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Publication Date

1998-06-01

LBNL-42053
LSBL-477

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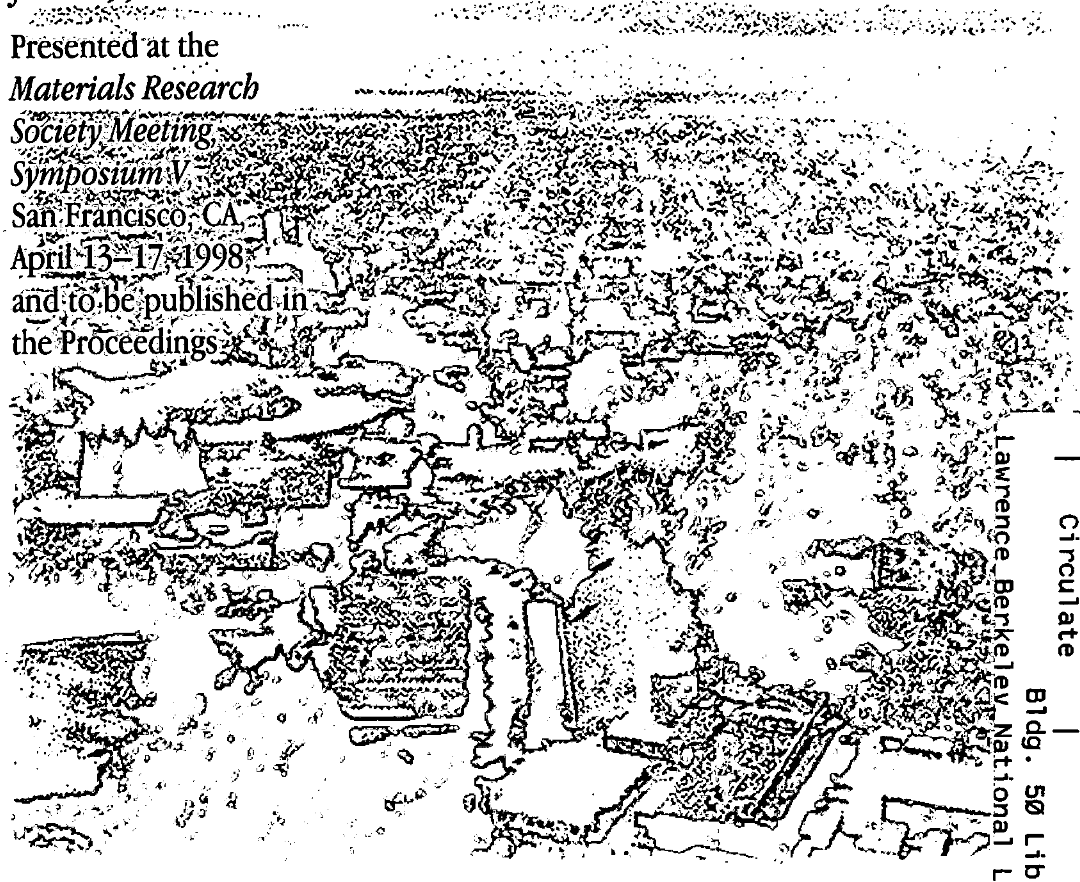
Advanced Light Source Division

June 1998



Presented at the
*Materials Research
Society Meeting,
Symposium V,*
San Francisco, CA,
April 13–17, 1998,
and to be published in
the Proceedings

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

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*This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098, and by Intel Corporation.

Light Source Note:
Author(s) Initials AM
Date
Group Leader's initials HAP 6/28/98
Date

LSBL 477

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

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ABSTRACT

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. A 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 a few seconds. The Laue pattern has allowed the determination of the crystallographic orientation of individual grains along the line length. The experimental and analysis procedures used are described, as is a grain orientation result. The future direction of this program is discussed in the context of strain measurements in the area of electromigration.

INTRODUCTION

Electromigration is the physical movements 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 lead 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 (1,2,3), 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 (see for example ref. 4). 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 in the environment that they will be used.

EXPERIMENTAL

Figure 1 shows the experimental setup. The synchrotron 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

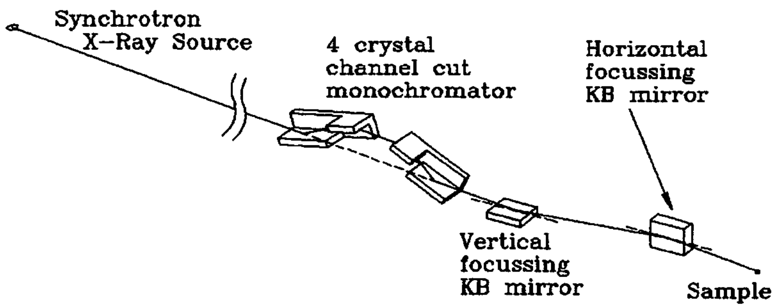

Figure 1. Schematic layout of the K-B mirrors and the four crystal channel-cut monochromator

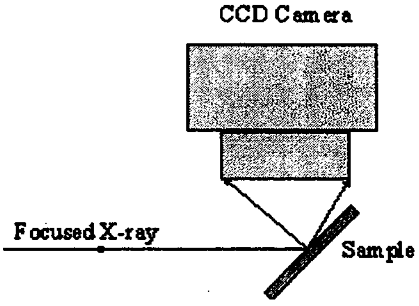

Figure 2. Schematic layout of the arrangement around the sample

mirrors (5). 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. The x-ray probe motion on the sample between white and monochromatic modes has been measured to be less than 0.5-μm. White radiation is chosen for Laue experiments which allow for crystal grain orientation determination. Monochromatic radiation is to be used for d-spacing measurements to determine 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 a 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 and figure 4 shows the Laue patterns from the silicon substrate with the fainter diffraction spots from a single grain in the aluminum line. Digital subtraction of the silicon pattern (Fig. 3) from the silicon and aluminum pattern (Fig.4) results in the Laue pattern of the single aluminum grain under observation. (Fig.5)

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 (6). Figure 6 shows the simulated pattern with reflections indexed indicating good agreement for the spot positions. Confirmation of the indexation was also achieved by inserting the 4 crystal monochromator into the beam, thus illuminating the aluminum grain with monochromatic light. The photon energy was scanned and the rocking curve (of the central aluminum spot in Figure 4) mapped out. Knowing the diffracted photon energy (7323eV) and the angular direction of the diffracted spot allowed the determination of the d-spacing of this spot and confirmed its indexation as Al (111). In principle the accurate determination of the photon energy and diffraction angle allows for accurate measurement of the d-spacing and consequent strain measurement within the grain, but the present equipment only allowed for confirmation of the indexation.

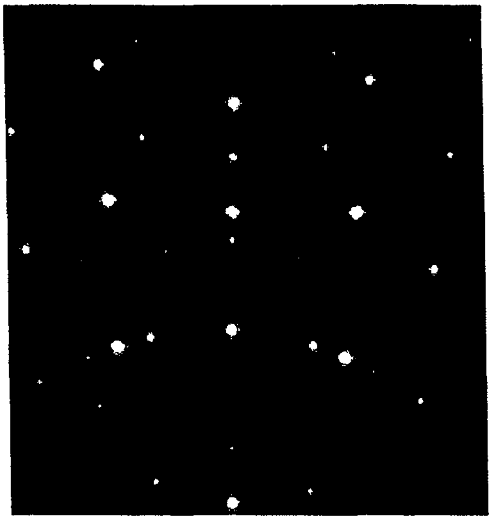

Figure 3. Laue pattern of silicon substrate

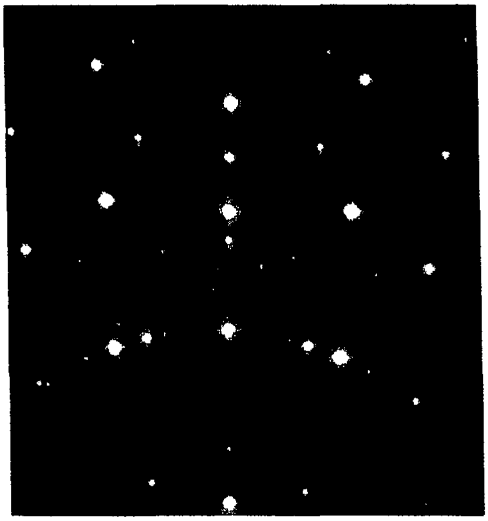

Figure 4. Laue pattern of a single grain in aluminum line as well as the silicon substrate.

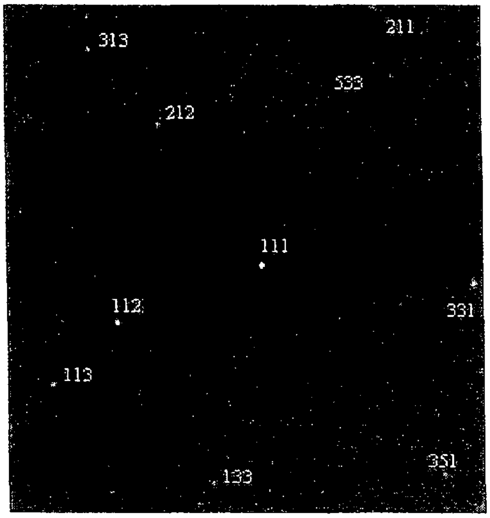

Figure 5. Laue pattern of a single aluminum grain obtained by substracting the silicon pattern (Fig.3) from Fig. 4

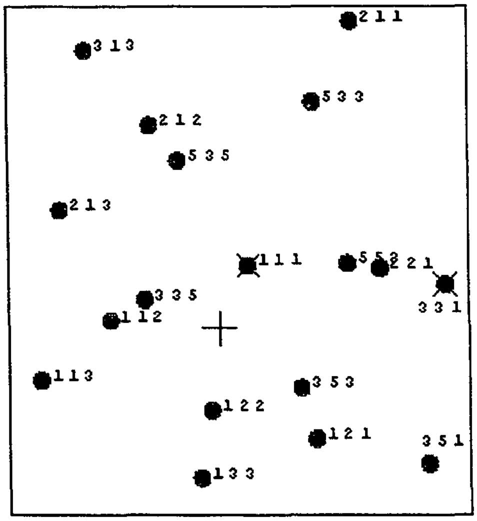

Figure 6. Simulated Laue pattern with the aluminum spots indexed

The aluminum grain orientation can be referenced to the silicon substrate based on the orientation matrix $\mathbf{R}_{Si}$ and $\mathbf{R}_{Al}$ of 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 Laue diffraction patterns from aluminum grains are always accompanied by the Laue pattern from the silicon substrate. We use the silicon substrate as the reference for the aluminum grain orientation.

The experimental accuracy in the determination of the orientation matrix **M** depends mainly on the angular resolution of the Laue camera system. In the present case, the CCD has a pixel size of 23.5-µm and the sample-to-CCD distance was 16.4 mm. This result in a misorientation angle determined to a precision of several minutes of arc.

CONCLUSION AND FUTURE DEVELOPMENT

We have demonstrated that 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 high accuracy to determine the stress and strain state of individual grains along the length of the aluminum interconnect line whilst passing a high current as in a typical electromigration experiment. This work is underway.

ACKNOWLEDGEMENTS

This work was supported by the Director, Office of Basic Energy Sciences, Materials Sciences Division of the US Department of Energy, under Contract no. DE-AC03-76SF00098. Samples from T. Marieb and equipment support from Intel Corporation, Santa Clara, CA.

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Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098