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Precise Measurement of Carrier Concentrations in n-Type GaN by Phase-Shifting Electron Holography

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Electron holography (EH) has been used for evaluating carrier concentration activated by dopants in semiconductor devices. In particular, to observe compound semiconductors (for example GaAs, GaN) having low dopant concentrations (less than 10^{17} atoms/cm^3), it is necessary to use a thicker TEM sample because thicker depletion layers are inevitably formed on both sides of the TEM sample. However, such a thicker TEM sample increases an inelastic scattering of incident electrons, therefore, it is difficult to form finer interference fringes with enough visibility, which deteriorates the spatial- and phase-resolution of the reconstructed phase image. Phase-shifting electron holography (PS-EH) [1,2] is a superior phase imaging technique to the common EH with Fourier transformation reconstruction. The PS-EH retrieves high-quality phase image from coarse interference fringes with higher visibility, and achieves phase-resolution of 0.01 rad order in wide observation regions [3]. Here, we applied PS-EH to precisely visualize different dopant concentrations, 10^{19}-, 10^{18}-, 10^{17}-, 10^{16}-atoms/cm^3, in a n-type GaN sample.

We prepared a model sample of the n-GaN layers with different concentrations of Si dopants, as illustrated in Fig. 1(a). The concentration of the layers was step-like increased with regard to the GaN substrate by one digit from 5×10^{16} to 5×10^{19} atoms/cm^3. The depth profile of dopant concentration measured by SIMS is shown in Fig. 1(b). We used a cryo-FIB to prepare the uniform TEM sample (350 nm thick) to reduce the damage layers and subtle distortion. To record a series of holograms having uniform interference fringes for PS-EH, we used a 300 kV holography TEM (Hitachi, HF3300-EH) with triple electron biprisms.

Figure 1(b) shows a cross-sectional TEM image, superposed with the SIMS profile. In this image, the layers cannot be distinguished. The dark region on the left is a protection layer of carbon deposited by vacuum evaporation. Figure 1(c) shows one of the typical holograms without Fresnel fringes. The interference fringes are slightly shifted at the interfaces of the layers. Figures 1(d) and 1(e) show the reconstructed phase image and its phase profile across the layers. All layers with dopant concentration of 10^{19}～10^{16} atoms/cm^3 are clearly visualized. Moreover, it is clear that the width of the phase drop broadened as concentrations decreased, namely, 10 nm, 19 nm, and 38 nm as indicated in Fig. 1(d).

These variations of the width are reliable because the spatial resolution is about 1 nm in this profile. We also estimated the thicknesses of active layers in the layers from the experimental results and theoretical simulation, they were 118 nm in 10^{19}-, 67 nm in 10^{18}-, and 17 nm in 10^{17}-atoms/cm^3.

In summary, we have precisely visualized all layers activated by different-concentration dopants, 10^{19}-, 10^{18}-, 10^{17}-, 10^{16}-atoms/cm^3. Using theoretical simulation of GaN, we also estimated the thickness of the active layer in each layer. In the conference, we will discuss the possibility of detecting a much lower concentration in 10^{15}- and 10^{16}-atoms/cm^3.

References:
[1] Q. Ru, G. Lai, K. Aoyama, J. Endo, and A. Tonomura, *Ultramicroscopy* **55** (1994) 209-220.
[2] K. Yamamoto, I. Kawajiri, T. Tanji, M. Hibino, and T. Hirayama, *J. Electron Microsc.* **49** (2000) 31-39.
[3] S. Anada, K. Yamamoto, H. Sasaki, N. Shibata, M. Matsumoto, Y. Hori, K. Kinugawa, A. Imamura, and T. Hirayama *Microscopy* (2018) (in press): doi: 10.1093/jmicro/dfy131.
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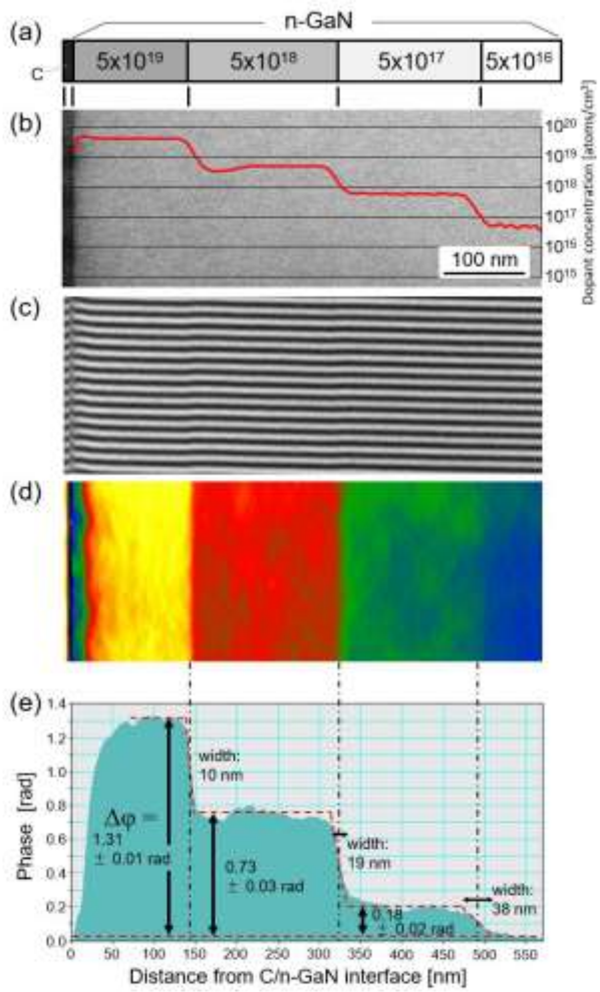

Figure 1. Phase-shifting electron holography of n-type GaN model sample with different dopant concentrations. (a) Illustration of the model sample. (b) Cross-sectional TEM image of the sample and Si dopant profile measured by SIMS. (c) Hologram. (d) Reconstructed phase image. (e) Phase profile across the layers.

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