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HRTEM Image Simulations for Gate Oxide Metrology

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High resolution transmission electron microscopy (HRTEM) has found extensive use in the semiconductor industry for performing device metrology and characterization. However, shrinking device dimensions (gate oxides are rapidly approaching 10Å) present challenges to the use of HRTEM for many applications, including gate oxide metrology. In this study, we performed HRTEM image simulations of a MOSFET device to examine the accuracy of HRTEM in measuring gate oxide thickness. Length measurements extracted from simulated images were compared to actual dimensions in the model structure to assess TEM accuracy. The effects of specimen tilt, specimen thickness, objective lens defocus and coefficient of spherical aberration (C_s) on measurement accuracy were explored for nominal 10Å and 16Å gate oxide thicknesses.

The gate oxide was modeled as an amorphous silicon oxide situated between a gate electrode and substrate, both modeled as single crystal Si(100). Image simulations of the sandwich structure were performed in cross-section (with Si[110] parallel to beam direction) using the multislice approximation for a 200 kV microscope with C_s=0.5mm.[1] Amorphous slices were added to the top and bottom of the specimen to simulate the amorphization that occurs during typical specimen preparation. The actual gate oxide thickness, T, is defined as the distance between the bounding Si atoms in the model structure (Fig. 1a). The gate oxide thickness was also measured directly in pixels from the simulated image (Fig. 1b). We use a statistical routine to calculate the standard deviation in pixel intensity for each horizontal row (or y-coordinate) in the simulated image (Fig. 1c). Local minima in the standard deviation, which correspond to low-intensity regions between Si[110] dumbbells, were used to calibrate the image length scale. The measured gate oxide thickness was then compared to the actual (model) thickness to assess accuracy for a variety of microscope and specimen conditions (Table I).

Results reveal no consistent trends in measurement accuracy as a function of specimen thickness, specimen tilt, or objective lens defocus. Specimen tilts as large as 25 mrad do not necessarily decrease measurement accuracy, but in some cases may actually improve it.[2] Surprisingly, minimum contrast defocus (f = -156Å) is observed to yield greater accuracy than Scherzer defocus (f = -425Å) for at least one specimen thickness (246Å). Although Scherzer defocus yields the most accurate representation of the projection of the specimen potential for a thin specimen, the best defocus for accurate projection of thicker structures moves steadily in the overfocus direction as specimen thickness is increased.[3] Measurement errors (percent) for the 16Å gate oxides are generally lower than those for the 10Å gate oxides. Images simulated using C_s = 0.0 mm consistently yield the most accurate measurement of gate oxide thickness, with an error of 1% or less. Significantly, measurement accuracy in these simulations is maintained even at larger specimen thicknesses that are likely to be encountered in practice. Based on these results, we believe that accurate metrology of 10Å gate oxides (i.e. to within several per cent) is feasible on a consistent basis using a C_s-corrected microscope. However, the effects of Si-SiO$_2$ interface roughness on measurement accuracy should be explored in greater detail to assess the applicability of zero-C_s microscopy to metrology of real systems.

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4. Work funded by Intel Corporation. Access to computing facilities at the National Center for Electron Microscopy is gratefully acknowledged. The NCEM is supported by the Director, Office of Science, Office of Basic Energy Sciences, Material Sciences Division, of the U.S. Department of Energy, under contract No. DE-AC03-76SF00098.

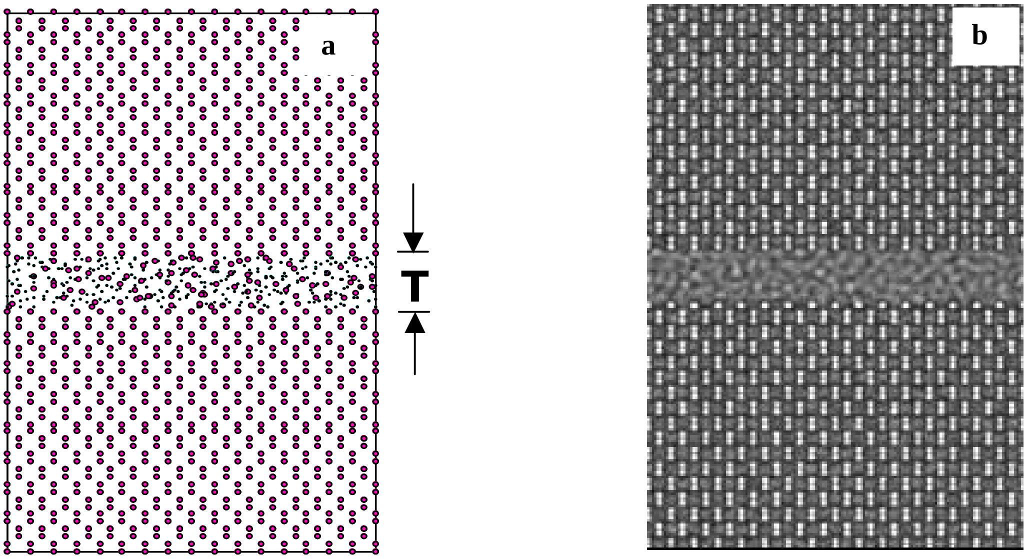

Fig 1

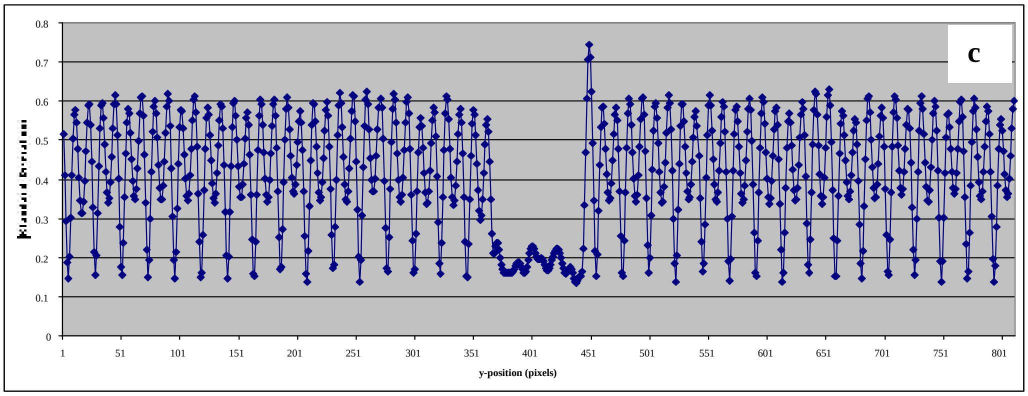

FIG 1 (a) Model structure, (b) simulated image and (c) plot of standard deviation versus y-coordinate for 10Å gate oxide structure at Cs=0.0 mm (specimen thickness = 154Å).

Table 1

Specimen Thickness (Å)	Specimen Tilt (mrad)	Defocus (Å)	C_s (mm)	Model Thickness (Å)	Measured Thickness (Å)	% Error
154	0	-425	0.5	10.56	9.84	-6.8
154	0	-156	0.5	10.56	11.40	+8.0
154	0	-20	0.0	10.56	10.44	-1.1
154	12.6	-425	0.5	10.56	9.12	-13.6
154	25	-425	0.5	10.56	10.68	+1.1
246	0	-425	0.5	10.56	8.88	-15.9
246	0	-156	0.5	10.56	10.92	+3.4
246	0	-20	0.0	10.56	10.56	0.0
246	6.3	-425	0.5	10.56	9.48	-10.2
154	0	-425	0.5	16.29	18.94	+0.5
246	0	-425	0.5	16.29	19.21	+0.9
246	0	-156	0.5	16.29	19.55	+2.7