Study of leakage defects on GaN films by conductive atomic force microscopy

JC Moore¹, JE Ortiz¹, J Xie², H Morkoç², AA Baski¹∗

¹Department of Physics and ²Department of Electrical Engineering, Virginia Commonwealth University, Richmond, Virginia 23284

Email: aabaski@vcu.edu

Abstract. We have used the techniques of atomic force microscopy (AFM) and conductive AFM (C-AFM) to investigate the forward and reverse bias conduction properties of defects in GaN films grown by molecular beam epitaxy (MBE) on metal organic chemical vapor deposition (MOCVD) templates. The surface morphology consists of holes interspersed between undulating spiral “hillocks” terminated by pits that have been associated with screw dislocations. For C-AFM measurements, a Pt-coated AFM tip was brought into contact with the GaN surface to form a microscopic Schottky contact. Reverse-bias current leakage is observed for ~10% of hillocks up to 12 V, and increases to approximately 50% of both hillocks and holes for bias voltages above 25 V. Leakage sites initially occur at ~10 V and increase substantially in number above ~15 V.

1. Introduction

In GaN films, surface terminations of threading dislocations with a screw component have been shown to exhibit reverse-bias current leakage, which is problematic for device applications. From previous studies of films grown via molecular beam epitaxy (MBE), the features that demonstrate such leakage behavior are generally spiral “hillocks,” which are presumably associated with screw dislocations. Previous studies report that 10 to 30% of spiral hillocks demonstrate leakage at sample biases of 12 V, which appear to correlate with TEM data showing similar percentages for screw dislocations. The exact mechanism responsible for such leakage is still debated, and has been attributed to both excess Ga incorporation and oxygen-related impurities in the vicinity of screw dislocation cores.

Both edge and screw dislocations have been imaged by techniques such as scanning Kelvin probe microscopy (SKPM) and scanning capacitance microscopy (SCM). It has been shown that edge dislocations have an intrinsic negative charge, but do not exhibit reverse-bias leakage. In contrast, dislocations with a screw component have no inherent charge but demonstrate leakage. Therefore, no strong correlation exists between charged dislocations and localized reverse bias leakage, implying that these phenomena have different origins.

Local I-V curves have been obtained in the vicinity of dislocations and defect regions. Shiojima et al. have found no change in I-V spectra taken on and off dislocations, whereas Spradlin et al. and our previous studies have shown discernible differences in both forward and reverse bias for defect regions on GaN films grown on hydride vapor phase epitaxy (HVPE) and metal organic
chemical vapor deposition (MOCVD) templates. Studies by Miller et al.\textsuperscript{16} have attributed leakage to two mechanisms: field-emission tunneling and exponential temperature dependence consistent with trap-assisted tunneling or 1D hopping associated with threading dislocations. Spradlin et al.\textsuperscript{4} attributed forward bias conduction to field-emission and Frenkel-Poole conduction in regions off and on leakage sites, respectively, which were confirmed by the authors of this paper.\textsuperscript{15} In addition, both Miller et al.\textsuperscript{17} and Spradlin et al.\textsuperscript{4} report a shift in forward-bias turn-on voltage, as well as the formation of insulating bumps on hillocks showing leakage after successive scans.

In this study, we have used conductive atomic force microscopy (C-AFM) to probe the local $I$-$V$ characteristics of regions on and off leakage defects for MBE GaN films grown on MOCVD templates. We have also investigated leakage behavior at higher voltages (>12 V) via C-AFM current maps.

2.  Experiment

GaN films were grown by MBE on 1-2 μm thick GaN templates prepared by MOCVD on sapphire substrates. The Ga source consisted of two double-zone Ga cells, and nitrogen was supplied by an RF plasma source. Before loading into the MBE chamber, the MOCVD templates were cleaned by HNO$_3$:HCl (1:3) acid (100 °C, 20 min). The films were grown under Ga-rich conditions with substrate temperatures of 650 to 700 °C. After opening the Ga cell shutters for 10 s, the nitrogen RF source was opened with a power setting of 300 W. Typical growth rates were 200 to 300 nm/hr, where a 1×1 RHEED pattern was observed for Ga-rich growth conditions.

For C-AFM data acquisition, Ohmic contacts were formed on all samples using Ti/Al/Ti/Au metallization, and a microscopic Schottky contact was formed between the metallized C-AFM tip and sample. Data were acquired using a Veeco Dimension 3100 AFM with Ti/Pt-coated cantilevers and a current amplifier module with a range of 1 pA to 1 μA. Typically, higher-resolution tapping-mode topography images were acquired prior to C-AFM imaging, and contact-mode topographs were acquired simultaneous with C-AFM current images. For high voltage studies (>12 V) the external bias voltage was applied to the sample surface via a selectable battery source (1.5 – 60 V).

3.  Discussion

The surface morphology of the GaN film is shown in figure 1(a) and consists of spiral hillocks with a low density of interspersed holes. The holes have typical diameters of ~150 nm, depths of ~350 nm, and a density of ~2×10$^8$ cm$^{-2}$. Samples grown under less Ga-rich conditions showed a higher density of such holes with larger diameters. These holes may be the result of edge dislocations formed during hillock coalescence. In the centers of hillocks, small pits or dislocations are seen that are 15-30 nm wide and 50-85 nm deep [see figure 1(b)]. These pits are most likely associated with the termination of screw dislocations at the surface. Figure 1(c-d) shows a contact-mode topograph and simultaneously acquired reverse-bias current map, respectively, of the area shown in figure 1(a). Current conduction can be seen at a hole [black circle in figure 1(c,d)] and more prominently at the top of a hillock [white circle in figure 1(c,d)]. At bias voltages up to ~12 V, approximately 10% of the hillocks show leakage behavior. After multiple scans in an image area, the leakage current observed at a defective hillock decreases and the height of the hillock increases. This effect is apparent in figure 1(c), where the marked hillock appears brighter, i.e. higher, than in figure 1(a) taken a few scans earlier. As suggested by Miller et al.,\textsuperscript{17} this height increase is most likely due to the growth of a gallium oxide island on the hillock that results from an electrochemical reaction between the GaN and the ambient environment. This phenomenon will be discussed in more detail later in this paper as part of our higher voltage studies.
Figure 1: (a) Tapping-mode AFM image (2×2 μm², Δz = 3 nm) showing spiral hillocks (white circle) with interspersed holes (black circle). (b) Higher-resolution image of the hillock circled in (a) with a visible pit at its apex. (c) C-AFM contact-mode image (Δz = 4 nm) of the same area with (d) simultaneous current image at 10 V reverse bias (ΔI = 10 pA).

In addition to C-AFM imaging, we acquired local I-V spectra up to 12 V that were taken from leakage sites on hillocks and from nearby non-leakage areas. Figure 2(a-b) shows that enhanced current conduction occurs in both forward and reverse bias on a hillock leakage site. In reverse bias, detectable current occurs at 10 V on the hillock, whereas no measurable current occurs off the hillock. In forward bias, the current has a lower turn-on voltage and increases more rapidly on the hillock as compared to off the hillock. This difference in forward turn-on voltage may indicate charge-trapping effects. Note that the I-V data presented here were recorded immediately after location of a leakage site. It was found that subsequent I-V spectra indicated lower leakage currents, which is consistent with our imaging observations (see figure 4).

As mentioned earlier, reverse-bias current leakage occurs on approximately 10% of hillocks at 12 V, which is consistent with previous studies on MOCVD templates.10 Hsu et al.6 has proposed that these leakage paths are associated with pure screw dislocations, an assertion supported by a combined C-AFM and TEM study of different GaN templates. Our study has found, however, that a significantly higher percentage of hillocks, as well as holes, demonstrate leakage behavior at applied potentials greater than 12 V. Figure 3 shows the leakage site density as a function of potential for a sequence of large-scale C-AFM images. The leakage site density increases dramatically at ~15 V and continues to rise until approximately 50% of both hillocks and holes show leakage above 25 V. These higher voltage data suggest that edge and/or mixed dislocations are also associated with leakage sites, since screw dislocations have a lower density than that of the leakage sites.
Figure 3: Total and new leakage site densities for all features (holes and hillocks) as a function of applied potential. These data were obtained from a sequence of large-scale C-AFM images.

Figure 4: (a) C-AFM contact-mode image (left, 5×1.25 μm², Δz = 8 nm) with simultaneous current image (right) at 0 V. (b-d) Sequential C-AFM scans of the same region at 28 V reverse bias (Δz = 50 nm, ΔI = 1 nA) recorded for the indicated scan number. (e) Plot of height vs. scan number for the island indicated by the white circle in (b).

It was noted in the discussion of figure 1 that sequential scans of hillock leakage sites resulted in an apparent increase in the hillock height. This effect is even more pronounced at higher voltages for C-AFM data acquisition. Figure 4 shows a sequence of C-AFM contact-mode images and simultaneous current images at 28 V reverse bias for the same region taken after a number of scans. As is evident in figure 4(b-d), the six hillocks that initially demonstrate leakage in figure 4(b) show an increase in island height and decrease in leakage current with subsequent scans. This behavior has been previously observed\(^\text{15,17,18}\) and has been attributed to local oxidation of the surface.\(^\text{17}\) We have found that the apparent island height initially increases in a linear manner with scan number [figure 4(e)], but eventually reaches a maximum value. This limiting behavior is consistent with oxidation since the electrochemical reaction must eventually stop due to the decrease in leakage current. It is noteworthy, however, that the apparent height of the islands can change when acquiring C-AFM images under forward-bias conditions. In this case, depressions can be observed in the centers of the hillocks where islands previously were present. This effect could be caused by local charging of the islands that results in an additional attractive Coulombic force between the tip and sample, resulting in a decreased effective surface height in topography images. Using this same argument, it is also possible that the observed island heights under reverse-bias conditions can be modified by local charging effects.
4. Summary
In summary, C-AFM data have been shown for a GaN film grown by MBE on a GaN template prepared by MOCVD on a sapphire substrate. As expected, current images show that reverse-bias leakage occurs primarily at defective hillocks on the surface at lower voltage (<12 V). Such hillocks are presumably associated with screw dislocations that lead to this leakage behavior. Local I-V spectra taken on defective hillocks show enhanced current leakage in reverse bias and lower turn-on voltages in forward bias. Under higher bias conditions, however, C-AFM images show that approximately half of all hillocks and holes show current leakage above 25 V. This observed increase in leakage site density at higher bias voltage as compared to previous studies at lower voltage suggests that pure screw dislocations are not solely responsible for current leakage.

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