doi:10.1017/S1431927610057685
Microsc. Microanal. 16 (Suppl 2), 2010

Three-Dimensional Imaging of Semiconductor Device Structure using Contrast Tuning EFTEM Tomography

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Energy-filtered transmission electron microscopy (EFTEM) has emerged as a powerful tool for semiconductor device analysis in recent years. Among the EFTEM imaging modes, contrast tuning is often used to enhance the contrast of selected phase(s) and to visualize the processing defects in devices [1]. The principle of contrast tuning is that EELS spectra from different parts of a specimen have differences in the variation of the spectrum intensity with increasing energy loss or overlapping ionization edges [2]. In this paper, tomographic reconstruction from a tilt-series of two-dimensional (2D) contrast tuning images is attempted using semiconductor device samples. Assuming a single scattering event, the intensity $I(E)$ of a contrast tuning image contributed by an atomic species at a given pixel can be described as [3]

$$I(E) \approx I_0 n_a t \left(\frac{d\sigma}{dE} \right) + I_0 \left(\frac{dP_s}{dE} \right) \tag{1}$$

where I_0 is the zero-loss intensity, n_a is the number of atoms per unit volume, t is the specimen thickness, $d\sigma/dE$ is the energy differential cross-section and dP_s/dE represents surface mode scattering. If the projected thickness of the feature of analysis is small ($t < \lambda$, the inelastic mean free path) even at high tilts, there will be a monotonic relationship between image intensity and sample thickness, which satisfies the projection requirement [4] for electron tomography.

Fig.1a shows a multi-phase device structure containing silicon nitride, silicon oxide, cobalt silicide and silicon. While different energy filtering enhances different phases, maximum contrast and good separation of the phases are obtained with the energy loss E=50 eV. Using a tilt-series of the 50eV-loss images (10eV energy window, -66^o to 66^o tilt range, 3^o tilt step), a three-dimensional (3D) image was reconstructed and its reprojection along the 0^o tilt direction is shown in Fig.1b. Clearly, the reconstruction projection almost duplicates the overall structure shown in the original 2D projection (Fig.1a), indicating that the contrast tuning imaging is suitable for 3D reconstruction.

Plasmon imaging is a special case of contrast tuning. The strong signals of plasmon images provide high contrast and high SNR tilt-series with short acquisition time. Fig. 2a is a 2D silicon plasmon image taken at 16eV energy loss with 10eV energy window, showing a device structure with poly silicon layers on the patterned [110] silicon substrate. The 3D reconstruction was conducted with a tilt-series ranging from -50^o to +50^o at 1^o steps. Fig.2b shows the 3D geometry of the silicon structure. The diffraction contrast shown in the 2D plasmon images is significantly reduced in the reconstructed volume due to the averaging effect. Once a 3D image is formed, its enough resolution ensures that any defect related to silicon should be clearly detected through an appropriate visualization method.

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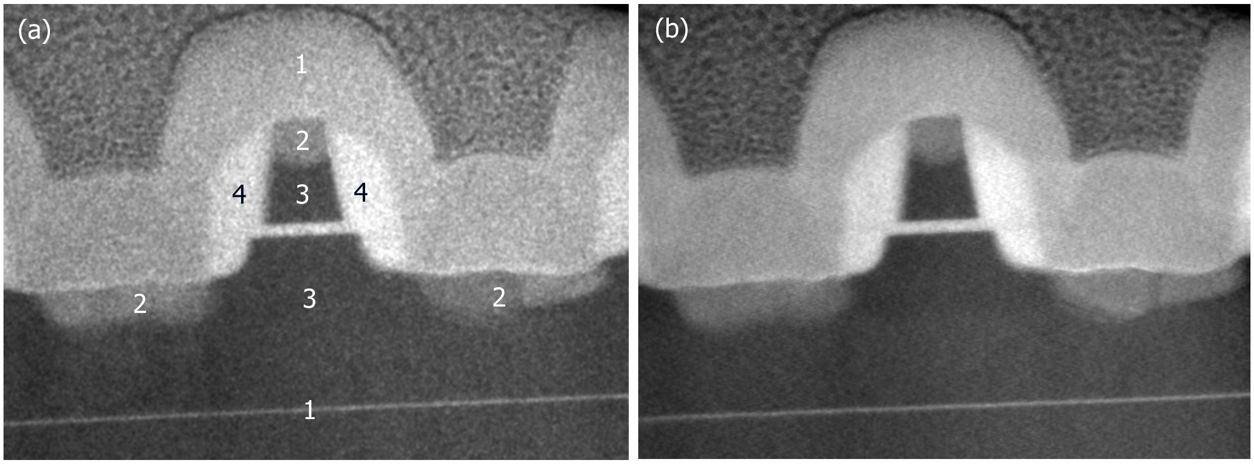

FIG. 1. (a) Contrast tuning image of a multi-phase device structure taken at 50eV energy-loss with 10eV window (1-silicon oxide, 2-cobalt silicide, 3-silicon, 4-silicon nitride). The top layer is the Pt deposition layer showing a mottled contrast characteristic of amorphous materials. (b) Reprojection of the 3D reconstruction in the zero degree tilt direction.

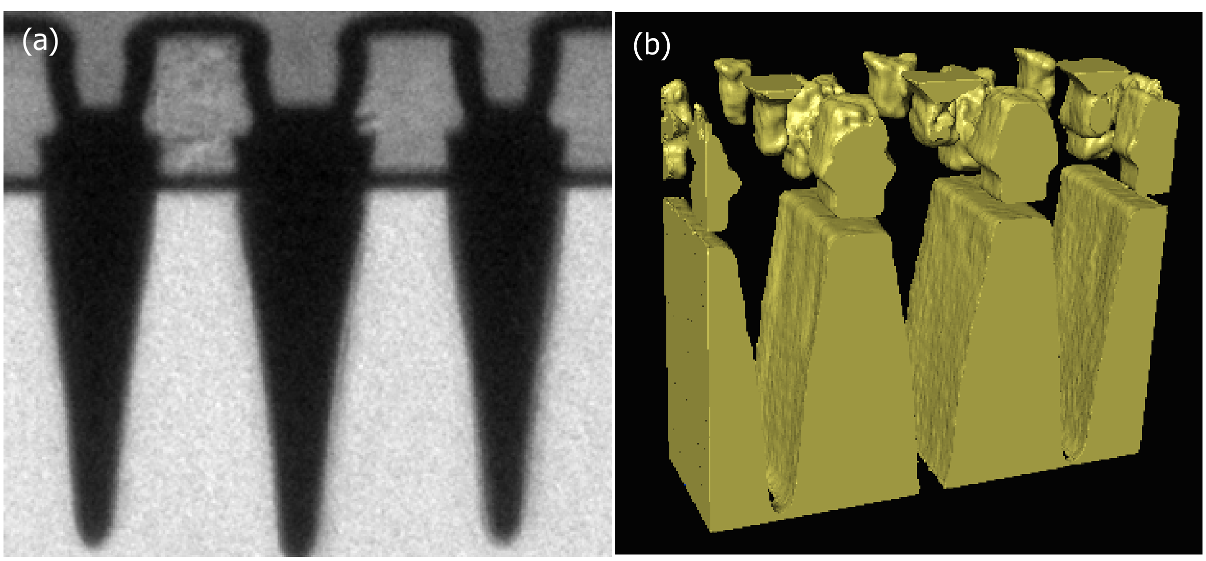

FIG. 2. (a) Silicon plasmon image of a device structure showing multi-layers of silicon (bright contrast). (b) 3D reconstruction from a tilt-series of silicon plasmon images.

https://doi.org/10.1017/S1431927610057685 Published online by Cambridge University Press