Mapping electrostatic potentials in semiconductor devices using electron holography

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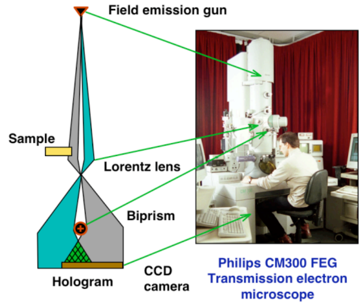
Electron holography

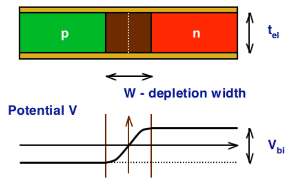
The off-axis mode of electron holography relies on the use of an electron biprism to overlap a high energy electron wave that has passed through a specimen with another part of the same electron wave that has passed only through vacuum. The resulting interference fringe pattern can be used to measure the phase shift of the electron wave, which is sensitive to the electrostatic potential in the specimen. In principle, the technique can be used to provide two-dimensional maps of depletion region potentials in semiconductors at a spatial resolution that can approach the nanometer scale.

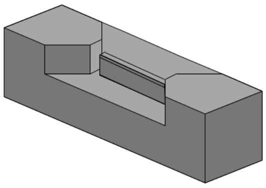
This poster shows examples of progress towards developing electron holography as a technique for characterizing electrostatic potentials in doped semiconductors that have been prepared for examination in the transmission electron microscope (TEM) using focused ion beam (FIB) milling .

R E Dunin-Borkowski, M R McCartney & David J Smith. Electron holography of nanostructured materials. Chapter in the "Encyclopaedia of Nanoscience and Nanotechnology" (American Scientific Publishers, 2004). ISBN 1588830012.



Electrostatic potentials in FIB-milled TEM specimens



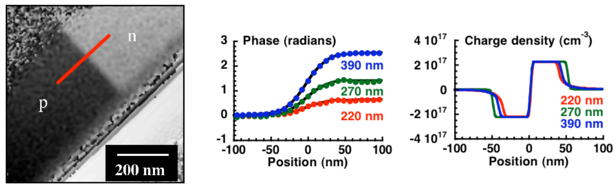


The phase shift of a high energy electron wave that passes through a TEM specimen is proportional to the electrostatic potential in the specimen integrated in the electron beam direction.

However, specimen preparation affects the electrical properties of the specimen surfaces. In particular, FIB milling, which is a desirable technique for preparing specimens for holography because of its site specificity, results in physical damage and Ga implantation.

A C Twitchett, R E Dunin-Borkowski and P A Midgley. Quantitative electron holography of biased semiconductor devices. Phys. Rev. Lett. 88 (2002), 238302.

Results from standard FIB-milled specimens

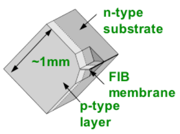


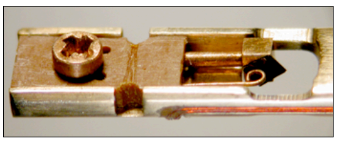
A phase image recorded from an FIB-milled Si p-n junction with a dopant concentration in excess of 10^{18} cm^{-3} reveals the position of the junction directly. Intermediate contrast close to the specimen edge confirms the presence of a modified surface layer.

Although the phase shift increases with specimen thickness as expected, the charge density in the depletion region, inferred from the data, is slightly lower than expected.

A C Twitchett, R E Dunin-Borkowski, R F Broom and P A Midgley. Off-axis electron holography of biased semiconductor devices. J. Phys. Cond. Matt. 16 (2004), S181.

Specimen and holder design for *in situ* electrical biasing



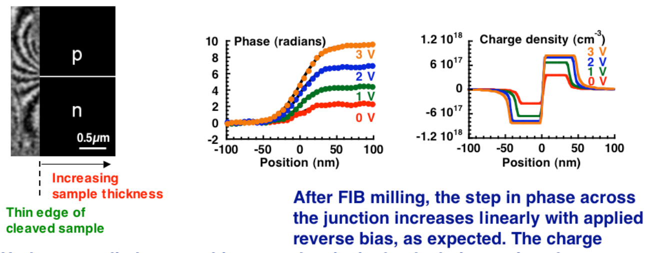


Semiconductor devices can be biased electrically in the TEM by using a modified specimen geometry that involves cleaving a small square of wafer, one corner of which is FIB-milled to electron transparency.

The resulting specimen can be clamped between two spring contacts in order to acquire electron holograms of working semiconductor devices.

R E Dunin-Borkowski, A C Twitchett, J S Barnard, R F Broom, P A Midgley, A C Robins, D W Smith, J J Gronsky and P E Fischione. An ultra-high-tilt two-contact electrical biasing specimen holder for electron holography and electron tomography of semiconductor devices. Paper to be presented at Microscopy and Microanalysis, Savannah, 2004.

Results from reverse-biased FIB-milled specimens

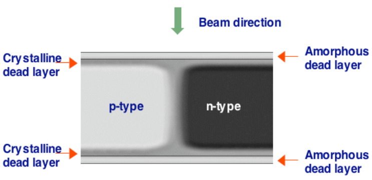


Under an applied reverse bias, electrostatic fringing fields are only seen outside the edge of a Si p-n junction specimen before it is FIB-milled.

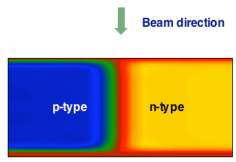
After FIB milling, the step in phase across the junction increases linearly with applied reverse bias, as expected. The charge density in the depletion region also increases, suggesting that some of the dopant that was deactivated by specimen preparation can be reactivated by reverse biasing the junction *in situ* in the TEM.

A C Twitchett, R E Dunin-Borkowski, R J Hallifax, R F Broom and P A Midgley. Off-axis electron holography of electrostatic potentials in unbiased and reverse biased focused ion beam milled semiconductor devices J. Microsc. 214 (2004), 287.

Simulations



Schematic diagram



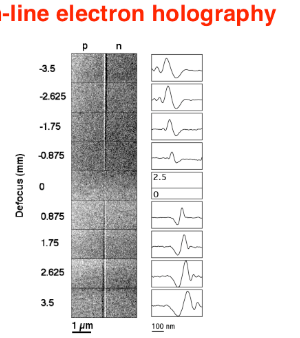
Simulation

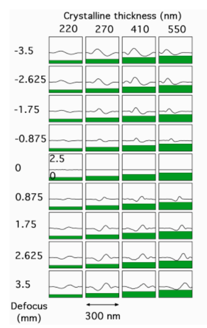
Our experimental results suggest that the surfaces of FIB-milled specimens are always equipotentials, and that the electrical properties of the junction vary through the thickness of the TEM specimen.

Classical solutions to the drift and diffusion equations in three dimensions confirm this picture, and illustrate the asymmetry of the potential close to the specimen surfaces.

P Somodi, R E Dunin-Borkowski, A C Twitchett, C H W Barnes and P A Midgley. Simulations of the electrostatic potential distribution in a TEM sample of a semiconductor device. Inst. Phys. Conf. Ser. 180 (2003), 501.

In-line electron holography





Higher spatial resolution information about the variation in potential across the junction can be obtained from a series of Fresnel defocus images, or in-line holograms, of the junction.

A comparison of the in-line and off-axis data also allows the level of the phonon background (shown in green) in the defocus series to be determined as a function of specimen thickness.