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HAADF-STEM and electron holography observations of AlInGaN/GaN heterostructures

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AlGaN/GaN heterostructures have attracted much attention because of powerful applications to high-power, high-frequency and high-temperature devices [1,2]. In addition to a large conduction band offset at interfaces, an intense internal electric field caused by both spontaneous and piezoelectric polarizations in an AlGaN layer grown on a GaN layer induces the formation of a two-dimensional electron gas (2DEG) at the interfaces [3]. With increasing Al content, the internal electric field is expected to become larger, leading to the increase of the 2DEG density. However, such higher Al content increases the lattice mismatch of AlGaN/GaN and consequently forms a larger number of defects at the interface, which results in the degradation of the device performance.

Recently, in order to reduce the unfaborable defects by minimizing the lattice mismatch, the incorporation of indium in AlGaN (namely AlInGaN) has been proposed, in where the electrical properties of AlInGaN/GaN were better than that of AlGaN/GaN [3,4]. However, structural and compositional evaluations of the AlInGaN layer and the effects of them on the 2DEG have not been examine microscopically so far.

In the present work, we characterize an atomic structure, compositional uniformity and charge distribution of 2DEG at the AlInGaN/GaN quantitatively by high-angle annular dark field scanning transmission electron microscopy (HAADF-STEM) and electron holography.

The observed samples were a MOCVD grown GaN layer, followed by a thin layer of $Al_{0.345}In_{y0.015}Ga_{0.64}N$ (about 20 nm thick), on the sapphire substrate. This composition is theoretically expected to allow the sample to possess the same lattice strain as that for $Al_{0.275}Ga_{0.725}N$, which is largely below the structural critical. However, this material is expected to demonstrate the internal electric fields larger than that for $Al_{0.275}Ga_{0.725}N$ mainly due to larger spontaneous polarization.

We prepared [11-20] oriented AlInGaN/GaN cross-section samples by a chemical mechanical polishing combined with a wedge technique [5]. The HAADF-STEM and electron holography observations were performed using JEM-2500SES equipped with Cs-corrector and JEM-3000F, respectively.

Figure 1 shows a HAADF-STEM image of the AlInGaN/GaN interface. Two different contrast zones are recognized as the difference of atomic number Z. It is clear that the composition changes abruptly with a width of about 1nm. The detailed analysis of ADF counts showed that the estimated compositional fluctuation for In was less than 0.89%, exhibiting a quite high uniformity in the AlInGaN layer.

Figure 2(a) shows a bright field TEM image of the AlInGaN/GaN sample. A dashed line indicates the interface position. The sample was tilted a bit from the [11-20] zone axis to avoid the dynamical diffraction effect [6]. Figure 2(b) and 2(c) show an electron hologram and reconstructed phase image, respectively. The charge density distribution was extracted from the phase map using a Poisson equation and the result is shown in Fig.2(d). The line profiles of the phase and the charge density along [0001] direction are shown in Fig. 2(d). The negative charge accumulation, e.g., the 2 DEG, is detected in the GaN side of the interface and its charge density is about $8x10^7$ C/m^2. The positive charge accumulation in the AlInGaN side of the interface is considered to be due to polarization induced charges. Assuming that

the width of the 2DEG is 0.5 nm, the sheet charge density is evaluated to be about $2x10^{13}$ cm^{-2}. This value is in good agreement with the the result obtained by Hall measurement.

In summary, we succeeded in quantitative characterization of crystallinity, compositional uniformity and charge distribution of 2DEG at the AlInGaN/GaN.

References
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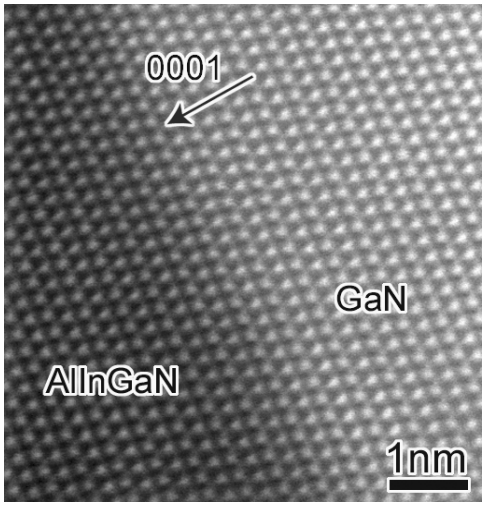

FIG. 1 HAADF-STEM image of AlInGaN/ GaN heterointerface.

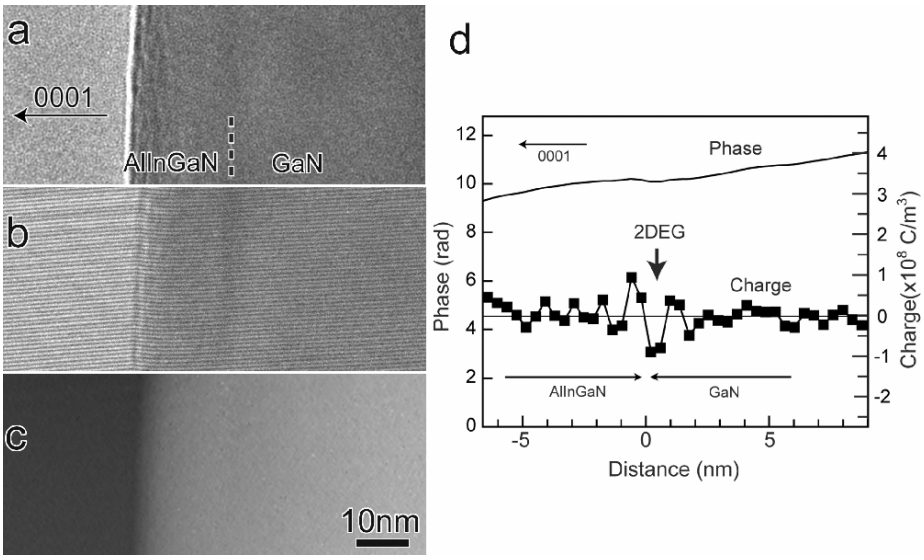

FIG. 2 (a) TEM image, (b)electron hologram and (c) reconstructed phase image of AlInGaN/GaN heterostructure. (d) Line profiles of phase and charge distribution along [0001] across the interface.