Interpretation of electron-beam-induced charging of silicon oxide layers in a transistor structure studied using off-axis electron holography

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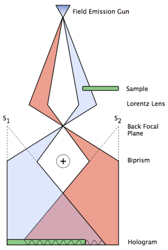
Off-axis electron holography

Off-axis electron holography relies on the use of an electron biprism to overlap a high energy electron wave that has passed through a TEM specimen with another part of the same electron wave that has passed only through vacuum.

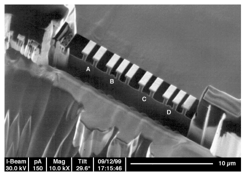
The resulting interference fringe pattern can be used to infer the projected electrostatic potential and offers the prospect of mapping dopant potentials in semiconductors.



G. Mateucci, G. F. Missiroli, and G. Pozzi. Electron holography of long range electrostatic fields. Advances in Imaging and Electron Physics 99 (1997), 171.

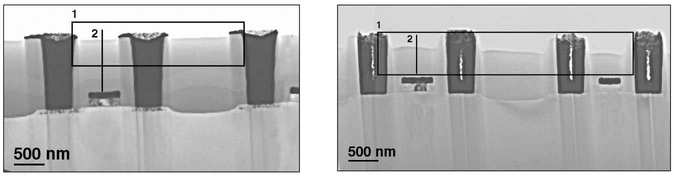
Electron holography of transistors

Here we compare experimental electron holography results with simulations to understand electron-beam-induced charging effects arising from the presence of oxide layers in FIB-prepared TEM specimens of a Si transistor structure (shown in the figure).

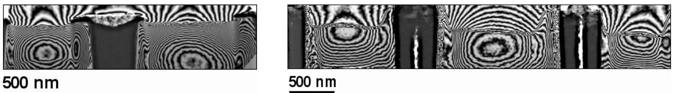


R. E. Dunin-Borkowski, S. B. Newcomb, T. Kasama, M. R. McCartney, M. Weyland and P. A. Midgley. Conventional and back-side focused ion beam milling for electron holography of electrostatic potentials in transistors. Ultramicroscopy 103 (2005), 67.

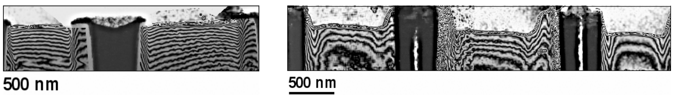
Experimental electron holography results



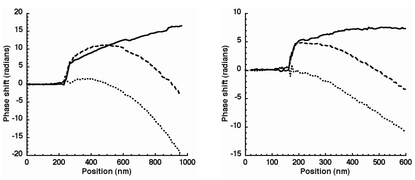
Bright-field images of PMOS transistors in 'trench-type' FIB-prepared TEM specimens of nominal thickness 400 nm (left) and 150 nm (right).



Eight-times-amplified phase contours measured using electron holography from the regions marked '1'. Specimen charging results in the presence of electrostatic fringing fields in the vacuum region outside the specimen edge, as well as elliptical phase contours in the Si oxide layers between the W contacts.

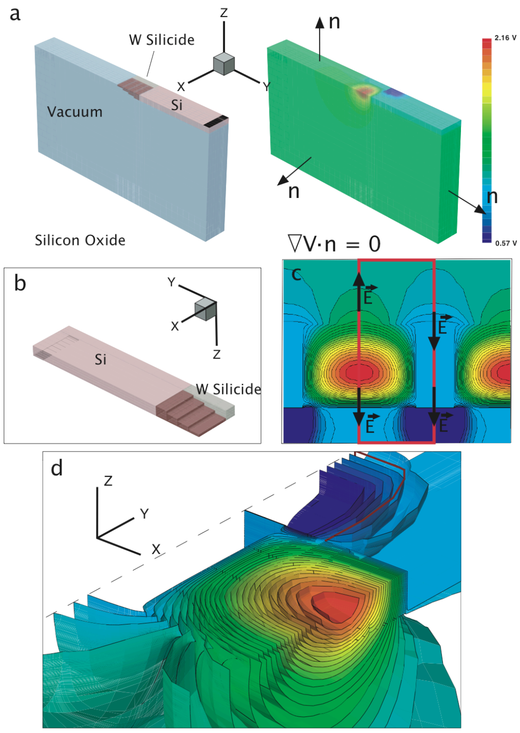


Contoured phase images recorded after coating the specimen on one side with 20 nm of carbon to mitigate the effects of charging. The contours now follow the expected mean inner potential contribution to the phase shift in the oxide layers, and there is no electrostatic fringing field outside the specimen edge.



Phase profiles measured along the lines marked '2'. The dashed and solid lines were obtained before and after coating with carbon. The dotted lines show the differences between the solid and dashed lines.

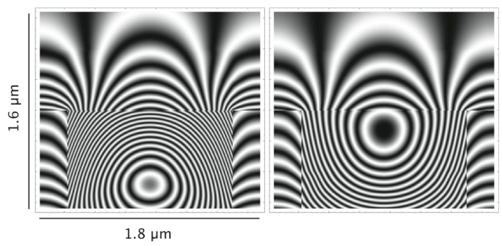
Simulation geometry and boundary conditions



(a - c) Geometry used for simulations of electrostatic potentials in TEM specimens containing transistors using the the commercial software ISE-tCad tools Mesh and DESSIS, with periodic boundary conditions.

(d) 3D equipotential contours showing the fringing field outside the specimen.

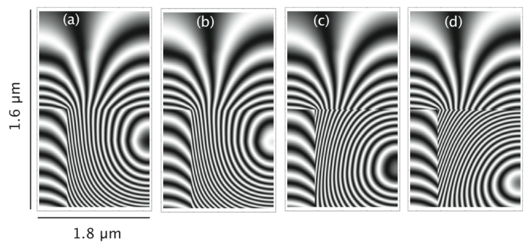
Simulations for different TEM specimen thickness profiles



Simulated phase contours for an oxide thickness that decreases from 400 to ~100 nm at the specimen edge (left) and a constant thickness of 150 nm (right).

Best-fitting simulations to the experimental results are for a uniform oxide charge density of 5×10^{15} cm^{-3}. The simulations assume a mean inner potential of 10 V for Si oxide and a distance of 2 μm to the vacuum reference wave.

The effect of the mean inner potential and vacuum reference



Simulations for an oxide thickness that decreases from 400 to ~100 nm at the specimen edge: (b) and (d) include the effect of the vacuum reference wave. (c) and (d) include the effect of the mean inner potential.

Such comparisons of phase images with simulations are essential, as oxide charging complicates studies of dopant potentials in the underlying device.