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Evaluation of the Grain and Grain Boundary Strength in Copper Interconnections Based on the Order of Atom Arrangement

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Abstract

In order to clarify the effect of microstructure of copper interconnections on their strength, electron back-scatter diffraction (EBSD) analysis and micro tensile test system were applied in this study. The image quality (IQ) value obtained from EBSD was used for the evaluation of the crystallinity (defect density) of a grain or grain boundary. It was found that there was a strong crystallinity dependence of the strength of a copper grain in electroplated copper thin films.

1. Introduction

Semiconductor devices have been dramatically improved in information processing speed by the miniaturization of transistors and improvement of the integration density. A three-dimensional integrated circuit is an integrated circuit manufactured by stacking silicon wafers or dies and interconnecting them vertically using Through-Silicon Vias (TSVs). Copper has been used for the interconnection in the TSV structure because of its low electrical resistivity and high thermal conductivity. However, electrical and mechanical properties of electroplated copper thin film interconnections have been found to vary drastically depending on their microtexture, resulting that it is getting harder to guarantee the long-term reliability of products. The reason for this variation of physical properties is that the electroplated copper thin films mainly consist of fine columnar grains and the high volume ratio of porous grain boundaries. Actually, it was found that EM (electromigration) tends to occur along the grain boundaries in the interconnection material [1], and thus, the lifetime of the interconnection components is strongly dominated by the strength of grain boundaries. Therefore, it is necessary to quantitatively evaluate the grain and grain boundary strength of electroplated copper interconnections for estimating the lifetime of the interconnection in order to assure the product reliability. In this study, grain and grain boundary quality in terms of order of atomic arrangement was evaluated by using the analysis parameter IQ (Image Quality) value obtained from electron back-scatter diffraction (EBSD) method, and relationship between the strength and quality of electroplated copper thin films was investigated experimentally by applying micro tensile test.

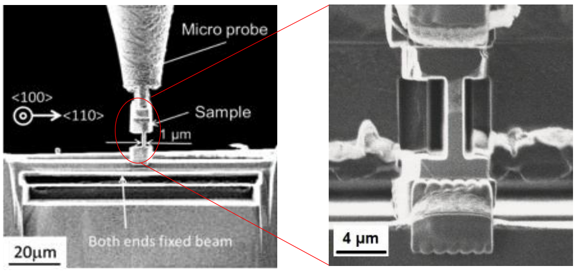

Fig.1 Micro tensile test system

2. Evaluation method of the grain and grain boundary strength based on the order of atom arrangement

EBSD analysis is a microstructural-crystallographic characterization technique to determine the local crystallographic orientation of grains and quality of grains and grain boundaries based on the order of atom arrangement. The crystallographic quality of grains and grain boundaries of polycrystalline copper thin films was analyzed by using the IQ value. The IQ value is the average sharpness of the Kikuchi lines in the EBSD observation area, and the intensity of each Kikuchi line strongly correlates with the order of atomic configuration. Therefore, it was assumed that the area with high IQ value was the area with high crystallinity. The grain and grain boundary strength was evaluated quantitatively by applying micro tensile test using FIB (Focused Ion Beam) technologies [2]. The scanning ion microscope (SIM) image of the micro tensile test is shown in Fig. 1. The sample was fixed rigidly to a silicon beam and a micro probe respectively as shown in Fig. 1. The micro probe was pulled up by uniaxial actuator and the deformation of the silicon beam was observed by SIM in real-time until the sample was fractured. The load applied to the sample was calculated by the observed deformation of the beam. In this study, the spatial resolution of the observation was 72 nm. By using these new characterizing methods of materials, it is possible to clarify the relationship between the crystallinity of a grain and a grain boundary and their strength.

3. Crystallinity-induced variation of the strength of a grain

In this study, two types of copper specimens: single crystal and bicrystal specimens, were used. The single crystal specimens were extracted from a single crystal copper sheet with (110) orientation of the surface. The bicrystal specimen which had two grains with different crystallographic orientation was cut off from a polycrystalline copper thin film electroplated at 10 mA/cm^2. Figure 2 shows examples of IPF (inverse pole figure) and IQ map of the bicrystal specimens. The grain boundary in the bicrystal specimen was roughly normal to the applied tensile stress.

Figures 3 shows the measured stress-strain curves of single-crystalline copper specimens and SIM images at fracture of the specimen with IQ value of 5700 is also shown in this figure. The ductile fracture occurred in one grain and the strength of single-crystalline copper decreased with the increase of its IQ value. The reason for this decrease is attributed to the decrease in the density of various defects with the increase of IQ value. Similar phenomenon was observed in the bicrystal specimens as shown in Fig. 4 and no brittle fracture appeared at any grain boundaries in the specimens, indicating that the cleavage strength of a grain boundary was larger than that the critical resolved shear stress (CRSS) of grains. Since the brittle fracture occurs by cleavage of crystallographic planes with low bonding, the grain boundary strength is strongly depend on the density of crystallographic defects, and thus the crystallinity of a grain boundary. The average IQ values of grain boundaries in the bicrystal specimens was more than 4000 while the maximum IQ value when the brittle fracture occurs at a grain boundary was about 3500 in previous study [3]. This result implied that the density of defects around a grain boundary was not so high that the cleavage of the grain boundary occurred.

In the micro tensile test, most of the fractures occurred in a grain with higher Schmidt factor, and thus CRSS was calculated for all samples. CRSS is the value of resolved shear stress at which yielding of the grain started to occur, marking the onset of plastic deformation. The CRSS-IQ relationship is summarized in Fig. 5. The CRSS decreased drastically from about 210 MPa to 40 MPa with the increase of IQ value from 3900 to 9000. This decrease was due to the decrease in the defect density in a grain. Similar tendency was confirmed in the single-crystalline copper. All the plots existed on the same relationship between the IQ value and CRSS as shown in this figure. Their strength saturated when the IQ value exceeded about 5500. Therefore, it was concluded that the properties of a copper grain is strongly dominated by the crystallinity of the grain which was quantitatively determined by the IQ value obtained from EBSD analysis, and the crucial IQ value was 5500 in this study. The yielding stress varied by about five times when the IQ value of a copper grain varied from 3900 to 5500. This is due to the change of the density of defects such as vacancies, dislocations, local strain, and so on in the grain. Therefore, it is very important to control the crystallinity of copper thin films for assuring the high reliability of interconnections in advanced semiconductor devices.

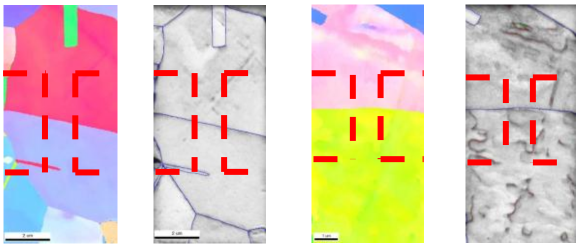

Fig. 2 IPF and IQ maps of bicrystal specimens

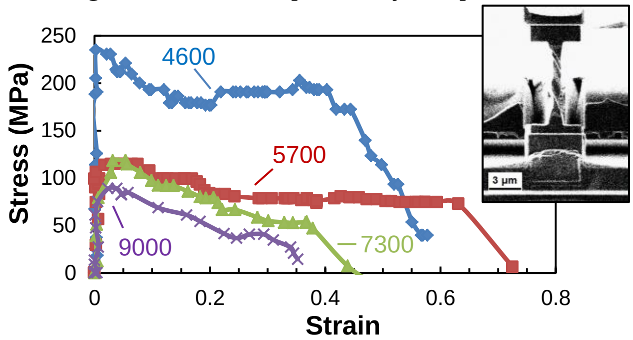

Fig. 3 Stress-strain curves of single-crystalline specimens

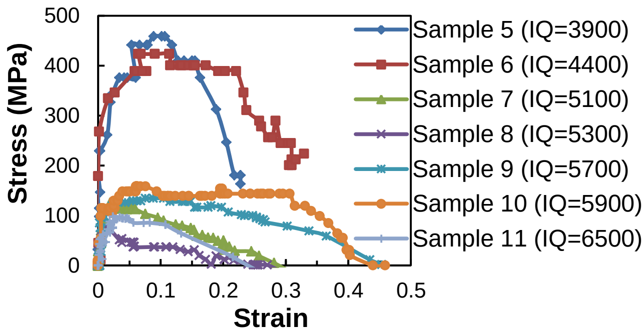

Fig. 4 Stress-strain curves of bicrystal specimens

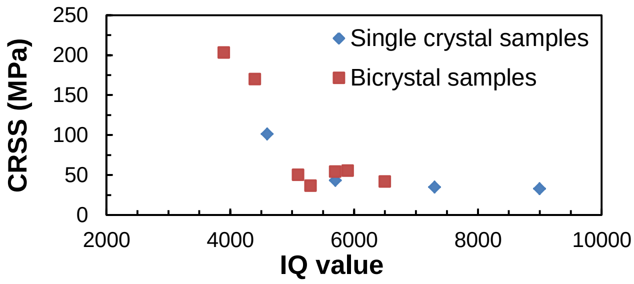

Fig. 5 Crystallinity dependence of CRSS of a copper grain

4. Conclusions

The yielding stress of a copper grain varied by about five times as a strong function of IQ value. It is very important, therefore to control the crystallinity of copper interconnections used for highly-reliable electronic devices.

Reference

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