High Voltage GaN Schottky Rectifiers

Gerard T. Dang, Anping P. Zhang, Fan Ren, *Senior Member, IEEE*, Xianan A. Cao,
Stephen J. Pearton, *Senior Member, IEEE*, Hyun Cho, Jung Han, Jenn-Inn Chyi, C.-M. Lee,
C.-C. Chuo, S. N. George Chu, and Robert G. Wilson

***Abstract*—Mesa and planar GaN Schottky diode rectifiers with reverse breakdown voltages (V_{RB}) up to 550 and >2000 V, respectively, have been fabricated. The on-state resistance, $R_{\rm ON}$, was 6 mΩ·cm^2 and 0.8 Ω cm^2, respectively, producing figure-of-merit values for $(V_{RB})^2/R_{\rm ON}$ in the range 5–48 MW·cm^{-2}. At low biases the reverse leakage current was proportional to the size of the rectifying contact perimeter, while at high biases the current was proportional to the area of this contact. These results suggest that at low reverse biases, the leakage is dominated by the surface component, while at higher biases the bulk component dominates. On-state voltages were 3.5 V for the 550 V diodes and ≥ 15 for the 2 kV diodes. Reverse recovery times were <0.2 μs for devices switched from a forward current density of ~ 500 A $\cdot$ cm^{-2} to a reverse bias of 100 V.**

***Index Terms*—GaN, power electronics, rectifiers.**

I. INTRODUCTION

WIDE bandgap diode rectifiers are attractive devices for a range of high power, high temperature applications, including solid-state drives for heavy motors, pulsed power for electric vehicles or ships, drive trains for electric automobiles and utilities transmission and distribution [1]. To date, most effort has been focussed on SiC and a full range of power devices including thyristors, insulated gate bipolar transistors, metal oxide semiconductor field effect transistors and pin and Schottky rectifiers, has been reported [2]–[13]. The GaN materials systems is also attractive for ultra high power electronic devices because of its wide bandgap and excellent transport properties [13], [14]. A potential disadvantage for thick, carrier-modulated devices is the low minority carrier lifetime, but for unipolar devices GaN has the potential for higher switching speed and larger standoff voltage than SiC. Efforts to fabricate high power GaN devices are in their infancy and there have been reports of simple Schottky rectifiers with reverse breakdown voltage (V_{RB}) in the range 350–450 V [15], [16]. While pin rectifiers would be expected to have larger blocking voltages, the Schottky rectifiers are attractive for their faster switching speed and lower forward voltage drop.

In this paper we report on the fabrication of mesa and planar GaN Schottky diode rectifiers. We have found that mesa structures formed by dry etching can have similar V_{RB} values to planar diodes provided the dry etch damage is removed by annealing or wet etch clean-up. The mesa diodes have lower specific on-resistances because ohmic contacts can be formed on a heavily doped GaN layer below the undoped standoff layer.

II. EXPERIMENTAL

Two different types of GaN were grown on c-plane sapphire substrates by metal organic chemical vapor deposition using trimethylgallium and ammonia as the precursors. For structures intended for vertical depletion, a 1 μm thick n$^+$ (3×10^{18} cm^{-3}, Si doped) contact layer was grown in a low temperature GaN buffer and then followed with either 4 or 11 μm of undoped ($n \sim 2 \times 10^{16}$ cm^{-3}) GaN. For structures intended for lateral depletion, a 3 μm thick resistive ($n < 10^{15}$ cm^{-3}) active region was grown on a low temperature buffer.

The mesas were formed by Cl$_2$/Ar inductively coupled plasma etching (300 W source power, 40 W rf chuck power, corresponding to a dc self-bias of -85 V) at a rate of 1100 Å$\cdot \mathrm{min}^{-1}$, using a photoresist mask. The samples were annealed at ~800 °C to remove dry etch damage [17]. Ohmic contacts were formed by lift-off of e-beam evaporated Ti/Al, subsequently annealed at 750 °C for 20 s under N$_2$. The rectifying contacts with diameter 60–1100 μm were formed by lift-off of e-beam evaporated Pt/Au.

On the lateral diodes, n$^+$ contact regions were formed by implantation of Si$^+$ followed by annealing at 1150°C for 10 s under N$_2$. The GaN was protected by a dielectric encapsulant during the annealing step. The ohmic and rectifying contacts were formed as described above. Schematics of the two different structures are shown in Fig. 1. The current–voltage (I–V) characteristics were recorded on a HP 4145A parameter analyzer.

III. RESULTS AND DISCUSSION

A. Mesa Diodes

A typical I–V characteristic for the 11 μm undoped depletion layer diodes is shown in Fig. 2. The V_{RB} for these devices was 550 V at 25 °C, with typical V_F's of 3–5 V (100 A$\cdot$ cm^{-2}). The specific on-resistance was in the range 6–10 m$\Omega\cdot$ cm^2, leading

---

Manuscript received August 20, 1999; revised November 2, 1999. The work at the University of Florida was supported in part the National Science Foundation under Grant DMR-9732865 (L. Hess) and by a DARPA/EPRI Grant (D. Radack/J. Melcher), MDA 972-98-1-006 monitored by ONR (J. C. Zolper). The work at National Central University was sponsored by the National Science Council of R.O.C. under Contract NSC-88-2215-E-008-012. The work of R. G. Wilson was supported in part by a grant from ARO (J. M. Zavada). The review of this paper was arranged by Editor A. S. Brown.

G. T. Dang, A. P. Zhang, and F. Ren are with the Department of Chemical Engineering, University of Florida, Gainesville, FL 32611 USA.

X. A. Cao, S. J. Pearton, and H. Cho are with the Department of Materials Science and Engineering, University of Florida, Gainesville, FL 32611 USA (e-mail: spear@mse.ufl.edu).

J. Han is with the Sandia National Laboratories, Albuquerque, NM 87185 USA.

J.-I. Chyi, C.-M. Lee, and C.-C. Chuo are with the Department of Electrical Engineering, National Central University, Chung-Li 32054, Taiwan, R.O.C.

S. N. G. Chu is with Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974 USA.

R. G. Wilson is a Consultant in Stevenson Ranch, CA 91381 USA.

Publisher Item Identifier S 0018-9383(00)02708-8.

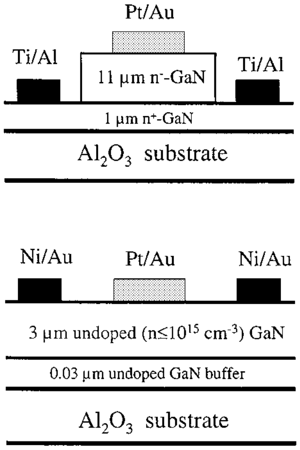

Fig. 1. Schematic of mesa and planar GaN diodes.

to a figure-of-merit $(V_{RB})^2/R_{\rm ON}$/ of 48 MW·cm^{-2}. The breakdown voltage is approximately a factor of three lower than the theoretical maximum value for this doping and thickness. Secondary ion mass spectrometry showed that the main background impurities present were O (9×10^{17} cm^{-3}), C ($\sim10^{17}$ cm^{-3}), Si (4×10^{17} cm^{-3}) and H (3×10^{18} cm^{-3}). While O and Si can produce shallow donor states, it is clear that these impurities have only fractional electrical activation. The surfaces of the material were relatively smooth with root-mean-square roughness of $\sim$0.2 nm (1×1 μm^2) and 1.5 nm (10×10 m^2). Cross-sectional transmission electron microscopy (TEM) views of the structure are shown in Fig. 3. The threading dislocation density at the top surface was $\sim10^8$-cm^{-2}, typical of high quality, heteroepitaxial GaN.

For the 4 μm thick active region structure, the room temperature V_{RB} was 356 V, with typical V_F's of 3–5 V (100 Å· cm^{-2}). The specific on-resistance of these devices was 28 mΩ· cm^2, leading to a value of $(V_{RB})^2/R_{\rm ON}$ of 42 MW·cm^{-2}. Fig. 4 shows a forward 3-V characteristic at 25 °C of one of these diodes. At biases just above the turn-on voltage, the ideality factor is 2 suggesting recombination. At slightly higher biases (4–4.5 V), the ideality factor is 1.5. This type of result has been reported previously in SiC diodes [6] and a multiple level recombination model involving the presence of both shallow and deep levels in the space charge region was developed to explain that data [18]. In our diodes, we used the linear part of the I–V curves to obtain the on-resistance. Once again the breakdown voltage was approximately a factor of three lower than the theoretical maximum value. In these diodes we observed a negative temperature coefficient for V_{RB}, with a value of -0.92 V·K^{-1} in the range 25–50 °C and 0.17 VK^{-1} in the range 50–150 °C. If impact ionization were the cause of breakdown, one would expect to observe a positive temperature coefficient for V_{RB}, as has been reported for GaN heterostructure field effect transistors and p$^+$pn$^+$diodes [19]–[21]. In analogy with some reports from some SiC Schottky diodes with negative V_{RB} temperature coefficients, we believe the breakdown mechanism in our diodes is defect-assisted tunnelling through surface or bulk states [10].

Fig. 5 shows the reverse current density in the 4 μm active layer diodes at a low bias (15 V) and a bias approximately half of V_{RB} (i.e., 150 V). For the low bias condition the current density scales as the perimeter/area ratio, while at the high bias condition the current density is constant with this ratio. This data indicates that at low biases the surface perimeter currents are the dominant contribution, while at higher biases the current

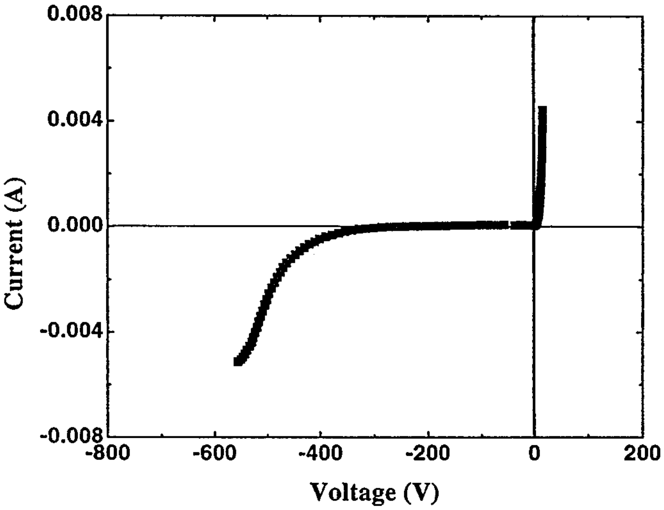

Fig. 2. I–V characteristic at 25 °C from mesa diode with 11 μm thick blocking layer.

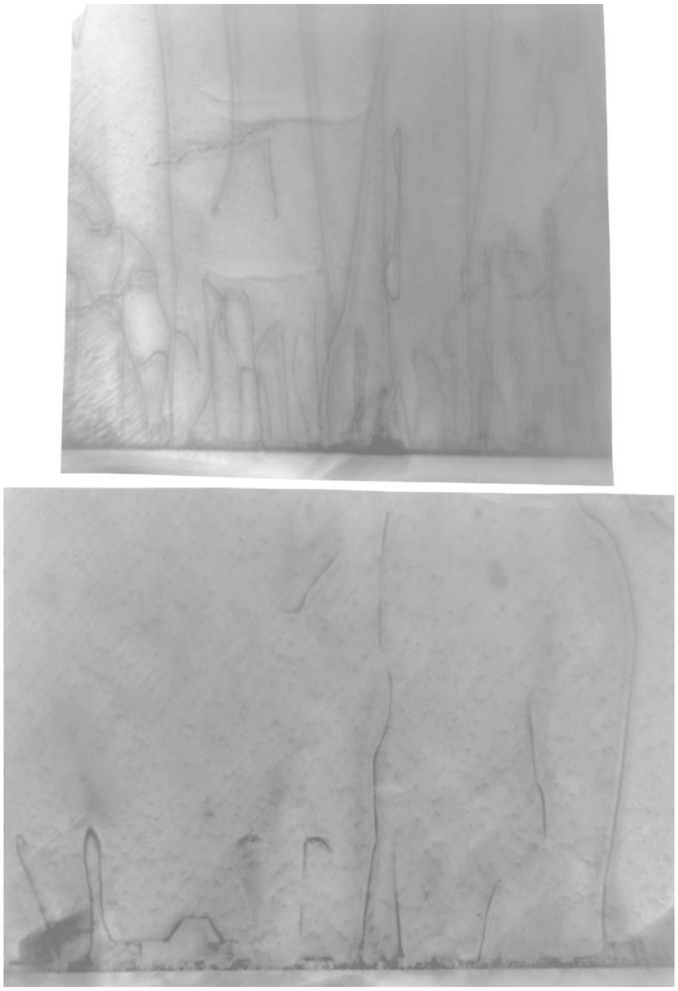

Fig. 3. TEM cross sections of the MOCVD-grown structure with 11 μm thick blocking layer.

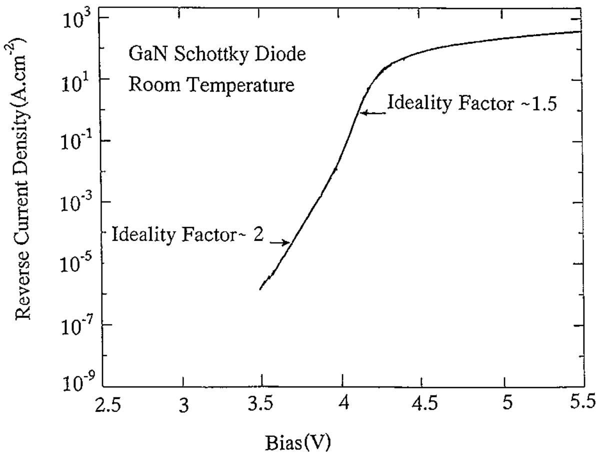

Fig. 4. Forward I–V characteristics at 25 °C from mesa diode with 11 μm thick blocking layer.

is proportional to contact area indicating that bulk leakage is dominant. In SiC devices it has been reported that increases in leakage current in the voltage range approximately half the V_{RB} of the diodes are due to the presence of this interfacial layer (typically as oxide) between the rectifying contact and the semiconductor. This oxide can sustain a voltage drop, but is thin enough for carrier tunnelling [6]. Fig. 6 shows reverse recovery current transient waveforms from a diode switched from a forward current density of 500 A·cm^{-2} to a reverse voltage of 100 V. The recovery time is ≤ 0.2 μs, similar to values reported for SiC rectifiers [6].

In all wide bandgap diode rectifiers (both SiC and the GaN reported here), the magnitude of the reverse leakage currents are generally one to two orders higher than the theoretical values based on image-force lowering of the Schottky barrier [6]. Our GaN diodes have slightly higher reverse leakage relative to SiC devices at the same biases, which probably reflects the earlier stage of maturity of the former.

B. Lateral, Planar Diodes

Fig. 7 shows a room temperature I–V characteristic from the 3 μm thick structure. The V_{RB} was >2000 V (the limit of our test setup), with a best V_F of 15 V (more typically 50–60 V). The specific on-resistance was 0.8 $\Omega \cdot \text{cm}^2$ producing a $(V_{RB})^2/R_{\text{ON}}$ value of >15 MW·cm^{-2}. For this structure we believe the depletion is lateral, because for the larger thickness and doping a vertical device would breakdown at 1000V. TEM cross-sections of the structure showed a threading dislocation density of $\sim 3 \times 10^8$ cm^{-2}, typical of high quality GaN of this thickness.

To place the results in context, Fig. 8 shows a plot of specific on-resistance for Schottky diode rectifiers as a function of breakdown voltage. The lines are theoretical values for Si, 4H–SiC, 6H–SiC and GaN and the points are experimental values for SiC and GaN devices [2]–[6], [10], [13], [15], [16]. Note that the 356 V and 2 kV diodes reported here essentially fit on the line expected for perfect Si devices, but the 550 V diode has clearly superior performance to Si. However there is still significant improvement required before GaN matches the reported performance of SiC Schottky rectifiers.

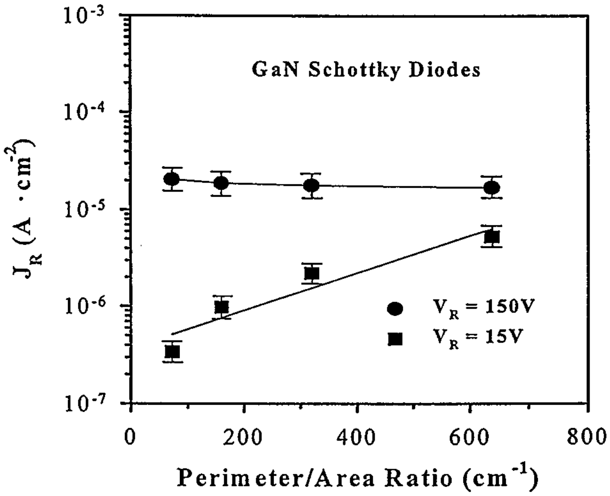

Fig. 5. Reverse current density in GaN mesa diodes (4 μm thick blocking layer) as a function of perimeter-to-area ratio, at two different reverse biases.

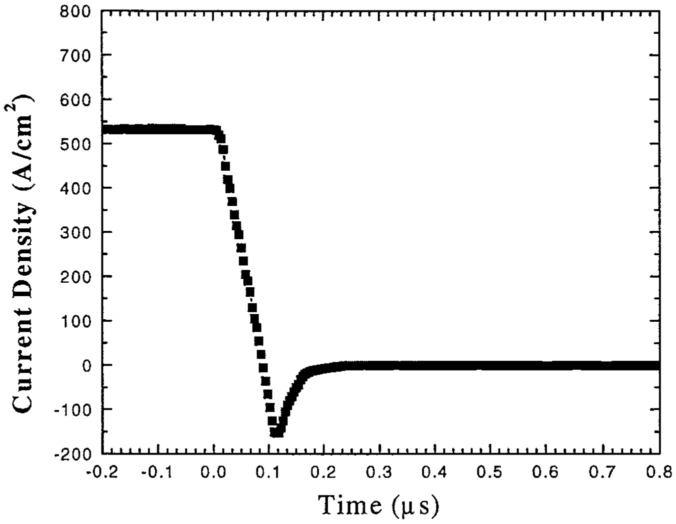

Fig. 6. Reverse recovery current transient waveform measured for GaN rectifier (550 μm diameter) at 25 °C. The device was switched from a forward current density of 500 A·cm^{-2} to a reverse voltage of 100 V.

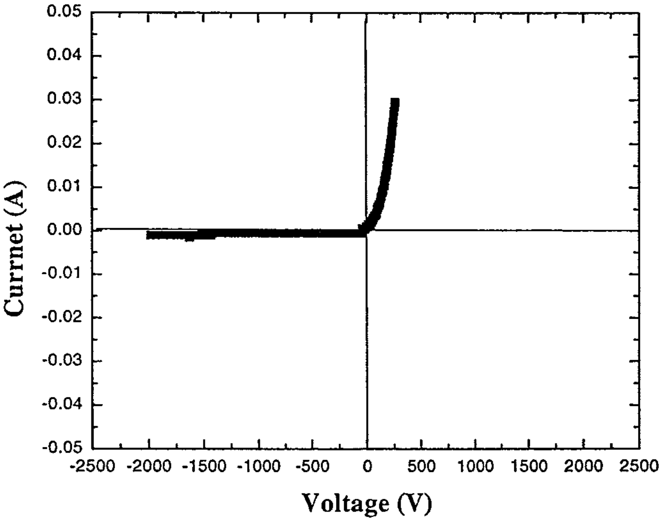

Fig. 7. I–V characteristic at 25 °C from planar diode with 3 μm thick blocking layer.

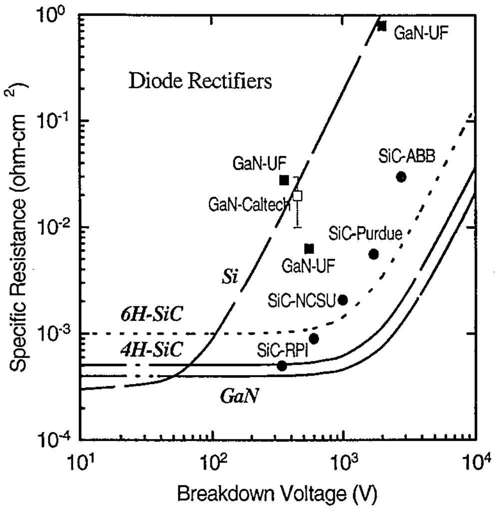

Fig. 8. Specific on-resistance versus blocking voltage for SiC and GaN Schottky diode rectifiers. The performance limits of Si, SiC, and GaN devices are shown by the solid lines.

IV. SUMMARY AND CONCLUSIONS

The main conclusions of our study can be summarized as follows.

1) Mesa diodes with V_{RB} equal to planar diodes, but with improved R_{ON} values, have been fabricated in GaN using $\mathrm{Cl_2/Ar}$ dry etching, followed by annealing to remove the plasma damage.
2) V_{RB} values up to 550 V with figure-of-merit 48 MW·cm^{-2} have been achieved on mesa diodes fabricated on thick (12 μm total) MOCVD GaN.
3) V_{RB} values >2 kV have been achieved in lateral diodes fabricated on resistive GaN grown by MOVCD.
4) For the mesa diodes, the V_{RB} values are approximately a factor of three lower than the theoretical maximum for GaN based on avalanche breakdown. Similarly, the reverse leakage currents are several orders of magnitude higher than the theoretical values.
5) At low reverse biases, the leakage current is dominated by contributions from the surface, while at higher biases bulk leakage dominates.

REFERENCES

[1] E. R. Brown, "Megawatt electronics," *Solid-State Electron.*, vol. 42, p. 2117, 1998.

[2] Q. Wahab *et al.*, "A 3kV Schottky barrier diode in 4H–SiC," *Appl. Phys. Lett.*, vol. 72, p. 445, 1998.

[3] K. J. Schoen, J. M. Woodall, J. A. Cooper, and M. R. Melloch, "Design considerations and experimental analysis of high voltage SiC Schottky barrier rectifiers," *IEEE Trans. Electron. Devices*, vol. 45, p. 1595, 1998.

[4] O. Kordina *et al.*, "A 4–5kV SiC rectifier," *Appl. Phys. Lett.*, vol. 67, p. 1561, 1995.

[5] R. Raghunthan, D. Alok, and B. J. Baliga, "High voltage 4H–SiC Schottky barrier diodes," *IEEE Electron. Device Lett.*, vol. 16, p. 226, 1995.

[6] V. Khemka, R. Patel, T. P. Chow, and R. J. Gutmann, "Design considerations and experimental analysis for SiC power rectifiers," *Solid-State Electron.*, vol. 43, p. 1998, 1999.

[7] M. Trivdei and K. Shenai, "Performance evaluation of high power, wide bandgap semiconductor rectifiers," *J. Appl. Phys.*, vol. 85, p. 6889, 1999.

[8] G. Kelner and M. Shur, "SiC electronics," in *Properties of SiC*, G. L. Harris, Ed. London, U.K.: INSPEC, IEE, 1995.

[9] B. J. Baliga, *Power Semiconductor Devices*. Boston, MA: ITP, 1996.

[10] C. I. Harris and A. O. Konstantinov, "Recent developments in SiC device research," *Phys. Scripta*, vol. T79, p. 27, 1999.

[11] J. N. Shenoy, M. R. Melloch, and J. A. Cooper Jr., "High voltage, double implanted power MOSFET's in 6H–SiC," *IEEE Electron. Device Lett.*, vol. 18, p. 93, 1997.

[12] J. B. Casady *et al.*, "4-H SiC power devices for use in power electronic motor control," *Solid-State Electron.*, vol. 42, p. 2165, 1998.

[13] C. E. Weitzel *et al.*, "SiC high power devices," *IEEE Trans. Electron Devices*, vol. 43, p. 1732, 1996.

[14] M. Shur, "GaN-based transistors for high power applications," *Solid-State Electron.*, vol. 42, p. 2131, 1998.

[15] Z. Z. Bandic *et al.*, "High voltage (450V) GaN Schottky rectifiers," *Appl. Phys. Lett.*, vol. 74, p. 1266, 1999.

[16] J.-I. Chyi *et al.*, "Growth and device performance of GaN Schottky rectifiers," *MRS Internet J. Nitride Semicond. Res.*, vol. 4, p. 8, 1999.

[17] X. A. Cao *et al.*, "Depth and thermal stability of dry etch damage in GaN," *Appl. Phys. Lett.*, vol. 75, p. 232, 1999.

[18] R. Patel *et al.*, "Phosphorus-implanted high-voltage 4H–SiC n$^+$p junction rectifiers," in *Int. Symp. Power Semiconductor Devices and ICs 1998*, Kyoto, Japan, 1998, pp. 387–390.

[19] N. Dyakonova *et al.*, "Temperature dependence of impact ionization in AlGaN–GaN HEMTs," *Appl. Phys. Lett.*, vol. 72, p. 2562, 1998.

[20] V. A. Dmitriev, K. G. Irvine, C. H. Carter Jr., N. I. Kuznetsov, and E. V. Kalinic, "Electric breakdown in GaN p-n junctions," *Appl. Phys. Lett.*, vol. 68, p. 229, 1996.

[21] A. Osinsky, M. S. Shur, and R. Gaska, "Temperature dependence of breakdown field in p-i-n GaN diodes," in *Proc. Materials Research Soc. Symp.*, vol. 512, 1998, p. 15.

Gerard T. Dang is a graduate student in the Chemical Engineering Department, University of Florida, Gainesville. He has published approximately 15 papers on GaN processing and device.

Anping Zhang is a Graduate Student in the Chemical Engineering Department, University of Florida, Gainesville. He has published approximately 15 papers on bipolar junction transistors and heterojunction bipolar transistors.

Fan Ren (SM'96) received the Ph.D. degree in 1991 from Brooklyn Polytechnic, Brooklyn, NY.

has been a Professor of Chemical Engineering at the University of Florida, Gainesville, since 1998. Prior to this, he spent 12 years at AT&T Bell laboratories (now Bell Labs, Lucent Technologies). He has published more than 300 journal papers on compound semiconductor electronics.

Dr. Ren is a Fellow of The Electrochemical Society.

Xianan Cao is a graduate student in the Materials Science and Engineering Department, University of Florida, Gainesville. He has published more than 25 papers on wide bandgap semiconductor technology.

Stephen Pearton (SM'93) received the Ph.D. degree in 1983 from the University of Tasmania, Australia.

He has been a Professor of Materials Science and Engineering, University of Florida, Gainesville, since 1994. Prior to this, he spent ten years at AT&T Bell Laboratories (now Bell Laboratories, Lucent Technologies). He has published more than 750 journal papers and given more than 100 invited talks at international conferences.

Dr. Pearton is a Fellow of The Electrochemical Society.

Hyun Cho received the Ph.D. degree in 1997 from Hanyang University, Korea.

He is a Post-doctoral Researcher in the Materials Science and Engineering Department, University of Florida, Gainesville. He has published more than 40 papers on dry etching of electronic and magnetic materials.

Jung Han received the Ph.D. degree in 1995 from Brown University, Providence, RI.

is a Senior Member of Technical Staff at Sandia National Laboratories, Albuquerque, NM. . His research interests include MOCVD growth of the AlGaInN system for optoelectronic devices such as UV LED's, quantum well detectors, and laser diodes.

Jenn-Inn Chyi is a Professor in the Department of Electrical Engineering, National Central University, Chung-Li, Taiwan, R.O.C. His research interests include the growth of compound semiconductors and their application to high speed electronics.

C.-M. Lee is a graduate student in the Department of Electrical Engineering, National Central University, Chung-Li, Taiwan, R.O.C. He has published several papers on the growth of GaN by MOCVD.

C.-C. Chuo is a graduate student in the Department of Electrical Engineering at the National Central University, Chung-Li, Taiwan, R.O.C. He has published several papers on growth of GaN device structures.

S. N. George Chu received the Ph.D. degree in 1980 from the University of Rochester, Rochester, NY.

He is a Distinguished Member of Technical Staff at Bell Laboratories, Lucent Technologies, Murray HIll, NJ, where he has been employed since 1980. He has published several hundred papers on characterization of compound semiconductor device structures.

Dr. Chu is a Fellow of the Electrochemical Society. Among several honors he has received is the 1999 Electronics Division Award of ECS.

Robert G. Wilson retired recently from Hughes Aircraft Company after more than 30 years in the fields of ion implantation and SIMS characterizations of semiconductors. He is currently consulting for Charles Evans and Associates.