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 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 photolithography 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 nm)/SiO$_2$(100 nm)/Al-1%Si(700 nm)/SiO$_2$(500 nm)/ 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 nm thick Al-1%Si thin films were sputter deposited onto 500 nm thermally oxidized SiO2 on p-Si(100). UV exposure was done at 300 mJ/cm² after PR coating. RIE (Reactive Ion Etching, Cl₂ + BCl₃) was used for Al-1%Si(700 nm) etching. PSG(800 nm)/SiO2(100 nm) passivations on top of Al-1%Si were formed using an APCVD (atmospheric pressure chemical vapor deposition). Rectangular and diamond shaped wide and narrow link patterns with the dimensions of 1000 μm long, 3 μm wide, 0.7 μm 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% resistance 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 μm were fabricated. The line width of test patterns was 3 μm. The current densities applied were in the range of 10⁶ to 10⁷ A/cm². Temperatures from a room temperature to 270 °C 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 1.75×10⁵ A/cm². 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 nm)/SiO2(100 nm) passivated Al-1%Si interconnections with the dimensions of 21080 μm long, 3μm wide, 0.7 μm thick, as appeared in Fig. 2(b). The current densities of 2×10⁶ and 1×10⁷ A/cm² were applied under a P.D.C. condition at the frequencies of 0.2 MHz and 1 MHz with a duty factor of 0.5.

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
Electromigration Characteristics in PSG/SiO$_2$ Passivated Al-1%Si Thin Film Interconnections

![Graph](image)

Fig. 3. TTF vs. cumulative failure percent(%) of Al-1%Si interconnections with geometry effects structures (i=4.5×10$^6$ A/cm$^2$, 270 °C): (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/cm$^2$ at 270 °C. 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 °C 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 1(e). 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 interconnections 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/cm$^2$. 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 ∝ exp (a/l), where a 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 limilly 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.

Multilevel thin film interconnections are of a great interest for the continuing integration in a microelectronic 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

![Graph showing 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)]

![Graph showing Relative mean lifetime of the top Al-1%Si thin film interconnections at various voltages applied between bottom and top interconnections]

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)

Fig. 6. Relative mean lifetime of the top Al-1%Si thin film interconnections at various voltages applied between bottom and top interconnections
1.75 × 10^6 A/cm² under the electric field stressed between top and bottom interconnections. 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 × 10^6 A/cm² and j = 1 × 10^7 A/cm² under a D.C. condition (b) Resistance change ratio(%) vs. current stressing time at j = 2.0 × 10^6 A/cm² and j = 1.0 × 10^7 A/cm² under a P.D.C. condition.

Fig. 8. (a) Resistance change ratio(%) vs. current stressing time at j = 2 × 10^6 A/cm² 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 $2 \times 10^5 \text{ A/cm}^2$ is longer than the TTF at higher current density of $1 \times 10^5 \text{ A/cm}^2$ 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 thick 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