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Electromigration in a Single Crystal Submicron Width Aluminum Interconnection

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Electromigration properties of a single crystal submicron width aluminum interconnection formed on Si(111) have been examined by resistance change measurements and newly developed drift velocity measurements. It has been revealed that a single crystal aluminum has extremely high endurance against electromigration induced open circuit failures compared with polycrystal copper and aluminum. The mechanism of high endurance is considered to be the high uniformity of atom flux. It is strongly suggested that a single crystal aluminum has high potential for future ULSIs where a high current density will be operated.

1.Introduction

One of the most important reliability problems of thin film metallurgy in LSI is electromigration (EM) induced open circuit failures. Since the current density of an interconnection inevitably increases with further scale shrinkage, EM induced failures become more serious in ULSIs of lower submicron scales. It is commonly considered that a failure by EM occurs at grain boundaries due to flux divergences of migrating atoms. Hence, it would be desirable to eliminate grain boundaries for an improvement of EM endurance. The object of this work is to examine the EM endurance of a single crystal submicron width aluminum interconnection, with a view of future interconnection materials in ULSIs. A standard EM accelerating test has been accomplished for a single crystal aluminum interconnection in comparison with polycrystal aluminum and copper interconnections. Furthermore, newly developed drift velocity measurements of void have been carried out in order to understand mechanisms of high EM endurance of single crystal aluminum.

2.Experimentals

A single crystal Al (111) film was deposited on Si(111) substrate of high resistivity (2000 Ωcm) by gas temperature controlled CVD technique[1]. A polycrystal Al film was deposited by the DC magnetron sputtering method onto a similar substrate. The Al film thicknesses were 0.8 μm. Then both Al films were patterned into the same size of 500 μm length and 0.77 μm width.

The interconnections were patterned so that the line directions were perpendicular to the plane including the $\langle 111 \rangle$ and $\langle 1\bar{1}1 \rangle$ axes of the single crystal Al film.

A 0.4 μm thick polycrystal copper film was deposited by the DC magnetron sputtering method onto a 1500 A Al_2O_3 film, which was formed on a 8000 A thick thermal SiO_2 by reactive sputtering. Then, it was patterned by the wet etching method using $(NH_4)_2S_3O_8$. The dimensions of the copper interconnection was 500 μm in length and 1.5 μm in width, so that the cross-sectional areas of Cu and Al were almost the same.

The mean grain sizes of polycrystal copper and aluminum were 0.3 and 0.2 μm, respectively.

The current density for the electromigration accerelating test was $1x10^7$ A/cm^2, and the ambient temperature was 150 ℃. The Al interconnections were unannealed before the test and unpassivated. The copper interconnection was also unannealed but covered with a 8000 A thick sputtered SiO_2 film so as not to be oxidized.

For measurements of EM drift velocity, movement of voids in single crystal aluminum have been observed by SEM. The drift velocity V_d of atom flux has been formulated by

$$V_d = DZ^* eE / kT \qquad (1)$$

where D is the self-diffusion coefficient, E is the electric field, and Z^*e is the effective charge of the ion.[3] Void movement directly reflects the atom flux, since it is pursued by the mass depletion at the cathode site of it and the mass accumulation at the anode site. In order to eliminate the influence of aluminum-oxide formed on void surfaces, stess induced voids [2] were introduced by the deposition of CVD SiO_2 film on single crystal aluminum interconnections. In unpassivated cases, void movements were prohibited by the existance of aluminum oxide on the void surfaces. Then CVD SiO_2 film was thinned to the thickness less than 1000 A so as to enable SEM observations through it.

Displacements of void after DC current stressing test (the current density $1x10^7$ A/cm^2, and the temperature between 100℃ and 200℃) have been measured by SEM. Markers of 1 μm diameter have been engraved at interval of 10 μm in the vicinity of each void by focused Ga ion beam.

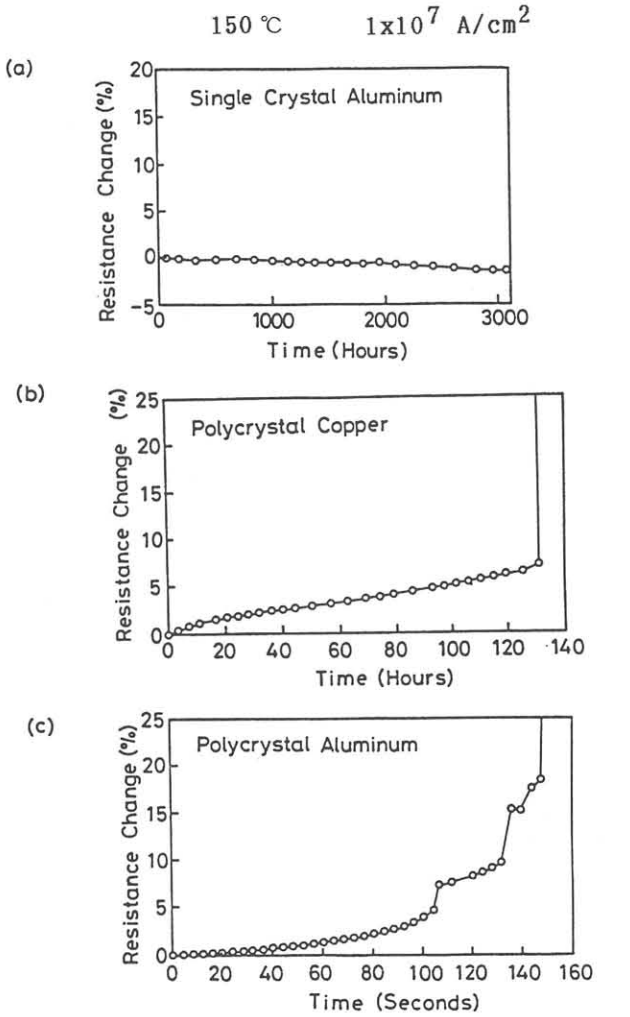

Fig.1 Resistance changes of (a) single crystal aluminum, (b) polycrystal copper, and (c) polycrystal aluminum during electromigration accerelating test.

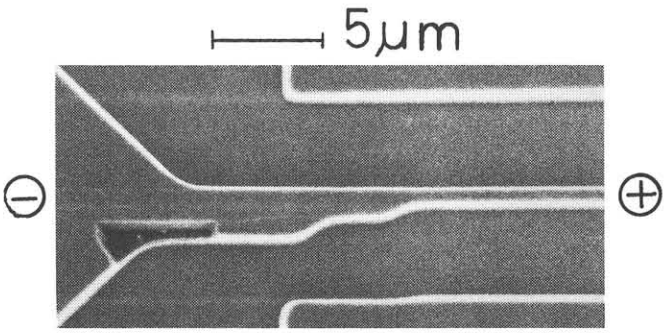

Fig.2 SEM observation of the void, which was formed at the cathode pad after 3100 hours electromigration test in the single crystal aluminum.

3.Results

The EM accelerating test had been continued until 3100 hours passed since the start. The resistance changes of single crystal aluminum, polycrystal copper, and polycrystal aluminum are shown in Figs. 1-(a),(b), and (c), respectively. The single crystal aluminum did not disconnect during the test, while the times to failure (TTF) of polycrystal copper and aluminum were 135 hours and 150 seconds, respectively. It is noticeable that the single crystal aluminum exhibited a slight decrease (nearly 1%) in resistance during the 3100 hours, but polycrystal copper and aluminum exhibited resistance increases of more than 5 % before failures. The resistance decrease observed in the single crystal aluminum is supposed to be due to annealing out of defects.

The SEM photograph of single crystal aluminum after the test is shown in Fig.2. It is noticeable that a void surrounded by {111} facets was formed at the cathode pad. There were little damages in the middle of the line. The in-situ observation using SEM revealed that the void at cathode pad had grown by the accumulation of many chamfer-like voids formed in the line.

Figure 3 shows the void movement during 20 hours test at 120 ℃. A chamfer-like void in Fig.3-a moved to the cathode direction and elongated (Fig.3-b). Displacement of the middle point of the void was 1.0 μm. Temperature dependencies of drift velocity thus obtained are shown in Fig.4. Movement of void toward cathode direction has been observed in every case. The activation energy for the void movement has been found to be 0.62 eV.

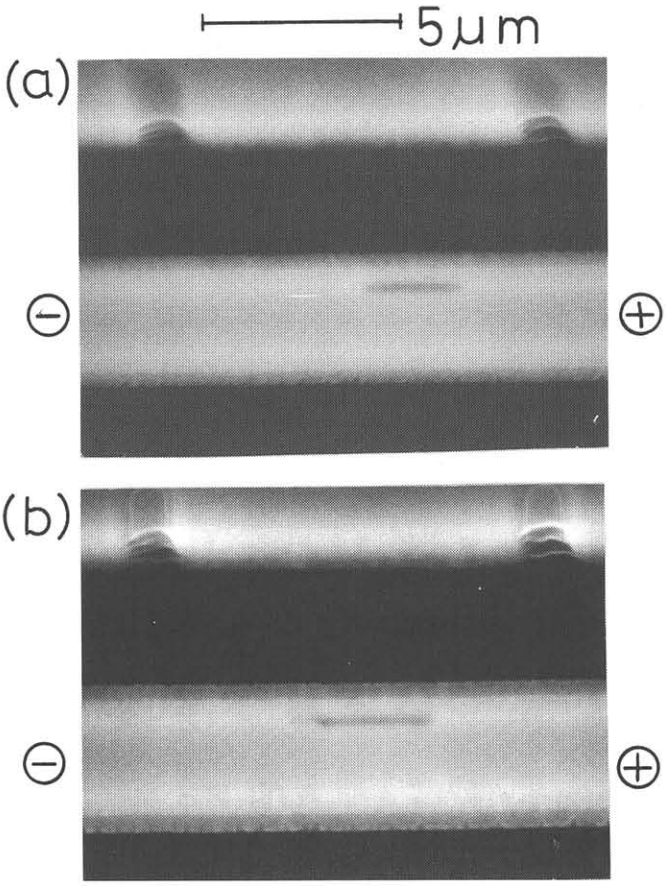

Fig.3 SEM observations of the void movement. (a) Before the test. (b) after 20 hours test. The temperature was 120 ℃, and the current density was $1 \times 10^7 A/cm^2$.

4.Discussions

It is considered that the extremely high endurance against EM of single crystal aluminum is attributed to the high uniformity of atom flux. The fact that void moved along long distance to the cathode pad suggests that there were scarcely any flux divergences. In polycrystal interconnections, flux divergences originated at grain boundaries are so large that open circuit failure due to void growth takes place before a void reaches the cathode pad.

The activation energy measured by the void drift velocity (Ea=0.62eV) is between that of ideal surface diffusion (Ea=0.28 eV) and of lattice diffusion (Ea=1.4eV).[4] It is speculated that diffusion of atoms at interface between aluminum-oxide and aluminum plays the essential role for the

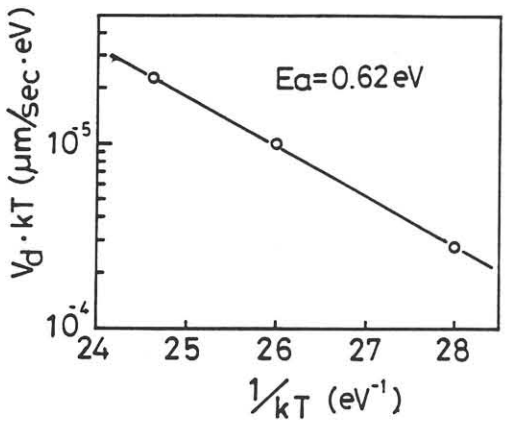

Fig.4 Temperature dependence of the void drift velocity.

void movement.

It should be noted that the observed activation energy did not necessarily correspond to that of EM MTF. The EM failure process can be devided into two periods. The first is an incubation period for a void nucleation, and the second is a period of void growth and movement. The observed activation energy corresponds to that of the second period. Though the activation energy of the first period could not be measured, it is expected to be that of lattice diffusion.

5.Conclusions

It is concluded that a single crystal aluminum has an extremely higher endurance against EM induced failures than poly-crystal copper and aluminum. The mechanism is attributed to the high uniformity of atom flux in single crystal aluminum. The strong tendency of voids to be parallel to the line direction and the movement into the cathode pad further assisted the endurance against EM. The activation energy of void movement has been found to be 0.62 eV, which implies that the diffusion along the interface between aluminum-oxide and aluminum plays the essential role in the void movement.

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