High Precision Phase-Shifting Electron Holography with Multiple Biprisms for GaN Semiconductors

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Electron holography is one of the phase imaging TEM techniques to quantitatively observe electromagnetic potential distribution in functional materials, such as semiconductor devices. In a common reconstruction method based on fast Fourier transformation, spatial resolution of the phase image is determined from interference fringe spacing in a hologram, it corresponds to 2 or 3 fringe spacings. Thus, it is necessary to form the finer interference fringes to obtain the image with higher spatial resolution. However, the fringe contrast drastically decreases because of limited coherency of electron waves and inelastic scattering in samples, so that it deteriorates the phase detection efficiency.

Phase-shifting electron holography (PS-EH) [1,2] is able to overcome the above trade-off issues, that is, it improves the spatial resolution and the phase detection at the same time. First, we record a series of holograms whose interference fringes are shifted one after another by tilting the incident electron beam in a TEM. Second, we reconstruct the phase value in each pixel from the intensity variation in the holograms. The spatial resolution is equal to the 1 pixel size on a specimen plane, and the phase detection efficiency generally increases with the number of holograms.

In this study, we applied the PS-EH to GaN semiconductor devices. We prepared three kinds of bulk sample having GaN/$Al_xGa_{1-x}N$ (x = 0.20, 0.25, 0.30) interfaces. It is known that 2-dimensional electron gas (2DEG) layer is formed at the interface, and charge density of the 2DEG increases with the Al composition [3]. We prepared the TEM samples (250-nm-thickness) using a cryo-FIB system at 130 K to reduce the FIB damage layer. Figures 1(a) and 1(b) show the TEM image and hologram around the GaN/$Al_{0.25}Ga_{0.75}N$ interface. The interference fringes without Fresnel fringes were recorded under the double biprism lens condition in our 300-kV TEM (HF3300-EH). Figure 1(c) shows the phase image reconstructed from 50 holograms by PS-EH method. Brighter contrast is clearly observable in the GaN side at the interface. Figure 1(d) shows one-dimensional phase profile across the interface. We clearly observed the sharp potential change due to the 2DEG layer. The spatial resolution was about 1 nm and the precision of the phase detection was about 0.02 rad (2π/300 rad). We also report that the height and width of the sharp potential increased with the Al composition.

In conclusion, we have succeeded in observing clear potential distribution in the GaN semiconductor device using PS-EH. The sample preparation using the cryo-FIB also contributed to the clear observation. The PS-EH is a powerful phase imaging technique to observe the image in thick semiconductor samples. It would be possible to observe lower dopant areas (for example, $10^{17}/10^{16}/10^{15}$ /cm^3 level) in near future.

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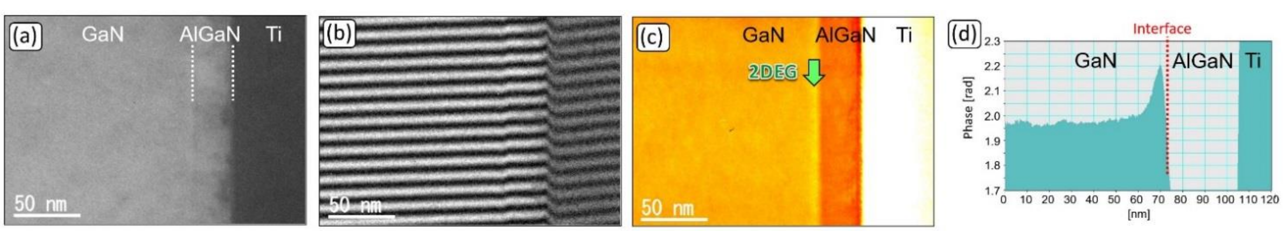

Figure 1 (a) TEM image, (b) hologram, (c) reconstructed phase image, (d) phase profile around GaN/$Al_{0.25}Ga_{0.75}N$ sample.