Combined High Voltage SEM and X-Ray Microdiffraction Studies of Damascene Copper Interconnects

B.C. Valek[1], N. Meier[1], N. Tamura[2], R. Spolenak[3], R.S. Celestre[2], A.A. MacDowell[2], H.A. Padmore[2], J.C. Bravman[1], and J.R. Patel[2,4]

[1] *Dept. Materials Science & Engineering, Stanford University, Stanford CA 94305 USA*

[2]Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

[3]Bell Laboratories, Lucent Technologies, Murray Hill NJ 07974 USA

[4]SSRL/SLAC, Stanford University, P.O.BOX 43459, Stanford CA 94309 USA

INTRODUCTION

Metallic interconnects in modern integrated circuits experience very high current densities during service. These high current densities lead to the reliability issue of electromigration, the transport of atoms in a metallic interconnect along the direction of electron flow. The net motion of atoms in the line can cause failure by voiding (open circuit failure) or hillocking (extrusion of material to form a short circuit). The purpose of this work is to understand the relationship between electromigration phenomena and microstructure. High Voltage Scanning Electron Microscopy (HVSEM) has the ability to image voids and regions of metal accumulation in the line beneath a passivation layer (usually $Si0_2$) non-destructively. X-Ray Microdiffraction allows grain orientation mapping of the line with submicron resolution and an accuracy of about 0.1°. In addition to this microstructural information, x-ray microdiffraction can also measure the full stress/strain tensor with an accuracy of about $2\ 10^{-4}$ in strain. The ability of HVSEM and X-ray microdiffraction to probe the sample non-destructively is of utmost importance. Other techniques used to obtain microstructural information from metallic interconnects (such as TEM or EBSD) require special sample preparation and are not suited for predetermining the microstructure of the line. In addition, HVSEM and X-ray microdiffraction allow for *in-situ* testing.

EXPERIMENT

The experimental setting for the X-ray Microdiffraction Laue technique is described elsewhere [1,2]. The samples tested are single level damascene copper interconnects (300 µm long, 1.1 µm wide, 0.75 µm thick) with one micron of nitride passivation. The metallization was deposited by either sputtering or electroplating. Before electromigration testing, 65 µms at both ends of the line are scanned using x-ray microdiffraction. An orientation map is formed by scanning the sample on a piezoelectric stage in submicron increments under a submicron white x-ray beam. At each position, a diffraction pattern is collected using a large area CCD camera. The grain structure can be constructed by analyzing the variation in the intensities of the Laue patterns for individual crystallites as the beam moves across the sample. The sample then undergoes *in-situ* electromigration testing in the HVSEM, described in [3]. The evolution of voids and regions of accumulation or depletion of metal is recorded during the test. The sample is then rescanned by x-ray microdiffraction to determine if there was any change in the microstructure during the test and to measure any change in the stress state of the line.

RESULTS AND DISCUSSION

Preliminary results have been obtained at Beamline 7.3.3 of the Advanced Light Source. Fig. 1 shows a region of a sputtered copper damascene interconnect that has undergone electromigration testing. The bottom right inset shows an HVSEM image taken just after the electromigration test, near the anode end. The metal build-up region (marked by a black circle) appears as a slightly darker blue area zone in the electromigrated line. The corresponding orientation and resolved shear stress (calculated from the measured distortional stresses and considering the 12 gliding systems of Cu: (111) type planes in the <110> directions) maps obtained by X-ray microdiffraction are displayed on the left. The grain structure has a random out-of-plane orientation and a near-bamboo structure. The indices, next to the map, indicate the approximate out-of-plane orientation of the largest grains. At the location of the local buildup region, the resolved shear stress dramatically increases to reach a maximum value of about 600 MPa. The orientation map shows that metal has accumulated at the interface of a (111) bamboo grain just before the location of a (115) twin and after a series of small-size randomly oriented grains (fast diffusion path). The width of the Bragg reflections also contains information on the dislocation density and provides an indication on the level of stress and plastic deformation inside a particular grain. The peak width of the (113) reflection is plotted (top right) in function of the position along the 2 µm long (111) grain (indicated by the red arrow in the orientation map), which contains the (115) blocking twin. The peak is clearly broader in the buildup region next to the twin boundary.

This particular example shows the ability of X-ray microdiffraction to provide quantitative data such as grain orientation, structure, and stress at the local level in passivated interconnects, greatly improving the understanding and modeling of electromigration phenomena. This technologically important problem is shown to be much more complex when the line dimensions shrink to a size where microstructural local effects could no longer be neglected.

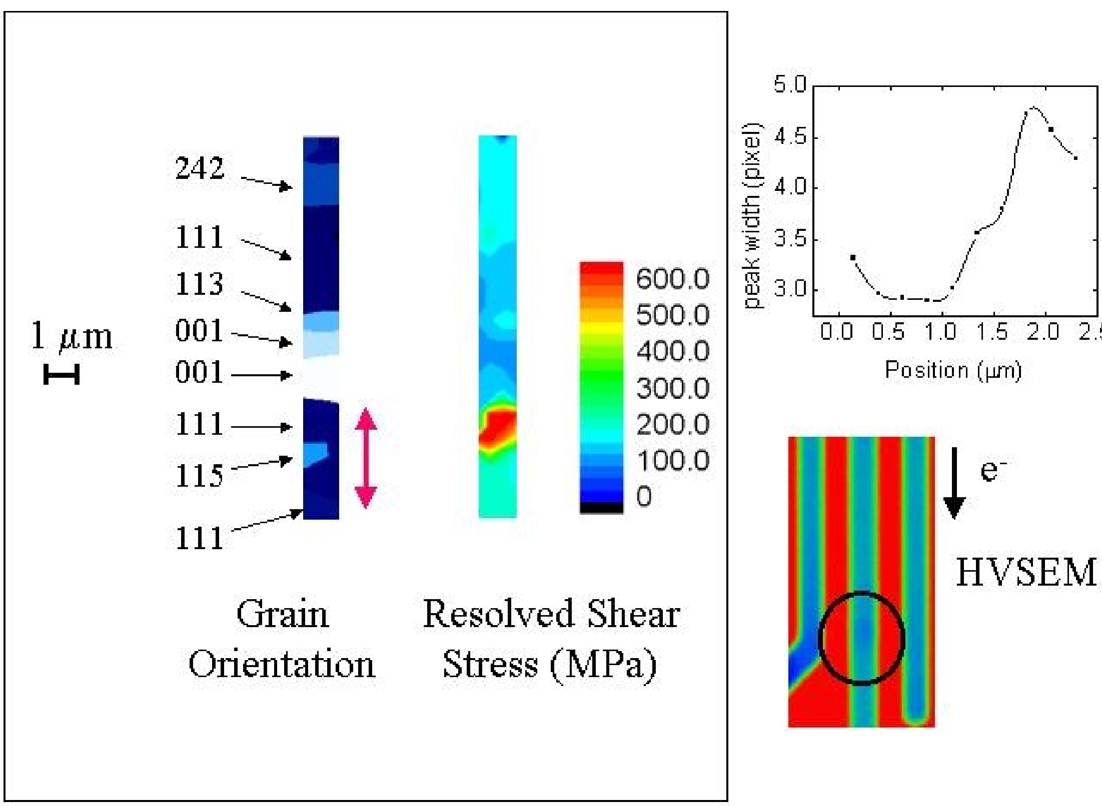

Fig 1.- Grain orientation and resolved shear stress maps obtained by the X-ray Microdiffraction Laue technique. The HVSEM image (bottom right) shows region of metal accumulation (See text).

REFERENCES

1. Tamura, N., Spolenak R., Valek, B.C., Celestre R.S., MacDowell A.A., Padmore H.A., and Patel, J.R., "Orientation and Stress Mapping at beamline 7.3.3.: a New Tool to Study Material Properties at Submicron Scale", This volume, Abstract 2000
2. MacDowell, A.A., Celestre, R.S., Tamura, N., Spolenak, R., Valek, B.C., Brown, W.L., Bravman, J.C., Padmore, H.A., Batterman, B.W. & Patel, J.R., Proceeding of the 7th International Conference on Synchrotron Radiation Instrumentation, in press (2000)
3. Flinn, P.A., Lee, S., Doan, J.C., Marieb, T.N., Bravman, J.C., and Madden, M., *AIP Conf. Proc*. 418, 250 (1997)

This work was initiated with support from the LBNL Laboratory Director's Research and Development Fund. Additional support was provided by NIH grant GM51487 and by the US Department of Energy, Office of Basic Energy Sciences, under contract # DOE-AC03-765F00098. We thank Intel Corp. for partial funding of the beamline.

Principal investigator: Nobumichi Tamura, Advanced Light Source, Lawrence Berkeley National Laboratory. Email: ntamura@lbl.gov. Telephone: 510-486-6189.