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Effect of the crystallinity on the grain boundary diffusion of copper atoms in electroplated copper thin-film interconnections

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Abstract

In order to clarify dominant factors of EM (Electromigration) degradation of electroplated copper thin-film interconnections, the change of the surface morphology of the electroplated copper thin-film interconnections before and after the EM test was observed by using SPM (Scanning Probe Microscopy), and the crystallinity of grain boundaries in the interconnection was evaluated by applying an EBSD (Electron Back-Scatter Diffraction) method. It was found that the main diffusion paths under EM loading was the grain boundaries with low crystallinity regardless of the crystallographic orientation.

1. Introduction

In order to improve the performance and to reduce power consumption of electronic products, the size of semiconductor devices has been miniaturized, and consequently, the minimum width of interconnections in integrated circuits has been reduced to less than 100 nm. The size reduction of interconnections should increase their resistance, and thus, degrades the performance of the devices due to the increase in signal delay and Joule heating. In addition, failure of the interconnection caused by electromigation (EM) becomes a more serious issue for its reliability because the operating current density is increasing due to the decrease of the cross-sectional area of the interconnection. Therefore, electroplated copper thin-films have been applied to interconnections because copper has higher electrical and thermal conductivities and EM resistance. However, since the electroplated copper thin films tend to have porous grain boundaries due to the large mismatch in the lattice constant between copper and seed layer materials for electroplating, the degradation of their crystallinity is accelerated by grain boundary diffusion under EM loading[1]. Therefore, it is necessary to suppress the grain boundary diffusion for improving the EM resistance and thus, the long-term reliability of the interconnections.

In this study, the crystallinity of grain boundary and atomic diffusion were investigated experimentally. The quality of the electroplated copper thin film interconnection was degraded by EM test. The change of microtexture around grain boundaries during the EM test was observed by SPM. In addition, the change of the crystallinity of the copper thin film was evaluated before and after the EM test using the IQ (Image Quality) value obtained by EBSD method. Considering the relationship between the change of microtexture and IQ value, the dominant factor for controlling the grain boundary diffusion was investigated in detail from the view point of the order of atom arrangement in the interconnection.

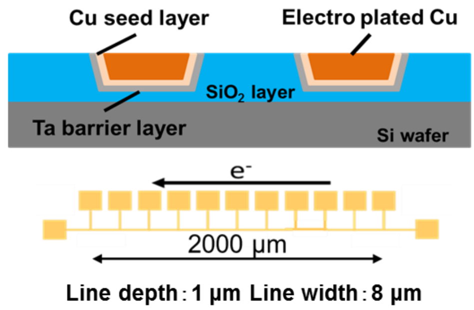

Fig. 1 Schematic image of the electroplated copper thin film interconnection

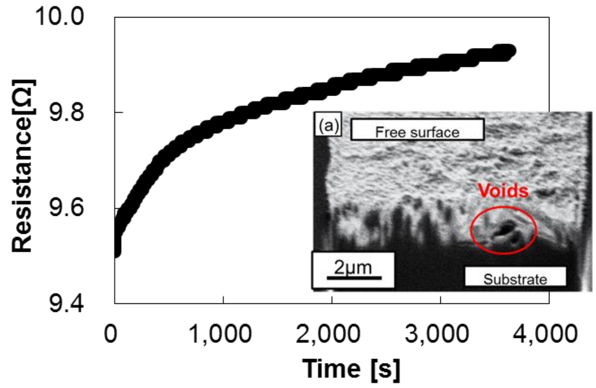

Fig. 2 Change of the electrical resistance of the interconnection during the EM test and SIM image of the cross-section surface of the interconnection after the EM test

2. Sample preparation and EM test

Fig. 1 shows a schematic structure of the test sample. The test thin-film interconnection was made by conventional damascene process. In this test sample, there were 2 electrode pads at both ends for loading current, and 11 pads were located every 200 μm for deciding the position of the observation by the SPM and the evaluation by the EBSD method. In this study, the surface of the interconnection was free surface, without the passivation, to be evaluated by EBSD method and the SPM. Thus, the surface diffusion of the interconnections should be accelerated comparing with that of the interconnections covered by passivation films.

The EM test was performed under the current density of 7 MA/cm^2 for an hour in atmosphere. The stage temperature was fixed at 30°C. Fig. 2 shows the change of the electrical resistance of the interconnection during the EM test. This figure indicates that the resistance increased monotonically with time due to EM. The cross-sectional surface of the interconnection after the EM test is also shown in Fig. 2. The local elevation of the surface and interval voids were observed. The increase in the resistance was attributed in the increase in the concentration of voids in the interconnection. The change of the surface morphology of the interconnection occurred due to the local accelerated diffusion and accumulation of copper atoms caused by EM.

3. Effect of the crystallinity on the grain boundary diffusion

Figs. 3(a) and 3(b) show SPM images of interconnection before and after the EM test, respectively. After the EM test, the surface morphology changed drastically, and the white lines were observed along the grain boundaries. Fig. 3(c) shows the distribution of the characteristics of grain boundaries; red lines show random grain boundaries and blue lines show CSL (Coincident Site Lattice) grain boundaries. Although both grain boundaries existed randomly in the interconnection, the distribution of random grain boundaries agreed very well with white lines observed on the SPM image after the EM test shown in Fig. 3(b). Fig. 4 shows the distribution of the detailed surface morphology before and after the EM test on the line AB shown in Fig. 3(a). This diagram shows that the surface roughness of the interconnection increased clearly after the EM test. In addition, it was confirmed that white lines appeared on the surface of the interconnection after the EM test corresponded to the area at which the surface rose, in other words, copper atoms diffused into this area and accumulated.

Next, local distribution of the IQ value was analyzed in the areas C and D shown in Fig. 3(b). The IQ value is the average intensity of the Kikuchi lines observed in the EBSD analysis, and thus, the quality of atom arrangement in the observed area is quantitatively evaluated by the IQ value. Fig. 5 shows the distribution of the IQ value before the EM test and the surface morphology after the EM test. In the area C, there were two types of random grain boundaries, one is random grain boundary with low IQ value (under 3000) and the other is that with relatively high IQ value (higher than 4000). Fig. 5(a) clearly indicates that the local elevation of the surface occurred on the area of grain boundaries with low IQ value. On the other hand, the IQ values of CSL grain boundaries in the area D were relatively low (under 3000), and it was confirmed that the local diffusion along these CSL were accelerated and thus, the local elevation of the surface was observed on this area. From these results, it was indicated that the grain boundary diffusion was accelerated along grain boundaries with low IQ value, in other words, grain boundaries with low crystallinity. However, the crystallinity is weak relationship with the crystallographic orientation of grain boundaries. The long-term reliability of interconnections, therefore, should be dominated by the concentration of the grain boundaries with low crystallinity.

4. Conclusions

The surface morphology was roughened locally and drastically due to the accelerated diffusion of copper atoms along both random and CSL grain boundaries with low crystallinity. It was concluded that the main atomic diffusion paths were grain boundaries with low crystallinity.

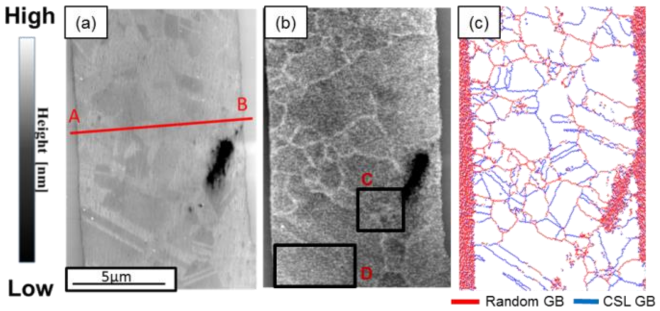

Fig. 3 Change of microtexture of the interconnection: (a) before the EM test, (b) after the EM test and (c) distribution of grain boundaries

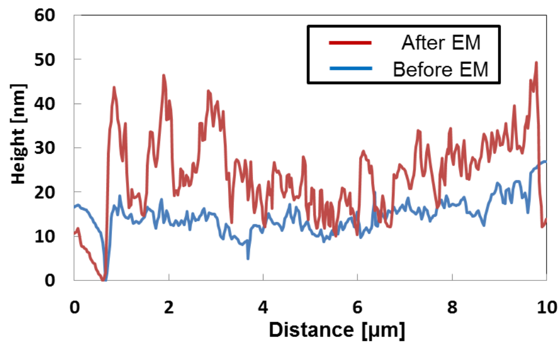

Fig. 4 Surface morphology of (a) before and (b) after the EM test on the line AB shown in Fig. 3(a)

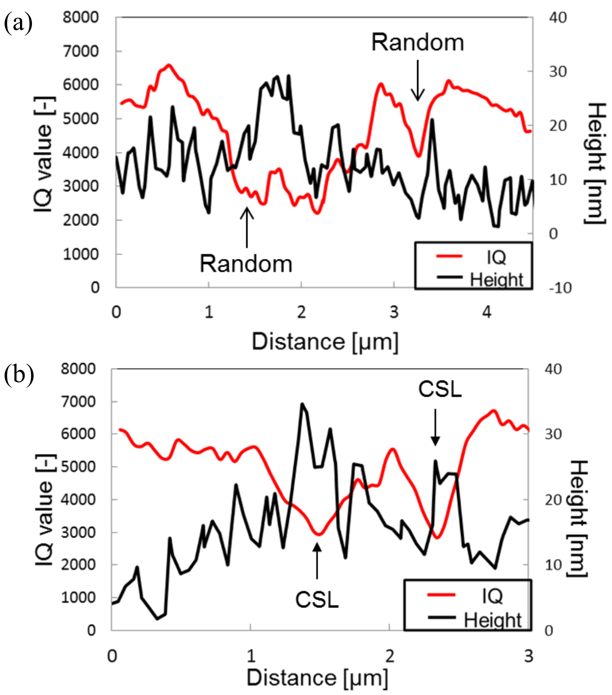

Fig. 5 Distributions of IQ value and and surface morphology (a) in the area C and (b) area D shown in Fig. 3(b)

References

[1] T. Kato, K. Suzuki and H. Miura, ASME2016 International Mechanical Engineering Congress and Exposition IMECE2016, Proceedings, IMECE2016-67619, pp.1-6.