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Increase in Electrical Resistivity of Copper and Aluminum Fine Lines

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The resistivities of thin films and fine lines of copper (Cu) and aluminum (Al) were measured by a resistance ratio method (referred to as "RR method" hereafter), which measures the ratio of room-temperature resistance to liquid-nitrogen-temperature resistance. This method can predict resistivity exactly without the need for precise and detailed line or film dimension measurements. Thinner films and finer lines have higher resistivities in the case of both Cu and Al, with Cu showing larger resistivity increases (films and lines) than Al. From the present data, we estimated the electron mean free path of Cu to be 55 nm, which is close to most of the previously reported values, and that of Al to be 22 nm. Line resistivities depend not only on the line width but also on line thickness. We propose a simple equation for expressing line resistivity in terms of line thickness and width.

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1. Introduction

One requirement of semiconductor Si technology is that the resistance of interconnect-lines must be low. So Cu has started to be used for lines because it has lower resistivity than Al. However, the electron theory of metals[1] predicts that surface or interface scattering will increasingly become predominant and the resistivity will rise as the metal film thickness or line width approaches the conduction electron mean free path (l). Some experiments have reported that resistivities of Cu metals are related to film thickness and line width.[2–5]

The theoretical prediction has been basically confirmed experimentally for thin Cu films formed by an advanced high-vacuum deposition system.[2,3] These two studies gave similar values for the experimentally determined electron mean free path (27 nm and 39 nm, respectively). These values indicate a rapid increase in resistivity for thinner films, particularly ones thinner than 100 nm. Kuan *et al*.[4] reported measured resistivities of very fine (50-nm wide) Cu lines. The values were more than 5–10 times that of bulk Cu ($>$7–13 nΩ·m), which suggests that the resistivity of fine lines will increase significantly. However, the scattering of the data must be reduced to give a more reliable value of the resistivity.

For more precise prediction of the resistivity, we performed similar experiments and analyzed the data scattering. Although the main cause of the data scattering was the film texture, some scattering was due to the dimension (width and thickness) measurements, which were carried out to determine the line cross section. In addition to these factors, especially in the case of the damascene process, non-uniformity of the line thickness reduces the reliability of the determined resistivity, as pointed out by Kuan *et al*.[4] The inaccuracy of the dimension measurements performed by scanning electron microscopy (SEM) was estimated to be 5–10 nm, and the variation in thickness along the line was estimated to be 10–50 nm, producing more than 50% error in approximately 100-nm-wide lines. Furthermore, it is difficult to estimate and subtract the barrier metal thickness at the sidewalls and at the bottom of the Cu line because the thickness of the barrier metal is not uniform.

In this paper we propose a new resistivity estimation method and present precise resistivity values for Cu and Al fine lines.

2. Experimental

We measured the resistivities of Cu and Al films of various thicknesses and of Cu and Al fine lines of various widths and thicknesses.

We prepared Cu films layered with a barrier (Cu/Ta/TaN, referred to as upper layer/lower layer) and mono-layer Al films with thicknesses ranging from 15 to 900 nm. An ultrathin Ta/TaN liner (Ta: 10 nm; TaN: 5 nm) and thin Cu and Al films were deposited at room temperature using an ultrahigh vacuum sputtering apparatus (base pressure: $\sim 3.99 \times 10^{-7}$ Pa) on SiO_2/Si substrates. Then 400°C thermal annealing was performed without breaking the vacuum in a highly purified low-pressure Ar atmosphere. A film sample, 800-nm-thick electroplated Cu on 100-nm-thick sputtered Cu, was also prepared. Cross-sectional SEM observation showed that the sample films had a smooth and continuous surface; the roughness of even the thinnest samples (15 nm thick) was less than 20% of the total thickness.

Line samples of Cu were produced by two different processes. Samples with line widths ranging from 0.2 to 20 µm were fabricated by the standard damascene process. Line slots with lengths ranging from 500 to 2000 µm and thicknesses of about 250 nm or 400 nm were formed in a SiO_2 layer on a Si substrate. The Ta/TaN barrier-layers and a Cu seed layer were first sputter-deposited. Then the slots were filled with electroplated Cu. Chemical mechanical polishing (CMP) subsequently delineated the lines.

Finer line samples of Cu (60 nm to 2 µm wide) were produced in another process (line length: 100, 500, or 1000 µm). Line slots 100 nm deep were produced on a SiO_2 layer, and filled back with CVD-SiN (50 nm). The barrier Ta/TaN (10 nm/5 nm) and seed-Cu were sputtered on the slots. In order to fill Cu in the line slots, we tried three deposition methods: (1) high-temperature sputtering, (2) annealing at high temperature after low temperature sputtering, and (3) electro-

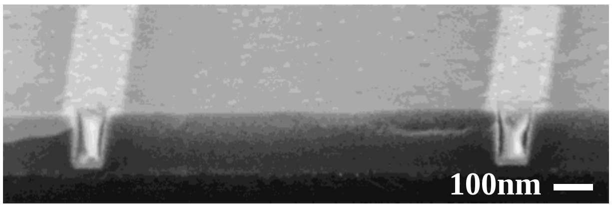

Fig. 1 SEM micrograph of 70-nm-wide Cu lines.

plating. The first two methods filled the slots to only half the depth (about 50 nm). The third method filled the slots to the full depth of 100 nm. Figure 1 shows an SEM micrograph of 70-nm-wide Cu lines.

Line samples of Al (with 0.5%Cu) layered with TiN barrier (bottom and top) were fabricated by standard reactive ion etching. The lines were 50 nm to 10 μm wide, 625 nm long, and about 350 nm thick. The effective widths of the lines were calculated from the measured resistances, which correspond to the average cross section along the lines; SEM confirmed some of the cross sections.

The resistivity was deduced by the RR method (measures the ratio of room-temperature resistance to liquid-nitrogen-temperature resistance), which was described in the previous paper.[5,7] The resistivity was calculated by the following formula:

$$\rho(300\,\mathrm{K}) = \mathrm{RR}/(\mathrm{RR}-1) \times [\rho_{\mathrm{bulk}}(300\,\mathrm{K}) - \rho_{\mathrm{bulk}}(77\,\mathrm{K})], \tag{1}$$

where $\mathrm{RR} = R(300\,\mathrm{K})/R(77\,\mathrm{K})$, where ρ is resistivity and R is resistance.

For Cu, we used the bulk resistivity values of $\rho_{\mathrm{bulk}}(300\,\mathrm{K}) = 1.75 \times 10^{-8}\,\Omega\cdot\mathrm{m}$ and $\rho_{\mathrm{bulk}}(77\,\mathrm{K}) = 0.21 \times 10^{-8}\,\Omega\cdot\mathrm{m}$ and for Al, we used $\rho_{\mathrm{bulk}}(300\,\mathrm{K}) = 2.92 \times 10^{-8}\,\Omega\cdot\mathrm{m}$ and $\rho_{\mathrm{bulk}}(77\,\mathrm{K}) = 0.25 \times 10^{-8}\,\Omega\cdot\mathrm{m}$. These values were deduced from the material characteristics table[8] by extrapolation or interpolation. We can thus calculate the resistivity from resistance values measured at two different temperatures without measuring the line dimensions.

The resistivity measured by the RR method was in good agreement with that measured by the conventional method (from sheet resistance multiplied by the measured film thickness) for Cu films,[7] which shows that the RR method is applicable to this experiment.

The cross-section ratio of the barrier (Ta/TaN for Cu line; TiN for Al line) to Cu or Al was about unity in the thinnest film. The contribution to the conductance from the barrier was less than 2%, because the resistivity ratio of barrier to Cu or Al was about 50–100. We did not correct for the influence from the barrier in any of the samples.

3. Results and Discussion

The resistivities of Cu and Al films are plotted as a function of the inverse film thickness in Fig. 2. The relationship is almost linear. Assuming complete diffuse scattering at surfaces and interfaces, as in the previous treatment,[2–4,6] we deduced the electron mean free path (l) to be 55 nm for Cu and 22 nm for Al.

A classical experiment on Cu film by Coutts and Mathews

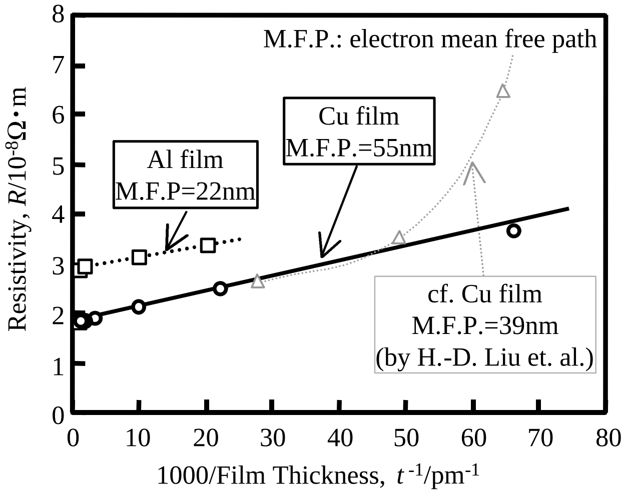

Fig. 2 Resistivity values as a function of film thickness.

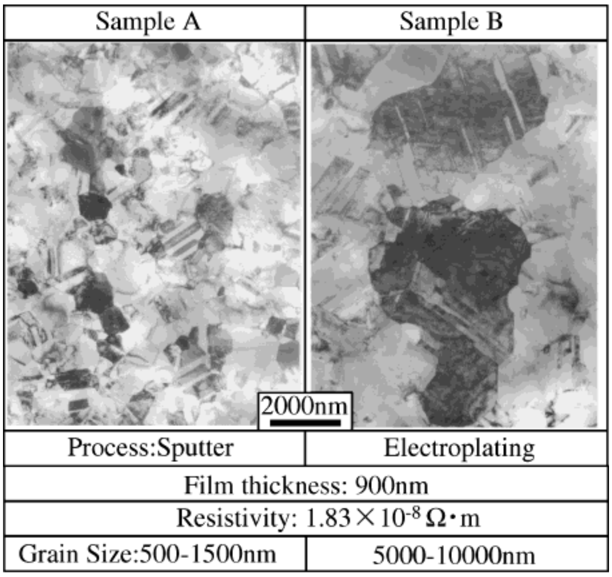

Fig. 3 TEM image of Cu films.

gave l of 27 nm,[2] and two recent experiments gave l of 39 nm (Liu *et al.*[3]) and about 80 nm (Kuan *et al.*[4]). Within the estimated experimental error of 10–20%, our measured l value is close to those previous results, being especially close to that of Liu *et al.*, except below 20 nm as shown in Fig. 2. Liu *et al.* attributed the rapid increase in resistivity below 20 nm to the surface roughness of their films. The surface of our thinnest film appeared smoother than theirs. This smoothness may suppress the rapid increase in resistivity and explain why we did not observe it in our films.

Transmission electron microscope (TEM) images of two kinds of Cu films of the same thickness (900 nm) are shown in Fig. 3. Sample A was made by sputtering and sample B was made by electroplating. They had different average grain sizes (sample A: 0.5–1.5 μm, sample B: 5–10 μm), but their resistivities were the same and close to the bulk value. This means that when the grain sizes are sufficiently larger than the mean free path they hardly affect the resistivity.

The resistivities of four series of Cu lines of different thicknesses are plotted as a function of line width in Fig. 4. The

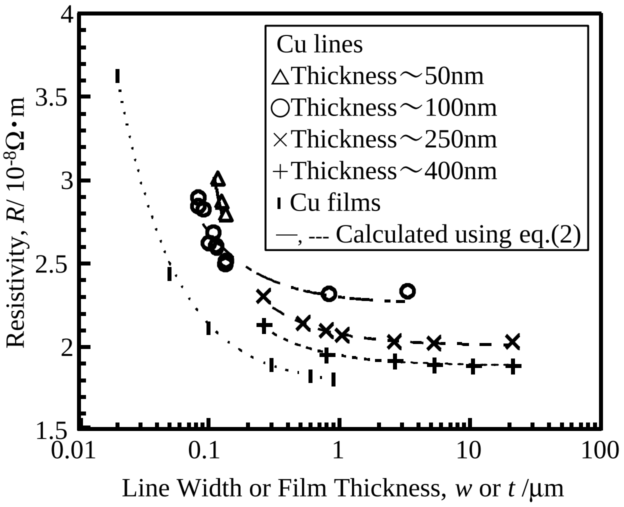

Fig. 4 Resistivity of Cu samples (as a function of line width).

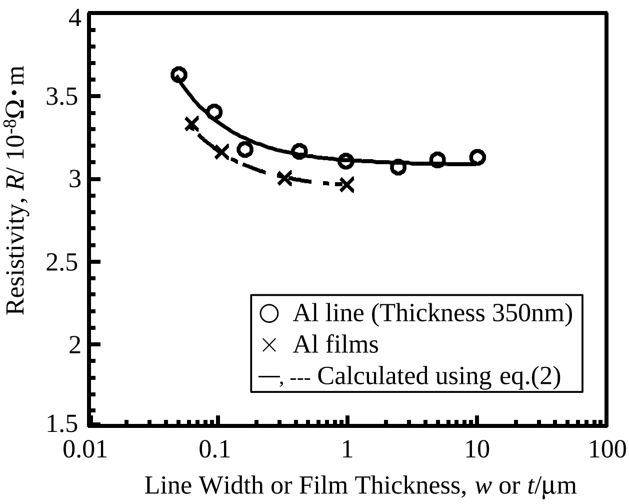

Fig. 5 Resistivity of Al samples (as a function of line width).

film data are also plotted as a function of thickness. The resistivities of the fine lines were much greater than those of the films. The finest and thinnest line (60 nm wide and 50 nm thick) had a resistivity 1.7 times as large as bulk.

In Fig. 4, the resistivity of a Cu line depends not only on the line width but also on line thickness. The saturation resistivities for the widest lines we examined depended on the film thickness; thicker lines had lower resistivities. We think the tendencies in Fig. 4 coincide with the theory of surface scattering, indicating that the line resistivity is a function of its thickness as well as its width. This corresponds to the fact that electrons are scattered not only by the top and bottom surfaces but also by the side surfaces of the line samples. We propose a simple extension of the previous formula:

$$\rho_{\text{line}}/\rho_{\text{bulk}} = 1 + 3/8 \times (1 - p) \times \{l/w + l/t\}, \qquad (2)$$

where ρ_{line} is the line resistivity, ρ_{bulk} is the bulk resistivity, p is the electron scattering parameter, l is the electron mean free path (constant), w is the line width, and t is the line thickness. Figure 4 includes lines representing eq. (2) with $l = 55$ nm (estimated from Fig. 2). The overall tendencies of the data points fit well with the lines from eq. (2).

The resistivities of Al films and lines are plotted in Fig. 5. The lines were drawn according to eq. (2) using $l = 22$ nm (estimated from Fig. 2). The calculated values are in good agreement with the measured plots.

Comparing Figs. 4 and 5, we see that the resistivity of Cu increases faster than that of Al.

It is reasonable to expect that as line widths will become thinner in future, the resistivity of Cu lines will become larger than that of Al of the same dimension. There is some possibility of occurring the turn-over at a width and thickness less than several tens of nano meters.

4. Conclusion

We precisely evaluated the resistivity of Cu fine lines, Cu films, Al fine lines, and Al films using a resistance ratio method. The results show that this method can predict precise resistivity without the need for precise and detailed line-dimension measurements. We deduced electron mean free path values of 55 nm in Cu film and 22 nm in Al film. The resistivities of the fine line were much greater than those of films, depending not only on the width but also on the thickness. We proposed a simple equation for expressing the line resistivity, which can explain the measured values. The resistivity of Cu samples increased faster than that of Al, because Cu has a longer electron mean free path than Al. There is some possibility of occurring the turn-over at a width and thickness less than several tens of nano meters.

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