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Dominant Factors of Stress-Induced Migration in Electroplated Copper Thin Films Used for Through Silicon Via (TSV) Interconnections

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1. Introduction

Three-dimensional (3D) integration of microelectronic devices using TSVs (Through Silicon Vias) is indispensable for improving the electronic functions and packaging density. Electroplated copper thin films have been applied to the TSV structure because of low electric resistivity and high thermal conductivity of copper. However, both electrical and mechanical properties of electroplated copper thin films are often inferior to those of bulk copper. This is because that micro texture of electroplated copper thin films varies markedly depending on electroplating conditions and thermal hysteresis after the electroplating. As a solution of this problem, annealing at high temperature is necessary for improving the crystallographic quality of electroplated copper thin films. The electroplated copper thin film which consists of fine grains with porous gain boundaries intends to shrink by the annealing because the densification due to recrystallization occurs during the annealing. However, the volumetric shrinkage of the electroplated copper thin film in TSVs is constrained by rigid Si substrate and therefore, high tensile residual stress exists in the film. This means that not only thermal stress caused by cooling process after annealing but also the intrinsic stress caused by the constraint of the shrinkage of the annealed film coexist in the TSV structure after the annealing. The amplitude of the residual stress often exceeds the yielding stress. Once the residual stress in the films exceeds their yielding stress, stress-induced migration occurs in the annealed films and thus, degrade the long-term reliability of the annealed films. It is necessary, therefore, to minimize the residual stress of electroplated copper thin films used in the TSV structure for assuring the stable operation of devices.

In this study, the dominant factors of the stress-induced migration in the TSV interconnections was analyzed by considering the change of intrinsic stress of the electroplated copper thin films due to the change of their micro texture on annealing. .In addition, since micro texture change causes the drastic change of the material properties, the change of mechanical properties of the annealed film was investigated quantitatively by comparing the FEM (Finite element method) analysis with the measurement of the change of the residual stress in the films during heat cycles.

2. Measurement of residual stress of electroplated copper thin films during thermal cycling

Self-made electroplated copper thin films were used for the measurement of residual stress during thermal cycling. A thin Ta layer (50 nm) as a barrier layer and a Cu layer (150 nm) as a seed layer were continuously deposited onto a Si wafer by PVD (Physical Vapor Deposition). Subsequently, copper thin films were electroplated on the Si substrate under the constant current density of 50 mA/cm^2 at 30^{o}C. The thickness of the electroplated copper films was 5 μm. The composition of the plating bath was controlled by diluting 80 g of CuO powder and 186 g of H_2SO_4 into 1000 ml of purified water.

The specimens were subjected to temperature cycles between room temperature and 200 or 400^{o}C. The residual stress in the electroplated copper thin film was determined based on the elastic deformation of a substrate after deposition and temperature cycles. The change of the wafer warpage during temperature cycles was measured by a laser displacement meter. Assuming that the residual stress in the deposited or annealed film is uniform, the residual stress in the film was calculated by the measured change of the radius of the substrate.

Figure 1 shows stress-temperature curves of the electroplated copper thin film. The residual stress in as-electroplated copper thin films was tensile. During heating to 75^{o}C, the stress decreased linearly with temperature and changed to compressive one. After having maximum compressive stress at 100^{o}C, the compressive stress decreased with increase in temperature to 200^{o}C. On further heating to 400^{o}C, the stress changed to tensile around 300^{o}C. During the cooling down from 200 and 400^{o}C, the stress increased monotonically and finally, the residual stresses in the annealed films at room temperature were higher than those in the as-electroplated films.

The cross sectional micro textures of the films are shown in Fig. 2. Compared with the as-electroplated film, grain

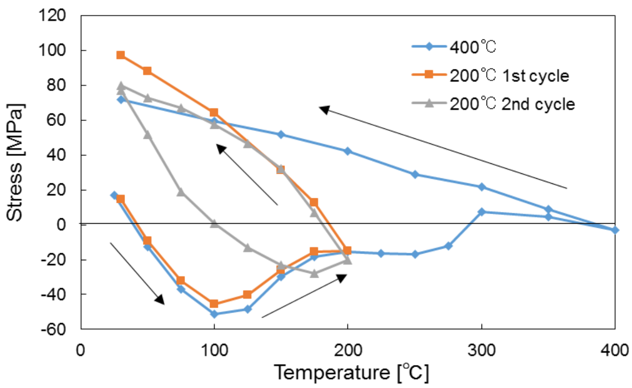

Fig. 1 Change of residual stress in electroplated copper thin films during thermal cycling

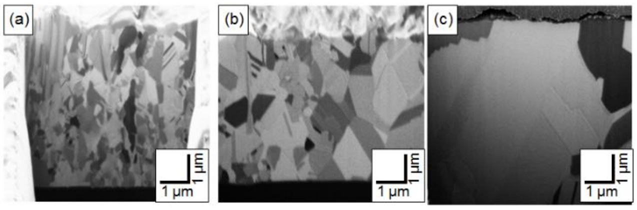

Fig. 2 SIM (Scanning Ion Microscope) photographs of the cross section of electroplated copper thin films, (a) as-electroplated, (b) annealed at 200°C and (c) annealed at 400°C

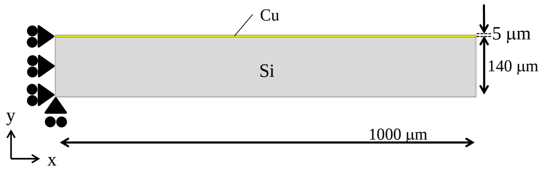

Fig. 3 The model for finite element analysis

coarsening by recrystallization is found in both annealed films and the average grain size increases with increasing annealing temperature. As was described before, when the shrinkage of the films due to recrystallization is constrained by their surrounding structures, high tensile stress remains in the films after annealing. The result of the decrease in the compressive stress from 100°C to 200°C on heating process, as shown in Fig. 1, suggests that the grain coarsening by recrystallization started to occur at temperatures around 100°C. As a result, the residual stress in the electroplated copper thin film increases after annealing.

3. Estimation of Young's modulus of the annealed films

As shown in Fig.1, the slope of stress-temperature curves on the cooling step were different between annealing at 200°C and 400°C. The slope values obtained from the stress-temperature curves were 0.6 MPa/°C at 200°C and 0.2 MPa/°C at 400°C. This result indicates that materials properties of the films after annealing at 200°C and 400°C were different. Assuming that the coefficient of thermal expansion of each annealed film is constant, Young's modulus of the annealed films should be different. Thus, the Young's modulus of the annealed films was estimated by applying a FEM analysis. Figure 3 shows a finite element model for the stress analysis. The Young's modulus of copper was varied from 15 to 130 GPa and the residual stress in the copper film at thermal load of -170°C was evaluated. The change rates of residual stress of the copper films having Young's modulus of 15 GPa and 30 GPa were evaluated to be 0.2 MPa/°C and 0.6 MPa/°C, respectively. From this analysis, the Young's modulus of the electroplated copper thin films was found to vary depending on annealing temperature and thus their micro texture.

4. Stress-induced migration in the annealed films

The change of the surface morphology of the annealed interconnections was investigated as a function of annealing temperature. After the annealing at 400°C, voids and hillocks caused by stress-induced migration appeared on the surface of the interconnection, as shown in Fig. 4(c). The stress

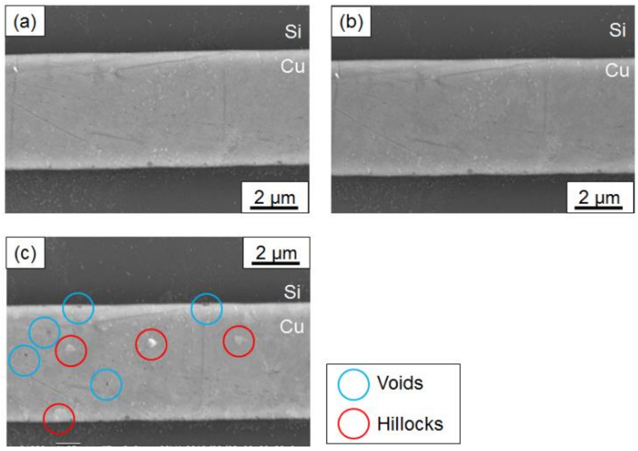

Fig. 4 The change of the surface morphology of the annealed films; (a) as-electroplated, (b) annealed at 200°C, (c) annealed at 400°C

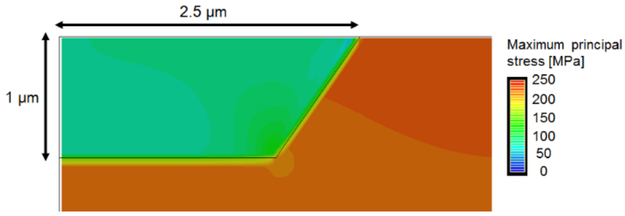

Fig. 5 Stress distribution of cross-sectional view of the interconnection by using FEM analysis (Young's modulus of copper: 15 GPa)

distribution in the interconnection structure was analyzed by using a FEM. Figure 5 shows the distribution of the residual stress in the interconnection structure when Young's modulus of copper was 15 GPa. High residual stress of about 90 MPa was found to occur at the surface of the interconnection. Since this residual stress in the interconnection was higher than the yield stress of about 80 MPa in the films annealed at 400°C [1], the stress-induced migration was expected to occur in the interconnection after the annealing at 400°C. On the other hand, the residual stress at the surface of the interconnection with Young's modulus of 30 GPa was 110 MPa, which was lower than the yield stress of about 150 MPa in the films annealed at 200°C. Therefore, no stress-induced migration was found in the interconnection after the annealing at 200°C, as shown in Fig. 4(b). From these results, the change of the Young's modulus and yield stress of electroplated copper thin films due to the recrystallization during the heat treatment is one of the dominant factors for controlling the stress-induced migration.

5. Conclusions

Considering the change of material properties of electroplated copper thin films during the heat treatment is indispensable for evaluating the stress-strain field in the TSV structures quantitatively, and thus, assuring the long-term reliability of future advanced 3D electronic modules.

Reference

[1] N. Murata, N. Saito, K. Tamakawa, K. Suzuki, and H. Miura: Proc. of ASME InterPACK2011, No IPACK2011-52048, (2011).