In situ x-ray microscopic observation of the electromigration in passivated Cu interconnects

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X-ray imaging of electromigration in a passivated Cu interconnect was performed with 100-nm spatial resolution. A time sequence of 200 images, recorded with the European Synchrotron Radiation Facility x-ray microscope in 2.2 h at 4 keV photon energy, visualizes the mass flow of Cu at current densities up to $2 \times 10^7$ A/cm$^2$. Due to the high penetration power through matter and the element specific image contrast, x-ray microscopy is a unique tool for time-resolved, quantitative mass transport measurements in interconnects. Model calculations predict that failures in operating microprocessors are detectable with 30 nm resolution by nanotomography. © 2001 American Institute of Physics. [DOI: 10.1063/1.1356446]

The interconnect structures in modern microelectronic devices are currently 500 nm wide and operate at very high current densities of nearly $10^8$ A/cm$^2$ without excessive Joule heating, because the heat is dissipated into the bulk silicon and the dielectric layers surrounding the thin film conductors. At these current densities one of the major failure mechanisms is electromigration (EM), i.e., the transport of atoms in a metallic interconnect along the direction of electron flow. The material transport can result in voids in the wire, leading to open circuit failures, as well as hillocks, which extrude from the original interconnect causing short circuits. EM is one of the principal factors limiting microprocessor performance, and an understanding of the EM is vital for current and future reliability driven design.\(^1\)

In place of Al, Cu is increasingly being employed as an interconnect material due to its higher conductivity and better resistance against EM failure. Cu interconnects have to be encapsulated with special metallic or dielectric barriers to prevent Cu diffusion into the silicon as Cu does not form an adherent oxide diffusion barrier like Al. Therefore, the interfaces between Cu and the surrounding barriers could be an easy EM pathway, and interface or surface diffusion may be very important for the EM behavior of a Cu multilevel metallization system.\(^2,3\)

In a passivated interconnect the mass flow due to EM is constrained by encapsulation. This leads to a high mechanical stress in the interconnect which influences the material transport significantly. Furthermore, for accelerated failure measurement the temperature distribution in the device under test depends strongly on the layers surrounding the stressed interconnect. Thus, in situ observation of EM should be done in an intact layer system including all barriers and passivation layers. For this purpose an imaging technique is required which maintains high spatial resolution when penetrating through several microns of dielectrics. Optical microscopy does not provide the necessary spatial resolution. Transmission electron microscopy can only image thin layers with less than 1 $\mu$m thickness.\(^4\) Surface sensitive techniques like atomic force microscopy\(^5\) or scanning electron microscopy (SEM)\(^6\) either require destructive sample preparation or provide only a limited resolution due to electron scattering in thick passivation layers.

In this letter, we report the direct x-ray microscopic observation of the dynamics of matter transport in a passivated Cu interconnect during an EM experiment. Due to the shorter wavelength and high penetration power of x-rays, x-ray microscopy overcomes several limitations of the conventional techniques. It utilizes the natural absorption contrast between the elements of interest, i.e., Cu interconnects embedded in SiO$_2$ or polymers. To demonstrate the x-ray imaging method applied to an interconnect we have investigated the EM of Cu lines using the well-known National Institute of Standards and Technology (NIST) test structure (Fig. 1).\(^7\) To ensure sufficient x-ray transparency, the samples were thinned from the backside by wet etching to about 5 $\mu$m thickness.

X-ray imaging of EM in the interconnect was performed with the full-field transmission x-ray microscope (TXM) installed at the ID21 beamline of the European Synchrotron Radiation Facility.\(^8\) In this TXM a zone plate condenser focuses the monochromatized undulator beam with a photon energy of $E=4$ keV and an energy bandwidth of $E/\Delta E$
=6000 through a Si₃N₄ window onto the object located outside the vacuum chamber in air. A microzone plate objective (MZPO) of 55 μm diameter forms a magnified image on a charge coupled device (CCD) camera. The outermost zone width Δᵣₐ of a MZPO largely determines the achievable lateral resolution. In this work a MZPO fabricated in gold with smallest zone structures of Δᵣₐ=60 nm was used. The MZPO has a numerical aperture of 0.003 at 4 keV and provides a Rayleigh resolution of 73 nm.

To visualize the dynamics of the EM, the sample was stressed by increasing the applied dc current in two steps from 20 to 40 mA in 30 min and then slowly from 40 to 43.4 mA in 100 min. A sequence of about 200 images—each with an exposure time of 30 s—was recorded with the TXM, displaying directly the dynamical transport of matter caused by EM. Selected x-ray micrographs of the transition region between the wide and the small part of the test structure close to the cathode are shown in Fig. 2(a).

Spatial frequency analysis of the EM micrographs indicates that the accuracy of the mass displacement measurement is about 100 nm. Now we calculate the optimal imaging conditions for high-resolution x-ray microscopic studies of the EM in multilevel integrated circuit (IC) interconnect structures. A model for a three interconnect layer system is sketched in Fig. 3. The cubes of a =30 nm in size represent hillocks and voids detectable by using multiple viewing angles θ. This takes into account the possibility that hillocks and voids can be colinear with a given viewing direction and cancel in the image, e.g., consider hillock 1 and void B at θ=0°. A major advantage of x-ray microscopy is the long depth of focus δₑ (μm)=1.97×10⁻³ Δᵣₐ² (nm²) E (keV) of x-ray objectives, especially for multi-keV imaging. Due to the small numerical apertures of x-ray objectives, δₑ is in the range of 3.2–7.1 μm for 1.8 keV≤E≤4 keV and Δᵣₐ=30 nm. Therefore, all object details of a sample are simultaneously in focus and the images can be treated as projections. By tilting the object perpendicular to the optical axis, it is possible to perform computed tomography with a resolution approaching the lateral resolution. Artifacts in the reconstructed volume are minimized, if the reconstruction is based on at least 100 images taken under viewing angles with -75°<θ<+75°. To minimize the number of photons required for an x-ray micrograph and the radiation dose applied to the sample, the optimal photon energy for x-ray
imaging passivated interconnects in ICs has to be determined.

We calculate the photon density \( n_0 \) required for object illumination to enable detection of a structure, like a void or a hillock, for tilt angles of 0° and 75° with a given signal-to-noise ratio (SNR). The projected photon density \( n(x,y) \) through an object is related to its mass distribution

\[
n(x,y) = n_0 \eta \exp\left(- \int \mu(E,x,y,z)\,dz \right),
\]

where \( n_0 \) denotes the illumination photon density, \( \int \mu(E,x,y,z)\,dz \) is the line integral of the energy dependent linear photoelectric absorption coefficient along the \( z \) axis at \((x,y)\) and \( \eta \) is the efficiency of the MZPO. Note that \( \mu(E) \) is characteristic for an element. Therefore, its mass distribution can be determined quantitatively if we measure \( \mu(E,x,y,z) \) at different times. The signal for detection of features is \( S = N(i,j) - N(i+1,j) \), where \( N(i,j) \) is the number of photons in pixel \((i,j)\) of the CCD passing through the layer system including the feature of interest (see Fig. 3), and \( N(i+1,j) \) denotes the number of photons of a neighbor pixel where \( x \)-rays just miss the feature. The dominant noise source is photon noise given by \( \sqrt{N(i,j)+N(i+1,j)} \), and the signal-to-noise ratio is

\[
SNR = \frac{N(i,j) - N(i+1,j)}{\sqrt{N(i,j)+N(i+1,j)}},
\]

For a given sample and SNR, \( n_0 \) has a minimum as a function of photon energy.

Numerical results using Eqs. (1) and (2) for the interconnect layer system are plotted in Fig. 4 for two different viewing angles. Imaging at \( \theta = 0° \) with \( E = 1.83 \) keV requires the lowest photon density. However, imaging at higher energies \( E = 4-6 \) keV or above the Cu \( K \)-absorption edge at 9 keV becomes advantageous if the thickness of the layer system increases, e.g., for complete microprocessors. Imaging at \( E \geq 2 \) keV has two difficulties. First, the image contrast \( C = |N(i,j) - N(i+1,j)|/(N(i,j) + N(i+1,j)) \) of a 30 nm Cu cube in SiO\(_2\) is lower, e.g., \( C = 3.4\% \), 0.36\% and 0.37\% at \( E = 1.83, 4, \) and 9 keV, respectively. Second, the required height of the zone structures for highly efficient MZPOs increases significantly with \( E \), e.g., \( \eta \approx 20\% \) requires gold zones with heights of 370, 700, and 1000 nm at \( E = 1.83, 4, \) and 9 keV, respectively. Currently, nanostructuring capabilities allow aspect ratios (zone height divided by zone width) of about 10:1.12-14 Therefore, it is realistic to fabricate gold MZPOs and condenser ZPs with \( \Delta t = 30 \) nm and 200 nm zone height corresponding to \( \eta(E=1.83 \) keV\) = 10\%. Assuming a bending magnet \( x \)-ray source with a critical energy of 2.5 keV installed in an electron storage ring operating at 1.7 GeV, such a condenser ZP with 10 mm in diameter located in 30 m distance focuses \( 3 \times 10^{11} \) photons/(250 mA s 0.4\% BW) onto the object. We conclude that interconnect structures in an object field of 15 \( \mu \)m can be investigated at \( E = 1.83 \) keV with 30 nm resolution in exposure times of 0.1-2 s (depending on the tilt angle).

In summary, as we have demonstrated by the \textit{in situ} observation of the EM and simulation of multilevel interconnect systems, the TXM is an important new tool to study mass distributions and transport phenomena in electronic devices. Recently, \( x \)-ray microdiffraction has also been applied to study \( Cu \) interconnects.15 In the future, \( x \)-ray imaging and microdiffraction could be combined to provide simultaneous temporally as well as spatially resolved data about the mass flow and the corresponding grain orientation.

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