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Improvement of Crystallographic Quality of Electroplated Copper Thin-Film Interconnections for 3D TSVs

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1. Introduction

Both electrical and mechanical properties of the electroplated copper thin films, such as resistivity, Young's modulus and the tensile strength, were found to vary drastically comparing with those of the conventional bulk copper. [1] The reason for the variation of these physical properties was that the electroplated copper thin films mainly consisted of fine columnar grains with porous grain boundaries that were easily etched off by ion beams. [2] Brittleness and high electrical resistivity often appears in the electroplated copper films. These variation and fluctuation of the mechanical and electrical properties of the electroplated copper thin films should degrade the reliability of electronic devices seriously. From this point of view, it is necessary to clarify the effect of their micro-texture on their mechanical and electrical properties and to establish a method for controlling their mechanical and electrical properties in order to assure the reliability of electronic products. In this study, both the electrical and mechanical properties of the electroplated copper films were investigated experimentally considering the change of their micro texture. The change of the crystallinity of the polycrystalline copper thin-film interconnections was observed by using an EBSD (Electron Back-Scattering Diffraction) method. Finally, it was found that base material before electroplating dominates the quality of the electroplated copper thin films.

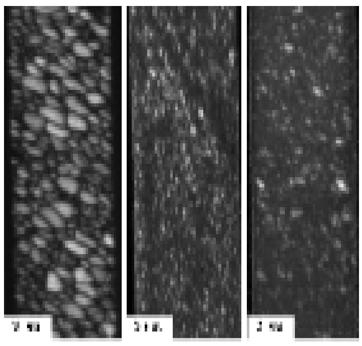
2. Evaluation method of the crystallinity of thin-film interconnections

A novel evaluation method of the crystallinity of grain boundaries was proposed by analyzing the quality of Kikuchi lines obtained from the conventional EBSD analysis. This method can evaluate the porous and brittle grain boundaries by IQ (Image Quality) and CI (Confidence Index). Both IQ and CI values are the parameters that are calculated from the observed result of the Kikuchi pattern obtained from the area where electron beams penetrate during EBSD analysis. The diameter of an electron beam determines the spatial resolution of the IQ and CI values. The IQ value indicates the crystallinity of the measured area. It is average intensity of Kikuchi lines obtained from the measured area during EBSD analysis. The CI value indicates the position of a grain boundary in the measured are. The CI value varies from 0 to 1. When the crystallinity of the two grains is close, this CI value becomes almost 0. On the other hand, the CI value is 1, when the measured are consists of one grain. Thus, the position of the grain boundaries is determined by this CI value, and the crystallinity of the film around the grain boundaries is evaluated by the IQ value quantitatively. In this study, the diameter of an electron beam was fixed at 50 nm, and it was scanned two-dimensionally on the surface of each interconnection.

3. Variation of the crystallinity of thin-film interconnections

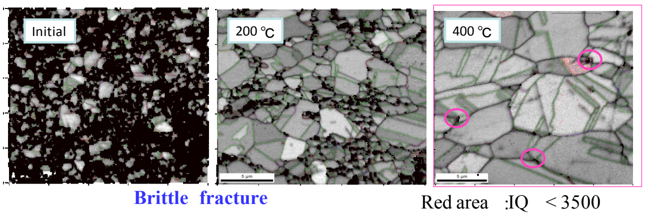
Figure 1 shows the change of the distribution of the IQ values on the surface of electroplated copper thin-film interconnections as a function of the current density during electroplating. In this example, 1.5-mm thick SiO2 layer was deposited on a Si wafer by Plasma-CVD first. Next, the SiO2 layer was locally etched off to make thin trenches whose depth was 1.0 mm. Thin tantalum and copper layers were deposited by sputtering. It is clear that the crystallinity of the electroplated copper thin film was improved by decreasing the current density. The average grain size of the film electroplated at 10 mA/cm2 was much larger than that at 50 mA/cm2. In addition, the IQ value of the film electroplated at 10 mA/cm2 was much higher than that at 50 mA/cm2. Thus, it was confirmed that the current density during electroplating is one of the dominant factors that determine the crystallinity of the electroplated films.

Figure 2 shows the change of the color map in the typical measured area of the films as a function of annealing temperature. The area painted by red indicates the area with



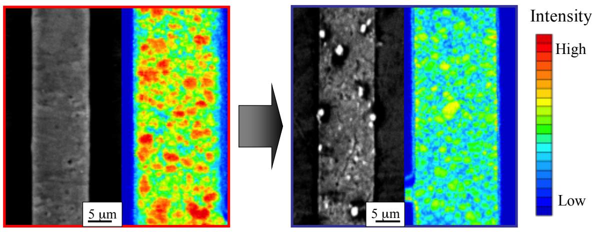
(a) 10 mA/cm^2 (b) 30 mA/cm^2 (c) 50 mA/cm^2

Fig. 1 Change of distribution of IQ value depending on the current density during electroplating.



(a) As-electroplated (b) Annealed at 200ºC (c) Annealed at 400ºC

Fig. 2 Change of the crystallinity of the electroplated copper thin films evaluated by the combination of the IQ and CI values (Red areas indicate the grain boundaries with low crystallinity.)



(a) Just after the annealing (b) 3 months after the annealing

Fig. 3 Change of the crystallinity of the electroplated copper thin film interconnections evaluated by the combination of the IQ and CI values

low CI value and low IQ value and this area consists of the grain boundaries with low crystallinity. There are a lot of red areas in grains and along grain boundaries in the as-electroplated film (Fig. 2 (a)). This result indicates that the film consisted of both grain and grain boundaries with low crystallinity. When the film was annealed at 200ºC, the number of the grain boundaries colored by red decreased drastically as shown in Fig.2 (b). However, there still remained the continuous porous grain boundary network in this film. The most red areas disappeared after the annealing at 400ºC as shown in Fig. 2(c). Black marked areas, in other words, high quality grain boundaries existed along both high angle grain boundaries and CSL Σ3 grain boundaries. Therefore, it can be concluded that the crystallinity of grain boundaries was improved significantly by annealing at 400ºC.

However, the crystallinity of the film was degraded again due to the stress-induced migration as shown in Fig. 3. The formation of many hillocks on the surface of the film indicates that a lot of vacancies remained in the film. Since the local fusion occurred in this degraded film, the vacancies should have segregated around grain boundaries where the diffusion of copper atoms was accelerated by the stress-induced migration. Therefore, it was concluded that the crystallinity of the grain boundaries of the electroplated copper thin films varies the reliability of the film. It is very important, therefore, to improve the quality of their crystallinity in order to assure the reliability of products.

4. Improvement of the Crystallinity of the Electroplated Copper Thin Films

The reason for the low crystallinity of the electroplated copper thin-film interconnections was attributed to the low

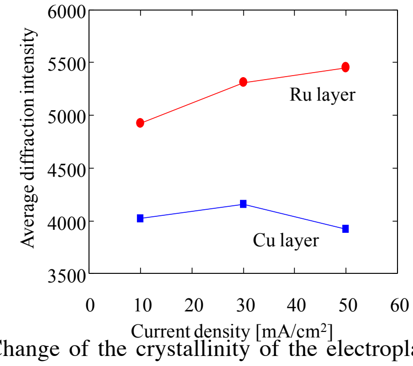


Fig. 4 Change of the crystallinity of the electroplated copper interconnections as functions of base material and current density during electroplating

quality of the base copper film deposited on the tantalum (Ta) layer which was used for the diffusion barrier of copper (Cu) into silicon dioxide and silicon. The low crystallinity was considered to be caused by large mismatch in the lattice constant between Cu and Ta. The mismatch was about 18%. Thus, a new material, ruthenium (Ru), was introduced between the Ta layer and the electroplated copper layer. The mismatch between Ta and Ru was about 8%, and that between Cu and Ru was about 6%. This low mismatch among the three-stacked layers should improve the quality of atomic configuration in each layer.

Figure 4 summarizes the change of the crystallinity of the electroplated copper interconnections as functions of base material and current density during electroplating. It was found that the average IQ value of the films grown on the Ru layer was about 30% higher than that on the Cu layer regardless of the current density during electroplating. This result clearly indicates that the crystallographic quality of the base material for electroplating dominates the crystallinity of the electroplated copper thin films. In addition, the improvement of the crystallinity decreased the electrical resistivity of the electroplated films. This improvement of the crystallinity also improved the lifetime of the interconnection during the electromigration test.

3. Conclusions

It was confirmed that the crystallinity of the electroplated films changed drastically depending on the conditions of electroplating, and Ru is one of the effective base material for improving the crystallinity of the films.

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