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Electron beam induced charging of focused ion beam milled semiconductor transistors examined using electron holography

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Off-axis electron holography is increasingly used to characterize doped semiconductors as it provides access to the electrostatic potential in the specimen, which is, in turn, sensitive to the distribution of electrically active dopant atoms. However, specimen preparation has a profound influence on the potential in a doped semiconductor. In particular, focused ion beam (FIB) milling can result in physical damage, implantation and doping of the specimen surface with Ga, as well as thickness corrugations. Here, we use off-axis electron holography to characterize a Si transistor specimen, which was prepared for holography using conventional 'trench' FIB milling in an FEI FIB 200 workstation.

A bright-field image of one of the transistors in the device is shown in Figure 1a, for a specimen of nominal thickness 400 nm. Off-axis electron holograms of this region were recorded at 200 kV using a Philips CM200-ST FEG TEM equipped with a Lorentz lens and an electron biprism. Figure 1b shows eight-times-amplified phase contours obtained from region '1' in Figure 1a. Surprisingly, 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 associated with charging of the oxide as a result of secondary electron emission from the specimen during electron irradiation. Figure 1c shows a similar image obtained after coating the specimen on one side with ~20 nm of carbon. The effects of charging are now 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. Phase profiles were generated from the images used to form Figures 1b and c along line '2', and are shown in Figure 1d. The dashed and solid lines correspond to results obtained before and after coating the specimen with carbon, respectively, while the dotted line shows the difference 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 2×10^7 V/m, just below the breakdown electric field for thermal SiO_2 of 10^8 V/m. The effect of specimen charging on the dopant potential in the source and drain regions of the transistors is just as significant. The phase gradient in Figure 1d continues into the Si substrate, and the dopant potential is always undetectable before carbon coating, whether or not a phase ramp is subtracted from the recorded images. Surprisingly, after FIB milling the specimen from the substrate side of the wafer ('back-side milling'), carbon coating is not required to prevent specimen charging, presumably because of the sputtering and subsequent redeposition of Si onto the oxide layers during milling [1].

References

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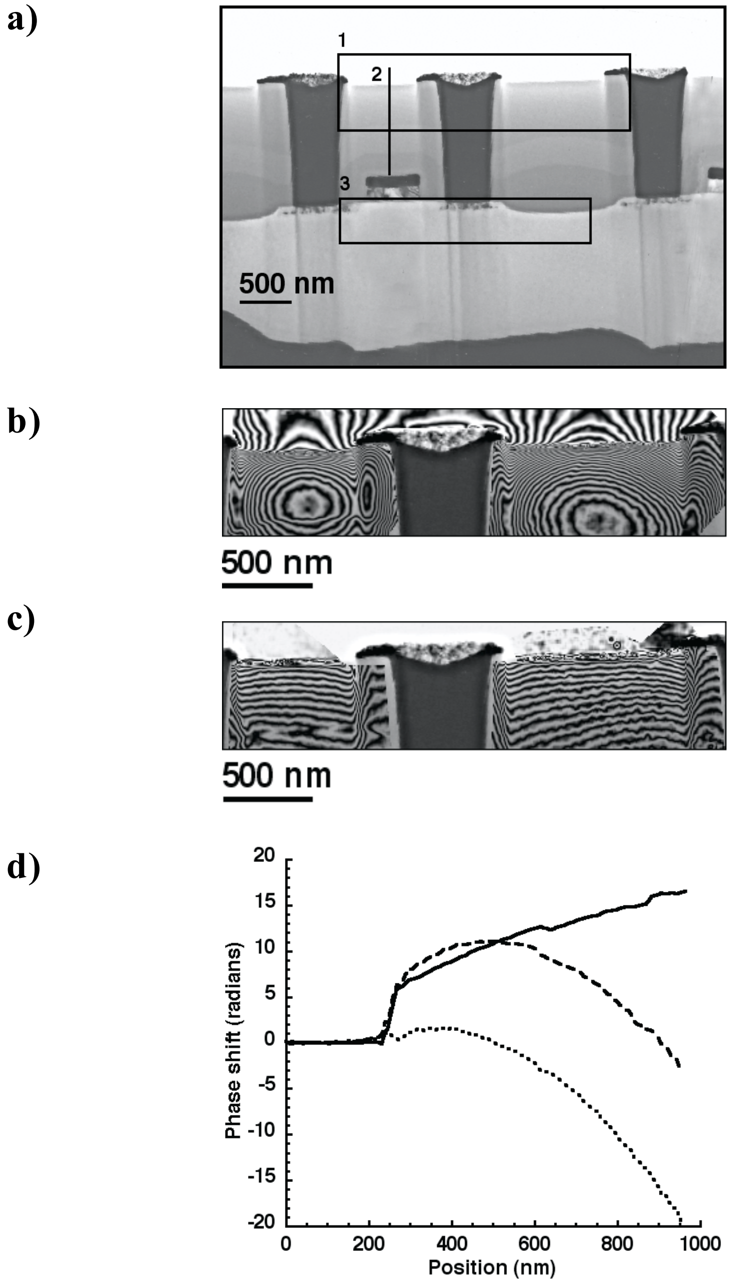

FIG. 1. Bright-field image of a focused ion beam milled PMOS (0.5µm gate) Si transistor of nominal thickness 400 nm. Thickness corrugations are visible in the Si substrate. The gates are formed from W silicide, while the amorphous layers above the gates and between the W plugs are Si oxides that have different densities. b) Eight times amplified phase contours, calculated by combining phase images from several holograms obtained across the region marked '1'. Specimen charging results in the presence of electrostatic fields outside the specimen edge, as well as elliptical phase contours in the oxide layers between the W contacts. c) shows an equivalent phase image obtained after coating the specimen on one side with approximately 20 nm of carbon to remove the effects of charging. d) shows one-dimensional profiles obtained from the phase images in b) and c) along the line marked '2'. The dashed and solid lines were obtained before and after coating the specimen with carbon, respectively. The dotted line shows the difference between the solid and dashed lines.