Time-resolved x-ray microscopy studies of the electromigration in inlaid Cu line/via structures were performed on focused-ion-beam-prepared cross sections of an advanced interconnect layer system. Multiple x-ray images were recorded at 1.8 keV photon energy while stressing the passivated Cu structures with an applied current. The image sequences show that void formation is a 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 postmortem high voltage transmission electron and scanning electron micrographs indicates that the void nucleation occurs at grain boundaries in the copper, and that the voids migrate along these grain boundaries during electromigration. By taking multiple images at different viewing angles, the three-dimensional arrangement of an interconnect stack with Cu line / via structures was reconstructed. In future studies time-resolved tomography will be used to visualize void dynamics within the volume, thereby identifying pathways for Cu diffusion. © 2002 American Vacuum Society.

I. INTRODUCTION

In state-of-the-art microprocessors, more than 100,000,000 transistors have to be integrated. As the number of devices increases, and both transistor and interconnect dimensions decrease, the overall performance of the microprocessors is increasingly determined by interconnect design and materials. Al-based interconnects are being replaced by inlaid copper, as copper has a higher conductivity and improved electromigration (EM) performance. Nevertheless, EM and stress-induced migration phenomena remain reliability concerns for inlaid copper interconnects, especially as the dimensions of the interconnect lines continue to shrink. The formation of voids induced by high current densities (electromigration) during integrated circuit operation can cause an open circuit or an increase in resistance, resulting in malfunction or speed degradation.

Many failure-analysis studies using postmortem EM test structures have been performed, but the degradation mechanisms during EM are still not well understood. Some studies of unpassivated interconnect structures exist, but these only partially represent the real case, because the sample surface is a dominant diffusion path in these samples and the stress state has been changed by sample preparation. Therefore, our approach is to perform in situ experiments of fully passivated interconnect structures to get some ideas about the effect of the copper microstructure on interconnect reliability as well as more detailed information concerning degradation mechanisms. Recently, in situ scanning electron microscopy (SEM) studies of copper interconnect structures embedded in about 100 nm thick passivation layers were reported. These experiments were very sensitive to the early stages of electromigration, as the formation and movement of interface voids could be clearly seen. However, it is difficult to detect bulk voids in SEM images. Tomography—based on transmission electron microscopy (TEM) images—provides high resolution three-dimensional (3D) information. However, it requires samples much thinner than 1 μm to avoid multiple scattering (in the case of 200–300 keV incident electron energy). The high-voltage TEM (with about 1 MeV electron
energy) permits imaging of thicker samples, but the high momentum transfer of the electrons to the atoms can lead to severe radiation damage. This problem is exacerbated when multiple images are required, as is the case for in situ EM studies. In addition, SEM and TEM studies do not permit quantitative mass transport measurements.

X rays can penetrate samples that are many micrometers thick. Additionally, because of the nature of their interactions with matter, they provide a natural image contrast between different elements, e.g., Cu structures embedded in SiO$_2$. Therefore, in this work x-ray microscopy is used to study the dynamics of void development in passivated Cu line/via structures.

II. SETUP OF THE X-RAY MICROSCOPE

Model calculations showed 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. In addition, the photon flux emitted by a bending magnet installed in an electron storage ring like the Advanced Light Source (ALS) in Berkeley operating at 1.9 GeV electron energy is close to its maximum at this photon energy. However, the full-field x-ray microscope XM-1 installed at the ALS was originally designed for imaging samples with soft x rays below 0.8 keV photon energy. Its x-ray optical setup, which is shown in Fig. 1, originally incorporated a Ni-coated mirror operating at a fixed angular position of 3$^\circ$. This had a very low reflectivity for photons with energies higher than $E_{ph} = 0.8$ keV. In order to extend the usable photon energy range of XM-1 to energies of about 1.8 keV, we manufactured a Ru/Si multilayer with $N = 45$ periods, a period of 15 nm, and a ratio (high Z material layer thickness/period) of $\gamma = 0.4$. This multilayer mirror has its reflectivity peak with 30% reflectivity at 1.8 keV photon energy. With this multilayer it is possible to perform microscopy experiments at photon energies between the K-absorption edge of carbon (0.27 keV) and the K-absorption edge of Si (1.8 keV) without changing the incidence angle of the mirror.

The mirror reflects the radiation from an ALS bending magnet onto a condenser zone plate (CZP) which monochromatizes the radiation and at the same time illuminates the sample. The focal length of zone plates increases linearly with photon energy while the beam divergence is reduced. Thus, we manufactured a CZP with a diameter of 8.53 mm and an outermost zone width of 53.3 nm for sample illumination with 1.8 keV radiation. At this energy, the CZP is fully illuminated with the bending magnet radiation. Additionally, we designed zone plate objectives that matched the geometrical requirements of the existing microscope for imaging at this photon energy in order to achieve sufficiently large magnifications. The maximum distance from the sample to the detector plane is 2 m, and the pixel size of the directly illuminated back-thinned charge coupled device (CCD) detector is 24 $\mu$m. Therefore, we used zone plate objectives with only 230 zones, a 35 nm outermost zone width and a focal length of 1.6 mm at $E_{ph} = 1.8$ keV to nearly fulfill the sampling theorem. 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.

III. SAMPLE PREPARATION

The test structures used for the EM experiments are located within the scribelines of production wafers. Figure 2(a) shows a schematic cross section of the EM test structures.
used in the experiments with a two-level copper interconnect. The samples were fabricated in dual-inlaid copper technology, using physical vapor deposition tantalum for the barrier and plasma-enhanced chemical vapor deposition Si$_3$N$_4$ as caplayer for the metal lines. The structure consists of an array of metal lines. Depending on which level of metallization is tested, this array of lines is 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 in the Metal 1 level. In this case, the Cu vias at the ends of the line are part of the device under test. According to lifetime measurements, 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 transmission x-ray microscope XM-1 requires that the samples are located in a lamella of about 10 mm length and 250 $\mu$m width, with the region of interest near the end of such a lamella.

The general preparation procedure is similar to TEM sample preparation. In a first step the lamella was extracted from the wafer using a wire saw. This lamella has to be about 250 $\mu$m wide to contain the bondpads which are necessary for electrical connection of the line under test. It was then mounted on a modified 24-pin test chip in a way that approximately 6 mm of the lamella stick out, containing the region of interest at its end. Using a focused ion beam (FIB) microscope, the final lamella at the region of interest was thinned to a thickness of about 2 $\mu$m [see Fig. 2(b)]. It is important to mill from both sides of the line under test until all neighboring metal lines are removed. Effectively, a 50 $\mu$m 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. Note that both the line and the via under test were kept fully passivated within the final lamella while all metal lines next to the one under test were removed. In a final step, electrical connections from the bondpads to the landing pads of the 24-pin test chip were made by wire bonding.

IV. ELECTROMIGRATION IN PASSIVATED COPPER VIAS

Figures 3(A)–3(E) show a sequence of x-ray micrographs of a copper via/line interconnect structure, which were captured during an in situ EM experiment with the XM-1 operating at $E_{ph}=1.8$ keV. The images clearly demonstrate the advantage of x-ray imaging. The x rays are able to penetrate through thick dielectric layers while at the same time providing a high absorption contrast image of the buried Cu structures. During the in situ experiment, the upper line of the two-level test structure was the line under test. The via was stressed at a temperature of about 150°C and at a current

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**Fig. 3.** Some selected images (A)–(E) from a sequence of x-ray micrographs taken at successive times showing void formation, movement, and agglomeration inside the buried copper via.

**Fig. 4.** X-ray micrograph imaged at 0.85 keV photon energy showing that the Cu line failed in the dc stressed sample.
density of about $3 \times 10^7 \text{ A/cm}^2$. This current density was chosen to perform the *in situ* experiment in a reasonable period of 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 h. The electron flow was from left to right in the image, and upward through the via. Figure 3(A) shows the initial state of the interconnect structure without any voids. During the experiment, void formation [Fig. 3(B)], movement [Figs. 3(C)–3(D)] and agglomeration [Fig. 3(E)] were seen in the via. The shadow-like features around the metal line 1 structure can be attributed to copper diffusion across the surface of the lamella. Since this metal line was originally wider than the lamella, it was cut by the FIB and, consequently, the copper was exposed to air and surface diffusion occurred. Figure 4 shows an x-ray micrograph of the EM sample which was imaged with a 0.85 keV photon energy. Note that different dielectric layers can even be distinguished at this photon energy.

Although it is difficult to distinguish clearly between bulk voids and interface voids based on x-ray micrographs (projection in one direction), the image sequence gives some

Fig. 5. High-voltage TEM bright field image (a) and SEM micrograph (b) showing the Cu line/via structure after the electromigration test. Grain boundaries that appear consistent with the path of the void as it migrated can be seen. The void that was formed during the electromigration experiment is also clearly visible.

Fig. 6. Some selected projections at different viewing angles of the multilevel Cu metallization layer system imaged at 1.8 keV photon energy.

Fig. 7. Slice representation of a multilevel Cu metallization layer system in different distances from the Si wafer surface. Since the projections were not well aligned regarding the rotation axis during data acquisition, the resolution obtained in the reconstruction is much lower than theoretically possible.
indications that initial voids are formed in the copper bulk structure, probably at grain boundaries or grain boundary triple points. To obtain detailed structural information of the via after the EM experiment, the National Center for Electron Microscopy’s JEOL atomic resolution microscope operating at an accelerating voltage of 800 kV was used to image the stressed sample. No additional thinning was necessary. The high-voltage TEM image in Fig. 5 shows that the large void in Fig. 3(F) is located next to the Ta barrier, i.e., copper has been dissolved but the Ta barrier still exists. There seems to be a significant mass transport along grain boundaries to the Cu/Ta interface at the via sidewall, where voids grow and agglomerate. Figure 5 shows a SEM image of a FIB cross section of this sample. There is a grain boundary leading to the large void. Small voids are visible along this grain boundary, giving evidence for the grain boundary diffusion mechanism.

V. COMPUTED TOMOGRAPHY OF MICROPROCESSOR INTERCONNECT STRUCTURES

X-ray transmission is quantitatively related to the mass distribution of the sample. This permits tomography as well as quantitative determination of the mass transport. To demonstrate that it is possible to determine the 3D structure of fully intact passivated Cu line/via structures with a full-field x-ray microscope, we have performed tomography of an interconnect stack with three Cu layers. The back-thinned CCD camera used in the EM study has a limited dynamic range at 1.8 keV. This limited dynamic range affects the attainable resolution by increasing shot noise, and thereby preventing the resolution limit—as determined by the x-ray microscope objective aperture—from being attained in a single exposure. To overcome this limitation, we have developed a system whereby a phosphor screen is coupled to the CCD. In this system, x rays are first converted into visible light with a thin aluminum-coated P43 (Gd₂O₂S:Tb) phos-
phor screen and then imaged with a visible light objective onto a CCD camera. Under these conditions, an increased dynamic range is obtained and radiation damage to the directly illuminated back-thinned CCD caused by 1.8 keV x rays is avoided. In addition, the pixel size is reduced to about 7 μm, which allows higher x-ray magnifications. The phosphor-coupled CCD is about five times less efficient than the directly illuminated back-thinned CCD, when collecting the visible light with an objective with a numerical aperture (NA) of NA = 0.357.

Figure 6 shows some selected images from 50 different viewing angles spanning an angular range of 140°. After alignment of the projections to a common rotation axis, a multiplicative algebraic reconstruction technique was applied to reconstruct the 3D structure of the copper interconnects. Figure 7 shows slices in different depth parallel to the Si wafer surface. Since the sample was not well aligned to the rotation axis, the quality of the reconstruction is much lower than under ideal conditions, and therefore, the resolution of the reconstruction is significantly lower than the theoretical limit. However, the individual Cu layers, as well as some structural details, are visible. The complete metallization system with copper lines and vias, which is obtained from this tomographic data set, is shown in Fig. 8. As the reconstruction shows, it will be possible to measure the mass transport of copper within the bulk with an x-ray microscope in a time-resolved manner. For this purpose, an improved tomography setup that allows heating and pre-aligning of the EM sample onto the rotation axis is required. These experimental improvements are currently under development at the ALS XM-1.

VI. CONCLUSIONS

In summary, we have developed a method to visualize void formation in buried copper interconnect structures. Our observations indicate that voids grow inside the copper and move along grain boundaries toward the interface where they agglomerate. To provide information about the exact location (bulk or interface) of voids during an EM experiment and to measure the mass transport in bulk copper quantitatively, time-resolved tomography based on x-ray micrographs will be performed in future in situ EM experiments. By correlating this information with the copper microstructure of vias obtained from high-voltage TEM micrographs, the dominant diffusion pathways can be identified.

ACKNOWLEDGMENTS

The authors wish to thank Peter Hübler, Inka Zienert, Eckhard Langer, and Holger Saage (AMD Saxony Manufacturing GmbH Dresden) for stimulating discussions. They gratefully acknowledge B. Harteneck and D. Richardson for technical support. This work was supported in part by the Deutsche Forschungsgemeinschaft under Contract No. SCHN 529/1-1 and by the Director, Office of Science, Office of Basic Energy Sciences, Division of Materials Sciences, U.S. Department of Energy under Contract No. DE-AC03-76SF00098.