In-situ X-ray Photoemission Spectromicroscopy of Electromigration In Patterned Al-Cu Lines with MAXIMUM

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Electromigration (EM) is the diffusion of atoms in a conductor under the influence of an electric current. This process is one of the major reliability concerns in microelectronics industry because of its damaging effects on metal interconnect lines. Al, which has been the industrial choice for interconnect metallization, is especially susceptible to this damage mechanism. As the interconnect line width and thickness' continue to shrink electrical current densities increase together with the reliability problem. [1] Addition of small amounts of Cu (0.5-4%) to Al has been found to increase the lifetimes of interconnect lines against electromigration damage significantly and it is practiced commonly in industry. [2] However, a consensus still has not been reached upon the mechanism by which Cu slows down electromigration. One great source of difficulty is the low solubility of Cu in Al, and existence of different phases at operation and test conditions. Most of the Cu added to Al lines is found in the (θ) Al_2Cu phase precipitates under equilibrium conditions. In some experiments grain boundaries were also shown to be rich in Cu.[3]

The dominant path for electromigration is through grain boundary networks and Cu must be effective in slowing down the electromigration along grain boundaries to cause the observed effect. [4] Therefore it is essential to obtain information on the Cu content of grain boundaries, its chemical state and the dynamics of Cu distribution between grain boundaries, grains and Al_2Cu precipitates during process, operation and test conditions. MAXIMUM, a spectromicroscope with chemical sensitivity and sub 0.1μm spatial resolution, installed on Beamline 12.0 at the ALS is a suitable tool to study this problem.[5] It can map the distribution of an element and can differentiate chemical states of the same element (like Al or Cu). MAXIMUM is especially powerful in examining the dynamics of the surface electromigration process thanks to its surface sensitivity.

It is essential to do the EM testing *in situ* to preserve the chemical states of newly EM created surfaces, and identify the differences between 'before' and 'after' pictures. For this reason a special stage and a sample holder were constructed for in-situ testing of electromigration samples at accelerated conditions in the UHV chamber of the microscope. We were able to heat the sample above 300°C and bring four separate electrical contacts to the sample with this arrangement.

For the EM test samples, 600nm of Al-Cu alloy was sputter deposited onto thermally oxidized Si wafers. Three different Cu concentrations, 0.5, 2 and 4% (weight) was chosen to observe effect of Cu content in our experiments. Lines were patterned using photolithography and wet etching processes. After patterning wafers were annealed at 450°C for 30 minutes in forming gas to set the microstructure. No passivation was deposited onto the samples. Samples were etched before introducing into the microscope slightly in a solution of Ammonium-oxalate-monohydrate in ammonium hydroxide to reveal the Cu precipitates.[6]

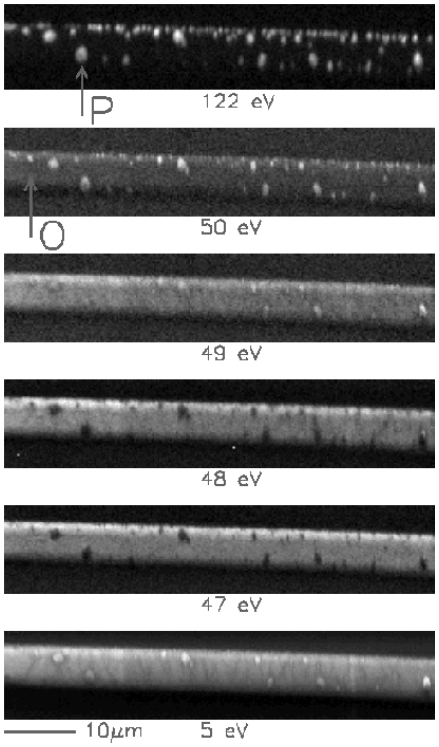

Figure 1. 60 μm X 10 μm images of 5 μm wide Al-4%Cu line *before* electromigration stressing acquired using photoelectrons of indicated energies

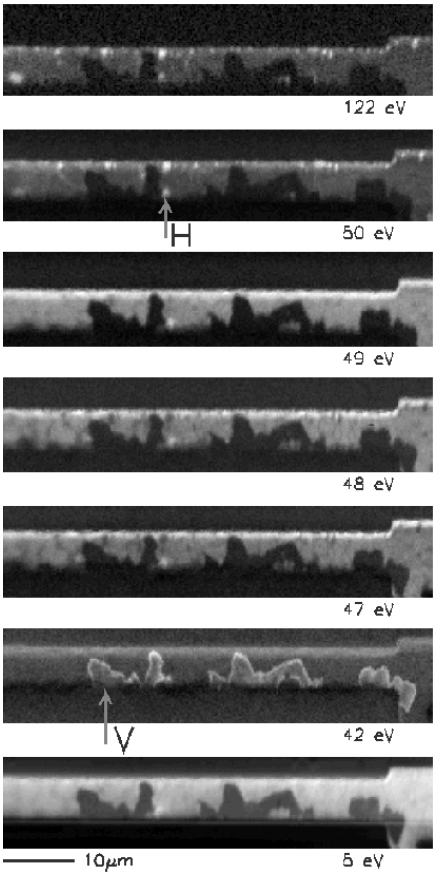

Figure 2. 60 μm X 10 μm images of 5 μm wide Al-4%Cu line *after* electromigration stressing acquired using photoelectrons of indicated energies

Samples were characterized before and after EM testing using the spectromicroscope MAXIMUM. This is done by acquiring images of the sample at interesting photoelectron energies and micro-EDCs (energy distribution curve) on interesting spatial features on the sample. In this way we were able to compare the images and EDCs before and after the EM process and evaluate the changes that has occurred. The stressing was stopped after an open circuit failure was obtained in the line.

Figure 1 shows a typical set of images acquired in an area of sample at six different photoelectron energies before testing for EM. The sample in that case is a 5μm wide Al-4%Cu line. For reference, the image acquired at 5eV kinetic energy (KE) is due to secondary electrons; contrast at this energy arises from sample topography as well as elemental inhomogeneity. Grain boundaries are resolved in that image and they appear darker due to topography. The 122 eV image is acquired at the Cu 3d core level and shows the distribution of Cu in the sample. Bright spots on that image correspond to the Cu-rich precipitates. Figure 3 shows two EDC's acquired at points P (precipitate) and O (ordinary) that are marked in Figure 1. Presence of Cu 3d signal is clearly evident as a shoulder around 121 eV. Images at 47, 48, 49 and 50 eV are acquired around the Al 2p core level. To understand the contrast mechanism in those images let us look at the Al 2p core level EDC's shown in Figure 4. The two micro EDC's shown in this figure are again taken at positions P and O in Figure 1. The Al 2p core level exhibits a shift of 0.45eV towards higher kinetic energy in the Cu ruch area. Going back to the images shown in Figure 1, this core level shift causes Cu rich precipitates to appear bright in the 50 eV image, and dark in the 47 and 48 eV images.

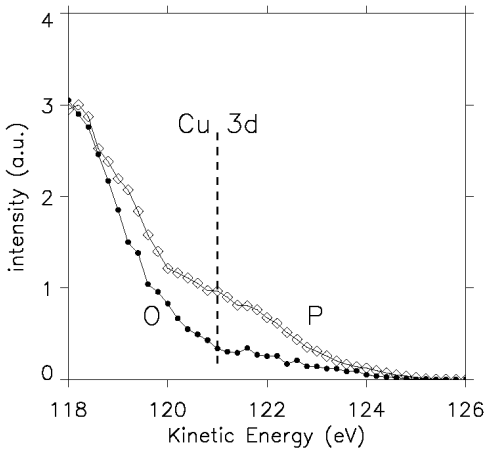

Figure 3. Micro-EDC's acquired at points **P** (precipitate) and **O** (ordinary) in Figure 1 showing the presence of Cu 3d signal at P

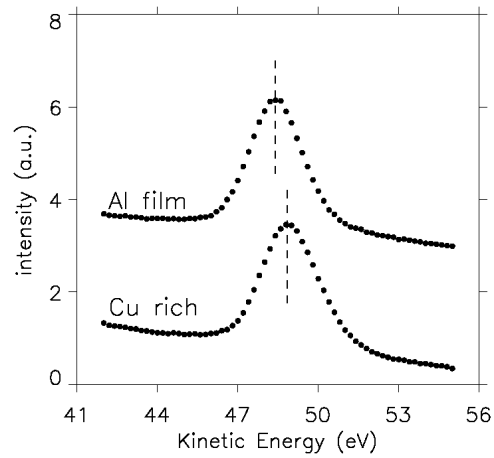

Figure 4. Micro-EDC's acquired at points **P** (precipitate) and **O** (ordinary) in Figure 1 showing the shift of Al 2p core level towards higher kinetic energy due to the presence of Cu at P

Figure 2 shows a set of images taken after electromigration stressing. The images show the *cathode* end of the Al-Cu line. Extensive voiding is apparent in those images which appear as dark regions in all images except the one taken at 42 eV kinetic energy. Figure 5 shows a micro EDC (labeled void) acquired at point V in Figure 2. Here several shifted Al 2p core level components are present near 45 eV. We attribute this energy shift in the void areas to the charging of Al that is left behind on the substrate. The charging is due to the electrical isolation of the left over Al in the voids from the rest of the line. Therefore the void areas appear bright in the 42 eV image. Images acquired at 47 and 48 eV in this set show some grain boundaries as dark areas. Some of the same grain boundaries appear as bright regions in the 50 eV and 122 eV images. This suggests an increased presence of Cu in the grain boundaries after EM.

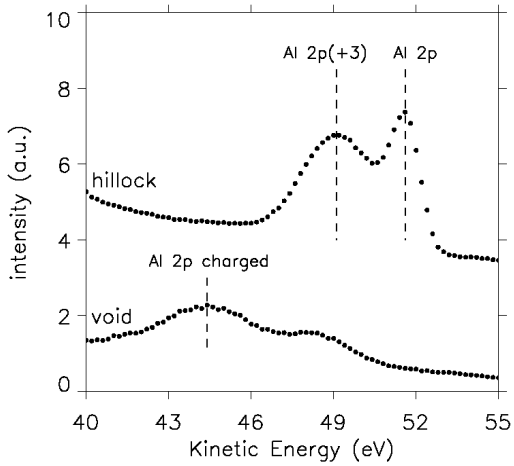

Figure 5. Micro-EDC's of the Al 2p core level acquired at points **H** (hillock) and **V** (void) in Figure 2

Figure 5 shows another micro-EDC (labeled hillock) acquired at point H marked in Figure 2. The narrow peak in that EDC at 51.6 eV is due to metallic Al 2p core level. This is fresh Al that was carried here by the EM flux. Oxidation of Al in that hillock is slowed down by the UHV

environment of the microscope chamber. This area (H) appears bright in images acquired at all phototelectron energies due to high emittance of clean Al surface.The fact that we observe metallic Al only in the hillocks and not anywhere else on the line indicates that surface electromigration did not take place in our experiment. In other words the EM was strictly limited to the grain boundary network.

In conclusion we report here the first photoemission spectromicroscopy study of electromigration in Al-Cu lines. Our preliminary results indicate that we are able to resolve Cu in grain boundaries and precipitates using the Cu 3d emission and the chemical shift of Al 2p core level in the Cu rich phase. We found no evidence of surface electromigration even under favorable conditions of the UHV environment. Finally, MAXIMUM which was installed recently on beamline 12.0 as a permanent endstation is routinely operating with better than 0.1μm spatial resolution which made this experiment possible.

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