# Reverse-bias leakage current reduction in GaN Schottky diodes by electrochemical surface treatment

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An electrochemical surface treatment has been developed that decreases the reverse-bias leakage current in Schottky diodes fabricated on GaN grown by molecular-beam epitaxy (MBE). This treatment suppresses current flow through localized leakage paths present in MBE-grown GaN, while leaving other diode characteristics, such as the Schottky barrier height, largely unaffected. A reduction in leakage current of three orders of magnitude was observed for Schottky diodes fabricated on the modified surface compared to diodes fabricated on the unmodified surface for reverse-bias voltages as large as −20 V. In addition to suppressing reverse-bias leakage, the surface treatment was found to improve substantially the ideality factor of the modified surface diodes compared to that of unmodified surface diodes, suggesting that such a surface modification process could be useful for a variety of GaN-based electronic devices.  [DOI: 10.1063/1.1554484]

Large reverse-bias leakage currents can constrain the use of electronic devices fabricated with group III-nitride material due to the large power consumption and noise levels that can be present in circuits that incorporate such devices.[1] In GaN-based devices that utilize heterostructures grown by molecular-beam epitaxy (MBE), leakage currents can arise due primarily to the existence of discrete, dislocation-related leakage paths.[2] Previous studies have shown that these leakage paths can be blocked by the formation of insulating layers over these leakage paths using an atomic force microscope (AFM).[3] Because this process is not practical as a large-scale surface treatment due to the time-intensive nature of the AFM surface modification procedure, an alternative technique suitable for efficient treatment of large surfaces would be desirable.

The electrochemical oxidation of the surface of group III–V semiconductors in a basic solution is well understood,[4] and oxidation is believed to occur during anodic etching of GaN films in a NaOH electrolyte.[5] This method provides an attractive and much more efficient method by which to duplicate the physical process that is occurring in the AFM surface modification, in which negatively charged ions are attracted to the surface by applying a positive bias to the sample relative to the AFM tip as it scans across the sample surface.

In this letter, we describe a large-scale, electrochemical surface treatment based on the same physical process as the AFM surface modification, one which yields a similar reduction in reverse-bias leakage current. Detailed electrical characterization showed no significant change in the Schottky barrier height for diodes fabricated on the modified surface compared to diodes on the unmodified surface, as well as a substantial improvement in the ideality factor. An AFM was used in this work to characterize the surface after the electrochemical treatment, and no evidence was found of a uniform oxide layer on the surface, nor of localized insulating layers over the leakage paths as was seen in our previous study. However, the discrete, dislocation-related leakage paths were not observed on the modified surface using conductive AFM (CAFM).

The GaN samples used in this investigation were grown by MBE on a template that consisted of a thick GaN layer grown by metalorganic chemical vapor deposition (MOCVD) on a sapphire substrate. The MBE-grown GaN layer was approximately 350 nm thick, and it was grown close to the upper crossover point in the Ga droplet regime[6] with a dopant concentration in the mid-$10^{16}$ $cm^{-3}$ range. Surface modification was accomplished by anodizing the sample in a highly basic NaOH solution using a sample holder designed to make electrical contact to the sample while immersed in the solution, as shown in Fig. 1. The $p$H of the solution remained nearly constant at approximately 13.1 during the treatment, and the temperature was maintained at 30 °C. This process should attract $OH^-$ ions which are present in high concentrations in the solution to the GaN surface, similar to the AFM surface modification process in which the positive sample bias attracts ions from the thin water layer typically present on the surface as the tip passes over leakage paths.[3] Ohmic contacts employing Ti/Al/Ti/Au metallization[7] annealed at 750 °C for 30 s were fabricated on the sample surface prior to surface treatment to decrease the resistance between the cathode contact wire and the sample. Schottky contacts consisting of 1200 Å Ni were fabricated on the modified and unmodified surfaces.

AFM and CAFM were performed on modified and unmodified areas of the GaN surface to determine whether the localized leakage current paths had been blocked and

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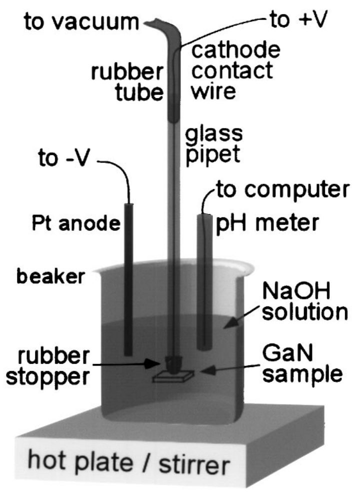


FIG. 1. Experimental apparatus used for the electrochemical surface treatment procedure.

whether the topography of the modified surface had been altered during the surface modification procedure. The procedure used to perform CAFM is described elsewhere.[3] The measured tip–sample currents for the unmodified and modified surfaces are shown in Figs. 2(a) and 2(b), respectively. A typical, high concentration of discrete leakage current spots is observed on the unmodified surface, as expected from previous studies of MBE-grown GaN heterostructures.[2,3] However, a significantly lower concentration of leakage current spots with dramatically reduced conductivities is observed on the modified surface, showing that the electrochemical surface treatment was highly successful in blocking the leakage current paths. Figures 2(c) and 2(d) show the topography of typical unmodified and modified surfaces, respectively. Based on AFM surface modification experiments of GaN, which employed similar physical principles to block the leakage current paths in the material,[3] small insulating is-

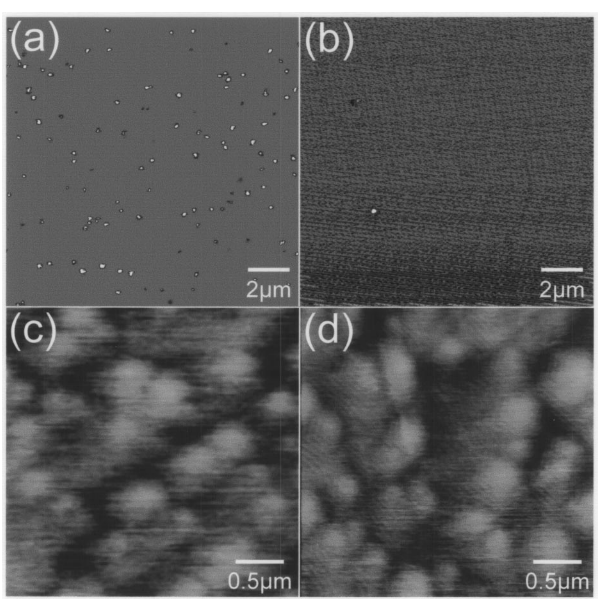


FIG. 2. Tip–sample current for unmodified and modified areas of the GaN surface (a), (b) and typical topographic images of unmodified and modified areas (c), (d). Bright spots in the current images (a), (b) correspond to approximately 10 $\mu$A and 100 pA, respectively. The vertical scale for topography images (c), and (d) is 10 nm.

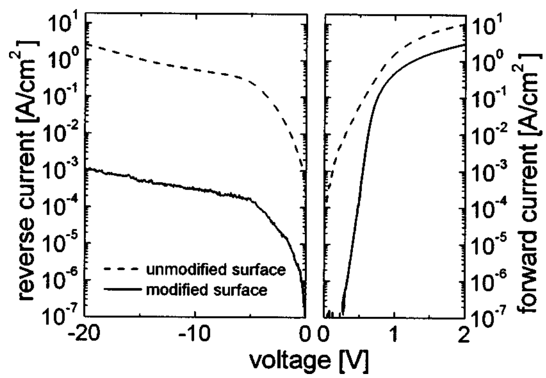


FIG. 3. Measured current–voltage characteristics of diodes with Schottky contacts fabricated on modified and unmodified areas showing the significant reduction in reverse-bias leakage current that is achieved by the electrochemical surface treatment.

lands were expected to be observed on the modified surfaces with density comparable to the density of leakage current paths observed in the unmodified surfaces. Contrary to these expectations, no significant change was observed in the topography of the surface after electrochemical treatment. This observation suggests that local modification of the current leakage paths occurs near, but below, the surface, or that a uniform oxide layer is formed on the surface of the GaN; the latter possibility will be discussed later.

Forward- and reverse-bias current–voltage characteristics measured at room temperature for typical diodes fabricated on the modified and unmodified surfaces are shown in Fig. 3. The reverse-bias leakage current in the diode fabricated on the modified surface is significantly reduced compared to that in the diode fabricated on the unmodified surface. The forward-bias characteristics also show a difference in current level for the two types of diodes. This is due primarily to the increase in series resistance of modified surface diodes, which is approximately four times as large as the series resistance in unmodified surface diodes. However, the drop in voltage across the series resistance in both diodes has a negligible effect on the reverse-bias current–voltage characteristics until approximately $-20$ V, at which point the drop in voltage across the series resistance in the unmodified surface diode becomes significant due to its high level of current. The current in the modified surface diode is sufficiently small that its series resistance can be neglected.

A reduction in leakage current of approximately three orders of magnitude in the electrochemically modified surface diode is observed for reverse-bias voltages as large as $-20$ V. In comparison, the AFM surface modification process achieved a reduction in leakage current of approximately two to four orders of magnitude for reverse-bias voltages as large as $-7$ V, and at $-20$ V bias, the leakage current was reduced by a factor of 10–100. Thus, the electrochemical surface treatment yields leakage current reduction comparable or superior to the AFM surface modification process, and the current reduction in the electrochemically treated diodes is significantly less voltage dependent.

The most obvious explanation for the reverse-bias leakage current reduction in the modified surface diodes would be the growth of an insulating oxide over the entire GaN surface. As stated earlier, electrochemical oxide growth on GaN in a basic solution has been previously reported during

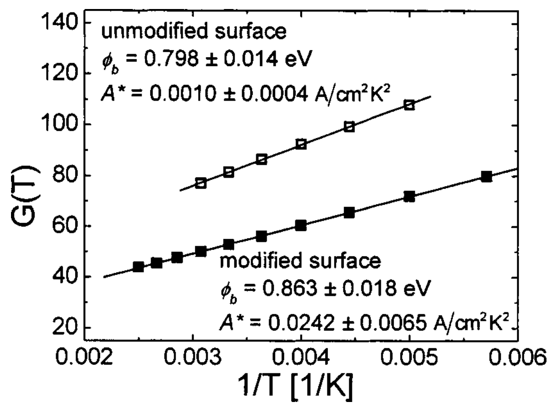


FIG. 4. Extraction of the Schottky barrier height and Richardson constant from linear fits to the function $G(T)$ for diodes fabricated on modified and unmodified surfaces.

the anodic etching of GaN; however, this growth is strongly influenced by the presence of $Cl^-$ ions and the intensity of UV light on the sample surface.[5] In this work, no evidence of an oxide layer of significant thickness on the GaN surface after electrochemical treatment was observed in AFM topographic images taken of the surface after treatment, as shown in Fig. 2(d) in which atomic growth steps are clearly visible.

The presence of an oxide layer would have also been evident in the forward-bias current–voltage characteristics of the modified surface diode. The Richardson constant $A^*$ and barrier height $\phi_B$ were extracted from $I-V$ measurements taken at several temperatures $T$, using the modified Norde function,[8] defined as

$$F1=\frac{qV}{2kT}-\ln\left(\frac{I}{T^2}\right), \tag{1}$$

where $q$ is the electron charge and $k$ is the Boltzmann constant. Plots of $F1$ vs $V$ exhibit a minimum $F1_{\min}(T)$ at voltage $V_{\min}$ with associated current $I_{\min}(T)$ at each temperature. For a known ideality factor $n$ and using $F1_{\min}(T)$ and $I_{\min}(T)$, a quantity of $G(T)=2F1_{\min}(T)+(2-n)\ln(I_{\min}/T^2)$ can be defined. The ideality factors of the modified and unmodified surface diodes were $1.13\pm0.02$ and $1.74\pm0.01$, respectively, supporting the earlier conclusion, based on the conductive AFM data shown in Figs. 2(a) and 2(b), that the electrochemical process suppressed the nonthermionic transport mechanism associated with conduction along discrete leakage current paths. For $V\gg kT/q$, $G(T)$ is given by

$$G(T)=2-n[\ln(AA^*)+1]+\frac{nq\phi_B}{kT}, \tag{2}$$

where $A$ is the area of the Schottky contact. Plots of $G(T)$ vs $1/T$ are shown in Fig. 4 for the unmodified surface diode (open squares) and for the modified surface diode (closed squares). A linear fit to the data for the unmodified surface diode yields a Richardson constant of $0.0010\pm0.0004\ \mathrm{A/(cm^2\,K^2)}$ and a barrier height of $0.798\pm0.014$ eV, while a linear fit to the data for the treated surface yields $A^*=0.0242\pm0.0065\ \mathrm{A/(cm^2\,K^2)}$ and $\phi_B=0.863\pm0.018$ eV. Both values for the Schottky barrier height are in good agreement with values reported for Schottky contacts fabricated on GaN grown by MOCVD-related methods without an oxide present,[9–11] and are well below the value that would be expected for a metal–oxide–semiconductor interface.[12] Furthermore, the forward-bias characteristics show that the series resistance of the modified surface diode is increased by only a factor of 4 compared to the series resistance of the unmodified surface diode, suggesting that no significant insulating layer has grown.

To test the theory that the dislocation-related leakage paths were preferentially altered during surface treatment as opposed to the entire surface of the GaN being modified, the electrochemical treatment was repeated on GaN samples grown by hydride vapor-phase epitaxy (HVPE), in which CAFM experiments show that discrete leakage paths are not present.[13] Schottky diodes fabricated on modified and unmodified surfaces of the HVPE-grown sample exhibited similar levels of reverse-bias leakage current, strongly suggesting that conduction specifically along the dislocation-related leakage paths in the MBE-grown GaN sample was prevented by electrochemical treatment.

In summary, an electrochemical surface treatment involving the anodization of a GaN surface in a highly basic, NaOH solution has been used to decrease the reverse-bias leakage current in Schottky diodes fabricated on modified GaN surfaces compared to those fabricated on unmodified GaN surfaces. A reduction in leakage current of approximately three orders of magnitude has been observed for modified surface diodes up to reverse-bias voltages of −20 V. No evidence of an insulating layer was observed on the modified surface based on high-resolution AFM images and detailed analysis of the forward-bias characteristics of the modified and unmodified surface diodes. However, blockage of the discrete, dislocation-related leakage paths is apparent from conductive AFM images, and the suppression of this nonthermionic current transport mechanism by the electrochemical process is confirmed by the improvement in the ideality factors of the modified-surface diodes.

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