Electron holography of a tapered FIB-prepared Si *p-n* junction

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Keywords: electron holography, semiconductors, dopant profiling

The physical and electrical properties of the surfaces of electron-transparent specimens have a significant effect on measurements of electrostatic potentials in doped semiconductors using off-axis or in-line electron holography [1,2]. Both surface damage and Ga implantation are particularly significant for samples that have been prepared using focused ion beam (FIB) milling [3], and such artefacts are increasingly problematic as device dimensions are reduced. In order to assess whether electron holography can provide a viable dopant profiling technique for the examination of FIB-prepared samples of future device generations, we have undertaken a systematic study of electron holograms of doped semiconductor devices as a function of sample thickness by making use of tapered specimen geometries.

Three tapered FIB membranes with wedge angles of 10, 20 and 30º were prepared from a silicon wafer containing a 2.5 µm *p*-type doped layer on an *n*-type substrate, with nominal dopant concentrations of 5×10^{18} cm^{-3}. Figure 1 shows a secondary electron image of the membranes acquired in the FIB workstation. The membranes were examined in a Philips CM300 field emission TEM at an accelerating voltage of 200 kV. Off-axis electron holograms were acquired using the Lorentz mini lens as the primary focusing lens, with an electron biprism voltage of 120 V used to provide a holographic interference fringe spacing of 5 nm. Figure 2(a) shows a reconstructed phase image of the 20º membrane with the position of the *p-n* junction marked. The phase change observed between the *p-* and *n*-type doped regions increases with specimen thickness, as predicted by the relation $\Delta\phi = C_E V_{bi} t$ where $\Delta\phi$ is the measured phase change across the junction, V_{bi} is the junction built-in voltage, C_E is a specimen-independent constant and t is the 'electrically active' specimen thickness [4]. In-line electron holograms (Fresnel defocus images, see Figure 2(b)) of the same specimen were acquired using a defocus range of -3.5 to +3.5 mm. The specimen thickness was calibrated using energy-filtered and holographic amplitude images, as well as convergent beam electron diffraction (CBED) patterns.

Line profiles of the contrast across the junction were extracted from the off-axis and in-line electron holograms and analysed using an iterative fitting routine, which allowed an accurate electrostatic potential profile to be obtained by fitting simulated potential profiles to the experimental results [5]. In the simulations, the depletion width across the *p-n* junction was allowed to vary through the thickness of the TEM sample, as illustrated in Figure 2(c). Figures 2(d) and (e) show fitted and experimental in-line profiles for a single specimen thickness, confirming that the simulations provide a good fit across the entire defocus range. The results indicated that for a total specimen thicknesses of below ~180 nm the signal to noise ratio was too low and no dopant contrast across the *p-n* junction could be measured. This arises from the FIB damaged surfaces in addition to the fact that the standard approach of averaging the contrast along the junction to improve the signal to noise ratio, used to analyse parallel-sided FIB-prepared membranes, cannot be applied to a specimen of constantly varying thickness. Further analysis of these results is in progress to examine the effect of specimen thickness on the electrostatic potential distribution in the specimen, as well as to develop approaches for removing the damaged and electrically inactive surface layers that result from FIB specimen preparation.

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6. We would like to thank Philips Research Laboratories (Eindhoven) for providing the Si device and the Royal Society, Newnham College, Cambridge and the EPSRC for financial support.

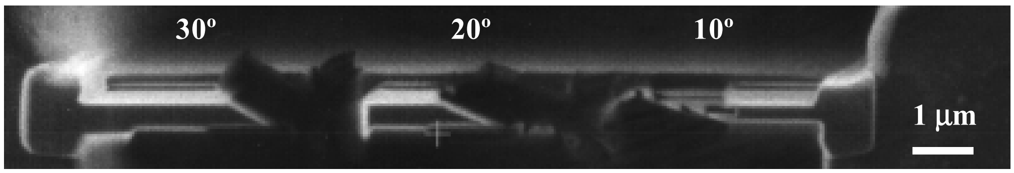

Figure 1. Secondary electron image of the FIB prepared tapered membranes indicating the wedge angle of each membrane. Excessive milling has rendered the 10º membrane unusable.

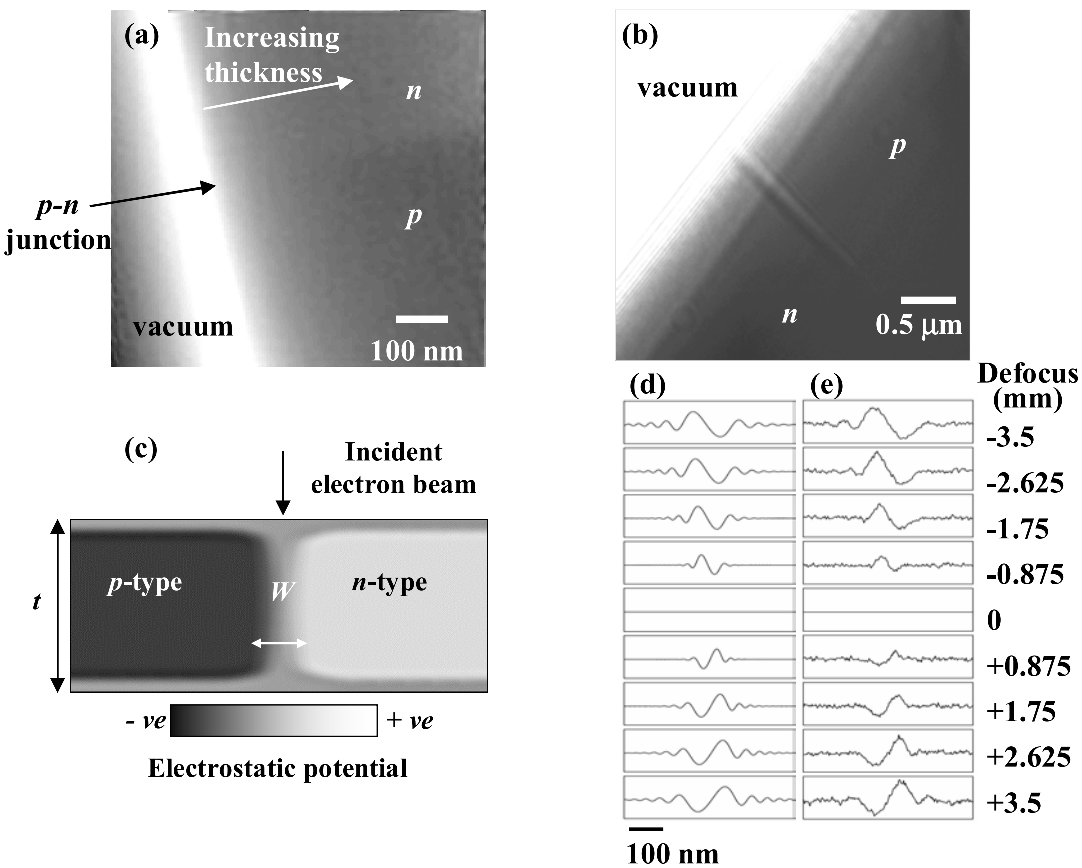

Figure 2. (a) Reconstructed phase image of the 20º tapered membrane, showing an increase in phase change across the *p-n* junction with thickness (after subtracting a ramp in the specimen arising from mean inner potential contributions to the phase shift). (b) In-line hologram of the 20º membrane acquired at -3.5 mm defocus. (c) Schematic diagram of the model used to simulate the electrostatic potential in the TEM membranes. (d) Simulated and (e) experimental Fresnel fringe profiles across the *p-n* junction for a sample thickness of 280 nm.