Journal of the Korean Vacuum Science & Technology; JKVST
Vol.5, No.1, 2001, pp.11~18

Dielectric Passivation and Geometry Effects on the Electromigration Characteristics in Al-1%Si Thin Film Interconnections

Jin Young Kim※

Department of Semiconductor and New Materials Engineering, Kwangwoon University
447-1 Wolgye-Dong Nowon-Ku, Seoul 139-701, Korea
(Received February 12, 2001)

Abstract

Dielectric passivation effects on the EM(electromigration) have been a great interest with recent ULSI and multilevel structure trends in thin film interconnections of a microelectronic device. SiO_2, PSG(phosphosilicate glass), and Si_3N_4 passivation materials effects on the EM resistance were investigated by utilizing widely used Al-1%Si thin film interconnections. A standard photolithography process was applied for the fabrication of 0.7 ㎛ thick, 3 ㎛ wide, and 200㎛~1600 ㎛ long Al-1%Si EM test patterns. SiO_2, PSG, and Si_3N_4 dielectric passivation with the thickness of 300 nm were singly deposited onto the Al-1%Si thin film interconnections by using an APCVD(atmospheric pressure chemical vapor deposition) and a PECVD(plasma enhanced chemical vapor deposition) in order to investigate the passivation materials effects on the EM characteristics. EM tests were performed at the direct current densities of $3.2\times10^6 \sim 4.5\times10^6$ A/㎠ and at the temperatures of 180 ℃, 210 ℃, 240 ℃, and 270 ℃ for measuring the activation energies(Q) and for accelerated test conditions. Activation energies were calculated from the measured MTF(mean-time-to-failure) values. The calculated activation energies for the electromigration were 0.44 eV, 0.45 eV, and 0.50 eV, and 0.66 eV for the case of nonpassivated-, Si3N4 passivated-, PSG passivated-, and SiO_2 passivated Al-1%Si thin film interconnections, respectively. Thus SiO_2 passivation showed the best characteristics on the EM resistance followed by the order of PSG, Si_3N_4, and nonpassivation. It is believed that the passivation sequences as well as the passivation materials also influence on the EM characteristics in multilevel passivation structures.

1. Introduction

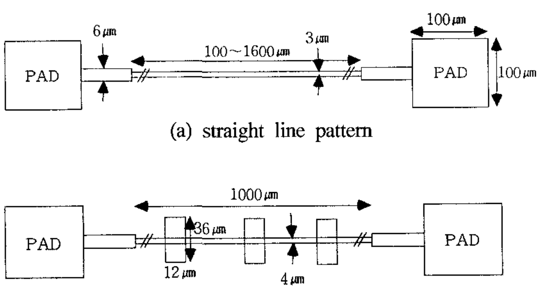
The minimum feature size of large-scale integrated circuits continues to scale down to a quarter micron and below [1]. Dielectric passivation effects on the EM characteristics are of a special interest with continuing integration and multilevel structure trends in thin film interconnections of a microelectronic device. EM induced failures appear to be one of the critical problems with current and forthcoming ULSI interconnections because of the high current densities resulting from the narrow line width [2-4]. The EM induced mass transport, which results in the failures by the formation of voids and hillocks in a circuit, is caused by so called "electron wind" force at high current densities stressed in thin film interconnections. Dielectric passivations have been reported to reduce the EM induced mass transport specially in Al alloy interconnections [5-6]. The general agreement of the results on the passivation effects is that the MTF is proportional to the passivation thickness [5,6]. In this paper, the dielectric passivation materials effects on the EM characteristics were investigated using SiO_2,

※ E-mail : jykim@gwu.ac.kr

PSG, Si_3N_4, their sandwiches, etc.

II. Experiment

EM test patterns were fabricated by using a standard photolithography and an electron beam lithography process. 700 ㎚ thick Al-1%Si thin films were sputter-deposited onto 500 ㎚ thermally oxidized SiO_2 on p-Si(100). The line widths and the line lengths of Al-1%Si thin films were 3～4 ㎛ and 400～800 ㎛, respectively. For the photolithography, UV exposure was done at 300 mJ/㎠ after photoresist coating. For the electron beam lithography, electron exposure was done at 30 μC/㎠ after SAL 601-ER7 coating. RIE(reactive ion etching, Cl_2+BCl_3) was used for Al-1%Si(700 ㎚) etching. SiO_2 and PSG passivations on top of Al-1%Si was formed by using an APCVD. Si_3N_4 passivations were formed by using a PECVD. The single passivation thicknesses were 200～300 ㎚. The current densities stressed were 3.15×10^6 ～4.5×10^6 A/㎠. The temperatures used for the EM tests were 180 ℃, 210 ℃, 240 ℃, 270 ℃, etc. at a hot plate. Fig. 1 shows EM test patterns. Straight lines and 12×36 μm^2 rectangular shaped wide and narrow link lines were used. The TTF(time-to-failure) values were taken at the current stressing time with the 100% resistance change ratio, that is, electrically open state. And the MTF values and standard deviation σ were calculated from the TTF values. Activation energies were calculated by Black equation, MTF=A j^{-n} exp (Q/kT) [7-8].



(a) straight line pattern

(b) 12×36 μm^2 rectangular wide and narrow link pattern

Fig. 1 Electromigration test patterns

III. Results and discussion

Fig. 2 shows the TTF versus cumulative failure percent of nonpassivated-, SiO_2 passivated-, PSG passivated-, and Si_3N_4 passivated 400 ㎛ long Al-1%Si thin film interconnections at a current density of 4.5×10^6 A/㎠. At temperatures of 180 ℃, 210 ℃, and 240 ℃, the MTFs of nonpassivation were decreased 60 s(σ=0.42), 26 s(σ=0.45), 16 s(σ=0.54), the MTFs of SiO_2 passivation were decreased 1753 s(σ=0.29), 902 s(σ=1.16), 241 s (σ=0.78), the MTFs of PSG passivation were decreased 497 s(σ=1.04), 286 s(σ=0.53), 111 s(σ=0.63), and the MTFs of Si_3N_4 passivation were also decreased 337 s(σ=0.40), 170 s(σ=0.73), 86 s(σ=0.33), respectively. The SiO_2 passivated Al-1%Si thin film interconnections showed the longest MTF value, that is, the best characteristics on electromigration followed by the order of PSG, Si_3N_4, and nonpassivation. The increase of the MTF by SiO_2 passivation in Al alloy interconnections has been reported in the literature [5-6]. For all of passivations, the MTFs decreased as the temperature increased as commonly predicted [9]. In comparision with nonpassivated films, passivated thin films showed the increased MTF values, that is, the decreased EM induced mass transport due to the dielectric passivation effects at the interface between the dielectric overlayer and the Al-1%Si interconnection.

Fig. 3 also shows the TTF versus cumulative failure percent of 800 ㎛ long Al-1%Si interconnections stressed at a current density of 4.5×10^6 A/㎠. At temperatures of 180 ℃, 210 ℃, and 240 ℃, the MTFs of nonpassivation were again decreased 49 s(σ=0.35), 32 s (σ=0.53), 15 s(σ=0.32), the MTFs of SiO_2 passivation were decreased 1058 s(σ=0.52), 550 s(σ=0.55), 205 s (σ=1.04), the MTFs of PSG passivation were decreased 351 s(σ=0.72), 197 s(σ=0.94), 110 s(σ=0.73), and the MTFs of Si_3N_4 passivation were also decreased 296 s(σ=0.70), 124 s(σ=0.91), 83 s(σ=0.77), respectively. The same passivation material effects on the MTF are also observed in case of 800 ㎛ long Al-1%Si interconnections as described. As in 400 ㎛ long Al-1%Si

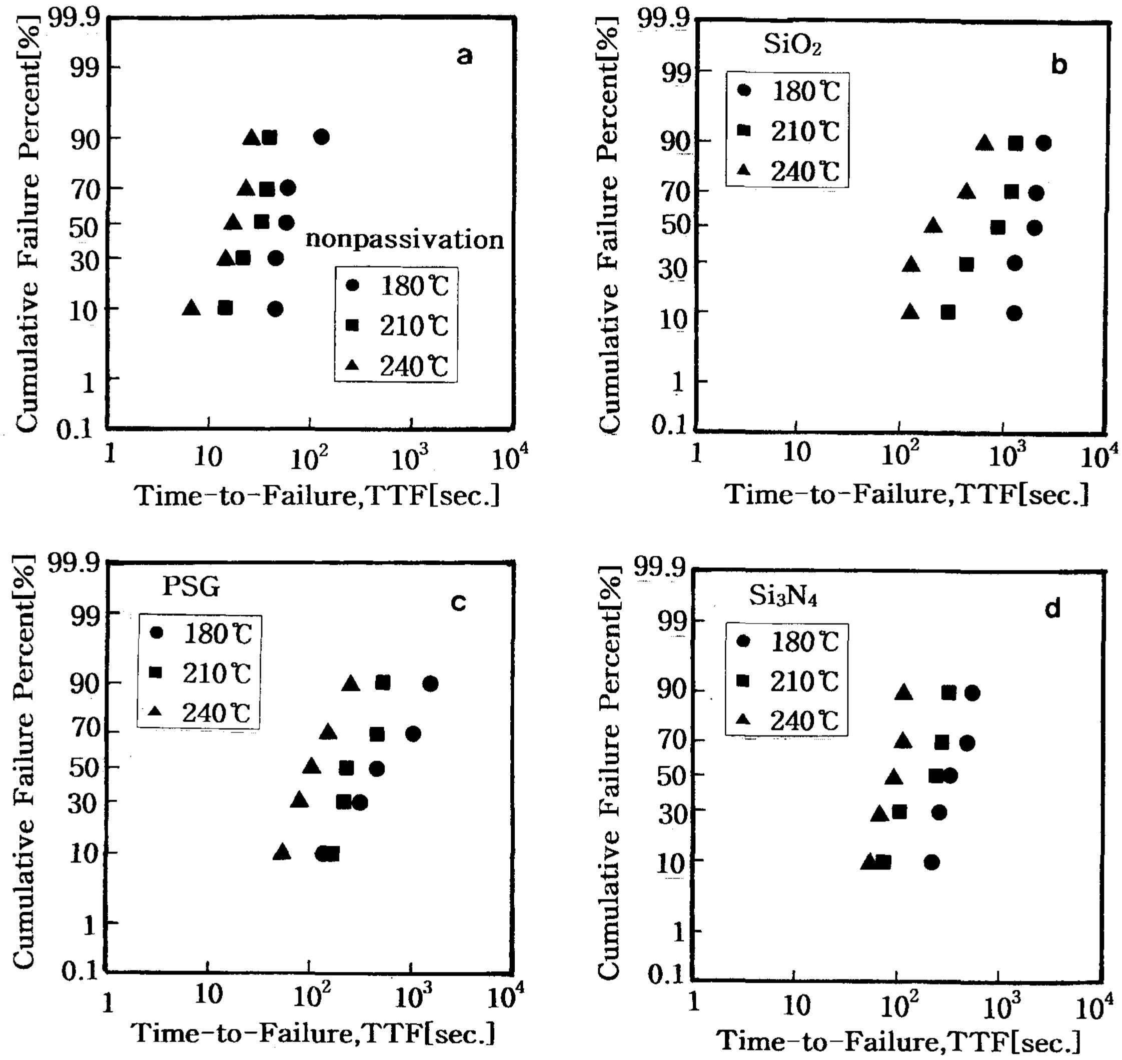


Fig. 2 TTF vs. cumulative failure percent(%) of Al-1%Si interconnections with various passivation materials (400 ㎛ length, j=4.5×10^6 A/㎠). (a) nonpassivation, (b) SiO_2, (c) PSG, (d) Si_3N_4.

interconnections, SiO_2 passivaion showed the best EM resistance characteristics followed by the order of PSG, Si_3N_4, and nonpassivation. In this experiment, all passivation materials with same thickness were fabricated. It is thus believed that passivation materials influence to the EM characteristics in thin film interconnections. On the other hand, all the MTFs of 400 ㎛ long Al-1%Si interconnections showed longer lifetime than those of 800 ㎛ long Al-1%Si interconnections for all passivation materials. It demonstrates the line length dependence of lifetime in interconnections of a microelectronic device. The MTFs initially decrease with increase of the line length and then reach a saturation above a critical length. The decrease of the MTF at a long line is considered to be due to the greater probability of encountering severe defects in an interconnection [10]. Similar line length dependence on the lifetime is seen in Fig. 4(a) and 4(b), which show MTF values of nonpassivated Al-1%Si interconnections with various line lengths measured at 60 ℃ and 100 ℃, respectively. The critical

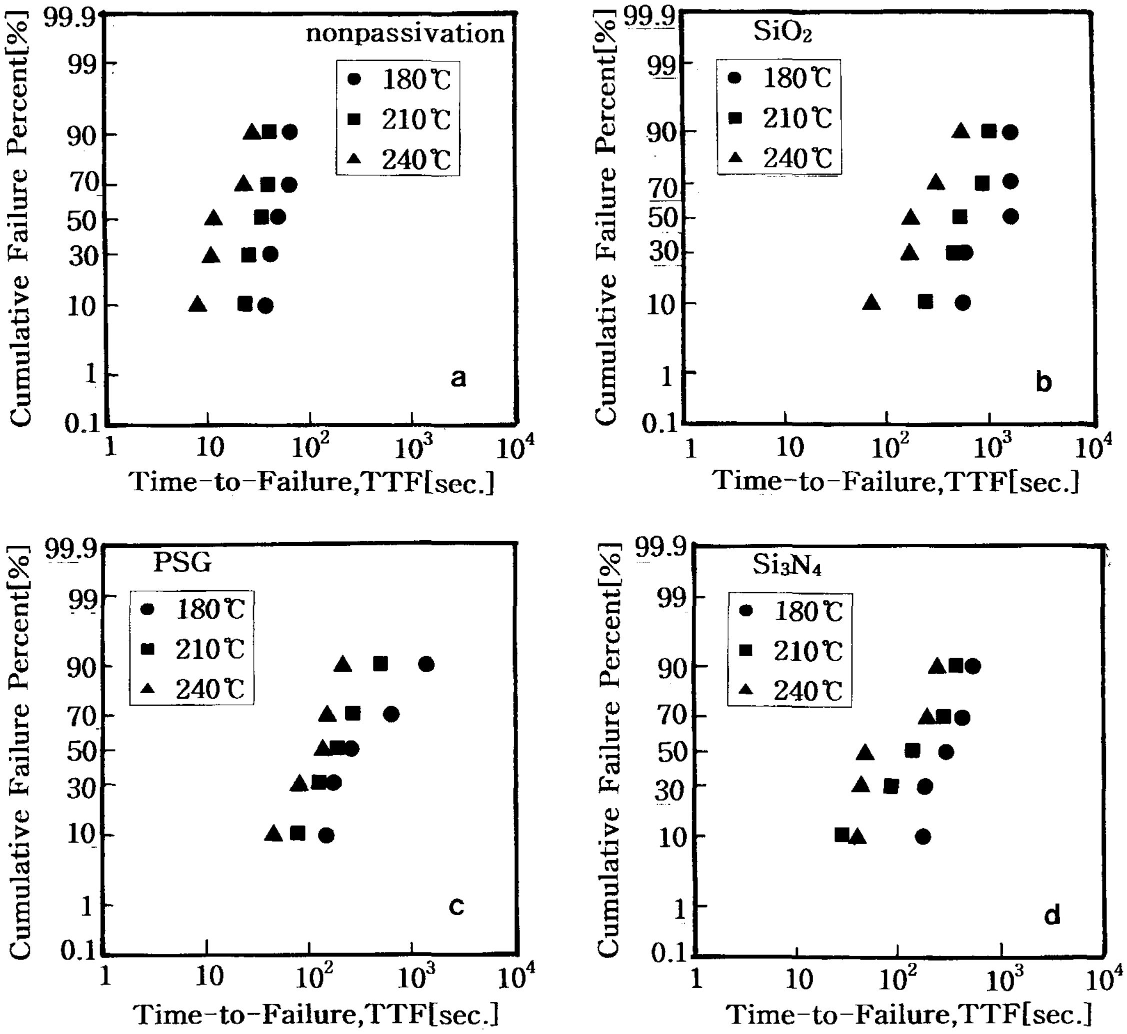


Fig. 3 TTF vs. cumulative failure percent(%) of Al-1%Si interconnections with various passivation materials (800 μm length, j=4.5×10^6 A/cm²). (a) nonpassivation, (b) SiO_2, (c) PSG, (d) Si_3N_4

length seems to decrease as the temperature increases.

Fig. 5(a) and 5(b) show the typical resistance change ratio(%) versus direct current stressing time of nonpassivated- and SiO_2 passivated Al-1%Si thin film interconnections with 400 μm length, respectively. In this study, the TTF values were determined at the current stressing time at 100% resistance change ratio, that is, electrically open state. The SiO_2 passivated Al-1%Si interconnections shows longer TTF value than the nonpassivated interconnection. Similar resistance changes were also observed in PSG passivated- and Si_3N_4 passivated Al-1%Si interconnections.

Activation energies for electromigration in Fig. 6 were calculated by taking Arrhenius plot of Black equation [7] from the measured MTF values and temperatures. The calculated activation energies were 0.44 eV, 0.66 eV, 0.50 eV, and 0.45 eV for the case of nonpassivation, SiO_2 passivation, PSG passivation, and Si_3N_4 passivation, respectively. The passivation on Al-1%Si interconnections results in the decrease of the EM induced mass transport at the interface between passivation overlayers and the

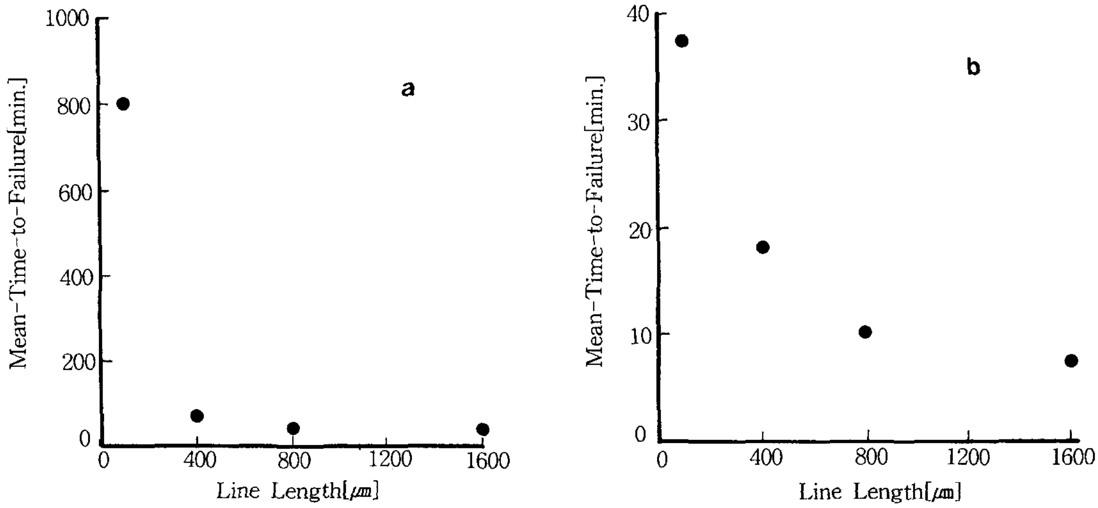


Fig. 4 MTF of nonpassivated Al-1%Si interconnections with various line lengths measured at (a) 60 ℃, (b) 100 ℃ (j=4.5×10^{6} A/cm^{2}).

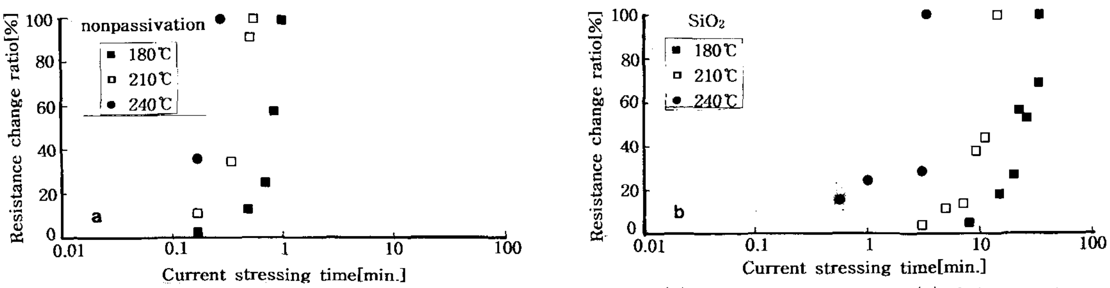


Fig. 5 Resistance change ratio(%) vs. current stressing time of (a) nonpassivated- and (b) SiO_2 passivated Al-1%Si interconnections (400 μm length, j=4.5×10^{6} A/cm^{2}).

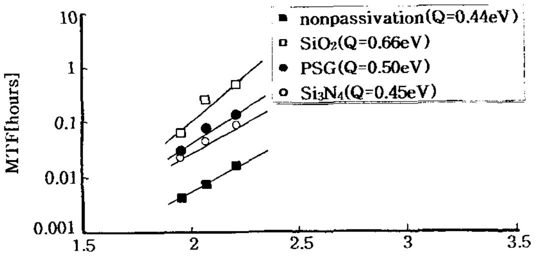


Fig. 6 Activation energies(Q) of nonpassivated-, SiO_2 passivated-, PSG passivated-, and Si_3N_4 passivated Al-1%Si interconnections (400 μm length).

Al-1%Si films. The passivation effects are believed to depend on the passivation materials as well as passivation thickness [10].

The passivation dependence on the EM characteristics is also observed in multilevel passivations in Al-1%Si interconnections. Fig. 7 shows the TTF versus cumulative failure percent in Si_3N_4/SiO_2/Al-1%Si/SiO_2/p-Si(100), $SiO_2/Si_3N_4/SiO_2$/Al-1%Si/SiO_2/p-Si(100), and SiO_2/PSG/SiO_2/Al-1%Si/SiO_2/p-Si(100) structures. Electron beam lithography was utilized for the patterning 4 μm wide, 1000 μm long, 700 nm thick straight lines and 12×36 μm^{2} rectangular shaped wide and narrow link lines as shown in Fig. 1. EM tests were performed at the temperature of 270 ℃ and at the current density of 3.15×10^{6} A/cm^{2}. Fig. 7(a) and 7(b) show the TTF values versus cumulative failure percent for the straight lines and the 12×36 μm^{2} rectangular shaped interconnections, respectively. The MTFs of straight lines for SiO_2/Si_3N_4, $SiO_2/Si_3N_4/SiO_2$, and SiO_2/PSG/SiO_2 are 17.8 min.(σ=0.39), 45.2 min.

(σ=1.23), and 76.7 min.(σ=0.39), respectively. The MTFs of the 12×36 μm^2 rectangular shaped interconnections for SiO_2/Si_3N_4, $SiO_2/Si_3N_4/SiO_2$, and SiO_2/PSG/SiO_2 are 18.2 min.(σ=0.30), 29.2 min.(σ=1.24), and 46.0 min. (σ=1.27), respectively. The shorter MTF values in 12×36 μm^2 rectangular patterns than straight lines are believed to be caused by the larger area change. The larger area change in 12×36 μm^2 rectangular shaped interconnections causes larger EM induced mass transport gradient, which results in easier formation of voids and hillocks at the depletion and accumulation region, respectively. In any cases, the SiO_2/PSG/SiO_2 passivation on Al-1%Si interconnections showed the best passivation effects on the EM resistance in this study. For all multilevel passivation structures used, the first passivation layers on Al-1%Si thin films were SiO_2. It is thus believed that the passivation sequences as well as the passivation materials also seem to influence on the EM characteristics in multilevel

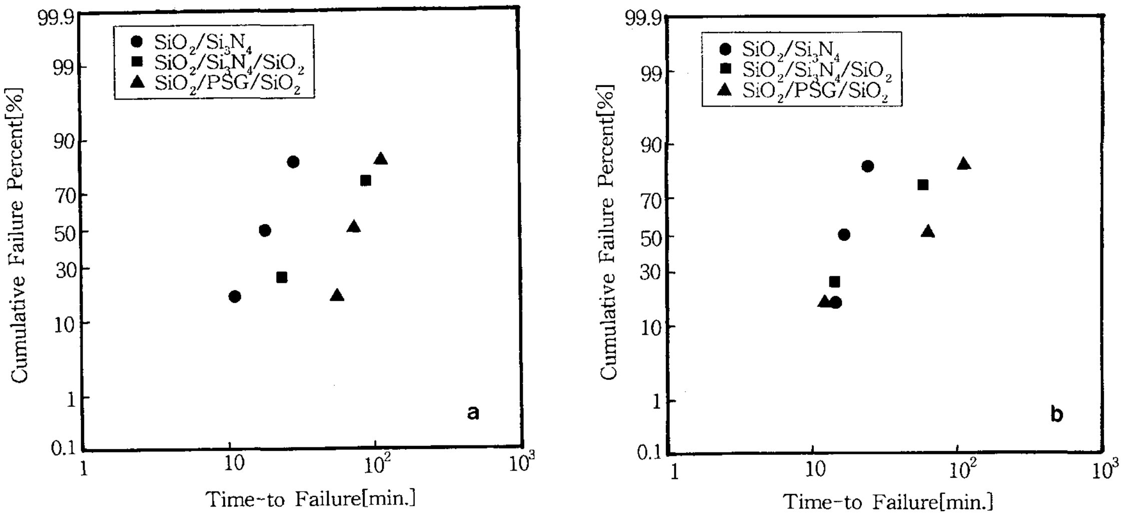


Fig. 7 TTF vs. cumulative failure percent(%) of SiO_2/Si_3N_4, $SiO_2/Si_3N_4/SiO_2$, and SiO_2/PSG/SiO_2 passivated Al-1%Si interconnections(1000 μm length, j=3.15×10^6 A/cm², T=270 ℃). (a) straight lines, (b) 12×36 μm^2 rectangular shaped interconnections.

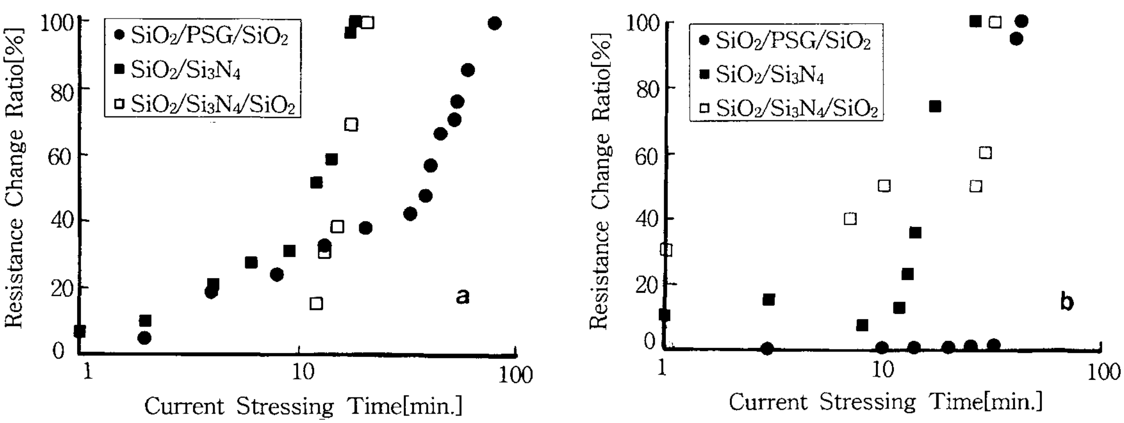


Fig. 8 Resistance change ratio(%) vs. current stressing time of SiO_2/Si_3N_4, $SiO_2/Si_3N_4/SiO_2$, and SiO_2/PSG/SiO_2 passivated Al-1%Si interconnections (1000 μm length, j=3.15×10^6 A/cm², T=270℃). (a) straight lines, (b) 12×36 μm^2 rectangular shaped interconnections

passivation structures. Good EM resistance characteristics of SiO_2/PSG passivation on Al-1%Si interconnections have been reported to be caused by the stress relaxation effects of the PSG layer on SiO_2 and the increased resistance effects to the moisture, etc. [11].

The typical resistance change ratio(%) versus current stressing time for variously passivated Al-1%Si interconnections for the straight line and for the 12×36 μm^2 rectangular patterns is shown in Fig. 8(a) and 8(b), respectively. As mentioned earlier, the TTF values were determined at 100% resistance change ratio, that is, electrically open state. The long TTFs in SiO_2/PSG/SiO_2 passivated Al-1%Si interconnections can be seen in both the straight lines and the rectangular patterns. Electromigration induced failures of cracks(voids) and surface extrusions(hillocks) are shown in Fig. 9(a) and 9(b), respectively.

Ⅳ. Conclusion

The experimental data presented in the preceeding sections lead to the following conclusions: (1) The calculated activation energies for electromigration were 0.44 eV, 0.45 eV, 0.50 eV, and 0.66 eV for the nonpassivated-, Si_3N_4 passivated-, PSG passivated-, and SiO_2 passivated Al-1%Si interconnections, respectively. (2) Thus passivation materials influence on the EM characteristics. Al-1%Si interconnections with the SiO_2 passivation show the best EM resistance characteristics in comparision with nonpassivation, PSG passivation, and Si_3N_4 passivation. (3) Passivation sequences as well as the passivation materials also seem to influence on the EM characteristics in multilevel passivation structures. (4) The interconnection line length dependence on the MTF shows a saturation tendency above the critical length which seems to decrease as the temperature increases.

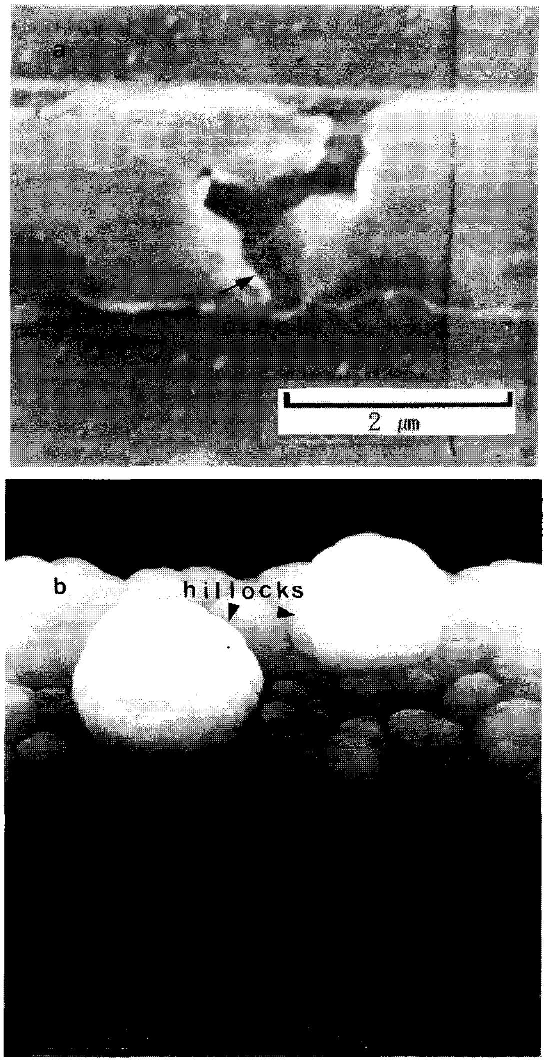


Fig. 9 SEM micrographs of (a) cracks(voids) and (b) hillocks formed after an EM test.

Acknowledgements

The present research has been conducted by the Research Grant of Kwangwoon University in 2001.

References

[1] T. Usui, T. Watanabe, S. Ito, M. Hasunuma, M. Kawai, and H. Kaneko, *Proceedings of the 37th IEEE International Reliability Physics Symposium*, 221 (1999).

[2] C. K. Hu, K. P. Rodbell, T. D. Sullivan, K. Y. Lee and D. P. Bouldin, IBM J. Res. Develop. **39**, 465 (1995).

[3] J. Proost, A. Witvrouw, and K. Maex, J. Appl.

Phys. **87**, 86 (2000).

[4] L. Arnaud, G. Tartavel, T. Berger, D. Mariolle, Y. Gobil, and I. Touet, Microelectron. Reliab. **40**, 77 (2000).

[5] L. Yau, C. Hong, and D. Crook, *Proceedings of the 23rd IEEE International Reliability Physics Symposium*, 115 (1985).

[6] L. E. Felton, J. A. Schwarz, R. W. Pasco, and D. H. Norbury, J. Appl. Phys. **58**, 723 (1985).

[7] J. R. Black, IEEE Trans. Electron Devices, **E-16**, 338 (1969).

[8] *Annual Book of ASTM Standards*, **10.04**, 671 (1989).

[9] H. Kawasaki, C. Lee, and T.K. Yu, Thin Solid Films, **253**, 508 (1994).

[10] B. N. Agarwala, M. J. Attardo, and A. P. Ingraham, J. Appl. Phys. **41**, 3954 (1970).

[11] S. Wolf, *Silicon Processing for the VLSI Era*, Vol. 2 (Lattice Press, California, 1990) p. 197.