# The Origins of Leaky Characteristics of Schottky Diodes on p-GaN

L. S. Yu, L. Jia, D. Qiao, S. S. Lau, J. Li, J. Y. Lin, and H. X. Jiang

***Abstract*—The possible origins of leaky characteristics of Schottky barrier on p-GaN have been investigated. The as-grown samples did not show any electrical activities using Hall measurements. Ni diodes made on as-activated samples, either at 950 °C for 5 s or at 750 °C for 5 min exhibited quasiohmic behavior. Upon sequential etching of the sample to remove a surface layer of 150 Å, 1200 Å, and 5000 Å from the sample, the $I$–$V$ behavior became rectifying. $I$–$V$–$T$ measurements showed that the slopes of the ln$I$–$V$ curves were independent of the temperature, indicative of a prominent component of carrier tunneling across the Schottky junction. $C$–$V$ measurements at each etch-depth indicated a decreasing acceptor concentration from the surface. The highly doped ($>1.7 \times 10^{19}$ cm$^{-3}$) and defective surface region (within the top 150 Å from surface) rendered the as-activated Schottky diodes quasiohmic in their $I$–$V$ characteristics. The leaky $I$–$V$ characteristics, often reported in the literature, was likely to be originated from the surface layer, which gives rise to carrier tunneling across the Schottky barrier. This highly doped/defective surface region, however, can play an important role in ohmic contact formation on p-GaN.**

***Index Terms*—Doping, p-GaN, Schottky barriers, surface, tunneling.**

## I. Introduction

P-TYPE GaN is an important semiconductor material for optical and electronic devices. Growth of p-GaN with sufficient hole concentrations has been difficult. Usually, hole concentrations of about $10^{17}$ cm$^{-3}$ can be achieved by activating the highly resistive as-grown samples doped with Mg at temperatures higher than 700 °C [1]–[5]. Due to the low hole concentrations (~$10^{17}$ cm$^{-3}$) and the high barrier height of metals on p-GaN [6] (>2.0 eV), a strong rectifying junction is expected for Schottky contacts on p-GaN. However, it is often observed that Schottky contacts on activated p-GaN usually exhibit leaky $I$–$V$ characteristics, rendering the measurement of Schottky barrier heights difficult using $I$–$V$ and $C$–$V$ methods [7]. As a result, very limited information on the barrier heights and acceptor concentrations obtained by the conventional $I$–$V$ and $C$–$V$ methods are available in the open literature [8], [9]. In this paper, the origins of large leakage currents of Schottky contacts on p-GaN was explored using sequential etching of surface region and temperature dependent current–voltage ($I$–$V$–$T$) and capacitance–voltage ($C$–$V$) measurements.

Three types of concentration were mentioned in this study: 1) Mg dopant concentration, 2) acceptor concentration, $N_A$, and 3) hole concentration, p. Mg atoms introduced into GaN during the MOCVD growth usually were passivated by the H atoms. This causes the Mg atoms to become inactive, rendering the as-grown p-GaN samples highly resistive. The total amount of Mg doped into GaN can be measured by secondary ion mass spectroscopy, SIMS. After annealing at temperatures higher than ~700 °C, certain amount of H atoms are released from the Mg-H complexes; Mg atoms, thus, become acceptors, $N_A$, which can provide holes. However, the hole concentration depends not only on the acceptor concentration, $N_A$, but also on the ionization energy, $E_A$, and the temperature. Due to the large ionization energy of Mg (~125–215 meV) [4], the hole concentration at room temperature is usually much smaller (~2 orders of magnitude) than the acceptor concentration. Using the temperature dependence of hole concentration measured by Hall effect, the average acceptor concentration of the entire p-layer can be deduced. $C$–$V$ measurement of Schottky diodes on p-GaN can provide the acceptor concentration at the edge of the depletion layer; thus, the depth profile of the acceptor concentration can be obtained by sequential etching and $C$–$V$ measurements.

## II. Experiment

Mg-doped GaN samples with a layer thickness of ~1.4 $\mu$m on a buffer layer of about 30 nm in thickness were grown on (0001) sapphire substrate using MOCVD. The Mg concentration was estimated to be ~$5 \times 10^{19}$ cm$^{-3}$ near the surface region and decreased to ~$2 \times 10^{19}$ cm$^{-3}$ using secondary ion mass spectroscopy performed on calibration samples grown in a similar fashion. The highly resistive as-grown samples were divided into two groups for activation. The first group was activated at 950 °C for 5 s and the other group at 750 °C for 5 min, both in flowing nitrogen ambient. After activation, the samples were characterized using the hot probe and Hall effect measurements (Van der Pauw configuration). The top view of the Schottky diodes and the ohmic contact bars is shown in Fig. 1(a). Ohmic contacts were made on the activated samples after cleaning in organic solvents, and lightly etched in a HF : HCl : $H_2O$ solution. The ohmic metallization consisting of a bilayer of Au/Ni (200 Å/200 Å)/p-GaN was deposited using e-gun evaporation, followed by annealing in air at 500 °C for 10 min [10]. Ni Schottky contact dots with a diameter of ~125 $\mu$m

Manuscript received August 1, 2002. This work was supported by BMDO (Dr. K. Wu) monitored by the U.S. Army Space and Strategic Defense Command, and by the OSD/ONR under the POLARIS MURI (Dr. C. Wood). The review of this paper was arranged by Editor C.-P. Lee.

L. S. Yu is with the Department of Electrical and Computer Engineering, University of California at San Diego, La Jolla, CA 92093 USA, on leave from Peking University, Peking, China (e-mail: lsyu@ece.ucsd.edu).

L. Jia, D. Qiao, and S. S. Lau are with the Department of Electrical and Computer Engineering, University of California at San Diego, La Jolla, CA 92093 USA.

J. Li, J. Y. Lin, and H. X. Jiang are with the Department of Physics, Kansas State University, Manhattan, KS 66506-2601 USA.

Digital Object Identifier 10.1109/TED.2002.808558

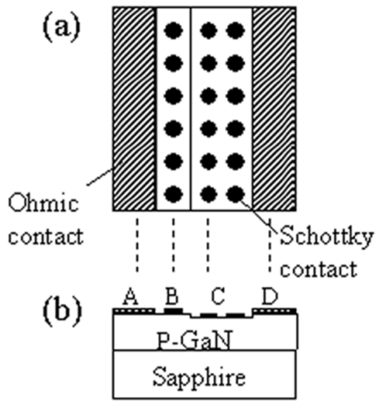


Fig. 1. Configuration of Schottky diodes (a) top view and (b) cross section of etched sample.

and a thickness of ~600 Å were made by e-gun evaporation on the samples after ohmic contact formation. The current–voltage ($I$–$V$), capacitance–voltage ($C$–$V$) and conductance–voltage ($G$–$V$) characteristics were measured with an HP4155A semiconductor parameter analyzer and an HP 4284A LCR meter in the parallel mode.

The Schottky diodes electrical behaviors were investigated repeatedly after sequential removal of the surface layer of the samples using reactive ion etching, RIE, with $CCl_2F_2$ as a gas source. After each electrical measurement, the Ni Schottky contacts were first removed using HCl and HF, followed by etching the GaN surface using RIE and the deposition of Ni Schottky contacts on the etched surface. The etch depth was measured with a profilometer (DEKTAK). The "hot probe" and $I$–$V$ behaviors showed that the sample remained p-type after each etching step. Fig. 1(b) shows the schematic side view of the sample after etching. Ni Schottky diodes were made in both etched and unetched portions of the sample. We used this structure to examine the possible surface leakage due to processing, as explained in the following section.

## III. Results and Discussion

### A. Temperature Dependence of the Hole Concentration

Fig. 2 shows the dependence of the hole concentration measured by Hall effect on the reciprocal of temperature for a sample activated at 750 °C for 5 min. Similar temperature dependence of the hole concentration was also obtained on samples activated at 950 °C for 5 s. This observation is in agreement with the theoretical prediction based on a hydrogen release model, [11] in that these two activation processes release similar amount of H from the sample and would lead to similar hole concentrations. Using a simple model with a single acceptor level, $E_A$, and a single compensating donor level, $E_D$, the acceptor concentration, $N_A$, and compensating donor concentration, $N_D$, as well as $E_A$ can be extracted by fitting the experimental data to the following equation [4], [12]:

$$\frac{p(p+N_D)}{N_A-N_D-p}=\frac{N_V}{g}\exp\left(-\frac{E_A}{kT}\right) \qquad (1)$$

where $T$ is the temperature, $k$ the Boltzmann constant, $g$ the acceptor degeneracy factor (assumed to be 4) and $N_V$ the effective

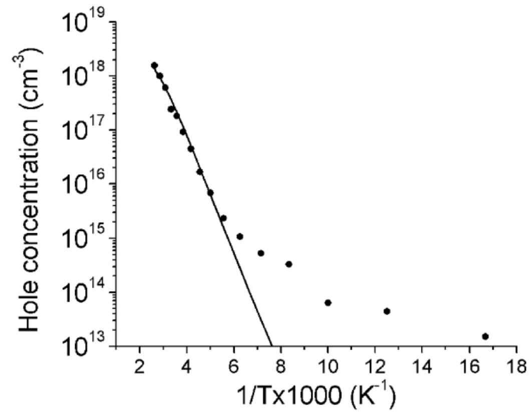


Fig. 2. Temperature dependence of hole concentration measured by Hall effect. The line was fitted to (1) using $E_A = 192$ meV, $N_A = 1.3 \times 10^{19}$ cm$^{-3}$, and $N_D = 1.2 \times 10^{18}$ cm$^{-3}$.

valence band density of states. The value of $N_V$ was calculated using the following equation:

$$N_V = 2(2\pi m_h^* kT)^{3/2}/h^3 \qquad (2)$$

where the effective mass of hole, $m_h^*$, was taken to be $2.2m_0^{13}$ and $h$ the Plank constant. $N_V$ was calculated to be $1.2 \times 10^{19}$ cm$^{-3}$ at room temperature using (2). An acceptor concentration of $1.3 \times 10^{19}$ cm$^{-3}$ and a compensating donor concentration, $N_D$, $1.2 \times 10^{18}$ cm$^{-3}$ were obtained by curve fitting the experimental results in the high temperature region shown in Fig. 2 to (1). An acceptor ionization energy, $E_A$, of 192 meV was also obtained by this curve fitting in agreement with reported results [4]. The compensation ratio $N_D/N_A$ was found to be ~0.092. This ratio was smaller, in general, than the reported values between 0.1 and 0.58 [4], [14], suggesting that our p-GaN samples were of reasonably good quality. At the low temperature region the hole concentration deviated from (1), suggesting that the transport was likely due to hopping or impurity-band conduction in highly doped semiconductors [2], [4].

### B. Schottky Barrier Behavior as a Function of Depth

Ni Schottky diodes were made on p-GaN samples activated both at 950 °C for 5 s and at 750 °C for 5 min. The current–voltage, $I$–$V$, characteristics of the Schottky diodes on both types of as-activated samples were quasiohmic. This observed nearly linear $I$–$V$ behavior can be due to junction leakage or surface lateral leakage or both. To examine the origin of the leaky $I$–$V$ behavior, electrical measurements were made on a specially designed sample structure. Fig. 1(b) shows a schematic diagram of such a sample, where ohmic contacts were made on the unetched surface, Ni Schottky diodes were made on both the etched (~150 Å removed) and unetched portions of the sample. Fig. 3 shows the $I$–$V$ behavior between various contacts. It can be seen that the $I$–$V$ curve was quasiohmic between ohmic contact D and Schottky contact B, both on unetched surface, but separated by an etched area. The $I$–$V$ curve between Schottky contact C (two rows of Ni Schottky diode on the etched surface) and contact D (ohmic) showed rectifying characteristics. This observation strongly

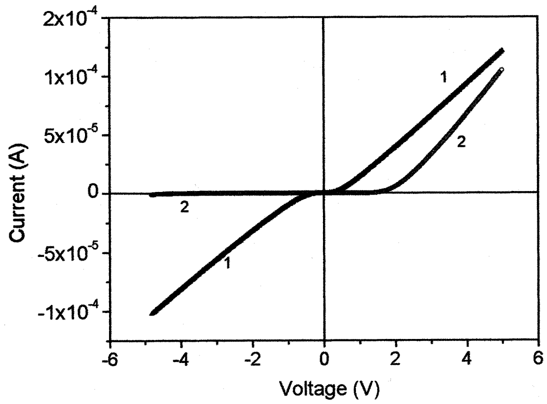


Fig. 3. Comparison of current–voltage characteristics at room temperature of Schottky diodes on unetched area between Schottky contact B and ohmic contact D, separated by an etched area (curve 1), and diodes on the surface with 150 Å removed by RIE between the Schottky contact C and the ohmic contact D (curve 2) (see Fig. 1).

suggested that the quasiohmic behavior was primarily due to junction leakage, and not a result of surface leakage shunting the Schottky diode.

The temperature dependence of the current–voltage behavior, $I$–$V$–$T$, was investigated at etch-depths of 150 Å, 1200 Å, and 5000 Å. Fig. 4 shows the $I$–$V$–$T$ characteristics for the diode at an etch-depth of 1200 Å. It can be seen that the $\ln I$ versus $V$ curves had about five decades of linear region, and that the curves measured at temperatures ranging between 24 °C and 140 °C were parallel. Similar results were also observed on samples etched to different depths, i.e., temperature independent slopes and deviation from linearity at higher voltages (>2 V) due to series resistance. This parallel behavior is in marked contrast to that predicted by the Schottky diode equation based on the thermionic emission model [12]

$$I = AA^*T^2 e^{-q\phi_b/kT}(e^{qV/nkT} - 1) \tag{3}$$

where $q\phi_b$ is the barrier height, $n$ the ideality factor, $A$ the device area, $A^*$ the effective Richardson constant, and $V$, $k$, $T$ have the usual meanings. The value of $A^*$can be calculated using $A^* = 4\pi q m^* k^2/h^3$. The thermionic emission model (3) predicts a $1/kT$ dependence of the linear region of the $\ln I$ versus $V$ curves, in contrast to the parallel slopes of the $\ln I \sim V$ curves, shown in Fig. 4. This parallel behavior of the $\ln I$–$V$ curves is commonly observed for carrier transport with a dominant tunnel component [12], [15]. It is more appropriate to analyze the $I$–$V$ characteristics using a tunneling model

$$I \sim AA^*Be^{-q\phi_b/E_{00}}e^{qV/E_{00}} \tag{4a}$$

$$E_{00} = q\hbar\,\sqrt{(N_A/m^*\varepsilon_s)}\Big/2 \tag{4b}$$

where $N_A$ is the acceptor concentration, $\varepsilon_s$ the dielectric constant of semiconductor, $B$ a parameter related to the temperature and the Fermi level in the semiconductor. The parameter $E_{00}$ is a characteristic energy related to the tunneling probability. The value of $E_{00}$ increases with the square root of $N_A$. The defect-assisted tunneling across the barrier would lead to an $E_{00}$ value larger than that calculated by (4b) based on acceptor concentration alone [15]. According to (4a), the slope of ln$I$–$V$ curves is independent of temperature. The parallel shifts of $I$–$V$ curves were due to the temperature-dependent pre-exponential factor, $B$. Furthermore, the slope of the $\ln I$ versus $V$ linear region yields the value of $E_{00}$. Based on the tunneling transport model and the experimental results, we deduced $E_{00}$ values of 0.20 eV, 0.11 eV, and 0.09 eV for samples etched to depths of 150 Å, 1200 Å, and 5000 Å, respectively. For $E_{00}$ values smaller than $kT$, the $I$–$V$ characteristics follow the thermionic emission model. However, the experimental values of $E_{00}$ were much larger than $kT$, suggesting the dominance of tunneling currents. The acceptor/defect concentration within the top 150 Å of the surface was much higher than that those measured at greater depths. The junction leakage of the unetched sample, therefore, appeared to correlate with a highly doped and/or highly defective surface layer, resulting in carrier transport by significant tunneling across a thin surface layer.

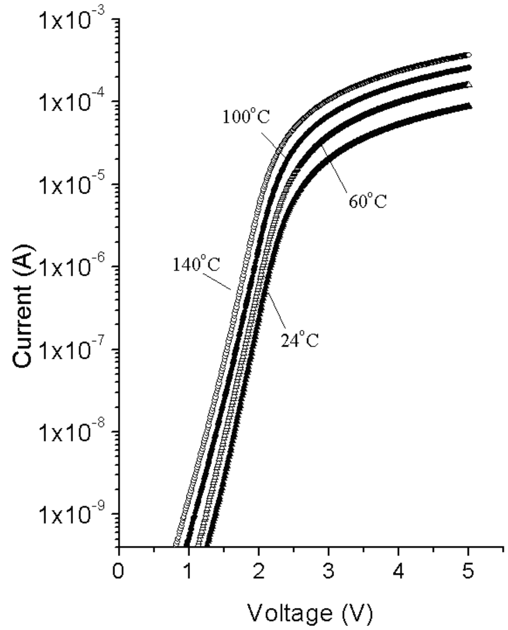


Fig. 4. Current–voltage characteristics in semi-logarithm scale of Schottky diodes at an etch-depth of 1200 Å.

### C. $C$–$V$ Measurement as a Function of Depth

$C$–$V$ measurements were made on the diodes at each depth to characterize the acceptor concentration. For a uniformly doped semiconductor, $1/C^2$ is linearly related to $V$ and is given by the following equation [12]:

$$\frac{1}{C^2} = \frac{2(V_{bi} - kT/q - V)}{A^2 q N_A \varepsilon_s} \tag{5}$$

where $V_{bi}$ is the built-in potential. The acceptor concentration and the flat band voltage can be deduced from the slope and the intercept of the $1/C^2$ versus $V$ plot, respectively. The equivalent circuit of a Schottky diode is shown in Fig. 5(a), where $C$ is the true junction capacitance, $G$ the junction conductance and $r_s$ the series resistance. Using the parallel mode of our $C$–$V$ measurement set-up, the equivalent circuit is shown in Fig. 5(b), where

TABLE I
SUMMARY OF RESULTS OBTAINED FROM $I$–$V$, $C$–$V$ AND HALL EFFECT MEASUREMENTS

| Etch-depth (Å) | 0 | 150 | 1200 | 5000 |
|---|---|---|---|---|
| I-V curves | Quasi-ohmic | rectifying | rectifying | rectifying |
| $N_A$ ($\times10^{19}$ $cm^{-3}$ from C-V)* | | 1.7±0.3 | 1.4±0.2 | 0.73±0.08 |
| $E_{00}$ (eV, calculated by eqn. 4b using $N_A$) | | 0.018 | 0.017 | 0.012 |
| $E_{00}$(eV, deduced from I-V) | | 0.20 | 0.11 | 0.09 |

*The acceptor concentration was obtained from C-V measurement at each-etch step. Hall effect measurement was also used to characterize the sample before etching. It was found that $N_A$~$1.3\times10^{19}$ $cm^{-3}$, $N_D$~$1.2\times10^{18}$ $cm^{-3}$, $E_A$~192 meV by curve fitting the temperature dependence of the Hall results (Fig. 2) to equation (1). The hole concentration was found to be $2.43\times10^{17}$ $cm^{-3}$ at room temperature.

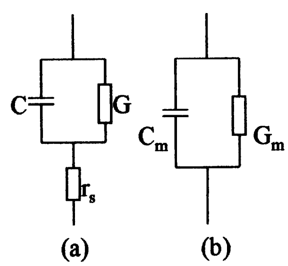


Fig. 5. Equivalent circuit of (a) Schottky diode and (b) the parallel mode of C–V measurement.

$C_m$ and $G_m$ are the measured capacitance and conductance, respectively. The following equations relate these quantities [16]:

$$C_m = \frac{C}{(1+r_sG)^2 + (2\pi f r_s C)^2} \tag{6a}$$

$$G_m = \frac{G(1+r_sG) + r_s(2\pi fC)^2}{(1+r_sG)^2 + (2\pi f r_s C)^2} \tag{6b}$$

where $f$ is the measurement frequency. For small values of $r_s$ and $G$ (small leakage at reverse bias) and at low frequencies $f$, $C = C_m$. In our case here, $r_s$ (~20 kΩ) and the leakage conductance (~1–5 $\times$ $10^{-5}\Omega^{-1}$) were both rather significant. The junction capacitance, $C$, as a function of voltage should be corrected using versus (6a) and (6b). The corrected $C^{-2}$ versus $V$ results for Schottky diodes at three different etch-depths are shown in Fig. 6. It can be seen that at a reverse bias ranging from 0 to $-5$ V the corrected $C^{-2} \sim V$ relationships slightly curved up. For large acceptor concentrations of about $10^{19}$ $cm^{-3}$ in the p-GaN, reverse biasing the diode from 0 to $-5$ V should only increase the depletion width by 100–200 Å (based on measurements of $d \sim \varepsilon/C$). For this reason, the acceptor concentration can be assumed to be rather constant within such a small distance. Using the quasilinear part from 0 to $-4$ Vwe obtained an acceptor concentration of (1.67±0.31) $\times$ $10^{19}$ $cm^{-3}$, (1.44±0.21) $\times$ $10^{19}$ $cm^{-3}$ and (0.73±0.08) $\times$ $10^{19}$ $cm^{-3}$at

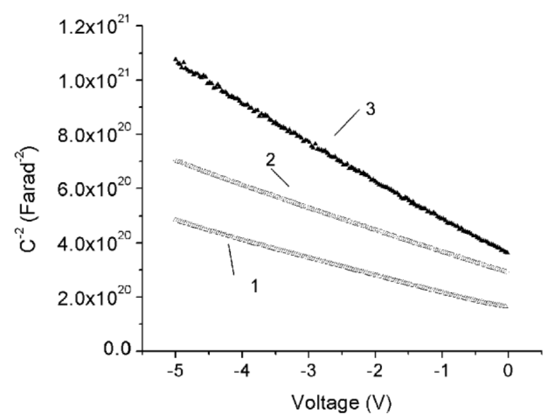


Fig. 6. Typical capacitance and voltage characteristics of Schottky diodes at an etch-depth of 150 Å (curve 1), 1200 Å (curve 2), and 5000 Å (curve 3). The measurement frequency was 100 kHz.

depths of 150 Å, 1200 Å, and 5000 Å, respectively. These concentrations were the average values obtained from seven diodes at each depth, and in reasonable agreement with the $N_A$ value concentration obtained by curve-fitting Hall effect results for the entire p-GaN layer to (1) showed in Table I. It is well known that RIE can cause surface damage during etching, thus creating surface states and modifying the Schottky barrier height [17], [18]. The apparent barrier heights were extracted from $C$–$V$ measurements, yielding values of 2.44 eV, 3.57 eV, and 2.53 eV for curve, 1, 2, and 3 in Fig . 6, respectively. While these values were in general agreement with the expected barrier height 2.5 eV of Ni/p-GaN, however, the barrier height may have been modified by the processing dependent surface states [17], [18]. On the other hand, acceptor concentrations can still be deduced by $C$–$V$ measurements at the edge of depletion region at reverse bias. For the case of Ni Schottky diodes on p-GaN with acceptor concentrations of around 1–2 $\times$ $10^{19}$ $cm^{-3}$, the depletion width was estimated to be about 200 Å, much larger than the penetration depth of the ions into the sample during our RIE condition, estimated to be ~20–50 Å using the TRIM 2000 code simulation [19], [20] at a plasma potential of 180 V. The acceptor concentrations can, therefore, be extracted from $C$–$V$ measurements with reasonable accuracy to a depth region of ~200 to 400 Å from the surface, with reverse bias ranging between 0 and 5 V. RIE etching of the samples did not appear to affect the use of $C$–$V$ measurements for the determination of acceptor concentrations. Based on the acceptor concentration obtained by $C$–$V$ measurements at each depth, $E_{00}$ values of 0.018 eV, 0.017 eV, and 0.012 eV were obtained using (5). These values of $E_{00}$ based on $N_A$, obtained by $C$–$V$ measurements, however, were 6 to 11 times smaller than those obtained from $I$–$V$–$T$ measurements, suggesting that the $I$–$V$ behavior was significantly affected by the defect-assisted tunneling [15]. These differences in $E_{00}$ suggested that surface damage may have occurred due to RIE, which increased the carrier tunneling probability. The results obtained from $C$–$V$, $I$–$V$–$T$ and Hall effect are summarized in Table I. Both the high value of acceptor concentration obtained by the $C$–$V$ measurements, and the high value of $E_{00}$obtained by $I$–$V$–$T$ measurements in the surface region strongly suggested that the leaky quasiohmic $I$–$V$ behavior of the Ni Schottky diodes on as-activated p-GaN layers is primarily due to a highly doped/defective surface layer.

## IV. Summary

The origins of the leaky characteristics of Schottky barrier on p-GaN grown by MOCVD were investigated. The as-grown samples did not show any electrical activities using Hall measurements. Ni Schottky diodes made on activated the p-GaN layer showed quasiohmic behavior. Upon sequential etching of the sample to remove a layer of ~150 Å to 5000 Å of GaN from the sample surface, the Schottky diodes became rectifying. The temperature dependence of the $I$–$V$ curves suggested a transport mechanism primarily due to tunneling of carriers to an etch depth of at least 5000 Å from the surface. Capacitance–voltage measurements indicated an acceptor concentration of $>1.7 \times 10^{19}$ cm$^{-3}$ within the top ~150 Å from the surface and decreased to ~$7.3 \times 10^{18}$ cm$^{-3}$ to a depth of ~5000 Å. Based on these experimental results, the leaky $I$–$V$ characteristics, commonly reported in the literature, was likely due to a highly doped and/or highly defective surface layer, resulting in carrier transport by tunneling across the Schottky barrier.


## Acknowledgment

The authors would thank Dr. R. Liu at UCSD for assistance.


## References


[1] S. Nakamura, N. Iwasa, M. Senoh, and T. Mukai, "Hole compensation mechanism of p-type GaN films," *Jpn. J. Appl. Phys.*, vol. 31, pp. 1258–1266, 1992.

[2] W. Gotz, N. M. Johnson, J. Walker, D. P. Bour, and R. A. Street, "Activation of acceptors in Mg-doped GaN grown by metalorganic chemical vapor deposition," *Appl. Phys. Lett.*, vol. 68, pp. 667–669, 1996.

[3] U. Kaufmann, P. Schlotter, H. Obloh, K. Kohler, and M. Maier, "Hole conductivity and compensation in epitaxial GaN : Mg layers," *Phys. Rev.*, vol. B 62, pp. 10 867–10 872, 2000.

[4] P. Kozodoy, H. Xing, S. P. DenBaars, U. K. Mishra, A. Saxler, R. Perrin, S. Elhamri, and W. C. Mitchel, "Heavy doping effects in Mg-doped GaN," *J. Appl. Phys.*, vol. 87, pp. 1832–1835, 2000.

[5] Q. Zhu, H. Nagai, Y. Kawaguchi, K. Hiramatu, and N. Sawaki, "Effect of thermal annealing on hole trap levels in Mg-doped GaN grown by metalorganic vapor phase epitaxy," *J. Vac. Sci. Technol.*, vol. A 18, pp. 261–267, 2000.

[6] Q. Z. Liu and S. S. Lau, "A review of the metal-GaN contact technology," *Solid-State Electron.*, vol. 42, pp. 677–691, 1998.

[7] H. Ishikawa, S. Kobayashi, Y. Koide, S. Yamasaki, S. Nagai, J. Umezaki, M. Koike, and M. Murakami, "Effects of surface treatments and metal work functions on electrical properties at p-GaN/metal interfaces," *J. Appl. Phys.*, vol. 81, pp. 1315–1322, 1997.

[8] L. S. Yu, D. Qiao, L. Jia, S. S. Lau, Y. Qi, and K. M. Lau, "Study of Schottky barrier of Ni on p-GaN," *Appl. Phys. Lett.*, vol. 79, pp. 4536–4538, 2001.

[9] K. Shiojima, T. Sugahara, and S. Sakai, "Large Schottky barriers for Ni/p-GaN contacts," *Appl. Phys. Lett.*, vol. 74, pp. 1936–1938, 1999.

[10] D. Qiao, L. S. Yu, S. S. Lau, J. Y. Lin, H. X. Jiang, and T. E. Haynes, "A study of the Au/Ni ohmic contact on p-GaN," *J. Appl. Phys.*, vol. 88, pp. 4196–4200, 2000.

[11] S. M. Myers, A. F. Wright, G. A. Petersen, W. R. Wampler, C. H. Seager, M. H. Crawford, and J. Han, "Diffusion, release, and uptake by hydrogen in magnesium-doped gallium nitride: Theory and experiment," *J. Appl. Phys.*, vol. 89, pp. 3195–3202, 2001.

[12] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. New York: Wiley, 1981, pp. 249–264.

[13] J. S. Im, A. Moritz, F. Steuber, V. Harle, F. Scholz, and A. Hangleiter, "Radiative carrier lifetime, momentum matrix element, and hole effective mass in GaN," *Appl. Phys. Lett.*, vol. 70, pp. 631–633, 1997.

[14] A. K. Rice and K. J. Malloy, "Microstructural contributions to hole transport in p-type GaN : Mg," *J. Appl. Phys.*, vol. 89, pp. 2816–2825, 2000.

[15] L. S. Yu, Q. Z. Liu, D. J. Qiao, S. S. Lau, and J. M. Redwing, "The role of the tunneling component in the current–voltage characteristics of metal–GaN Schottky diodes," *J. Appl. Phys.*, vol. 84, pp. 2099–2104, 1998.

[16] D. K. Schroder, *Semiconductor Material and Device Characterization*. New York: Wiley, 1990, p. 66.

[17] A. M. Cowley and S. M. Sze, "Surface states and barrier height of metal–semiconductor systems," *J. Appl. Phys.*, vol. 36, pp. 3212–3220, 1965.

[18] E. H. Rhoderick and R. H. Williams, *Metal–Semiconductor Contacts*, 2nd ed. Oxford, U.K.: Oxford, 1988, p. 151.

[19] J. F. Ziegler, J. P. Biersack, and U. Littmark, *The Stopping and Range of Ions in Solids*. New York: Pergamon, 1985.

[20] S. Zhang, J. A. van den Berg, D. G. Armour, S. Whelan, R. D. Goldberg, P. Bailey, and T. C. Q. Noakes, "Medium energy ion scattering analysis of damage in silicon caused by ultra-low energy boron implantation at different substrate temperatures," in *2000 Int. Conf. Ion Implantation Technology Proc.*, Alpbach, Austria, Sept. 2000, pp. 17–22.



**L. S. Yu**, photograph and biography not available at time of publication.

**L. Jia**, photograph and biography not available at time of publication.

**D. Qiao**, photograph and biography not available at time of publication.

**S. S. Lau**, photograph and biography not available at time of publication.

**J. Y. Lin**, photograph and biography not available at time of publication.

**H. X. Jiang**, photograph and biography not available at time of publication.