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STRAIN AND TEXTURE IN Al-INTERCONNECT WIRES MEASURED BY X-RAY MICROBEAM DIFFRACTION

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ABSTRACT

The local strain and texture in Al interconnect wires have been investigated using white and monochromatic x-ray microbeams on the MHATTCAT undulator beam line at the Advanced Photon Source. Intergrain and intragrain orientations were obtained with -0.01" sensitivity using white beam measurements on wide Al pads (-100 μm) and thin (2 μm) Al wires. Orientation changes of up to 1" were found within individual grains of the (111) textured Al interconnects. Deviatoric strain measurements indicate small intragranular strain variations, but intergranular strain variations were found to be quite large.

INTRODUCTION

Stress induced by differential thermal expansion and electromigration have long been recognized as major contributors to metal interconnect voiding and failure. Detailed information on interconnect microstructure, such as intergrain and intragrain crystallographic orientation and strain, is of key importance in formulating an understanding of such failures and improving the long-term reliability of electronic devices. In particular, high spatial resolution orientation and triaxial residual strain/stress measurements are needed for modeling void formation and predicting interconnect evolution under chip operating conditions. Such knowledge is lacking. Strain and stress measurements reported using the bending beam technique [1] provide average values for interconnect stress, and strain measured using ~ 10 μm resolution x-ray microbeams [2,3] have provided single strain components for individual grains. Micro-Raman measurements [4] provide hydrostatic stress with a resolution of -1 micron; however, they do not provide information on local triaxial stress in individual grains.

X-ray microbeams represent a powerful technique for investigating texture and strain at the sub-micron level, and they are particularly well suited for grain to grain analysis in metal interconnect wires. The ability to combine white and monochromatic measurements allows the measurement of dilatational and deviatoric strain [5], in addition to obtaining detailed measurements of local grain orientation and texturing. In this paper we report the first measurements combining grain-to-grain orientation and triaxial strain in individual grains for Al interconnect lines.

EXPERIMENT

Detailed x-ray microbeam measurements have been carried out using the MHATT-CAT beamline at the Advanced Photon Source, Argonne National Laboratory. Focused x-ray microbeams were produced using elliptically-figured Kirkpatrick-Baez (KB) mirrors. Details of the experimental configuration are described elsewhere [6]. In this paper we present results obtained using a submicron beam size of 0.7 by 0.7 μm^2 along with results obtained using a beam size of 1.5 by 2 μm^2. The measurements were performed on a commercially fabricated

microchip containing areas with 2 μm wide Al wires and 100 μm wide 'Al pads on (100) silicon substrates. The sample was mounted on a 0.05 μm resolution x-y-z translation stage, and x-ray microbeam measurements were made by translating along interconnect lines or pad areas. At each location, white-beam Laue patterns were taken using a CCD x-ray detector in order to determine the orientation of individual grains and to extract the triaxial strain. In addition, energy scans were performed on selected Bragg reflections using the monochromatic beam mode with -2 eV energy resolution. Details of the orientation, indexing, the extraction of deviatoric strain from Laue patterns, and of the determination of dilatational strain from energy measurement will be described elsewhere [7].

DATA ANALYSIS

To determine the orientation and strain in the interconnect wires from white-beam data, Bragg peaks from the Al wires were located and indexed by computer searches of the CCD patterns. The peak positions were determined to high precision by fitting the peaks with 2D elliptical Lorentzian or Pearson VII functions. For our conditions, the larger grains yielded from 10 to 15 Laue spots, of which typically 10 would be bright enough (compared to the background) to determine the peak position with an accuracy better than 0.01".

An important aspect of the measurement process is the determination of the parameters specifying the position and orientation of the CCD camera. Included in these parameters is geometrical information such as the sample to CCD camera distance, and tilts/rotations of the CCD phosphor screen. The geometrical parameters were determined using a perfect Ge reference crystal which provided about 60 spots in an energy band pass of 9-23 keV, on a CCD camera of 27.9 x 25.9 mm^2, at a distance d=25.8 mm from the sample. The complete deviatoric strain tensor for the Al interconnects was then obtained from the Al grain Laue patterns (using the Ge determined geometrical parameters of the camera) by non-linear least squares fitting.

GRAIN ORIENTATIONS, TEXTURE

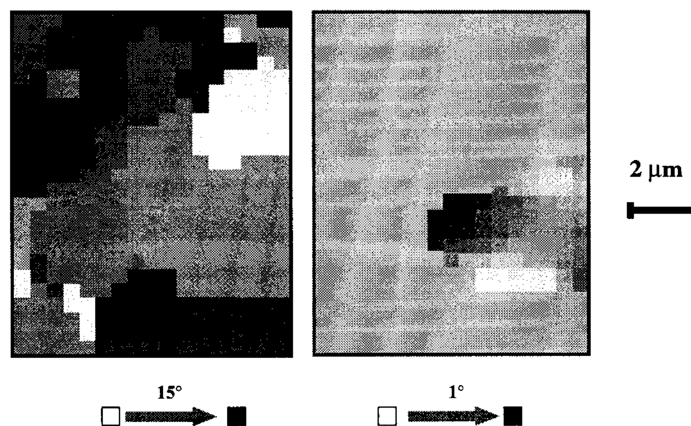

Fig 1.-Intergranular orientation (left) and intragranular orientation (right) map for a wide pad.

Figure 1 shows the results of a two-dimensional gram orientation scan in a wide pad region, measured by translating a 0.7 by 0.7 μm^2 beam with 0.5 μm steps in each direction. The figure displays an 8.5 x 12 μm^2 area, and indicates the orientation of the (111) axis of the glass passivated Al grains relative to the surface normal. The image indicates a distribution of grain sizes varying from less than 1 μm to more than 6 μm in diameter. The light colored pixels in Fig. 1 refer to grams with (111) directions closest to the surface normal and the dark pixels refer to tilts of ~15° away from the surface normal. The contrast of the large grain in the lower right comer has been enhanced in the panel to the right to show intragranular variations in orientation.

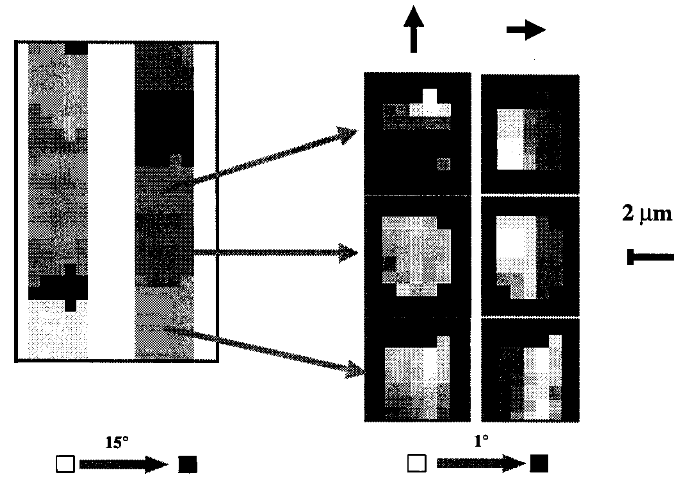

Fig 2.- *Intergranular orientation (Left) and Intragranular (Right) orientation maps of the thin wires.*

Fig 2 shows an orientation map obtained for a similar size area in a region containing 2 μm wires. Two neighboring wires appear. The bamboo (or near bamboo) structure of the wires is clearly evident with the 0.7 x 0.7 μm^2 measurement resolution. The enhanced contrast orientation plot to the right in Fig. 2 shows intragranular distortions to be ~+/- 0.5".

DEVIATORIC TRIAXIAL STRAINS

At present we have not completed the analysis of the 0.7x0.7 μm^2 resolution measurements shown in Figs. 1,2 in terms of triaxial strains. However, deviatoric strain analyses have been performed on measurements made using lower resolution, and in Fig. 3 we present triaxial strain results measured with a 1.5 by 2 μm^2 beam taking 1 μm step along the wire. Since this larger beam is not capable of resolving the smaller grams directly, a schematic orientation map has been made by assuming the grains to be bamboo-like and using the measured intensities of Laue spots as a function of distance along wire to extract an effective size. The white beam patterns provide directly the deviatoric strain tensor from the measured changes in the lattice angles a, β, and γ, and the relative changes in the unit cell parameters a, b, and c, for each grain seen in each Laue pattern.

Since the average gram size is about 2 μm, the larger grains appear in more than one Laue picture along the 1 μm step linear scan for a beam size of 1.5 x 2 μm^2. In most cases the fitting of the data to obtain the strain tensor gives similar results for different locations in the same grain to

within ~ 2 x 10^{-4}, which is the estimated accuracy of the present measurement. This uncertainty estimate includes the fact that some peaks are irregularly shaped and difficult to fit precisely. We note that the accuracy obtained for measurements on perfect bulk Ge is almost an order of magnitude higher, so the precision of our measurements can be expected to improve as analysis methods evolve. The deviatoric strain measured in our chip (more than 2 years after fabrication) varies from a few x 10^{-4} to -1 x 10^{-3} for this sample, and the measurements indicate the strain to be relatively constant within grains. On the other hand, intergranular strains seem to be essentially uncorrelated as they tend to vary strongly from grain to grain. For instance, the data in Fig. 3 indicate a number of cases in which a grain is in tension along the direction (x) of the wire, while neighboring grains are found to be stretched in the direction perpendicular (y) to the wire. In spite of the heterogeneities, there is an overall tendency for the larger grains to be stretched along the direction of the wire (x) and compressed perpendicular to the wire, as demonstrated by the fact that ε'_{xx} in Fig. 3 tends to be positive and ε'_{yy} tends to be negative. In the relatively small number of grains measured so far, neither the narrow wires nor the wide pads show equi-biaxial strains to be common; however, unlike the narrow wires, the wide pads do not appear to have a preferred tensile direction.

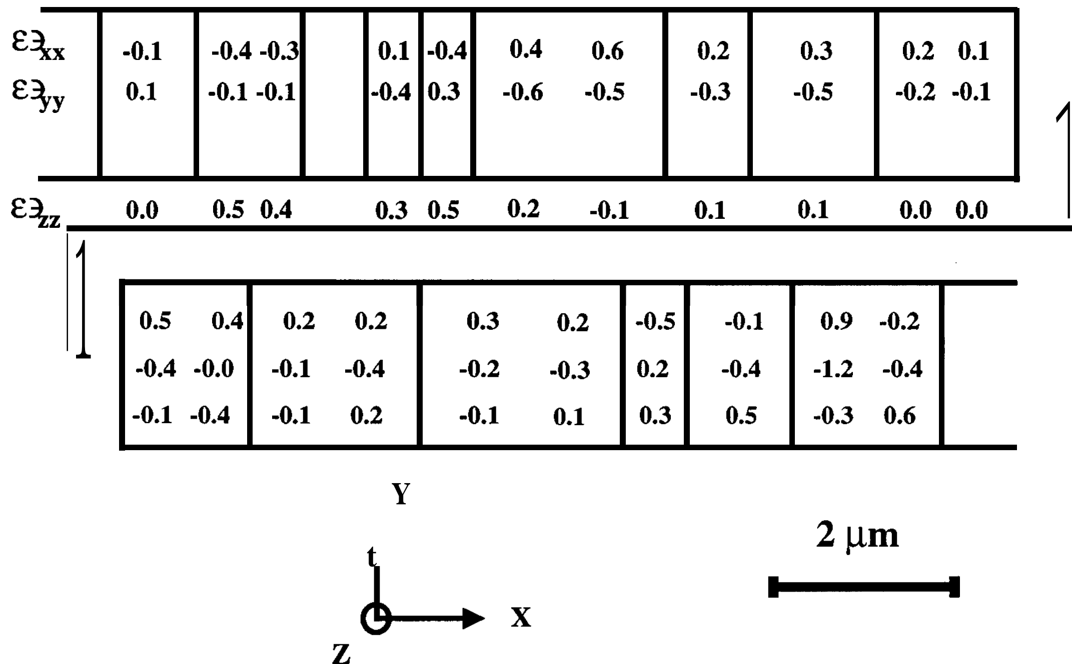

Fig 3. Deviatoric interconnect strain along x, y and z directions (z is the normal to the surface of the chip) measured on a 2 μm wire (x10^{-3}).

DILATATIONAL TRIAXAL STRAINS

As mentioned earlier, dilatational strains require knowing the absolute lattice spacing of at least one Laue reflection. Although straightforward, such measurements are somewhat tedious to perform and this analysis has not been performed on all grains. The procedure used for energy scans was to take the nominal energy for a particular (hkl) Laue peak from the indexing of the white beam pattern and perform an energy scan with 1-5 eV energy steps, collecting selected area CCD information on the shape and position of the reflected x-rays at each energy step.

Reflectivity measurements as a function of energy are shown for two positions within a single grain in Fig. 4. We note that the peaks are quite broad in energy (-1530 eV), a result that we have found to be quite typical. For x-ray energies in the 10 keV range, such widths correspond either to a variation in lattice strain of l-3 x 10^{-3}, or to a rotational variation of 0.1" - 0.2" within the area of the beam. Through the analysis of the precise position of the reflectivity peak in each selected area CCD image (i.e. at each energy in the scan), the absolute lattice spacing was determined for each point in the energy scan, as shown in Fig. 4.

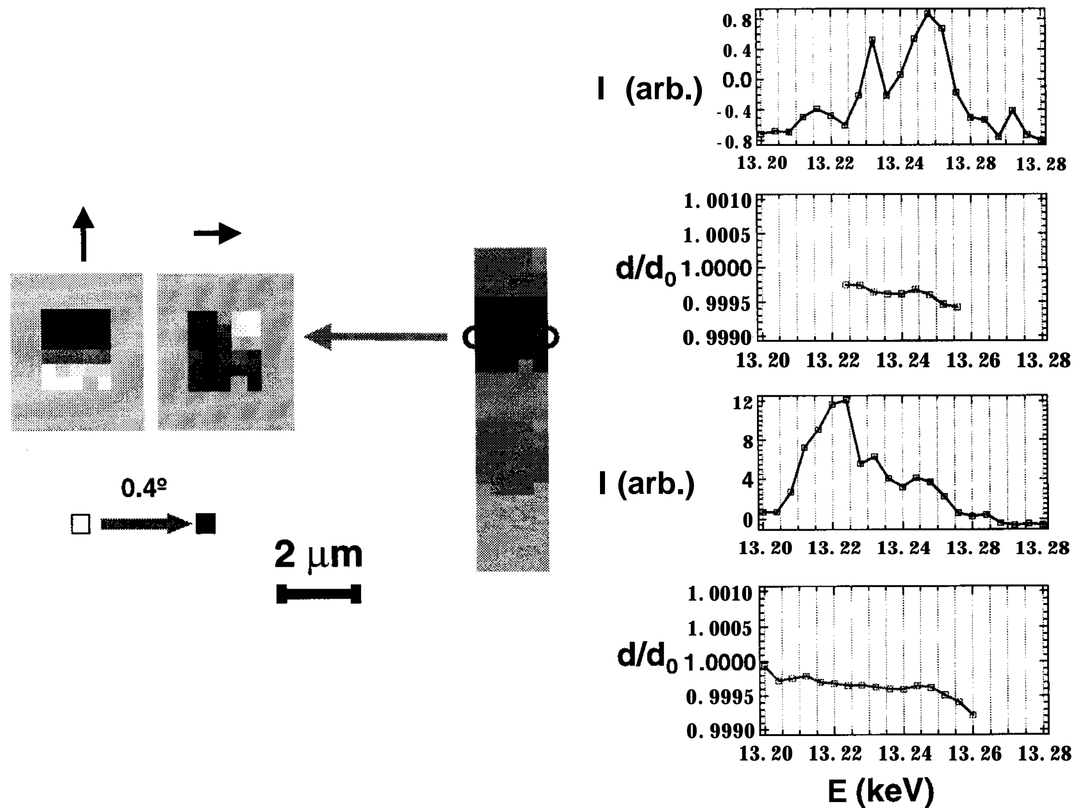

Fig 4.- Energy scan for the (3 3 3) reflection at two locations within a single grain in a thin wire. Intragranular orientation variations along, and perpendicular to, the direction of the wire are indicated by the 0.4" variation between the lightest and darkest regions. Energy scans at two locations and the corresponding d/d_0 are displayed. The average d/d_0 value for all the subgrains and locations is about -3.6 ±0.6 10^{-4}.

We conclude from the nearly constant strain as a function of energy that almost all of the broadness in the energy scans results from angular rotations (deformation) within the microbeam footprint of the grain and not to variations in the lattice parameter. This result is consistent with the observation of broadening in the white beam Laue peaks of Al interconnect grains compared to much sharper peaks measured in the CCD camera for perfect crystal Ge. That is, the x-ray reflections for Al interconnects are actually composed of several subpeaks corresponding to subgrains with slightly different orientations. This is consistent with the intragranular orientation maps in Figs. 1,2, where the 0.7 x 0.7 μm^2 measurements can be inferred to contain -0.1 – 0.2° orientation variations within the spot size. In contrast to the rather large energy widths for Al

interconnect grains in Fig. 4, perfect Ge crystal energy scans yield peak widths of only about 3-4 eV, as determined mainly by the converging nature of the focused microbeam.

The energy scan measurements and analyses made at two locations within the same grain in Fig. 4 indicate graphically the rotations as a function of position within the grain, but they indicate no significant strain variation. Considering the thermal cycling and differential thermal expansion induced stresses and yielding, it is not surprising to observe intragranular deformation. Of course the peak broadening and peak distortions observed in white beam Laue peaks provide information on deformation modes. However, the extent to which rotational variations within the size of the x-ray beam impact the measurement of strains using white beam Laue patterns is an important question that is presently under investigation.

CONCLUSIONS

X-ray microbeam measurements combining submicron white and monochromatic beam capabilities have been applied to the study of local texture and residual strain in Al interconnects. We report for the first time measurements of both intergranular and intragranular orientations and residual triaxal strains. Our results indicate that intragranular microstructural variations are composed mainly of lattice rotations resulting from stress relaxation rather than differential stress related variations in strain. Deviatoric strain levels were found to be quite heterogeneous, generally less than 1×10^{-3} in magnitude, and to have a tendency toward tensile strains along wire directions for the sample measured. As automated data analysis techniques are further developed, the availability of a large number of grain by grain triaxal strain measurements will enable a more complete understanding of the role of stress in voiding during electromigration.

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