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Site-Specific Lift-Out on Complicated Nanoscale Structures

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Transistor sizes continue to shrink causing the critical dimensions in FinFET structures to become exceedingly small—only a few nanometers wide. The challenge with atom probe tomography (APT) analysis of the smallest device structures is that the region of interest (ROI) must be placed within a specimen tip at sub-10-nm precision; a reliable landmark, within perhaps 10-nm or less form the target must be resolved to assure the necessary precision for extraction; surrounding materials that are substantially different in evaporation filed much be excluded; ion beam damage must be minimized through proper capping and cleaning process. In this work, we provide an example of a specimen preparation workflow that deals with small, complex device structures. Targeting, de-processing (gradually removing outer surface materials) and end-pointing are critical procedures to consider. Due to intellectual property concerns, images used in this abstract are only for the purpose of illustration rather than referring to specific device structures and no scale bars are displayed for these sub-14-nm-node device structures.

Locating a ROI from the sample surface are usually achieved by relying on surface features and landmarks. When necessary, ion milling can be applied to etch away unnecessary top layers to uncover landmarks more proximate to the ROI. Cross-sectional cuts in a “slice and view” fashion can be further used to confirm location of features beneath the surface. Testing and refining a workflow on a region with identical structure to the real ROI may be critical for achieving the necessary precision, especially when analysis of a specific device is required.

Our example process is shown in **Figure 1.** The desired depth of ROI is 100-500 nm below the surface, which provides sufficient protection during initial milling. In some situations, ex-situ capping or in-situ electron beam deposition may be needed to provide adequate surface protection. Analysis will be done in an inverted direction, so a ~2 μm tall prism-shaped conductive layer is applied and prevents charging. The inverted orientation is chosen to allow the specimens to be field evaporated starting in a low-field material and transitioning into the high-field material. In this case, the high-field tungsten metal gate on the sample surface was intentionally avoided. **Figure 1a** illustrates a wedge extracted using the standard FIB lift-out method [1]. On the extracted wedge, ROI should be aligned on the central axis to allow making multiple APT specimens from a single lift-out. To de-process from the backside, the wedge was transferred to the specialized ARM4™ stage from CAMECA. The stage is designed for making precise 90° uniaxial rotations along the wedge axis [3, 4]. As shown in **Figure 1b,** to obtain a smooth de-processed surface, the top side of the wedge was cut off and protected with a capping layer of sputtered Ni. **Figure 2a** shows image of the surface de-processed from the backside to the expose the metal gates in the vertical direction. A naturally sloped cross-sectional surface is critical and allows the exposure of features from various depths. De-processing was stopped when the tungsten gate started to emerge in the structural unit above the actual ROI. By carefully examining how the structure evolves, ~20 nm de-processing precision is possible to achieve. After getting the desired depth, the wedge is rotated by 90° for a second time. This flips the original sample surface onto the bottom side (**Figure 1c**). The de-processed surface now needs to be capped again. After capping surface features are no longer visible.

It requires great care to end-point a small ROI during the sharpening process. Here, cross-sectional cuts on the mount, as shown in **Figure 2b,** can be extremely helpful in centering annular patterns **Figure 2c** shows a specimen after annular milling with the ROI embedded behind the tungsten gate. Low energy ion beam cleaning is the last step in the procedure [5]. The lowest available beam energy should be used to minimize Ga implantation. Capping layer thickness is also critical for the yield and should be kept thin, ideally below 30 nm (capping options and considerations will be discussed in a separate abstract submitted to M&M 2022). During the sharpening process, specimens automatically develop their end-forms by virtue of the differential milling rates for features exposed to the ion beam. Once the capping layer is gone the specimen center naturally develops. These considerations need to be taken into account to develop a successful and efficient specimen preparation method.

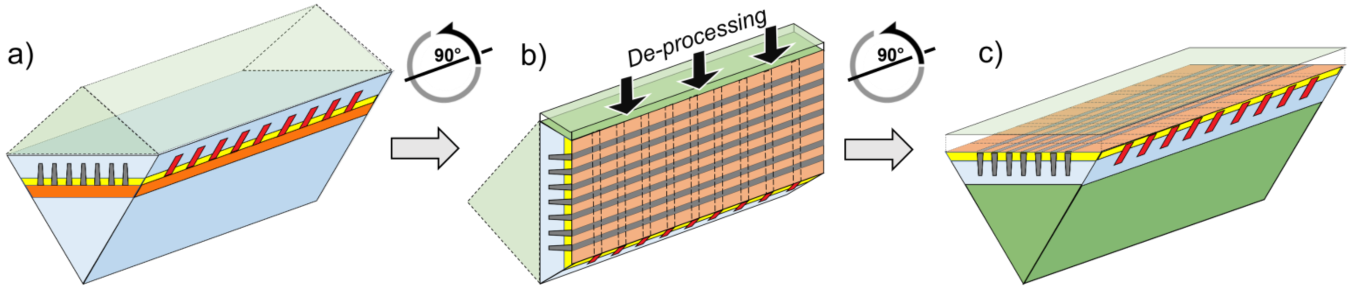

Figure 1. a) A lift-out wedge with capping material on top. The ROI is exposed to the cross-sectional surfaces. Ion-beam de-processing is illustrated in b), where the wedge has been rotated by 90º enabling milling parallel to the original surface. After another 90º rotation, the bottom side flipped to the top as shown in c). The flipped wedge is ready for the subsequent processes to provide specimens for APT.

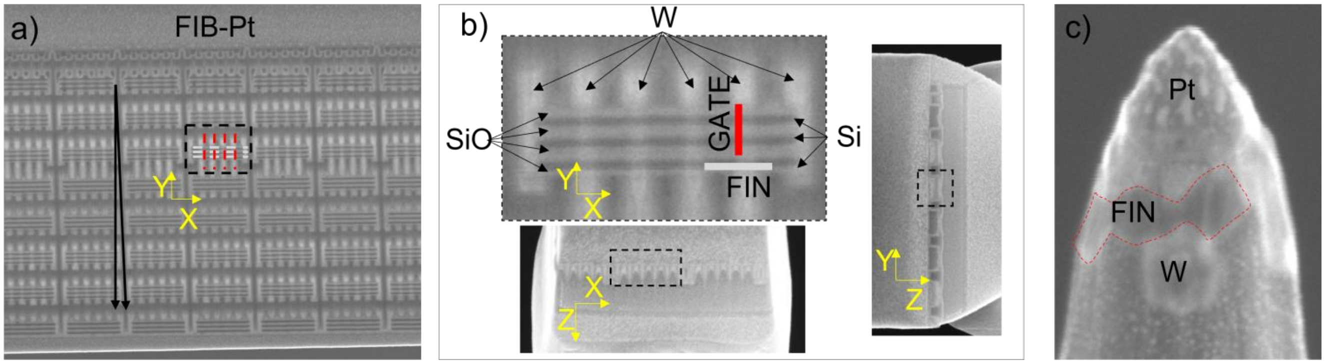

Figure 2. a) De-processed surface form the backside showing repeated blocks of a device structure. b) Three images for structure layout from the backside with corresponding cross-sectional images in orthogonal directions with W, SiO and Si regions indicated. c) Specimen centered on the gate/fin crossing point after annular milling. Low energy ion-beam cleaning is needed to complete the sharpening process.

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