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Polarization Field Mapping of AlGaN/GaN HEMT Devices using Lorentz-mode Electron Holography

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The AlGaN/GaN heterostructure provides the basis for the current generation of high electron mobility transistor (HEMT) devices [1]. In the case of III-nitride materials grown in the usual *c*-plane direction, spontaneous and piezoelectric polarization fields give rise to a two-dimensional electron gas (2-DEG) at the heterostructure interface. The presence of the 2-DEG leads to devices with high electron mobility that are suitable for high voltage, high frequency applications such as microwave communications and high power amplifiers [2]. Phase imaging by Lorentz-mode electron holography has been used to quantify the electric field across the AlGaN layer from source to drain in actual transistor devices. The transistors were prepared for electron holography observation by backside milling with a Nova 200 focused-ion-beam (FIB) system. Transistor cross-sections were lifted out using a forked probe tip, then mounted in a copper washer for backside milling using a shortcut press. Membranes were thinned to electron transparency from the substrate side with a final Ga ion-beam energy of 5 keV. Off-axis electron holography was performed using an electrostatic biprism and a Lorentz minilens to provide an expanded field of view [3].

Figure 1 shows SEM and TEM micrographs of a typical transistor cross-section after final FIB milling. The top of the gate was removed to allow the vacuum proximity that is necessary for off-axis electron holography observation. Hologram/reference image pairs of the AlGaN/GaN hetero-interface were recorded for several locations between the HEMT device source and drain. Phase and thickness images were calculated off-line. A typical phase profile of the region under the gate is shown in Figure 2. The magnitude of the electric field within the AlGaN layer was calculated from the slope of the phase (Δø) using the relationship: $E=\Delta ø/t/C_e$, where t is the sample thickness as determined from the thickness image, and C_e is an energy-dependent interaction constant. The vertical electric field was measured at several points between the source and drain, and the results are plotted in Figure 3. A peak electric field of 0.78 MV/cm was measured below the gate. The vertical electric field between the gate and source remained relatively constant at ~0.6 MV/cm, but its strength near the source dropped to ~0.4 MV/cm. A similar minimum was also measured close to the drain contact. These minima are possibly caused by contact/channel alloying during processing, which is visible in certain regions below the source in Figure 3 [4].

[1] O. Ambacher et al., *J. Appl. Phys.* 85 (1999) 3222-3233.
[2] U.K. Mishra et al., *Proc. IEEE* 96 (2008) 287-305.
[3] M.R. McCartney et al., *J. Appl. Phys.* 82 (1997) 2461-2465.
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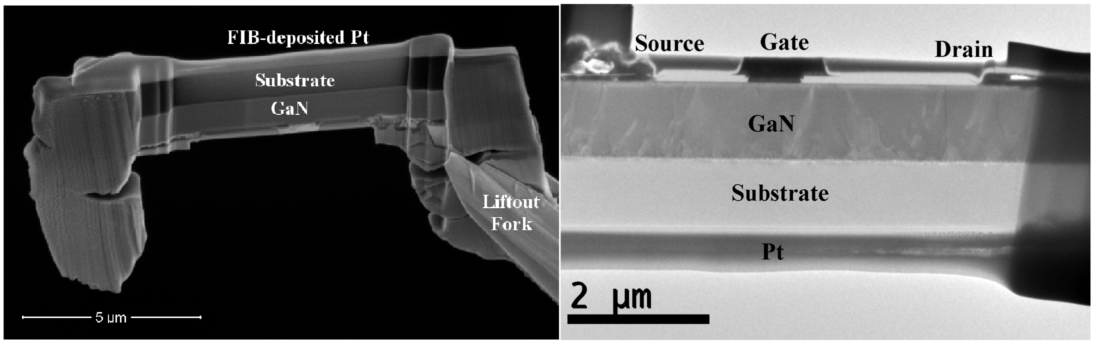

Figure 1. (Left) SEM and (right) TEM images of HEMT transistor device prepared for electron holography observation by FIB liftout method.

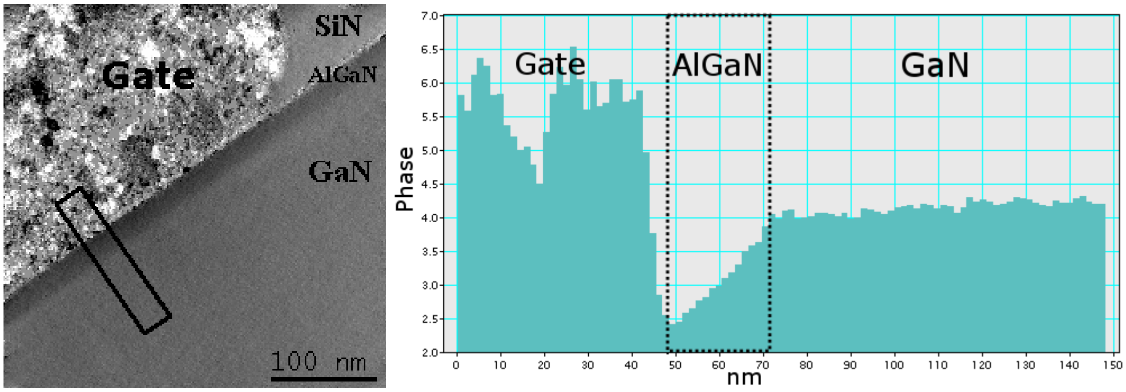

Figure 2. (Left) Electron holography phase image of AlGaN/GaN heterostructure in HEMT transistor device from region below the gate. (Right) Complementary phase profile. The slope of the phase in the AlGaN layer was used to quantify the intrinsic electric field arising from spontaneous and piezoelectric polarization.

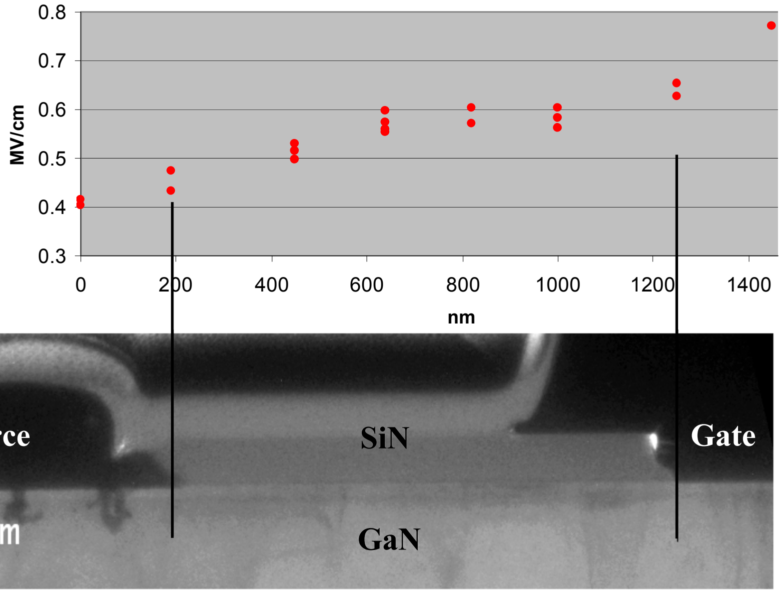

Figure 3. (Top) Plot of vertical electric field values across AlGaN layer measured at various points from source to gate. (Bottom) TEM image of area under investigation. The electric field was highest below the gate and lowest under the source and drain contacts.

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