Off-axis electron holography of focused ion beam milled GaAs and Si p-n and n-p junctions

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Off-axis electron holography of doped semiconductors

Off-axis electron holography

Off-axis electron holography uses a biprism to interfere an electron wave that has passed through a sample, with a 'reference' wave that has passed through vacuum. In the absence of magnetic fields and strong diffraction contrast, the phase change, $\Delta\phi$ of an electron wave passing through a material with electrostatic potential V_0 is given by the expression;

$$\Delta\phi = C_E V_0 t \quad (1)$$

where C_E is a constant that depends on the energy of the electron beam and t is the sample thickness.[1]

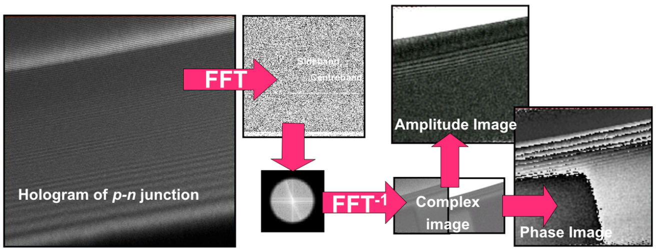


Fig 1. The reconstruction of an off-axis electron hologram. The FFT of the image produces a complex Fourier spectrum. A sideband is carefully selected and an inverse Fourier transform is performed. A complex image is formed from which phase and amplitude images are extracted.

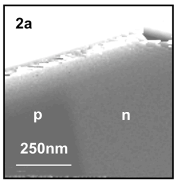
Motivation

- Electron holography can provide high resolution 2-D maps of the phase shift across a specimen.
- In some circumstances the phase shift is directly proportional to the mean inner potential, therefore the electrostatic potential arising from dopant atoms in the semiconductor device is revealed.
- Electron holography can provide the semiconductor industry with a 2-D and 3-D dopant profiling technique, which can reach sub-10nm resolution.

Sample preparation using focused ion beam milling.

FIB (focused ion beam) milling is a site-specific technique ideally suited for thinning samples containing semiconductor devices.

- Samples of uniform thickness can be prepared
- FIB milling creates amorphous surface layers with significant Ga implantation.
- In addition, sample preparation may also create surfaces with a different, unknown potential distribution.



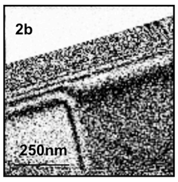


Fig 2a. A reconstructed phase image of a silicon p-n junction. The junction consists of a $4x10^{18}cm^{-3}$ B-doped (p type) layer on a $4x10^{18}cm^{-3}$ Sb doped substrate.

Fig 2b. Cosine of the phase image revealing the presence of an 'electrically altered' layer on the sample surface.

Electron holography of FIB-prepared Si and GaAs p-n and n-p junctions

Off-axis electron holograms of $4x10^{18}cm^{-3}$ doped symmetrical Si and $1x10^{18}cm^{-3}$ GaAs symmetrical p-n and n-p junctions were acquired using a Philips CM300-ST field emission gun transmission electron microscope operating at an accelerating voltage of 200kV.

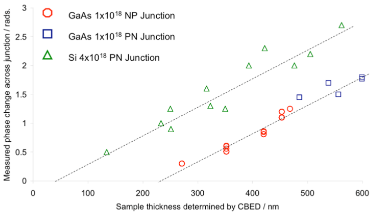


Fig 3. Measured phase change across p-n junction plotted against sample thickness measured using convergent beam electron diffraction, CBED. In a perfect p-n junction with no surface effects we would expect the gradient to pass through the origin. The magnitude of the x intercept reveals 'electrically dead' layers within the sample. From the gradient, the built-in potential across the p-n junction has been determined to be 0.68V and 0.71V for Si and GaAs respectively.

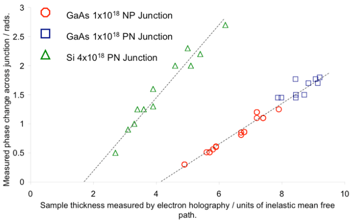


Fig 4. Measured phase change across p-n junction plotted against sample thickness in units of inelastic mean free path

$$t/\lambda = -2\ln A \qquad (2)$$

where t is the sample thickness, λ the inelastic mean free path and A the normalised image amplitude determined using electron holography.

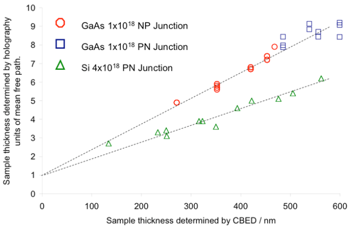


Fig 5. Thickness of sample determined using CBED compared to t/λ calculated from holograms. The y intercept corresponds to the thickness of the amorphous surface layers[2]. The gradient reveals a mean free path of inelastic scattering of 105nm in Si and 66nm in GaAs. The amorphous surface layers for Si and GaAs are 40nm and 16nm respectively. The thickness of the amorphous layer in GaAs is in agreement with recent high resolution electron microscopy experiments.[3]

Discussion of results

The built-in potential, V_{BI} across a p-n junction can be calculated using equation (3), where k is Boltzman's constant, T the temperature, q the charge on an electron, N_A the acceptor doping concentration, N_D the donor doping concentration and n_i the intrinsic doping concentration. This can be substituted into equation (1) to reveal the expected phase change across a p-n junction.

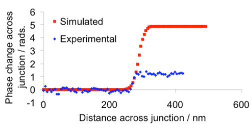
$$V_{BI} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) \quad (3)$$

Fig 6a. Simulated and experimentally determined phase change across p-n junction for a GaAs sample of crystalline thickness 470nm. **6b.** A schematic cross section of the p-n junction is also shown revealing a small electrically active layer in comparison with the damaged electrically dead layers.

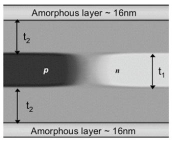
Fig 6c. Simulated and experimentally acquired phase change across p-n junction for a Si sample of crystalline thickness 470nm. **6d.** A schematic diagram is also shown revealing the electrically dead layers in relation to the active layers.

GaAs

6a.



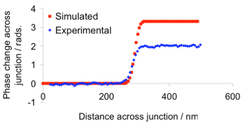
6b.



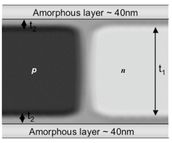
t_1 = 120nm and t_2 = 175nm.

Silicon

6c.



6d.



t_1 = 288nm and t_2 = 91nm.

Conclusions

- It has been shown that FIB-prepared GaAs samples have a larger electrically 'dead' layer than Si.
- The electrically 'dead' layers may be associated with Ga+ implantation in the FIB.
- Further work is required to determine the mechanism of this damage.
- More advanced sample preparation techniques are required in order to characterise the electrical properties of semiconductors using electron holography.

References

1. P.A. Midgley, Micron 32 (2001) 167-184.
2. A.C. Twitchett et al. Physical Review Letters, 88, 23 (2002)
3. Y. Yabuuchi et al. Journal of Electron Microscopy 53 (5) 471-477 (2004)

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