The Determination and Interpretation of Electrically Active Charge Density Profiles at Reverse Biased p-n Junctions from Electron Holograms

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It is important to understand the contrast seen in off-axis electron holograms of doped semiconductors. Here, we show that although electrostatic potential profiles measured from holograms of p-n junctions appear to agree with predictions, detailed charge density profiles across the junctions may be different from those expected for bulk samples. We have examined p-n junctions in Si, prepared for TEM examination by focused ion beam (FIB) milling, as a function of both reverse bias and sample thickness. Contacts were applied to the front and back surfaces of cleaved wedges, on which uniform thickness membranes had been prepared using FIB milling (Fig. 1a). Figure 1b shows a phase image from such a sample, in which the dark and bright contrast correspond to p and n-type regions in the sample, respectively. Qualitatively, phase profiles across the junction (Figs. 1c, d) are consistent with predictions as a function of bias and thickness, and several parameters can be inferred directly from the data. For example, if the phase change across the junction is plotted as a function of bias (Fig. 1e), the gradient of this graph can be used to infer that the 'electrically active' sample thickness is 340 nm. (The crystalline thickness was measured to be 390 nm). Similarly, the intercept of this graph provides a value for the built-in voltage of 0.9 V. Although the phase change plotted as a function of thickness is found to deviate from a straight line, this behavior can also be understood if it is assumed that the thickness of the 'electrically dead' layer on each sample surface increases slightly at the lowest sample thicknesses.

Unexpected results are obtained when simulations are used to obtain electric field and charge density profiles across the junction. Figures 2a and b show best fits to the data as a function of reverse bias for a symmetrical model that assumes a diffuse junction profile. The results are surprising for two reasons. Firstly, the charge density in an unbiased sample ($\sim 3\times10^{17}cm^{-3}$) is lower than the nominal value ($\sim 4\times10^{18}cm^{-3}$). Secondly, the charge density in the depletion region *increases* with bias voltage rather than remaining constant. As a result, the depletion width increases more slowly with applied bias than expected for a bulk sample (Fig. 3a). This behavior, which is not understood at present, may result from the effect of either the high-energy electron beam or sample preparation on the charge density in the sample. The insensitivity of the data to such charge density information, and the consequent need for simulations, is highlighted by the fact that a less physically realistic model (Fig. 2c) also provides a reasonable match to the data. Additional information can be obtained by comparing simulations with phase profiles as a function of sample thickness; the depletion width in an unbiased sample is found to increase slightly at the lowest thicknesses (Fig. 3b). A comparison of sample thickness measurements from holographic amplitude images with convergent beam electron diffraction reveals the presence of a 30 nm thick amorphous layer on each surface of the sample (Fig. 3c). The experimental data and simulations show that beneath these amorphous layers are ~25 nm thick crystalline but electrically dead layers and within these is the active junction, across which the phase change is broadly correct but whose charge density profile appears to be affected by the electron beam or sample preparation [1].

References

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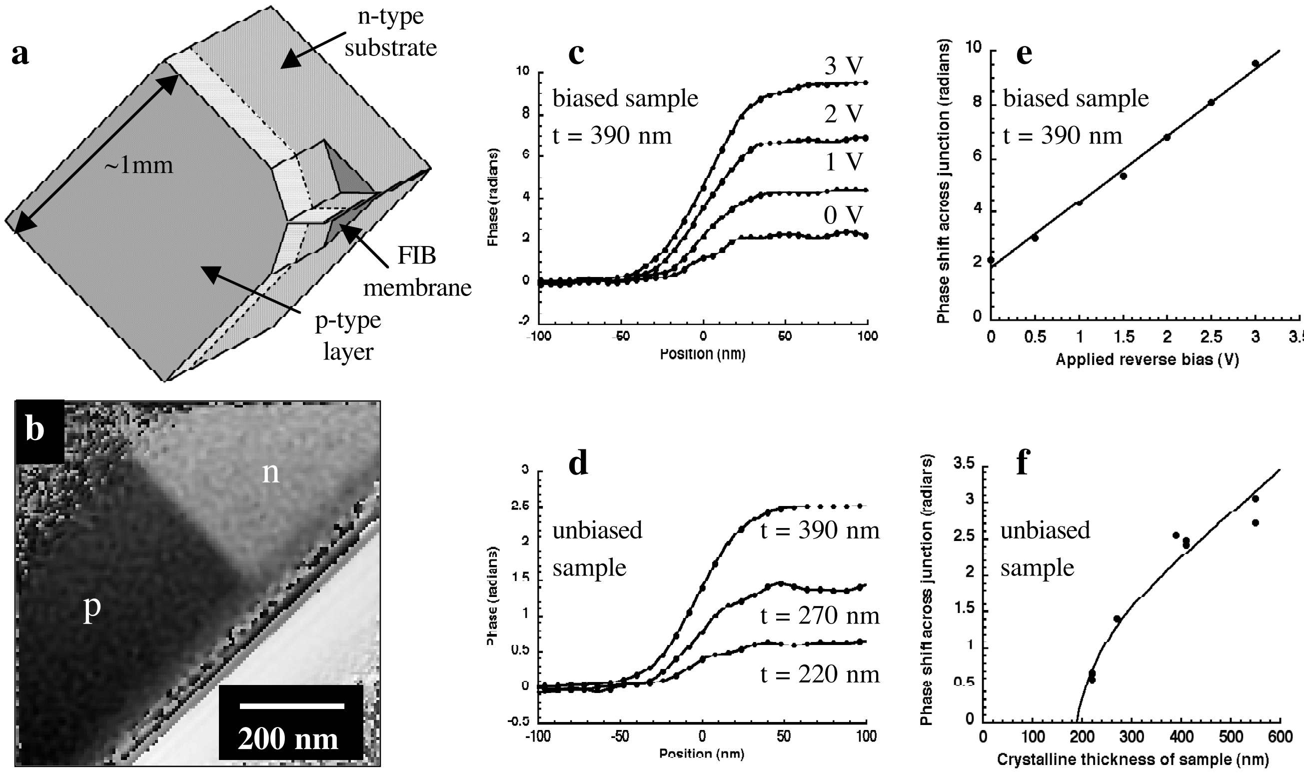

FIG. 1. (a) Sample geometry after cleaving and FIB. (b) Phase image of Si p-n junction. Phase profiles across junction (c) vs. reverse bias for a crystalline sample thickness of 390 nm and (d) vs. sample thickness for an unbiased sample. (e, f) Magnitude of step in phase across junction in (c) and (d).

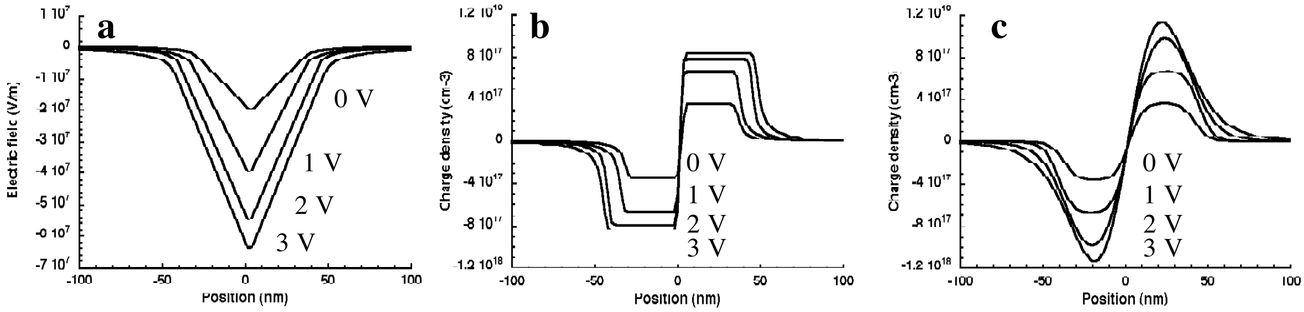

FIG. 2. Best-fitting (a) electric field and (b) charge density as a function of reverse bias; (c) Fits for an alternative charge density model that also provides a reasonable fit to the experimental phase images.

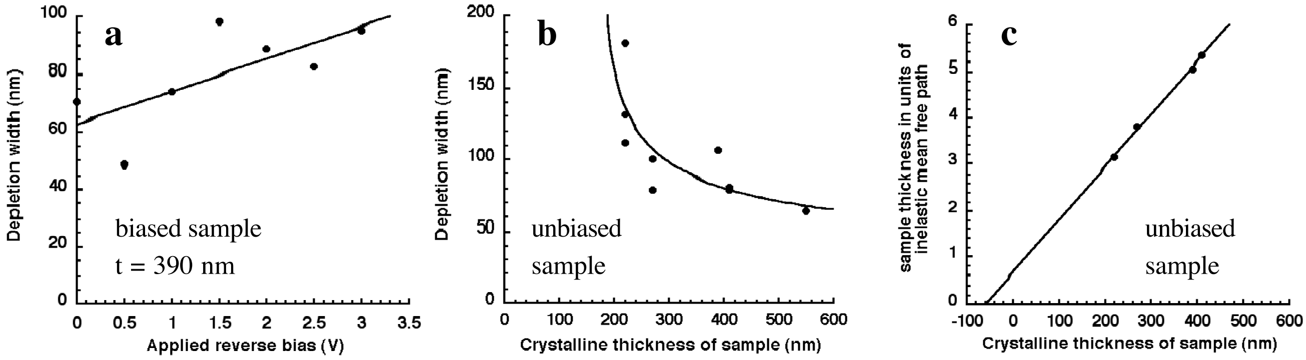

FIG. 3. Fitted depletion width as a function of (a) reverse bias and (b) sample thickness. (c) Sample thickness measured from holographic amplitude image and using convergent beam diffraction.