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.

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.

Experimental details

Here, we show how the mean inner potential contribution to a phase image of a very lightly 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 B 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^{19} cm^{-3}, which is much higher than the solubility limit reported for delta-doped layers of B in Si. 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 contribution (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).

Discussion and conclusions

The present study has concentrated on an independent measurement of the mean inner potential contribution to the potential. 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 infer the ratio of substitutional to interstitial B and the proportion of B that is electrically active.

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