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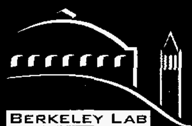

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GRAIN ORIENTATION MAPPING OF PASSIVATED ALUMINUM INTERCONNECT LINES WITH X-RAY MICRO-DIFFRACTION

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Grain Orientation Mapping of Passivated Aluminum Interconnect Lines with X-ray Micro-Diffraction

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A micro x-ray diffraction facility is under development at the Advanced Light Source. Spot sizes are typically about 1-μm size generated by means of grazing incidence Kirkpatrick-Baez focusing mirrors. Photon energy is either white of energy range 6-14 keV or monochromatic generated from a pair of channel cut crystals. Laue diffraction pattern from a single grain in a passivated 2-μm wide bamboo structured Aluminum interconnect line has been recorded. Acquisition times are of the order of seconds. The Laue pattern has allowed the determination of the crystallographic orientation of individual grains along the line length. The experimental and analysis procedure used is described, as is the latest grain orientation result. The impact of x-ray micro-diffraction and its possible future direction are discussed in the context of other developments in the area of electromigration, and other technological problems.

INTRODUCTION

Electromigration is the physical movement of atoms in metallic interconnect lines passing current at high electron density (typically in the range of 10^5 amp/cm^2). Significant material movement results in voids that consequently leads to breakage and circuit failure in the metal lines. This problem gets more severe as the line dimensions continue to shrink on integrated circuits. In spite of much effort in this field (1,2), electromigration is not understood in any depth or detail, but is strongly associated with the physical material properties (stress and strain) within the interconnect material. Throughout this century x-rays have been a powerful tool to measure such material properties, but the ability to make such measurements on the micron scale required by the semiconductor industry has only come into realization with the advent of the latest generation of high brightness synchrotron sources. In this paper we describe the beginnings of a program to carry out various x-ray diffraction measurements on the micron scale. It is presumed that the electromigration properties of a metal line will be dependent to some extent on the grain orientation of adjacent grains in the line. This paper describes the experimental and analysis techniques that allow the grain orientation and indexing of individual micron sized grains along the length of aluminum interconnect line.

X-rays are quite well suited to such measurements as they are able to penetrate several microns into matter. In general, interconnect lines are encased in the insulator silicon dioxide (passivation). X-rays are able to penetrate and study such buried samples.

EXPERIMENTAL

Figure 1 shows the experimental setup. The synchrotron

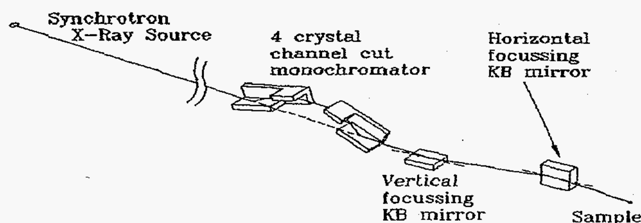


Figure 1. Schematic layout of the K-B mirrors and four crystal channel-cut monochromator.

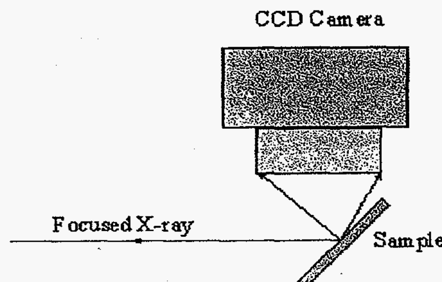


Figure 2. Schematic diagram of experimental arrangement.

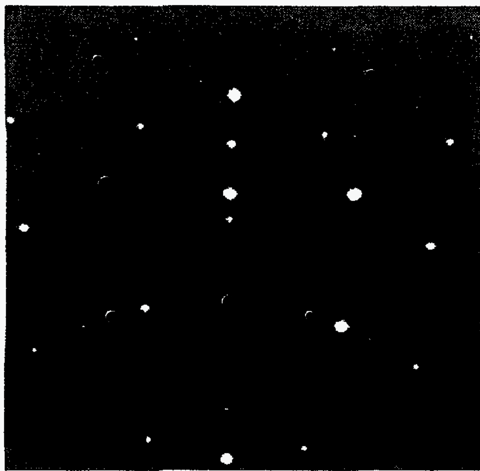


Figure 3. Laue pattern of silicon substrate.

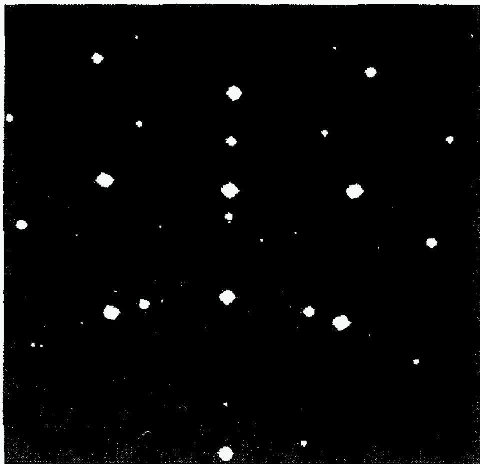
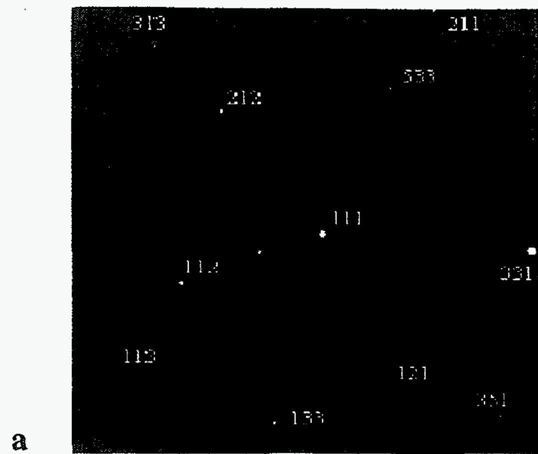


Figure 4. Laue pattern of a single grain in aluminum line as well as the silicon substrate.



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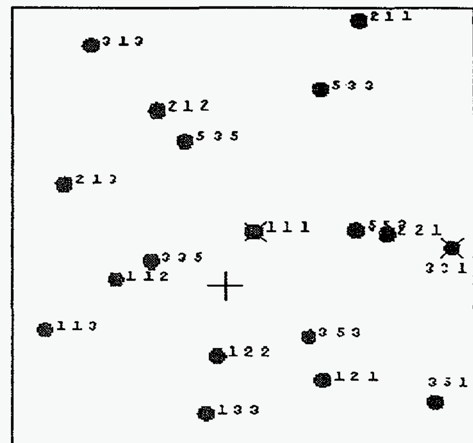

b

Figure 5. (a) Spot pattern of aluminum grain obtained by subtracting the silicon pattern (Fig. 3) from the aluminum pattern (Fig. 4). (b) Simulated pattern with the aluminum spot pattern indexed.

source of size typically 300 × 30 μm FWHM (horizontal and vertical) is imaged with demagnifications of 300 and 60 respectively by a set of grazing incidence platinum-coated elliptically bent Kirkpatrick-Baez (K-B) focusing mirrors (3). Imaged spot sizes on the sample are about a micron in size. Photon energy is either white of energy range 6-14 keV or monochromatic generated by inserting a pair of Si(111) channel-cut monochromator crystals into the beam path. A property of the four crystal monochromator is its ability to direct the monochromatic primary beam along the same direction as the white radiation. Thus, the sample can be irradiated with either white or monochromatic radiation. White radiation is chosen for Laue experiments for the orientation determination and monochromatic radiation for d-spacing measurements in stress/strain determination of single grains in the metal line.

The sample was an aluminum line deposited to 0.5-μm thickness and 2-μm width on an oxidized silicon substrate. The line was passivated with a plasma-enhanced chemical vapor deposition (PECVD) nitride at 300°C to 0.3-μm thickness. Laue patterns were collected using white radiation and an x-ray CCD camera. The exposure time was 0.5 sec and sample-to-CCD distance was 16.4 mm. Fig. 2 shows the arrangement of the sample and CCD detector.

RESULTS

Figure 3 shows the Laue pattern from the silicon substrate. Figure 4 shows the Laue patterns from the silicon substrate and the somewhat fainter diffraction spots from a single grain in the aluminum line. Fig. 5a shows the aluminum Laue pattern obtained following digital

subtraction of the silicon pattern (Fig. 3) from the silicon and aluminum pattern (Fig. 4).

The origin on the CCD detector array was determined by moving the CCD camera radially from the sample and recording the silicon Laue patterns at various distances from the sample. The origin was determined at the CCD where the lines drawn through the succession of the same Laue spots intersected. All aluminum spot positions were coordinated to the origin and indexed using an indexing software package - LaueX (4). Fig. 5b shows the simulated pattern with reflections indexed. For conformation of the indexation the 4 crystal monochromator was inserted into the beam and scanned in energy to determine the d-spacing of the Al (111) spot.

The aluminum grain orientation can be referenced to the silicon substrate based on the orientation matrix $\mathbf{R}_{Si}$ and $\mathbf{R}_{Al}$ *in the silicon substrate and aluminum grain, respectively.* The matrix $\mathbf{R}$ relates the crystal system S with axes parallel to the basic crystallographic axes in the crystal to the reference system S^R related to the primary beam direction:

$$S^R = \mathbf{R}S.$$

The aluminum grain orientation measured is then referenced to the silicon substrate as the following orientation matrix:

$$\mathbf{M} = \mathbf{R}_{Si}^{-1}\mathbf{R}_{Al}$$

$$= \begin{pmatrix} 0.707 & 0.475 & -0.524 \\ 0.003 & 0.737 & 0.676 \\ 0.707 & -0.481 & 0.518 \end{pmatrix}^{-1} \begin{pmatrix} 0.916 & 0.039 & 0.399 \\ 0.308 & 0.571 & -0.761 \\ -0.257 & 0.822 & 0.509 \end{pmatrix}$$

$$= \begin{pmatrix} 0.468 & 0.612 & 0.637 \\ 0.787 & 0.045 & -0.615 \\ -0.404 & 0.792 & -0.458 \end{pmatrix}.$$

The experimental accuracy in the determination of the orientation matrix $\mathbf{M}$ depends mainly on the angular resolution of the Laue camera system, because the Laue diffraction pattern of the aluminum grains always accompanies that of the silicon substrate that is the reference of the aluminum orientation. In the present case with the CCD of 23.5-μm pixel size and sample-to-CCD distance of 16.4 mm, the magnitude of the misorientation angle is determined within a precision of several minutes of arc.

CONCLUSION AND FUTURE DEVELOPMENT

We have demonstrated that the x-ray micro-diffraction is capable of determining the crystallographic orientation of individual grains in passivated interconnect lines. The orientation mapping can be done by collecting the Laue patterns from individual grains along the length of the lines. A computerized indexing code to automate this is under development. Beyond this the requirement is to measure the d-spacing of various aluminum planes to determine the stress and strain state of individual grains along the length of the aluminum interconnect line.

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