Targeted argon ion milling of advanced integrated circuits FIB specimens with automatic milling termination

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Integrated circuits (ICs) commonly include fin field effect transistors (FinFETs), which comprise multigate transistors with the source/drain (S/D) channels (fins) surrounded by a three-dimensional gate. While FinFET complexity is increasing, IC devices are decreasing in size, which makes physical failure analysis and metrology challenging. FinFET transmission electron microscopy (TEM) specimens are typically prepared using a Ga^+ focused ion beam (FIB). However, FIB milling typically leaves specimen artifacts, such as surface amorphization and Ga^+ implanted layers, both of which may limit analytical and high-resolution electron microscopy. In this work, we present Ar^+ milling that uses automated end-point detection and targeted milling as a method to remove FIB-induced artifacts and to prepare electron-transparent TEM specimens from a 14 nm node fin structure.

An Intel processor cross-section specimen was created in the FIB using the inverted method. The specimen was then thinned usinga sub-micron size Ar^+ beam rastered within a defined area. Imaging from in situ detectors - a secondary electron detector (SED) and a scanning transmission electron microscope (STEM) detector - was used for end-point detection. Prior to milling, the intensity value from the area of interest was noted. A user-defined threshold value (a percentage of the initial intensity value) was entered before milling operations commenced; milling was automatically terminated when the intensity value reached the user-defined threshold value. Small threshold values and decreasing energies (980 eV to 700 eV) were used for subsequent milling steps, followed by targeted milling steps at 700 eV to 300 eV. TEM characterization was performed before and after milling.

Thickness reduction was observed in situ using the STEM detector (Figure 1). A high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image (Figure 2a) acquired before ion milling shows different layers across the fins. The fin structure of the FinFET was targeted until the gate-oxide layers on both sides of the specimen were revealed (Figure 2b). Figure 3b shows the atomic-resolution, bright-field STEM image of the fin structure following ion milling. Electron energy-loss spectroscopy (EELS) thickness measurements of the specimen and analysis of the image intensities will be performed. Quantitative evaluation of the correlation between specimen thickness reduction and the change in detector image intensities is underway. X-ray characteristic emission method by energy dispersive X-ray spectroscopy (EDS) technique will be conducted to determine implanted Ga layer thickness.

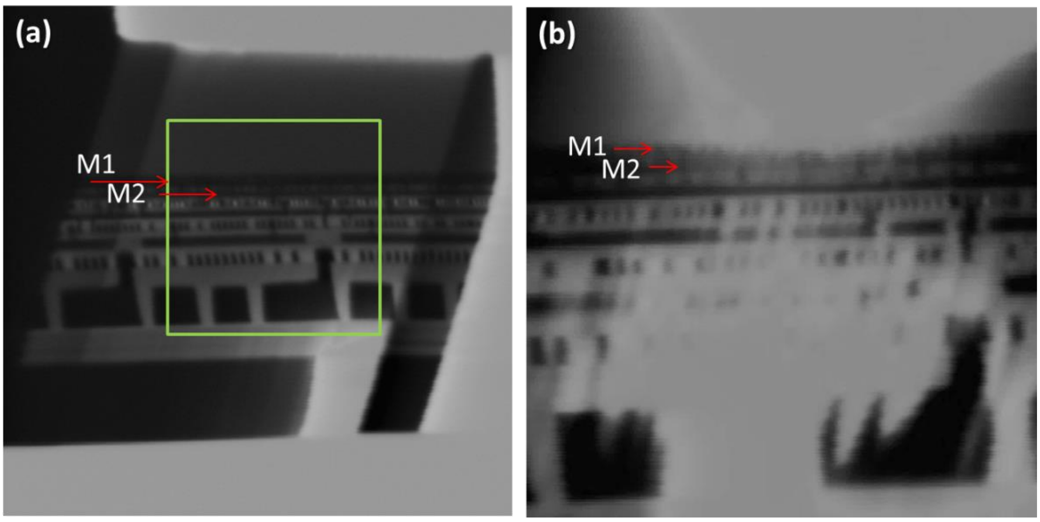

Figure 1. In situ STEM images before (a) and after (b) 300 eV ion milling. The area of interest is indicated by the green box in (a). Compare the change in contrast of metal line 1 (M1) and metal line 2 (M2) in (a) and (b).

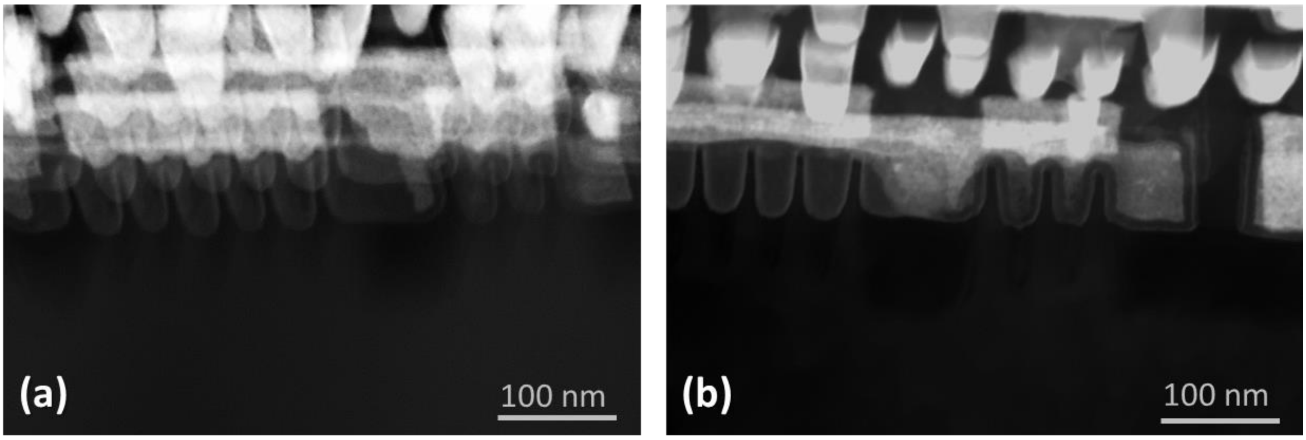

Figure 2. HAADF-STEM images before (a) and after (b) 500 eV milling. The gate oxide, spacer, and metal interconnect layers across the fin structure are visible.

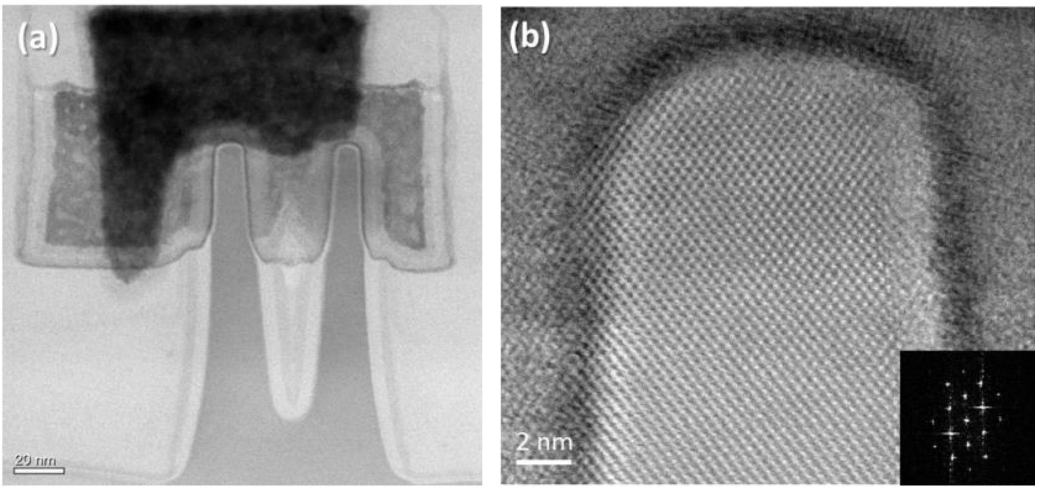

Figure 3. Bright-field STEM images of the FinFET structure after ion milling. Low magnification image of the FinFET (a) shows a homogeneous surface, free from redeposition. An atomic-resolution image of the fin (b) and a fast Fourier transform (FFT) acquired from the Si in the fin.

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