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In-Situ Observation of Electromigration in Cu Film with Scanning μ-RHEED Microscope

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We have observed void and hillock formation at the grain boundary and inside the grain in Cu line due to the electromigration(EM) by *in-situ* nondestructive micrograin imaging with a scanning μ-RHEED microscope. The accelerated electromigration testing was performed at a *dc* current density of $5x10^6 A/cm^2$ and at 250°C in the scanning μ-RHEED microscope. The triple point of grain boundaries was confirmed to weaken the EM endurance. Furthermore, we conjectured that the high EM endurance inside the grain was able to be achieved with current flow along [011] direction for f.c.c. metal such as Cu and Al.

1. Introduction

Electromigration (EM) and stress migration (SM) are primary failure mechanisms limiting the reliability of interconnection in VLSI. It is well known that the EM failure is caused by void and hillock formation. However, there have been few reports on the relation between void/hillock formation and crystallographic orientation of each polycrystal grain, because the crystallographic orientation of micrograins can not be nondestructively determined using the conventional methods such as TEM and X-ray diffraction methods. We have already developed a scanning μ-RHEED microscope for imaging of polycrystal grain structure in microresolution.[1,2] Using the scanning μ-RHEED images, we can nondestructively observed the distribution of normally rotated micrograins parallel to the surface. Single crystallization of Al on SiO_2 by thermal annealing was *in-situ* observed with the scanning μ-RHEED microscope.[3,4]

In this paper, we report on the *in-situ* observation of electromigration in Cu line whose grain's crystallographic orientations are nondestructively determined with the scanning μ-RHEED microscope.

2. Experimental

Figure 1 shows a schematic of the scanning μ-RHEED microscope, in which the accelerated EM testing is performed.

The electron beam from the RHEED gun was irradiated onto the sample surface with a glancing angle of 2°- 3°. The electron beam diameter was 0.1μm and the accelerated voltage was 20kV. The reflected diffraction beam from the sample was observed as a RHEED pattern on the fluorescent screen. Any three spots of the RHEED pattern were simultaneously selected for imaging. The scanning μ-RHEED images were obtained from the intensity change of the diffraction spots when the incident beam was scanned.

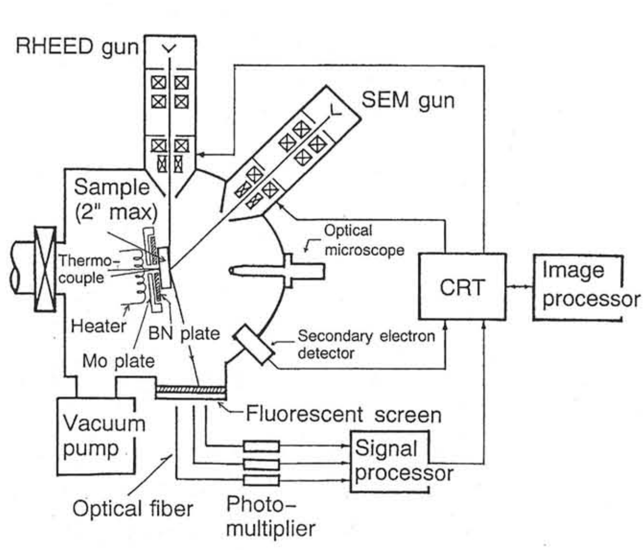

Fig. 1.
Schematic of scanning μ-RHEED microscope, in which the accelerated electromigration testing was performed.

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The image data were simultaneously introduced to the image processor. The scanning μ-RHEED images of different diffraction spots were able to be superimposed in the image processor. We have successfully observed the distribution of normally rotated micrograin inside the same plane's grain parallel to the surface with a resolution of less than one micron.[1,2]

The Cu line on SiO_2 tested was 5000Å thick film deposited by a bias-sputtering method.[5] At first, crystallographic orientations of each grain in the Cu line were determined from the scanning μ-RHEED images. Then, the Cu line was heated by resistive heating from the back surface. The temperature was measured with a thermocouple which was contact with the back surface of the sample. The accelerated EM testing was carried out at a *dc* current density of $5x10^6$A/cm^2 and at a temperature of 250°C. The pressure of the chamber during the EM testing was below $5x10^{-6}$Pa.

3. Results and Discussion

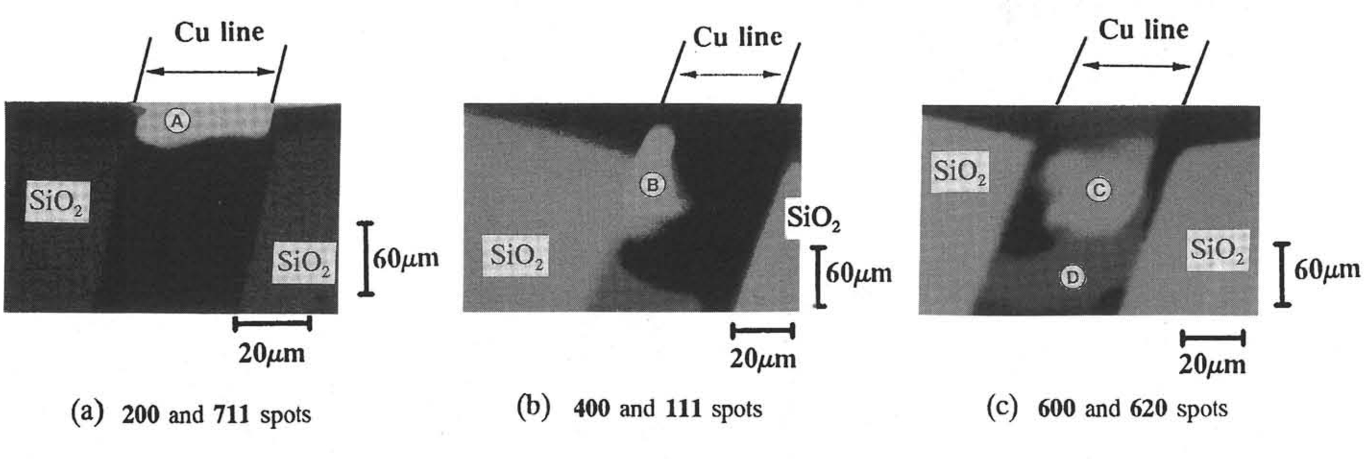
Micrograin structure in the Cu line before the EM testing was determined using the scanning μ-RHEED images of Figs. 2(a), 2(b) and 2(c). The micrograin structure is schematically summarized in Fig. 3.

When observing the scanning μ-RHEED images of Figs. 2(a) and (b), we observed the RHEED patterns which were observed when the electron beam was irradiated on (100) plane along [011] direction. In region ***A*** and ***B***, the intensities of two diffraction spots indicated below the figures were both strong. The crystal plane parallel to the surface was determined to be (100) and the plane perpendicular to the surface (parallel to the incident beam) was determined to be (011). From Figs. 2(a) and 2(b), the (011) plane of grains ***A*** and ***B*** in Fig. 3 were rotated with a several degree in the same (100) oriented grains. When observing the scanning μ-RHEED images of Fig. 2(c), we observed the RHEED pattern which was observed when the electron beam was irradiated on (100) plane along [001] direction. In region ***C*** where the intensities of **600** and **620** diffraction spots were both strong, the crystal plane parallel to the surface was (100) and the plane perpendicular to the surface (parallel to the incident beam) was (001). The crystallographic orientation of grain ***D*** in Fig. 3 was determined using the same manner observation.

During the EM testing at the current density of $5x10^6$A/cm^2 and at 250°C, we observed that hillocks and voids were formed at the grain boundaries and inside the grains. Figure 4 shows a secondary electron image after the EM testing for 48hr.

At the cathode side of triple points ***X*** and ***Y***, clear voids were observed at the grain boundaries between grain ***B*** and ***D***, and between grain ***B*** and ***C***, respectively. These voids at the grain boundaries were caused by the so-called grain boundary diffusion of Cu atom. Atom flux of Cu along the grain boundaries diverted at the triple point, so that voids were formed at the cathode side and hillocks were formed at the anode side. The typical hillocks were observed at grain boundaries ***HX*** and ***HY***. Thus, it was confirmed that the void and hillock were formed at the grain boundary.

Inside grain ***C***, voids and hillocks were formed in lines. The void-lines are parallel to [001] direction and nearly parallel to the electron flow direction. The voids and hillocks were caused by the surface migration or by the bulk diffusion. On the other hand, inside grains ***A*** and ***B***, voids and hillocks were not observed. In grains ***A*** and ***B***, [011] direction is nearly parallel to the electron flow direction. It was found, for the first time, that void and hillock tended to be formed when [001] direction was parallel to the electron flow, and not to be formed when [011] direction was parallel to the electron flow direction. It should be noted that the most nearest atom is sited along [011] direction and the second nearest atom is sited along [001] in f.c.c. metal such as Cu and Al. We conjecture that the high EM endurance can be



(a) **200** and **711** spots (b) **400** and **111** spots (c) **600** and **620** spots

Fig. 2. Superimposed scanning μ-RHEED images of Cu line before the EM testing. In regions ***A***, ***B*** and ***C*** of (a), (b) and (c), the intensities of two diffraction spots (indicated below each photographs) were both strong.

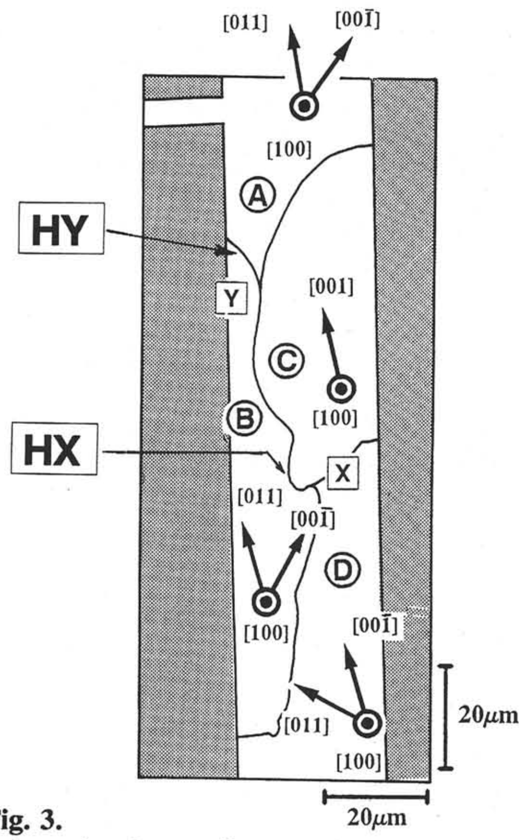


Fig. 3.
Schematic of normally rotated grain structure in (100)Cu line determined with the scanning μ-RHEED images of Fig. 2.

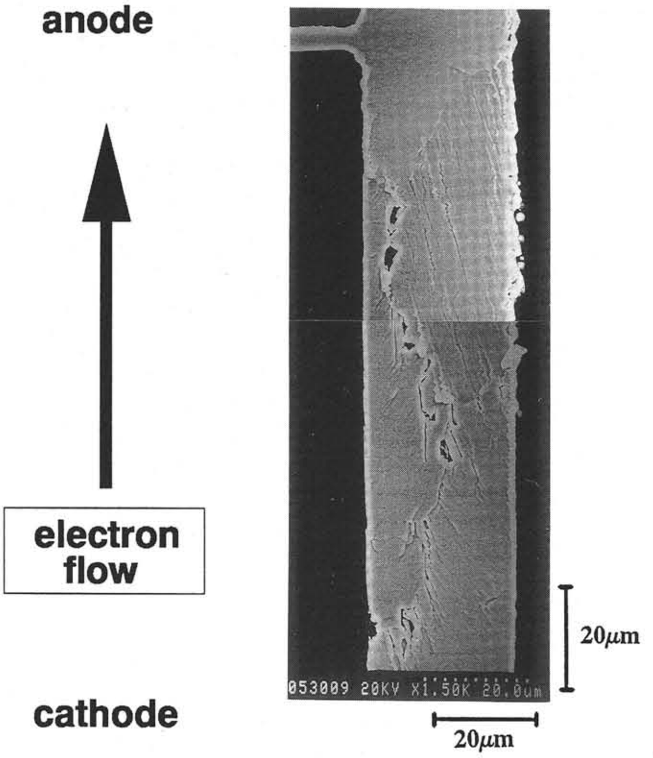


Fig. 4.
Secondary electron image of Cu line after the EM testing at $5x10^6 A/cm^2$ and 250°C for 48hr.

achieved when the current is flowed along the most-nearest-atom direction, *i.e.*, [011] direction for f.c.c. metal such as Cu and Al and [111] direction for b.c.c. metal such as W and Mo.

4. Summary

We have observed void and hillock formation at grain boundary and inside the grain in Cu line due to the electromigration(EM) by *in-situ* nondestructive micrograin imaging with a scanning μ-RHEED microscope. The triple point of grain boundaries was confirmed to weaken the EM endurance from the *in-situ* nondestructive micrograin observation. Furthermore, we conjectured that the high EM endurance inside the grain was able to be achieved with current flow along [011] direction for Cu. Consequently, high reliable interconnects should be single crystal or at least bamboo structure to eliminate the triple point of grain boundaries and the current should be flowed along [011] direction in f.c.c. metal such as Cu and Al.

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