Progress towards Quantitative Off-axis Electron Holography of Electrostatic Potentials in Doped Semiconductors

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Off-axis electron holography promises to fulfil the requirements of the semiconductor industry for a technique that can be used to provide quantitative information about dopant potentials in semiconductors with nanometre spatial resolution. In a specimen of uniform thickness, the measured phase shift is expected to provide a quantitative measure of the variation in potential associated with the presence of dopant atoms. However, TEM specimen preparation can have a profound influence on phase shifts measured from doped semiconductors. In addition to surface depletion resulting from the presence of the specimen surfaces, the electrostatic potential in the specimen may be affected by oxidation, physical damage and the implantation of Ar and Ga during preparation of the sample for electron microscopy, as well as by irradiation by high-energy electrons during TEM examination. Here, we assess the effect on electron holographic phase contrast of the use of focused ion beam (FIB) milling with Ga^+ to prepare GaAs-based semiconductor devices for electron holography.

FIG. 1 (a) shows a holographic phase image of a GaAs *p-n* junction that was prepared for TEM examination using FIB milling. In contrast to results obtained from FIB-milled Si specimens of similar thickness, the step in phase across the GaAs junction is indistinct and the phase image is noisy. FIGS. 1 (b) and (c) show that *in situ* annealing of this specimen in the TEM can be used to increase the phase shift across the junction, while at the same time decreasing noise in the recorded phase image. These results suggest that annealing can be used to remove defects resulting from Ga+ implantation and to re-activate dopant atoms in the thin specimen. A similar, although smaller, improvement is seen for FIB-milled Si specimens [1]. Although FIG. 1 shows that *in situ* annealing improves recorded phase images, discrepancies with predictions still remain. The experimental phase profiles that are shown in FIG. 2, which were obtained from a similar GaAs *p-n* junction, indicate that phase profiles measured across the junction are sensitive to the incident electron beam current (and therefore to the rate at which charge is dissipated from the area of interest), to the nature of the specimen surface and to the quality of the electrical contacts to the region of interest. Further insight into such discrepancies is provided by *in situ* electrical biasing experiments, which are described elsewhere [2]. All of these factors, in combination with simulations of the electrostatic potential in a TEM specimen that contains point defects, must be understood in order to develop electron holography into a technique that can be used to characterise semiconductor dopant potentials reliably.

[1] Cooper D., Twitchett A.C., Somodi P.K., Midgley P.A., Dunin-Borkowski R.E., Farrer I., and Ritchie D.A. *Appl. Phys. Lett.* **88** (2006) 063510
[2] Twitchett A.C., Dunin-Borkowski R.E., and Midgley P.A. *Phys. Rev. Lett.* **88** (2002) 238302
[3] We thank I Farrer and D A Ritchie for the GaAs specimens. RDB thanks the Royal Society for support.

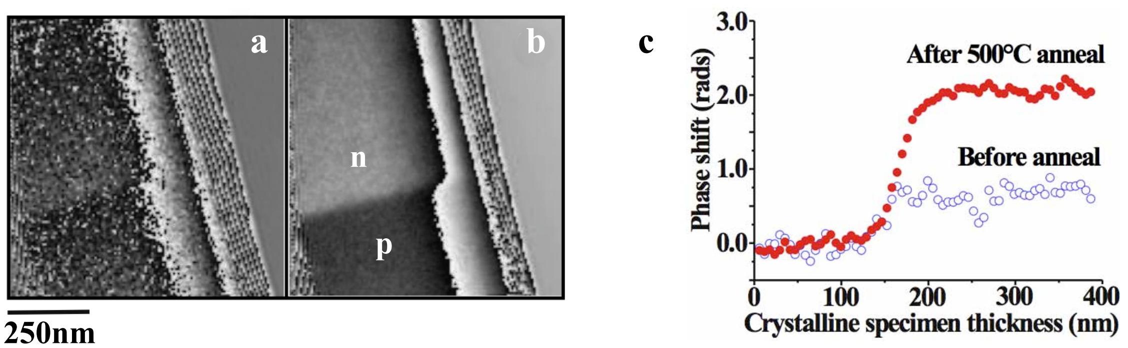

FIG. 1. Wrapped holographic phase images of a FIB-milled GaAs *p-n* junction of crystalline thickness 240 nm, recorded at room temperature (a) before and (b) after *in situ* annealing at 500 °C. (c) Phase profiles measured across a FIB-milled GaAs *p-n* junction in a sample of crystalline thickness 300 nm, before (open circles) and after (closed circles) annealing at 500 °C.

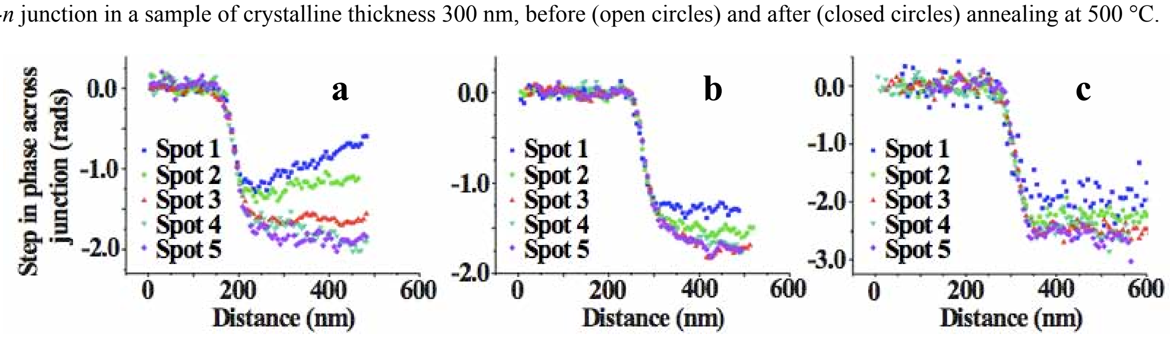

FIG. 2. (a) Phase profiles across a GaAs *p-n* junction of crystalline thickness 320 nm. (b) Profiles of the same specimen acquired after C coating. (c) Profiles acquired with improved electrical contacts applied to the specimen in a biasing holder.