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A New Application of Al-Si Films Coated with $TiSi_2$ in VLSI Multi-Level Interconnections

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Hillock-free and higher electromigration resistant interconnection has been developed by $TiSi_2$ coating onto Al-Si films. X-ray diffractometer traces and auger depth profile measurements showed the formation of $Ti_7Al_5Si_{12}$ compounds near the surface of Al-Si films. Both the hillock growth and the electromigration were inhibited by this ternary compounds which suppresses the Al atom migration along grain boundaries in Al-Si films. The activation energy of Al-Si/$TiSi_2$ interconnection was 0.83eV. The estimated MTF values of Al-Si/$TiSi_2$ conductors at condition of 85°C and $1X10^6$ A/cm^2 were 36.5 years which was twenty five times as long as that of Al-Si.

1. Introduction

In VLSI logic and memory devices, multi-level interconnection technology comes to be one of key technologies to reduce the interconnection resistsnce in effect and to make CAD in pattern layouts easy. Main problems in the technology are as follows; (1) discontinuities of Al conductors at steps of inter-level insulator caused by underlying Al conductors, (2) poor step coverage of Al films at via hole edges, (3) hillock growth on Al conductors which reduces the dielectric breakdown strength of interlevel insulater, (4) electromigration failure of Al fine lines.

Problems (1) and (2) were worked out by a new planarization and a round etching in which reactive ion etching technique was employed.[1] A number of works has been investigated for the other two problems over ten years. However it appears that there does not exist a perfect solution which satisfies suppression of hillock growth as well as improvement of electromigration.

This paper describes,first,the limitation of Al-Si conductors in electromigration resistance and, second,the features of Al-Si/$TiSi_2$ films which show no Al hillock growth and remarkable improvements in electromigration resistance.

2. Experimental Procedures

Al-1%Si films were deposited onto oxidized silicon wafers by dc magnetron sputtering. Two kinds of Al-Si films different in grain size (1) 1.7-2.4 µm and (2) 0.5-0.9 µm were prepared for electromigration test by different sputtering systems. Subsequently,$TiSi_2$ films were deposited on Al-Si films by sputtering hot pressed $TiSi_2$ target. Al-Si/$TiSi_2$ films had a layered structure of Al-Si(0.7µm thickness,large grain) / $TiSi_2$(300 Å) / Al-Si(500Å).

Al conductors (5mm length and 1-3µm width) were patterned by RIE(reactive ion etching). After the deposition of passivation films (1.0µm PSG), the patterned wafers were annealed in the forming gas (N_2+ H_2) at 450°C, 30 min prior to electromigration testing. Accelerated electromigration tests were carried out at a current density of 5 $X10^5$, 1 $X10^6$, and 2 $X10^6$ A/cm^2 in the 150°C to 250°C ambience.

An X-ray diffraction analysis was made on Al-Si /$TiSi_2$ film structure before and after a 450°C heat treatment. Auger depth profiles of Al,Si, and Ti were measured on the Al-Si/$TiSi_2$ films.

Hillock growth was observed after a 500°C , 20 min annealing in N_2 using scanning electron microscopy (SEM). The effect of hillocks in Al films on the integrity of inter-level insulator were examined by measuring the breakdown voltage distribution of LPCVD-SiO_2 (0.5µm thickness) on Al-Si and Al-Si/$TiSi_2$ films.

3. Results and Discussion

3.1. Electromigration of Al-Si(1%) conductors

In VLSI metallization, aluminum interconnection

width tends to be less than 1.5 μm and it is recognized that the electromigration will become one of the primary failure mode limitting the reliability of aluminum conductors. We examined the electromigration of Al-Si conductors with varying line width (1-3 μm) and thickness (0.4-0.8 μm). The lifetime of Al conductors has been theoretically[2] as well as experimentally[3] described to decrease lineary with line width. However, there was observed a reversal of trend with decreasing line width. This variation in lifetime with line width of Al-Si(1.7-2.4μm grain size) conductors is shown in Fig.1. Also, the electromigration lifetime as a function of conductor cross section (line width X film thickness) is shown in Fig.2 for two kinds of Al-Si films different in grain size.

In large grained Al-Si films the dependence of MTF on the conductor cross section was relatively weak. On the other hand, in small grained films, it was strong and MTF increased with decreasing the cross section in the range of below 1.0 μm^2. Recently, Schoen[4] reported the results of Monte Carlo calculations of structure-induced electromigration failures in Al and Al-alloy films. His results shows that lifetime is very dependent on grain size and line width. The results in Fig. 1 and Fig.2 are consistent with his caluculation.

Another important fact in Fig.2 is that the MTF values extrapolated to the case (cross section=0)

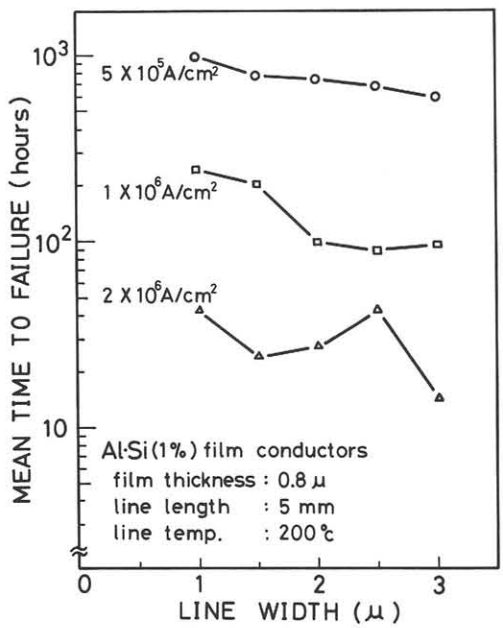

Fig.1. Sputtered Al-1%Si(large grain) MTF as a function of line width.

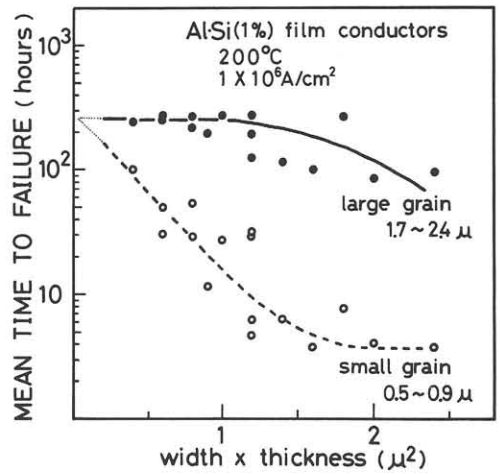

Fig.2. Correlation of MTF for Al-1%Si conductors with cross section (line width X film thickness).

for a large grain case (solid line) and a small grain case (dotted line) coincide with each other. This implies that there exists a limitation of Al-Si conductor lifetime regardless of grain size, and that the large grained Al-Si used in this experiment reaches the limit of lifetime. Consequently, further increase of the lifetime of Al-Si conductors is not able to be expected by employing Al-Si films only. The beneficial effect of Cu additions on the lifetime of Al film conductors was well known and Al-Si-Cu conductors would be applicable for VLSI interconnections.[5] However, it is not suitable for the application to VLSI multi-level interconnections, since a number of hillock growth takes place in Al-Si-Cu films during annealing.

3.2. Characteristics of Al-Si/$TiSi_2$ films

3.2.1. Hillock growth of Al-Si/$TiSi_2$ films

SEM micrographs of Al-Si and Al-Si/$TiSi_2$ films after a 500°C, 20 min annealing in N_2 are shown in Fig.3. There exists a number of hillocks larger than 1 μm size in Al-Si films, on the otherhand, Al-Si/$TiSi_2$ films show dramatic improvements in surface morphology and have no hillocks. Figure 4 shows the dielectric breakdown histgrams of LPCVD-SiO_2 film of 0.5 μm thickness deposited on Al-Si, Al-Si/$TiSi_2$ films, and a silicon substrate as a reference (no aluminum films). The breakdown voltage of Al-Si films is distributed below 100 V after a 450°C , 20 min annealing in forming gas, and this is due to the crack formation in LPCVD-SiO_2 caused by the hillock growth in Al-Si films.

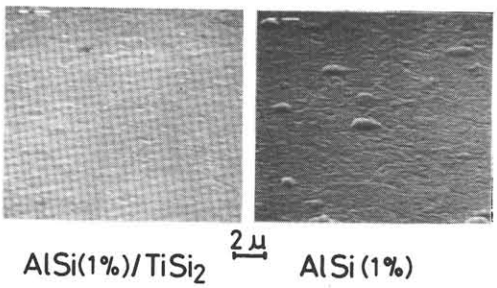

Fig.3. Scanning electron micrographs of Al-Si/$TiSi_2$ and Al-Si films after 20 min , 500°C annealing.

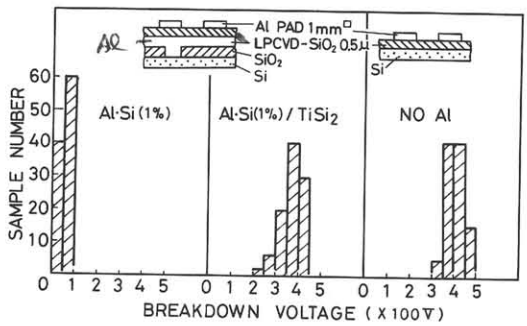

Fig.4. Breakdown voltage distribution of inter-level insulator (LPCVD-SiO_2, 0.5 μm thickness) after a 450°C annealing.

On the other hand, in the case of Al-Si/$TiSi_2$, the breakdown voltage distributed in the range of from 250 to 450 V. This breakdown voltage distribution is similar to that of SiO_2 film deposited directly on silicon substrate (no Al) where breakdown voltage is distributed in the range of 300 to 500 V as shown in Fig.4. This indicates that the hillock growth is almost suppressed in Al-Si/$TiSi_2$ films.

We investigated the X-ray diffraction spectrum of Al-Si/$TiSi_2$ films before and after a 450°C heat treatment to make the suppression mechanism for hillock growth clear. The results suggest that $Ti_7Al_5Si_{12}$ are formed after annealing as shown in Fig.5 and,from auger depth profile measurements , the formation of this Ti-Al-Si ternary compound is confirmed to be confined only to the surface region. Figure 6 is a schematic representation of the formation of Ti-Si-Al ternary compound, and it is conceivable that this compound formation proceeds also along the grain boundaries. The Al atom migration caused by thermal annealing is inhibited by this Ti-Si-Al ternary compound, which leads to the hillock growth suppression in the Al-Si films coated with $TiSi_2$ films.

3.2.2. Electromigration of Al-Si/$TiSi_2$ conductors

Electromigration life tests were carried out

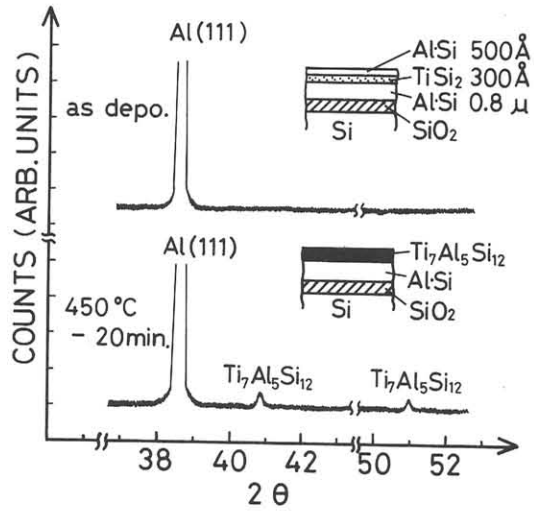

Fig.5. X-ray diffraction analysis of Al-Si/$TiSi_2$ films before and after annealing.

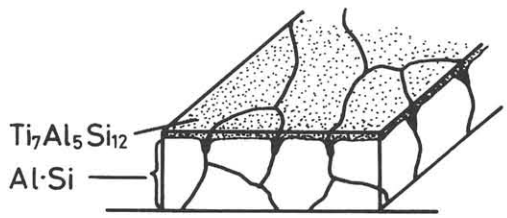

Fig.6. A schematic representation of Al-Si/$TiSi_2$ films after thermal annealing.

for Al-Si(large grain)/$TiSi_2$ conductors at a condition of 1 $X10^6$ A/cm^2,200°C. MTF values as a function of line width are shown in Fig.7 for the case of Al-Si/$TiSi_2$,Al-Si(large grain), and Al-Si (small grain). The MTF values of Al-Si/$TiSi_2$ is the longest of the three, and the lifetime of Al-Si /$TiSi_2$ are about three times as large as those of Al-Si(large grain). Thus, $TiSi_2$ coating improved the lifetime of Al-Si conductors as well as the suppression of hillock growth.

Figure 8 shows Arrhenius plot of MTF for Al-Si/ $TiSi_2$ and Al-Si(large grain). The activation energy in Al-Si conductors is 0.54 eV which is cosidered as an activation energy of grain bounday diffusion of Al in the previous other works.[6),7)] On the other hand, the activation energy in Al-Si/$TiSi_2$ conductors is 0.83 eV. This means that,for the electromigration in Al-Si/$TiSi_2$, Al bulk diffusion is more dominant than grain boundary diffusion, which would be caused by the inhibition for atom migration along grain boundary by the Ti-Si-Al ternary compound formation at

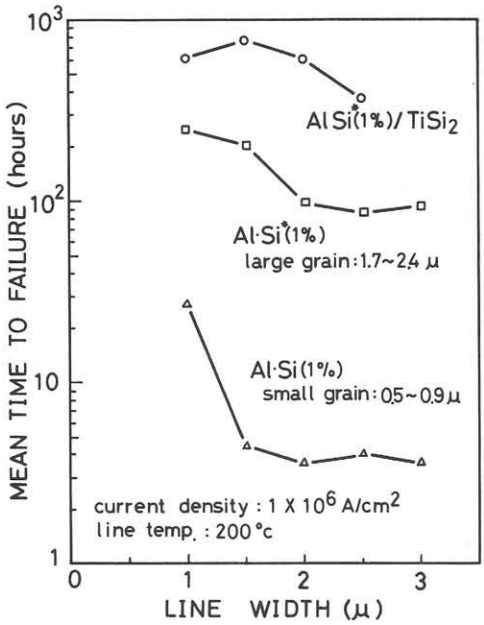

Fig.7. MTF for two kinds of Al-Si conductors and Al-Si/$TiSi_2$ conductors as a function of line width.

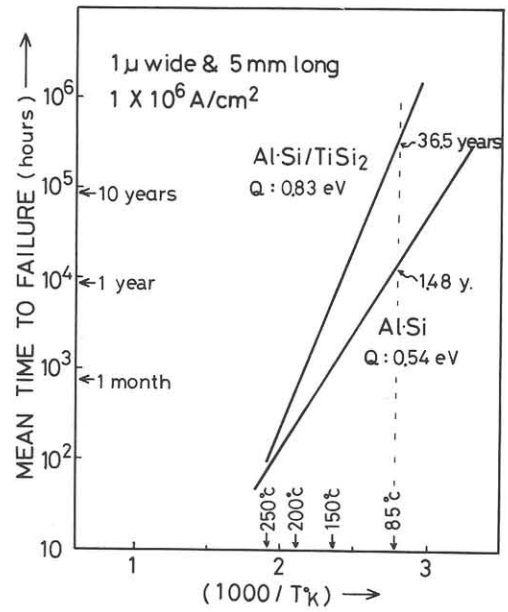

Fig.8. Arrhenius Plots of MTF vs.(1000/T k) for Al-Si/$TiSi_2$ and Al-Si film conductors.

grain boundaries of Al-Si films. As a results, the MTF value extraporated to the condition of 85 °C and 1 X10^6 A/cm^2 is 36.5 years and this value is about 25 times as long as that of Al-Si conductors.

4. Summary

Al-Si/$TiSi_2$ films was studied from a standpoint of their application to VLSI multi-level metallization. After the deposition of $TiSi_2$ onto Al-Si films, Ti-Si-Al ternary compound is formed near the surface of Al-Si films as well as along the Al-Si grain boundaries with annealing. Ti-Si-Al compound has an effect of suppressing hillock growth and inhibitting Al atom migration under current stress. The activation energy of the electromigration in Al-Si/$TiSi_2$ was 0.83 eV and the estimated MTF value at condition of 85°C and 1 X10^6 A/cm^2 is 36.5 years which is 25 times as long as the lifetime in Al-Si.

From these results, the Al-Si/$TiSi_2$ films was proved to be excellent conductor material for VLSI multi-level interconnections.

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Al-Cu 29.5y 0.7eV
Al-Si/TiSi2 36.5y 0.83eV
Al 0.15y 0.43eV
Al-Si 1. y