Interpretation of electrostatic potential profiles of delta-doped layers measured using electron holography

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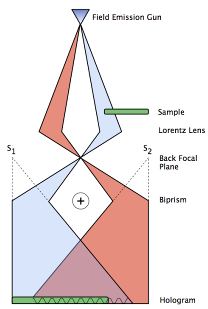
Introduction



Off-axis electron holography can be used to measure the real-space phase shift of the electron wave that has passed through a thin specimen, which is in turn sensitive to the electrostatic potential *V*.

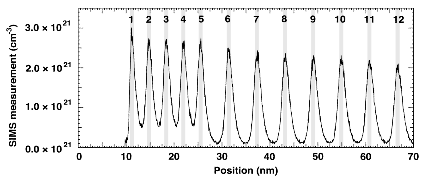
In a doped semiconductor, an important contribution to *V* is associated with the dopant potential. If the specimen is sufficiently thick that the effect of surface depletion is minimal and if specimen charging and dynamical diffraction are negligible then variations in dopant potential can in principle be measured quantitatively from a recorded phase image.

However, in the most modern semiconductor devices the dopant concentration can be sufficiently high that measurements of dopant potential can be affected by local variations in mean inner potential, which depend on the local composition and density of the specimen.

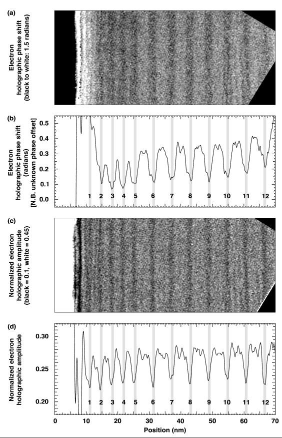
Experimental details

Here, we show how the mean inner potential contribution to a phase image of a very highly doped semiconductor can be determined independently in order to interpret the dopant potential in the specimen. We examine a series of closely-spaced B delta-doped layers grown on (001) Si, each of which is intended to comprise a narrow layer of dopant atoms and a space charge layer of opposite sign on either side of it.

A secondary ion mass spectrometry (SIMS) profile acquired from the layers is shown below. The peaks in the profile reach concentrations of 3×10^{21} cm^{-3}, which is much higher than the solubility limit reported for delta-doped layers of B in Si.



Results



The change in potential at each delta-doped layer was measured using electron holography. In the images shown on the left, (a) and (c) are phase and amplitude images recorded from a specimen of thickness 245 nm. (b) and (d) are corresponding line profiles. Two observations are significant:

First, the presence of dark contrast in the amplitude image indicates that changes in mean inner potential are likely to be sufficiently strong to influence the phase image.

Second, the layers are wider in the phase than in the amplitude, suggesting that the phase shift at each layer contains a significant contribution from the dopant potential, which is indeed expected to be wider than the compositional width.

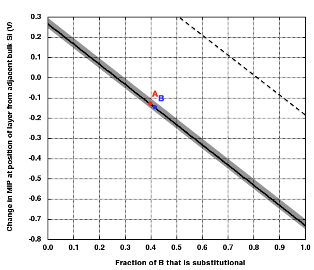
The approach that we introduce here to determine the mean inner potential contribution to the phase shift at each layer involves obtaining complementary information from the SIMS profile shown above and from an HAADF STEM image.

The first parameter that we use to determine the mean inner potential contribution to the measured potential independently is the total amount of B in each layer, n_B. We express n_B in the form of an equivalent number of atomic layers if the B atoms were all placed on a Si lattice. This value was determined, by integrating each peak in the SIMS profile numerically, to take an average value of 0.71±0.01.

The second parameter is the compositional width of each layer, *w*, which was measured from an HAADF STEM image to take an average value of 1.16±0.01 nm.

The third parameter is the rigid shift (*i.e.*, expansion or contraction) d_c of the Si lattice, relative to unstrained Si, across each layer. This parameter was determined using geometrical phase analysis to take the form of an *expansion* of the Si lattice relative to unstrained Si, whereas a contraction of the lattice would be expected for fully substitutional B. This observation provides evidence for the presence of a substantial proportion of interstitial B. The average value of d_c was measured to be -0.0208±0.0016 nm.

Discussion and conclusions



In the graph shown on the left, B marks the change in potential of -0.148±0.005 V at each layer measured using electron holography. The solid line shows the mean inner potential contribution to the potential determined from the SIMS and HAADF STEM measurements of n_B, *w* and d_c using the equation

$$\frac{\Delta V_0}{V_0} = \left(\frac{d_c}{w}\right) + n_B\left(\frac{a_{Si}}{4w}\right)\left(\frac{f_B}{f_{Si}} - x\right)$$

where f_{Si} and f_B are electron scattering factors at zero scattering angle for Si and B, a_{Si} is the lattice parameter of Si and V_0 is taken to be 12 V for unstrained Si. The graph is plotted as a function of *x*, the unknown fraction of B in the layer that is substitutional. The dashed line is for the lattice *contraction* that would be predicted for substitutional B alone, which is inconsistent with our experimentally measured value for d_c.

The solid line tells us that if the change in potential that we measure using electron holography were caused by the mean inner potential alone then approximately 40% of the B must be substitutional. However, the experimental values of dopant concentration (measured using SIMS) and lattice expansion (measured using geometrical phase analysis) indicate that the majority of the B must be interstitial. Hence, we infer that the dopant contribution to the potential is approximately -0.4 V (the difference between the value of the solid line at the left of the graph and the measured value of the potential).

The present study has concentrated on an independent measurement of the mean inner potential contribution. Process simulations should now be used to determine the different possible combinations of mean inner potential and dopant potential that are consistent with the experimentally measured phase profile, as well as to infer the ratio of substitutional to interstitial B and the proportion of B that is electrically active.

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