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Unexpected Mode of Plastic Deformation in Cu Damascene Lines Undergoing Electromigration

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ABSTRACT

An unexpected mode of plastic deformation was observed in damascene Cu interconnect test structure during an in-situ electromigration experiment and before the onset of visible microstructural damages (void, hillock formation). We show here, using a synchrotron technique of white beam X-ray microdiffraction, that the extent of this electromigration-induced plasticity is dependent on the line width. The grain texture of the line might also play an important role. In wide lines, plastic deformation manifests itself as grain bending and the formation of subgrain structures, while only grain rotation is observed in the narrower lines. This early stage behavior can have a direct bearing on the final failure stage of electromigration.

INTRODUCTION

Copper is a much better conductor than Aluminum but the difficulty in processing Cu to obtain patterned interconnect lines has long prevented its use in the semiconductor industry. With the advent of the damascene technique, Cu is now quickly replacing Al as the major metallization layer materials. Electromigration, the diffusion of the constitutive atoms of the metal lines under the influence of a high current density, still constitutes a major reliability challenge for the microelectronics industry.[1] Several solutions such as the use of “shunt” layers, were devised to alleviate or completely stop this phenomenon to take place in lines with the current micron and submicron dimensions. However, with the ever decreasing size of interconnect widths, current densities will rise to new high levels and the technologies of today will not be sufficient to prevent the occurrence of electromigration damage. A thorough understanding of the mechanisms leading to electromigration damage is therefore needed.[2-4] Recently, a very early stage of plastic deformation and microstructural evolution during an electromigration test was detected in Al(Cu) interconnect lines, long before any macroscopic damages become visible, by using a synchrotron technique involving white beam X-ray microdiffraction.[5] In particular it was observed that during *in-situ* electromigration a gradient of plastic deformation evolves along the line which results in bending and in polygonization of the largest grains between the cathode and the anode end. Smaller grains do not readily deform but do rotate as electromigration proceeds. Plastic deformation is initiated at the cathode end and gradually progresses toward the anode end while electromigration is occurring until a steady state is reached. The present paper presents preliminary findings on similar experiment performed on Cu damascene interconnect test structures.

The synchrotron technique of scanning white beam X-ray microdiffraction has been described elsewhere.[6] It consists of scanning the sample under a micron size X-ray beam and capturing a Laue diffraction pattern at each step with a CCD detector. Using a small beam allows us to consider each grain of the interconnect sample as a single crystal. The indexing of the Laue pattern gives the orientation of the grain while the shape of the Laue peaks yields information regarding plastic deformation of the individual grain.

EXPERIMENTALS

The test interconnect line here is an electroplated Cu damascene structure. The test line has dimensions of 70µm in length and approximately 1µm in thickness, with two variations of width of 1.6µm and 0.6µm. The schematic diagram of the test structure is shown in Fig. 1. The lines are passivated with 4µm of nitride and polymer. Several vias at either end of the line connect to a lower metallization level, which in turn connects to unpassivated bond pads for electrical connection to be made.

The white beam X-ray microdiffraction experiment was performed on beamline 7.3.3. at the Advanced Light Source, Berkeley, CA. The electromigration test was conducted first at 300^{o}C. Current and voltage across the sample were monitored at 10s increments. The sample (width = 1.6µm) was scanned in 0.5µm steps, 10 steps across the width of the line and 160 steps along the length of the line, for a total of 1600 CCD frames collected. A complete set of CCD frames takes about 6 to 7 hours to collect. The exposure time was 4s plus about 10s of electronic readout time for each frame. In this manner the Laue pattern and information regarding plastic deformation for each grain in the sample was collected for each time step during the experiment. The current was ramped up to 25mA (j = 1.9 MA/cm^2) over the course of 48 hours, then set at that value for the rest of the test.

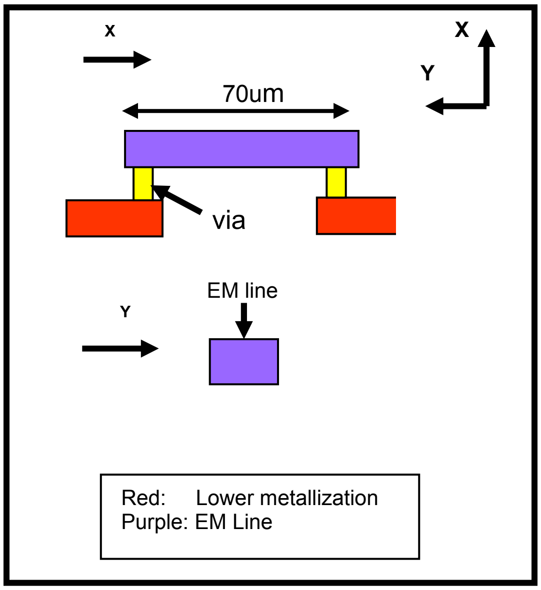

Figure 1. Cu electromigration test structure.

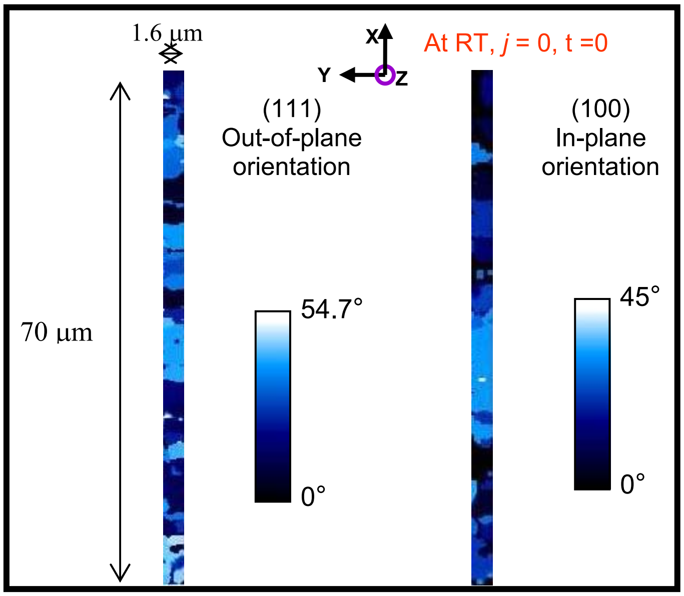

Figure 2. Grain map of a wide passivated Cu line.

The second group of tests were conducted at a higher temperature, 360°C, for reasons that will be discussed later in the article. The narrow sample (0.6μm) was scanned in the same manner as above, except that the current ramp up was up to 15mA (j = 2.8 MA/cm^2) over the course of 48 hours, then set at that value for the rest of the test.

RESULTS & DISCUSSIONS

We first describe the in-situ electromigration studies on the wide (1.6μm) damascene Cu test structures. A cross-section diagram of these structures with line dimensions is shown in Fig.1. The grain structure in these lines as determined by white beam x-ray microdiffraction through the passivation layer is shown in Fig. 2. The line shows all grains along the interconnect line with the [111] direction of individual grains varying from normal to the line to 54.7° away from the normal of the line.

If we examine the individual diffraction spots after electromigration in some detail we find that in certain grains the spots broaden not in any random direction but always in the y direction across the line. In Fig. 3 we show a Laue spot shape at a position near the anode end of the line under the electromigration conditions indicated. Broadening of the peak is observed, in this particular example, in a large single grain spanning across the width of the line. In that particular grain where broadening is observed we also show the peak profile through the broadening direction for reflection (111). Besides the broadening we note that the peaks are split, an indication of sub-grain formation. We can use the broadening and the peak splitting observed to obtain information on the dislocation structure in the grain induced by electromigration. From the streak length as measured in the CCD camera and the sample to detector distance we obtain the curvature angle of the grain of 0.75°. Since the grain map in Fig. 2 indicates a near bamboo structure the grain width is thus 1.6μm, from which we get the curvature radius of the grain R =126μm. The geometrically necessary dislocation density to account for the curvature observed can be calculated from the Cahn-Nye relationship $\rho = 1/Rb$ where b is the Burgers vector. The geometrically necessary dislocation density is then $\rho = 3 \times 10^9$ /cm^2. The total number of dislocations introduced is only 49. Furthermore, the observation of the peak profile at the end of the EM test indicates a splitting of the peak into two subpeaks. This shows that a low angle boundary has formed dividing the grain into two subgrains.

We now describe *in-situ* electromigration studies on the narrow (0.6μm) damascene Cu test structures. The higher test temperature of this group of experiment was designed to give more pronounced streaking effect of the Laue peaks as the grains undergo electromigration. A previous similar electromigration study on Al(Cu) system has shown an extensive broadening of peaks in the Al(Cu) system.[10] By increasing the test temperature, the homologous temperature (T/T_M) of our present experiment is now almost comparable to that of the previous electromigration study on Al(Cu) system.

However, our observation of the peaks of the grains along the narrow Cu line did not show any broadening of the peaks in the line during electromigration, as can be seen in Fig. 4. This is true despite the higher temperature used in the present experiment. The homologous test temperature (T/T_M) is now ~ 0.48, which is higher than that of our first group of experiment (~ 0.4). The homologous test temperature of the current study is almost similar to that of the previous study on Al(Cu) system, which was ~ 0.51.

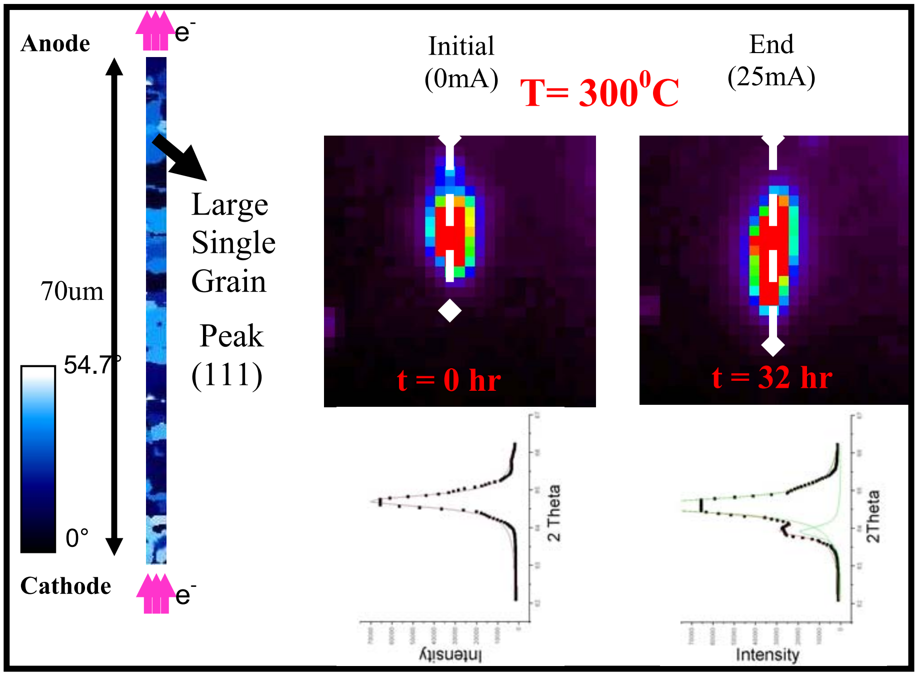

Figure 3. Broadening of a Laue peak of a large single grain near the anode end of the Cu line.

Apparent grain rotations are however observed both in the cathode-end, as shown in Fig. 4, in the middle of the line (at the highly-strained grains), as well as in the anode-end of the line. Grain rotations can be quantitatively detected by the shifts of the Laue peak as indicated in Fig. 4. From the Laue pattern, we have also a precise measure of the orientation matrix of a given grain. By comparing the orientation matrix before and after electromigration, we could deduce the angle of rotation as well as the axis of rotation. For the particular case of Fig. 4, we found that the grain rotated by 6.3 degrees around a (100) direction. The narrow Cu line seems to have higher electromigration resistance to plastic deformation inducing only grain rotation but no streaking of the peaks (compared to our previous results with wider Cu line). This finding and the reasons why grains rotate without the streaking of the Laue peaks in the narrow Cu line are still under investigation.

In terms of texture, this particular Cu narrow line consists of grains of three main groups. Fig. 5 shows the number of grains versus the out-of-plane orientation of the grains along the Cu line in this electroplated damascene test structure. Not many (111) oriented grains in the present sample are observed. This observation is in contrast to the texture known from sputtered Cu films. However, it is in agreement with observations made on annealed electroplated films.[7] The (115) twin texture had been found to be predominant. This is verified in the present experimental result. Almost half of the grains have their [111] directions 38.9° off the normal of the line – the theoretical angle between a (111) plane and a (115) plane. Additionally, there are also (111) components and indications for a sidewall texture (grains having their [111] directions between 15° and 25° off the normal of the line), as shown in Fig. 5. This has been known as a feature of electroplated Cu damascene structures and has been reported previously.[8]

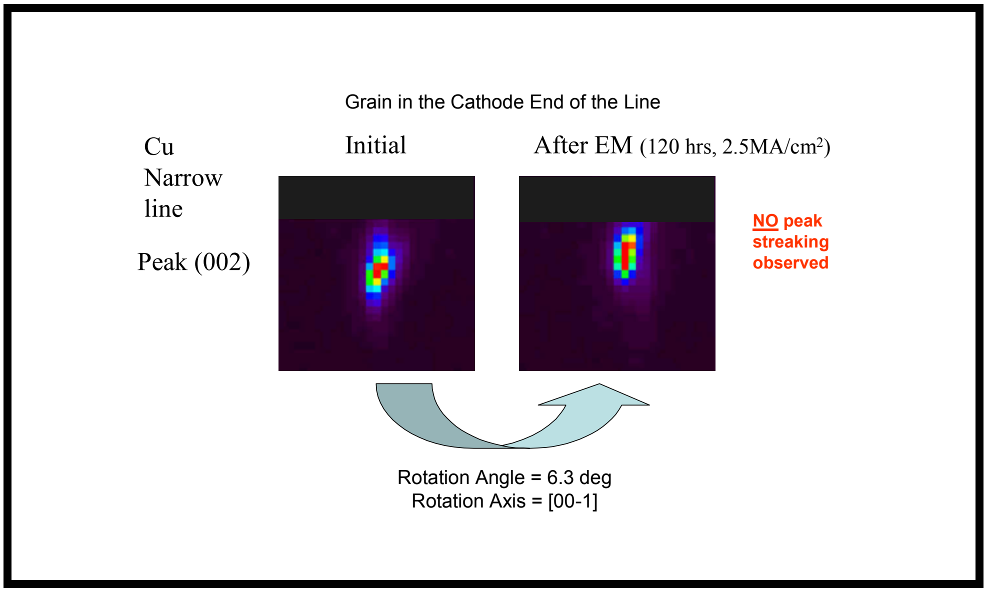

Figure 4. Grain rotation with no peak broadening observed in the EM of Cu narrow line.

Any model proposed must account for the bending of individual Cu grains transverse to the electron flow direction. The general outlines are similar to those proposed for the transverse bending of Al(Cu) grains where vacancies generated at the interface diffuse into grains. If the bottom half of the grain is rigidly constrained by the substrate the grain deforms by bending. To accommodate the bending dislocations of predominantly one sign are introduced with Burgers vector components in the direction of current flow. If we assume that for Cu lines it is the interface at the top of the line, between Cu and SiN_3 where defect generation and motion predominates, then at the anode end where matter accumulates we have a build up of stress in the top half of the grain. To relieve this stress grains deform in bending thereby introducing dislocations predominantly of one sign. The details of the process by which excess matter accumulates in the top half of a Cu grain are not yet completely understood. Since the bending is across the grain width, dislocations generated have components predominantly in the direction of current flow. Thus in addition to the flow of point defects at interfaces, dislocations provide an easy path for point defect transport in the bulk crystal.

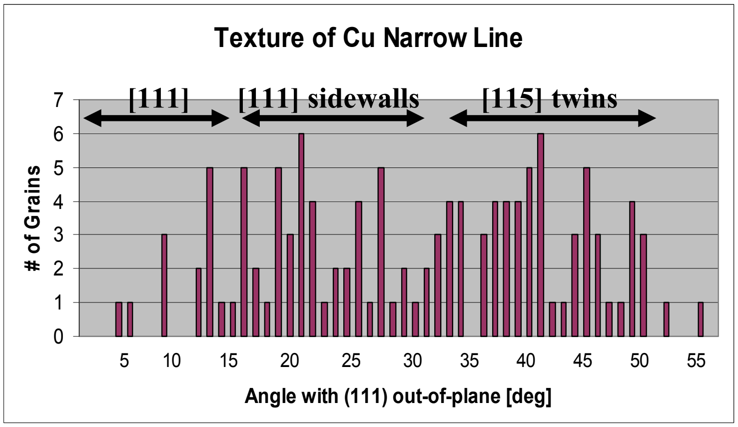

Figure 5. Texture of electroplated Cu narrow line.

From the experimental results available and the model that is proposed we can venture to make a few predictions. Since deformation of a grain requires some compliance of the dielectric surrounding it, we would expect that a stiffer dielectric will suppress deformation, thus retarding the flow of point defects from cathode to anode. Also smaller grains which have a higher yield stress will suppress bulk transport in individual grains. Both these predictions should extend electromigration lifetimes by delaying the final catastrophic events where voids and hillocks are formed.

CONCLUSIONS

We have described a pre-failure mode of plastic deformation during in-situ electromigration of Cu line. Broadening of Laue spots in Cu occurs transverse to the electron flow direction, and long before any macroscopic damage is observed (early stage). From the streak length and its subsequent break-up, we have calculated the dislocation density in an individual grain and determined the misorientation of grain sub-boundaries. In term of early stage plastic deformation, the narrow line seems to have higher electromigration resistance. A mechanism and model of plastic deformation during electromigration involving generation of point defects and their subsequent diffusion into the grains is proposed.

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