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Correlative HAADF-STEM and EDX-STEM Tomography for the 3D Morphological and Elemental Analysis of FinFET Semiconductor Devices

Julien Sorel[1,2], Martin Jacob[1], Toby Sanders[3], Adeline Grenier[1], Rafael Bortolin Pinheiro[1], Frédéric Mazen[1], Thierry Epicier[2] and Zineb Saghi[1]

1. Univ. Grenoble Alpes, CEA, LETI, Grenoble, France.
2. Univ Lyon, INSA-Lyon, Université C. Bernard Lyon 1, Villeurbanne Cedex, France.
3. School of Mathematical and Statistical Sciences, Arizona State University, Tempe, AZ.

The increasing complexity of semiconductor devices demands advanced three-dimensional (3D) characterization techniques for elucidation of structure-property relationships and optimization of process conditions. High angle annular dark field scanning transmission electron microscope (HAADF-STEM) tomography has greatly contributed to the 3D morphological and structural understanding of crystalline materials at the nanoscale [1]. 3D chemical analysis with energy-dispersive X-ray spectroscopy STEM (EDX-STEM) tomography is nowadays possible thanks to the recent developments in electron sources and X-ray detectors with improved efficiency [2]. Combining both techniques is a promising route to provide complementary insights into the characterization of nanodevices. In this work, we applied both techniques to a silicon fin-shaped structure implanted with Arsenic (As) as n-type dopant and encapsulated in silicon oxide (SiO_2). A needle-shaped sample was prepared by focused ion beam (FIB) and mounted onto a Fischione on-axis holder. The acquisitions were performed using an FEI Titan Themis operating at 200kV and equipped with a probe corrector and 4 SDD EDX detectors: an HAADF-STEM tilt series was acquired between -90° and +90° with 5° increment. The frame size was 2048x2048 pixels, with a frame time of 15 seconds and a pixel size of 0.26 nm. In parallel, every 10°, an EDX-STEM map was acquired using Esprit software (Bruker). In this case, a frame size of 193x163 pixels was chosen, with an acquisition time of 10 min/map and a pixel size of 1 nm. Hyperspy, a python-based software for hyperspectral data processing [3], was then used for the batch-processing of the 4D dataset. Spectral unmixing using non-negative matrix factorization (NMF) led to the identification of three chemical phases in the sample: Si, SiO_2 and As, as can be seen on Figure 1(b-d) (the corresponding HAADF-STEM image is shown in Figure 1(a)). The extracted tilt series, along with the HAADF-STEM dataset, were aligned using the common line and mass center methods, and the reconstructions were performed using the total variation minimization algorithm (TVM), necessary for such under-sampled datasets [4]. Figure 2(a) and (b) show the volume rendering and a slice through the HAADF-STEM reconstruction, where the roughness of the Si nanowire is well resolved, and can be reliably quantified in 3D using for instance the solidity measure (Volume/convex volume). The average volume of the As precipitates was estimated to ~15nm^3. The reliability of this measure depends on the accuracy of the segmentation step (and the robustness of the reconstruction algorithm). EDX-STEM tomography led to an As volume (Figure 2(d) and (f)) which was easier to segment, but with a worse resolution than HAADF-STEM, due to large pixel size and tilt increment. The average volume of the As precipitates in this case was estimated to ~20nm^3. EDX-STEM tomography however provided information about the 3D implantation of As that was not present in the HAADF-STEM volume. As shown in Figure 2(g), a depth profile though the fin shows an implantation of approximatively 20 nm.

In summary, it is shown here that HAADF-STEM tomography remains very useful in parallel to EDX-based 3D analysis of complex structures, the coupling of both approaches leading to a thorough and very complementary information.

References:

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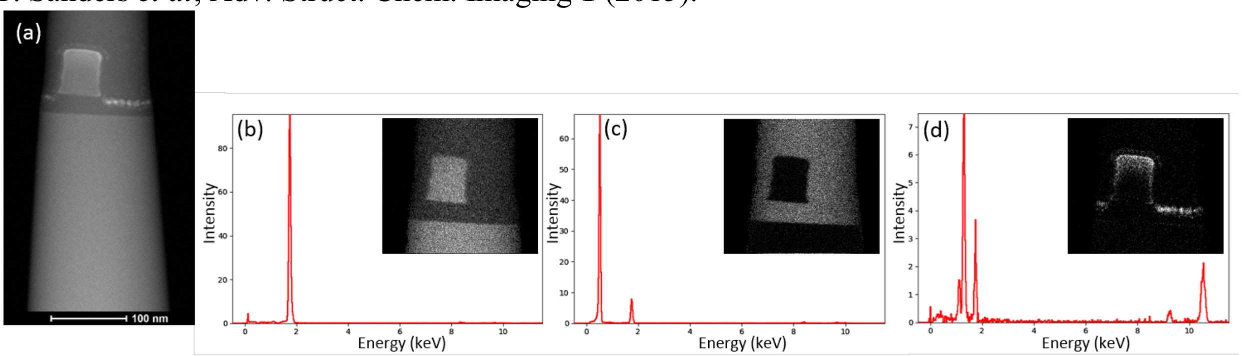

Figure 1. (a) HAADF-STEM projection of silicon fin-shaped structure at -5°. (b-d) NMF unmixing applied to the EDX-STEM tomographic dataset led to the identification of 3 chemical phases: Si, SiO_2 and As.

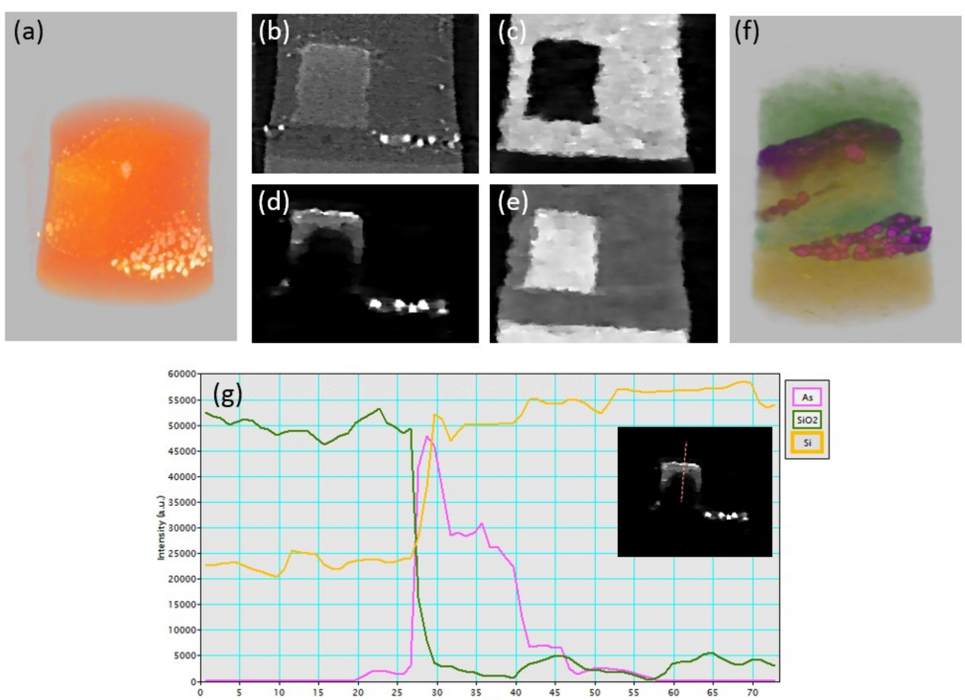

Figure 2. (a) Volume rendering and (b) a slice through the HAADF-STEM tomographic reconstruction. (c-e) are slices through the SiO_2, As, and Si reconstructions obtained with EDX-STEM tomography. (f) Volume rendering of the tomographic reconstructions of SiO_2 (green), As (purple) and Si (yellow) chemical phases. (g) A depth profile through the fin on a selected section (dotted line in the insert).