Characterisation of delta-doping potential profiles with 1 nm spatial resolution using electron holography

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Off-axis electron holography is a powerful technique for measuring electrostatic potentials in materials in the transmission electron microscope (TEM). In doped semiconductors, the characterisation of dopant potentials using electron holography requires the preparation of electron-transparent specimens of highly uniform thickness, whose electrical properties are affected minimally by specimen preparation from those in the bulk device. If the specimen thickness is large enough for the effect of surface depletion on the measured phase shift to be 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.

Most previous studies of dopant potentials in semiconductors using electron holography have involved the examination of specimens in which the dopant concentration is low enough (below about 10^{19} cm^{-3}) that local changes in dopant species or concentration could not be discerned in bright-field or dark-field TEM images. A spatial resolution of between 5 and 10 nm in recorded electron holograms was then also usually sufficient. However, in some of the most modern semiconductor devices the dopant concentration may change sufficiently rapidly that a spatial resolution of approximately 1 nm is required in electron holographic phase images, while the dopant concentration can be sufficiently high that there may be two significant contributions to the phase change associated with the dopants in the specimen: one originating from the dopant potential of primary interest and one from the local variation in mean inner potential. The application of electron holography to such specimens requires not only the use of a highly stable microscope and a long acquisition time to measure small changes in phase with high spatial resolution but also the development of approaches to separate the dopant potential from the contribution to the measured potential associated with changes in local scattering factor and density.

Here, we show how the mean inner potential contribution to a phase image recorded from a very highly doped semiconductor can be determined independently in order to interpret the dopant potential in the specimen. We illustrate the method through the examination of a series of twelve closely-spaced delta-doped B layers in Si, each of which comprises an ultra-narrow layer of dopant atoms (thinner than a few unit cells). The fraction of the dopant that is substitutional is considered when comparing the predicted changed in mean inner potential with the experimentally measured potential profile [1].

References

[1] Cooper, D, Dunin-Borkowski, R.E, Interpretation of phase images of delta-doped layers, Microscopy, in press, 2013.