3-D analysis of the dopant potential of a Si *p-n* junction using holographic tomography

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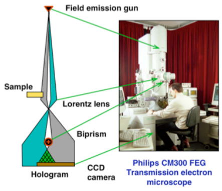
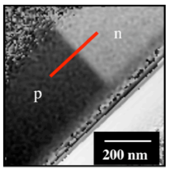
Off-axis electron holography of semiconductor devices

Traditionally, electron holography is used to provide 2-dimensional maps of electrostatic potentials in doped semiconductor specimens.

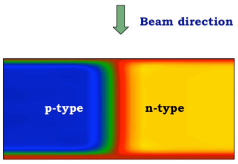


Here, a phase image recorded from a conventional 'trench' FIB-milled Si *p-n* junction with a dopant concentration in excess of 10^{18} cm^{-3} shows a step in potential at the position of the junction.



A. C. Twitchett, R. E. Dunin-Borkowski and P. A. Midgley, *Phys. Rev. Lett.* 88, 23, 8302-8304 (2002)

The need for electron tomography



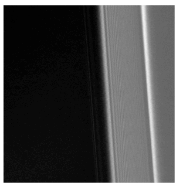
The electrical properties of the *p-n* junction are thought to vary through the thickness of the specimen. This effect can be assessed by combining electron holography with electron tomography to record a three-dimensional image of the potential in the specimen.

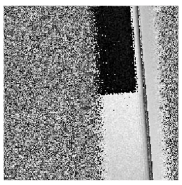
P. K. Somodi, R. E. Dunin-Borkowski, A. C. Twitchett, C. H. W. Barnes and P. A. Midgley, Simulations of the electrostatic potential distribution in a TEM sample of a semiconductor device. Inst. Phys. Conf. Ser. 180, 501 (2003)

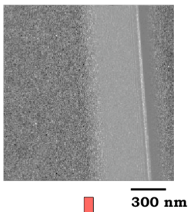
Experimental procedure

Experimental holograms → (Reconstruct with reference hologram) → **Phase image** ($-\pi$ to $+\pi$) + **Amplitude image**

-70° to +70°
@ 2° increments



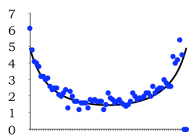


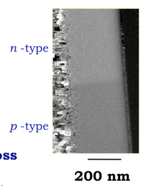


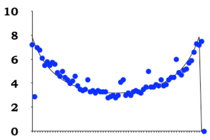
Unwrapped phase → (SIRT reconstruction) → **3D phase information**

Thickness information

2-D phase information







1-D phase change ($\Delta\varphi$) across the *p-n* junction can be plotted as a function of tilt angle and compared to theoretical predictions of the built-in voltage, V_{bi}

$\Delta\varphi = C_E V_{bi} t$

t/λ plot is used to determine which images are affected significantly by diffraction contrast. These are excluded from the tomographic reconstruction.

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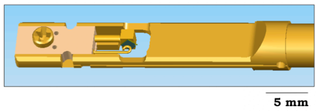
Holder design and specimen geometry

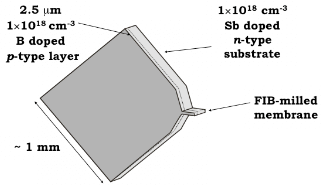
FISCHIONE INSTRUMENTS

A transmission electron microscope (TEM) sample holder has been developed in collaboration with Fischione Instruments that allows semiconductor devices to be examined under an applied bias using electron holography and electron tomography. It also allows samples to be transferred between the TEM and a scanning electron microscope (SEM), a focused ion beam (FIB) workstation and an Ar ion miller.

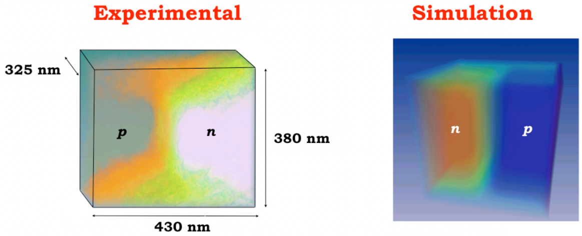


The end of the sample holder contains a removable cartridge, which is used to make electrical contacts to the front and back surfaces of a cleaved square of semiconductor, via a conducting block and a spring.

A thin membrane is prepared using the FIB at the vertex of a cleaved square of silicon. This sample geometry allows full 360° rotation without shadowing the membrane by the bulk specimen.



3-D electrostatic potential



Voxel size = 5.8 nm

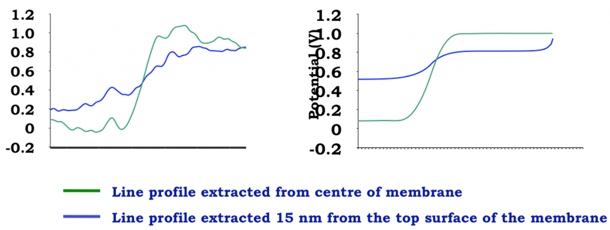
Spatial resolution ~ 10 nm

Phase resolution ~ 0.1 radians

Simulations conducted for:

300 nm thick Si specimen
Crystalline surfaces
1×10^{18} cm^{-3} dopant concentration
0.7 eV surface energy

Line profiles can be extracted from the 3D data sets to examine properties close to the centre and surfaces of the membrane



Conclusions

- **We have successfully demonstrated reconstruction of the 3-D electrostatic potential in a semiconductor device using combined electron holography and tomography**
- **Quantitative results are achievable to determine both mean inner potential, V_0, and the dopant-related potential at any position in a thin specimen**
- **Very promising technique for examination of real device structures**