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Stress-Induced Migration and Microstructural Features in Cu Metallization

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1. Introduction

Cu metallization have been utilized for interconnect lines in ULSI devices. However, various problems should be solved before full-scale application is realized. Stress-induced migration is one of the major reliability problems that occur during thermal processing. The present paper focuses on stress-induced voiding and its mechanisms in Cu blanket films and in damascene trenches. Possible ways to improve the stressmigration resistance are discussed.

2. Stress-induced voiding in blanket films

The possibility of stress-induced voiding were investigated in two types of blanket thin films: (1) a highly (111)-textured film and (2) a random-textured film. These films were prepared by electroplating on $Ta/SiO_2/Si$ and were subject to heat treatment in vacuum at 450 °C. . After heat treatment, SEM images in Fig. 1 indicate that the (111)-textured films exhibited the formation of microvoids at twin corners and intersections [ref]. A good correlation was found between experimentally observed voided sites and calculated stress concentration sites. In contrast, the random-textured films exhibited no void formation despite the presence of twins or of stress concentration [ref]. The SEM images also indicate the formation of grain-boundary grooves supposedly at general grain boundaries. However, the groove formation can be avoided by passivating Cu surface.

The type of twin interfaces was then analyzed using an electron diffraction technique. It was found that the twin interfaces are incoherent {322} type in the (111)-textured films, while coherent {111} interface in the random-textured films. Thus, stress-induced voiding in highly (111)-textured films can be ascribed to stress concentration acting as a driving force and to incoherent interfaces acting as fast diffusion paths.

Weakening the (111) texture prefers the formation of coherent twin interfaces along which diffusivity is expected to as low as volume diffusivity. Thus, no stress-induced voiding is observed despite the presence of twins and associated stress concentration.

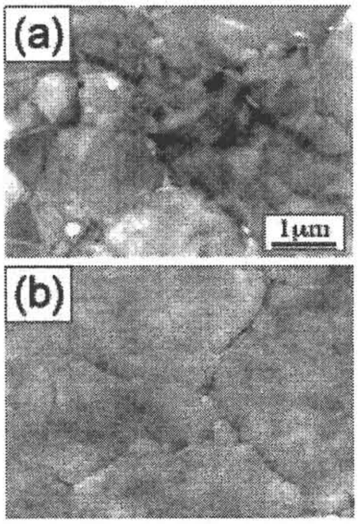

Fig. 1 SEM images of Cu surface after heat treatment at 450 °C. (a) a highly (111) textured film, (b) a random textured film.

3. Stress-induced voiding in Damascene lines

Damascene Cu lines were prepared by electroplating of plasma-etched trenches of 100 nm in width having sputter-seeded Cu and barrier layers of Ta/TaN on a SiO_2/Si substrate. The samples were subject to the same heat treatment as for the blanket films. Cross sectional images were observed using an FIB microscope.

Figure 2 shows an FIB image of Cu lines before and after heat treatment. Typical examples of stress-induced failure are selected from larger regions and are in (a) for incomplete filling of Cu in the trenches and in (b) for pull-out of Cu from the trenches. Notice that there are no twin-related voids because of the coherent types of twin interfaces. Other failures not shown here are the formation of slit-like voids at trench shoulders and the coalescence of voids. We can demonstrate that these stress-induced failures are related to the interface energy, or synonymously, adhesion strength or wettability between Cu and barrier layers.

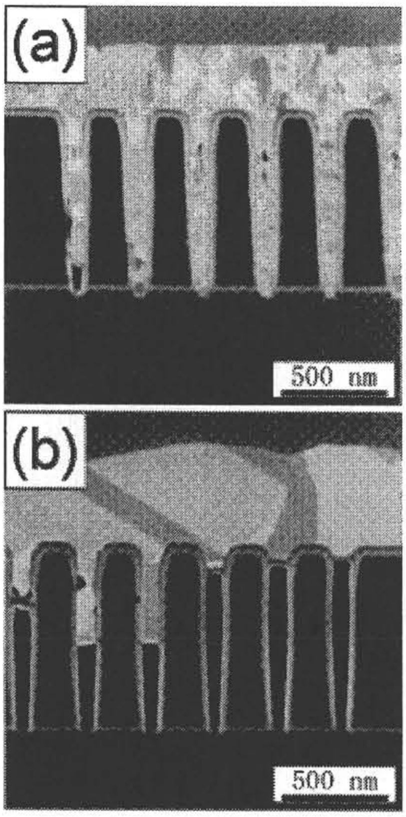

Fig. 2 (a) Incomplete filling of Cu showing voids at the bottom, side walls, and center of the trenches. (b) Pull-out of Cu from the trenches after heat treatment.

For the slit-like voids, Sekiguchi et al. reported that their formation is caused by the delamination of Cu under large shear stresses concentrated at trench shoulders and suggested [ref]. For the void coalescence and the pull-out, thermodynamic consideration leads to the following equations for the pull-out pressure acting on Cu surface and the time for complete pull-out of Cu from a trench having a width of w and a depth of x_0 [ref].

$$P = \frac{2(\gamma_{\mathrm{Cu/barr.}} - \gamma_{\mathrm{barr.}})}{w}$$

$$t = \frac{RTw^2 x_0^2}{8\delta_{\mathrm{int}} D_{\mathrm{int.}} V_{\mathrm{m}} (\gamma_{\mathrm{Cu/barr.}} - \gamma_{\mathrm{barr.}})}$$

Here, γ is the interface or surface energy of the materials given in the subscripts, and $\delta_{\mathrm{int.}} D_{\mathrm{int.}}$ is the thickness and the diffusivity of Cu/barrier interfaces. According to these equations, Cu in narrower lines is subject to larger pull-out pressure and undergoes pull-out in a shorter time period. Since the line width cannot be compromised, the interface energy can be considered instead for the improvement of the stress-induced phenomena. As the energy difference ($\gamma_{\mathrm{Cu/barr.}}$-$\gamma_{\mathrm{barr.}}$) decreases, the pull-out pressure becomes smaller and the pull-out time becomes longer. This relation provides a theoretical background for the choice of barrier layers and for the modification of the Cu/barrier interface, based on the interface energy consideration.

4. Summary

Experimental examples of stress-induced voiding were shown for blanket Cu thin films and for damascene Cu lines having a trench width of 100 nm. A voiding mechanism related to twins was presented in terms of stress concentration and twin-interface structure. The pull-out of Cu from trenches was also discussed and two governing equations were proposed to predict the pull-out pressure and time.

Acknowledgements

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