Effect of defect density on the electrical characteristics of n-type GaN Schottky contacts

Kenji Shiojima, Jerry M. Woodall, Christopher J. Eiting, Paul A. Grudowski, and Russell D. Dupuis

Citation: Journal of Vacuum Science & Technology B **17**, 2030 (1999); doi: 10.1116/1.590866
View online: http://dx.doi.org/10.1116/1.590866
View Table of Contents: http://scitation.aip.org/content/avs/journal/jvstb/17/5?ver=pdfcov
Published by the AVS: Science & Technology of Materials, Interfaces, and Processing

Effect of defect density on the electrical characteristics of *n*-type GaN Schottky contacts*

Kenji Shiojima[a)]
NTT System Electronics Laboratories, 3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan

Jerry M. Woodall
School of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana 47907-1285

Christopher J. Eiting, Paul A. Grudowski, and Russell D. Dupuis
Microelectronics Research Center, The University of Texas at Austin, Austin, Texas 78712-1100

(Received 15 January 1999; accepted 9 July 1999)

The effect of defects in *n*-type GaN epitaxial layers on the electrical characteristics of Ni contacts was studied. The defect density of GaN layers was characterized, and Ni dots deposited on four *n*-GaN wafers with different mobilities were examined by current–voltage ($I-V$) and capacitance–voltage ($C-V$) measurements. Ni contacts deposited on undoped GaN with a mobility of 6.7 $cm^2/V\,s$ showed ohmic behavior with a specific contact resistance on the order of 0.1 $\Omega\,cm^2$. In contrast, Ni contacts deposited on Si-doped GaN with a mobility of over $100\,cm^2/V\,s$ exhibited Schottky behavior with a Schottky barrier height of 0.75 eV from $I-V$ and 1.10 eV from $C-V$. These results suggest the formation of small areas with low barrier height at the interface due to defects and dislocations. [S0734-211X(99)03905-0]

I. INTRODUCTION

Recently, GaN-based materials have been the subject of intensive research for both optoelectronic devices and high-temperature/high-power electronic devices. Visible light-emitting diodes,[1] ultraviolet (UV) detectors,[2] microwave-operation AlN/GaN field-effect transistors (MESFETs),[3,4] and high-electron-mobility transistors (HEMTs)[5] have been demonstrated. Because MESFETs and HEMTs require both ohmic and Schottky contacts, the study of these contacts to *n*-GaN is of interest.

The Schottky barrier height ($q\phi_B$) is expected to be dependent on the metal work function due to the ionic nature of GaN;[6] however, the available data are contradictory. For *n*-GaN, it has been reported that slope (S) parameters of the barrier ($S=\partial q\phi_B/\partial\chi_s$, where χ_s is the metal electronegativity) are 0.385,[7] 0.7,[8] and almost unity,[9] while Ni, Pd, and Pt contacts to *n*-GaN do not obey this rule.[10–12] There are at least two possible reasons for this discrepancy. One is that an adequate surface passivation treatment before metal deposition has not been established, as GaN cannot be etched with any chemical solution at room temperature. The other is that the quality of epitaxial GaN films is strongly dependent on the growth method and growth conditions, including the choice of substrate. In addition, we have found strong Fermi level (E_F) pinning in W and Nb contacts to *n*-GaN, which could be due to the process-induced damage during the sputtering for metal deposition.[13] This suggests that the metal deposition technique is also important in determining the metal-semiconductor contact performance.

In this article, we report on the possible role that defects in GaN epitaxial layers play in determining the electrical characteristics of contacts to *n*-GaN. GaN wafers were characterized by Hall measurements, x-ray diffraction, transmission electron microscopy (TEM), and atomic force microscopy (AFM), and then Ni contacts formed on four *n*-GaN wafers with different mobilities were examined by current–voltage ($I-V$) and capacitance–voltage ($C-V$) measurements.

II. EXPERIMENT

Both unintentionally doped and Si-doped *n*-GaN films were grown on (0001) sapphire substrates using metal-organic chemical vapor deposition (MOCVD) in a modified EMCORE D125 high-speed rotating-disk vertical reactor operating at 76 Torr. This reactor has produced high-quality GaN, AlGaN, and InGaN films, as described previously.[14] A mixture of SiH_4 in H_2 was the Si precursor for all of the *n*-type layers. The films were grown at $T_G\sim 1050\,°C$ with $\sim$30-nm-thick low-temperature ($T_G\sim 550\,°C$) GaN unintentionally doped buffer layers. Typical molar flow rates employed during the growth of the epitaxial layers were 0.57 moles/min for ammonia (NH_3), 222.0 μmoles/min for trimethylgallium (TMG) (V/III$\sim$2600), and 4.1–81.2 nmoles/min for SiH_4. Hydrogen was the carrier gas in all cases. The growth rate for these GaN epitaxial films was $\sim$2.0 μm/h. The temperature ramping and gas switching processes were identical for all of the samples used in this study. Four GaN wafers, denoted samples A–D, were grown as shown in Table I. Residual oxygen concentration of all the GaN films was less than the detection limit ($1\times10^{18}\,cm^{-3}$) of secondary ion mass spectrometry (SIMS) measurements.

The GaN surface was degreased in acetone and methanol, and then the surface oxide was removed in buffered hydrofluoric acid solution (BHF) prior to loading the samples into the chamber for metal deposition. Ni (100 nm thick) was

*No proof corrections received from author prior to publication.

[a)]Electronic mail: shiojima@aecl.ntt.jp

TABLE I. Structure of GaN wafers and their carrier concentration, thickness, and electron mobility. Wafers were characterized by Hall measurements.

Samples	Film structure	n (cm^{-3})	Thickness (μm)	Mobility (cm^2/V s)
A	Undoped GaN	2×10^{17}	1.5	6.7
B	Undoped GaN	5×10^{16}	1.0	10–20
	on Si-doped GaN	1×10^{19}	0.5	···
C	Si-doped GaN	2×10^{17}	1.6	107
D	Si-doped GaN	5×10^{17}	1.7	330

deposited by electron-beam evaporation through a metal mask with 100-μm-diam circular openings.

The $I-V$ method was used to determine the electrical properties, i.e., $q\phi_B$ and the ideality factor (n value), with the following equation in terms of the thermionic emission model:[15]

$$J=A^{**}T^2\exp(-q\phi_B/kT)[\exp(qV/nkT)-1], \tag{1}$$

where A^{**} is the effective Richardson constant (24 A/cm^2 K^2 for n-GaN based on $A^{**}=4\pi m^* qk^2/h^3$ and $m^*=0.20m_0$),[16] T is the temperature, q is the charge of the electron, k is the Boltzman constant, and V is the applied voltage.

$C-V$ measurements were also performed at a frequency of 1 MHz. The $C-V$ relationship for a Schottky contact is

$$(1/C)^2=(2/\epsilon qNd)(V_{bi}-V-kT/q),$$
$$\phi_B=V_{bi}+(kT/q)\ln(Nc/Nd), \tag{2}$$

where ϵ is the permittivity ($\epsilon_{GaN}=9.5\epsilon_0$), Nd is the donor concentration, and $Nc=2.60\times10^{18}\,cm^{-3}$ based on $Nc=2(2\pi m^* kT/h^2)^{3/2}$.[15]

III. RESULTS AND DISCUSSION

The quality of epitaxial GaN layers was characterized as the first step of the examination. Figure 1 shows x-ray diffraction results of the GaN layers grown on sapphire. For all four samples, only h-GaN (0002) and (0004) peaks were detected, and the full width at half maximums (FWHM) of (0002) are in the same range as shown in the inset. This confirmed that all samples had identical macroscopic crystal quality.

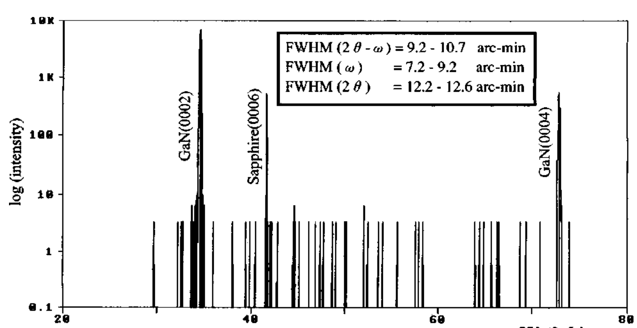

FIG. 1. X-ray diffraction results of GaN layers grown on sapphire. All the samples show similar values of FWHM of the (0002) peak shown in the inset.

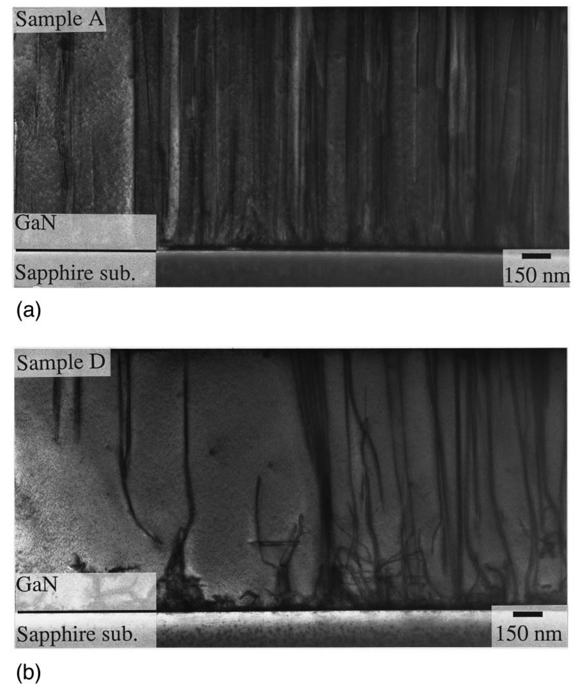

FIG. 2. Cross-sectional TEM images of samples A and D.

Table I gives the electron mobility and carrier concentration of the four GaN films, which were characterized by Hall measurements. The Si-doped samples have higher mobilities than the undoped samples. Figure 2 shows cross-sectional TEM images of samples A and D. Many threading dislocations are seen, and as expected, Sample A contains much higher dislocation density than sample D. The reduction of dislocation density in GaN films by Si doping has been previously reported.[17] Thus, electron mobility has been found to correlate with the estimated defect density, which explains the differences in the Hall measurement. The origin of donors in the undoped GaN has not yet been identified, but we believe that the undoped GaN grown for this study contains a higher density of point defects, such as N vacancies, which are donors.

Next, AFM was conducted to observe the GaN surface morphology. AFM images of a 2×2 μm area with typical values of dislocation density (D_{dis}) are shown in Fig. 3. All the surfaces are atomically flat, as steps are observed. Especially, for sample D, it is clearly shown that the steps terminate with dark spots. These spots are known to be threading screw dislocations.[18] The dislocation density ranged from high $10^8\,cm^{-2}$ to high $10^9\,cm^{-2}$ and depended on the electron mobility. These values are in the same range as those of generally reported GaN films grown on sapphire by MOCVD.

Ni dots were deposited on the GaN wafers, and then the electrical properties were examined. Typical $I-V$ characteristics of the Ni/n-GaN contacts of samples A and B are shown in Fig. 4. Sample A showed good linearity in a linear plot. The specific contact resistance (r_c) of sample A was estimated to be of the order of 0.1 $\Omega\,cm^2$ by the four-point

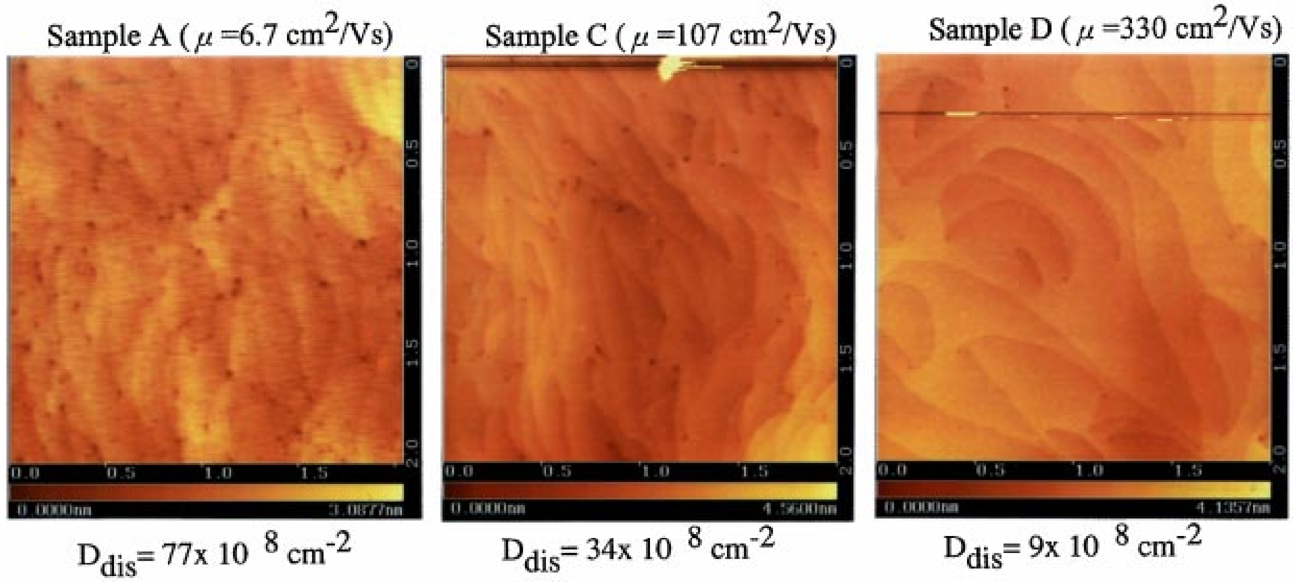

FIG. 3. AFM images of a 2×2 μm area with typical values of dislocation density D_{dis}.

method.[19] On the other hand, sample B showed a very leaky behavior. In contrast, samples C and D exhibited Schottky behavior, as shown in $I-V$ and $C-V$ plots of Fig. 5. Linear forward $I-V$, and $1/C^2$ curves are observed. Barrier heights and n values are summarized in Table II. The $q\phi_B$ from $I-V$ is lower than that from $C-V$, and the carrier concentrations from $C-V$ are of the same order as those from Hall measurements.

It is clear that a large defect density correlated with ohmic behavior. The $I-V$ curve for sample A is ohmic, but the r_c is very high. This suggests the formation of small areas with a low barrier height, as a shunt path of a current, due to defects and dislocations, rather than a lowering of $q\phi_B$ in the entire contact. When we consider the origin of the shunt path, we focus on the relationship between $I-V$ characteristics and the absolute value of screw dislocation density observed in the AFM results. The $I-V$ curves for samples A and C are completely different; however, the D_{dis} of sample A is only two times larger than that of sample C. This suggests that we should categorize dislocations in order to explain the results. In general, there are three kinds of dislocations in MOCVD grown GaN on sapphire: edge dislocations, screw dislocations, and nanopipes. In this study, both edge and screw dislocations were observed in the TEM images and screw dislocations were observed in the AFM images, but the existence of nanopipes was not confirmed due to the small observation areas in these methods. Since a nanopipe is a screw dislocation with a large Burgers vector, it is likely that

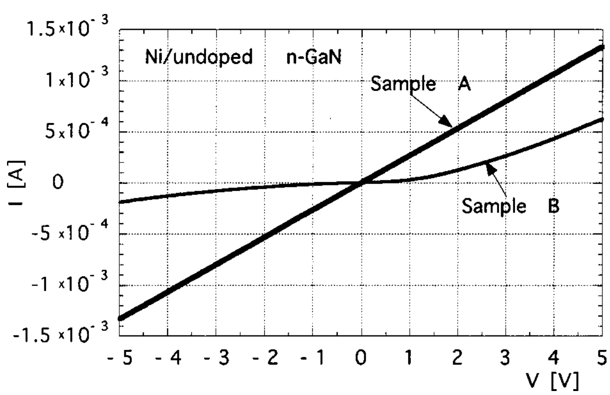

FIG. 4. $I-V$ characteristics of Ni/undoped n-GaN contacts in a linear plot.

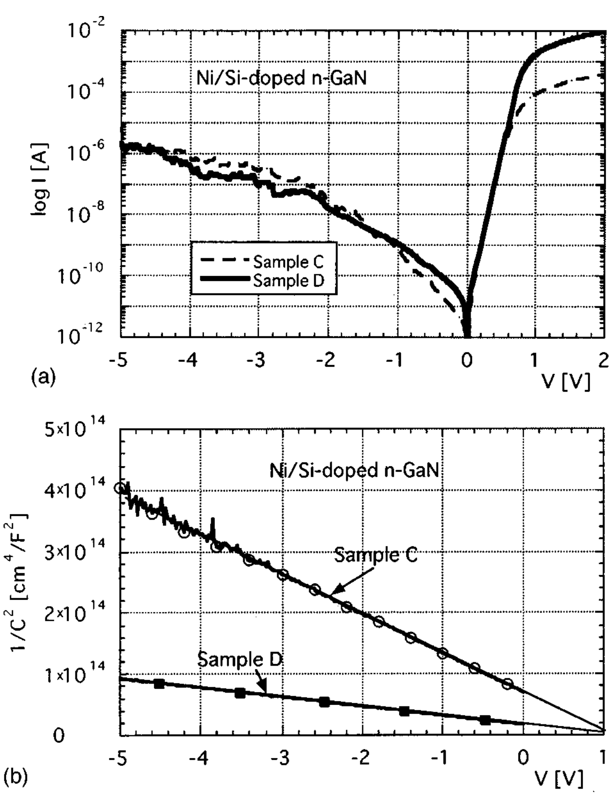

FIG. 5. Typical $I-V$ curves of Ni/Si-doped n-GaN contacts in a (a) semilog plot and (b) $1/C^2-V$ plot.

TABLE II. Summary of $I-V$ and $C-V$ measurements of Ni/GaN contacts.

Samples	Electrical characteristic	$q\phi_B$ ($I-V$) (eV)	n value	$q\phi_B$ ($C-V$) (eV)	n (cm^{-3})
A	Ohmic ($r_c=0.1\ \Omega\ cm^2$)	⋯	⋯	⋯	⋯
B	Very leaky Schottky	⋯	⋯	⋯	⋯
C	Schottky	0.76	1.67	1.10	1.7×10^{17} ($C-V$)
D	Schottky	0.75	1.82	1.17	7.5×10^{17} ($C-V$)
in Ref. 9	Schottky	1.15	1.17	1.11	1×10^{18} ($C-V$)
in Ref. 7	Schottky	0.99	1.04	1.13	1×10^{17} ($C-V$)
in Ref. 10	Schottky	0.66	1.15	0.56	2×10^{17} (Hall)

a larger screw dislocation density induces a larger density of nanopipes. Accordingly, it is possible that a nanopipe could form above a certain screw dislocation density and act as a shunt path of a current at the interface.

For samples with a smaller estimated defect density, the $I-V$ became rectifying. Samples C and D, which have mobilities over 100 $cm^2/V\,s$, showed a $q\phi_B$ of 0.75 and 0.76 eV from $I-V$ and 1.10 and 1.17 eV from $C-V$, respectively. Kalinina *et al.* have reported that the $q\phi_B$ of n-GaN contacts depends on the metal work function with $S=1$ in epitaxial GaN wafers grown on SiC.[9] Schmitz *et al.* have also reported similar results with $S=0.385$ in GaN on sapphire.[7] On the other hand, Guo *et al.* have reported that the $q\phi_B$ does not obey this rule in GaN grown on sapphire with a mobility of 300 $cm^2/V\,s$.[10] The reported $q\phi_B$'s of the Ni contacts in both cases are also summarized in Table II.

Our $q\phi_B$ from $C-V$ is consistent with Kalinina's and Schmitz's $q\phi_B$'s, but our $q\phi_B$ from $I-V$ is lower by 0.4 and 0.25 eV, respectively, and our n value is higher than theirs. Since $q\phi_B$ is estimated from the edge of the depletion layer in $C-V$, the shape of the barrier at the interface does not affect $q\phi_B$, while $I-V$ is sensitive to the barrier shape. Thus, even when the mobility is over 100 $cm^2/V\,s$, very small sections of leaky interface are formed by defects, such as threading dislocations, and are responsible for the low $q\phi_B$ and high n value. Guo *et al.* have also reported the $q\phi_B$ from $C-V$ increased from 0.56 to 1.02 eV upon annealing at as low as 100 °C due to interfacial reaction.[10] Conducting an annealing study for our samples would make a clearer comparison with their results possible in the discussion of an absolute value of $q\phi_B$ and interfacial reaction.

IV. CONCLUSION

GaN wafers were characterized by Hall measurements, x-ray diffraction, TEM, and AFM, and then Ni contacts formed on four n-GaN wafers with different mobilities were examined by $I-V$ and $C-V$ measurements. For samples with a smaller estimated defect density, the electrical characteristics of the contacts varied from ohmic to rectifying. This result suggests the formation of small areas with a low $q\phi_B$ at the interface due to defects and dislocations. This study enables us to form both ohmic and Schottky contacts to n-GaN with the same metal.

ACKNOWLEDGMENTS

The work at The University of Texas at Austin was partially supported by the National Science Foundation under Grant No. DMR-93-12947 and by ONR under Contract No. N00014-95-1-1302.

[1] S. Nakamura, T. Mukai, and M. Senoh, Appl. Phys. Lett. **64**, 1687 (1994).
[2] M. A. Khan, J. N. Kuznia, D. T. Olson, J. M. Van Hove, M. Blasingame, and L. F. Reitz, Appl. Phys. Lett. **60**, 2917 (1992).
[3] M. A. Khan, J. N. Kuznia, A. R. Bhattarai, and D. T. Olson, Appl. Phys. Lett. **62**, 1786 (1993).
[4] S. C. Binari, L. B. Rowland, W. Kruppa, G. Kelner, K. Doverspike, and D. K. Gaskill, Electron. Lett. **30**, 1248 (1994).
[5] M. A. Khan, J. N. Kuznia, D. T. Olson, W. Schaff, J. W. Burn, and M. S. Shur, Appl. Phys. Lett. **65**, 1121 (1994).
[6] J. S. Foresi and T. D. Moustakas, Appl. Phys. Lett. **62**, 2859 (1993).
[7] A. C. Schmitz, A. T. Ping, M. A. Khan, Q. Chen, J. W. Yang, and I. Adesida, J. Electron. Mater. **27**, 255 (1998).
[8] S. C. Binari, H. B. Dietrich, G. Kelner, L. B. Rowland, K. Doverspike, and D. K. Gaskill, Electron. Lett. **30**, 909 (1994).
[9] E. V. Kalinina, N. I. Kuznetsov, V. A. Dmitriev, K. G. Irvine, and C. H. Carter, Jr., J. Electron. Mater. **25**, 831 (1996).
[10] J. D. Guo, F. M. Pan, M. S. Feng, R. J. Guo, P. F. Chou, and C. Y. Chang, J. Appl. Phys. **80**, 2686 (1989).
[11] L. Wang, M. I. Nathan, T-H. Lim, M. A. Khan, and Q. Chen, Appl. Phys. Lett. **68**, 1623 (1996).
[12] J. D. Guo, M. S. Feng, R. J. Guo, F. M. Pan, and C. Y. Chang, Appl. Phys. Lett. **67**, 2657 (1995).
[13] K. Shiojima, D. T. McInturff, J. M. Woodall, C. J. Eiting, P. A. Grudowski, and R. D. Dupuis, J. Electron. Mater. (to be published).
[14] P. A. Grudowski, C. J. Eiting, J. Park, B. S. Shelton, D. J. H. Lambert, and R. D. Dupuis, Appl. Phys. Lett. **71**, 1537 (1997).
[15] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), pp. 245–311.
[16] A. S. Barker and M. Ilegems, Phys. Rev. B **7**, 743 (1973).
[17] S. Ruvimov *et al.*, Appl. Phys. Lett. **69**, 990 (1996).
[18] S. J. Rosner, E. C. Carr, M. J. Ludowise, G. Girolami, and H. I. Erikson, Appl. Phys. Lett. **70**, 420 (1997).
[19] L. E. Terry and R. W. Wilson, Proc. IEEE **57**, 1580 (1969).