AIP Applied Physics Letters

Inhomogeneous spatial distribution of reverse bias leakage in GaN Schottky diodes

J. W. P. Hsu, M. J. Manfra, D. V. Lang, S. Richter, S. N. G. Chu et al.

Citation: Appl. Phys. Lett. **78**, 1685 (2001); doi: 10.1063/1.1356450

View online: http://dx.doi.org/10.1063/1.1356450

View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v78/i12

Published by the American Institute of Physics.

Inhomogeneous spatial distribution of reverse bias leakage in GaN Schottky diodes

J. W. P. Hsu,[a] M. J. Manfra, D. V. Lang, S. Richter, S. N. G. Chu, A. M. Sergent, R. N. Kleiman, and L. N. Pfeiffer
Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

R. J. Molnar
Massachusetts Institute of Technology, Lincoln Laboratory, Lexington, Massachusetts 02420-9108

(Received 12 December 2000; accepted for publication 24 January 2001)

The reverse bias leakage current in macroscopic GaN Schottky diodes is found to be insensitive to barrier height. Using a scanning current–voltage microscope, we show that the reverse bias current occurs at small isolated regions, while most of the sample is insulating. By comparing the current maps to topographic images and transmission electron microscopy results, we conclude that reverse bias leakage occurs primarily at dislocations with a screw component. Furthermore, for a fixed dislocation density, the V/III ratio during the molecular beam epitaxial growth strongly affects reverse leakage, indicating complex dislocation electrical behavior that is sensitive to the local structural and/or chemical changes.
[DOI: 10.1063/1.1356450]

GaN and its alloys show promise for high power, high frequency transistors. However, excess reverse bias gate leakage is one factor presently limiting device performance. As the GaN community pushes for commercialization, it is important to understand the origin of this excess reverse leakage. Miller *et al.* have shown that while the reverse bias leakage in AlGaN/GaN can be analyzed in a conventional tunneling model, unphysically high donor densities are necessary to fit the data.[1] Several groups have suggested that defects, in particular dislocations, might play an important role in the reverse bias leakage.[1,2,3] Yet to date the exact path of reverse bias current flow has not been probed directly.

In this work, we analyze the macroscopic $I-V$ characteristics of Schottky diodes made on high quality GaN films and AlGaN/GaN heterostructures, and show that reverse bias leakage does not depend sensitively on the barrier height. Furthermore, we use a conducting tip to map the spatial variation of reverse bias current. By comparing the current map to topographic and transmission electron microscopy (TEM) images, we find that the reverse bias leakage is localized around screw and mixed dislocations. This work provides the first direct evidence that dislocations are primarily responsible for the reverse bias leakage in nitride materials.

The GaN and AlGaN films were grown by nitrogen plasma assisted molecular beam epitaxy (MBE) on GaN templates prepared by hydride vapor phase epitaxy (HVPE). The HVPE templates were nominally 15 μm thick. TEM shows the pure screw dislocation density is $\sim 2-4\times 10^8$ cm^{-2} while the total dislocation density is 10^9 cm^{-2}. No new dislocations were generated in the MBE layer. The thickness of the MBE GaN is typically 0.4 μm. The background net donor concentration is below mid 10^{15} cm^{-3} in the MBE GaN layer according capacitance–voltage measurements. As previously reported, the two-dimensional electron gas (2DEG) in AlGaN/GaN heterostructures grown this way displays exceptionally high quality transport behavior.[4]

Macroscopic Schottky diodes are formed with 100-Å-thick Pt dots as the Schottky contact and soldered In as the ohmic contact. The Pt dot diameter is 125 μm. We found that the reverse bias current density at a given bias can vary by 3–4 orders of magnitude among MBE GaN and AlGaN/GaN samples depending on the exact growth conditions. Most importantly, the reverse bias leakage is not sensitive to the barrier height measured under forward bias. To illustrate this finding, the voltage dependence of the absolute current density ($|J|$) for three samples is shown in Fig. 1. Samples A and B are MBE GaN grown on HVPE templates. Sample A was grown under Ga-rich conditions with clear Ga droplets on the surface. (Ga droplets were removed using concentrated HCl prior to Schottky diode fabrication.) Sample B was grown under Ga-lean conditions. Sample C was grown similarly to sample B, but contains a 30 nm $Al_{0.15}Ga_{0.85}N$ on top of the MBE GaN layer. To obtain the barrier height, we analyze the forward bias data in terms of thermionic emission over the Schottky barrier[5]

$$J=J_s \exp\left(\frac{qV}{nkT}\right)=A^*T^2 \exp\left(-\frac{q\phi}{kT}\right)\exp\left(\frac{qV}{nkT}\right), \qquad (1)$$

where A^* is the effective Richardson constant, q is the fundamental electronic charge, k is the Boltzman constant, T is temperature, ϕ is the barrier height, and n is the ideality factor. Equation (1) is valid for $V>3kT/q$. The barrier height for samples A, B, and C is found to be 1.04, 1.01, and 1.18 eV, respectively. The ideality factor is between 1.3 and 1.4, comparable to other measurements.[6] Samples A and B have approximately the same barrier height, but their reverse bias current density at -1 V differs by three orders of magnitude. On the other hand, based on the difference in ϕ, reverse bias current density for samples B and C should have differed by three orders of magnitude according to Eq. (1), while the measured $|J|$ for the two samples is very similar. Furthermore, the curves in Fig. 1 appear to be the sum of (i)

[a]Electronic mail: jhsu@lucent.com

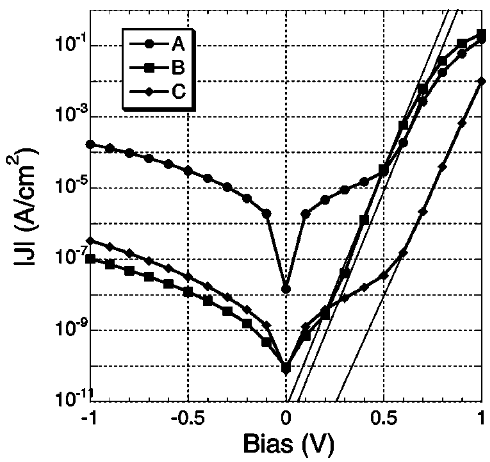

FIG. 1. Bias dependence of current density ($|J|$) measured from macroscopic size (125 μm diameter) Schottky diodes. All three samples were grown by MBE on top of HVPE GaN templates. The circles represent sample A, a GaN film grown under Ga-rich conditions. The squares represent sample B, a GaN film grown under Ga-lean conditions. The diamonds represent sample C, an AlGaN/GaN heterostructure with 30 nm $Al_{0.15}Ga_{0.85}N$ barrier. The straight lines to samples B and C are fits to the forward bias data according to Eq. (1). For sample A, there are not enough points for a meaningful fit, so the fit to sample B was shifted parallelly. The saturation of $|J|$ near 10^{-1} A/cm^2 is due to the current limit of the In ohmic contact.

an asymmetric $I-V$ such as for a good Schottky junction and (ii) additional leakage that is symmetric in bias direction. The excess reverse bias current comes from the symmetric contribution. Hence, something other than the barrier height is determining the reverse bias leakage.

To further investigate the origin of reverse bias leakage, we performed scanning current–voltage microscopy (SIVM) measurements on samples A and B. In the SIVM experiment, a voltage bias is applied between the tip and sample while current that flows through the conducting tip is detected using a current preamplifier.[7] In this case, the tip acts as a microscopic Schottky contact to the GaN sample.[8] All data were taken using a boron-doped conducting diamond tip,[9] and the experiment was performed in air at room temperature. SIVM allows us to directly map spatial variation of sample conductivity.

Figure 2(a) shows a topographic image of sample A. Films grown under such Ga-rich conditions display a smooth surface morphology with monolayer steps with dislocations containing a screw component appearing as spiral hillocks.[10,11] Figure 2(b) shows a SIVM image taken under reverse bias at -6 V. The reverse current is defined with a negative sign; thus, the current is nonzero in dark regions of Fig. 2(b). Evidently, the reverse current distribution is highly nonuniform. Most of the sample does not conduct, i.e., with current below the detection limit of 4×10^{-13} A. Reverse bias current flow concentrates on small isolated regions. In Fig. 2, the density of these leakage regions is $\sim2.5\times10^{8}$ cm^{-2}, with diameters ranging from 47 to 105 nm. The size of leakage region increases with increasing reverse bias. To correlate the locations of reverse bias current with topographic features, Fig. 2(c) is an overlay of 2(b) on 2(a). Most leakage spots correspond to spiral hillocks, suggesting that the leakage occur at screw and mixed dislocations.

To see whether the current observed in the SIVM images can account for the reverse bias leakage measured in macroscopic Schottky diodes, we compare $|J|$ obtained in the two methods. In the case of macroscopic Schottky diodes, we have no knowledge of spatial inhomogeneity in the current distribution; hence, $|J|$ is calculated by dividing the total current by the Pt dot area. At -5 V reverse bias, $|J|\sim5\times10^{-2}$ A/cm^2 for sample A from the macroscopic measurement. In the case of SIVM, current measured at a given position is the local current density times the effective area of the tip. To obtain $|J|$ averaged over an area, i.e., analogous to the macroscopic diodes, we calculate the average current divided by the tip area. Taking (50 nm)^2 as the effective tip area, at -5 V reverse bias, we obtain $|J|\sim4\times10^{-2}$ A/cm^2. The two results are of the same order of magnitude. Hence, conduction through the screw/mixed dislocations is the

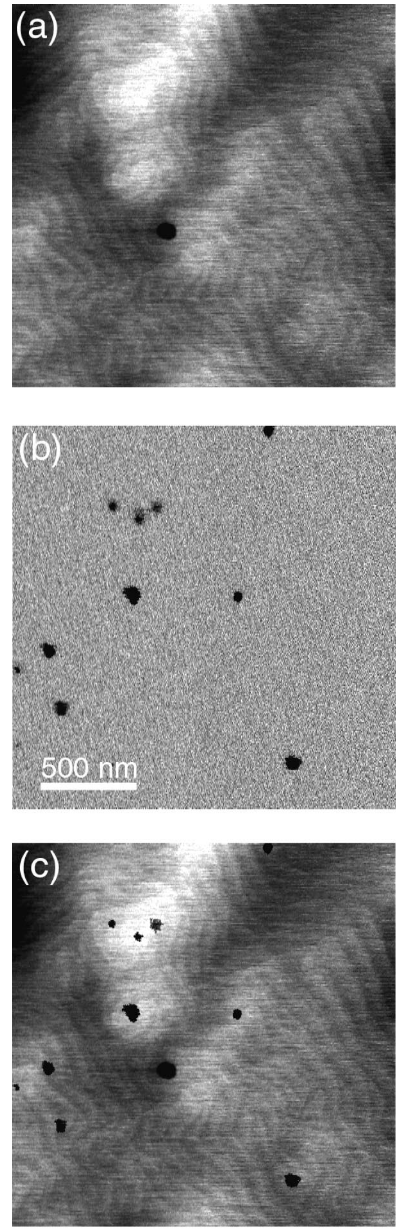

FIG. 2. 2 μm$\times$2 μm (a) topographic images of a GaN film grown by MBE under Ga-rich conditions (sample A). (b) Simultaneously taken current image under reverse bias -6 V. Grayscale represents 3 nm in (a) and 2×10^{-11} A in (b). (c) Overlay of (b) on (a) to show that regions of nonzero current [dark spots in (b)] coincide with hillocks. The topographic image [Fig. 2(a)] shows a deep pit at the center of the image. We observe such pits on some samples, but with a density at least one order of magnitude lower than that of spiral hillocks. There is no reverse leakage current at the pit.

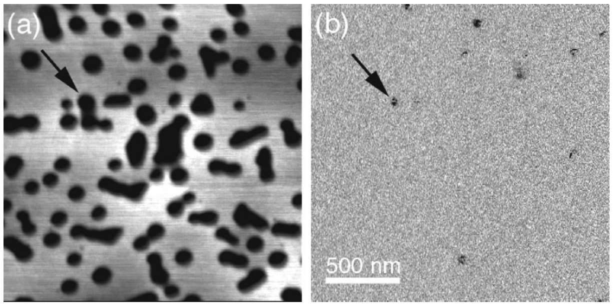

FIG. 3. 2 μm$\times$2 μm (a) topographic images of a GaN film grown by MBE under Ga-lean conditions (sample B). (b) Simultaneously taken current image under reverse bias -7 V. Gray scale represents 10 nm in (a) and 5×10^{-12} A in (b). The arrows indicate the same position on the two images.

dominant source for reverse bias leakage, i.e., the symmetric part of $I-V$. Detailed study of the bias dependence will be published separately.[12]

Figure 3(a) shows a topographic image of sample B grown under Ga-lean conditions. Samples grown under such conditions display a pitted morphology, with smooth regions between pits.[10] Figure 3(b) shows the simultaneously taken SIVM image at reverse bias of -7 V. Again, the reverse leakage current can only be measured at isolated regions. In Fig. 3, the density of the leakage spots in this sample is $\sim2.2\times10^8\ \mathrm{cm}^{-2}$. They correspond to some surface pits, but most pits do not conduct. The arrows mark the same sample position in Fig. 3. Furthermore, we found that the lowest reverse bias voltage at which any current can be detected in the SIVM image is 2–3 V higher for Ga-lean samples than that for Ga-rich samples. In macroscopic Schottky diode measurements, we also found that the bias is 2–3 V higher in Ga-lean samples for a given $|J|$. When the same experiment was done on an undoped HVPE GaN film, no measurable current was detected in this sample up to -12 V reverse bias.

The SIVM results show that the reverse bias leakage is not uniformly distributed in the sample. A small portion of the sample is responsible for the majority of the leakage. The correlation between reverse bias leakage locations and topographic hillocks in sample A suggests that reverse bias leakage primarily occur at screw/mixed dislocations. Further confirmation comes from the similar density between the leakage spots and screw/mixed dislocation density determined by TEM. The fact that samples A and B have a distinctly different morphology but show similar density of leakage spots argues that the origin of this reverse bias leakage is the same in the two samples. Since our MBE growth does not generate new dislocations, the dislocation density is determined by the HVPE templates and is the same in both samples. Hence, our results indicate that screw/mixed dislocations contribute significantly more to gate leakage than pure edge dislocations. Previous works also found that screw/mixed dislocations are more effective recombination centers[13] and have reduced barrier heights[14] compared to pure edge dislocations.

It is striking that the reverse bias leakage is orders of magnitude different for samples grown under slightly different conditions. We routinely find that reverse bias current is orders of magnitude higher for Ga-rich samples. Given that dislocations with a screw component are responsible for the reverse bias leakage and their density is the same for the HVPE template and the two MBE/HVPE films, our results suggest that dislocation electrical activity is sensitive to local chemical and/or structural changes, which depend on growth methods and conditions. Edge dislocation core structures and the dominant defect were investigated theoretically and found to depend on background doping and growth stoichiometry.[15] Similar effects might be expected for screw dislocations, but have not been studied. Since our MBE background doping is very low, the difference in the two MBE GaN samples is most likely due to the stoichiometric effect. In particular, it is possible that excess Ga can decorate the dislocation cores under Ga-rich conditions. On the other hand, the difference in dislocation electrical activity between HVPE and MBE films is more likely due to different local chemical environment. Further research is underway.

In conclusion, $I-V$ results from macroscopic Schottky diodes show definitively that reverse bias leakage is not sensitively related to the Schottky barrier height in III nitrides. SIVM results reveal that reverse bias current distribution is highly nonuniform. Most current flows through screw and mixed dislocations. Thus, analysis of reverse bias $I-V$ data must consider inhomogeneous distribution of current flow. In addition, dislocation electrical activity is shown to depend on the growth methods and conditions.

The Lincoln Laboratory portion of this work was sponsored by the Office of Naval Research under Air Force Contract No. F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and not necessarily endorsed by the United States Air Force.

[1] E. J. Miller, X. Z. Dang, and E. T. Yu, J. Appl. Phys. **88**, 5951 (2000).
[2] F. Zhang, D. C. Reynolds, and D. C. Look, J. Electron. Mater. **29**, 448 (2000); D. V. Kuksenkov, H. Temkin, A. Osinsky, R. Gaska, and M. A. Khan, Appl. Phys. Lett. **72**, 1365 (1998); J. C. Carrano, T. Li, P. A. Grudowski, C. J. Eiting, R. D. Dupuis, and J. C. Campbell, J. Appl. Phys. **83**, 6148 (1998).
[3] P. Kozodoy, J. P. Ibbetson, H. Marchand, P. T. Fini, S. Keller, J. S. Speck, S. P. DenBaars, and U. K. Mishra, Appl. Phys. Lett. **73**, 975 (1998).
[4] M. J. Manfra, L. N. Pfeiffer, K. West, H. L. Stormer, K. W. Baldwin, J. W. P. Hsu, D. V. Lang, and R. J. Molnar, Appl. Phys. Lett. **77**, 2888 (2000).
[5] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), Chap. 5.
[6] U. Karrer, O. Ambacher, and M. Stutzmann, Appl. Phys. Lett. **77**, 2012 (2000); H. C. Casey, J. Muth, S. Krishnankutty, and J. M. Zavada, *ibid.* **68**, 2867 (1996).
[7] C. Shafai, D. J. Thomson, M. Simard-Normandin, G. Mattiussi, and P. J. Scanlon, Appl. Phys. Lett. **64**, 342 (1994); S. Richter, M. Geva, J. P. Garno, and R. N. Kleiman, *ibid.* **77**, 456 (2000).
[8] J. W. P. Hsu, D. V. Lang, S. Richter, R. N. Kleinman, A. M. Sergent, and R. J. Molnar, Appl. Phys. Lett. **77**, 2873 (2000).
[9] Conducting diamond tips, NANOSENSOR GmbH.
[10] J. W. P. Hsu, M. J. Manfra, D. V. Lang, K. W. Balwin, L. N. Pfeiffer, and R. J. Molnar, J. Electron. Mater. (in press).
[11] B. Heying, E. J. Tarsa, C. R. Elsass, P. Fini, S. P. DenBaars, and J. S. Speck, Appl. Phys. Lett. **85**, 6470 (1999).
[12] J. W. P. Hsu, D. V. Lang, M. J. Manfra, A. M. Sergent, S. Richter, S. N. G. Chu, and L. N. Pfeiffer (unpublished).
[13] T. Hino, S. Tomiya, T. Miyajima, K. Yanashima, S. Hashimoto, and M. Ikeda, Appl. Phys. Lett. **76**, 3421 (2000).
[14] E. G. Brazel, M. A. Chin, and V. Narayanamurti, Appl. Phys. Lett. **74**, 2367 (1999).
[15] A. F. Wright and U. Grossner, Appl. Phys. Lett. **73**, 2751 (1998); K. Leung, A. F. Wright, and E. B. Stechel, *ibid.* **74**, 2495 (1999).