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Crystal plasticity in Cu damascene interconnect lines undergoing electromigration as revealed by synchrotron x-ray microdiffraction

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Plastic deformation was observed in damascene Cu interconnect test structures during an *in situ* electromigration experiment and before the onset of visible microstructural damage (voiding, 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 linewidth. 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. The deformation geometry leads us to conclude that dislocations introduced by plastic flow lie predominantly in the direction of electron flow and may provide additional easy paths for the transport of point defects. Since these findings occur long before any observable voids or hillocks are formed, they may have direct bearing on the final failure stages of electromigration. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2210451]

There is a great deal of interest in the mechanical behavior of materials especially in today's nano- and microscale devices, built near the scale of their microstructural inhomogeneities. The 2004 Update of the International Technology Roadmap of Semiconductors[1] (ITRS) has called for linewidths of Cu interconnects well into the nanometer range in the coming years. Major reliability and device concerns with such nanoscale Cu lines include electromigration,[2] interface instability due to thermal stress associated with Joule heating,[3] and increased resistivity due to interface and grain boundary scattering.[4] Crystal plasticity and how it progresses during device operation might play an important role. For instance, texture has been known to impact the electromigration performance of the interconnect line.[5] Understanding the exact mechanism and evolution of the plastic deformation in a certain texture therefore might just lead us to a texture of higher resistance towards electromigration.

Recently, in a related study,[6] 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 damage became visible, by using a synchrotron technique[7] involving white beam x-ray microdiffraction. In the present letter we study the evolution of plasticity in Cu polycrystals observed during similar electromigration experiments. We find linewidth-dependent plasticity which is strongly correlated with the direction of the applied electromigration current.

The synchrotron technique of scanning white beam x-ray microdiffraction has been described in a complete manner elsewhere.[7] Other *in situ* microstructure characterization studies have given valuable insights on the degradation mechanism of electromigration in a Cu line.[8–10] To complement, the high brilliance synchrotron radiation here allows *in situ* studies of crystal lattice rotation and its evolution during electromigration.

The test interconnect structure here is an electroplated Cu damascene line. The test line has dimensions of 70 μm in length and approximately 1 μm in thickness, with two different widths of 1.6 and 0.6 μm. The lines are passivated with 4 μm of silicon nitride and polymer. Both vias at either end of the line connect to a lower metallization level, which in turn connects to unpassivated bond pads which are used for electrical connection.

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 at 300 °C for the wide line (1.6 μm) group of samples. The wide sample was scanned in 0.5 μm steps, 10 steps across the width of the line and 160 steps along the length of the line. The current was ramped up to 50 mA ($j = 3.1 \mathrm{MA/cm^2}$) over the course of 96 h, then set at that value for the rest of the test. The narrow sample (width=0.6 μm) tests were conducted at a higher temperature, 360 °C, for reasons that will be discussed later in the letter. The narrow sample was scanned in the same manner as above, except that the current ramp up was up to 20 mA (j

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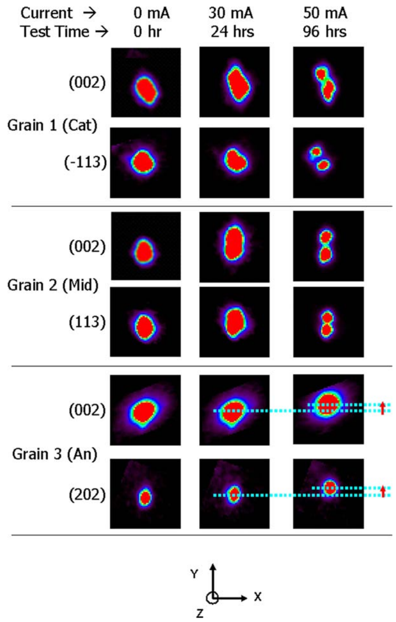

FIG. 1. (Color online) Evolution of Laue diffraction spots (in q space) of three grains (one at the cathode end, another in the middle, and the last one at the anode end of the line) during an *in situ* EM experiment. For each reflection, the area of q space is kept constant with length of each side of 0.03 $\AA^{-1}$. Following the evolution of each spot, the reference location is kept constant.

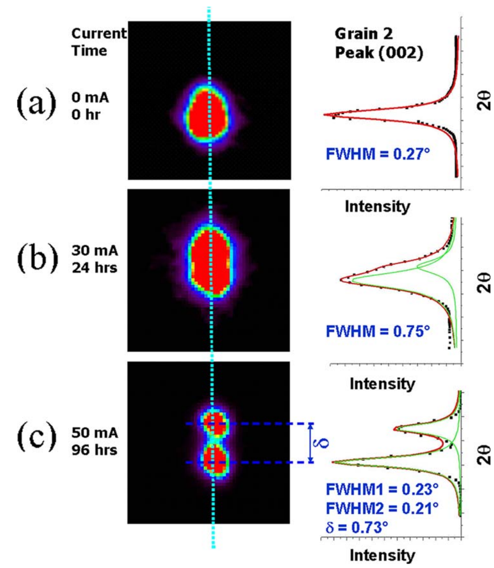

FIG. 2. (Color online) Quantitative measurement of the evolution of a Laue diffraction spot of grain 2 of the three grains mentioned above during an *in situ* EM experiment. Broadening is shown as the spot evolves from (a) to (b), while peak splitting, signifying the formation of low-angle grain boundaries, is evident in (c) as EM progresses.

$=3.3$ MA/cm^2) over the course of 96 h, then set at that value for the rest of the test.

We begin by describing the *in situ* electromigration (EM) studies on the wide (1.6 μm) damascene Cu test structures. Figure 1 shows the evolution of the Laue diffraction spots for several grains in this line during the *in situ* EM experiment.

The diffraction spots have been converted to q space (reciprocal space), with the x axis along the length of the line, the y axis across the line, and the z axis normal to its surface. We find that as the EM test progresses in certain grains the spots broaden, and in some grains, they split into two different spots. This broadening and splitting of diffraction spots is observed not in any random direction but always along the y axis in q space, which translates physically to the direction across the Cu line.

Broadening of the peak is observed, in this wide test structure sample, in a few grains that tend to be the large ones and the ones spanning across the width of the line. In one particular such grain, grain 2 (in the middle of the line), we also show (Fig. 2) the results of digital intensity traces across the broadening direction of the diffraction spots in the initial, mid, and end states (after the end of the EM test).

Such broadening and splitting of the diffraction spots were observed in all three different wide test structure samples examined in our experiments. In each of them, a few grains (between 5 and 9) among a total of usually around 100–150 grains were found with this observed behavior after similar electromigration test time, current, and temperature.

The broadening of the diffraction spots represents crystal bending of the Cu grains in the line, whereas the split diffraction spots indicate the formation of low-angle boundary subgrain structures. From the amount of broadening we can calculate the bending of the Cu crystal, and from the amount of splitting, the angle of misorientation. In particular, Fig. 2 shows broadening of an initially single-peaked Laue reflection followed by splitting of the peak into two clearly separated peaks, which signifies the evolution of this particular grain as electromigration progresses.

We can then use the broadening and the spot splitting observed to obtain information about the dislocation structure in the grain induced by electromigration. For instance, from the streak length of Fig. 2(b) 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 mapping of the out-of-plane orientation of the crystal along the Cu line indicates a near bamboo structure, the grain width is about the same as the width of the line (1.6 μm), from which we get the radius of curvature of the grain, $R=126$ μm. 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 $\rho=3\times10^9/\text{cm}^2$. The total number of dislocations introduced is only 49.

We now describe *in situ* electromigration studies on the narrow (0.6 μm) damascene Cu test structures. The higher test temperature of this group of experiments was designed to give more pronounced streaking of the Laue peaks as the grains undergo electromigration. A previous similar electromigration study has shown an extensive broadening of peaks in the Al(Cu) system.[6] By increasing the test temperature of this group of experiments, we aim to have a comparable homologous temperature (T/T_M) to that of the previous study on Al(Cu). However, our observation of the peaks of the grains in the narrow Cu line (width$=0.6$ μm) did not show any broadening of the peaks during electromigration. This is true despite the higher temperature used in this group of experiments. Instead, grain rotations, similar to that of grain 3 in Fig. 1, are observed throughout the length of the line. The rotation of grains manifests itself as a shifting in the position of the Laue spot; from the direction and magnitude of the shift, we can calculate the axis and amount of the crystal rotation.

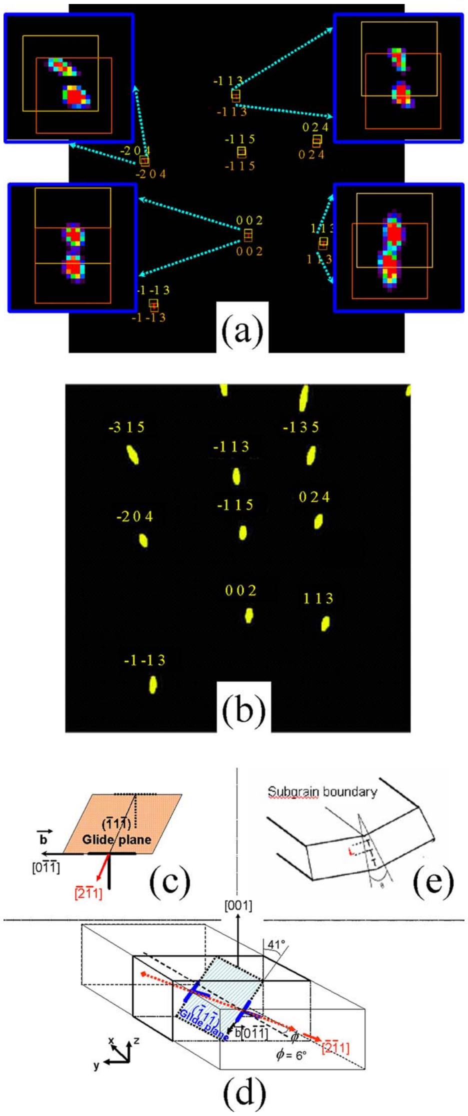

FIG. 3. (Color online) (a) Laue reflection spots at the initial stage (orange) and after they split into the second set of reflection spots (yellow). (b) Simulation of the same initial set of reflection spots based on a particular slip system showing a match with experiment. (c) The active slip system for which the simulation predicts the movement of reflection spots correctly. (d) Modeling of slip deformation in grain 2. (e) Illustration of subgrain boundary formation through polygonization.

The narrow Cu line thus seems to have higher electromigration resistance (compared to the wider Cu line). The resistance to plastic flow and the reasons why only grain rotation occurs in the narrow Cu line are not well understood at present. However, higher resistance to plastic deformation in smaller structures, especially in the case of Cu line structures, has also been reported by Spolenak *et al.*[11]

Going back to the wide lines, Figs. 3(a) and 3(b) show the movement of Laue spots of grain 2 during the EM test and a comparison with simulation results. We discovered that indeed the movement of the diffraction spots in Fig. 3(a) can be simulated by certain dislocation slip processes belonging to a slip system known to operate in fcc crystals [Fig. 3(b)].

We also observe that the ⟨112⟩ type direction for the tilt axis of the crystal is very close (within a few degrees) to the direction of the electron flow, or in other words, to the direction along the length of the line. The example in Fig. 3(d) shows a 6° deviation between the axis of tilt and the direction of electron flow. Further studies confirmed that the particular ⟨112⟩ tilt axis observed in each of the grain bending/polygonization/rotation experiments is always the ⟨112⟩ direction closest to the direction of electron flow. This suggests a correlation of the proximity of certain ⟨112⟩ line directions to the direction of electron flow with the occurrence of plastic behavior. One important practical implication of this particular finding is that the grain texture of the line might thus play an important role in giving higher resistance towards early plastic response of the Cu line upon the electromigration loading.

In conclusion, we have observed plastic deformation behavior of Cu polycrystals during electromigration experiments, using a synchrotron technique involving white beam x-ray microdiffraction. The extent of the plastic behavior was found to be dependent on width of the line test structure. Of all the grains in the line test structure, the few grains that exhibit bending and polygonization or rotation, tend to be the largest grains, spanning across the cross section of the line and having orientations with a ⟨112⟩ direction nearly parallel to the line corresponding to the activation of a known fcc slip system by the application of current. We believe that crystal plasticity in small scale devices under some electrical loading may have a direct bearing on the performance and reliability of today's nanoscale devices.

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[1] International SEMATECH, *ITRS Update*, Interconnect (2004).
[2] K. N. Tu, J. Appl. Phys. **94**, 5451 (2003).
[3] R. H. Havemann and J. A. Hutchby, Proc. IEEE **89**, 586 (2001).
[4] T. S. Kuan, C. K. Inoki, G. S. Oehrlein, K. Rose, Y. P. Zhao, G. C. Wang, S. M. Rossnagel, and C. Cabral, Mater. Res. Soc. Symp. Proc. **612**, D7.1.1 (2000).
[5] L. Vanasupa, Y. C. Joo, P. R. Besser, and S. Pramanick, J. Appl. Phys. **85**, 2583 (1999).
[6] B. C. Valek, J. C. Bravman, N. Tamura, A. A. MacDowell, R. S. Celestre, H. A. Padmore, R. Spolenak, W. L. Brown, B. W. Batterman, and J. R. Patel, Appl. Phys. Lett. **81**, 4168 (2002).
[7] N. Tamura, A. A. MacDowell, R. Spolenak, B. C. Valek, J. C. Bravman, W. L. Brown, R. S. Celestre, H. A. Padmore, B. W. Batterman, and J. R. Patel, J. Synchrotron Radiat. **10**, 137 (2003).
[8] M. A. Meyer, M. Hermann, E. Langer, and E. Zschech, Microelectron. Eng. **64**, 375 (2002).
[9] A. V. Vairagar, S. G. Mhaisalkar, A. Krishnamoorthy, K. N. Tu, A. M. Gusak, M. A. Meyer, and E. Zschech, Appl. Phys. Lett. **85**, 2502 (2004).
[10] J. C. Doan, S. Lee, S. H. Lee, N. E. Meier, J. C. Bravman, P. A. Flinn, T. N. Marieb, and M. C. Madden, Rev. Sci. Instrum. **71**, 2848 (2000).
[11] R. Spolenak, N. Tamura, B. Valek, A. A. MacDowell, R. S. Celestre, H. A. Padmore, W. L. Brown, T. Marieb, B. W. Batterman, and J. R. Patel, AIP Conf. Proc. **612**, 217 (2002).