

Electromigration in sputtered copper films on polyimide

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Electromigration damage (EMD) is one of the major causes for the failures of interconnects. In this study, the electromigration of Cu on polyimide is investigated. An empirical formula is used to evaluate the EMD of Cu film. The activation energy (Q) obtained is significantly less than those of lattice and grain boundary diffusion. This suggests that the electromigration in copper proceeds via an interfacial diffusion path. The geometry of the metallization also affects the activation energy. Any abrupt change in the interconnect direction and metal width causes current crowding and should be avoided. The current exponents (n), calculated from EMD data, are 3.58 and 3.35 for straight and zig-zag Cu films, respectively.

1. Introduction

Copper, with its low resistivity, high melting point, and high mechanical strength, has been considered as a substitute for Al interconnect in VLSI devices. Electromigration damage (EMD) in Al or Al alloy has been known to be a primary reason for circuit failure [1–3]. Although Cu is believed to have higher resistance to EMD than Al [4–7], very few studies on the electromigration of d.c. sputtered Cu films have been made [8].

Scaling of ultralarge-scale integrated (ULSI) circuits to critical dimensions of polysilicon under $0.5\ \mu\text{m}$ tends to decrease the width of interconnection according to the CMOS design rules [9]. With the further reduction of device dimensions, multilevel wiring schemes become more important. The dielectric between the wiring levels must have good thickness uniformity, electrical integrity and thermal stability. Polyimide, with its good planarization properties, high temperature ($> 400\ ^\circ\text{C}$) stability, and low dielectric constant, is a good candidate for the dielectric material [10].

Sputtering can deposit films over large areas at rates comparable to other thin film deposition methods, such as, electron-beam evaporation and chemical vapour deposition. D.C. sputtering is considered to be one of the best methods for preparing Cu films. High quality Cu films prepared by d.c. sputtering have been reported [11].

In this study, d.c. sputtering is employed to deposit Cu film onto polyimide-coated Si substrates and the electromigration of Cu studied. An empirical formula $(dR/dt)(1/R_0) = AJ^n \exp(-Q/kT)$ [12–15] is employed to evaluate the EMD of Cu film. The activation energy Q for EMD and the exponent n of the current density on Cu film obtained by an isothermal annealing electrical resistance method are calculated and discussed.

2. Experimental procedures

Fig. 1 shows the flow chart of the experimental sequence. Copper films were sputtered onto a polyimide-coated Si substrate. P-type (1 0 0) oriented Si wafers with nominal resistivity of 1 to $10\ \Omega\text{cm}$ (Topsil Inc., USA) were employed. The Si wafers were cleaned with the standard RCA cleaning process.

Polyimide 2540 (Pyralin[®], Du Pont, USA) or its precursor, polyamic acid, was statically dispensed and spun on the cleaned Si wafers. The dispense-and-spread cycle was carried out at 1000 r.p.m. for 20 s and the final ramp cycle was 5000 r.p.m. for 30 s.

Curing (completely imidized) of polyimide was carried out in a quartz tube with nitrogen ambient to prevent the polyimide from degradation. The cured thickness of polyimide, measured with an ellipsometer (Autoel-II, Rodolph Research, USA), was $2.5\text{--}3.0\ \mu\text{m}$. The curing profile is shown in Fig. 2. The nitrogen flow rate was $1416\ \text{sccm}$ (i.e. $3\ \text{ft}^3/\text{h}$).

The polyimide-coated Si substrate was then processed with conventional photolithography to obtain the test pattern. Samples with positive photoresist patterns were transferred to a vacuum chamber for the sputtering of Cu film. High purity Ar gas was introduced through a mass flow controller after the vacuum chamber was evacuated to about $1.33 \times 10^{-4}\ \text{pa}$. Before deposition, the target was presputtered for 1 min to remove any contaminates. The gas pressure was kept at $0.266\ \text{pa}$ and the sputtering power employed during deposition was 300 W. After deposition of the Cu film, some specimens were subjected to a lift-off process to produce a pattern for an EMD test. Samples were then annealed at $400\ ^\circ\text{C}$ for 30 min. The EMD test pattern is shown schematically in Fig. 3.

The film thickness was measured with a stylus surface

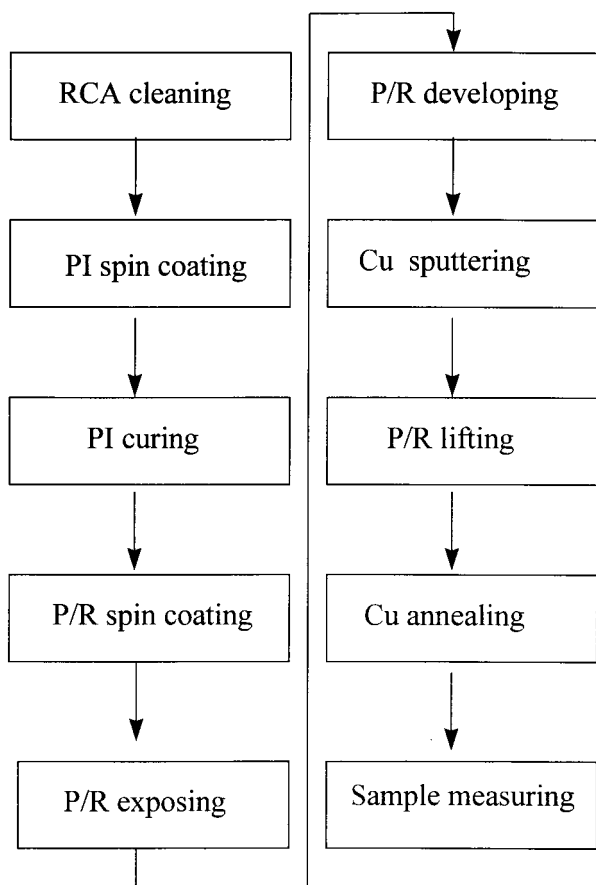


Figure 1 Flow chart of the experimental sequence. PI= polyimide, P/R= photoresist.

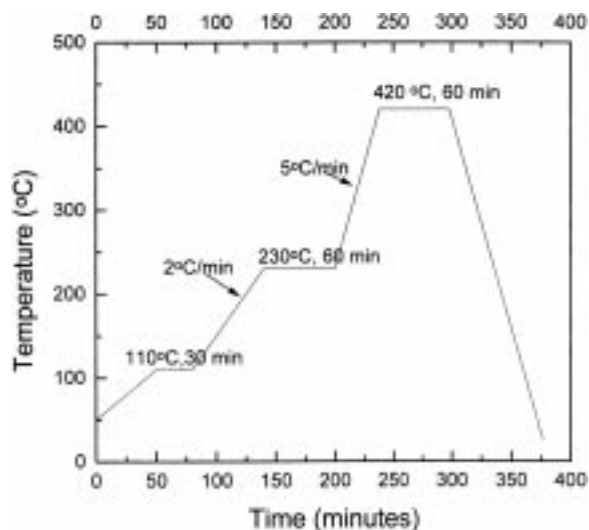


Figure 2 Curing profile of polyimide 2540.

profiler. The sheet resistance of the samples was measured with a four-point probe. An X-ray diffractometer was used to identify the crystalline phase of the films. The microstructures of samples were examined with a field emission scanning microscope (FESEM, S-4000, Hitachi, Japan). An optical microscope was employed to examine samples after development and lift-off. Secondary ion mass spectrometry (SIMS, IMS-4F, Cameca, France) was used to analyse the concentration profile of the films. The electromigration tests were carried out in a quartz tube at temperatures ranging from 110 °C to 230 °C in N₂ atmosphere. The four I/O pads of

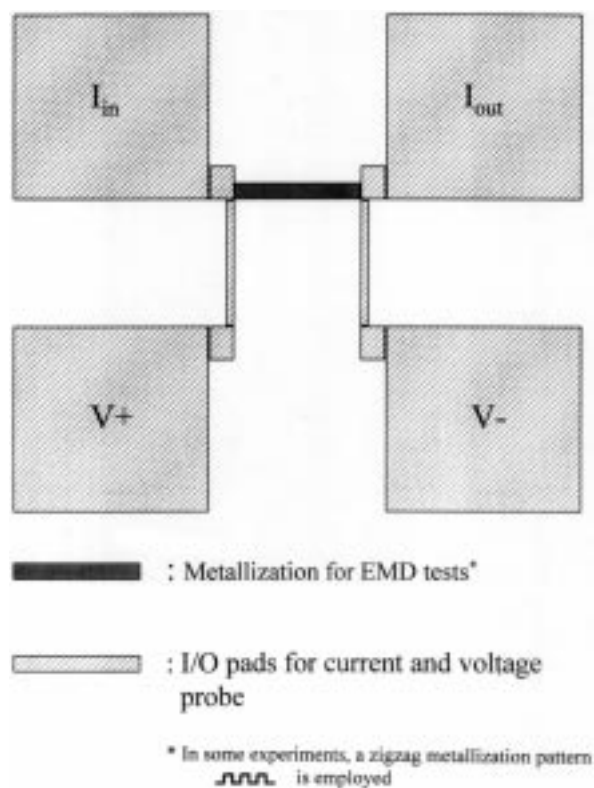


Figure 3 Schematic diagram of the EMD test pattern.

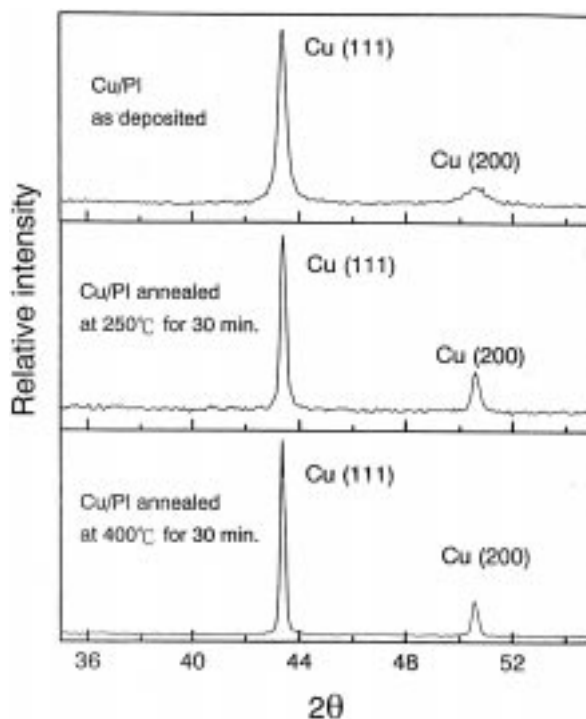


Figure 4 X-ray diffraction patterns of Cu films on PI 2540 substrate with different annealing temperatures.

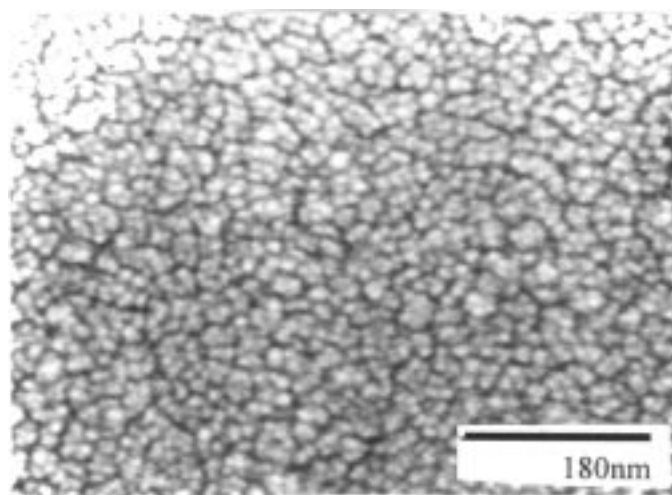
the samples were connected to a constant current source (Model 220, Keithley, USA) and a micro-voltage meter (Model 197, Keithley, USA).

The leads between the samples and measurement system were covered with aluminum foil as an electromagnetic shielding to avoid external electro-magnetic interference. The voltage was acquired once per minute or per ten minutes automatically. The resistance was obtained by dividing the voltage by the current.

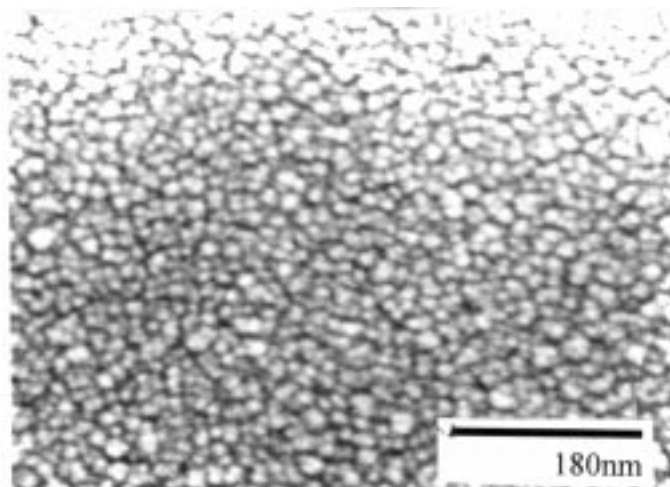
3. Results and discussion

The X-ray diffraction patterns of Cu on polyimide are shown in Fig. 4. The full width at half maximum of the Cu(1 1 1) peak becomes narrower for samples annealed at higher temperatures. This suggests that the degree of crystallinity is improved as the annealing temperature is

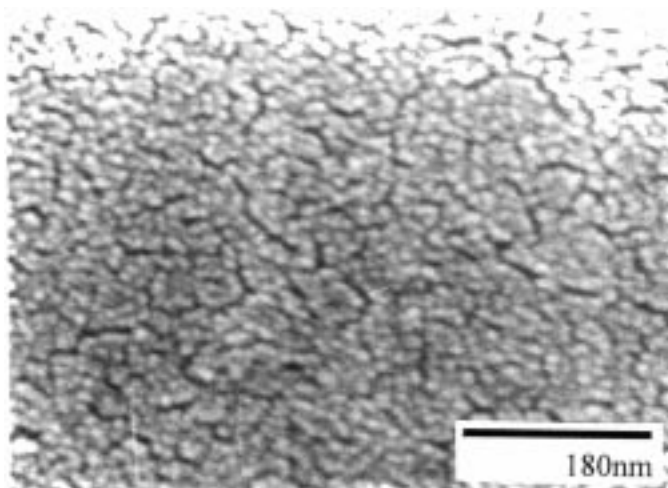
raised. The SEM photographs of Cu films are exhibited in Fig. 5, no apparent difference in film morphology is observed between samples annealed at different temperatures. A SIMS depth profile, shown in Fig. 6, indicates that diffusion of Cu into polyimide occurs after annealing, and the migration of Cu is enhanced with



(a)



(b)



(c)

Figure 5 SEM micrographs of Cu films annealed at various temperatures (a) as-deposited, (b) 250 °C for 30 min, and (c) 400 °C for 30 min.

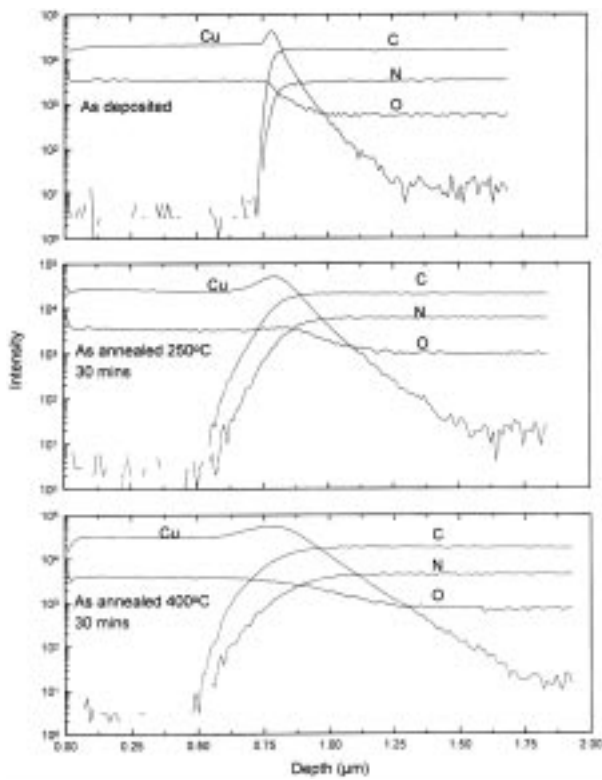


Figure 6 SIMS depth profile of the samples Cu films on PI 2540 substrate with different annealing temperatures.

increase of annealing temperature. Similar phenomena have been reported by Ohuchi and Freilich [6]. The sheet resistance of Cu film decreases from $\sim 76 \text{ m}\Omega/\square$ for the as-deposited film to $\sim 36 \text{ m}\Omega/\square$ for films annealed at 250°C and above.

The kinetics of electromigration damage (EMD) is studied with an isothermal resistance change analysis method. Fig. 7 exhibits the relative resistance R/R_0 of Cu film as a function of time at various temperatures. The resistance increases more rapidly at higher soaking

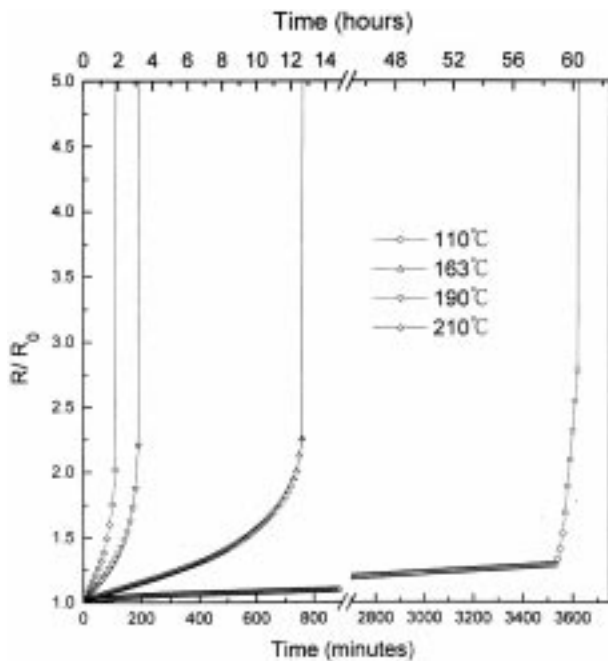


Figure 7 EMD tests of the Cu films at a current density $J = 1.31 \text{ MA cm}^{-2}$ at various temperatures. Samples annealed at 400°C for 30 min before EMD tests.

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 [12–15]:

$$\frac{dR}{dt} \frac{1}{R_0} = AJ^n \exp(-Q/kT) \quad (1)$$

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 n -th power, T is temperature and Q is the activation energy for EMD. The activation energy of sputtered Cu film on polyimide, obtained from a $\ln(dR/dt)(1/R_0)$ versus $1/T$ plot, shown in Fig. 8, is 0.77 eV . The activation energy for lattice electromigration in Cu is of the order of 2.3 eV , while that for grain boundary diffusion is about 1.2 eV [4]. The low activation energy obtained for Cu electromigration in this study and other studies [8, 12, 16–20] suggests that lattice and grain boundaries are not the major paths for electromigration in Cu. Migration via interfacial diffusion paths, such as surface diffusion, may play an important role in Cu electromigration.

Electromigration occurs only at high current densities ($> 10^6 \text{ A cm}^{-2}$). It is anticipated that local current crowding could also affect the migration of Cu. In order to study this possibility, Cu metallizations with zig-zag patterns were prepared and the EMD tested. As shown in Fig. 9, the activation energy of a zig-zag Cu film (0.50 eV) is smaller than that of a straight one (0.77 eV). Fig. 10 shows a schematic plot of equipotentials and current flow in an L-shaped region of the metallization [21]. Current tends to flow parallel to the edges of the region. When the metallization has a bend in it, the bend disturbs the current flow and results in current crowding. This may be one of the causes for the low activation

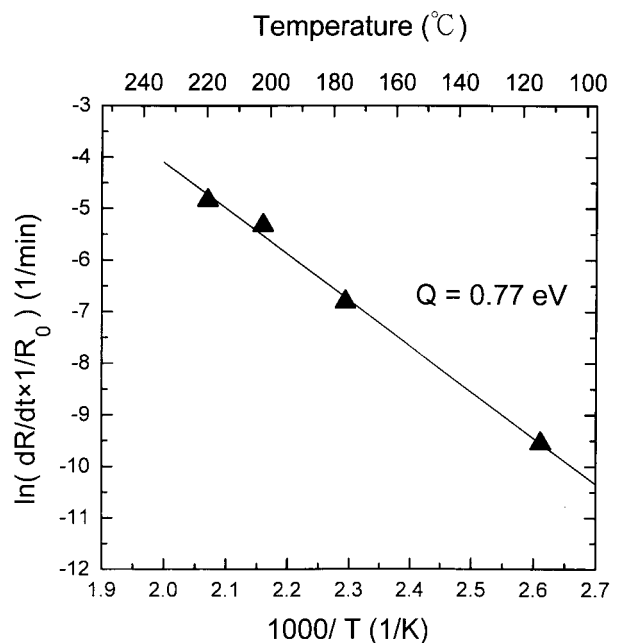


Figure 8 $\ln(dR/dt)(1/R_0)$ versus $1/T$ for Cu films during EMD test. Current density $J = 1.31 \times 10^6 \text{ A cm}^{-2}$.

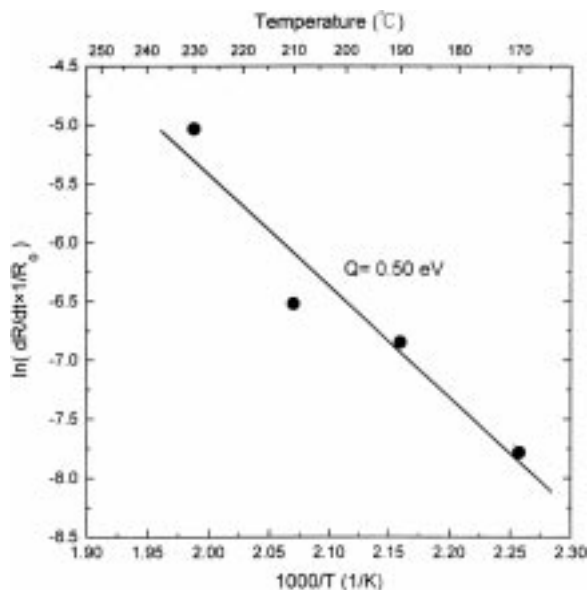


Figure 9 $\ln(dR/dt)/(1/R_0)$ versus $1/T$ for zig-zag Cu films during EMD test. Note that the activation energy Q (0.50 eV) is smaller than that of a straight Cu film shown in Fig. 8 (0.77 eV).

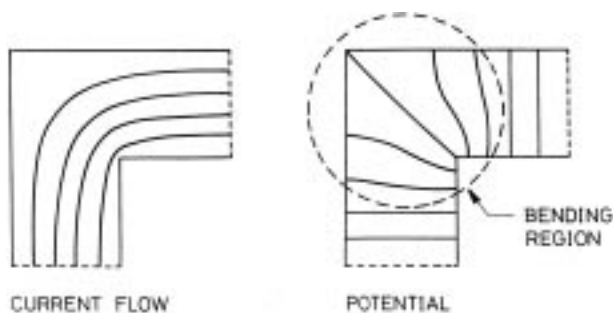


Figure 10 Equipotentials and current flow in an L-shaped region of the metallization.

energy of the zig-zag Cu film. Hence, in the design of a reliable interconnection, it is preferable not to use patterns which zig-zag and/or have an abrupt change in metallization width.

The current exponents (n) in Equation 1, calculated from the EMD data are 3.58 and 3.35, for straight and zig-zag Cu films, respectively. A current exponent of 2 has been obtained by solving a relatively simple diffusion equation where mass transport due to both a concentration gradient and the electromigration force are treated concurrently [13]. Values of n greater than 2 can probably be attributed to Joule heating effects which result in a temperature gradient-induced flux divergence. Some models predicted values of 1 to 15 depending on Joule heating [22]. However, there are many factors, such as electrical field, temperature gradient, residual stress, etc., which would influence the migration of Cu. The root cause for the empirical parameter n is yet to be revealed.

4. Conclusions

The electromigration in sputtered Cu film on polyimide is studied with an isothermal resistance change analysis

method. SIMS depth profile suggests diffusion of Cu into polyimide after annealing. The activation energies for migration failures in straight and zig-zag Cu metallizations are 0.77 eV and 0.50 eV, respectively. Current crowding near the L-shaped region of the zig-zag Cu film is believed to affect Cu migration and result in a low activation energy and should be avoided in the design of a reliable interconnection. 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 surface migration, play an important role in Cu migration.

Acknowledgement

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References

1. C. K. HU, *Thin Solid Films* **260** (1995) 124.
2. S. H. KANG, C. KIM, J. W. MORRIS, Jr. and F. Y. GENIN, *J. Appl. Phys.* **79** (1996) 8330.
3. J. R. LLOYD and R. H. KOCH, *Appl. Phys. Lett.* **52** (1988) 194.
4. J. R. LLOYD and J. J. CLEMENT, *Thin Solid Films* **262** (1995) 135.
5. R. J. GUTMANN, T. P. CHOW, S. LAKSHMINARAYANAN, D. T. PRICE, J. M. STEIGERWALD, L. YOU and S. P. MURARKA, *ibid.* **270** (1995) 472.
6. F. S. OHUCHI and S. C. FREILICH, *J. Vac. Sci. Technol. A* **6** (1988) 1004.
7. C.-K. HU, B. LUTHER, F. B. KAUFMAN, J. HUMMEL, C. UZOH and D. J. RERSON, *Thin Solid Films* **262** (1995) 84.
8. T. NITTA, T. OHMI, T. HSOHI, S. SAKAI, K. SAKAIBARA, S. IMAI and T. SHIBATA, *J. Electrochem. Soc.* **140** (1993) 1131.
9. N. H. E. WEATE and K. ESHRAGHIAN, "Principles of CMOS VLSI Design", 2nd Edn (Addison Wesley Company, CA, 1993) p. 145.
10. D. S. SOANE and Z. MARTYENKO, "Polymers in Microelectronics: Fundamentals and Applications" in *Polyimide Use in IC fabrication*, (Elsevier Science Publishers, 1989) p. 153.
11. J.-C. CHIOU, K.-C. JUANG and M.-C. CHEN, *J. Electrochem. Soc.* **142** (1995) 2326.
12. C. W. PARK and R. W. VOOK, *Mater. Res. Soc. Symp. Proc.* **225** (1991) 119.
13. R. E. HUMMEL, R. T. DEHOFF and H. J. GEIER, *J. Phys. Chem. Solids* **37** (1976) 73.
14. M. SHATZKES and J. R. LLOYD, *J. Appl. Phys.* **59** (1986) 3890.
15. R. ROSENBERG and L. BERENHAUM, *Appl. Phys. Lett.* **12** (1968) 201.
16. H.-K. KANG, Proceedings of the IEEE VMIC Conference (IEEE, New York, 1993) p. 223.
17. J. S. H. CHO, *Tech. Dig.* (1993) 265.
18. T. FUKADA, T. MORI, Y. TOYODA, M. HASEGAWA, K. NAMBA and K. OGATA, *Appl. Surf. Sci.* **91** (1995) 227.
19. B. LUTHER, Proceedings of the IEEE VMIC Conference (IEEE, New York, 1993) p. 269.
20. C.-K. HU and B. LUTHER, *Mater. Chem. Phys.* **41** (1995) 7.
21. M. HOROWITZ and R. W. DUTTON, *IEEE Trans. on CAD Cad-2* (1983) 145.
22. R. A. SIGSBEE, *J. Appl. Phys.* **44** (1973) 2533.

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