Electric force microscopy of induced charges and surface potentials in GaN modified by light and strain

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We have studied molecular beam epitaxy grown GaN films using electric force microscopy to detect sub-1 μm regions of electric field gradient and surface potential variations associated with GaN extended defects. The large piezoelectric coefficients of GaN together with strain introduced by crystalline imperfections produce variation in piezoelectrically induced electric fields around these defects. The consequent spatial rearrangement of charges can be detected by electrostatic force microscopy, and can be additionally modified by externally applied strain and illumination. The electron force microscopy signal was found to be a function of the applied tip bias, showed reversal under externally applied strain, and was sensitive to above band gap illumination. © *1999 American Vacuum Society.* [S0734-211X(99)05704-2]

I. INTRODUCTION

Nitride based devices have been of great interest in the last few years, notably due to their success in optoelectronics, where blue light emitting lasers and diodes have been demonstrated, and later successfully commercialized.[1] Further applications of nitrides are expected in the arena of high power and high temperature devices,[2–4] as well as solar blind ultraviolet detectors.[5] It has been recently demonstrated that the large intrinsic piezoelectric coefficients of GaN and AlN are responsible for an anomalously large concentration of two-dimensional electron gas at the AlGaN/GaN interface in GaN/AlGaN heterojunction field effect transistors (HFET).[6,7] Other possibilities exist for the enhancement of electric properties of contacts to nitrides by piezoelectric engineering as recently demonstrated in the case of Schottky contacts.[8] While most of the recent research has emphasized electronic device aspects of the piezoelectric effect,[6–8] comparatively little work has concentrated on the investigation of fundamental properties and nanoscale characterization of piezoelectrically induced phenomena. One consequence of the piezoelectric effect is that it allows electrostatic force imaging of charge redistribution around defects due to local variations in strain caused by crystalline imperfections. Albeit nonquantitative, electric force microscopy (EFM) of electric field gradients can provide interesting insight into the nature of both defects and piezoelectric effect in nitrides, while surface potentiometry can quantitatively map the change in surface potentials due to charge redistribution.[9,10]

II. EXPERIMENT

The gallium nitride layers studied here were grown on c-plane sapphire substrates by radio frequency plasma assisted molecular beam epitaxy (MBE). Details of the growth conditions are presented elsewhere.[11,12] The GaN films were nucleated using AlN buffer layers, and are predominantly Ga polar as determined by reflection high energy electron diffused diffraction (RHEED) reconstruction at low temperature,[13] and by KOH etching.[14,15] Growth conditions were slightly Ga rich, leading to locally flat (0001) Ga-face films which contain pits on the surface induced by dislocations or $(000\bar{1})$ inversion domains threading along the growth direction. These pits are readily observed in atomic force microscopy (AFM) images.[16]

The EFM data were collected using a Digital Instruments Nanoscope IIIa controller and a Bioscope scanning probe microscope operating in tapping mode. EFM was performed in two ways: by detecting the electric field gradient and by detecting the surface potential. To detect the electric field gradient, a voltage is applied to a metallic coated AFM tip which is scanned across the surface at a constant tip–sample separation. Phase differences induced by electrostatic forces on the oscillating tip are detected and give a qualitative measurement of local electric field gradients. To detect the local surface potential, an oscillating voltage is applied directly to the AFM tip; $V_{applied} = V_0 \cos(\omega t)$. The tip feels a force of $F = (dC/dz)(V_{tip} - V_{sample})V_{applied}$ where (dC/dz) is the vertical derivative of the tip–sample capacitance. In order to determine the surface potential of the sample, the tip voltage is adjusted to equal the sample potential so that the tip feels no force. In all cases the tip–sample separation was set at 50 nm.

III. RESULTS AND DISCUSSION

The electric field gradient was measured as a function of tip voltage to rule out topographical artifacts. Topography can affect the EFM image for films with a permanent polarization, **P**, since the surface charge $\sigma_s = \mathbf{P} \cdot \hat{\mathbf{n}}$ where $\hat{\mathbf{n}}$ is the surface normal, will not be constant over a rough surface. Variation in the induced surface charges result in a force differential between the tip and the surface that increases with tip voltage which can be observed in the series of EFM images in Fig. 1. It was also found that the force gradient was a function of the magnitude of the tip voltage and not the sign, consistent with the theoretical V^2 dependence.[10,17]
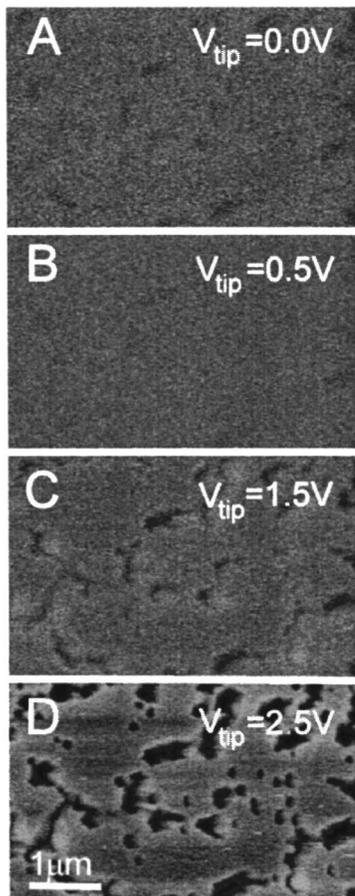

FIG. 1. Electric field gradient image as a function of tip applied voltage to an unstrained, unilluminated sample. The AFM tip bias increases from A–D.
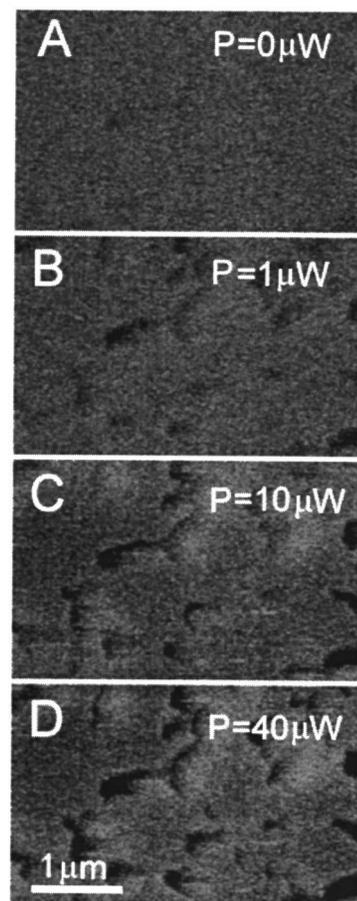

FIG. 3. Electric field gradient image as a function of optical power at 325 nm. Optical power increases from A to D. Tip bias = 5 mV, and the tip-sample separation was 50 nm.
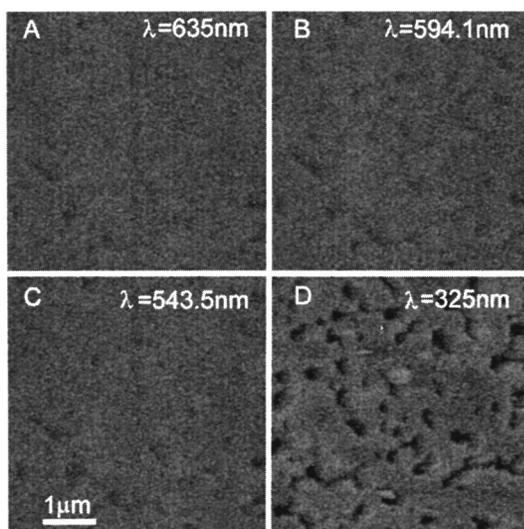

FIG. 2. Electric field gradient images at different illuminating wavelengths indicated in the upper right of each image. The tip bias was held at 5 mV with 50 nm tip–sample separation in all cases. A: 20 mW red diode laser; B: 1 mW yellow HeNe laser; C: 1 mW green HeNe laser; D: 10 μW from an UV HeCd laser.

The electric force was also found to be light sensitive and was measured at several discrete wavelengths above and below the GaN band gap energy (3.4 eV = 365 nm) using lasers at 635, 594.1, 543.5, and 325 nm as shown in Fig. 2. The sample was illuminated at a small glancing angle to eliminate interference with the AFM. The tip voltage was held constant at 5 mV, creating very weak contrast in the EFM image without illumination as observed in Fig. 1A or 3A. When the sample was illuminated with a photon energy below band gap (Figs. 2A–2C) no apparent difference in EFM contrast could be observed, even with optical powers above 1 mW. However, there is a significant increase in EFM contrast when the sample is exposed to light with a photon energy above the band gap (Fig. 2D). This increase is associated with the generation of electron-hole pairs, which cannot be obtained with photons of energy smaller than the GaN band gap. We speculate that the separation of generated charges by internal polarization fields, as well as the increase in the sample conductivity are responsible for the observed change.

Figure 3 shows the EFM images obtained with tip voltage held constant at 5 mV, illuminated with the 325 nm laser, as
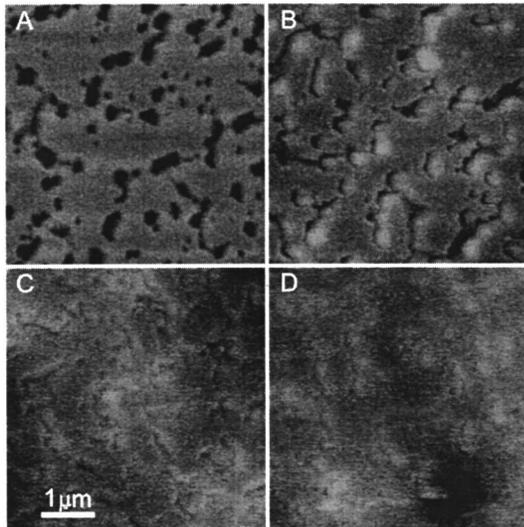
FIG. 4. A: Electric field gradient of an unstrained sample; B: electric field gradient of a strained sample. In both cases, the tip voltage was held at 2.0 V; C: surface potential of an unstrained sample; D: surface potential of a strained sample. In all cases the sample was unilluminated and the tip-sample separation was 50 nm.

a function of the optical power. The optical power required to produce a visible change in the EFM image was found to be as small as 1 μW. No change could be observed for the longer wavelengths even for optical powers up to three orders of magnitude greater.

Since the piezoelectric effect will change the magnitude of the internal fields and consequently the surface charge distribution/potential, a homebuilt stage was used to externally apply strain to GaN films by bending the sapphire substrate. The induced strain is tensile and approximately 1%. Subsequently, both electric field gradient and surface potential measurements were made on unstrained and strained samples and are shown in Fig. 4. Contrast reversal is observed in the electric field gradient signal of the strained sample as shown in Figs. 4A and 4B. Strained samples also showed regions which had changes in the surface potential of approximately 0.1 V as indicated in Figs. 4C and 4D. The strain induced polarization fields are believed to be responsible for the observed changes in electric field gradients and surface potential.

These experimental results clearly show that defects in GaN can induce electric field and potential inhomogeneities that are detectable by EFM. The exact nature of these inhomogeneities, however, remains unclear. We can speculate on several possibilities, including the effects of inversion domains and threading dislocations. First, in the case of inversion domain defects, the spontaneous and strain-induced polarization within these domains is antiparallel to that of the bulk crystal, and obviously would induce opposite surface charging effects. The presence of inversion domains can explain the contrast reversal observed for samples under applied strain. In the case of threading dislocations, localized strain will result in piezoelectric charging where the dislocation intersects the surface. Other possibilities include Fermi level pinning effects and local band bending.

IV. CONCLUSIONS

In summary, we have successfully demonstrated that EFM technique can be used to detect local variations in piezoelectrically induced charge and potential on the sub-1 μm scale. We have found that electron-hole pair generation by light illumination can significantly enhance observed contrast in the EFM images, which we associate with the charge separation due to builtin polarization fields. External application of strain caused contrast reversal in EFM signal which is attributed to the increase in induced polarization fields over the builtin polarization fields.

ACKNOWLEDGMENTS

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