Microstructure evolution of tin under electromigration studied by synchrotron x-ray micro-diffraction

Albert T. Wu[1,3] , J. R. Lloyd[2], N. Tamura[3], and K. N. Tu[1]
[1]Dept of Materials Science and Engineering, UCLA, Los Angeles, CA 90095; [2]IBM T. J. Watson Research Center, PO Box 218, Yorktown Heights, NY 10598; [3]Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720.

***Abstract*- Under constant current electromigration, white tin (β-Sn) exhibited a resistance drop of up to 10%. It has a body-center tetragonal (BCT) structure, and the resistivity along the a and b axes is 35% smaller than that along the c axis. Microstructure evolution under electromigration could be responsible for the resistance drop. Synchrotron radiation white beam x-ray microdiffraction was used to study this evolution. Both stress and grain orientation was studied. Grain-by-grain analysis was obtained from the diffracted Laue patterns about the changes of grain orientation during electromigration testing in ex-situ and in-situ samples. We observed that high resistance grains re-orient with respect to the neighboring low resistance grains, most likely by grain rotation of the latter. A different mechanism of microstructure evolution under electromigration from the normal grain growth is proposed and discussed.**

I. INTRODUCTION

In a very-large-scale-integration (VLSI) of circuits on a device, the dimension of the interconnects are in the trend of the range of sub-micron or nano size. If an Al or Cu thin film line of 0.5 μm wide and 0.2 μm thick is subjected to a current of 1 mille amp, the current density can reach up to 10^6 A/cm^2. It causes mass transport in the line at the device operation temperature of 100°C and leads to void formation at the cathode and extrusion at the anode, which is the phenomenon called electromigration. It is the most persistent and serious reliability failures in thin film integrated circuits. As device miniaturization demands smaller and smaller interconnects, the current density goes up, so does the probability of circuit failure induced by electromigration. It is a subject which has demanded and attracted much attention. Moreover, in solder joints, the traditional eutectic Sn-Pb solder is going to be replaced by Pb-free solder, in which the composition is mainly pure Sn, due to the environmental concern. The electromigration behavior on pure Sn is fundamental and crucial for the future understanding and application of Pb-free solder [1,2,3].

Lloyd observed a voltage drop while studying the electromigration behavior in Sn thin film strip [4]. For the same amount of current, the voltage drop implies that the resistance drops in the line. It is legitimate to think that it's the anisotropic property of tin that causes the phenomenon. White tin (β-Sn) has a body center tetragonal structure with lattice parameter of a=b=5.83Å, and c=3.18 Å. The resistivity along a, b is 13.25μm-cm and c is 20.27 μm-cm, respectively. Due to this anisotropic property, it is reasonable to think that the microstructure evolves while passing current through the strip. The high resistance grain might rotate and align themselves in the direction of the low resistance grains in order to minimize the dissipation of energy [5]. Furthermore, under electromigration, compress stress builds up at anode and tensile stress builds up at cathode. Either case increases the strain energy in the line. The stress might be locally released due to electromigration. To examine the stress change and grain orientation, synchrotron radiation is suitable for this study. It allows us to measure the lattice parameter from Laue patterns and calculate the grain orientation and stress distribution as well.

II. EXPERIMENTAL

The x-ray micro-diffraction apparatus at beamline 7.3.3. at Advanced Light Source (ALS) in Lawrence Berkeley National Laboratory was used to study Sn strip. This instrument is capable of delivering white x-ray beam (6-20 keV) focused to 0.8 to 1 μm via a pair of elliptically bent Kirkpatrick-Baez mirrors. In the apparatus, the beam also can perform raster scan over an area of 100 μm by 100 μm at steps of 1 μm. Since the diameters of the grains are larger than 1 μm, each of them can be treated as a single crystal with respect to the incoming micro-beam and the structural information such as stress and orientation could be obtained by using white beam (Laue) diffraction. The technique of Scanning X-ray Microdiffraction (SXRD) that we used here is described by Tamura et al. [6,7].

Laue patterns were collected with a large area (9 x 9 cm^2) Charge Coupled Device (CCD) detector with an exposure time of 1 second, from which the orientation and strain tensor of each illuminated grain can be deduced. Because of the low absorption of x-rays, several grains through the thickness of the finish are illuminated under the x-ray at the same time, but the grain of interest (the one below the surface) can be discriminated from the intensity of the reflections. The distortional strain tensor of the Sn grains were measured based on the changes of the lattice parameter measured from each pattern. By converting the strain to the deviatoric stress by multiplying the stiffness of Sn, we are able to collect the data of the stress distribution of the line before and after electromigration testing. A custom-made software developed at the ALS is capable to determine the orientation of each of the grains and to display the distribution of the unit cell axis of these grains. The geometrical parameters (distance between CCD detector and sample, tilts of the detector with respect to the incoming beam) were least-square fitted using a Laue pattern from the silicon substrate as a strain-free reference. Hence, this internal reference enables us to determine the relative stress in the grains with respect to the Si substrate.

Corresponding Author Contact E-mail : tcwu@ucla.edu

III. Results and Discussion

An as-received Sn sample was scanned first. Sample was taken out from the stage after finishing the scan and applied current for 7 hours at 150^oC. After electromigration testing, sample was scanned again.

The orientation changes of the grains has been reported else where [5]. If we examine the result of stress distribution, an obvious stress relaxation can be observed after electromigration. This can be seen in figure 1 (a) and (b).

Since tin has a CTE (coefficient of thermal expansion) of 22 x 10^{-6} /^oC and Si substrate has 2.6 x 10^{-6} /^oC. The sample should be under tension after cooling down from the post annealing after deposition. During the post annealing for 2 months after deposition, the internal stress was considered fully released. Therefore, the residue stress measured in figure 1 was believed to be the stress due to the difference of thermal expansion. Under electromigration, tin strip was undergone another thermal cycle from room temperature to 150^oC and then cool down again. The thermal stress actually can be cancelled out during these two thermal treatments, as can be seen in figure 2. The relaxation happens especially at some local area.

The back stress in Al strip has been well studied. It is due to the change of vacancy concentration which causes a gradient from the cathode toward the anode. [8,9] It is also expected to see the back stress in the tin strip under electromigration. However, from figure 1 (a) and (b), the back stress cannot be clearly detected. One reason is that the critical length at the current density value of 6.25×10^3 A/cm^2 would be around 150μm in tin. In the testing tin strip in this study, the length of the strip is 200 μm. The stress gradient might not be obvious to be detected. On the other hand, the sample was testing ex-situ, it is not easy to maintain the stress level after stopping the current since the stress would be released quickly. Nonetheless, we sill are able to observe that the total strain energy inside the grains which rotate after electromigration is reduced. Since strain can be calculated from knowing the lattice parameter, it allows us to calculate the stress by multiplying elastic moduli to the stain we measured. Therefore, we can calculate the strain energy by using

$$E_{total} = \frac{1}{2}\sum \sigma_{ij}\varepsilon_{ij}.$$

The strain energy was further divided by the pixels we measured in the specific grain in order to obtain the average strain energy for comparison. We found that for those grains rotate after electromigration, the total strain energy reduced. However, for those grains which were not affected by electromigration didn't have much of the change in grain energy. In some grains, the average strain energy even increased. It is not clear why there is an increase of energy under electromigration. It might due to the local build-up of the back stress under electromigration. But why the stress was not released needs to be studied more carefully. For those grains that have low resistance, to lower the strain energy during electromigration seems to be another prossible driving force to rotate the grain.

IV. Summray

The x-ray microdiffraction analysis has proved to be suitable for the study of microstructure evolution. The stress analysis is crucial in thin film metallic strips since they are the crucial components in the packaging. The total stress distribution in the strip was released after electromigration. The strain energy was also calculated and have comparison between the grains which have been previous recognized to have rotation under electromigration and for those weren't affected by the current. We proposed that the reduction of strain energy might be another driving force to rotate the grains.

Corresponding Author Contact E-mail : tcwu@ucla.edu

References

[1] P. S. Ho and T. Kwok, Rep. Prog. Phys., **52**, 301 (1989).

[2] R. Rosenberg, D. C. Edelstein, C. K. Hu, and K. P. Rodbell, Annual Review Mater. Sci., **30**, 229 (2000).

[3] K. N. Tu, J. Appl. Phys., **94**, 5451 (2003).

[4] J Lloyd, J. Appl. Phys. **94**, 6483 (2003).

[5] A. T. Wu, K. N. Tu, J. R. Lloyd, N. Tamura, B. C. Valek, and C. R. Kao, Appl. Phys. Lett., **85**, 2490 (2004).

[6] A. A. MacDowell, R. S. Celestre, N. Tamura, R. Spolenak, B. Valek, W. L. Brown, J. C. Bravman, H. A. Padmore, B. W. Batterman, and J. R. Patel, Nuclear Inst. and Meth., **A 467**, 936 (2001).

[7] N. Tamura, A. A. MacDowell, R. S. Celestre, H. A. Padmore, B. Valek, J. C. Bravman, R. Spolenak, , W. L. Brown, T. Marieb, H. Fujimoto, B. W. Batterman, and J. R. Patel, Appl. Phys. Lett., **80**, 3724 (2002).

[8] I. A. Blech, J. Appl. Phys., **47**, 1203 (1976).

[9] I. A. Blech and C. Herring, Appl. Phys. Lett., **29**, 131 (1976).

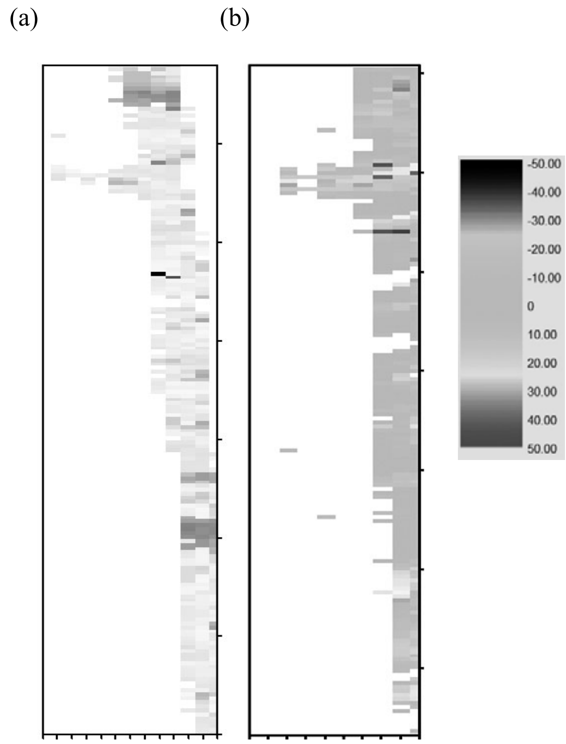

FIG 1 Grain maps of tin stripes deviotoric σ'_{11} stress along X-axis (a) before electromigration (b) after electromigration

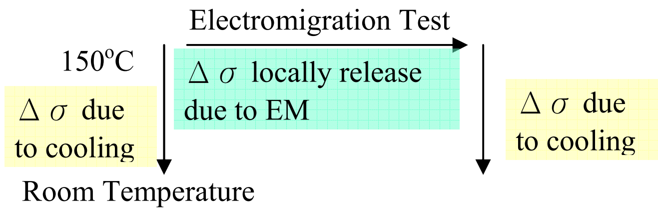

FIG 2 The diagram explain the stress relaxation process during the thermal cycling.

Corresponding Author Contact E-mail : tcwu@ucla.edu