

## Magnetron-Plasma CVD System and Its Application to Aluminum Film Deposition

Takashi Kato, Takashi Ito, Hajime Ishikawa, and \*Mamoru Maeda

FUJITSU LABORATORIES LTD., ATSUGI  
10-1 Morinosato-Wakamiya, Atsugi 243-01, Japan  
\*FUJITSU LIMITED  
1015 Kamikodanaka, Nakahara, Kawasaki 211, Japan

The authors have developed a new deposition system, magnetron-plasma CVD (MPCVD), allowing the practical application of metal organic CVD of Al films. With this system, it has been found that the plasma chemical reaction is confined to the surface region of the substrate by an applied planar magnetic field. A hillock-free Al film with a resistivity of  $3.8 \times 10^{-6}$  ohm-cm and other properties suitable to VLSI was obtained.

### 1. INTRODUCTION

Plasma-enhanced chemical vapor deposition of various films has been extensively studied for application to LSI fabrication. Recently, several investigations of the effects of applying a magnetic field to the region of the plasma deposition reaction have been reported<sup>1)-4)</sup> as same as reported in the reactive ion etching.<sup>5)</sup> The disadvantages of poor quality and low deposition rate were improved by using a magnetically enhanced plasma reaction. In this system, however, the plasma reaction could not be confined to the surface region of the substrate.

On the other hand, as the dimensions of LSIs decrease, the problems in aluminum multi-level metalization become more serious. Various CVD systems such as photo-chemical<sup>6)</sup>, thermal<sup>7)-10)</sup>, and plasma<sup>11)</sup> have been proposed to improve the step coverage and other aspects. The aluminum films deposited by these systems, however, are not practical yet. Surface roughness and resistivity are still problems in thermal and plasma CVD, respectively.

The authors have developed a new deposition system, magnetron plasma CVD (MPCVD), for practical use of metal organic CVD Al films. This paper outlines the MPCVD system and its application to Al film deposition. In this system

using a planer magnetron, it has been found that the plasma chemical reaction is confined within a surface region by an applied magnetic field.

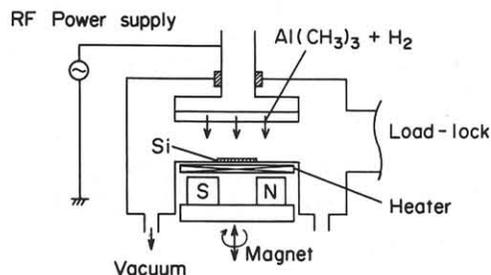


Fig. 1. Schematic diagram of MPCVD system.

### 2. MPCVD SYSTEM

Figure 1 is a schematic diagram of the MPCVD system with load-lock capability. Plasma enhanced deposition has been carried out in this parallel plate, 25 cm in diameter, reactor with a pair of rectangular bar magnets. RF power from 400 to 900 W at 13.56 MHz was applied to the upper electrode with the source gas nozzle. The magnetic field from the turnable-mounted permanent magnets located under the reactor was applied to the Si wafer through the heater. The strength of the

magnetic field is varied from 20 to 800 Gauss by moving the magnets up and down. The locus of magnetic field lines parallel of the substrate surface is a closed path. It is believed that there will be less oxygen contamination from the chamber wall, allowing densified Al films to be obtained, because the strong plasma region is localized at the surface by a powerful magnetic field.

### 3. DEPOSITION of Al FILM

The Al films were deposited on 4 inch diameter Si wafers using trimethyl aluminum (TMA). The TMA storage cylinder was kept at 5°C. TMA mixed with hydrogen gas was supplied to the reactor via the upper electrode nozzle. The carrier H<sub>2</sub> gas of TMA and dilute H<sub>2</sub> gas flow rates were mainly 16 sccm and 1.5 slm, respectively. The substrate temperature was from 50 to 100°C and the pressure was 2.3 Torr.

There are the following optimum conditions of plasma reaction. Figure 2 shows that the deposition rates of Al films depend on the RF power density. There is a peak of deposition rate at RF power density of about 1.4 W/cm<sup>2</sup>, however the resistivities of these deposited films do not show the same power dependency. The optimum power density for both deposition rate and resistivity is 1.0 W/cm<sup>2</sup>. RF power is the most severe factor which influences not only the deposition rate but also the resistivity and uniformity. As shown in Figure 3, under an RF power density of 1.0 W/cm<sup>2</sup>, keeping other conditions constant, the deposition rate increases with increasing the carrier gas flow. Then, at a carrier gas flow above about 15 sccm, the deposition rate decreases at the center of the Si wafer. The uniformity of film thickness observed at excess source gas conditions is the same as found at a lower RF power conditions. It may be considered that at the center of a wafer, the plasma reaction is not magnetically enhanced with the excess source gas, because the mean free path of the cycloidal motion electrons is decreased. There is a lower limit of the amount of dilute H<sub>2</sub> gas, as indicated in Figure 4. After the ratio of H<sub>2</sub>/TMA exceeds 80, the deposition rates become constant and the resistivities are gradually reduced.

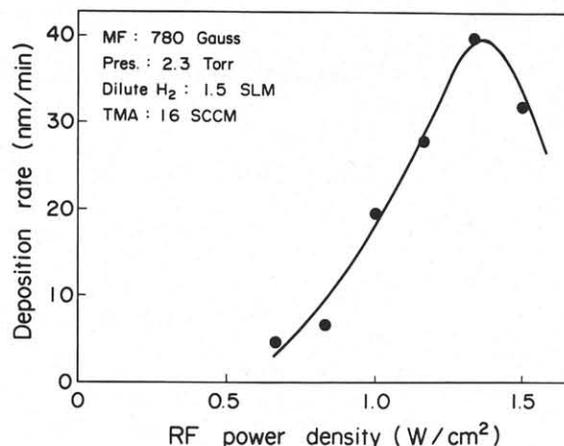


Fig. 2. Deposition rate of Al film as a function of RF power density.

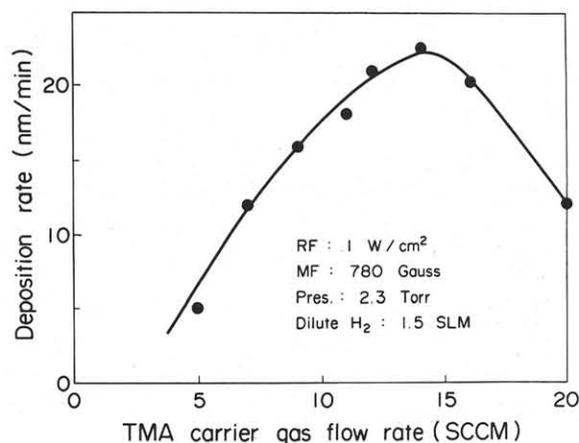


Fig. 3. Deposition rate vs. carrier H<sub>2</sub> gas flow rate.

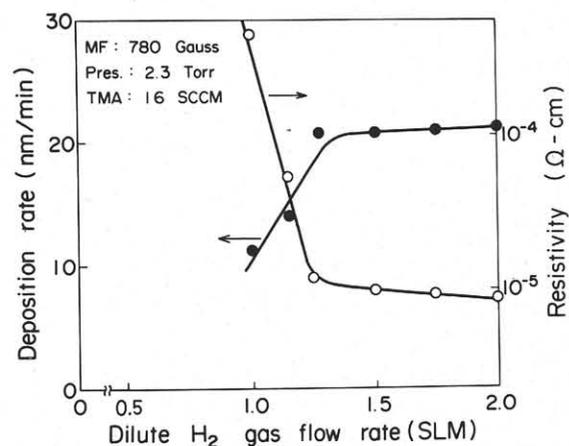
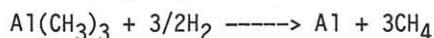


Fig. 4. Effect of dilute H<sub>2</sub> gas on deposition rate.

Figure 5 shows that the resistivities of Al films deposited by MPCVD decrease with increasing horizontal magnetic field at the wafer surface. This result shows that the effect of the magnetic field is as expected. This appears especially above 200 Gauss. Figure 6 shows an Auger depth profile of a film deposited by MPCVD under an RF power density of 1.0 W/cm<sup>2</sup>, TMA of 15 sccm, a pressure of 2.3 Torr, and a dilute H<sub>2</sub> gas flow of more than 1.5 slm. The thickness of the Al film deposited on a Si substrate is 100 nm. The excess oxygen and the 5.7% uniformly distributed carbon are observed at the surface layer and through the whole film, respectively.

Generally, the following reaction can be considered as hydrogen addition to TMA.



In the MPCVD system, it is believed that this reaction occurs strongly at the Si wafer surface because the molecules or the atoms of TMA and hydrogen are more excited by collisions with the electrons with helical or cycloidal motions. It is considered that if the complete decomposition reaction does not occur, the deposited films include the undecomposed TMA. In these films, the resistivity is higher than that of the film deposited by complete reaction. This is why the resistivities of deposited films decrease with increasing magnetic field as shown in Figure 5. This was also supported by the results of AES and SIMS, namely much carbon and hydrogen were observed in films deposited without a magnetic field reaction.

#### 4. ANNEALING of DEPOSITED FILM

The resistivities of MPCVD Al films can be further reduced by annealing as shown in Figure 7. After annealing at 600°C, a resistivity of 3.8 × 10<sup>-6</sup> ohm-cm was obtained. This is equal to that of a conventional sputtering deposition. Figure 8 illustrates the same annealing effect for films deposited by plasma reaction that is not magnetically enhanced. The reducing ratios of resistivity and thickness before and after annealing are larger than that shown in Figure 7. This shows that Al film deposited by MPCVD is denser than that deposited by a reaction which is not magnetically enhanced. The latter may be

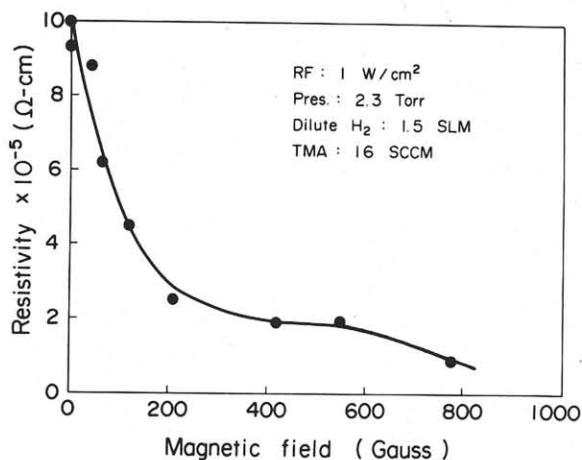


Fig. 5. Resistivity of Al film vs. horizontal magnetic field.

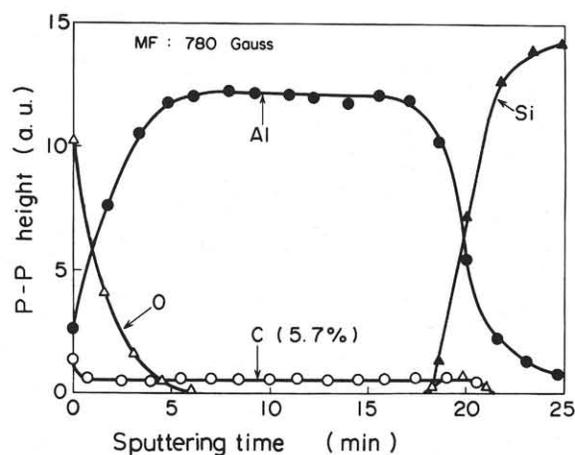


Fig. 6. AES depth profile of MPCVD Al film(100nm) achieved by ion-beam sputtering with Xe.

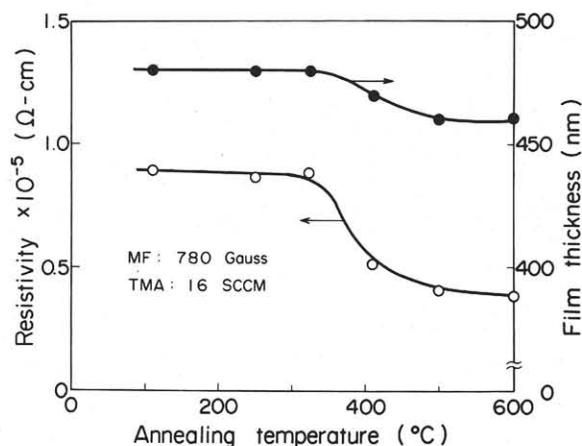


Fig. 7. Resistivity and thickness of Al film deposited by MPCVD as a function of annealing temperature.

porous or include hydrogen. The measurement results of AES and SIMS indicate that hydrogen diffuses out and carbon remains in the film after annealing. This also shows that undecomposed TMA included in the film can be dissociated by annealing.

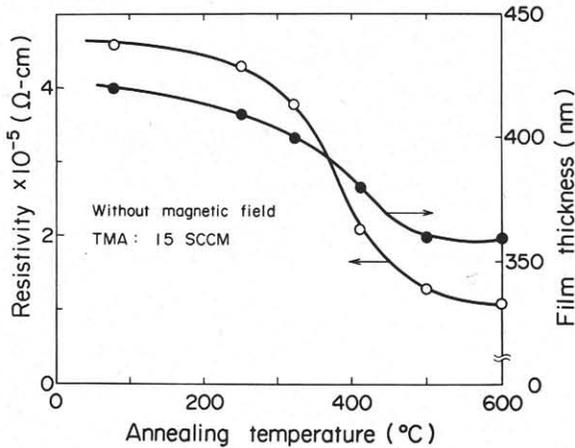


Fig. 8. Resistivity and thickness of Al film deposited by PCVD without magnetic field as a function of annealing temperature.

As shown in Figures 9(A) and (B), there are problems of surface roughness and hillock growth in thermal CVD Al and evaporated Al, respectively. On the contrary, the MPCVD Al film maintained a smooth surface even after annealing at 600°C, as shown in the Figure 9(C). This shows that the migration of Al atoms is suppressed. Although this mechanism is not yet clear, the carbon contained in the film plays an important role in the suppression of migration.

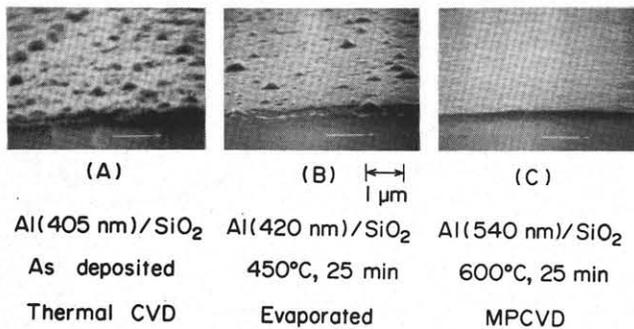


Fig. 9. SEM of Al film surfaces deposited by (A)thermal CVD, (B)evaporation, and (C)MPCVD. Samples (B) and (C) were annealed in 4 %H<sub>2</sub>/N<sub>2</sub> at 450°C and 600°C, respectively.

## 5. CONCLUSION

Al films were deposited using TMA by the MPCVD system in which plasma chemical reaction was confined locally by a magnetic field. There is less oxygen contamination from the chamber wall, and decomposition reaction occurs completely. A resistivity of  $3.8 \times 10^{-6}$  ohm-cm was obtained after enough annealing. To be hillock-free even after annealing at 600°C is an excellent property never before obtained with the conventional Al film. MPCVD will be a very interesting deposition method for VLSI technology and new material fabrication.

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