Electromigration in Sputtered Copper Film on Plasma-Treated Hydrogen Silsesquioxane Dielectric

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Electromigration (EM) damage is one of the major causes for the failure of interconnects. Plasma treatment, such as dry etching, is frequently employed in the fabrication of multilevel interconnection patterns. This work investigates the hydrogen silsesquioxane (HSQ) and copper integrated systems and the effect of H_2 plasma treatment on the EM of Cu. Hydrogen plasma bombardment induces a rough HSQ surface and results in a coarse morphology of the Cu film deposited on HSQ. The crystallographic texture of Cu is also affected by the plasma treatment. A decrease in the Cu I(111)/I(200) peak ratio is observed for a specimen treated with H_2 plasma. The activation energy for EM in Cu and the EM lifetime of the Cu interconnect decreases with an increased degree of plasma treatment. The activation energies obtained, ranging from 0.76 eV to 0.94 eV, suggest that the electromigration in copper proceeds via an interfacial diffusion path. Possible mechanisms for the effects of plasma treatment are explored. The rough surface and the retarded Cu (111) orientation induced by H_2 plasma bombardment are the major causes for the decrease of activation energy and EM lifetime.

Key words: Electromigration, interconnect, plasma treatment, Cu-low k dielectric, reliability, hydrogen silsesquioxane

INTRODUCTION

With the shrinking in dimensions of ULSI circuits, there is a need for faster performance and greater circuit density. Interconnect time delay and current density in the metallization increase as the device dimensions are scaled down. Copper has better conductivity, better mechanical properties, and greater electromigration resistance than aluminum. However, copper has some challenges, such as the lack of a stable self-passivating copper oxide, poor adhesion to dielectric materials, and diffusion of Cu into substrates.[1–6]

Multilevel wiring schemes are more important with the reduction of device dimensions. The dielectric between the wiring levels must have high quality and reliability, low stress, simplicity of process, and ease of integration. Hydrogen silsesquioxane (HSQ) is one of the promising candidates with a highly porous three-dimensional network structure.

The general formula for HSQ is $(HSiO_{1.5})_{2n}$ where n = 3–8. Hydrogen silsesquioxane has many advantages, including a low dielectric constant, carbon-free, non-etchback processing, excellent gap filling, good planarization, and low moisture uptake. However, HSQ also has many integration issues such as Si-H bond thermal dissociation, oxidation, and susceptibility to plasma damage.[7] It was reported that with appropriate plasma treatments, the thermal stability of HSQ could be enhanced.[8] Nevertheless, the plasma treatment may damage the surface or change the surface chemistry of HSQ[9–11] and the reliability of the low k dielectric HSQ may degrade. The presence of a Ta barrier not only improves the adhesion between Cu and HSQ, but also enhances the Cu microstructure and improves the Cu electromigration resistance.[12]

In this work, the feasibility of HSQ and a copper integrated system, the effect of H_2 plasma treatment on the electromigration phenomenon of the HSQ, and the copper system with Ta as a barrier layer are studied. The kinetics of electromigration damage (EMD)

are studied by an isothermal resistance change analysis method using an empirical formula:[13]

$$(dR/dt) \times (1/R_0) = Aj^n \exp(-Q/kT) \qquad (1)$$

The activation energy Q for EMD is calculated and discussed.

EXPERIMENTAL PROCEDURES

The flow chart for sample preparation is shown in Fig. 1. Four-inch-diameter P-type (100) Si wafers with nominal resistivity of 10 Ω-cm were used as substrates. The Si wafers were cleaned with the standard RCA cleaning process. Coating and curing of HSQ are described in detail elsewhere.[11] H_2 plasma treatment was applied to the as-cured HSQ for 0–10 min at a pressure of 40 Pa, a plasma power of 100 W, and a chamber temperature of 250°C. The plasma-treated specimens were then processed with conventional photolithography to obtain a test pattern. Samples with positive photoresist patterns were transferred to a vacuum chamber for the sputtering of Ta and Cu films.

High-purity Ar gas was introduced through a mass flow controller after the vacuum chamber was evacuated to about 6×10^{-7} torr. The flow rate of argon was 24 sccm. The sputtering targets were 99.99% Cu disc and 99.95% Ta disc. Before deposition, the target was presputtered for 10 min to remove any contaminant. The gas pressure was kept at 6×10^{-3} torr and the sputtering power employed during deposition was 500 W for Ta and 1500 W for Cu. Copper film was sputtered after Ta deposition without breaking the vacuum. The film thicknesses were 250 nm copper and 10 nm Ta. The lift-off process was carried out after the sputtering of Ta and Cu to pattern for the EMD test. TEOS films, deposited by the decomposition of tetraethyl orthosilicate, with 500 nm in thickness were deposited onto Cu films with Plasma Enhanced Chemical Vapor Detection (PECVD) at 250°C and 100 mTorr.

Conventional photolithography was used to define the contact hole through the TEOS SiO_2. Blanket Al was then deposited on a specimen for EM test by a thermal coater, which was followed by photolithography. The solution of H_3PO_4:HNO_3:CH_3COOH:H_2O = 50:2:10:9 was used to etch excess Al. Samples were then annealed in N_2 ambient at 400°C for 1 h.

X-ray diffraction (XRD) was used to examine the metal film's phase structure. Field-emission scanning electron microscopy (SEM) was used to observe the surface morphology and microstructure. An atomic force microscope (AFM) was used to measure the surface morphology and roughness. A secondary ion mass spectrometer was employed to analyze elemental depth profiles.

The electromigration tests were carried out in a quartz tube at temperatures ranging from 225°C to 300°C in air atmosphere. The four I/O pads of the samples were connected to a constant current source and a microvoltage meter.

RESULTS AND DISCUSSION

The surface roughness of HSQ films increases with the increase of plasma treatment time, as shown in Fig. 2. The SEM micrographs of copper film on HSQ, exhibited in Fig. 3, suggest a slight increase of grain size for the as-deposited Cu films on 10-min plasma-treated HSQ. Although Cu films on 10-min plasma-treated HSQ show more distinct topographical features (Fig. 3c and f), probably a result from the rougher HSQ surface (Fig. 2c), no apparent difference in grain size is observed for the annealed Cu films on HSQ with various plasma treatment times (Fig. 3d–f). The XRD patterns of Cu films, given in Fig. 4, indicate a decrease in the peak ratio I(111)/I(200) as the HSQ plasma treatment time increases. In addition, the film
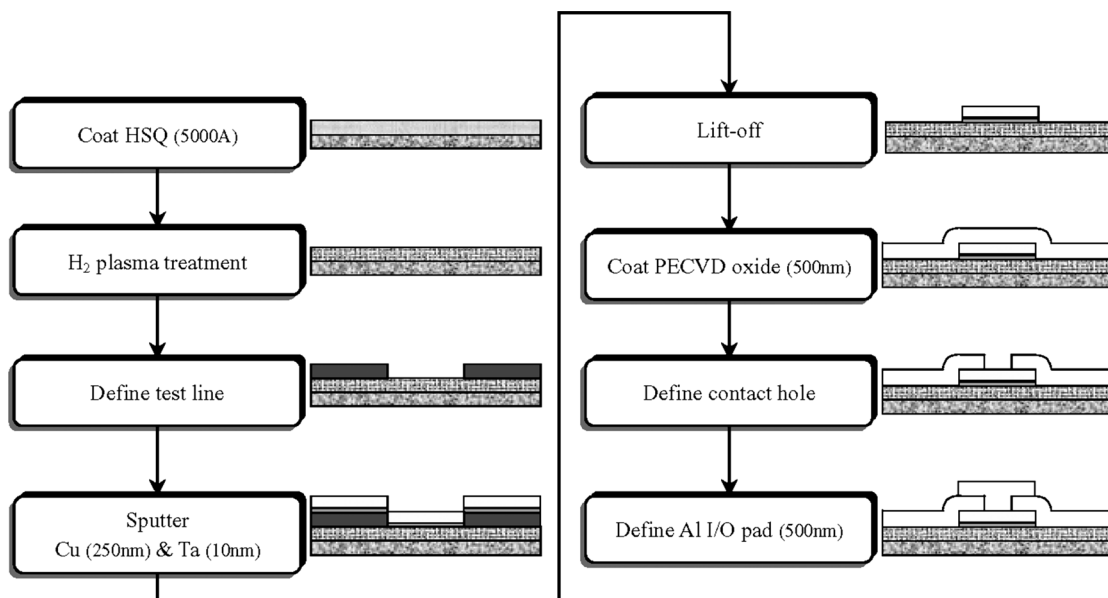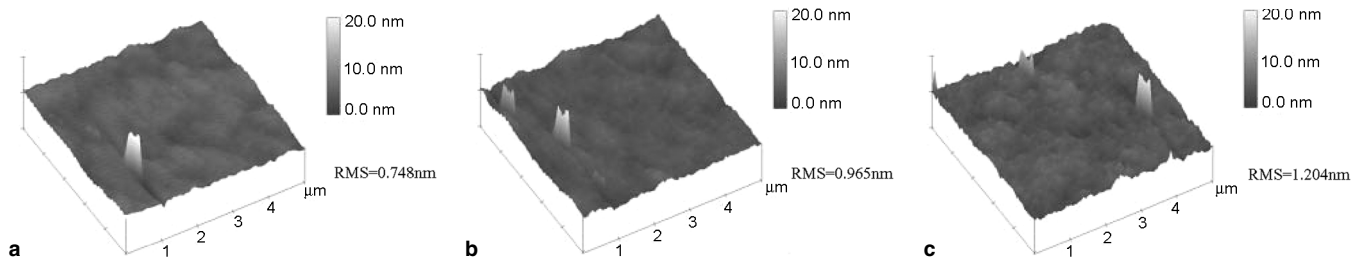

Fig. 1. Flow chart for sample preparation.

Fig. 2. AFM graphs and root mean square surface roughness of HSQ with (a) 0 min, (b) 5 min, and (c) 10 min H$_2$ plasma treatment.

a   r: 35nm   b   r: 35nm   c   r: 35nm

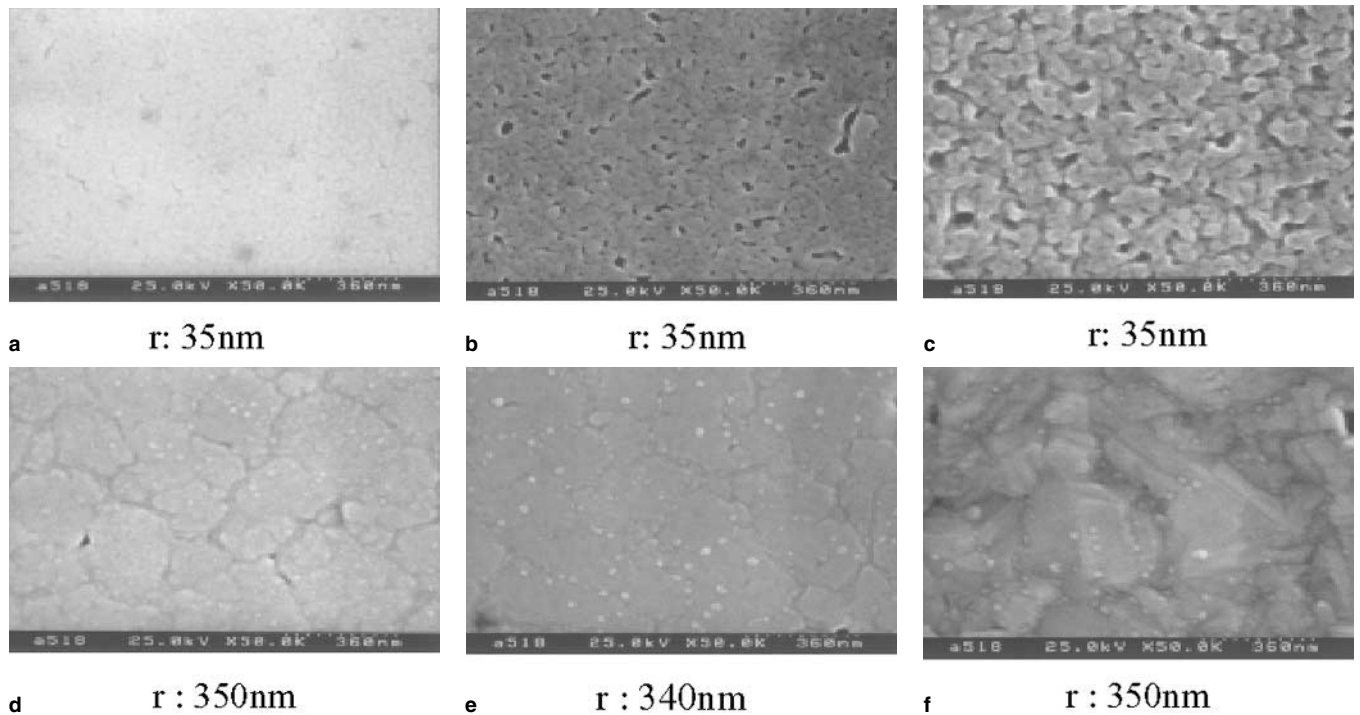d   r : 350nm   e   r : 340nm   f   r : 350nm

Fig. 3. SEM micrographs of Cu films on HSQ treated with H$_2$ plasma for (a) and (d) 0 min, (b) and (e) 5 min, and (c) and (f) 10 min. (a)–(c) Before annealing and (d)–(f) after annealing. Annealing conditions: 400°C for 1 h. Also show in the figure is the average grain size r of Cu film.
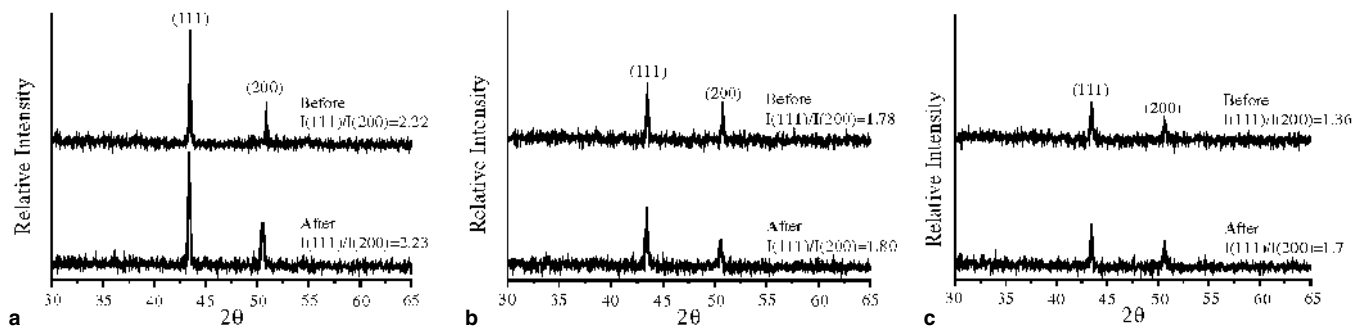

Fig. 4. XRD patterns of copper films deposited on HSQ treated with H$_2$ plasma for (a) 0 min, (b) 5 min, and (c) 10 min before and after annealing at 400°C for 1 h.

resistivity increases with an increase of plasma treatment time.

The kinetics of EM damage was studied with the isothermal resistance change analysis method. The resistance increases more rapidly at higher soaking temperatures. By defining a resistance change of 4.5% as the criterion of early stage failure, i.e., assuming the dimensions of the maximum voids are much less than the line width, the time rate change

of electrical resistance dR/dt due to electromigration damage is thermally activated and can be expressed by the following empirical equation:[13]

$$(dR/dt) \times (1/R_0) = Aj^n \exp(-Q/kT) \qquad (1)$$

where R_0 is the initial resistance at a given temperature, A is a pre-exponential factor, j^n is the electron current density raised to the nth power, T is temperature, and Q is the activation energy for EMD. The
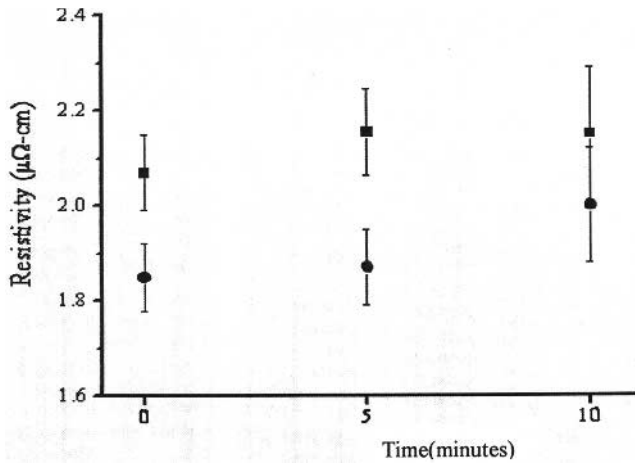
Fig. 5. Resistivities of Cu films on plasma-treated HSQ as a function of plasma treatment time. ■: before annealing, and ●: after annealing. Annealing conditions: 400°C for 1 h.

activation energies of sputtered Cu on HSQ with various energy plasma treatments obtained from a $\ln[(dR/dt) \times (1/R_0)]$ versus $1/T$ plot, shown in Fig. 6b, 7b, and 8b, are 0.94 eV (without plasma treatment), 0.81 eV (5 min H_2 plasma), and 0.76 eV (10 min H_2 plasma), respectively. The activation energy for electromigration in Cu decreases as the plasma treatment time increases.

The activation energy for lattice electromigration is on the order of 2.3 eV, while that for grain boundary diffusion is about 1.2 eV.[14] The activation energy for surface migration is 0.47 eV,[15] and the activation energy for interface migration ranges from 0.7 eV to 1 eV.[16,17] The activation energies obtained for Cu electromigration in this study suggest that lattice and grain boundaries are not the major paths for electromigration in Cu. Migration via interfacial diffusion paths may play an important role in Cu

electromigration. There are several interfaces in the TEOS SiO_2/Cu /Ta/HSQ system of this study. However, plasma treatment on HSQ shows significant affects on the EMD of Cu so the dominant mass transport path appears to be via the interface between metallization and HSQ.

Crystallographic texture affects the EM of copper. Ryu et al. reported that the EM lifetime of (111) CVD Cu is 4 times longer than that of (200) CVD Cu.[18] Abe et al. showed that enhancing Cu (111) crystallographic orientation with a TiN underlayer improved the EM lifetime of Cu.[19,20] Chin et al. found that the EM resistance of Cu interconnect is improved by enhancing the (111) texture (i.e., increasing the I(111)/I(200) peak ratio) and the surface smoothness of Cu films.[3] The H_2 plasma bombardment roughened the surface of the HSQ substrate and resulted in a course surface morphology of the Cu film, as shown in Figs. 2 and 3, respectively. In addition, the Cu (111) crystallographic orientation is retarded and the I(111)/I(200) peak ratio decreased for Cu films on plasma-treated HSQ, as indicated by the XRD patterns shown in Fig. 4. The rough surface and the retarded Cu (111) orientation induced by H_2 plasma bombardment of HSQ are the major causes for the decrease of the activation energy for electromigration in Cu and, hence, the decrease of EM lifetime. The lifetimes of Cu interconnect at 225°C, as shown in Figs. 6, 7, and 8, are ~195 h (without plasma treatment), 181 h (5 min H_2 plasma), and ~46 h (10 min H_2 plasma).

Plasma etching or plasma bombardment is frequently used in the fabrication of multilevel interconnection systems. However, as discussed previously, the plasma treatment may enhance the thermal stability of HSQ,[8] while it may damage the surface or change the surface chemistry of HSQ[9–11] and degrade the EM resistance of Cu interconnect, as observed in
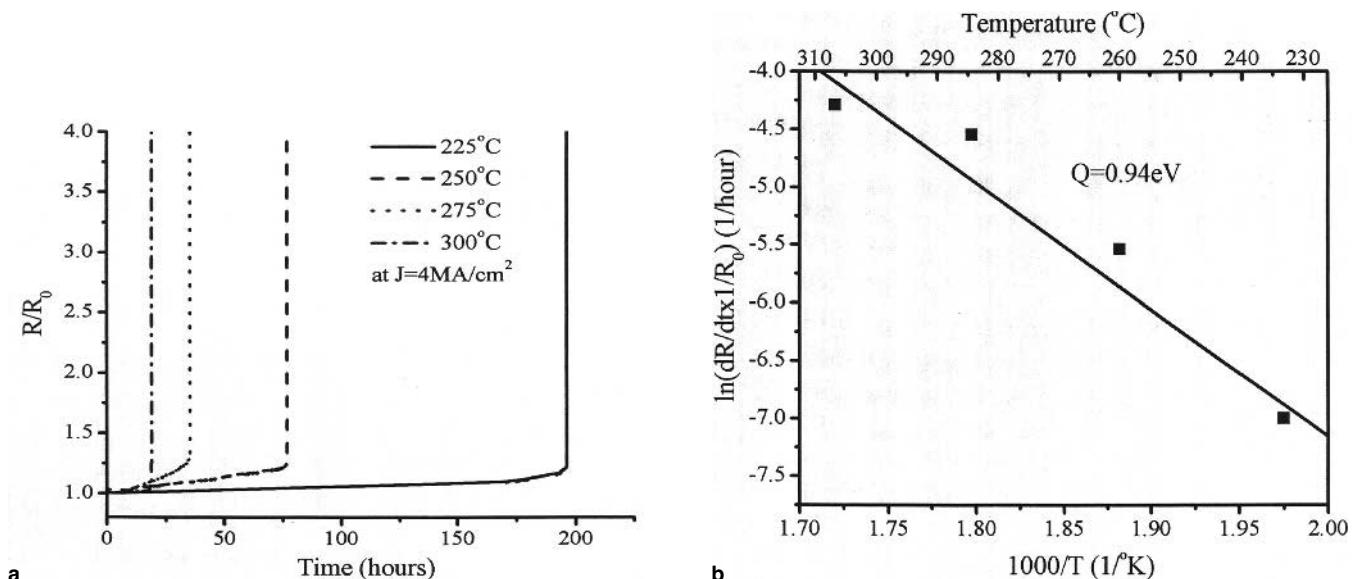

Fig. 6. (a) Relative resistance R/R_0 as a function of current stressed time, and (b) $\ln[(dR/dt)(1/R_0)]$ versus $1/T$ of Cu films on HSQ without plasma treatment.
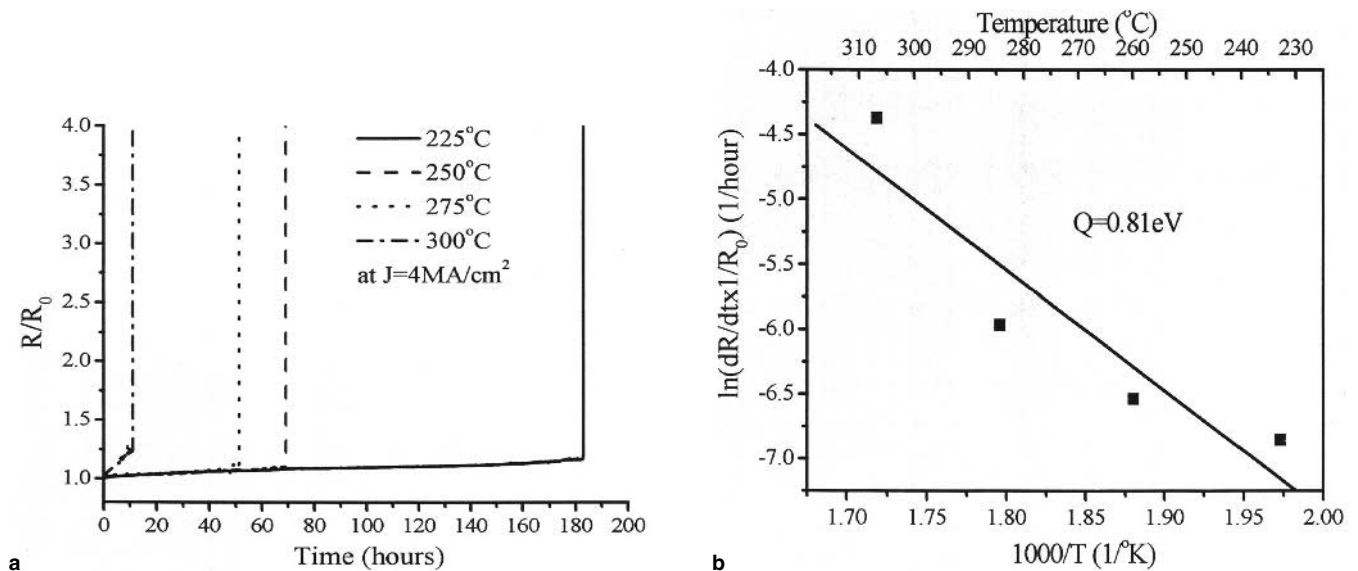
Fig. 7. (a) Relative resistance R/R_0 as a function of current stressed time, and (b) ln $[(dR/dt)(1/R_0)]$ versus 1/T of Cu films on HSQ without plasma treatment on HSQ with 5-min H_2 plasma treatment.
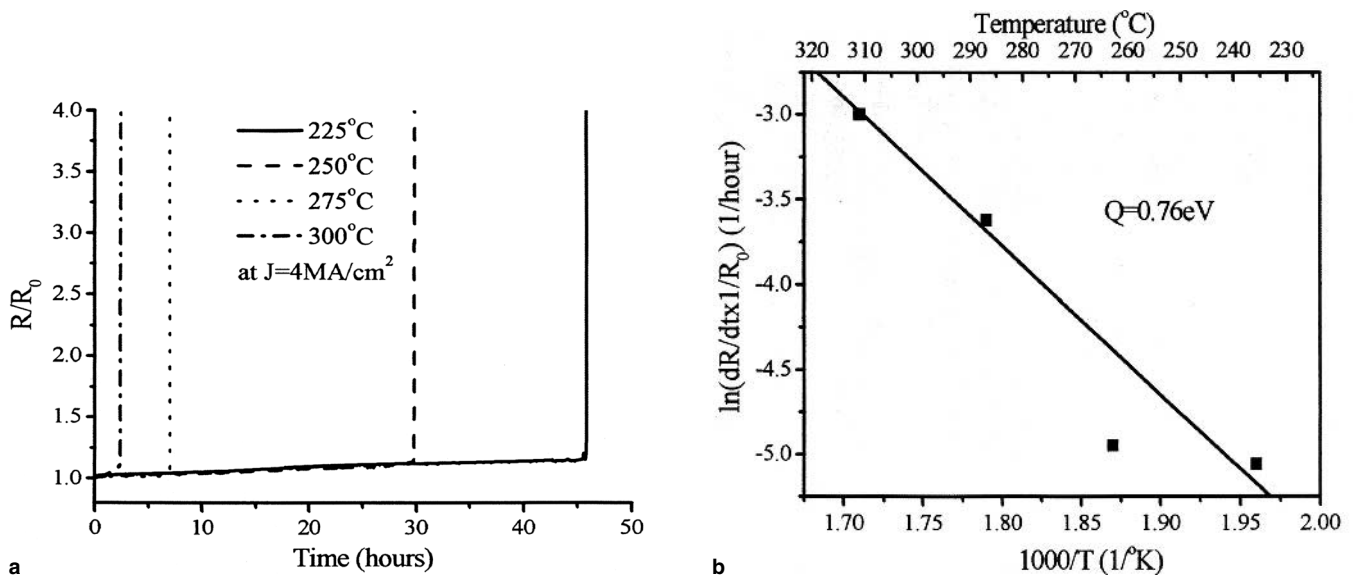

Fig. 8. (a) Relative resistance R/R_0 as a function of current stressed time, and (b) ln $[(dR/dt)(1/R_0)]$ versus 1/T of Cu films on HSQ without plasma treatment on HSQ with 10-min H_2 plasma treatment.

this study. The role the plasma plays in the Cu–low k integrated system is very complex and is worthy of further study.

CONCLUSIONS

In this study, hydrogen silsesquioxane thin film was treated with H_2 plasma before the deposition of Cu films, and the effect of plasma treatment on the electromigration in sputtered Cu film is studied with an isothermal resistance change analysis method. The plasma bombardment increases the surface roughness of the HSQ film. The Cu films on plasma-treated HSQ show a coarse surface morphology. The XRD patterns indicate a decrease in the Cu I(111)/I(200) peak ratio with the increase of plasma treatment. Both the activation energies for electro-

migration in Cu and the EM lifetime of Cu interconnect decrease with increased plasma treatment. The activation energy decreases from 0.94 eV for the untreated films to 0.76 eV for films subjected to 10 min H_2 plasma, while the EM lifetime at 225°C changes from ~195 h (without plasma treatment) to ~46 h (10 min H_2 plasma). The activation energies obtained in this study are smaller than those for lattice migration (2.3 eV) and grain boundary diffusion (1.2 eV) in Cu. This suggests that other short-circuit diffusion paths, such as interface migration, play an important role in Cu migration. Crystallographic texture affects the EM of copper. Previous work showed that the EM lifetime of Cu can be improved by the enhanced Cu(111) preferred orientation. The suppression of the Cu (111) crystallographic orientation of the

plasma-treated sample results in the decrease of the EM lifetime.

ACKNOWLEDGEMENTS

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