Direct imaging of reverse-bias leakage through pure screw dislocations in GaN films grown by molecular beam epitaxy on GaN templates

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Excess reverse-bias leakage in GaN films grown by molecular beam epitaxy on GaN templates is correlated with the presence of pure screw dislocations. A scanning current–voltage microscope was used to map the spatial locations of leakage current on high quality GaN films under reverse bias. Two samples with similar total dislocation density ($\sim 10^9$ cm^{-2}) but with pure screw dislocation density differing by an order of magnitude were compared. We found that the density of reverse-bias leakage spots correlates well with pure screw dislocation density, not with mixed dislocation density. Thus, pure screw dislocations have a far more detrimental impact on gate leakage than edge or mixed dislocations. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1490147]

High electron mobility transistors (HEMTs) based on AlGaN/GaN heterostructures are the building blocks of wide band gap nitride electronics for high power, high frequency applications. A high mobility two-dimensional electron gas (2DEG) is formed at the interface of AlGaN and GaN due to the piezoelectric and spontaneous polarization fields in wurtzite III nitrides. Molecular beam epitaxy (MBE) has become a leading growth method for HEMTs because of its low background impurity and precise control of layer thickness in the nanometer range. Due to the lack of lattice matched substrates, high densities of threading dislocations are present in today's nitride films, typically 10^8–10^{10} cm^{-2}. Threading dislocations extend the entire thickness of an epitaxial film and propagate through active layers of electronic devices. Dislocations have been reported to limit 2DEG mobility due to their charges,[1,2] as well as provide unwanted current pathways.[3,4] The latter results in reverse-bias gate leakage in GaN diodes[5] and shorting through base electrodes in heterobipolar transistors.[4] In order to reduce the threading dislocation density in devices, some groups are exploring MBE growth of GaN on GaN templates, which are produced by hydride vapor phase epitaxy (HVPE)[2] or metalorganic chemical vapor deposition (MOCVD).[6] In the case of epilayers grown on templates, if dislocations act as conduction paths into the template layer, a parallel conduction channel of lower density and mobility can coexist with the 2DEG and degrades device performance. As the GaN community pushes for commercialization, it is important to understand the electronic transport properties of threading dislocations.

All three types of dislocations, differentiated by their Burgers vector ($\mathbf{b}$): pure edge ($\mathbf{b}=\mathbf{a}$), pure screw ($\mathbf{b}=\mathbf{c}$), and mixed ($\mathbf{b}=\mathbf{a}+\mathbf{c}$) dislocations, are present in wurtzite nitride films.[7] Currently the effect of each type of dislocations on device performance is not understood. Several experiments found that edge dislocations are less electrically active than pure screw or mixed dislocations.[3,8] The question remains whether the electrical activity is different for pure screw and for mixed dislocations. Due to the high density of dislocations, spatially resolved techniques are needed to separate intrinsic from defect-induced properties. In this letter, we show that pure screw, not mixed, dislocations are the primary culprit in reverse-bias gate leakage. This conclusion was arrived by performing scanning current–voltage microscopy (SIVM) experiments on high quality GaN films grown by MBE that contain drastically different densities of pure screw dislocations.

A SIVM is a modified atomic force microscope, with a voltage bias applied between a conducting tip and the sample and the resulting current detected using a current preamplifier. The tip acts as a nanometer-size Schottky contact to the GaN sample. This method directly maps the locations of nonzero reverse-bias current, determines the density of leakage spots, and measures the magnitude of the current density. The capability of SIVM to simultaneously acquire topographic images allows us to correlate electrical properties with surface features. The SIVM experiments were performed in air at room temperature. Indium was soldered on the samples as ohmic contacts. All images were taken using boron-doped conducting diamond tips.

Sample A is an undoped GaN film grown on a template prepared by HVPE. The background doping concentration in the MBE layer is typically below mid 10^{15} cm^{-3}.[2,9] The HVPE templates were nominally 15 μm thick, and the thickness of the MBE GaN is $\sim$0.4 μm. Sample A was grown under Ga-rich growth conditions. The Ga droplets were removed by HCl before electrical measurements. Transmission electron microscopy (TEM) studies of this type of samples were reported previously.[10] The total dislocation density is $\sim 1\times10^9$ cm^{-2}, with ~ 2–4×10^8 cm^{-2} being pure screw

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dislocations. No new dislocations were generated in the MBE layer. Thus, the dislocation density and type on the surface of the MBE GaN are determined by the HVPE template. Sample B is Si doped (10^{17} cm^{-3}) GaN grown on a MOCVD template. This sample was grown near stoichiometric conditions but on the Ga rich side. The MBE layer was 0.5 μm thick and the template was 2 μm thick. Compared with HVPE film, MOCVD GaN contains a smaller percentage of pure screw dislocations. In HVPE films, we found the ratio of screw/mixed/edge dislocations to be roughly 1/3 each,[10] in agreement with other TEM results.[11] But in MOCVD films, well below 10% of the dislocations have pure screw character and the majority of dislocations is either edge or mixed.[12] Detailed TEM studies on samples similar to sample B can be found in Ref. 14. Consequently, a MOCVD sample with total dislocation density of 1×10^9 cm^{-2} has a pure screw dislocation density in the low 10^7 cm^{-2}. Comparing SIVM images taken on these two samples enables us to sort out the contribution to reverse-bias leakage due to pure screw versus mixed dislocations since their pure screw dislocation densities differ by an order of magnitude while mixed dislocation densities are comparable.

Figure 1 shows representative 2 μm$\times$2 μm images taken on sample A. Figure 1(a) shows the characteristic surface morphology of GaN grown under Ga-rich growth conditions: monolayer steps between hexagonal hillocks. These hillocks are pure screw or mixed dislocations.[6,9] Figure 1(b) is the SIVM image simultaneously taken under reverse bias of -5 V, in which dark regions are locations of nonzero current. Clearly, the reverse-bias current distribution is highly nonuniform; current flow concentrates in small isolated regions [dark spots in Fig. 1(b)] while most of the sample does not conduct. The density of leakage spots in sample A is $\sim2.5\times10^8$ cm^{-2}. Since TEM results on this sample show a total dislocation density of 1×10^9 cm^{-2}, only a quarter of the threading dislocations are conducting paths. Note in Fig. 1 that leakage spots occur at the center of hillocks [Fig. 1(c)] though some hillocks do not show leakage. These results indicate that reverse-bias leakage arises from dislocations with a screw component, while pure edge dislocations are less deterimental. However, more definitive statements on the difference between pure screw and mixed dislocations cannot be drawn from this sample alone.

Figure 2 shows a representative 5 μm$\times$5 μm area of sample B. Figure 2(a) is a topographic image taken under tapping mode, in which small pits are dislocations. Their density is $\sim1\times10^9$ cm^{-2}, in agreement with expected total dislocation density. Monolayer steps are visible, indicative of Ga rich growth conditions. Figure 2(b) is a SIVM image taken under reverse bias of -8 V at the same sample position as Fig. 2(a). We use the large pits, which are not individual dislocations, to crosscorrelate results from the two measurements. The current features associated with these large pits are most likely topography artifacts because they show no bias dependence but depend on the scan direction. In contrary, dislocation-induced leakage spots which depend on bias but not scan direction. While samples A and B display different surface morphology, the SIVM results can be compared because we previously established that the density of leakage spots is independent of MBE film morphology.[3] The density of leakage spot in sample B is $\sim3.7\times10^7$ cm^{-2}. Every leakage spot corresponds to a pit. That is, 4% of the dislocations are reverse-bias leakage paths. Since mixed or edge dislocation density is an order of magnitude larger, this density agrees well with the pure screw dislocation density.

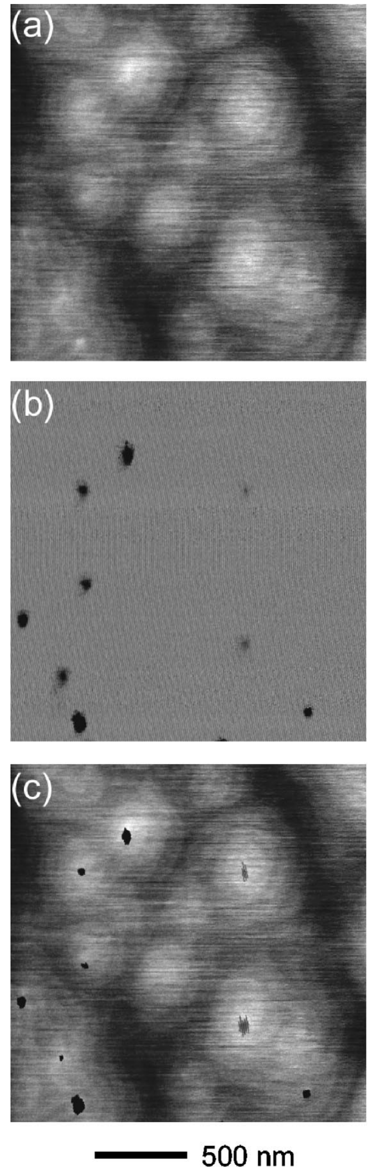

FIG. 1. Representative 2 μm$\times$2 μm SIVM images of a MBE/HVPE film (sample A). (a) Contact-mode topographic image and (b) simultaneously taken SIVM image under reverse bias -5 V. The reverse-bias current is defined with a negative sign. Hence, in (b), current level is below the detection limit (4×10^{-13} A) in gray areas and dark regions mean there is measurable current. (c) Overlay of leakage spots from (b) on topography. Grayscale represents 3 nm in (a) and 1.6×10^{-11} A in (b).

The result of this experiment is significant because, despite that the two MBE GaN films were grown in different reactors on different templates, contained different background dopant concentration, and displayed different surface morphology, they behave similarly under reverse bias. Both samples show isolated reverse-bias leakage spots, the magnitude and the size of which become larger as bias increases, and develop insulating bumps on top of the leakage at high reverse bias.[13] With our previous results,[3] this confirms that the density of leakage spots is solely determined by the tem-

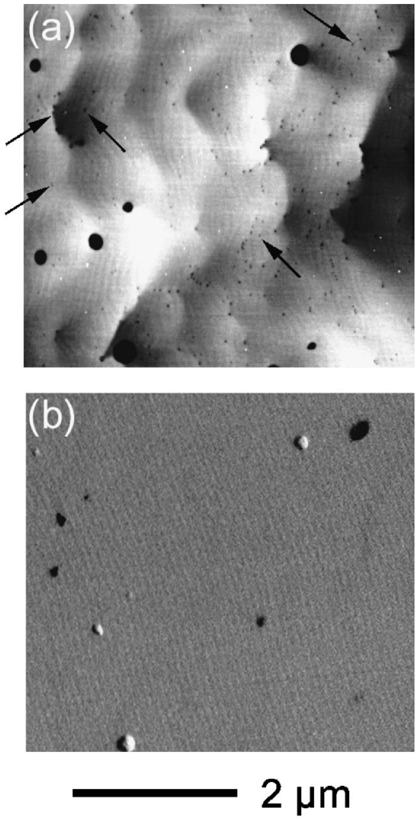

FIG. 2. Representative 5 μm×5 μm (a) tapping-mode topographic image and (b) SIVM image taken under reverse bias −8 V of a MBE/MOCVD film (sample B). The topographic images were not acquired simultaneously with the current image. The tapping-mode operation is necessary to obtain the high resolution needed to resolve dislocation pits. The arrows indicate the pits that are associated with reverse leakage spots. Grayscale represents 8 nm in (a) and 2×10^{-11} A in (b).

plate. In this study, the HVPE and MOCVD templates have similar total dislocation density, but the pure screw dislocation density is an order of magnitude higher in the HVPE compared to the MOCVD template. The finding that the density of leakage spots correlates with that of pure screw dislocations indicates pure screw dislocations are the primary source for reverse-bias leakage.

Currently little is known about the structure of pure screw dislocations. Theoretically, an open core structure was found for screw dislocations[14] based on balance of surface and elastic energy. However, recent first-principles total energy calculations show that, under Ga-rich growth conditions, a structure with a Ga-filled core is energetically more favorable than an open core structure.[15] Experimentally, both a full core[16] and an open core (nanopipe)[17] structure have been reported. Nanopipes in GaN are hollow tubes of diameter 2–50 nm and are associated only with pure screw dislocations. The fact that nanopipes are found in GaN films grown on sapphire by MOCVD[17] and HVPE,[18] but not by MBE, suggests that the screw dislocation core structure is sensitive to growth methods and stoichiometry. Previously we show that MBE growth stoichiometry has a significant impact on the dislocations' core structure and affects the magnitude of the reverse-bias leakage.[9] Nevertheless, the leakage spot density is comparable to the screw/mixed dislocation density for both Ga-rich and Ga-lean films. Since Ga is a surfactant during GaN growth[19] and nanopipes in the template provide additional surfaces, it is reasonable that excess Ga during the MBE growth can have a large influence on pure screw dislocation core structure. Such an effect is not expected for pure edge or mixed dislocations because they do not contain nanopipes. More detailed research on core structure of screw dislocations are underway.

In summary, pure screw dislocations are shown to be the primary source for reverse-bias gate leakage in GaN grown by MBE on GaN templates. This conclusion was reached by comparing reverse-bias leakage maps for two samples with drastically different pure screw dislocation densities. We discuss how the presence of nanopipes in the template might be responsible for the observed electrical behavior.

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