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Microstructural influences on stress migration in electroplated Cu metallization

A. Sekiguchi, J. Koike,[a] and K. Maruyama
Department of Materials Science, Tohoku University, Sendai 980-8579, Japan

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Stress migration in advanced Cu interconnects leads to device failure and to poor production throughput. In this work, microstructural effects on stress-migration resistance were investigated in two types of electroplated Cu metallization having a ⟨111⟩ texture and a random texture. Transmission electron microscopy showed incoherent twins in the ⟨111⟩ textured films whereas coherent twins in the random textured films. The incoherent twins were found to accompany stress-induced voids because of a weak bonding at twin interfaces. Unlike conventional Al interconnects, a strong ⟨111⟩ texture should be avoided to minimize stress-migration failure in Cu interconnects. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1609238]

Cu is an interconnect material to replace conventional Al alloys for fast-speed and high-density semiconductor devices. Under a current technology node of 130 nm or less, interconnect lines extend to several kilometers in total length and have been considered to be a major component to influence device reliability. One of the important reliability issues is void formation during thermal processing at elevated temperatures, which is induced by thermal stresses acting upon Cu interconnect.[1–5] Since the stress-induced voiding, or stress migration, leads to device failure and substantially reduces device throughput, detailed understanding of voiding mechanism is an urgent issue in the field of semiconductor reliability.

In Al interconnects, crystallographic texture was reported to influence stress-migration and electromigration resistance. A strong ⟨111⟩ texture has been recommended for better reliability because of specific natures of grain boundaries such as a small magnitude of tilt and twist angles.[6–9] In the case of Cu interconnects, earlier reports had followed the conventional knowledge of the Al interconnects on the relationship between texture and migration resistance. However, our recent report on stress-migration resistance in sputtered films of Cu indicated otherwise. Namely, the ⟨111⟩ textured films exhibit very poor stress-migration resistance in comparison with the ⟨100⟩ textured films.[10] We also found that microvoids are formed at twin interfaces in the ⟨111⟩ textured films because of concentrated stresses acting as a driving force for void formation.[11] Thus, the conventional knowledge on Al as a nontwin forming metal does not apply to Cu as a twin forming metal. The microstructural features and associated stress distribution play an essential role in stress migration failure.

In practice, advanced metallization technology utilizes an electroplating technique that produces a random textured film.[12–15] Detailed study on stress-migration resistance of the random textured films has not been reported in relation to the microstructure of the films. The present work is focused on this point with a special emphasis on twin interface structure and associated stress concentration. Comparison was made between two types of electroplated samples having a random texture and a strong ⟨111⟩ texture.

Two types of samples having different texture were prepared to compare the voiding tendency in relation to the texture-dependent microstructure. Cu thin films of 900 nm in thickness were deposited by electrolytic plating on different substrates of Ta (20 nm)/SiO_2 (1700 nm)/Si (300 μm) and TaN (25 nm)/SiO_2 (300 nm)/Si (300 μm). Numbers in the parentheses indicate the thickness of each layer. Though not shown here, x-ray diffraction analysis revealed that the Cu/Ta/SiO_2/Si exhibited only 111 peaks, indicating a strong ⟨111⟩ texture, while Cu/TaN/SiO_2/Si exhibited multiple peaks of 111, 200, and 220, indicating a random texture. These samples were subject to thermal cycling at a heating and a cooling rate of 3.3 K/min in a temperature range between room temperature and 723 K in vacuum of 5×10^{-3} Pa. Microstructural observation was carried out by transmission electron microscopy (TEM) in order to identify the voiding tendency in two samples.

Figures 1(a) and 1(b) show plan-view TEM images of the ⟨111⟩ textured film and the random textured film, respectively, after thermal cycling. Many twins are observed in both samples, but the voiding tendency is different. In Fig. 1(a), void formation is observed at some intersections and corners of twins indicated by arrows. In contrast, in Fig. 1(b), void formation is not observed. The same voiding tendency was confirmed by the observation of a larger area using a scanning electron microscope. These results suggest that voiding tendency is dependent on the film texture. It is also found that the twin interfaces accompany a fringe line contrast, indicating that the interface planes are tilted with respect to the film surface normal. The wider the fringed interfaces are, the larger the tilting angle is. The average tilting angle of the twin interfaces is 8° in the ⟨111⟩ textured film, while 20° in the random texture film. As will be shown later, the difference in the tilting angle is related to the difference in twin type.

For the observed twins and the matrices, distribution of thermal stress was calculated using a finite element method (FEM) code with consideration of actual crystallographic

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[a] Author to whom correspondence should be addressed; electronic mail: koikej@material.tohoku.ac.jp

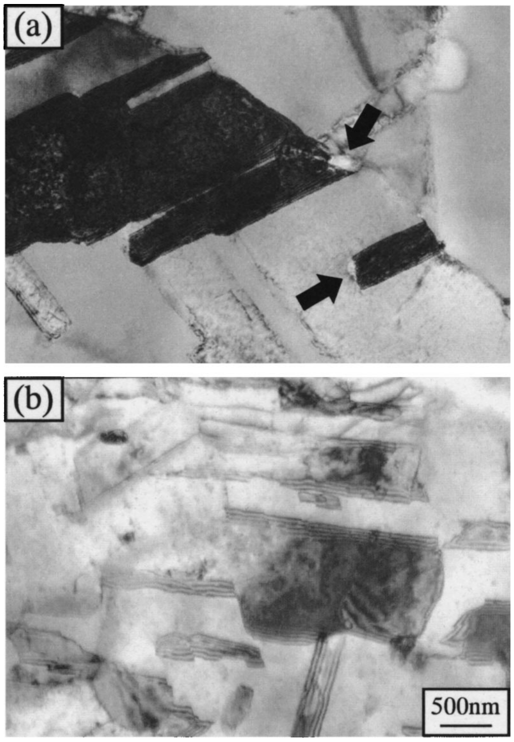

FIG. 1. Plan-view TEM images after thermal cycling, (a) Cu/Ta/SiO_2/Si having a ⟨111⟩ texture and (b) Cu/TaN/SiO_2/Si having a random texture.

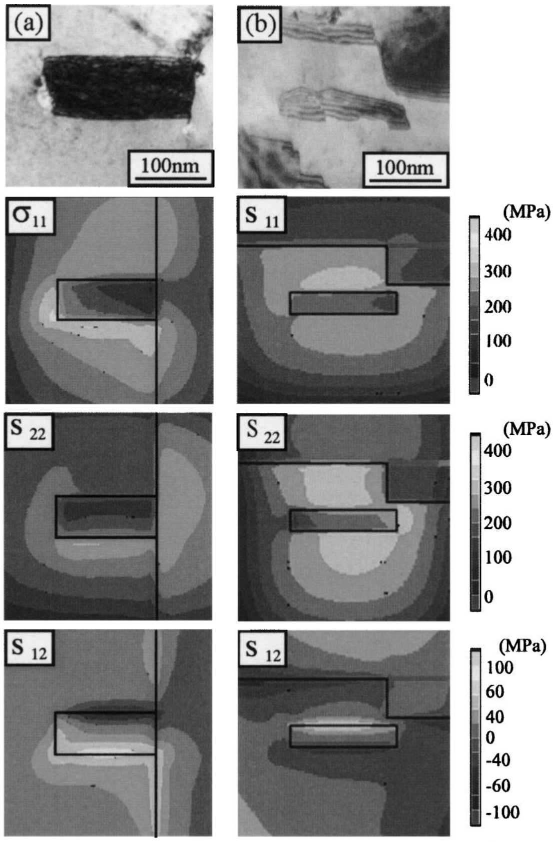

FIG. 2. Plan-view TEM images and corresponding stress distribution around (a) a twin with a void in the ⟨111⟩ textured film and (b) a twin without any voids in the random textured film.

orientations determined experimentally by analyzing Kikuchi diffraction patterns. Calculation was performed in three dimensions with a boundary condition of zero displacement at the Cu/substrate interface and with an ordinary boundary condition for Cu free surface. The difference in thermal expansion coefficients between Cu and Si was assigned to the Cu layer. Tensile thermal stress was imposed on the Cu layer by decreasing temperature by 100 K from the zero stress state.

Figure 2 shows portions of TEM images and corresponding stress distribution near twins of both samples. Shear and tensile stress components of σ_{11}, σ_{22}, and σ_{12} are shown as representative cases of all stress tensor components in a planar cross section at the middle position of the film thickness. In order to demonstrate accurate distribution, twin interfaces and grain boundaries in the corresponding TEM micrographs are mimicked in drawing the FEM mesh structure and are indicated by solid lines in the figures. The magnitude of stress is indicated in gray scale, as shown on the right side of the figures. Stress calculation was performed in the ⟨111⟩ textured film for eight different voided sites and ten unvoided sites. As reported in Ref. 11, stress concentration always accompanies voiding. Figure 2(a) shows a typical example of these cases in which all σ_{11}, σ_{22}, and σ_{12} components are concentrated at voided sites. On the other hand, in the random textured film, it was found that three out of 12 twins are associated with stress concentration of a similar magnitude to Fig. 2(a). However, no void was observed at the stress concentration sites. The typical example of this case is shown in Fig. 2(b) where no void can be seen at the stress concentration sites. These calculations indicate that there is no correlation between the magnitude of stress concentration and its gradient and voiding tendency in the random textured films. This apparent discrepancy may be attributed to difference in twin types between the two samples, as inferred in Fig. 1 by the different tilting angles of twin interfaces.

The orientation of twin interfaces was determined by analyzing Kikuchi diffraction patterns in combination with the use of stereographic projection. Figures 3(a) and 3(b) show stereographic projections for the ⟨111⟩ textured and the random textured films, respectively. In the ⟨111⟩ textured films, the {001} poles of the matrix and the twin are symmetric with respect to the trace of the $(\bar{2}3\bar{2})$ plane. On the other hand, in the random textured film, the {001} poles of the matrix and the twin are symmetric with respect to the trace of the $(\bar{1}1\bar{1})$ plane. These results indicate that the twin plane

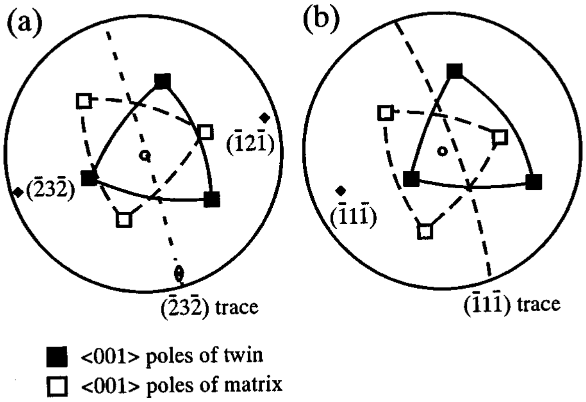

FIG. 3. Stereographic projection of the ⟨001⟩ poles in (a) the ⟨111⟩ textured film and in (b) the random textured film.

of the ⟨111⟩ textured films is the $(\bar{2}3\bar{2})$ plane, while the twin plane of the random textured film is the $(\bar{1}1\bar{1})$ plane. Although {111} twin planes are commonly observed in fcc crystals, {322} twin planes have not been observed except in artificially synthesized bicrystals.[16,17] The obtained results suggest a strong correlation between voiding tendency and twin-plane index. In order to consider the validity of this possibility, the interface structure of {322} twins is discussed next.

In bulk bicrystal of Cu, Ernst *et al.*[16] have investigated the structure and energy of $\Sigma 3$ ⟨110⟩ tilt boundaries both theoretically and experimentally. Their results indicated that the {322} twins are incoherent twins having a disordered atomic array along the interface. They also showed that the interface energy of the {322} twins is much larger than that of the {111} twins. Based on these information together with the present results, three possibilities can be considered for the origin of the voiding tendency and its dependence on twin types. In the first, voids may be an extended structure of deep surface groove formed along the incoherent twins. If the voids were parts of grooves, we would expect the voids to be associated with all the {322}-type twin interfaces. However, some {322} twins accompany voids and others are not. Moreover, the voids would be located throughout the twin interfaces where the interface energy is high and homogeneous. However, actual voids were never observed all along the twin interfaces, rather they were observed at the ends and corners of the twins. Therefore, the possibility of grooving as a voiding mechanism can be eliminated based on the present results. In the second, voids may be formed by vacancy diffusion in a stress gradient field and by subsequent vacancy condensation at twin interfaces. In this case, driving force (stress gradient) and diffusion paths (twin interface) should be discussed separately. One may notice that the gradient of stress concentration is steeper in Fig. 2(a) for the ⟨111⟩ texture film than in Fig. 2(b) for the random texture film. However, our FEM calculation of other stress-concentration sites indicated that the steepness of stress gradient varies from one interface to another regardless of the film texture and regardless of the voiding tendency. Thus, the steepness of stress gradient is considered to be irrelevant to the voiding tendency. With regard to the diffusion paths, one may consider that the faster diffusivity is expected along the incoherent {322} twins than along the coherent {111} twins, which would lead to a greater susceptibility to voiding at the {322} twins. However, careful observation of stress distribution indicates that the dominant stress gradient that drives vacancy diffusion is not along the twin interfaces but along the perpendicular direction to the twin interfaces. Thus, the structure type of twin interfaces does not affect the degree of stress-induced diffusion of vacancies. On the other hand, as the third possibility, the ease of void nucleation may depend on the structure type of twin interface. The work necessary to nucleate a void can be estimated from a value of twice the surface energy minus the twin interface energy. As shown by Ernst *et al.*,[16] the twin interface energy is much larger for {322} twins than for {111} twins. This suggests that under the presence of concentrated stress, the void nucleation is easier for the {322} twins than for the {111} twins. The void nucleation may occur either by vacancy condensation or by interface decohesion at stress concentration sites. The former case of vacancy condensation requires stress-induced diffusion. We discussed stress-induced diffusion earlier and found no correlation with the twin type. In contrast, the latter case of interface decohesion can be supported experimentally by a good correlation of the voiding tendency with a large interface energy and a large stress concentration. Similarly in Cu trench structure, Sekiguchi *et al.*[2] reported void formation at Cu/barrier interfaces under a large shear stress concentration. Since shear stress concentration does not cause stress-induced diffusion, the observed voids were considered to be formed by interface decohesion.

Thus, the effects of film texture on stress voiding can be summarized as follows. In the ⟨111⟩ textured films, stress concentration is large enough to cause decohesion failure along the weak {322} twin interfaces or at twin corners. Once decohesion failure occurs, their shape changes to a round shape by diffusion on the crack surface. Since the magnitude of stress concentration is dependent on the orientation of neighboring twins and matrices, a good correlation can be found between stress concentration and voiding tendency in the ⟨111⟩ textured films. On the other hand in the random textured films, some twins are accompanied by stress concentration of similar magnitude and distribution to the twins in the ⟨111⟩ textured films. However, even under the same level of stress concentration as in the {322} twin interface, the coherent {111} interfaces are too strong to nucleate decohesion-type voids. Thus, no correlation can be found between stress concentration and voiding tendency in the random textured films.

Finally, the present results clearly indicate that the random textured film prepared by electroplating is resistant to microvoid formation during thermal processing.

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