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Three-dimensional Imaging of Nano-Voids in Copper Interconnects using Incoherent Bright Field (IBF) Tomography

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Transmission electron microscopes (TEMs) are necessary tools in the microelectronic industry to analyze structures with fine detail (5-50nm). The overlap of small, dense features in projection complicates image analysis. Electron tomography (ET) is a solution that extracts the lost information in the projection direction from a tilt-series of two-dimensional images assuming a monotonic relationship between intensity and material thickness [1]. Failure of this relationship occurs for TEMs in crystal-containing materials, common in microelectronics, where non-monotonic image intensities depend on diffraction and phase conditions within the sample [2, 3]. Incoherent imaging via annular dark field (ADF) techniques in scanning TEMs (STEMs) has been used to avoid this problem but also creates contrast reversal in objects containing highly scattering materials [3]. This phenomenon describes situations when a highly scattering object that should appear intensely bright in an ADF image is instead dark. Hence, discerning whether voids in an image are due to missing material or image artifacts is difficult. It occurs when most of the electrons undergo multiple and/or large scattering events that spread them beyond the range of the detector (backscattering is an extreme example). The high tilts required by ET increase the projected thickness by a fact of three and exacerbate this phenomenon.

A Monte-Carlo electron scattering program [4] was written to quantitatively model the interaction of an electron beam and a solid. Fig. 1 shows the simulated transmission intensity through Cu films of different thicknesses for different outer annulus radii. The peak in each curve indicates the largest thickness at which physically meaningful information can be collected, i.e. it is still monotonic. Electrons with typical (S)TEM energies (100-200keV) have ranges that exceed even the thickest specimens of interest and therefore must exit the sample at some point. Contrast reversal could be avoided by collecting all highly scattered electrons, but this impossibly requires using a detector that completely encompasses the specimen. Instead, we propose collecting the complement of the ADF signal in the form of the forward scattered electrons contained in the STEM bright field (BF) signal. Fig. 2 shows Monte-Carlo simulations for disc-like STEM BF detectors with increasing radii that predicts this technique yields a linear, monotonic transmission function even for thick materials.

This technique has not been considered for ET because a STEM BF detector commonly collects electrons scattered from 0-10mrad and is susceptible to the same undesirable coherent imaging conditions as TEM. This signal can be made incoherent by increasing the outer detection angle up to 100mrad [5]. We used such a detector to analyze a stressmigration void in a 0.25 μm copper interconnect structure with Ta liners. A projection view, seen in Fig. 3a, shows an ADF image, where heavy materials appear white, with a Ta liner that has undergone contrast reversal (note arrow). Figure 3b is an IBF image, where heavy materials appear dark, of the same structure, but it does not contain this artifact. A slice of the reconstructed volume (Fig. 4a) and the thresholded view (Fig. 4b) reveal the exact location of the void and that the void did not interrupt the via's connection to the copper line. Through image segmentation it was found that the void's volume is $(210nm)^3$. [6]

References

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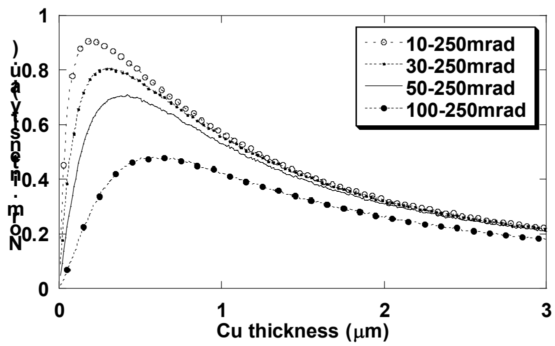

FIG. 1. Transmission function simulations of Cu for dark field detectors with different inner detection angles. The peak value determines the thickness at which contrast reversal occurs.

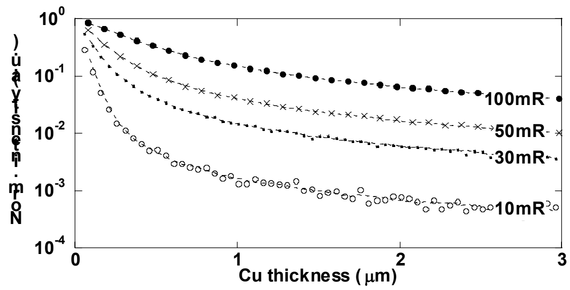

FIG. 2. The simulated transmission function for BF STEM detectors with different outer collection angles (in mRad) do not significantly deviate from Beer's law for large half-angles. The signal does not undergo contrast reversal and allows thick sections of highly scattering material to be reconstructed in 3D.

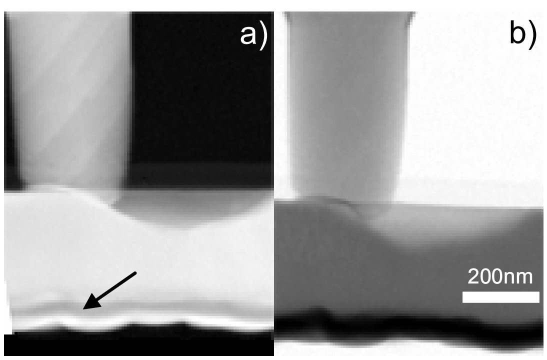

FIG. 3. a) ADF 2D-projection shows a stress void in a Cu interconnect with an arrow pointing to an artificial void created by contrast reversal of the Ta liner. This should be the brightest part of the image but is instead dark. b) IBF 2D-projection of the same liner shows no contrast reversal. Both a) and b) show the void possibly undercuts the via.

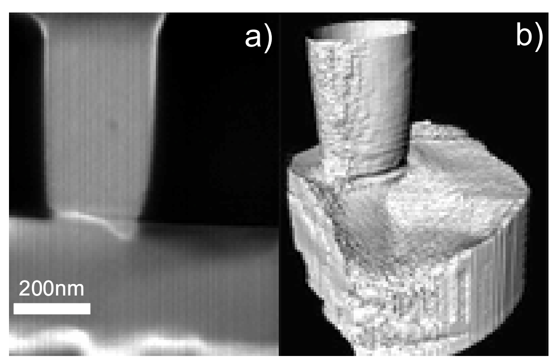

FIG. 4. a) A slice from the IBF 3D-reconstruction reveals the interconnect is not undercut, it was a projection artifact. b) The IBF reconstruction also shows the void is faceted, which could only be determined using electron tomography