Stress-induced Migration of Electroplated Copper Thin Film Interconnections Depending on Thermal History

Ken Suzuki and Hideo Miura
Fracture and Reliability Research Institute,
Graduate School of Engineering, Tohoku University
Sendai, Japan
kn@rift.mech.tohoku.ac.jp

Osamu Asai, Naoki Saito and Naokazu Murata
Department of Nanomechanics,
Graduate School of Engineering, Tohoku University
Sendai, Japan

Abstract— **Effect of the change of crystallinity and micro texture of electroplated copper thin films by annealing on the stress-induced migration was investigated experimentally and theoretically. The micro texture of electroplated copper thin films changed drastically as a function of their electroplating conditions and the annealing temperature after the electroplating. The crystallinity of the electroplated film was improved by annealing at 400°C for 3 hours. However, stress-induced migration was activated even though interconnection was kept at room temperature without any application of electrical current after annealing. This is because high residual stress was caused by shrinkage of electroplated copper due to change of crystallinity. Molecular dynamics simulations showed that copper atoms diffused significantly around the grain boundaries in the annealed film in which high residual tensile stress existed.**

Keywords-component; Reliability, Electroplated copper thin film interconnection, Stress-induced migration

I. INTRODUCTION

Electronic products such as mobile phones and PCs have been miniaturized continuously and their functions are improved drastically [1]. Electroplated copper thin films have started to be applied to not only interconnections in printed wiring boards, but also thin film interconnections and TSV (Through-Silicon Via) in semiconductor devices because of its low electrical resistivity and high thermal conductivity. However, it was reported that mechanical properties of electroplated copper thin films such as Young's modulus and tensile strength [2] were quite different from those of bulk copper. In some cases, super plastic deformation [3] occurred in electroplated copper thin films. In addition, the electrical resistivity of the films was found to vary significantly and the lifetime of some films under EM (Electro Migration) tests was incredibly shorter than that expected [4, 5]. The reason for these unexpected characteristics of electroplated copper thin films was explained by fine grains and the low crystallinity of their grain boundaries. Since these variations and fluctuation of physical characteristics of the films should degrade the reliability of electronic devices seriously, heat treatment of the films is necessary for improving their crystallinity after electroplating. However, it was also observed that high tensile residual stress occurred in the interconnections after annealing [6] and large voids grew in the interconnection by stress-induced migration of copper atoms. In this way, the crystallinity of the films degrades drastically by stress-induced migration and therefore, it is necessary to clarify the dominant factors of the stress-induced migration and to establish the design guideline for highly reliable copper interconnections in order to assure the long term reliability of electronic products. In this study, the effect of the change of crystallinity and micro texture of electroplated copper thin films by annealing on stress-induced migration was investigated experimentally and theoretically.

II. CHANGE OF MICRO TEXTURE BY ANNEALING AND STRESS MIGRATION CAUSED BY RESIDUAL TENSILE STRESS

A. Preparation of Electroplated Copper Thin Films

The dependence of the crystalliniy and micro texture of electroplated copper thin film interconnections on thermal history was investigated experimentally. Figure 1 shows schematic of the interconnection used in the investigation. This interconnection structure was made by using the popular damascene process. First, 1.5-μm thick SiO_2 layer was deposited on a Si wafer by Plasma-CVD. Next, the SiO_2 layer was locally etched off to make thin trenches whose depth was 1.0 μm. The width of the interconnection was 8 μm. Ta (50 nm) / Cu (150 nm) layer was deposited by sputtering. The trench was filled with copper by electroplating. Finally, the excess copper layer was mechanically-polished to make isolated interconnections. After the fabrication of the

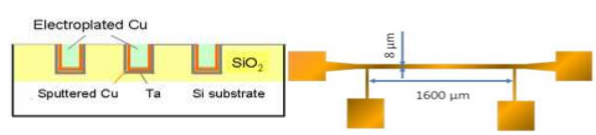

Figure 1. Example structure of the electroplated copper thin film interconnections

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interconnection, the interconnection was annealed at 400°C for 3 hour in Ar gas. Electrical resistivity (1.98×10^{-8} Ω·m) of the interconnection annealed at 400°C was superior to that (3.33×10^{-8} Ω·m) of the interconnection without annealing. Therefore, electrical resistivity was improved by the annealing because of coarsening of fine grains and improving the crystallinity.

B. Stress-induced migration in the annelaed interconnection

Figure 2 shows the change of the electrical resistance of each interconnection with applied current density of 7 MA/cm^2. Abrupt electrical open failure caused by local fusion was often observed in the as-electroplated (no annealing) interconnection within a few hours as shown in Figs. 2 and 3(a). On the other hand, the lifetime of the annealed interconnection became longer than that of the interconnection without annealing as shown in Fig. 2. However, the stress-induced migration occurred in the annealed interconnection as shown in Fig. 4. Hillocks appeared without current loading on the surface of the annealed interconnections 72 hours later at even room temperature after the annealing as shown in Fig. 4(b). The number of hillocks had increased continuously for about 3 months as shown in Fig. 4(c). This stress-induced migration was caused by high tensile residual stress which occurred in the film during cooling process after the annealing due to the constraint of the shrinkage of the films by rigid oxide around them. Thus, the residual stress of each film was measured after electroplating and annealing. The residual stress in thin films was determined based on the elastic deformation of a substrate after deposition and annealing of the thin films without patterning. Assuming that the residual stress in the deposited or annealed film was uniform, the residual stress in the film was calculated by the measured change of the radius of the substrate. Table 1 summarizes the measured results of the residual stress in each film. The residual stress of the as-electroplated films changed drastically depending on the current density during electroplating. The residual stress of the film electroplated at current density of 50 mA/cm^2 was much higher than that at current density of 10 mA/cm^2 and it was about 90 MPa. On the other hand, the residual stress in each film increased significantly after the annealing at 400°C, and it reached almost the same value of about 170 MPa. Therefore, after the annealing at 400°C, the tensile residual stress of about 170 MPa remained after the annealing at 400°C regardless of the current density during electroplating. These results clearly indicate that the control of residual stress is indispensable for improving the reliability of the electroplated copper thin film interconnections.

The change of the crystallinity of the electroplated copper thin film interconnections depending on thermal history was observed by using an EBSD (Electron Back Scatter Diffraction) method. This method can evaluate the crystallinity of both grain and grain boundaries by using IQ (Image Quality) value. The IQ value is average intensity of Kikuchi lines obtained from the measured area during EBSD analysis. Since the IQ value is high when the crystallinity of a measured area is high, the crystallinity of the film is evaluated

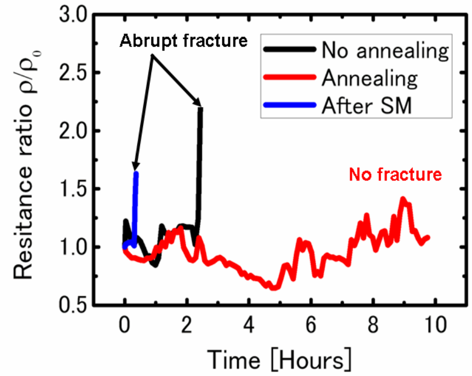

Figure 2. Examples changes of resistance of the thin film interconnections

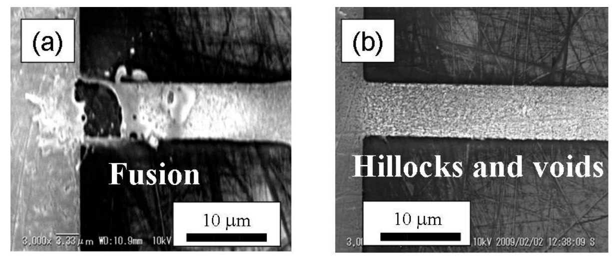

Figure 3. SEM photographs of the surface of the film after electro-migration test; (a) As-electroplated. (b) Annealed at 400°C

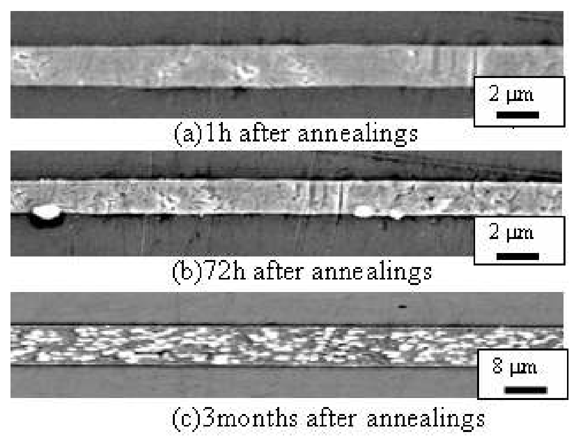

Figure 4. Change of the surface morphology of the annealed electroplated copper thin film interconnection caused by stress-induced migration

TABLE I. Current density dependence of the residual tensile stress of as-electroplated film and after the annealing

Current density [mA/cm^2]	Resideual tesile stress [MPa] As-deposited	400°C
50	90	170
10	5	161

by the measuring of IQ values. Figure 5 shows the change of the crystallinity of the electroplated copper thin film interconnections depending on thermal history. In this figure, blue area corresponds to the area with low IQ. Area color changes from blue to red with the increase of IQ value. It was clear that the crystallinity of interconnection was improved by annealing. The crystallinity of the interconnection with annealing (Average IQ value = 4095) was much higher than that of interconnection without annealing (Average IQ value = 1897). This result indicates that the there were a lot of fine grains and grain boundaries with low crystallinity in the as-electroplated interconnection. Therefore, abrupt fracture of the as-electroplated interconnection shown in Fig. 2 was caused by local Joule heating at grain boundaries with low crystallinity. On the other hand, most grain boundaries with low crystallinity disappeared and grain coarsening was caused by annealing. Therefore, local Joule heating at area with low crystallinity did not occur and the annealed interconnection showed long life time. However, the crystallinity of the annealed film was degraded again due to the stress-induced migration as shown in Fig. 5(c). This result and formation of many hillocks on the surface of the film shown in Fig. 4(c) indicate that a lot of vacancies remained in the film by stress-induced migration. Since the local fusion occurred in this degraded film as shown in Fig. 2, the vacancies should have segregated around grain boundaries where the diffusion of copper atoms was accelerated by the stress-induced migration.

III. Molecular Dynamics Simulations of Stress-Induced Migration in Annealed Copper Films

A. Analytical method

We found that the crystallinity of the electroplated copper thin films varies depending on thermal histroy. In order to investigate the effect of change of crystallinity by annealing on the stress-induced migration, molecular dynamics (MD) simulations were applied to investigate the diffusion behavior of copper atoms. Figure 6 shows the simulation models of fine grain structures of copper thin films without and with annealing at different temperatures. The structure of the annealed copper thin film models were prepared by the annealing calculation of the fine grain model at 673 K, 873 K and 1073 K for 1000 ps under fixed volume condition (no fluctuation of the lengths of the unit cell during the simulation). Lengths of the unit cell in x-, y- and z-axis were 400.4, 231.2 and 12.58 Å, respectively. These lengths were equilibrium values evaluated from MD simulation of bulk (single) copper crystal model where (111) planes parallel to xy plane at 300 K. The volumetric atomic density of the models was 95% of the density of bulk copper at 300 K to simulate the electroplated copper interconnections with porous grain boundaries. After the annealing calculation of the fine grain model, the grain size was found to be increased with increase of the annealing temperature as shown in Fig. 6. In order to investigate the stress-induced migration in the annealed film, MD simulations under the fixed volume condition at 300 K were carried out for 3000 ps. The embedded atom method (EAM) potential [7] of LAMMPS code was used for all simulations.

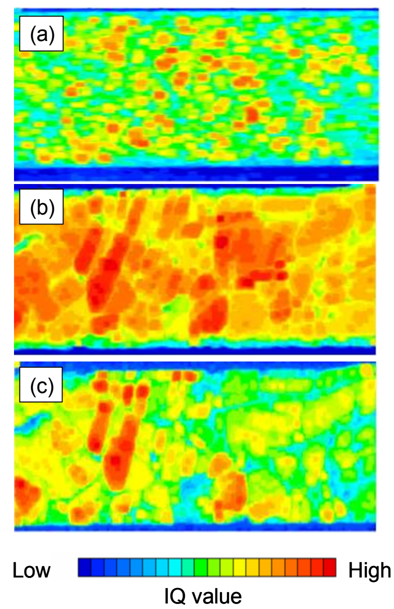

Figure 5. Change of the crystallinity of thin film interconnection: (a) without annealing, (b) annealed at 400°C and (c) three month after annealing

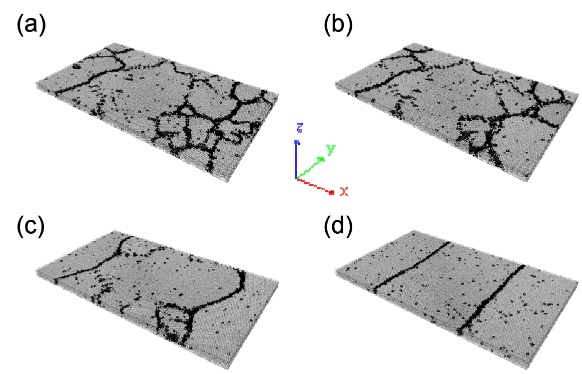

Figure 6. Simulation models of copper thin films, (a) without annealing, (b) annealed at 673 K, (c) annealed at 873 K and (d) annealed at 1073 K. Black color indicates the region of grain boudnaries.

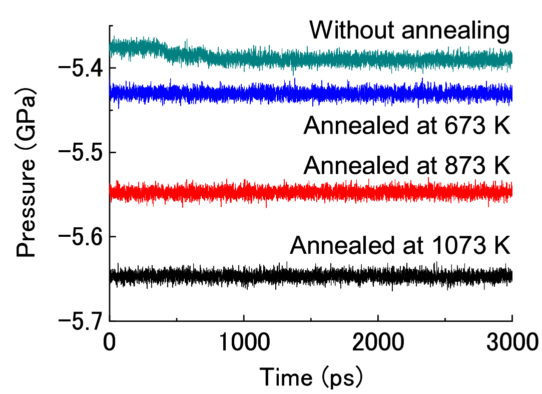

Figure 7. Change of pressures in the copper thin films without and with the annealing during the simulation at 300 K

B. Analytical results

Figure 7 shows change of pressures in the unit cells of annealed copper films during the simulation at 300 K. In this figure, tensile stress in the film has negative value of pressure. Magnitude of negative value of pressures increased with increase of grain size depending on annealing temperature. When the copper thin film was annealed, the copper film structure intended to shrink because of the atomic rearrangement in the film. However, the volumetric shrinkage of the copper film was constrained and therefore, high residual tensile stress occurred in the copper film after the annealing. Observed high residual stress caused by the constraint of shrinkage of the copper thin film is considered to be a dominant factor in the stress-induced migration of electroplated copper thin film interconnections because the actual electroplated copper interconnections are constrained by surrounded silicone dioxide used for isolation in the interconnection structure. Figure 8 shows the example of atomic displacement vectors in the annealed copper film during the simulation at 300 K. Copper atoms around the grain boundaries of the annealed films moved significantly even at 300 K. Figure 9 shows the mean square displacements (MSD) of copper atoms in the films annealed at different temperatures. The diffusion constants of copper atoms were defined by the slope of the MSD with time. The MSD value in the film annealed at 1073 K increased sharply compared to that in other films, indicating that the diffusivity of copper atoms was increased significantly in the annealed film in which high tensile residual stress existed. From these results, it was found that diffusion of copper atoms around grain boundaries was enhanced significantly even at room temperature by high tensile residual stress due to the change of crystallinity. This result suggests that the electroplated film is degraded without any application of electrical current after the annealing by the stress-induced migration. Thus, the electrical properties of the electroplated copper interconnections varied drastically depending on not only the electroplating condition, but also the thermal history after the electroplating.

IV. CONLUSION

In this study, the effect of change of crystallinity and micro texture of electroplated copper thin films by annealing on stress-induced migration was investigated experimentally and theoretically. It was found that the both average grain size and the crystallinity of grains and grain boundaries changed drastically by annealing. The electrical properties of the film were also improved by annealing. However, the diffusivity of cooper atoms was significantly increased around grain boundaries in the annealed film and consequently, large voids and hillocks grew during the custody of the film even at room temperature without any application of electrical current after the annealing. This is because high residual stress was induced by shrinkage of electroplated copper due to change of crystallinity. It is, therefore, very important to control the micro texture and the crystallinity of the electroplated copper thin film interconnections to assure the reliability of electronic products.

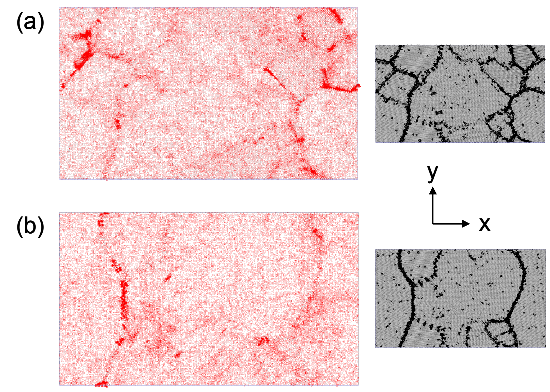

Figure 8. Displacement vectors (red color) of copper atoms in the annealed films during the simulation: (a) annealed at 673 K amd (b) annealed at 873 K

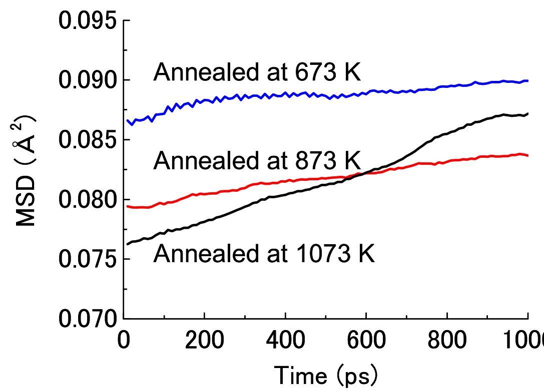

Figure 9. Mean square displacements (MSD) of copper atoms in the annealed copper films

REFERENCES

[1] International Technology Roadmap for Semiconductor 2009 (2009).

[2] K. Tamakawa, K. Sakutani, and H. Miura, "Effect of Micro Texture of Electroplated Copper Thin Films on Their Mechanical Properties", *Journal of The Society of Materials Science Japan*, vol. 56, No. 10, (2007.10), pp. 907-912. [in Japanese]

[3] L. Lu, M-L. Sui, and K. Lu, "Superplastic extensibility of nanocrystalline copper at room temperature", *Science,* vol. 287, (2000), pp. 1463-1466.

[4] C. T. Lin, and K. L. Lin, "Effects of current density and deposition time on electrical resistivity of electroplated Cu layers", *Journal of Materials Science; Materials in Electronics*, vol. 15, (2004), pp.757-762.

[5] A. V. Vairagar, S. G. Mhaisalkar, and Ahila Krishnamoorthy, " Electromigation behaviour of dual-damascene Cu interconnections-Structure, width, and length dependences", *Microelectronics Reliability*, vol. 44 (2004), pp. 747-754

[6] H. Lee, S. S. Wong, and S. D. Lopatin, "Correlation of stress and texture evolution during self- and thermal annealing of electroplated Cu films", *Journal of Applied Physics*, col.93 (2003), pp. 3796-3804

[7] S. M Foiles, I. Baskes and M. S. Daw, *Phys. Rev. B* 33, 7983-7991 (1986).