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High Reliability Copper Interconnects through Dry Etching Process

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The modified high temperature dry etching technique, which enables anisotropic patterning with a high etching selectivity and self-aligned passivation of a sidewall of interconnect simultaneously, was developed for fabrication of sub-quarter micron Cu interconnects. Resistivities of the resulting Cu interconnects were in the range of 1.7 to 2.2 μΩ·cm for the line width of 0.2 - 3.0 μm. In consequence of electromigration (EM) tests, median time to failure (MTF) of the 0.3-μm line was 100 times longer than that of a conventional Al-1%Si line. Activation energy of electromigration damage (EMD) was 0.88eV.

1.Introduction

Copper is the major candidate to replace Al-alloys for sub-half micron interconnect, because of its low resistivity and long electromigration lifetime.[1] However, the major problems on realization of Cu interconnect are encountered during fabrication process, such as the difficulty of dry etching caused by low vapor pressure of etching-products, and corrosion and oxidation of Cu on processes between the dry etching and a subsequent SiO_2 deposition.[2] To circumvent this problem, we have been investigated modification of the high temperature dry etching, which includes the self-aligned passivation technique.[3] Using this technique, a SiON passivating film is formed on the sidewall during etching, and acts as a barrier to prevent Cu from oxidation during the subsequent SiO_2 deposition process.

In this work, we have formed TiN/ Cu/ TiN multilayered interconnects in sub-quarter micron wide using the advanced self-aligned passivation technique which realized the Cl-free sidewall film, and evaluated the EM lifetime.

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. A SiO_2 mask for etching Cu layer was prepared by etching through a resist mask obtained by i-line phase-shifting lithography.

Etching was performed on a magnetron reactive ion etching (RIE) system operating at a gas pressure of 30mTorr and a rf power of 500W, and an etching gas of a $SiCl_4$/ Cl_2/ N_2 mixture adding NH_3 was used to form a passivating film on a sidewall of the interconnect simultaneously. The temperature of a wafer during etching was controlled at 300°C.

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.

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 Micro-fabrication of Cu with simultaneous formation of Cl-free sidewall film

In use of the ternary gas mixture of $SiCl_4$/ Cl_2/ N_2, a SiON passivating film is formed on the sidewall during etching.[3] The resulting sidewall film contains chlorine of about 2 atomic% (Fig.3(a)). Although this sidewall film is

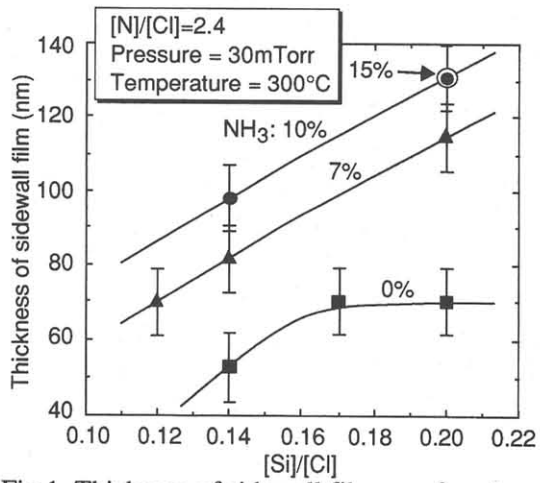

Fig.1 Thickness of sidewall film as a function of the [Si]/[Cl] ratio on some NH_3 flow ratios.

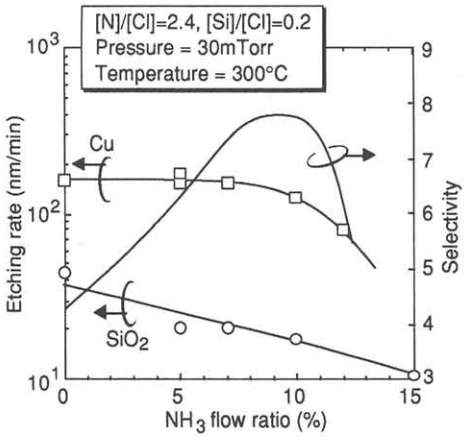

Fig.2 Etching rates and selectivity as a function of NH_3 flow ratio.

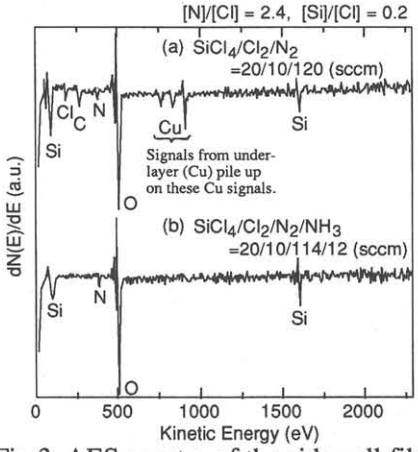

Fig.3 AES spectra of the sidewall films: (a) without and (b) with NH_3 flow.

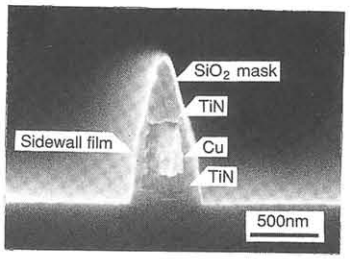

Fig.4 Cross-sectional view of the 0.2-μm-wide line.

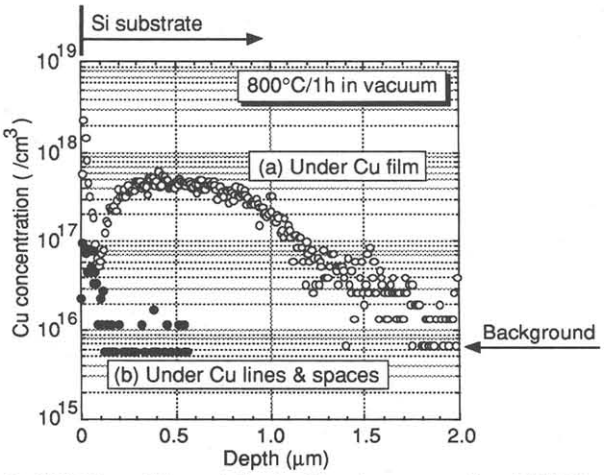

Fig.5 SIMS profiles of Cu in Si substrates after 800°C for 1 hour in vacuum. Structures of samples are (a) Cu film/thermal oxide film/Si substrate and (b) SiN/SiO_2/[TiN/Cu/TiN] L&S/thermal oxide film/Si substrate.

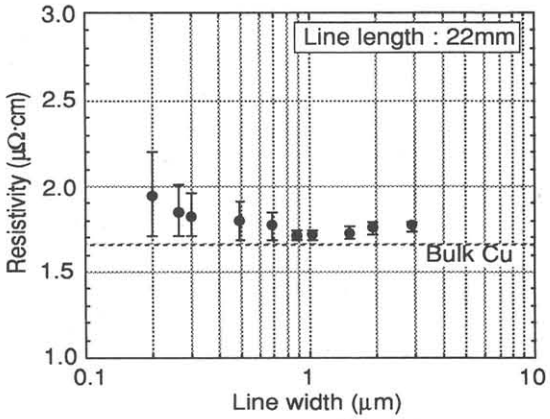

Fig.6 Resistivities of interconnects as a function of linewidth.

rather durable to corrosion, it is necessary to remove Cl completely for achieving long-term reliability. Hence, in expectation of dissociating the Si-Cl bond, NH_3 is introduced to the ternary gas mixture of $SiCl_4$/ Cl_2/ N_2. Ammonia releases Cl atoms on $SiCl_4$ in consequence of stimulating its dissociation.

As demonstrated a previous report,[5] etching was controlled by the [N]/[Cl] ratio and the [Si]/[Cl] ratio. Here, [N],[Si] and [Cl] represent the amount of each constituent element in the etching gas mixture. Since patterning Cu line without side-etching is achieved when the [N]/[Cl] ratio is more than 2, gas flows of NH_3 and N_2 were controlled so as to be the [N]/[Cl] ratio of 2.4, and NH_3 was added in the range of 0 to 15% of [N] in the etching gas. As shown in Fig.1, thickness of the sidewall film increases with increasing the [Si]/[Cl] ratio and the NH_3 flow ratio, and is saturated when addition of NH_3 is over 10%. As shown in Fig.2, etching rate of SiO_2 decreases monotonously with increasing the NH_3 flow ratio. On the other hand, that of Cu is almost constant in the low ratio region and it abruptly decreases when the NH_3 flow ratio is over 10 %. Therefore, the NH_3 flow ratio of 7-10% gives high etching selectivity of about 8. The sidewall film formed on use of NH_3 is composed of SiON without detectable impurities such as Cl, as shown in Fig.3(b). These analyses suggest that NH_3 has Cl-releasing activity. The composition of the SiON is 32, 59 and 9 atomic% for Si, O and N, respectively. A cross-sectional view of the 0.2-μm-wide line after etching and its 70-nm-thick sidewall film is shown in Fig.4. Owing to formation of the sidewall film, the resulting as-etched Cu interconnect did not corrode after exposure in air for 6 months. The sidewall film also prevents oxidation of Cu in air up to 220°C.

As shown in Fig.5, diffusion of Cu into a Si substrate was investigated on the Cu interconnects covered with passivating layers, SiN/ SiO_2. In comparison with the Cu film case, it is found that the sidewall film acts as barrier for Cu diffusion, in addition to TiN film.

In consequence of these results, it is found that the self-aligned passivation technique solves whole problems on fabrication of Cu interconnect.

Figure 6 shows that resistivities of the Cu intercon-

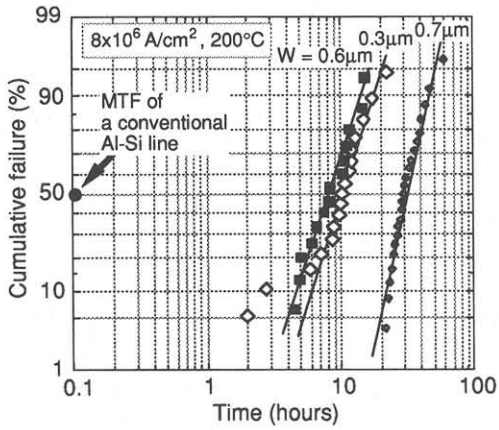

Fig.7 Cumulative failure rate of interconnects.

nects are in the range of 1.7 to 2.2 μΩ·cm for the line width of 0.2 - 3.0 μm, and these are close to the bulk resistivity of 1.67 μΩ·cm. It suggests that the applied etching technique forms the Cu interconnects without any structural defects, such as voids, impurities and oxidation of Cu.

3.2 EM lifetime of the Cu interconnect

Figure 7 shows the cumulative failure rate for EM test. The values of median time to failure (MTF) of 0.3, 0.6 and 0.7 μm wide line are 10, 7 and 30h, respectively. The MTF value of the 0.6-μm-wide line becomes minimum. The similar behavior has been observed in the Al-alloy case associated with its bamboo-type grain structure.[4] In this case, since the grain size of Cu is about 0.4μm, the grain structure of the 0.6-μm-wide line approaches bamboo-type. Even the minimum value of MTF on the 0.6-μm-wide line is about two orders of magnitude longer than that of a conventional Al-1%Si line. Figure 8 shows the resistance change of the 0.7-μm-wide line as typical characteristic of EMD. Slightly increasing resistance before catastrophic failure is surmised due to EM-induced void growth in Cu. Activation energy of EMD, Ea, was estimated by the resistance increase using the expression,[5]

$$(dR/dt)/Ro=AJ^n\cdot\exp(-Ea/kT),$$

where the current density, J, is a constant of $8\times10^6 A/cm^2$ and the line temperature, T, is varied in the range of 431K to 526K. Figure 9 shows Arrhenius plot of the time rate of resistance change in the 0.7-μm-wide line under EM tests. The value of Ea obtained from the line slope is 0.88eV, which is similar to that of other fabrication methods.[5,6]

4.Conclusions

We have developed the self-aligned passivation technique for dry etching of Cu, which enables anisotropic patterning with a high etching selectivity and self-aligned passivation of a sidewall of interconnect simultaneously. By means of addition of NH_3 in the etching gas mixture, the sidewall film is composed of SiON without any amount of chlorine. In consequence, the self-aligned passivation

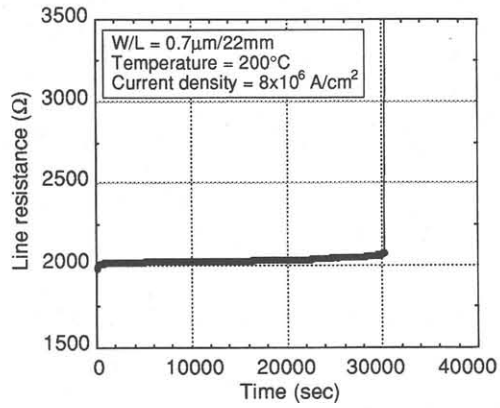

Fig.8 Resistance change during EM test.

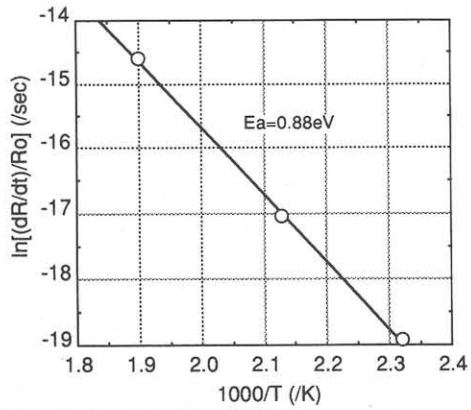

Fig.9 Arrhenius plot of the time rate of resistance change.

technique can solve whole problems on fabrication of Cu interconnect, such as difficulty of micro-fabrication, corrosion, oxidation, and diffusion of Cu.

Using this technique, sub-quarter micron Cu interconnects with low resistivity have been prepared successfully. The MTF of the 0.3-μm-wide line is 10h for EM test under $8\times10^6 A/cm^2$ at 200°C, and it is 100 times longer than that of a conventional Al-Si line. Activation energy of EMD of the 0.7-μm-wide line is 0.88eV.

Low resistivity and large activation energy of EMD show that the self-aligned passivation technique is suitable for the realization of high reliability Cu interconnects.

References

1) D. S. Gardner, J. Onuki, K. Kudoo and Y. Misawa: *VLSI Multilevel Interconnection Conference* (1991) p.99.
2) S. P. Murarka, R. J. Gutmann, A. E. Kaloyeros and W. A. Lanford: Thin Solid Films **236** (1993) 257.
3) Y. Igarashi, T. Yamanobe, T. Yamaji, S. Nishikawa and T. Ito: Jpn. J. Appl. Phys. **33** (1994) 462.
4) E. Kinsbron: Appl. Phys. Letters **36** (1980) 968.
5) C. W. Park and R. W. Vook: Appl. Phys. Letters **59** (1991) 175.
6) T. Nitta, T. Ohmi, T. Hoshi, S. Sakai, K. Sakaibara, S. Imai and T. Shibata: J. Electrochem. Soc. **140** (1993) 1131.