Journal of the Korean Vacuum Science & Technology; JKVST
Vol.7, No.2, 2003, pp.39 ~ 44

Electromigration Characteristics in PSG/SiO_2 Passivated Al-1%Si Thin Film Interconnections

Jin Young Kim†

Department of Electronic Materials Engineering, Kwangwoon University
447-1 Wolgye-Dong Nowon-Ku, Seoul 139-701, Korea

(Received May 29, 2003)

Abstract

Recent ULSI and multilevel structure trends in microelectronic devices minimize the line width down to a quarter micron and below, which results in the high current densities in thin film interconnections. Under high current densities, an EM(electromigration) induced failure becomes one of the critical problems in a microelectronic device. This study is to improve thin film interconnection materials by investigating the EM characteristics in PSG(phosphosilicate glass)/SiO_2 passivated Al-1%Si thin film interconnections. Straight line patterns, wide and narrow link type patterns, and meander type patterns, etc. were fabricated by a standard photholithography process. The main results are as follows. The current crowding effects result in the decrease of the lifetime in thin film interconnections. The electric field effects accelerate the decrease of lifetime in the double-layered thin film interconnections. The lifetime of interconnections also depends upon the current conditions of P.D.C.(pulsed direct current) frequencies applied at the same duty factor.

Keywords : electromigration, thin film interconnection, PSG/SiO_2 passivation, Al-1%Si, pulsed direct current

1. Introduction

In a recent microelectronic device, the failures by the EM induced mass transport are of considerable interest specially in Al-alloy thin film interconnections having widths down to a quarter micron and below [1-2]. They cause the gradual formation of voids/hillocks at high current densities resulting in electrical opens/shorts in the circuit interconnections, respectively. Several factors such as geometry [3-4], current conditions [3-6], line dimensions [7-8], passivations [9-10], material selections [11-12] and microstructures [13-14], etc. are generally known to influence on the electromigration characteristics in thin film interconnections of a microelectronic device.

The purpose of this study is to improve the thin film interconnection materials by investigating the EM characteristics in PSG/SiO_2 passivated Al-1%Si thin film interconnections. The EM induced failures in current crowding structured interconnections, electric fields effects on the lifetime(MTF, Median-Time-to-Failure) in double-layered interconnections, EM characteristics under a D.C.(direct current) and a P.D.C. conditions in Al-1%Si thin film interconnections, etc. are discussed in this paper.

2. Experiment

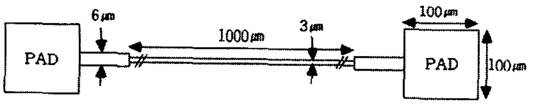
PSG(800 ㎚)/SiO_2(100 ㎚)/Al-1%Si(700 ㎚)/SiO_2(500 ㎚)/p-Si(100) substrate structures were used for EM characteristics. A typical photolithography process was applied for the fabrication of Al-1%Si thin film test patterns.

---

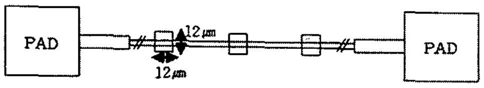
† E-mail : jykim@kw.ac.kr

The 700 ㎚ thick Al-1%Si thin films were sputter deposited onto 500 ㎚ thermally oxidized SiO_2 on p-Si(100). UV exposure was done at 300 mJ/㎠ after PR coating. RIE(Reactive Ion Etching, Cl_2 + BCl_3) was used for Al-1%Si(700 ㎚) etching. PSG(800 ㎚)/SiO_2(100 ㎚) passivations on top of Al-1%Si were formed by using an APCVD(atmospheric pressure chemical vapor deposition). Rectangular and diamond shaped wide and narrow link patterns with the dimensions of 1000 ㎛ long, 3 ㎛ wide, 0.7 ㎛ thick were utilized for the geometry effects. Test patterns used in this study are shown in Fig. 1.

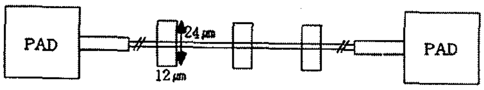
MTF was calculated from the TTF (Time-to-Failure) values which were taken at the current stressing time with the twice the resistance at the start, that is, 100% resitance change ratio. In order to study the line length dependence on the lifetime, Al-1%Si straight line patterns with the line lengths of 100, 400, 800, and 1600 ㎛ were fabricated. The line width of test patterns was 3 ㎛. The current densities applied were in the range of 10^6 to 10^7 A/㎠. Temperatures from a room temperature to 270 ℃ were utilized for an accelerated EM test. The electric field effects on the lifetime were examined between adjacent Al-1%Si interconnections with current stressed in the top interconnections and constant voltages of 0, ±30, ±60 applied between top and bottom interconnections. The current density stressed in the top Al-1%Si interconnections was 1.75×10^6 A/㎠. Fig. 2 shows the cross section and structure of EM test patterns used for the electric field effects. The TTF analysis under D.C. and P.D.C. conditions was performed by using meander type test patterns of PSG(800 ㎚)/SiO_2(100 ㎚) passivated Al-1%Si interconnections with the dimensions of 21080 ㎛ long, 3㎛ wide, 0.7 ㎛ thick, as appeared in Fig. 2(b). The current densities of 2×10^6 and $1x10^7$ A/㎠ were applied under a P.D.C. condition at the frequencies of 0.2 MHz and 1.0 MHz with a duty factor of 0.5.



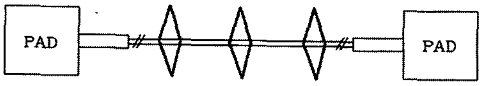
(a) straight line



(b) 12x12㎛^{2} square wide and narrow link



(c) 12x24㎛^{2} rectangular wide and narrow link



(d) 12x24㎛^{2} vertical diamond wide and narrow link

(e) 24x12㎛^{2}lateral diamond wide and narrow link

Fig. 1. Electromigration test patterns.

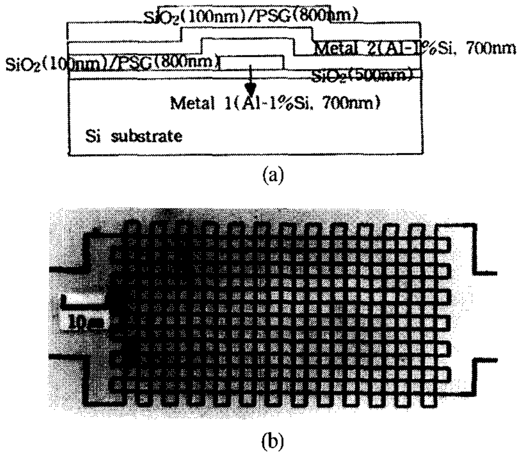


Fig. 2. Double layered electromigration test patterns: (a) schematic diagram of a cross section, (b) optical micrograph of a test stucture.

Voids and hillocks were observed using a SEM (scanning electron microscope). SEM samples were prepared without removing passivation layers from Al-1%Si thin film interconnections.

3. Results and discussion

Figure 3(a) shows the TTF versus cumulative failure

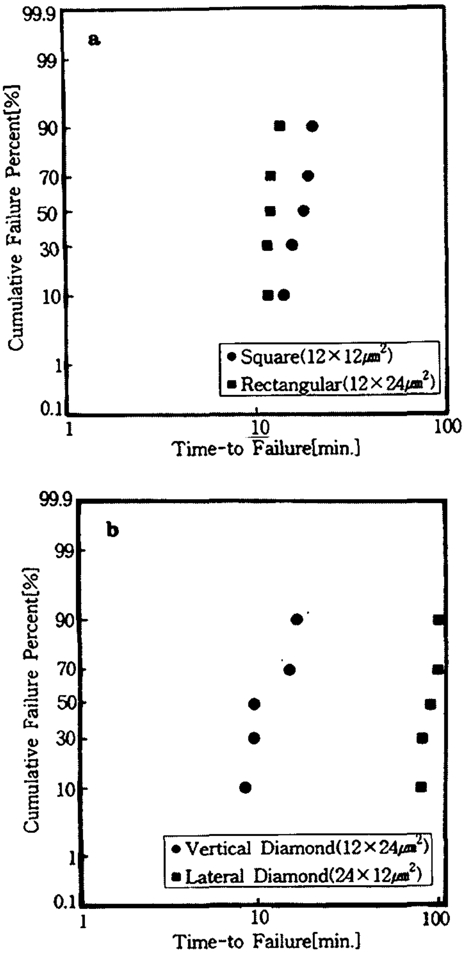


Fig. 3. TTF vs. cumulative failure percent(%) of Al-1%Si interconnections with geometry effects structures (j=4.5×10^6 A/cm², 270 ℃): (a) 12×12 μm^2 square shaped wide and narrow link interconnections, (b) 12×24 μm^2 rectangular shaped wide and narrow link interconnections.

percent of 12×12 μm^2 square- and 12×24 μm^2 rectangular shaped wide and narrow link interconnections (as shown in figure 1b and 1c, respectively) after stressing D.C. 4.5×10^6 A/cm² at 270 ℃. The MTF of a square shaped interconnection was 17.15 min. (σ=0.16) and that of a rectangular shaped interconnection was 12.07 min. (σ=0.07). The short MTF values in this study compared with conventional EM failure times are believed to be caused by the high current densities stressed at elevated temperatures up to 270 ℃ for an accelerated EM test. The shorter MTF value in a 12×24 μm^2 rectangular shaped pattern is believed to be caused by the larger area change in interconnections than 12×12 μm^2 square patterns. The larger area change in interconnections causes larger EM induced mass transport gradient, which results in easier formation of voids/hillocks at the depletion region/ accumulation region, respectively. These cause the EM induced failures in thin film interconnections.

Such geometry effects on the EM characteristics can be also observed in the diamond shaped wide and narrow link interconnections with the same area as 12×24 μm^2 rectangular patterns but the different directions each other as shown in Fig. 1(d) and 1e. The vertical diamond shaped pattern of Fig. 1(d) is expected to cause larger EM induced mass transport gradient than the lateral diamond shaped pattern of Fig. 1(e). This is observed and demonstrated in Fig. 3(b). The MTF value of 11.36 min. (σ=0.32) for the vertical diamond pattern appeared much shorter than that of 90.26 min. (σ=0.12) for the lateral diamond pattern. It is also noted that the MTF value of the straight line in Fig. 1(a) was measured at 100.5 min. (σ=0.72) which was longer MTF value than those of the other interconnections with the current crowding structured patterns in Fig. 1(b)-1(e). Thus the current crowding effects result in the decrease of the lifetime due to the increased EM induced mass transport gradient in thin film interconnections. Voids and hillocks formed in wide and narrow link interconnecions after an EM test are seen in Fig. 4(a) and 4(b), respectively. Voids(depletion of material) near the cathode and hillocks(accumulation of material) near the anode were observed.

Figure 5 depicts the line length dependence of MTF in PSG(800 nm)/SiO$_2$(100 nm) passivated Al-1%Si thin film interconnections measured at the current density of 4.5×10^6 A/cm². The MTF decreases rapidly in case of relatively short line lengths up to about 400 μm. However, the MTF does not seem to decrease further but does seem to saturate in case of relatively long

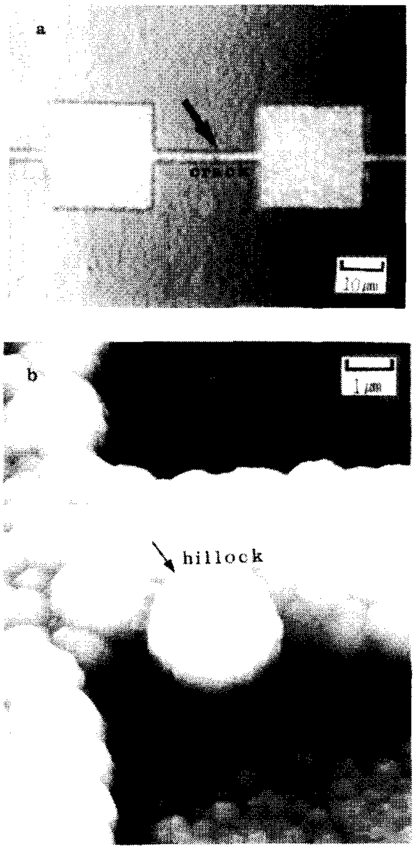


Fig. 4. (a) Cracks(voids) and (b) hillocks formed in wide and narrow link thin film interconnections after an EM test.

line lengths above about 800 μm. Thus the MTFs initially decrease with increase of the line length and then attain saturation above a critical length showing an empirical relationship of the following form: MTF $\propto$ exp (α/l), where α is a constant dependent on width and l is the line length [8]. 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. The saturation tendency of the MTF at longer lengths can be explained by assuming the existence of the severe defects which will be limitly contained in thin film interconnections above the critical line length [8]. Although the sigma is expected to be decreased at longer lines in this case, that could not be confirmed in this study because of the limited number of EM test samples.

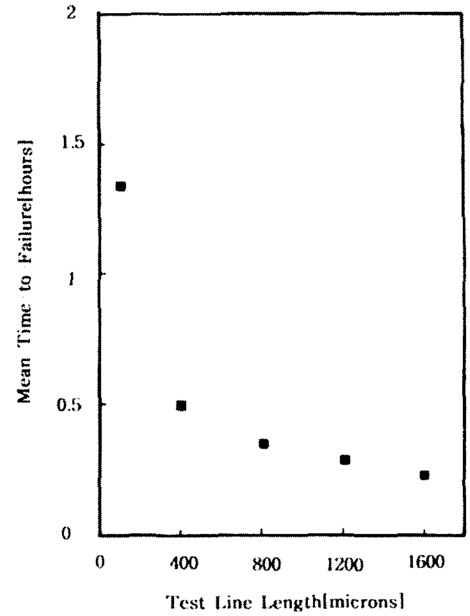


Fig. 5. MTFs of Al-1%Si thin film interconnections with various line lengths from 100 μm to 1600 μm (j=4.5×10^6 A/cm²)

Multilevel thin film interconnections are of a great interest for the continuing integration in a microelectonic device. Electric field effects may occur during operation in such a device. Electric field effects were examined by using an EM test pattern as shown in Fig. 2. Fig. 6 shows the relative mean lifetimes of the top Al-1%Si thin film interconnections at the current density of

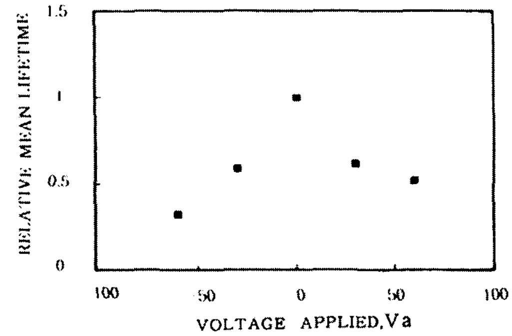


Fig. 6. Relative mean lifetime of the top Al-1%Si thin film interconnections at various voltages applied between bottom and top interco-nnections

1.75×10^6 A/㎠ under the electric field stressed between top and bottom inerconnections. The relative mean lifetime under the electric field decreased relative to that without electric field. The increase of the mass transport by EM is believed to be caused by the local increase of the current densities in the top conducting lines due to the diffraction of electrons under the electric fields stressed [17].

The dependence of current conditions on the EM characteristics is known to be longer lifetime at lower current density [15] and longer lifetime at P.D.C. conditions than at D.C. conditions [6]. Fig. 7 demonstrates that

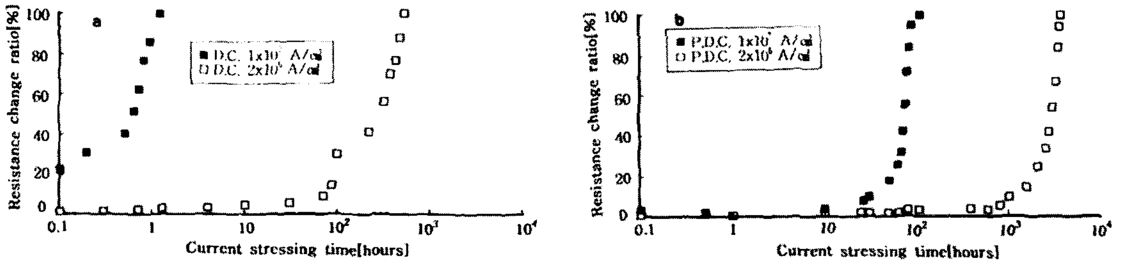


Fig. 7. (a) Resistance change ratio(%) vs. current stressing time at $j=2\times10^6$ A/㎠ and $j=1\times10^7$ A/㎠ under a D.C. condition (b) Resistance change ratio(%) vs. current stressing time at $j=2\times10^6$ A/㎠ and $j=1\times10^7$ A/㎠ under a P.D.C. condition.

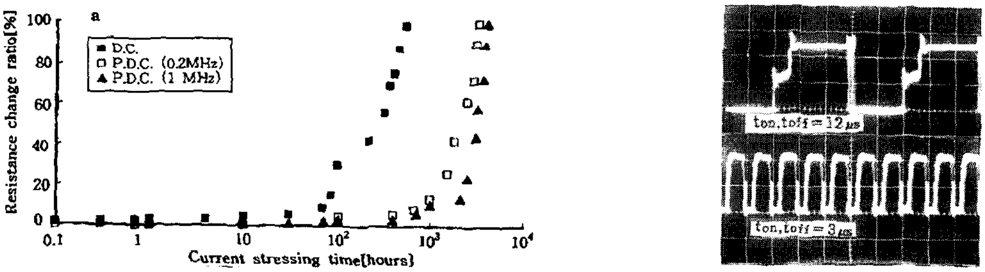


Fig. 8. (a) Resistance change ratio(%) vs. current stressing time at $j=2\times10^6$ A/㎠ under a D.C., 0.2 MHz P.D.C. and 1.0 MHz P.D.C. conditions (b) Applied wave forms of 0.2 MHz (ton, toff = 12 μs) and 1.0 MHz ((ton, toff = 3 μs) with the duty factor of 0.5.

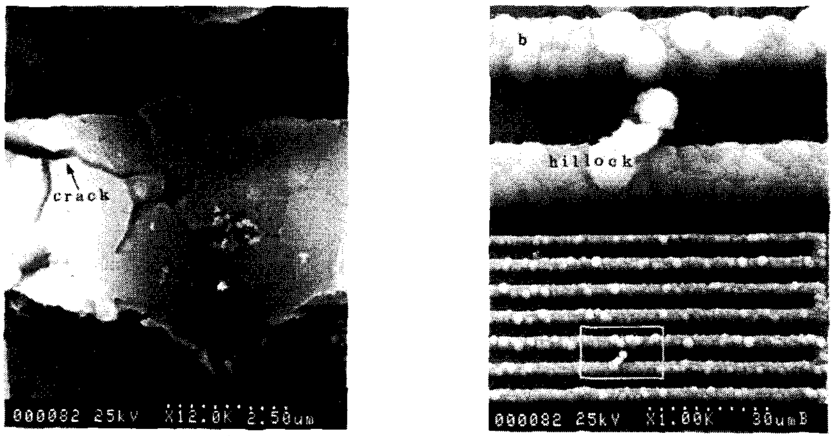


Fig. 9. SEM micrographs of (a) cracks(voids) and (b) hillocks formed after an EM test at P.D.C. conditions.

the TTF at 2×10^6 A/㎠ is longer than the TTF at higher current density of $1\text{x}10^7$ A/㎠ both in a D.C. and in a P.D.C. with the frequency of 0.8 MHz as commonly predicted [15]. It is also observed in Fig. 8(a) that the TTF under a P.D.C. condition increases with increasing the frequencies from 0.2 MHz to 1.0 MHz at a constant duty factor of 0.5 as appeared in Fig. 8(b). Thus the lifetime of thin film interconnections also depends upon the frequencies applied under a P.D.C. condition at the same duty factor. SEM micrographs in Figs. 9(a) and 9(b) show cracks(voids) and hillocks formed after a P.D.C. EM test, respectively. Voids near the cathode and hillocks near the anode were generally found.

4. Summary

The experimental data presented in the preceding sections lead to the following conclusions: (1) The current crowding effects result in the decrease of the lifetime in thin film interconnections. (2) The electric field effects accelerate the decrease of lifetime in multilevel thin film interconnections. (3) The lifetime of thin film interconnections depends upon the P.D.C. frequencies applied at the same duty factor.

Acknowledgements

The present research has been conducted by the Research Grant of Kwangwoon University in 2002.

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] D. W. Malone and R.E. Hummel, J. Appl. Phys. **83**, 5750 (1998).

[4] H. S. Rathore, R. G. Filippi, R. A. Wachnik, J. J. Estabil, and T. Kowk, Second International Stress Workshop on Stress Induced Phenomena in Metallization, American Institute of Physics, New York, 165 (1994).

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

[6] L. M. Ting, J. S. May, W. R. Hunter, and J. W. McPherson, Proceedings of the 31st IEEE International Reliability Physics Symposium, 311 (1993).

[7] G. Rajagopalan, M. L. Dreyer, N. D. Theodore, and T. S. Cale, Thin Solid Films **270**, 439 (1995).

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

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

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

[11] K. L. Lee, C. K. Hu, and K. N. Tu, J. Appl. Phys. **78**, 4228 (1995).

[12] A. G. Dirks, R. A. Augur, and A. E. M. De Veirman, Thin Solid Films **246**, 164 (1994).

[13] S. Kondo, O. Deguchi, and K. Hinode, J. Appl. Phys. **78**, 6534 (1995).

[14] J. A. Nucci, Y. S. Diamond, and J. E. Sanchez, Jr., Appl. Phys. Lett. **66**, 3585 (1995).

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

[16] *Annual Book of ASTM standards*, **10.04**, 671 (1989).

[17] T. Wada, H. Higuchi, and T. Ajiki, IEEE Trans. Reliabil. **R-34**, 2 (1985).