Shift happens: submilliradian goniometry of an electron beam

A. C. Madison, J. S. Villarrubia, D. A. Westly, R. G. Dixson, C. R. Copeland, J. A. Liddle, S. M. Stavis[*]
National Institute of Standards and Technology, Gaithersburg, Maryland 20899
[*]*samuel.stavis@nist.gov*

J. D. Gerling, K. A. Cochrane, A. D. Brodie, L. P. Muray
KLA Corporation, Milpitas, California 95035

Electron optical aberrations degrade the accuracy of scanning electron microscopy, reducing its reliability for diverse applications, including semiconductor metrology. Multiple calibrations may be necessary to identify and correct multiple effects within a single measurement. One aberration of concern is the axial tilt of the electron beam, which shifts the apparent positions and deforms the intensity profiles of features. Measurement of the beam tilt can enable physical correction of beam deflection, or analytical correction in a measurement function. We introduce a novel reference structure and image analysis method to measure such shifts, among other key effects. Our concept shows promise for new accuracy in scanning electron microscopy, with multifunctional standards enabling comprehensive calibrations of beam tilt and beyond.

A previous study[1] used pyramidal micropits in silicon to manifest shifts of image features. This study reported a submilliradian repeatability but lacked the goniometry necessary to quantify accuracy, defining the state of the art. An anisotropic etch couples the lateral and vertical dimensions of pyramidal micropits, yielding a trade-off between narrower features to densely sample the imaging field, and deeper features to sensitively manifest lateral shifts. Moreover, beam tilt is only one of several aberrations of concern, and it is unclear that pyramidal micropits are optimal for comprehensive calibrations.

To address these issues, we explore conical frustum arrays as multifunctional reference structures, using theory to guide ongoing experiments (Figure 1). For a tilt inclination θ, a centroid shift s happens between the top and bottom edges of a conical frustum. For a frustum height h, the tilt measurement function is simply $\theta = \sin^{-1}(s/h) \approx s/h$, facilitating null-tilt sensing and self-calibrating goniometry. To understand the limiting random effect of shot noise, we simulate frustum images using a physical model of electron scattering.[2] At a dose of 60 electrons per nm^2, model shifts show the feasibility of submilliradian accuracy for sidewall angles of greater than approximately 40 mrad. In experimental measurements, charge accumulation and hydrocarbon contamination may limit the achievable electron dose, while conical asymmetry among other systematic effects will ultimately limit accuracy. In initial experiments, we fabricate submicrometer frustum arrays in silicon using electron-beam lithography and reactive ion etching. These reference structures are ideal for correlative atomic-force, super-resolution optical, and scanning-electron microscopy. This workflow yields reference heights and positions that allow scale factor calibration and scanfield distortion correction,[3] enabling an integrative calibration that improves the accuracy of centroid localization to measure electron beam tilt and any spatial variation thereof across the imaging field.

---

[1] K. Setoguchi *et al.*, *Proc. SPIE 5752*, 2005.
[2] J. S. Villarrubia *et al.*, *Ultramicroscopy*, 154, 2015.
[3] C. R. Copeland *et al.*, *arXiv*, 2106.10221, 2021.

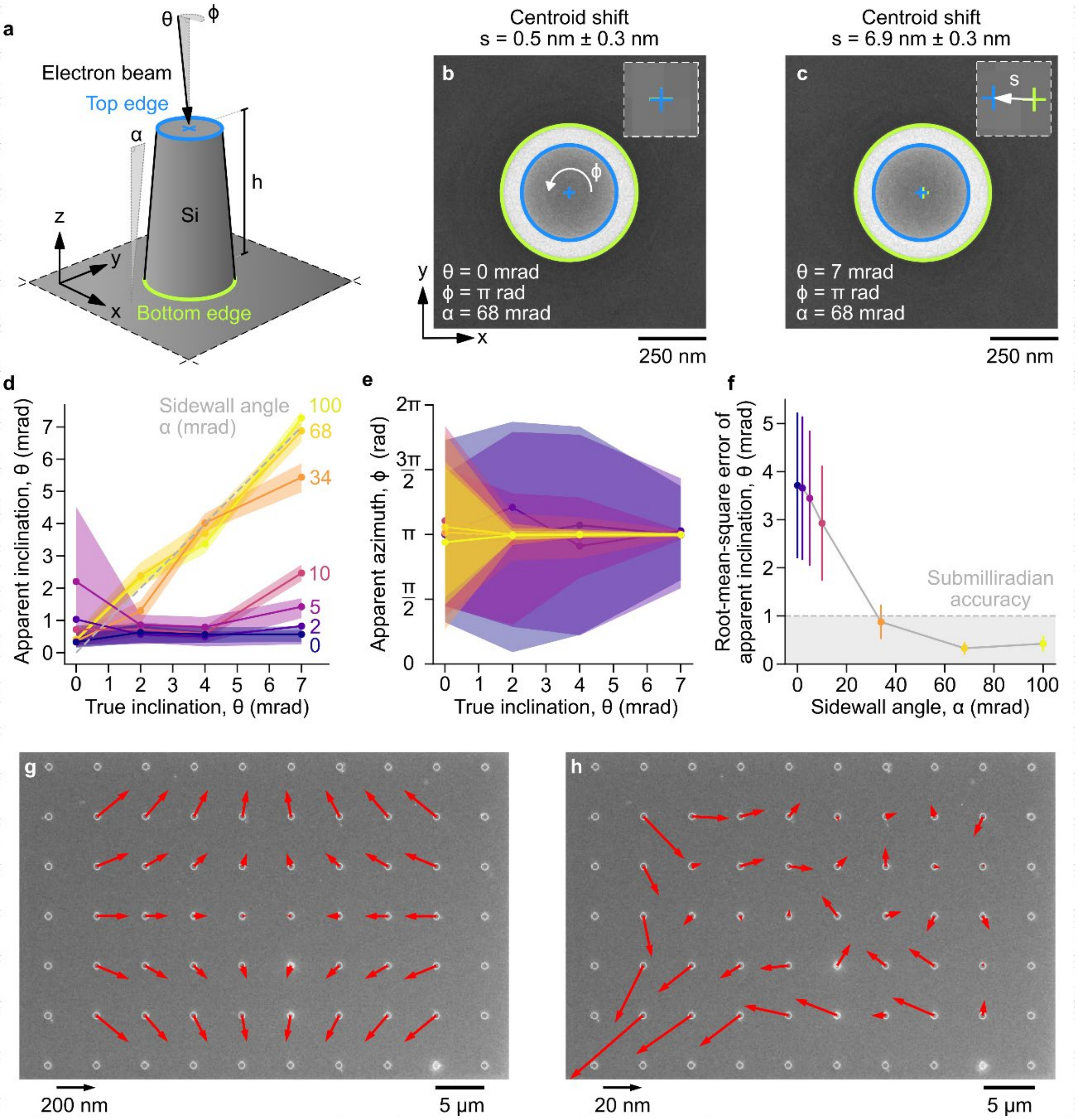

Figure 1. Shift happens: submilliradian goniometry of an electron beam. (a) Schematic showing a conical frustum with a sidewall angle α and an incident electron beam with a tilt inclination θ and azimuth ϕ. (b, c) Scanning electron micrographs showing synthetic images of silicon frusta, resulting from a physical model of electron scattering and emission. The frusta have top diameters of 500 nm, heights of 1000 nm, and sidewall angles of 68 mrad. The electron beam has an energy of 5 keV, a Gaussian profile with a standard deviation of 3.75 nm at best focus at the midsection of the frustum, a beam divergence angle of 17 mrad, an azimuth of π rad, and an inclination of (b) 0 mrad and (c) 7 mrad. A dose of 60 electrons per nm^2 results in approximately Gaussian shot noise. Blue and green ellipses show the results of edge detection, indicating shifts in the (crosses) centroids of the top and bottom edges of (c).
(d, e) Plots showing (d) apparent inclination and (e) apparent azimuth as a function of true inclination from simulations. Gray dash lines are true values. 68 % coverage intervals result from electron shot noise. (f) Plot showing root-mean-square errors of apparent inclination as a function of frustum sidewall angle in (d). (g, h) Scanning electron micrographs showing experimental images of a silicon frustum array, resulting from a scanning electron microscope with ordinary operating parameters. The array has a pitch of 5001.71 nm ± 1.32 nm at 68 % coverage, from a traceable chain of atomic-force and super-resolution optical microscopy. Red arrows denote position errors at each frustum prior to (f) scale factor calibration and (g) scanfield distortion correction.