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Copper Interconnects Fabricated by Dry Etching Process

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Electromigration (EM) lifetime of Cu interconnects fabricated by high-temperature dry etching was investigated. The Cu interconnects show much greater advantages in practical use condition than Al-Si-Cu interconnects. However, The activation energies for EM damage are relatively low in comparison with those for lattice and grain boundary diffusions. This finding implies that the diffusion mechanism consists of not only lattice and grain boundary diffusions but also surface diffusion. In order to extension of EM lifetime, Cu alloys for suppress surface and grain boundary diffusions should be investigated. Copper-zirconium alloys are proposed as one of the promising materials for this purpose.

1.Introduction

Copper is the major candidate to replace Al alloys for sub-quarter-micron interconnect, because of its low resistivity and long EM lifetime.[1] However, problems such as the difficulty of dry etching caused by low vapor pressure of etching products, and corrosion and oxidation of Cu during processes between Cu patterning and subsequent SiO_2 deposition hindered its use.[1] Difficulty of Cu patterning was the most serious of these problems. In recent years, some microfabrication processes for Cu interconnects have been proposed, such as chemical mechanical polishing (CMP)[2,3] and some dry etching techniques.[4-6] Consequently, Cu interconnects of sub-quarter-micron order are realized.

In this paper, EM lifetimes of the Cu interconnects fabricated by high-temperature dry etching using the self-aligned passivation technique[5] were investigated. Mechanisms for the dependence of EM lifetimes and its activation energies on linewidth was inferred from literature on Al interconnects. Since both Cu and Al have the same face-centered-cubic (fcc) crystal structure, the diffusion mechanism of Cu is thought to be almost the same as that of Al.[7,8]

2.Experimental

A multilayered film composed of TiN(0.1μm)/ Cu(0.4μm)/ TiN(0.1μm) was prepared on a thermally oxidized Si wafer by dc magnetron sputtering.
Patterning of the multilayered film was performed by high-temperature dry etching using the self-aligned passivation technique.[5]

After etching, a bilayer composed of SiO_2 (0.2μm) and SiN (0.8μm) was deposited as a passivating layer by plasma-enhanced CVD at 115°C and 350°C, respectively. Finally, the wafers were annealed in N_2/ H_2 mixture at 450°C for 2 hours.

Resistivity of Cu interconnects in the width range of 0.2 to 10 μm ranged from 1.7 to 2.2 μΩ·cm and was close to the bulk Cu value (1.67 μΩ·cm), that is, interconnects were formed without any structural defects that would affect their electrical resistivity, such as voids, impurities and oxidation of Cu.[9]

The EM lifetimes of the Cu interconnects were investigated under the stress current of $8x10^6 A/cm^2$. The temperature of the interconnects was controlled at 200°C taking account of Joule heating.

3.Results and Discussion

3.1 Mechanisms of electromigration for Cu interconnects

The resistance change of the 0.7-μm-wide line during an EM test is shown in Fig. 1. The slightly increasing resistance prior to catastrophic failure is considered to be due to EM-induced void growth in Cu. This behavior is a typical characteristic of EM damage. Therefore, the lifetime is defined as time until catastrophic failure occurs. Figure 2 shows the cumulative failure rate for EM test. The values of median time-to-failure (MTF) of 0.27-, 0.33-, 0.7- and 0.9-μm-wide lines are 9.5, 6, 32 and 73 h, respectively. The dependence of MTF on the linewidth is summarized in Fig.3, where it is found that the MTF value of the 0.33-μm-wide line is a minimum. As shown in Fig.4, since the grain size of Cu is about 0.4 μm and its distribution is independent of the linewidth, the behavior of MTF in Fig.3 is associated with the bamboo-type grain structure of Cu interconnects, similar to that observed in the Al-alloy case. As shown in Fig.2, the

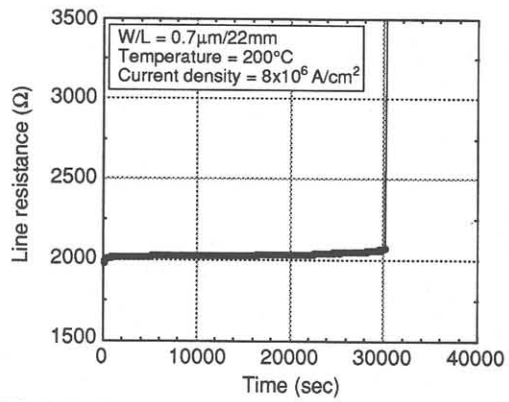

Fig.1 Resistance change of the 0.7-μm-wide line during EM test.

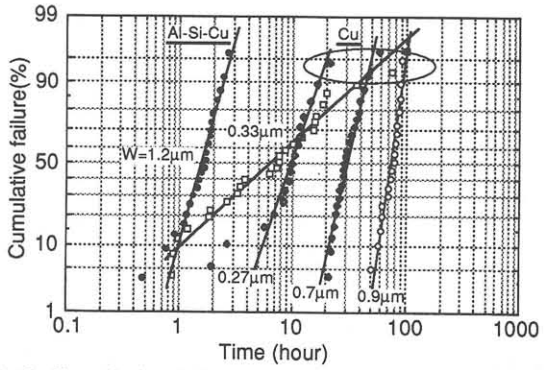

Fig.2 Cumulative failure rate of Cu interconnects and Al-Si-Cu interconnects on EM test ($8MA/cm^2$ and 200°C).

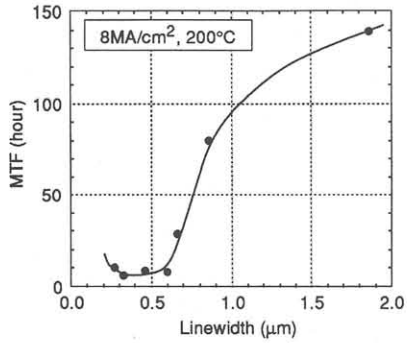

Fig.3 Median time-to-failure (MTF) as a function of linewidth.

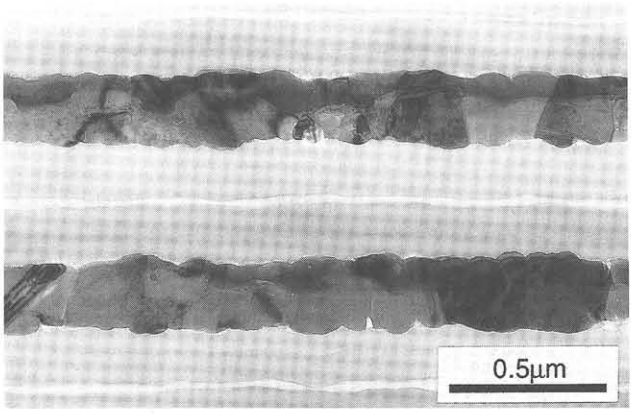

Fig.4 TEM photograph of 0.3-μm-wide lines.

minimum MTF of Al-Si-Cu interconnects owing to their bamboo-type grain structure was observed to be 1.5 hours for the 1.2-μm-wide line under the EM test condition. Since the interconnects with the minimum MTF consist of the single-grain and poly-grain segments, that is, both Cu and Al-Si-Cu interconnects have the same structure, EM lifetimes are compared between both interconnects using their minimum MTFs. The minimum MTF of the Cu interconnects (0.33-μm-wide lines) is found to be 4 times longer than that of the Al-Si-Cu interconnects (1.2-μm-wide lines) under the EM test conditions. Using Black's equation under the assumption that the current exponent (n) is 2 for both Cu and Al-Si-Cu, and that activation energies are 0.9 eV for Cu[9] and 0.6 eV for Al-Si-Cu,[7] the minimum MTFs extrapolated to the conditions for practical use, i.e., 90°C and $2x10^5 A/cm^2$, are estimated to be 882 years for Cu and 23.7 years for Al-Si-Cu. When these are extrapolated to 90°C and $1x10^6 A/cm^2$, the minimum MTFs are estimated to be 35.3 years for Cu and 0.95 years for Al-Si-Cu (Table 1). Consequently, taking account of the increase in the current density with the increase in the density of devices in the future, Cu interconnects could satisfy to use as high-current-density lines for sub-quarter-micron-feature devices instead of Al-alloy interconnects.

Table 1 Lifetimes extrapolated to the conditions for practical use.
Assumption: Al-Si-Cu (1.2μm) [n=2, Ea=0.6eV], Cu (0.33μm) [n=2, Ea=0.9eV]

Condition	Minimum Lifetime (Year)	
	Al-Si-Cu	Cu
200°C; 8MA/cm^2	(1.5 hours)	(6 hours)
90°C; 0.2MA/cm^2	23.7	887
90°C; 1MA/cm^2	0.95	35.5

Table 2 Activation energies of EM.

Linewidth (μm)	0.3	0.7	1.6
Ea (eV)	0.92	0.88	0.82

Activation energies of EM were estimated from the increasing resistance during EM tests as shown in Fig.1 [9] and are summarized as the dependence on the linewidth in Table 2. The activation energies increase with decreasing linewidth. The activation energy for the 1.6-μm-wide line composed of the poly-grain structure is 0.82 eV. According to the Al case, grain boundary diffusion is the dominant mechanism in this grain structure.[10] The activation energy for the 0.3-μm-wide line composed of poly-grain and single-grain structures as shown in Fig.4 is 0.92 eV. Since the activation energies for grain boundary diffusion and lattice diffusion of Cu are 1.0 eV[11] and 2.08 eV[8], respectively, the experimental values of 0.82 eV for the1.6-μm-wide line and 0.92 eV for the 0.3-μm-wide line are smaller than the activation energy of the grain boundary diffusion. In addition, the activation energy for single-grain structure without a passivation overcoat has been reported as 1.25 eV,[12] which it is also smaller in comparison with the activation energy of the lattice diffusion. This behavior is not observed in Al-alloy interconnects where surface diffusion along the Al surface is prevented by the aluminum oxide layer.[7] In contrast, the surface of Cu is not covered by a stable copper oxide layer because the copper oxide layer cannot prevent further oxidation and diffusion of oxygen proceeds to inward of Cu grains.[13] Therefore, the surface diffusion of Cu can act as one of the dominant mechanisms of mass transport for the Cu interconnects. Usually, activation energy of surface diffusion in fcc metals is five times smaller than that of lattice diffusion,[7] that is, it is smaller than that of the grain boundary diffusion. Considering the above findings, the mass transport mechanism for the Cu interconnects can be inferred as follows.

1) The diffusion mechanisms in the poly-grain structure mainly consist of grain boundary and surface diffusions.
2) The diffusion mechanisms in the structure composed of the single-grain and poly-grain segments consist mainly of grain boundary, lattice and surface diffusions.
3) The diffusion mechanisms in the single-grain structure mainly consist of lattice and surface diffusions.

Influence of surface diffusion becomes large when aspect ratio of interconnects, i.e., height/width, increases.

3.2 Refinement of Cu interconnects for future devices

For extension of EM lifetime, enlargement of activation energy and mechanical strength of materials are usually effective in the case of Al interconnects. For that purpose, Al alloys such as Al-Si-Cu and Al-Cu are applied to high-reliablility interconnects. As for Cu interconnects, alloying in order to extend EM lifetime has been tried only in few cases until now. Activation energy for Cu alloyed with Pd is larger than that of pure Cu because precipitates of Pd in grain boundary prevent diffusion of Cu.[14] Moreover, some Cu alloys, such as Cu-Cr, Cu-Mg and Cu-Zr, have been observed precipitation of solutes responsible for hardening alloys.[15-17]

These suggest that Cu alloys are suitable for extension of EM lifetime. Cu-alloy films with solutes whose concentration exceeds the low-temperature solubility limit lead to precipitation of compounds of solutes and/or solute metals at the grain interiors, the grain boundaries, the surface of Cu-alloy films and the interface between Cu-alloy film and underlayer after annealing. The solutes to be used for this purpose must satisfy the following requirements. First, a precipitation must occur at low temperatures (<500°C). Second, solid solubilities of solutes must be low enough for the formation of adequate precipitates. Third, resistivities of Cu alloys after annealing for precipitation must be lower than those of Al alloys (<3μΩ·cm).

Solutes which satisfy the above requirements are Cr,[15] Mg[16] and Zr.[17] In these alloys, Cu-Zr alloy is known as a typical precipitation hardening system without large degradation of conductivity,[17] and its mechanical strength is especially high in comparison with other low-resistivity alloys. This high mechanical strength is suitable for preventing the formation of voids associated with EM.[18] And precipitetion of Cu-Zr compounds occurs during a low-temperature anneal at 400°C.[17] Figure 5 shows resistivities of Cu-Zr films as a function of Zr concentration. The slope of the resistivity curve of the as-deposited films is 17 μΩ·cm/at%; however, after annealing at 500°C for 5 min in vacuum (1×10^{-7} Torr), the slope of the resistivity curve becomes 1.2 μΩ·cm/at%. Therefore, resistivity of less than 3 μΩ·cm is attained up to the Zr concentration of 0.8 at%. Depth profiles obtained using secondary ion mass spectrometry (SIMS) are shown in Fig.6. After annealing, Zr in the film is concentrated at the surface and the interface between the Cu-Zr film and SiO_2. These suggest that Zr compounds precipitate at these regions. Therefore, Cu-Zr alloy with precipitates may prevent

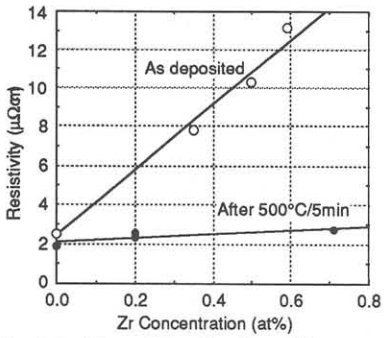

Fig.5 Resistivities of Cu-Zr alloy films as a function of Zr concentration.

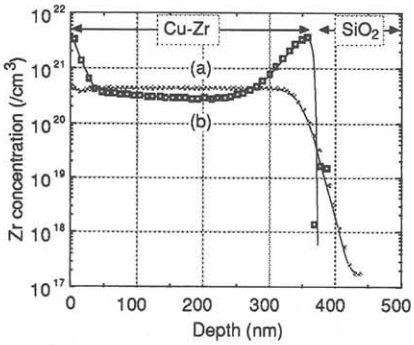

Fig.6 Depth profiles of Zr concentration: (a) deposited at room temperature, (b) deposited at 200°C and annealed at 400°C in vacuum.

not only grain boundary diffusion but also surface diffusion. These findings imply that Cu-Zr alloy is one of the candidate materials for the improvement of EM lifetime.

4.Conclusions

We have investigated the linewidth dependence of EM lifetime for Cu interconnects fabricated by high-temperature dry etching. The minimum lifetimes associated with the bamboo-type grain structure were compared between Cu interconnects and Al-Si-Cu interconnects. It is found that Cu interconnects show much greater advantages compared with Al-Si-Cu interconnects for practical use condition accompanied with high-current density, i.e., $>1\times10^6$A/cm^2.

Activation energies of Cu interconnects suggested that the diffusion mechanism associated with EM consists of not only lattice and grain boundary diffusions but also surface diffusion, which is different from the case of Al interconnects. Therefore, the EM lifetime of Cu interconnects would be extended by the suppression of surface and grain boundary diffusions. In this respect, Cu alloys should be examined as Cu interconnects of sub-quarter-micron order. Copper-zirconium alloys were assumed to be one of the promising materials for the refinement of Cu interconnects.

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