Characterizing Profile Tilt of Nanoscale Deep-Etched Gratings via X-ray Diffraction

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The Bosch deep reactive-ion etching (DRIE) process [1] has played an instrumental role in fabricating high-aspect ratio structures such as through-silicon vias, MEMS and memory devices, and nanoscale x-ray gratings. The profile tilt caused by non-uniformity in the plasma-sheath thickness can degrade yield and device performance in many applications. Design improvements of the plasma source have successfully reduced the tilt problem for microscale structures; however, no techniques exist to precisely measure the tilt of nanoscale features. Furthermore, the metrology to characterize the tilt is laborious, requiring front-to-backside alignment of test patterns with subsequent etching and SEM imaging [2, 3].

We present a fast, high-precision (<0.1 deg of uncertainty), non-destructive x-ray metrology technique developed to characterize profile tilt in nanoscale gratings. Test structures are 200 nm-pitch silicon gratings etched ~ 3 µm deep. They consist of four grating patches, 26 x 27 mm, patterned on a ~ 55 mm square chip. Each sample was bonded to full 4 or 6” carrier wafers for etching. After the grating etch, the substrate was thinned (to < $^1/_e$ x-ray absorption length) from the backside to enable observation of transmitted diffraction orders from x-ray illumination. Fig. 1 shows a SEM image of a cleaved sample. Gratings were illuminated with a collimated x-ray beam (Cu-K_α radiation, 50 µm diameter), similar to small-angle x-ray scattering (SAXS). The change of diffraction efficiencies (DEs) was recorded (Figure 2a) as a function of beam incidence angle. Modeling via rigorous coupled wave analysis [4] predicts extreme values (0^{th} order DE minimized, 1^{st} order DE maximized) when the local grating bar etch direction is parallel to the incident x-ray beam. To obtain the bar angles with respect to the surface normal, a laser was reflected off the surface with a known angle relative to the x-ray beam. The fast measurement can be repeated at arbitrary points along the direction perpendicular to the grating lines (z-direction in Fig. 2a) to study the variation of bar etch angle across the grating.

Figure 3 shows the measured change of bar angles for samples etched on both the SPTS Rapier and Pegasus etchers. The measurement accuracy is estimated to be ~0.3 deg with a clear path for improvements. The result shows good agreement with previous results on microscale etches; near constant tilt angles for the Rapier tool across the wafer and larger linear variations with a Pegasus etcher [2]. A rapid transition of profile tilt near the sample edge is clearly shown, which is likely due to non-uniformity of the plasma sheath.

[1] Lärmer F. and Schilp A., Patents US 5501893, 1996.

[2] Barnett R., et al. Electronic Components and Technology Conference 1056, 2010.

[3] Lea L. and Nicholls G., Report, Surface Technology Systems.

[4] Moharam M. G. and Gaylord T. K. *J. Opt. Soc. Am.* 7(71), 811, 1981.

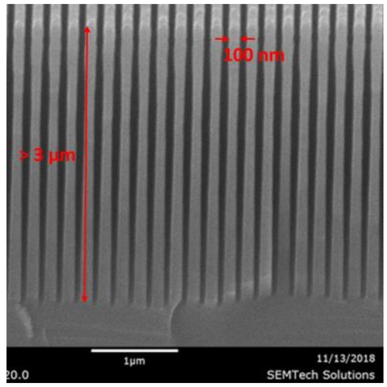

Figure 1: Inclined view of cleaved nanoscale grating for x-ray spectroscopy.

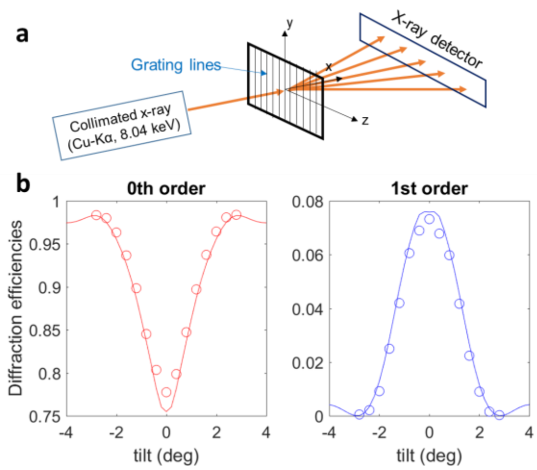

Figure 2: (a) Small-angle x-ray scattering schematic for measurement of bar tilt angle. The gratings are rotated around the y-axis. (b) Modeled (solid line) and measured (hollow circles) DEs for 0th and 1st orders with changing tilt angles.

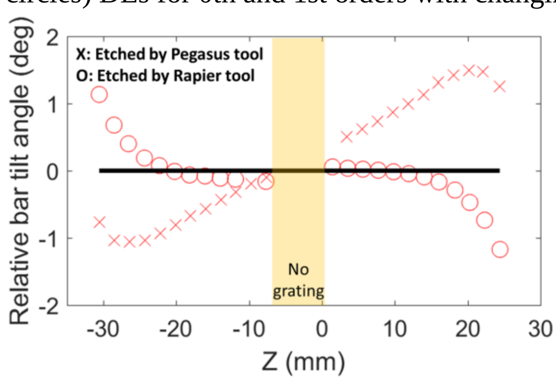

Figure 3: Measured bar tilt angle variation along z-direction (z-dir. shown in Fig. 2a) for the Rapier and Pegasus plasma etchers. The Rapier etcher showed much lower tilt than the Pegasus, and rapid changes of bar angles are observed near the edge of the sample and carrier wafer. No measurements were taken in the shaded orange area where there are no gratings (gap between grating patches).