Dynamical x-ray microscopy investigation of electromigration in passivated inlaid Cu interconnect structures

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ABSTRACT

The electromigration process is of fundamental interest in materials science and remains a critical reliability issue in advanced Cu interconnects. In this work, quantitative time-resolved x-ray microscopy mass transport studies of the early stages of electromigration in an inlaid Cu line/via structure were performed with about 40 nm lateral resolution. The image sequences show that void formation is a highly dynamic process, with voids being observed to nucleate and grow within the Cu via and migrate towards the via sidewall. Correlation of the real time x-ray microscopy images with post mortem high voltage electron micrographs of the sample indicates that the void nucleation occurs at the site of grain boundaries in Cu, and that the voids migrate along these grain boundaries during electromigration.

State of the art microprocessors – which operate at frequencies in the GHz range – require the integration of more than 100 million transistors. As the number of devices increases and the relative feature size becomes smaller, the overall performance of microprocessors is increasingly determined by interconnect design, technology and materials. In particular, Al-based interconnects are being replaced by inlaid Cu due to its higher conductivity and improved electromigration (EM) performance[1]. Nevertheless, EM and stress-induced EM phenomena remain as significant reliability concerns for inlaid Cu interconnects as the dimensions of the interconnect lines continue to shrink.[2] Formation of voids in the Cu lines may be induced by high current densities (electromigration) as well as by normal stresses at interfaces and hydrostatic stress components in the bulk (stress-induced migration). These voids may cause an opening to form in the interconnect, or may increase the net resistance in the line, leading to either malfunction or significant speed degradation.[3]

Despite many post-mortem studies of EM test structures, the exact degradation mechanisms during EM and stress-induced migration are still not well understood.[4] To date, there have been some studies of unpassivated interconnect structures, but these are only partially representative of the real behavior in an actual device, as the sample surface becomes a dominant diffusion path and the stress state is altered by the presence of the free surface as well as differences in sample preparation.[5] Our approach here is to perform in-situ experiments on passivated interconnect structures to determine the effect of Cu microstructure on interconnect reliability as well as observe the detailed degradation mechanisms. Recently, Meyer et al. have reported in-situ scanning electron microscope (SEM) studies of EM in Cu interconnect structures embedded in about 100 nm thick passivation layers.[6] However, because SEM images do not provide a linear relationship between mass loss and image intensity, bulk voids cannot be detected. Tomographic imaging based on transmission electron microscopy (TEM) images provides high resolution 3D information; however this technique requires electron energies of 300 keV or greater and needs samples significantly less than 1 μm in thickness to avoid multiple-scattering of the electrons. The high-voltage TEM, with about 1 MeV electron energy, permits imaging of thicker samples. However, the high momentum transfer of the electrons to the atoms in the sample can lead to severe radiation damage, especially if multiple images have to be recorded over hours, as in the case of our EM studies. In addition, real time quantitative mass transport measurements are not possible in either SEM or TEM studies.

In this Letter, we study void development and dynamics in passivated Cu line / via structures using x-ray microscopy. X-rays can penetrate samples that are many micrometers thick. Additionally, due to their unique interaction with matter, x-rays provide a natural image contrast between different elements, which we exploit to image Cu interconnect lines embedded within SiO_2.

The test structures used for the EM experiments were located within the scribelines of production wafers. Fig. 1A shows a schematic cross-section of the EM test structures used in the experiments with a two–level Cu interconnect. The samples were fabricated using dual–inlaid Cu technology, with a PVD-Tantalum barrier layer and a PECVD-Si_3N_4 (PEN) caplayer for the metal lines (see Fig. 1A). The structure consists of an array of metal lines. Depending on which level of metallization is tested, this array of lines is referred to as either Metal 1 or Metal 2 of a two-level structure. In this study, Metal 2 was tested and the connections to the bond pads are made to the Metal 1 level. Therefore, the Cu vias at the ends of the line are part of the device under test. According to other measurements of device lifetime, it is important for the EM degradation mechanism and for destructive failure analysis that the vias at the end of the line belong to the device under test for Metal 2. The design of the full-field transmission x-ray microscope (XM-1) installed at the Advanced Light Source at the Lawrence Berkeley National Laboratory (see Fig. 2) requires that the samples be prepared into a lamella of about 10 mm length and 250 µm width. The region of interest must be located near the end of the lamella.

In a first step the lamella was sawed from the wafer using a wire saw. This lamella has to be about 250 µm wide to contain the bondpads necessary for electrical connection of the line under test. It was then mounted on a modified 24-pin test chip in such a way that approximately 6 mm of the lamella protruded from the sample, containing the region of interest at its end. A Focused Ion Beam (FIB) was used to thin the lamella at the region of interest to a thickness of about 2 µm (see Fig. 1B and 1C). Material was removed from both sides of the line under test, so that all neighbouring metal lines were removed from the XM-1 field of view. Effectively, a 50 µm wide trench was cut perpendicular to the needle, leading to the area of interest. The X-ray beam of XM-1 penetrates the sample through this trench (see Fig. 1B). Note that both the line and the via under test were kept fully passivated within the final lamella during FIB thinning. As a final step, electrical connections from the bondpads to the landing pads of the 24-pin test chip were made by wire bonding. Figure 1B shows a SEM micrograph of the fully prepared sample with the region of interest. The trench that leads to the line under test and one of the bond wires can be seen. Fig. 1C shows a SEM micrograph of the cross-section of the layer system with the buried Cu line / via at higher magnification.

Model calculations show that the number of x-ray photons required to detect voids in Cu interconnects is at a minimum at a photon energy of E_{Ph}=1.8 keV [7]. However, the x-ray microscope XM-1 was designed for imaging samples with soft x-rays below 0.85 keV photon energy.[8] Its x-ray optical setup (which is shown in Fig. 2) originally incorporated a Ni mirror operating at fixed angular position of 3 degrees which blocked photons with $E_{Ph} \geq 0.85$ keV. In order to extend the usable photon energy range of XM-1 to photon energies of about 1.8 keV, we replaced the Ni mirror by a Ru/Si multilayer mirror, which has 30% reflectivity at E_{Ph}=1.8 keV. This mirror reflects the radiation from the storage ring bending magnet onto a condenser zone plate (CZP) which monochromates the radiation and at the same time illuminates the sample. Because the focal length of zone plates increases linearly with photon energy while the beam divergence is reduced, we used a new CZP with a diameter of 8.5 mm and an outermost zone width of 53 nm for sample illumination with 1.8 keV radiation. To match the geometrical requirements of XM-1 for imaging at E_{Ph}=1.8 keV and to achieve a sufficiently large magnification, we used a bilayer process[9] and e-beam lithography[10] to manufacture new zone plate objectives with 35 nm outermost zone width and a short focal length of only 1.6 mm. The maximum distance from the sample to the detector plane is 2 m and the pixel size of the CCD detector is 24 µm. Under these conditions, the pixel size in the x-ray images is 19 nm, which fits with the obtainable resolution determined by the zone plate objectives of about 40 nm.

Fig. 1D shows an x-ray micrograph of the passivated Cu line/via region taken with XM-1 at E_{Ph}=1.8 keV. The image clearly demonstrates the advantage of x-ray imaging: the penetration of the x-rays allows high absorption contrast images of the buried Cu structures to be obtained even through the thick dielectric layers. Note also that the x-ray absorption contrast mechanism is sensitive enough to permit different dielectric layers to be distinguished.

Figs. 3A – 3F present a sequence of x-ray micrographs of a via / line Cu interconnect structure captured during an in-situ EM experiment. During the in-situ experiment, the line under test was the upper line of the two-level test structure. The via was stressed at a temperature of about 150°C and at a current density of about 30 MA/cm^2. This current density was chosen to perform the in-situ experiment in a reasonable time. It is much higher than for standard EM experiments but is applicable for the study of principal degradation processes. The total in-situ EM experiment lasted 13 hours. The electron flow was from left to right in the image, and upwards through the via.

The x-ray micrograph in Fig. 3A shows the initial state of the interconnect structure without any voids. Void formation (Figs. 3B – 3C), movement (Figs. 3D – 3E) and agglomeration (Fig. 3F) can be clearly seen within the via as the test progresses. The shadow-like features around the Metal 1 structure can be attributed to Cu diffusion across the surface of the lamella. Because this metal line was originally wider than the lamella, it was cut by the FIB and therefore the Cu was exposed to oxygen and surface diffusion occurred.

The x-ray transmission is quantitatively related to the mass distribution of the sample, thereby permitting tomographic reconstruction as well as allowing quantitative determination of mass transport.[7] Fig. 4 shows the size and movement of voids as calculated from line scans (Figs. 3C, D and F) with 177 nm width across the region of void formation in the via. Up to Fig. 3C, the mass loss in the region of interest was 4 fg, increased to 11 fg in Fig. 3D and no further mass loss is observed within the accuracy of the measurement (about 1 fg) in the final image. Currently, the size of voids can be measured with a spatial resolution of about 40 nm.

Although the x-ray micrographs presented here are a projection in only one direction, the image sequence indicates that initial voids are formed in the Cu bulk structure, probably at grain boundaries or grain boundary triple points. To obtain detailed microstructural information of the via after the EM experiment, high voltage transmission electron microscopy was used to image the stressed sample. The JEOL Atomic Resolution Microscope operating at an accelerating voltage of 800 kV was used, and no additional thinning of the sample was necessary. The high-voltage TEM image in Fig. 5 shows that the large void in Fig. 3F is located next to the Ta barrier, i. e. Cu has been dissolved but the Ta barrier still exists. Additionally, by comparing the in-situ XM-1 images Figs. 3B and 3C with the electron micrograph, it is apparent that the locations of the early void formation coincide with grain boundaries. After the voids form, they appear to grow and migrate along pre-existing grain boundaries in the Cu until reaching the Cu / Ta interface. This failure mode is consistent with theoretical simulations, which reveal that this region is a “weak region” of the via / line structure because of the high local current density.[11]

In summary, we have developed a method to quantitatively study void formation and mass transport in passivated Cu line / via structures. Our measurements indicate that voids nucleate at grain boundaries within the via and then migrate along the grain boundaries to the sidewalls where they agglomerate. To provide 3D information about the exact location (bulk or interface) of void nucleation and migration during an EM experiment as well as to measure quantitatively the mass transport in the volume, future experiments must be based on time-resolved x-ray tomography. The dominant diffusion pathways for material transport could then be identified by correlating this information with the individual grain structure of vias obtained from either high-voltage TEM micrographs or electron tomography [12] of thinned samples.

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Figure captions

Fig. 1. A) Schematic of the cross-section of dual-inlaid Cu interconnects. B) Fully prepared sample for EM test with XM-1. C) SEM micrograph of the cross-section of the Cu metallization system which was thinned locally with FIB. Note that the passivation layer of about 500 nm thickness significantly reduces the obtainable resolution when imaging buried Cu line/via structures. D) X-ray micrograph recorded at 1.8 keV photon energy showing the sample region as Fig. 3C.

Fig. 2. Optical setup of the full-field transmission x-ray microscope XM-1. The Cu line / via under EM test is illuminated by E_{Ph}=1.8 keV photons with an energy bandwidth $E/\Delta E \approx 400$. The enlarged image of the sample formed by a micro zone plate objective is recorded on a directly illuminated back-thinned CCD-camera.

Fig. 3. Some selected images (A - F) from a sequence of x-ray micrographs taken at successive times showing void formation, movement and agglomeration inside the passivated Cu via.

Fig. 4. Cross-section of the voids as obtained from line scans (Figs. 3C, D and F) across the region of void formation (as indicated in Fig. 3D) in the via giving quantitative measurement of the void size and mass transport.

Fig. 5. High-voltage TEM bright field image showing the Cu line / via after the EM test. The void that formed during the EM experiment and the barrier layer are clearly visible. Grain boundaries that lie in positions consistent with the path of the void as it migrated can also be seen.

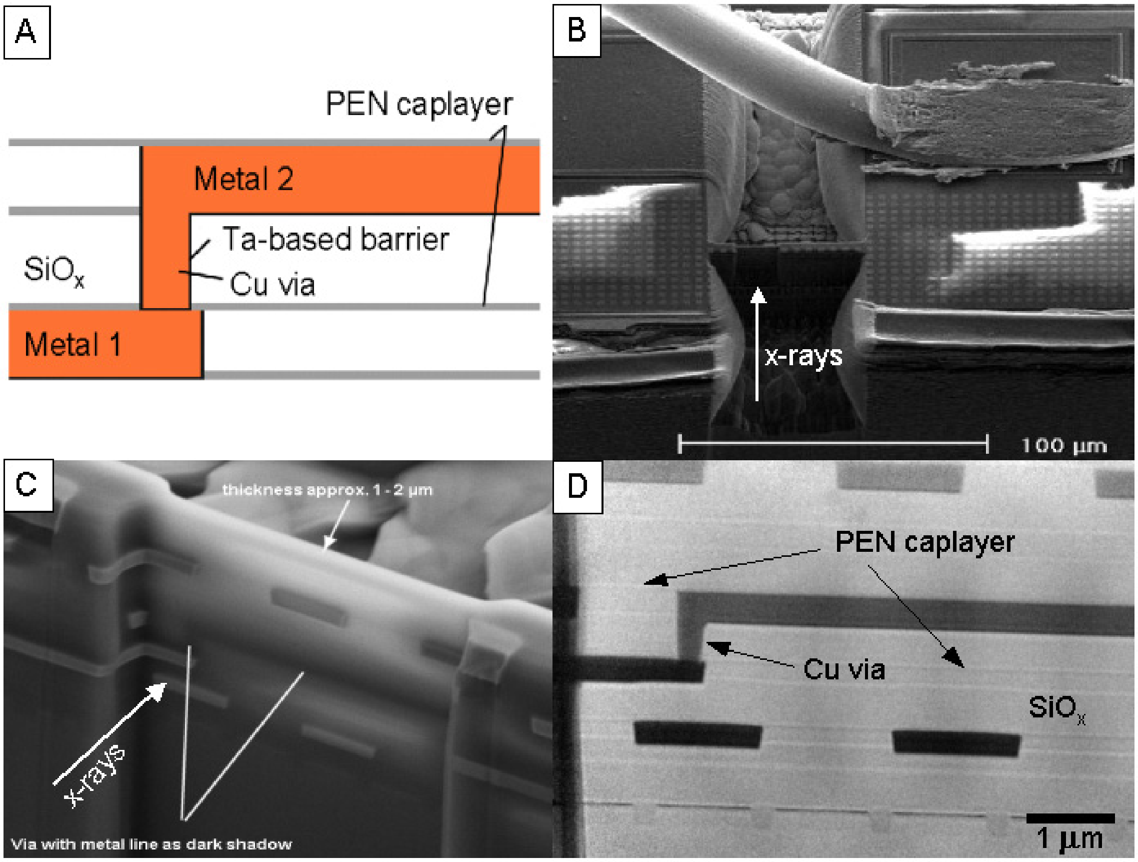

Fig. 1.

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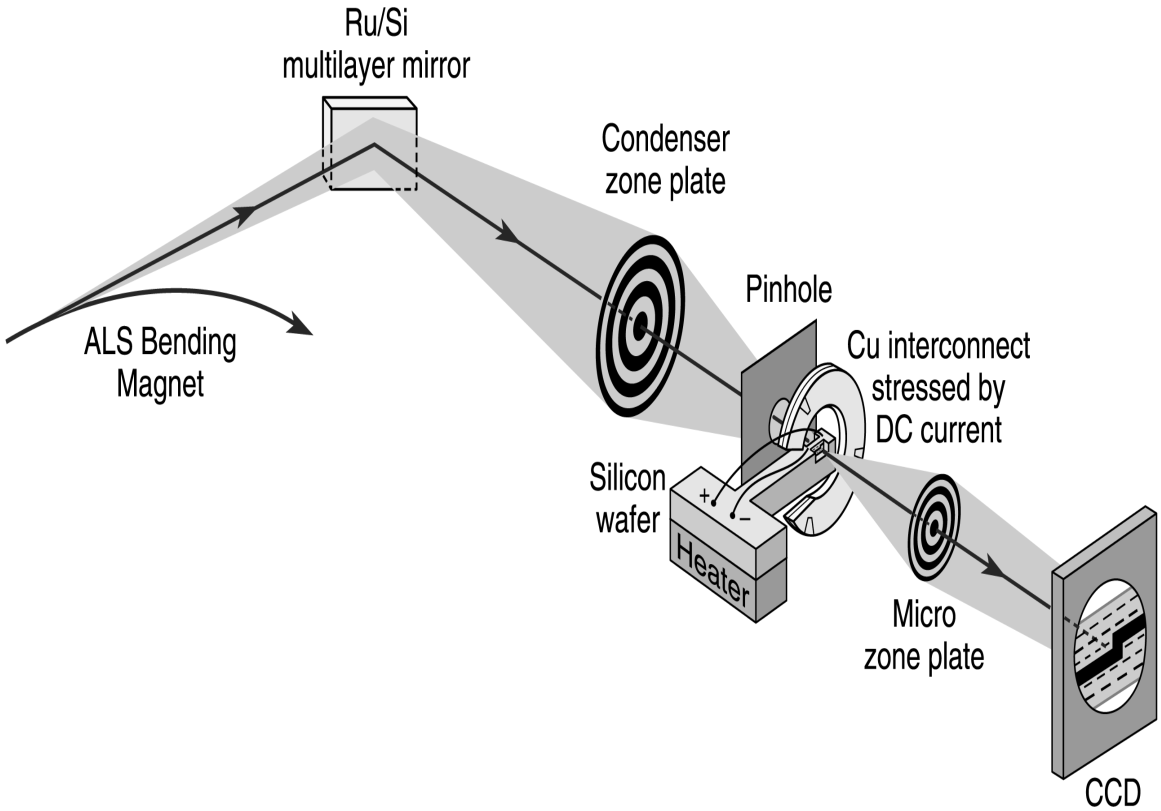

Fig. 2.

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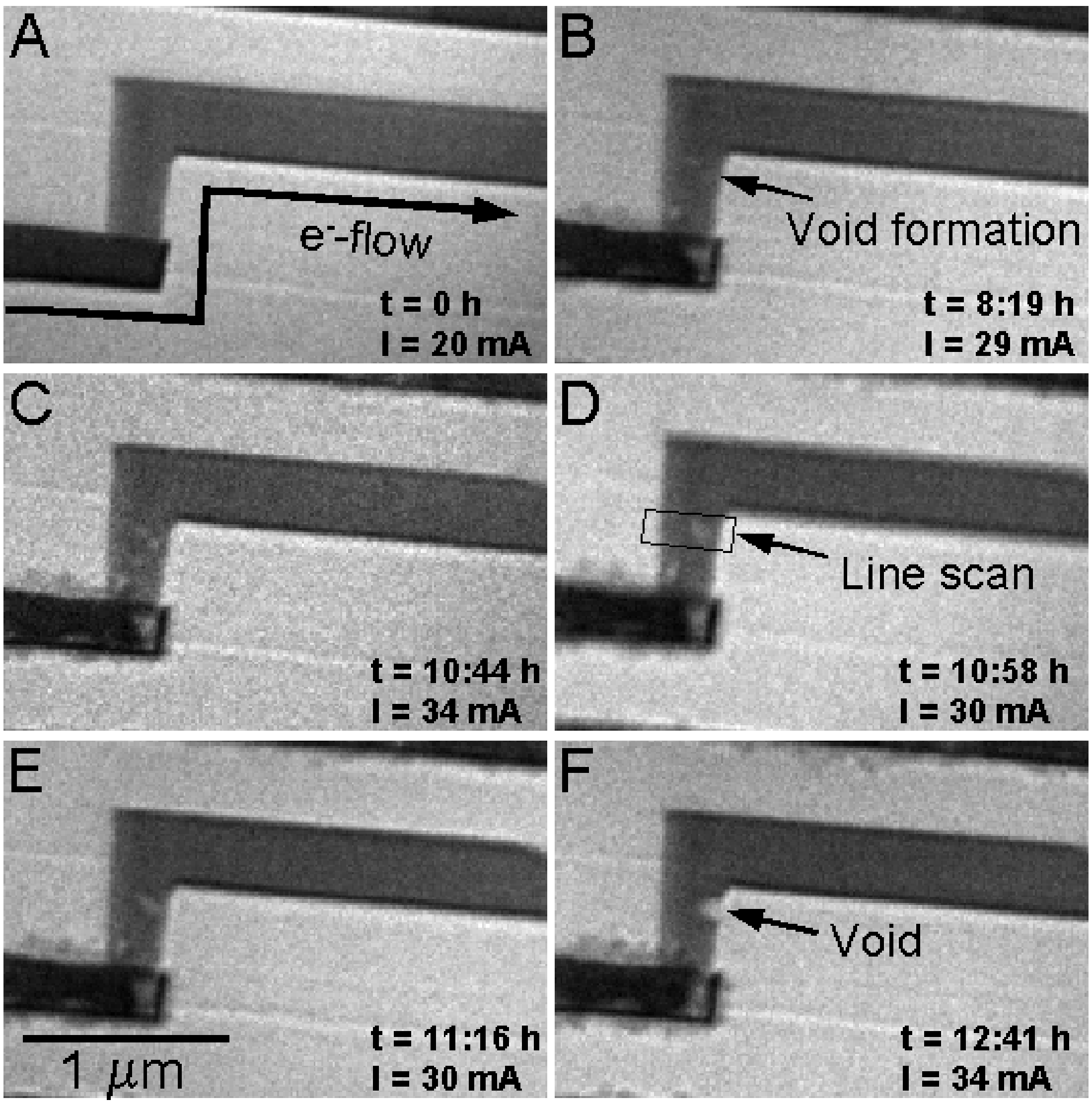

Fig. 3.

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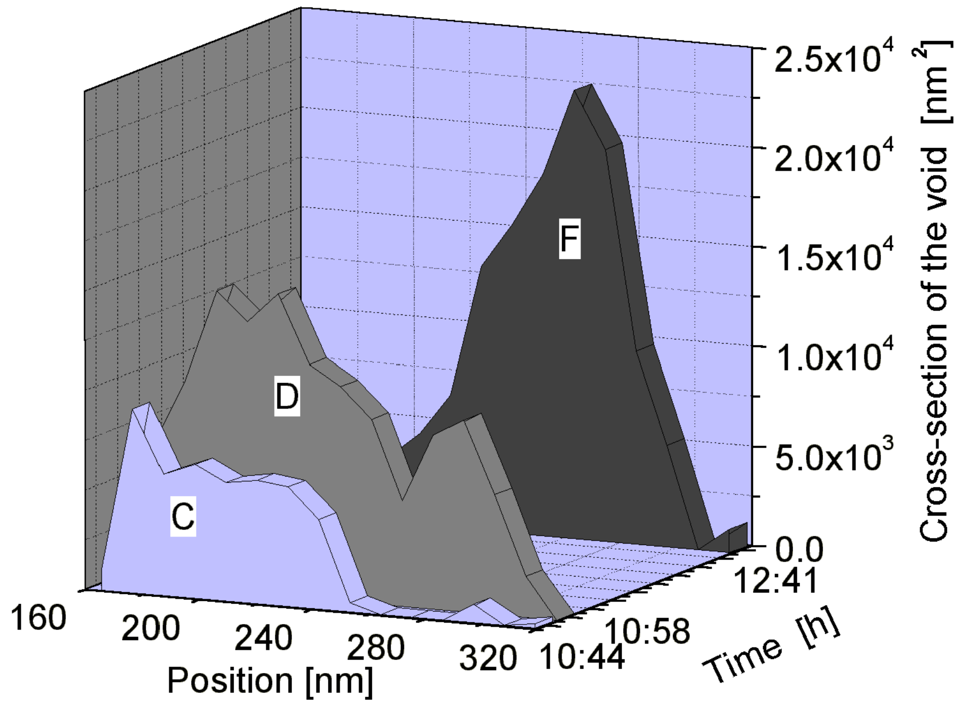

Fig. 4.

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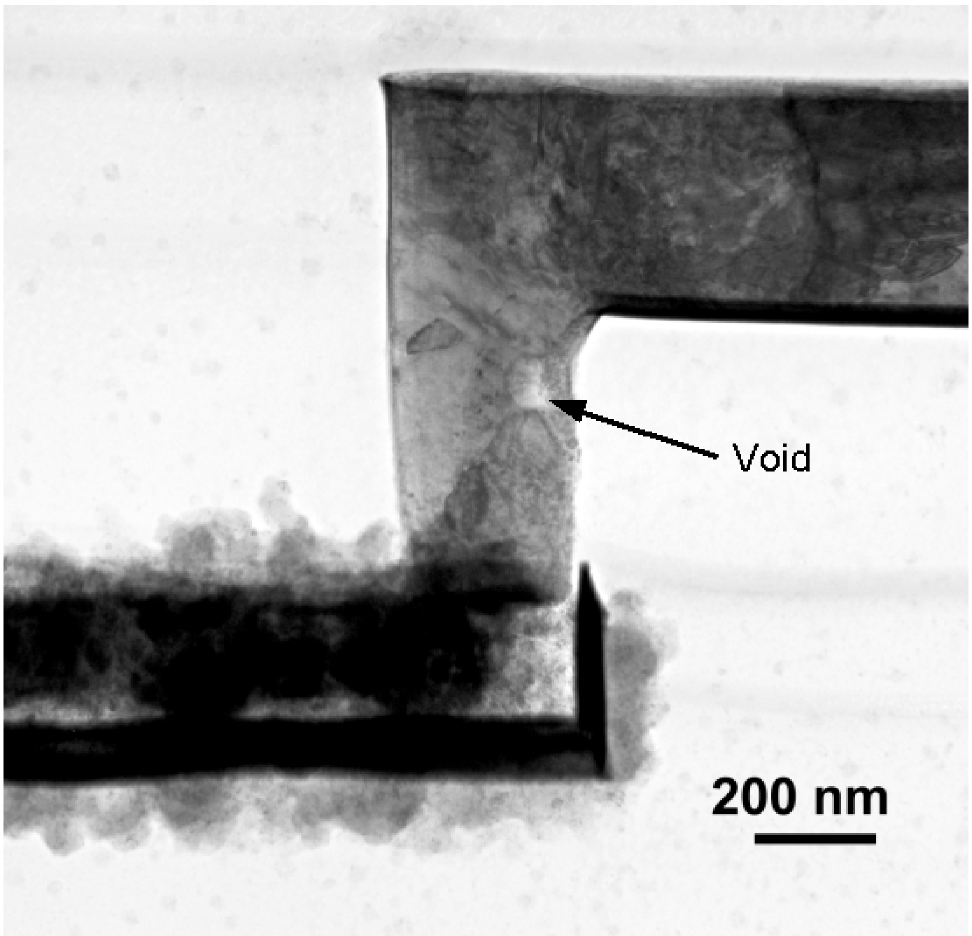

Fig. 5.

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