Origin and microscopic mechanism for suppression of leakage currents in Schottky contacts to GaN grown by molecular-beam epitaxy

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Dislocation-related conduction paths in *n*-type GaN grown by molecular-beam epitaxy and a mechanism for local suppression of current flow along these paths are analyzed using conductive atomic force microscopy, scanning Auger spectroscopy, and macroscopic current–voltage measurements. Application of an electric field at the GaN surface in an ambient atmospheric environment is shown to lead to local formation of gallium oxide in the immediate vicinity of the conduction paths, resulting in the strong suppression of subsequent current flow. Current–voltage measurements for Schottky diodes in which local conduction paths have been suppressed in this manner exhibit reverse-bias leakage currents reduced by two to four orders of magnitude compared to those in Schottky diodes not subjected to any surface modification process. These results demonstrate that the dislocation-related current leakage paths are the dominant source of leakage current in Schottky contacts to *n*-type GaN grown by molecular-beam epitaxy, and elucidate the nature of a microscopic process for their suppression.
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I. INTRODUCTION

Reverse-bias leakage current characteristics are a major concern for a wide range of electronic devices. Minimizing the impact of vertical leakage paths is crucial for vertical current-flow devices, such as heterojunction bipolar transistors, in which large emitter–collector currents have been observed.[1] Lateral current-flow devices such as heterostructure field-effect transistors[2,3] can also suffer due to gate leakage currents arising from excessively leaky Schottky contacts. However, with an improved understanding of the leakage current mechanisms in electronic devices based on the group-III-nitride material system,[4–6] rapid progress is currently being made to decrease the off-state leakage current in GaN-based electronic devices,[7,8] which has been a major obstacle to their use in low-noise and low-power circuit applications.[9]

Conductive atomic force microscopy (AFM) studies have shown that threading dislocations are associated with highly localized leakage current paths in nitride heterostructures grown by molecular-beam epitaxy (MBE).[5] We have recently demonstrated[10] that these dislocation-related leakage paths can be blocked by scanning the nitride semiconductor surface in an AFM with a voltage applied between the tip and sample to form a thin insulating layer in the vicinity of the discrete leakage paths. However, the chemical nature of the surface modification observed in these studies was not determined, and the resulting reduction in Schottky diode leakage current observed was relatively modest.

In the current investigation, we use a combination of conductive AFM, scanning Auger electron spectroscopy, and macroscopic current–voltage measurements to demonstrate that these localized conduction paths are the dominant source of leakage current in Schottky contacts to *n*-type GaN grown by MBE, and to elucidate the nature of a microscopic mechanism for their suppression. Conductive AFM is used to characterize localized conduction paths in MBE-grown GaN, and to induce a local modification of the surface in the vicinity of these conduction paths that strongly suppresses subsequent current flow. Scanning Auger electron spectroscopy of the resulting surfaces reveals that the scanning process leads to local oxidation of the surface in an ambient atmospheric environment. Current–voltage measurements performed on macroscopic Schottky contacts demonstrate that application of the AFM-induced surface modification process yields a reduction of reverse-bias leakage current of two to four orders of magnitude, providing definitive evidence that the localized conduction paths observed in these materials are the dominant source of leakage current in Schottky diodes.

II. EXPERIMENT

The sample used in this study consisted of a GaN layer approximately 350 nm in thickness grown by MBE close to the upper crossover point in the Ga droplet regime[11] on a GaN template grown by metalorganic chemical vapor deposition on a sapphire substrate. The dopant concentration in

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the MBE-grown GaN layer was in the mid-10^{16} cm^{-3} range. Ohmic contacts to the sample were fabricated using Ti/Al metallization annealed for 60 s at 650 °C. Scanning probe measurements were performed using a standard AFM under ambient atmospheric conditions (room temperature with relative humidity of 45%–55%) with a conducting $Co_{0.85}Cr_{0.15}$ probe tip. Current flow between the conducting probe tip and the sample was detected using an external preamplifier.

Spatially localized Auger electron spectra and images were obtained using a modified JEOL 7800F scanning electron microscope (SEM) Auger microprobe with a base chamber pressure of 8×10^{-11} Torr. Images of local chemical composition were obtained by mapping the intensities of Auger peak features corresponding to specific elements. The secondary-electron images and Auger measurements were acquired using an electron-beam energy of 10 keV and a current of 3 nA, corresponding to a spot size of 50 nm. The Auger electron energy resolution $\Delta E/E$ is approximately 0.6%, and the Auger spectrum step energy was 1 eV.

Schottky contacts to the GaN samples were fabricated using standard photolithography and liftoff processes with Ni metallization. Following ohmic contact fabrication, 20 μm $\times$20 μm square openings were patterned in photoresist to expose the GaN surface. For a subset of these openings, the exposed GaN surface was imaged using AFM with a conducting probe tip and a bias voltage of 12 V applied to the sample relative to the tip. As reported previously,[10] this process results in a local surface modification in the vicinity of each localized conduction path. To ensure that every conduction path was subjected to this surface modification process, a scan rate of 0.5 Hz and a scan line resolution of 512 lines/image were employed, resulting in a tip velocity of 25 μm/s and a line spacing of 49 nm for the 25 μm$\times$25 μm scan area typically employed. For an AFM tip radius of 15 nm and leakage paths with a radius of at least 15 nm, the AFM tip should pass over every leakage path in a given scan area. The time that the AFM tip spends over each leakage path can then be controlled by varying the number of scans of the surface performed with an applied tip–sample bias voltage. With repeated scans, uniform and thorough coverage of the entire scan area by the probe tip can be achieved. Subsequent Ni metallization followed by liftoff resulted in the simultaneous production of several Schottky diodes for which the GaN surface had been subjected to the AFM process described above, and a larger number of Schottky diodes not subjected to this process. Electrical current–voltage measurements were then performed on both types of diodes.

III. RESULTS AND DISCUSSION

20 μm$\times$20 μm exposed GaN surfaces within patterned photoresist windows were scanned by AFM with 12 V applied to the sample relative to the tip. As reported previously, highly localized current flow was observed at locations corresponding to screw dislocations in the sample.[5,6,10] The initial current is approximately 10 nA at each spot and decreases to less than 10 pA by the sixth scan due to the formation of an insulating layer over each conduction path.

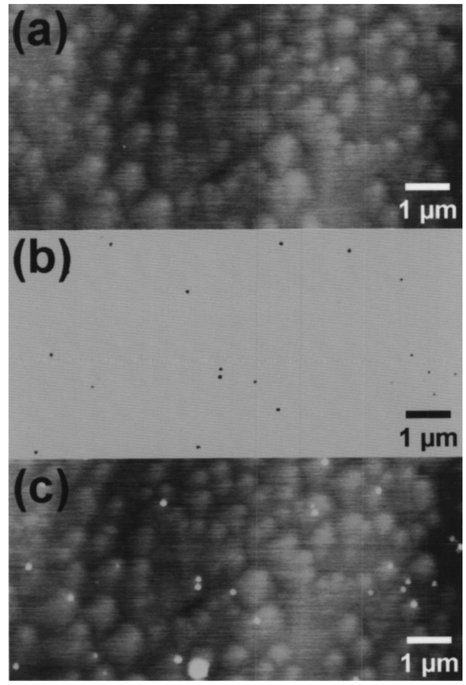

FIG. 1. AFM images of (a) topography of the exposed GaN surface obtained prior to the application of a tip–sample voltage, (b) tip–sample current measured through the same area as in (a) with an applied sample bias of 12 V, and (c) topography of the same area as in (a) and (b) after the AFM modification process, which shows the formation of small islands in the vicinity of the leakage paths. The vertical scale for the topographic images (a) and (c) is 15 nm and the dark spots in the current image (b) correspond to approximately 10 nA.

The thicknesses of the insulating layers were dependent on the number of times the surface was scanned with an applied tip–sample voltage and the magnitude of the tip–sample voltage that was applied during the scans.[10] In these experiments, the insulating layers typically reached thicknesses of approximately 10–20 nm due to the large voltage applied between the tip and sample, and were typically ~100–200 nm in diameter. To illustrate the growth of the insulating layer over the discrete locations where current flow is observed, a topographic image of the exposed GaN surface before the AFM modification process is shown in Fig. 1(a). The measured current through the same surface with 12 V applied between the tip and sample, shown in Fig. 1(b), is suppressed by the formation of insulating layers over each localized conduction path, which are apparent in the topographic image shown in Fig. 1(c) taken without an applied tip–sample voltage after scanning the surface five times with a tip–sample voltage applied.

The chemical nature of the surface modification induced by the AFM scanning process can be determined using high-resolution scanning Auger electron spectroscopy. Figure 2(a) shows a SEM image of a GaN surface subjected to the AFM surface modification process. Dark spots within the 20 μm $\times$20 μm area subjected to the AFM process are clearly visible in Fig. 2(a); these correspond to the localized insulating layers produced by the AFM process, and appear bright following extended imaging—possibly due to charging of the insulating material. Four locations are labeled in Fig. 2(a); those labeled 1 and 3 correspond to the dark regions, while 2

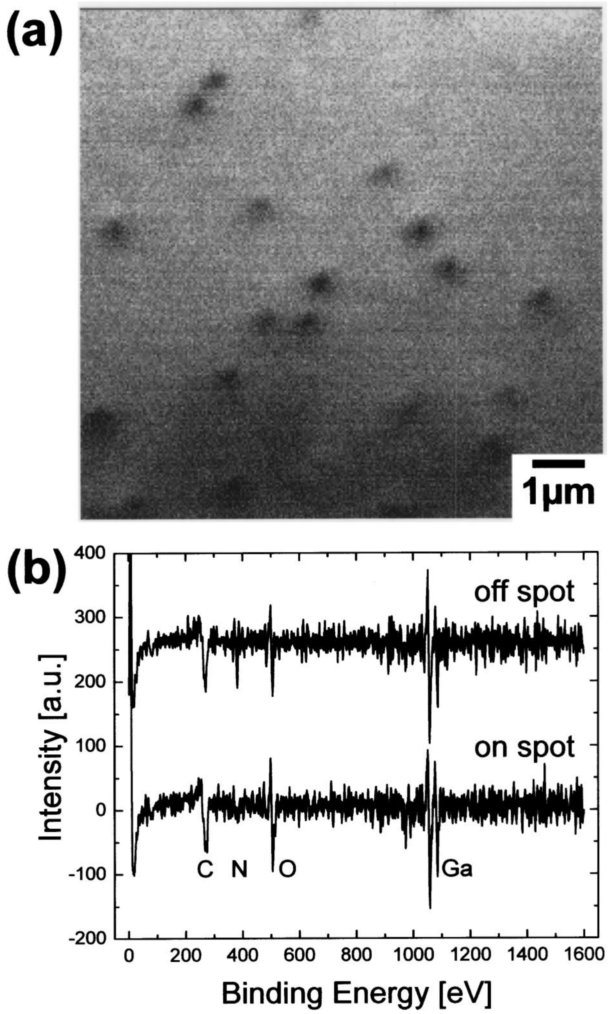

FIG. 2. (a) SEM image of a GaN surface subjected to the AFM surface modification process. The dark spots correspond to the insulating layers formed during AFM scanning. (b) Auger electron spectra acquired on and off dark spots visible in (a). Spectral features corresponding to C, N, O, and Ga are labeled.

and 4 coincide with the GaN background. In Fig. 2(b), Auger electron spectra from two of these locations on the GaN surface—one corresponding to a localized insulating layer formed during AFM scanning, labeled 3, and the other to an area not affected topographically by the AFM scanning process, labeled 4—are shown. The localized insulating layer displays increased Ga and O signals and a reduced N signal. Specifically, the Ga/N ratio for the background (location 4) is 1.06 ± 0.19 (as expected for stoichiometric GaN), while that for the localized insulating areas (location 3) is substantially higher, at 1.6 ± 0.07. In addition, the O signal is 30% higher within the localized insulating area compared to that for the GaN background region. This comparison suggests that the AFM scanning process induces local oxidation of the surface, most likely to form a gallium oxide—an unsurprising result given that the ambient atmospheric environment generally leads to the presence of a thin water layer on the GaN surface.

Figures 3(a)–3(d) show an SEM image and Auger compositional maps for O, Ga, and N, respectively. As shown in Figs. 3(b) and 3(c), the O and Ga concentrations are consis-

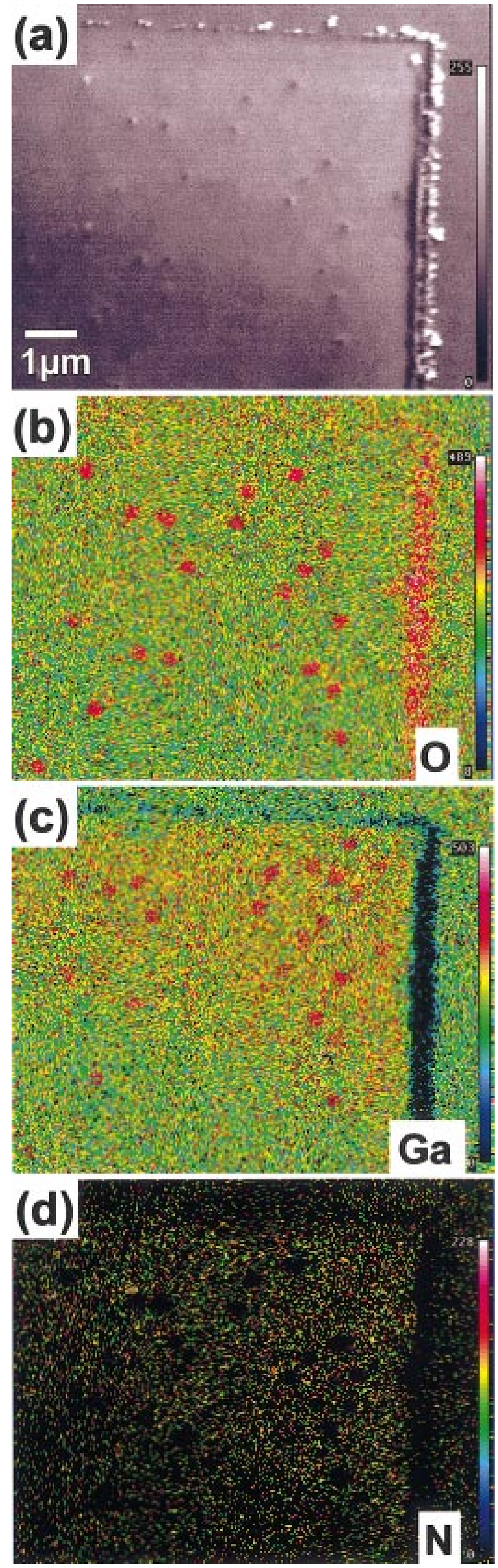

FIG. 3. (Color) (a) SEM image of a 20 μm$\times$20 μm window within which the GaN surface has been subjected to the AFM modification process. (b)–(d) Auger compositional maps of the same area showing local concentrations of (b) O, (c) Ga, and (d) N. The thin insulating layers formed in the vicinity of the localized conduction paths exhibit locally increased Ga and O concentrations, and locally decreased N concentration.

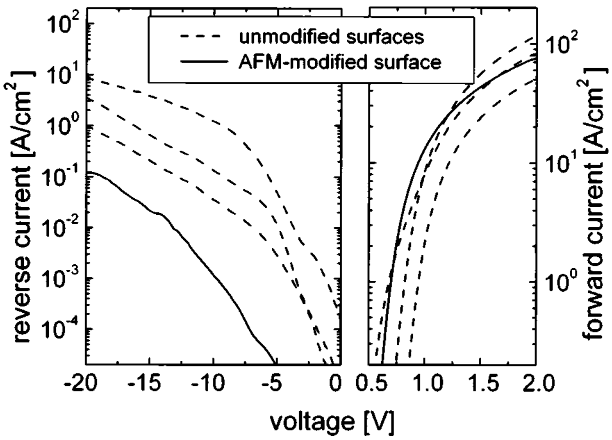

FIG. 4. Current–voltage characteristics of diodes with Schottky contacts fabricated on AFM-modified and unmodified areas with similar forward-bias characteristics.

tently elevated in the vicinity of the localized insulating layers, while the N concentration is reduced. The localized insulating areas visible in the SEM image are 180 ± 40 nm in diameter, while the regions exhibiting an altered chemical composition in the Auger compositional maps exhibit diameters of 180 ± 40 nm for O, 180 ± 50 nm for N, and 160–250 nm for the more poorly resolved Ga image. These sizes are in reasonable agreement with the sizes of the localized insulating layers observed in AFM topographic images. The spots in the Auger images shown in Fig. 3 appear slightly larger due to the greyscale contrast employed. These results provide further confirmation that the insulating layers formed in the vicinity of the localized conduction paths during the AFM scanning process are likely to consist of a gallium oxide and, in addition, that the areas away from the localized conduction paths are, within the detection limits of the Auger spectroscopy measurement, unaffected chemically by the scanning process.

To determine the extent to which the localized conduction paths shown in Fig. 1 contribute to the total reverse-bias leakage current observed in Schottky diodes fabricated on these materials, electrical current–voltage characteristics were obtained from Schottky diodes in which the GaN surface had been subjected to the AFM scanning process described above prior to metallization, and from diodes fabricated without incorporation of this process. The diodes that were fabricated on the AFM-modified surfaces exhibited a consistent and very substantial decrease in reverse-bias leakage current, as shown in Fig. 4, which compares a typical AFM-modified surface diode to three other diodes fabricated on unmodified surfaces with similar series resistance values as determined by the forward-bias characteristics of the diodes. A reduction in current of roughly two to four orders of magnitude is observed for reverse-bias voltages as large as -7 V, consistent with the reduction in current flow observed on a local basis for each dislocation-related conduction path. Even at a reverse bias of -20 V, the leakage current is reduced by a factor of 10–100. This result shows definitively that the reverse-bias leakage current in GaN Schottky contacts is dominated by current flow along discrete, localized conduction paths, as the leakage current is largely eliminated by the formation of a thin insulating layer over these conduction paths. The remaining reverse-bias leakage current that is observed in the diodes fabricated on the AFM-modified surfaces is most likely due to tunneling or other defect-assisted transport from the Schottky contact into the semiconductor[4,12] or to conduction along incompletely blocked conduction paths. Thermionic emission over the Schottky barrier[13] is insufficient to account for the measured current levels even when the effects of barrier lowering as a function of voltage are included.

While the time-intensive nature of the AFM-based surface modification procedure obviously limits its usefulness for large-scale device fabrication, the results presented here provide a clear confirmation of the dominant source of leakage currents in Schottky contacts to MBE-grown nitride material. In addition, these results elucidate the detailed nature of a microscopic mechanism for suppression of Schottky diode leakage current, and thereby provide insights into possible approaches for mitigation of these leakage-current effects by more practical techniques that replicate the local surface anodization that occurs during the AFM modification process. Indeed, we have recently developed a practical method based on these ideas in which electrochemical anodization of the GaN surface leads to selective suppression of localized conduction paths and a consequent reduction in reverse-bias leakage currents in Schottky diodes by a factor of approximately 10^3 while also improving the diode ideality factor and leaving the Schottky barrier height unchanged.[14]

IV. CONCLUSION

We have used conductive AFM to characterize localized dislocation-related conduction paths in *n*-type GaN grown by MBE, and to perform a highly localized surface modification process in which application of an electric field via a conducting probe tip induces the formation of a thin insulating layer above each conduction path that strongly suppresses subsequent current flow. Auger electron spectroscopy performed on GaN surfaces modified in this manner reveals that this thin insulating layer is most likely to be a gallium oxide compound, and that the chemical modification to the surface is confined to the immediate vicinity of each conduction path. A comparison of current–voltage characteristics for Schottky diodes fabricated with and without the incorporation of this surface modification process demonstrates that localized suppression of the dislocation-related conduction paths leads to a reduction in Schottky diode leakage currents of two to four orders of magnitude, and thereby provides definitive evidence that these conduction paths are the dominant source of leakage current in Schottky contacts to *n*-type GaN grown by molecular-beam epitaxy. The insights resulting from these studies suggest a variety of approaches for the development of more practical, easily implemented processes for leakage current suppression in Schottky contacts, one of which we have recently demonstrated and reported.

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