device.

Various research projects were performed under the program, with the ultimate goal of bringing the source-gate region into a high-field regime, thus improving important device properties including power added efficiency. These projects include reducing the length of the access region, reducing the source contact resistance, and introducing hot electron launching into the channel. The projects, and some of the research forming the basis of the projects, will be discussed in the remainder of this report.

2. NON-PLANAR SELECTIVE AREA GROWTH

Early in the program it was decided that selective area growth (SAG), with its design flexibility and potential for advanced structures, was an important tool with which to approach the source current choking problem. SAG is relatively well studied in the nitrides, in particular epitaxial lateral overgrowth for dislocation reduction. For SAG applications to AlGaN/GaN HEMTs however, a modification to the regular SAG technique, which we have called 'non-planar' SAG, is of more interest. Non-planar SAG involves a selective reactive ion etch into the device structure before the growth is commenced. The etch allows lateral contact between the regrown material and the device channel. Non-planar SAG behaves different from regular SAG, and at the start of the program, no detailed results on non-planar SAG of GaN had been published.

Processing techniques for sample preparation were first developed, and various regrowth mask materials were explored. SiO_2 was found to be the most practical mask material, while AlN was a viable alternative when reduced autodoping effects were desired.

Among the growth conditions explored, temperature had most impact on the growth results. For temperatures above 960°C, spontaneous mass-transport occurred, transporting GaN from unmasked bottom surfaces to the mask edges. The mass-transport phenomena and possible applications will be discussed in a later section. The mass-transport growth compromises the control of the material growth near the mask edge, which is the region of most importance for SAG applications to HEMTs. Based on this, it was decided that further work on non-planar SAG had to be performed at temperatures of 960°C or lower.

Throughout the program, numerous basic non-planar SAG experiments were performed with GaN and $Al_{0.1}Ga_{0.9}N$, studying the time-evolution of the growth profiles (see Figure 1), impurity incorporation and electrical properties, and Al-composition fluctuations for $Al_{0.1}Ga_{0.9}N$ growth, as a function of growth temperature and mask material. A paper based on the findings will be published shortly.

(S. Heikman, S. Keller, S. P. DenBaars, U. K. Mishra, F. Bertram, J. Christen *"Non-planar Selective Area Growth and Characterization of GaN and AlGaN"*, accepted for publication in Japanese Journal of Applied Physics, 2003)

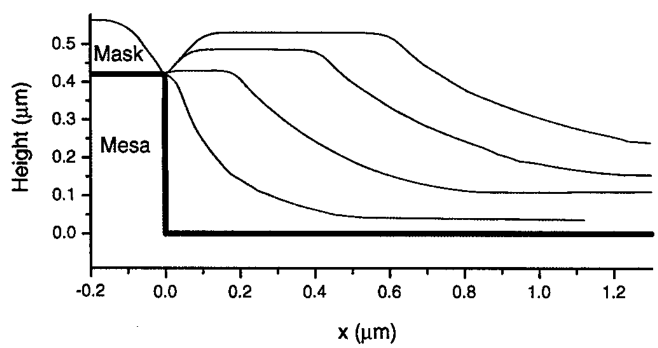

Figure 1. Time evolution of GaN non-planar selective area growth near a mask edge. The growth temperature was 960°C. Surface profiles were obtained by atomic force microscopy.

The developed regrowth technique was utilized in a device with the goal of increasing the electron velocity in the source-gate access region and under the gate. A bandgap discontinuity was introduced in the source-gate region, formed by non-planar SAG of a higher bandgap material in the source region (an example illustrated in Figure 2). Electrons entering the channel from the regrown source instantly gain velocity and become hot, and remain so until passing the gate, if the gate is short and placed close to the regrowth edge.

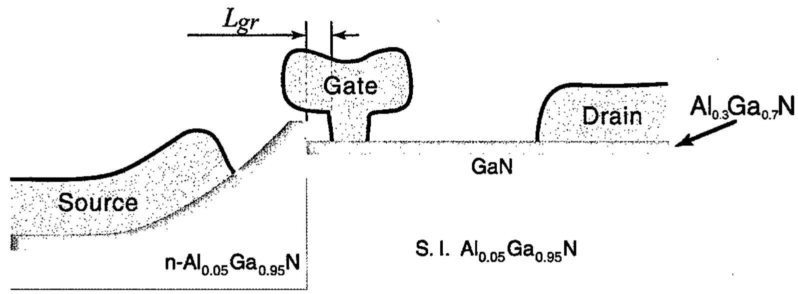

Figure 2. GaN channel HEMT with 5% AlGaN regrown source, for hot electron launching from source region into channel.

Various heterojunction source regrowths were performed: GaN regrowth on InGaN channel HEMTs, and AlGaN regrowth on regular GaN channel HEMTs. Variations in doping level, mask material, and cap layers were tried out. At the end of the program, the status of the project was as follows.

Signs of 2DEG degradation was found in the unetched material near the regrowth edge, varying in severity with the exact fabrication procedures. Some correlation was found between poor mask adhesion and 2DEG degradation, and the problem could to some extent be removed by improving the mask adhesion. With further work on the detailed sample preparation before regrowth, we believe the 2DEG degradation can be completely removed. The degraded 2DEG conductance near the source lead to an increased source access resistance. When characterizing devices with regrown source regions, the increased source access resistance was shown to have a negative impact on the desired device characteristics, thereby obscuring the benefits, if any, of the source-channel heterojunction. More details about these devices, and possible future directions, can be found in the Ph.D dissertation of Sten Heikman.

(S. Heikman "*MOCVD Growth Technologies for Applications in AlGaN/GaN High Electron Mobility Transistors*", dissertation, University of California Santa Barbara, September 2002)

3. MASS-TRANSPORT SELECTIVE AREA GROWTH

Annealing masked and etched samples in an ammonia atmosphere at temperatures above 960°C resulted in spontaneous mass-transport, which drastically affected the region near the mask. Figure 3 shows the results of ~1 min anneals performed at temperatures between 960°C and 1090°C. The driving force behind the mass-transport is the drive to minimize the surface energy of the system. At 960°C mass transport serves to smooth or roughen vertical facets, depending on the crystallographic orientation. This observation is significant for the growth of vertical heterojunctions and interfaces, as a smooth interface is typically desired. One situation when a smooth vertical regrowth interface is necessary is when the gate is closely aligned to the source regrowth region. At temperatures at or above normal growth temperature (~1050°C), mass transport rapidly moves material from unmasked bottom surfaces to sidewalls. This effect is undesirable when good control of the material deposited near the mask edge is needed, and effectively limits the growth temperature to less than 960°C for such applications.

The mass-transport effect can also be utilized, as a means to perform selective area growth without supplying an external gallium precursor, a technique that can potentially be performed in a simple ammonia annealing furnace. n+ GaN can be deposited along the edge of the unmasked region, in a wedge-shaped feature extending up to 2μm from the mask edge. Using this technique, ohmic contact formation by n+ GaN regrowth to AlGaN/GaN HEMTs was successfully demonstrated. The contacts exhibited a very smooth contact edge, and low contact resistances down to 0.23 ohm-mm for a $Al_{0.3}Ga_{0.7}N$/GaN heterostructure. More details of the process and the device results can be found in the publications below.

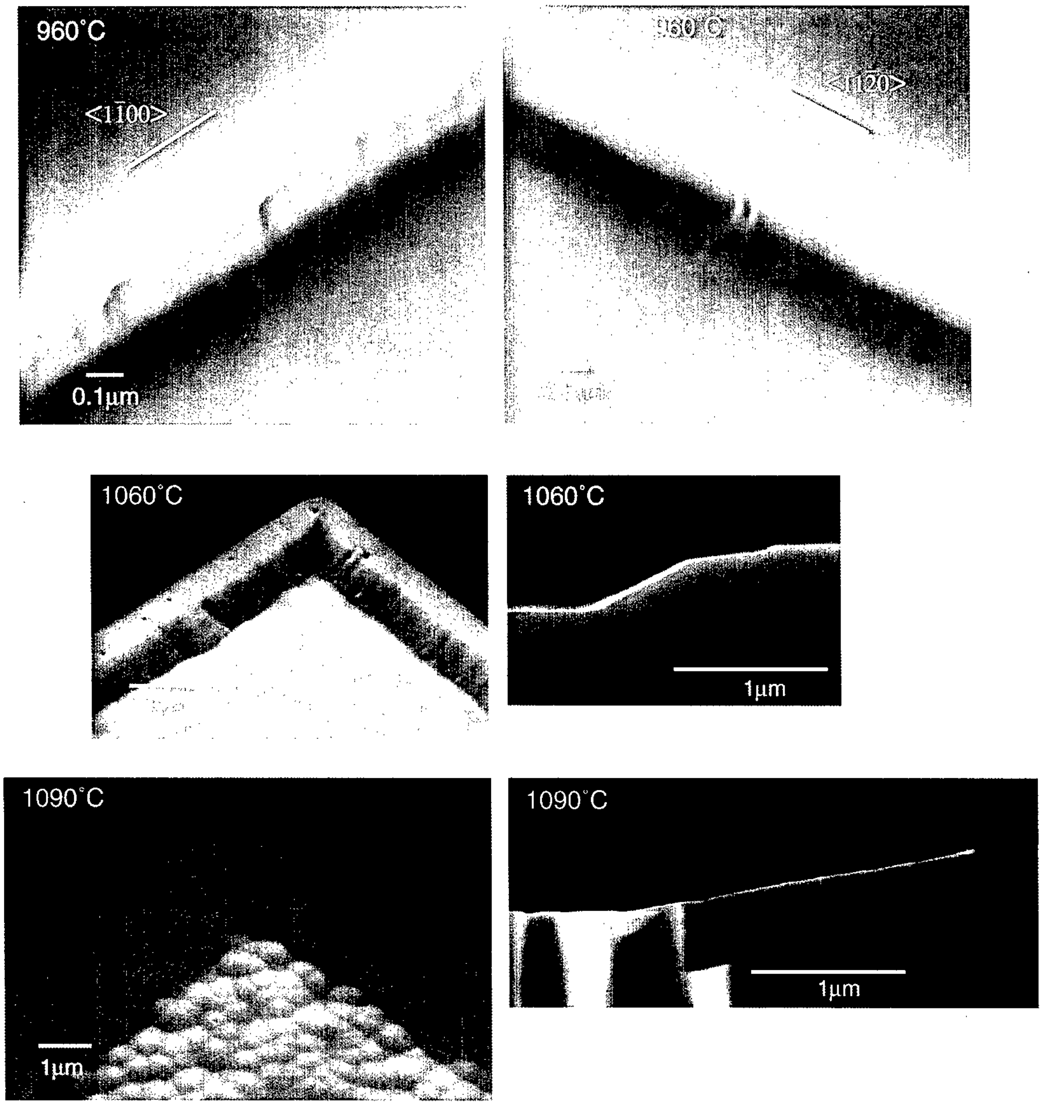

Figure 3. Annealing of masked and etched GaN samples in ammonia at three temperatures.

S. Heikman, S. P. DenBaars, and U. K. Mishra, "*Selective Area Mass Transport Regrowth of Gallium Nitride*" Jpn. J. Appl. Phys. **40**, 565 (2001)

S. Heikman, S. Keller, S. P. DenBaars, and U. K. Mishra, "*Mass Transport Regrowth of GaN for Ohmic Contacts to AlGaN/GaN*", Appl. Phys. Lett. **78**, 2876 (2001)

S. Heikman, S. Keller, B. Moran, R. Coffie, S. P. DenBaars, and U. K. Mishra, "*Mass Transport Regrowth of GaN for Ohmic Contacts to AlGaN/GaN*", Physica Status Solidi (a) **188**, 355 (2001)

4. GaN:Fe FOR SEMI-INSULATING BASE-LAYER

A reliable semi-insulating base-layer process is essential for MOCVD growth of HEMTs. A good semi-insulating buffer eliminates buffer leakage, which may otherwise lower the device efficiency, and it improves linearity. At the start of the program the state-of-the-art semi-insulating process on sapphire substrate relied on precisely controlled growth conditions, particularly the growth temperature, tailored to compensate donor impurities with increased dislocation densities and carbon incorporation. With the current level of maturity in nitride MOCVD technology, reactor conditions often drift, which makes processes such as the old semi-insulating process unstable.

In 2001 we demonstrated the use of Fe-doping in a very stable process for growth of semi-insulating GaN, and it has been part of our sapphire-based process since then. The Fe is introduced during the island coalescence stage of the growth, when high oxygen incorporation originating from the substrate is present. Fe is a deep acceptor in GaN, and it serves to compensate the shallow oxygen donor. With Fe doping, films can be rendered semi-insulating without compromising structural quality, since all growth parameters can be freely optimized to minimize the dislocation density. A 3 μm thick film, Fe doped during the first 0.3 μm of growth, showed a low field sheet resistance of 7×10^9 ohm/sq.

We found that Fe doping of GaN exhibits a slow turn-on and turn-off, as illustrated in Figure 4. This behavior is similar to that of Mg in GaN, where reactor memory effect in combination with Mg surface segregation is believed to cause the slow doping response. Through a series of growths characterized by SIMS, we showed that there is no memory effect involved in the growth of GaN:Fe, and that surface segregation is the dominant reason for the spread out doping profiles. More details of this study and general Fe-doping results can be found in the following two publications:

S. Heikman, S. Keller, S. P. DenBaars, and U. K. Mishra, "*Growth of Fe-doped semi-insulating GaN by metalorganic chemical vapor deposition*", Applied Physics Letters, vol. 81, no. 3, p. 439, 2002.

S. Heikman, S. Keller, T. Mates, S. P. DenBaars, and U. K. Mishra "*Growth and characteristics of Fe-doped GaN*", Journal of Crystal Growth, vol. 248, p. 513, 2003

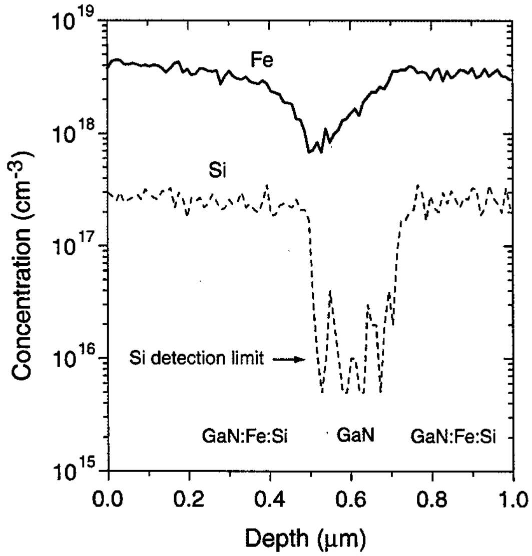

Figure 4. SIMS of Fe doped GaN, showing the slow Fe doping response.

5. POLARIZATION IN ALGAN/GAN AND GAN/ALGAN/GAN

A study of the polarization phenomena in GaN/AlGaN/GaN structures was performed partially funded under this AFOSR award. The study served to further our understanding of the interplay between free charge distribution, fixed polarization charge, and surface states. The influence of AlGaN and GaN cap layer thickness on Hall sheet carrier density and mobility was investigated for $Al_{0.32}Ga_{0.68}N$/GaN and GaN/$Al_{0.32}Ga_{0.68}N$ /GaN heterostructures deposited on sapphire substrates. The sheet carrier density was found to increase and saturate with the AlGaN layer thickness, while for the GaN-capped structures it decreased and saturated with the GaN cap layer thickness (illustrated in Figure 5). A relatively close fit was achieved between the measured data and 2-dimensional electron gas densities predicted from simulations of the band-diagrams. The simulations also indicated the presence of a 2-dimensional hole gas at the upper interface of GaN/AlGaN/GaN structures with sufficiently thick GaN cap layers. A surface Fermi-level pinning position of 1.7 eV for AlGaN and 0.9 - 1.0 eV for GaN, and an interface polarization charge density of 1.6×10^{13} - 1.7×10^{13} cm^{-2}, were extracted from the simulations.

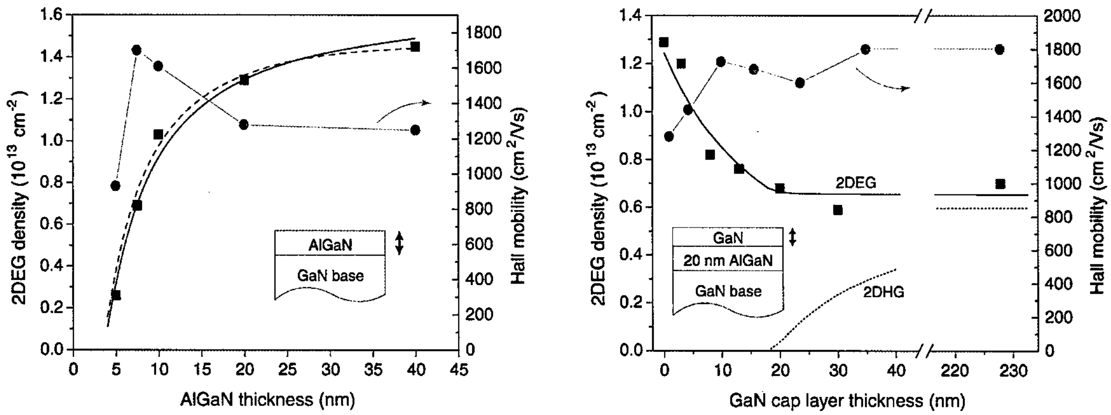

Figure 5. Annealing of masked and etched GaN samples in ammonia at three temperatures.

This work forms the basis for recent designs of AlGaN/GaN multiple channel heterostructures that can be implemented as double channel HEMTs. In these structures doping is utilized in conjunction with polarization effects to achieve high carrier mobility and high sheet carrier density in each channel, while maintaining a low energy barrier for majority carrier transfer between channels. By grading each GaN/AlGaN interface with negative polarization, and placing Si-doping in the graded region at a concentration equal to the polarization charge, the conduction band barrier between each channel can be lowered down to 0.06 eV. Figure 6 shows band diagrams and charge distribution of superlattices with and without optimum Si doping placement.

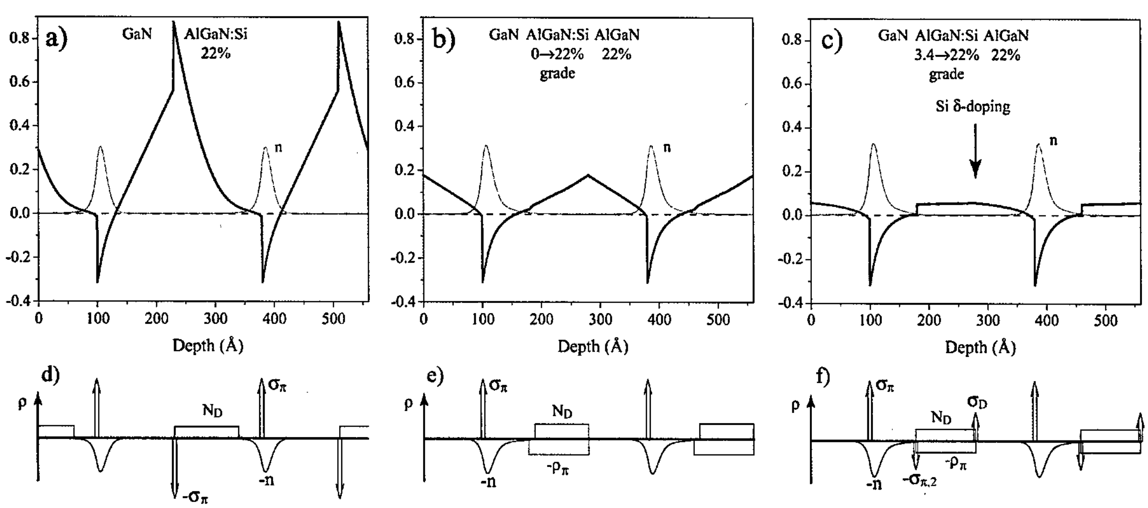

Figure 6. Band diagrams and charge distribution in modulation doped AlGaN/GaN superlattices. By proper placement of the Si doping, the conduction band barrier between channels can be minimized.

Using this design methodology, $Al_{0.35}Ga_{0.65}N$/GaN double channel heterostructures with sheet resistance down to 150 ohm/sq have been demonstrated. We believe that the use of double channels structures, in conjunction with gate recess technology, will enable tailoring of the source resistance in HEMTs, which will lead to enhanced linearity and efficiency. Further details can be found in:

S. Heikman, S. Keller, Y. Wu, J. S. Speck, S. P. DenBaars, and U. K. Mishra, "*Polarization Effects in AlGaN/GaN and GaN/AlGaN/GaN Heterostructures*", Journal of Applied Physics, vol. 93, no. 12, p. 10114, 2003

S. Heikman, S. Keller, D. S. Green, S. P. DenBaars, U. K. Mishra, "*High conductivity modulation doped AlGaN/GaN multiple channel heterostructures*", accepted for publication in Journal of Applied Physics, 2003.

6. OXYGEN DOPING OF GAN

Oxygen doping of GaN, as a means to reach higher n-type carrier concentrations than can be done with Si doping, was studied by MOCVD, using O_2 as precursor. Applications include n^+ contact layers for low resistance ohmic contacts.

The oxygen incorporation was strongly affected by the surface orientation of the film. At an O_2 partial pressure of 10 Pa, growth on a smooth (0001) GaN surface resulted in an oxygen concentration of 8×10^{16} cm^{-3}. However, the oxygen incorporation increased drastically to concentrations up to 3×10^{19} cm^{-3}, when the growth was performed on rough surfaces containing other crystal planes than (0001) GaN. Such surfaces include (0001) GaN with hexagonal pits, or the hexagonal islands formed during the initial stage of growth of GaN films on sapphire substrate. Furthermore, above a certain critical O_2 partial pressure, which depended on the growth temperature, oxygen itself caused a perturbation of the smooth GaN growth on (0001) surfaces, leading to the formation of hexagonal pits during growth (illustrated in Figure 7). The highest oxygen concentration attained during smooth growth was 3.5×10^{17} cm^{-3}. The results show that oxygen is not a suitable dopant for device quality n^+ (0001) GaN layers.

S. Heikman, S. Keller, S. P. DenBaars, and U. K. Mishra, "Oxygen doping of c-plane GaN by metalorganic chemical vapor deposition", *submitted to Physica Status Solidi, 2003*

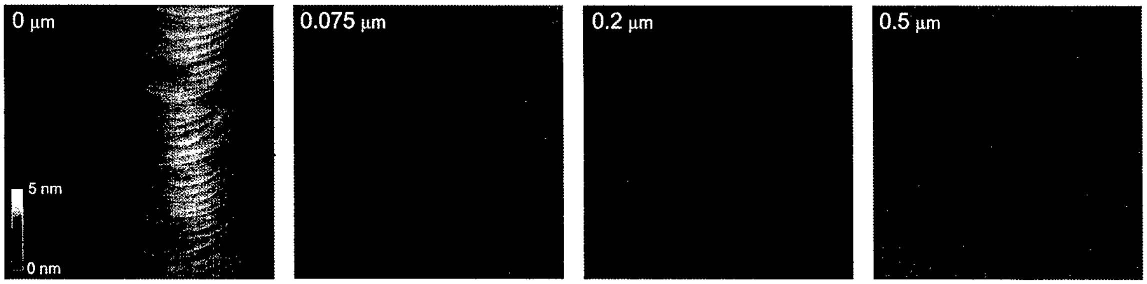

Figure 7. AFM images of samples with oxygen doped layer thicknesses between 0 and 0.5 μm, deposited at 990 °C with 10 Pa O_2 partial pressure. The oxygen doping caused the formation of hexagonal pits.

Publication List

S. Heikman, S. Keller, D. S. Green, S. P. DenBaars, U. K. Mishra, "High conductivity modulation doped AlGaN/GaN multiple channel heterostructures", *accepted for publication in Journal of Applied Physics,* 2003.

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S. Heikman, S. Keller, S. P. DenBaars, and U. K. Mishra, "Mass transport regrowth of GaN for ohmic contacts to AlGaN/GaN", *Applied Physics Letters*, vol. 78, no. 19, p. 2876, 2001.

S. Heikman, S. P. DenBaars, and U. K. Mishra, "Selective area mass transport regrowth of gallium nitride", *Japanese Journal of Applied Physics, Part 1*, vol. 40, no. 2A, p. 565, 2001.