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Interpretation of electron beam induced charging of oxide layers in a transistor studied using electron holography

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Abstract Off-axis electron holography has been used to characterize a linear array of transistors, which was prepared for examination in cross-sectional geometry in the transmission electron microscope using focused ion beam milling. In reconstructed phase images, regions of silicon oxide that are located between metal contacts show unexpected elliptical phase contours centered several hundreds of nm from the specimen edge. The experimental images are compared with simulations performed using three-dimensional calculations of the electrostatic potential inside and outside the specimen, which take into account the mean inner potential of the specimen and the perturbed vacuum reference wave. The simulations suggest that the oxide layers contain a uniform volume density of positive charge and that the elliptical contours result from the combined effect of the electrostatic potential in the specimen and the external electrostatic fringing field.

1. Introduction

Off-axis electron holography is a specialized electron microscopy technique that relies on the use of an electron biprism to overlap a high-energy electron wave that has passed through an electron-transparent specimen in the transmission electron microscope (TEM) with another part of the same electron wave that passed only through vacuum. The resulting interference fringe pattern can be used to provide a quantitative map of the electrostatic potential within and around the specimen, projected in the electron beam direction. The technique offers the prospect of mapping dopant potentials in semiconductors quantitatively. However, such measurements are often complicated by the effect on the electrostatic potential in the specimen of sample preparation for electron microscopy and both charging and current flow resulting from electron beam irradiation in the TEM. Here we attempt to understand the magnitude, location and distribution of electron beam induced charge in Si oxide layers in a transistor structure by comparing phase images acquired using electron holography with computer simulations of the three-dimensional electrostatic potential within and around the TEM specimen. It is important to study and to avoid such charging effects as they can complicate or preclude measurements of dopant contrast in adjacent regions of the device.

2. Experimental details and results

A Si transistor structure was prepared for TEM examination using focused ion beam (FIB) milling in 'trench' geometry and examined using off-axis electron holography at 200 kV in a Philips CM200-ST field emission gun (FEG) TEM equipped with a Lorentz lens and an electrostatic biprism [1]. Bright-field TEM images of the transistor structure, which contains Si oxide layers located between metal contacts, are shown in Fig. 1 for specimens prepared with nominal thicknesses of 400 and 150 nm. Fig. 2 shows eight-times-amplified phase contours recorded using electron holography from the regions marked '1' in Fig. 1. Unexpectedly, elliptical contours are visible in each oxide region and a fringing field is present outside the specimen edge. Both the elliptical contours and the fringing field are thought to be associated with charging of the oxide as a result of secondary electron emission from the specimen during electron irradiation in the TEM. Fig. 2 also shows similar phase images obtained after coating each specimen on one side with ~20 nm of carbon. The effects of charging now appear to be absent, there is no fringing field outside the specimen edge and the contours in the specimen follow the change in specimen thickness in the oxide. Fig. 3 shows line profiles obtained from the phase images used to form Figs. 2 and 3 along the lines marked '2' in Fig. 1. The dashed and solid lines correspond to results obtained before and after coating the specimen with carbon, respectively, while the dotted lines show differences between these lines. If the charge is assumed to be distributed throughout the thickness of the specimen, then the electric field in the oxide is $\sim 2\times10^{7}$ V m^{-1}, just below the breakdown field for thermal SiO_2 of $\sim 10^{8}$ V m^{-1}. The dopant potential in the source and drain regions of the transistors is always undetectable before carbon coating, whether or not a phase ramp is subtracted from the recorded images.

3. Simulation details and results

The experimental results shown in Fig. 2 were compared with simulated images that incorporated the effects of specimen charging on the three-dimensional electrostatic potential both within and around the specimen. Fig. 4 shows the specimen geometry used for the simulations, which were performed using the commercial software ISE-tCad tools Mesh and DESSIS. The software allows the specimen geometry, dopant concentration and permittivity to be incorporated, to provide numerical solutions for the electrostatic potential in the specimen and the surrounding vacuum by solving Poisson's equation and continuity equations for electrons and holes. The calculated potential was integrated in the electron beam direction to obtain simulated phase images. Periodic boundary conditions were used. A good fit to the experimental results was obtained by modeling the oxide as an insulator with a fixed uniform charge density. The simulations reproduced the elliptical phase contours. However, the true specimen thickness profile had to be incorporated in the simulations to fit the positions of the ellipses accurately, especially for the thicker specimen. Fig. 5 shows best-fitting simulated phase contours, taking into account the known specimen thickness profiles and assuming a mean inner potential of 10 V for Si oxide and a distance of 2 μm to the vacuum reference wave. The simulations suggest that the oxide is charged positively with a uniform volume charge density of $\sim 5\times10^{15}$ cm^{-3}. Fig. 6 shows the separate effects of including the mean inner potential and the perturbed reference wave [2] in the simulations for the 'trench' specimen of nominal thickness 400 nm. The figure shows that both contributions should be taken into account to interpret the experimental images accurately.

4. Conclusions

Elliptical phase contours were observed experimentally at the positions of oxide layers in a transistor structure using electron holography. Simulations of the internal and external electrostatic potential of the TEM specimen, taking into account specimen thickness variations, the influence of the perturbed reference wave and the mean inner potential of the specimen, were used to show that the contours are likely to result from the presence of a uniform positive charge density in the oxide of $\sim 5\times10^{15}$ cm^{-3}. The charging effects appear to be absent when the specimens are coated with carbon. However, further studies are required to fully understand the influence on recorded electron holographic measurements of both charging and current flow in thin TEM specimens.

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References

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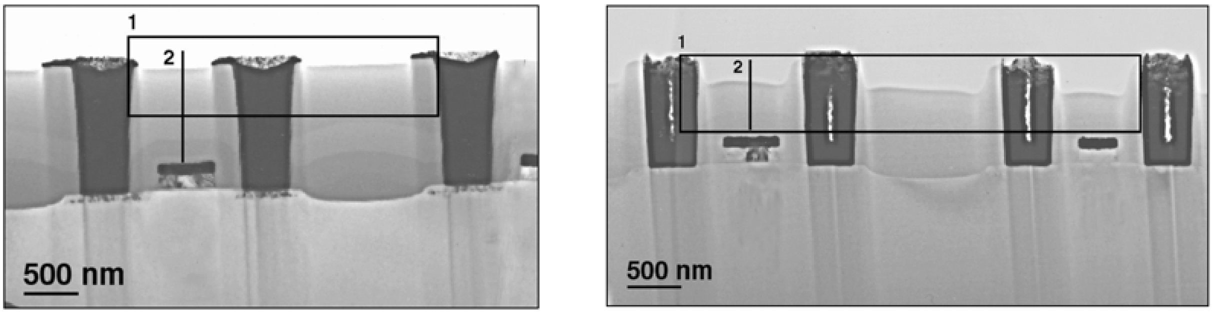

Fig. 1. Bright-field images of PMOS transistors in 'trench-type' FIB-prepared TEM specimens of nominal thickness 400 nm (left) and 150 nm (right).

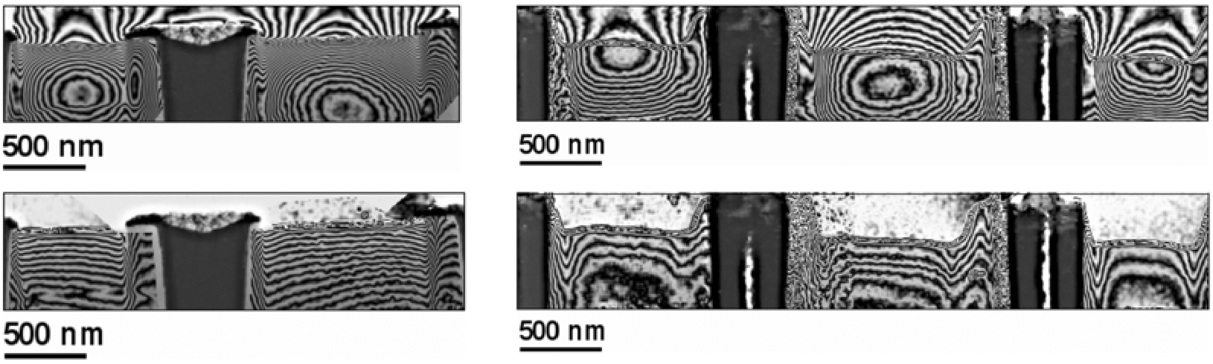

Fig. 2. Eight-times-amplified phase contours measured using electron holography from the regions marked '1' in Fig. 1 for the FIB-prepared TEM specimens of nominal thickness 400 nm (left) and 150 nm (right). Top: before carbon coating. Bottom: after carbon coating.

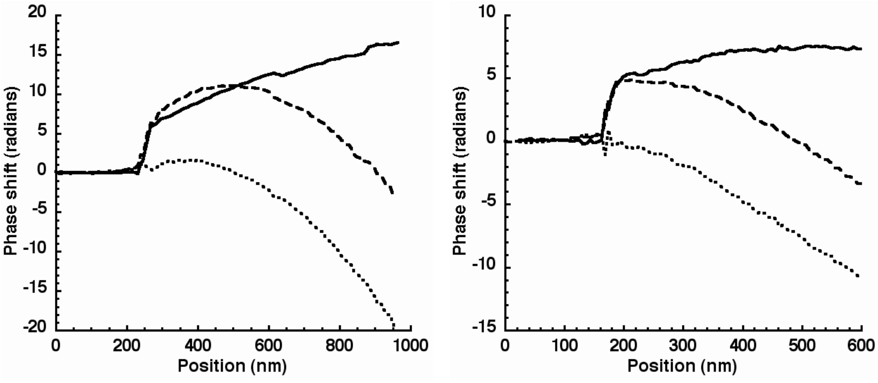

Fig. 3. Phase profiles measured along the lines marked '2' in Fig. 1. The dashed and solid lines were obtained before and after coating with carbon, respectively. The dotted lines show the differences between the solid and dashed lines.

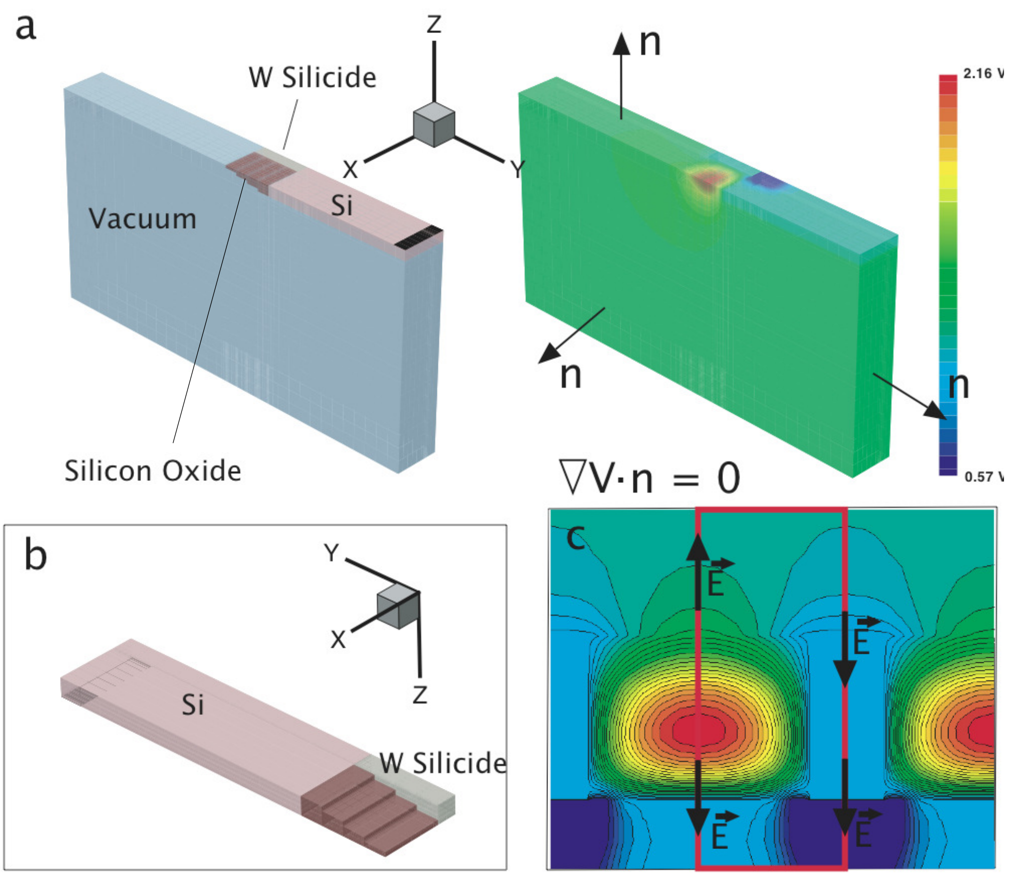

Fig. 4. Simulation geometry used for simulations of electrostatic potentials in TEM specimens containing transistors using the commercial software ISE-tCad tools Mesh and DESSIS, with periodic boundary conditions.

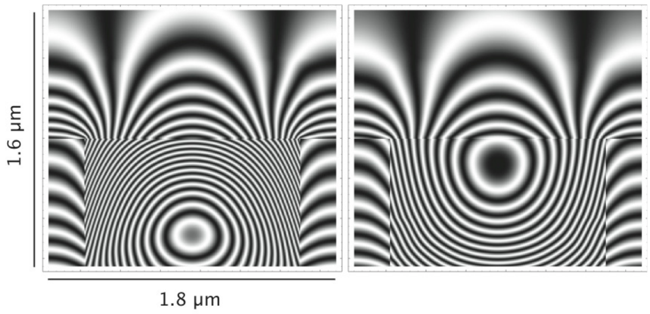

Fig. 5. Simulated phase contours for an oxide thickness that decreases from 400 to ~100 nm at the specimen edge (left) and a constant thickness of 150 nm (right). Best-fitting simulations to the results are for an oxide charge density of 5×10^{15} cm^{-3}. The simulations assume a mean inner potential of 10 V for Si oxide and 2 µm to the vacuum reference wave.

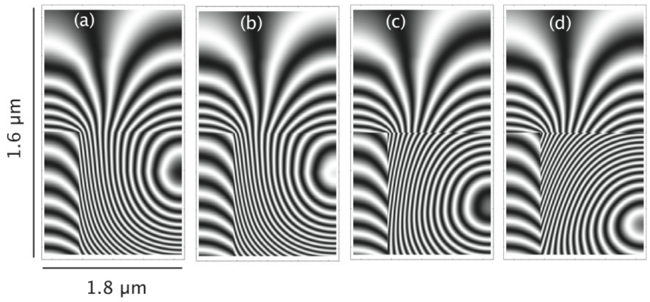

Fig. 6. Simulations for an oxide thickness that decreases from 400 to ~100 nm at the specimen edge: (b) and (d) include the effect of the vacuum reference wave. (c) and (d) include the effect of the mean inner potential. Both contributions to the phase need to be considered for interpretation of the experimental results.