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ECR (electron cyclotron resonance) plasma for thin film technology

Satoshi Nakayama

Advanced Technology Research Laboratories, Sumitomo Metal Industries, Ltd., 1-3 Nishinagasu-hondori, Amagasaki, Hyogo, 660, Japan

Abstract - ECR plasma has been used widely and industrially for CVD and etching in semiconductor processes. In this paper, the progress which has been made in ECR plasma equipments and processing has been reviewed. ECR plasma source has some excellent features such as low pressure plasma generation, the capability of ion energy control and high ionization efficiency. The magnetic plasma control and the high power microwave plasma generation techniques developed in our laboratories have improved uniformity and throughput in comparison with those in RF plasma. Satisfactory performances are obtained in various processes, which are interlayer planarization, a-Si CVD, tungsten CVD, SiO_2 and aluminum etchings.

1 INTRODUCTION

The ECR plasma source reported by Matsuo has some excellent features such as low pressure plasma generation, high ionization efficiency and effective plasma extraction (ref. 1,2). Some investigators have applied the ECR plasma source to CVD and etching in semiconductor device fabrication processes. Fundamental properties and the merits of ECR plasma process have been shown in their reports (ref. 3-8).
There are, however, two important problems to be overcome in ECR plasma processes: (1) poor plasma uniformity, and (2) low throughput. To overcome these problems, we have newly developed a high performance ECR plasma equipment with a magnetic field controller, a high power microwave generator and a large capacity exhaust. Interlayer planarization in LSI, a-Si CVD, tungsten CVD, Al and SiO_2 etchings are performed in this equipment and satisfactory results are obtained.

2 ECR PLASMA EQUIPMENT

The high performance ECR equipment developed is shown in Fig. 1. The equipment has nearly the same concept reported by Matsuo (ref. 1,2). 2.45 GHz microwave is introduced in a plasma chamber through a quartz window. The magnetic flux density is selected to be 0.0875 T in order to satisfy the ECR condition. A divergent magnetic field extracts the plasma from the plasma chamber to the reaction chamber. A wafer is cooled and held by a water cooled electrostatic chuck.
To improve plasma uniformity we set a dual magnetic coil (DMC) under the substrate stage, the magnetic field just above a wafer can be controlled by DMC. To obtain high throughput, a high power microwave generator (max. 3 kW) and two turbo molecular pumps are used. Source gas or etching gas flow rate can be raised up to more than 200 sccm in 0.133 Pa.

3 MAGNETIC FIELD CONTROL

Plasma is generated in the chamber of the ECR plasma source and extracted toward a substrate efficiently by a divergent magnetic field. The density of plasma stream extracted along the magnetic field is significantly high at the center, and is markedly reduced in near the fringe of the plasma stream, which causes convex distribution of deposition rate or etching rate in ECR plasma processes. The plasma can scarcely diffuse across the magnetic force line, electric particles in the plasma are confined in a magnetic flux tube throughout the extraction, and the plasma density thus correspond to the density of the magnetic flux tube, i.e. magnetic field density (ref.8).
The uniformity of the ECR plasma can be improved by a dual magnetic coil (DMC). The DMC consists of inner and outer coils with a cylindrical york located coaxially below the stage. The inner coil generates a cusp field and the outer coil generates a mirror field. The magnetic field modified by the DMC is schematically shown in Fig. 2. There is a low magnetic field core region just above the substrate surrounded by a relatively high field region. The extracted plasma approaches to the substrate, the plasma expands isotropically, but cannot expand beyond the outer relatively high field region. Thus, the uniformity of the plasma density is improved without decreasing in the plasma density.
Using the DMC, SiO_2 films were deposited on 6 inch wafers. The results are shown in Fig. 3.

The uniformity of the deposition rate is remarkably improved from 10% to less than 5% with the DMC. The film properties, refractive index and buffered hydrofluoric acid (BHF) etching rate, are not affected by using the DMC. In addition, the deposition rate is increased with the outer coil current, which shows that the plasma is confined inside the relatively high field region.

4 EFFECTS OF HIGH MICROWAVE POWER AND HIGH GAS FLOW RATE

The deposition or etching rates reported previously in ECR plasma process were about 0.2 μm/min at most. About 1 μm/min rate would be necessary for engineering use. The experimental result in SiO_2 deposition is shown in Fig. 4. The deposition rate increases with the increase in the gas flow rate and the microwave power, and attains to 1 μm/min rate. The BHF etching rate is very fast in a low microwave power, however, become normal in higher power than about 2.5 kW. This result implies there would be no limitation in increasing deposition rate if source gases and microwave power are sufficiently supplied (ref. 5).

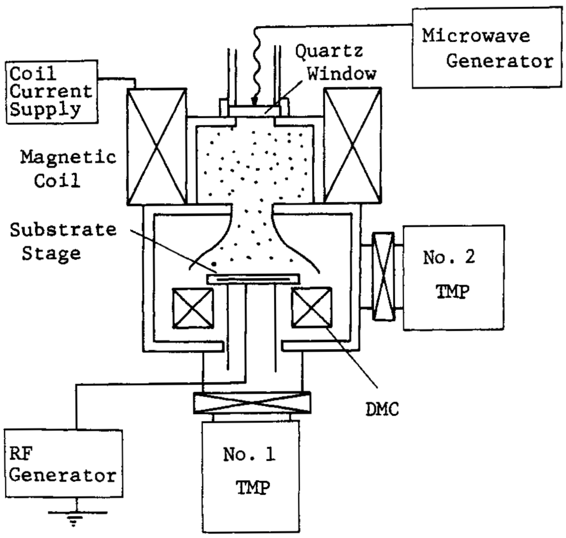

Fig. 1. Diagram of ECR plasma equipment.

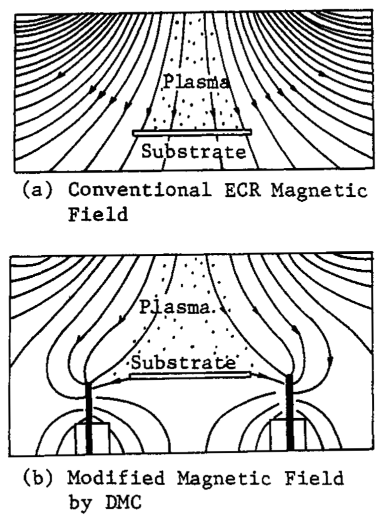

Fig. 2. Schematic diagram of magnetic force line.

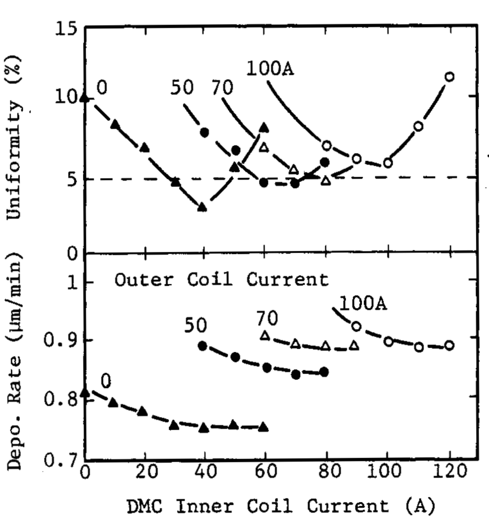

Fig. 3. Deposition rate and uniformity in a SiO_2 film prepared by ECR plasma CVD with DMC.

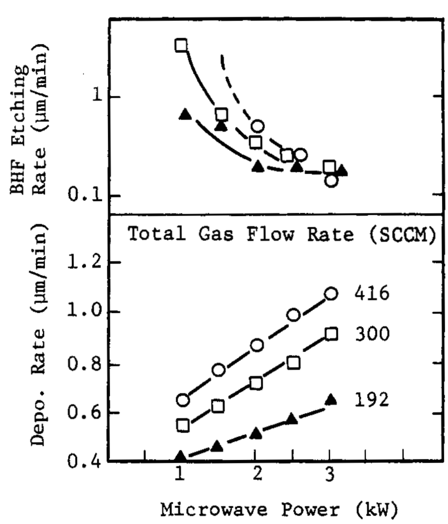

Fig. 4. Deposition rate and BHF etching rate in a SiO_2 film prepared by ECR plasma CVD. The gas ratio of SiH_4 to O_2 is 3/5.

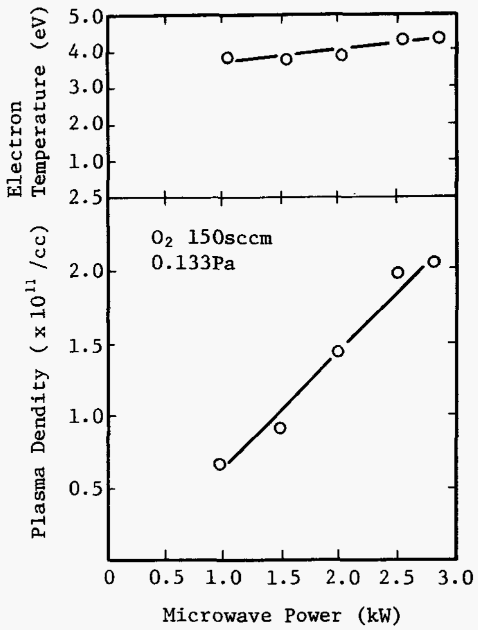

Fig. 5. The dependence of electron temperature and plasma density on microwave power.

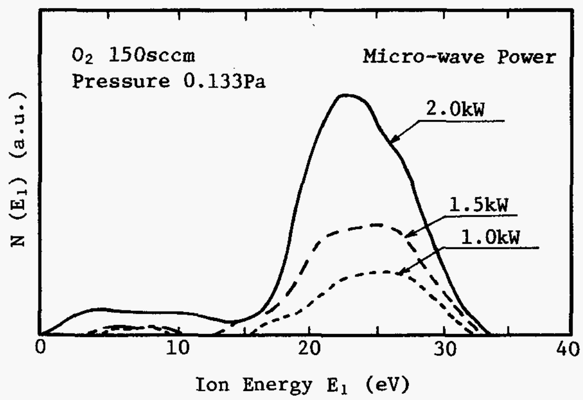

Fig. 6. The relationship between ion energy distribution and microwave power.

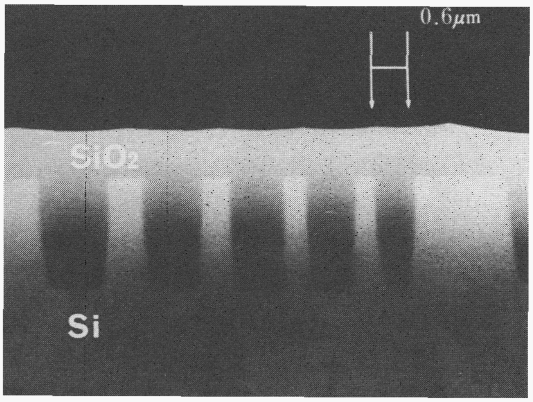

Fig. 7. Cross sectional view of planarization. Interlayer SiO_2 Microwave power 2.2 kW RF power 1.0 kW

The dependence of plasma density and electron temperature on microwave power are shown in Fig. 5. The plasma density increases linearly with microwave power and has no saturation tendency. The electron temperature increases slightly with microwave power. Fig. 6 shows the ion energy distributions for microwave powers. The microwave power increase does not change the ion energy distribution and only the number of ions increases. The properties of a deposited film are scarcely affected by icreasing microwave power.

Deposition under a relatively low gas pressure is desirable to obtain good film properties, because they are very sensitive to gas pressure. A large capacity exhaust is needed to keep a low gas pressure at high gas flow rate. Practical limit of deposition rate will be ruled by a capacity of a exhaust.

5 EXAMPLES OF APPLICATION

Interlayer planarization: RF biased ECR plasma CVD is effective for interlayer planarization in VLSI (ref. 3). By applying an RF bias to the substrate, CVD and sputter etching occur simultaneously on the surface of the wafer. The sputtering efficiency can be increased by inletting Ar gas in addition to SiH_4 and O_2 gases. The planarization of a submicron pattern with a high aspect ratio of 3 is obtained. A SEM photograph of a cross sectional view is shown in Fig. 7. It indicates almost a perfect planarization without a void.

A-Si CVD: Hydrogenated amorphous silicon (a-Si:H) films have been prepared by an RF plasma CVD. It was applied to many devices such as photoreceptors and photovoltaic cells. However, deposition of the RF plasma CVD is in the range of 0.01 μm/min to 0.1 μm/min and the deposition yield of the source gas is less than 10% (ref. 4).

We have applied the newly developed ECR plasma equipment to a-Si CVD. The obtained results are shown in Fig. 8. The deposition rate linearly increase with the increase in microwave power and high deposition rate was achieved at microwave power of 2.5 kW. In the case of RF plasma CVD, it is well known that photosensitivity is deteriorated when deposition rate extremely increases. This phenomenon did not appeared in the ECR plasma CVD. Photoconductivity (σ_p) increases with the increase in microwave power. Dark conductivity (σ_d) is independent of the microwave power and keeps low value of 10^{-12} S/cm. The films deposited at 1 µm/min have excellent photosensitivity of $\log(\sigma_p/\sigma_d) \geq 6$. The deposition yield of SiH_4 gas is more than 15%.

Tungsten CVD: Tungsten CVD has been applied to the interconnecting film in LSI. The tungsten film deposited by thermal CVD has had some problems such as high internal stress and inferior morphology. On the other hand, metal CVD by ECR plasma has been thought to be difficult, because microwave is reflected by the thin metal film deposited on a quartz window. Recently, we succeeded in preventing the formation of metal film on the quartz window, and applied ECR plasma to tungsten film deposition.

Figure 9 shows the relation between gas flow rate of SiH_4 and film characteristics. The film resistivities for SiH_4 gas flow rate of 0 and 5 sccm are less than 10 µΩ/cm, which are just close to that of bulk tungsten. The stresses of the films are low, and are between 1/2 and 1/4 of that in thermal CVD. A SEM cross sectional view of the film is shown in Fig. 10. The step-coverage of film is very excellent. 1 µm spaces are filled without void. The morphology of the film is smoother than that in thermal CVD. In thermal CVD, tungsten film can be deposited only on Si surface and not be deposited on SiO_2 surface. In ECR plasma CVD, tungsten film can be deposited on both surfaces without any difference.

Etching: The ECR plasma etching has some advantages, such as low energy ion bombardment, plasma generation under low pressure condition and the capability of ion energy control. Especially, the incident ion energy can be widely controlled from 10 eV to 200 eV by using RF bias control. From these features, ECR plasma etching can be applied to fabricate fine pattern in the film of various materials with high aspect ratio and minimal surface damages. The fundamental properties and the application to poly-Si, Molybdenum were previously reported (ref. 6,7). Here, we tried to etch Al-Si (1%) and SiO_2 films. The etching profiles obtained are shown in Fig. 11 and 12. It should be noted that little residues are found in

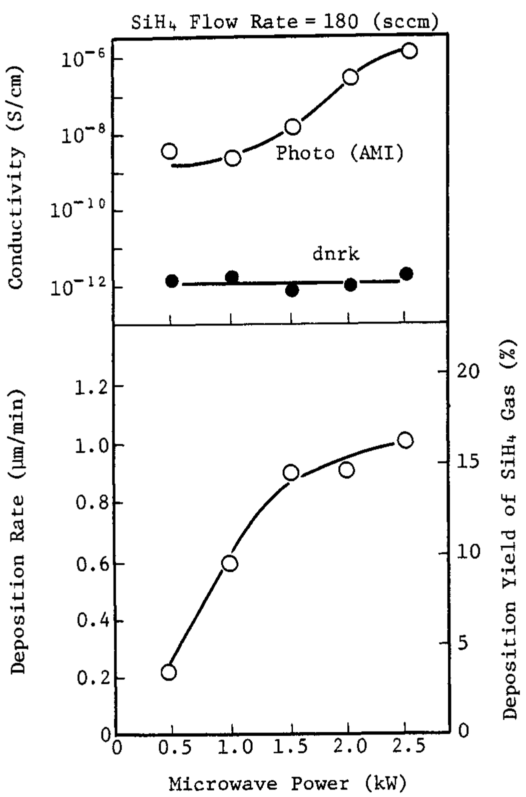

Fig. 8. Dependence of a-Si deposition rate and conductivity on microwave power. Pressure 0.133Pa, Wafer temperature 200°C.

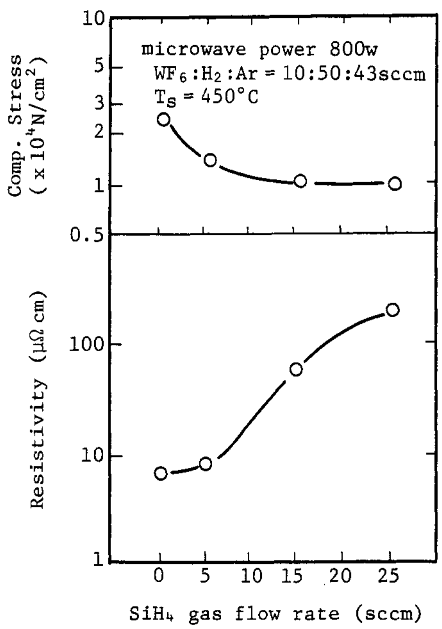

Fig. 9. Dependence of tungsten film resistivity and stress on SiH_4 gas flow rate.

the photograph of Al etching and there is no size change between the resist and the SiO_2 holes in the contact hole etching. They were performed by RF-bias ion energy control. The importance of micro-loading effects occurred at submicron pattern fabrication are pointed out recently. Since ECR plasma etching is performed at the pressure lower than that of RF plasma, micro-loading effect is also minimized as shown in Fig. 13.

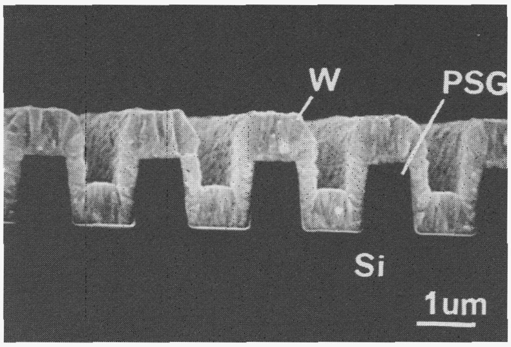

Fig. 10. Tungsten film prepared by ECR plasma CVD.
$WF_6:SiH_4:H_2:Ar=10:5:50:43$ sccm
Microwave power 800 W
Wafer temperature 450°C

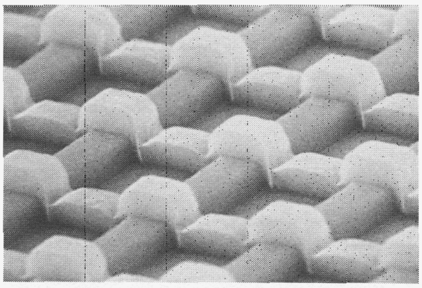

Fig. 11. Al-Si alloy etching profiles.
Pressure 0.53 Pa
Microwave power 800 W
RF power 140 W
Etching gas Cl_2+BCl_3

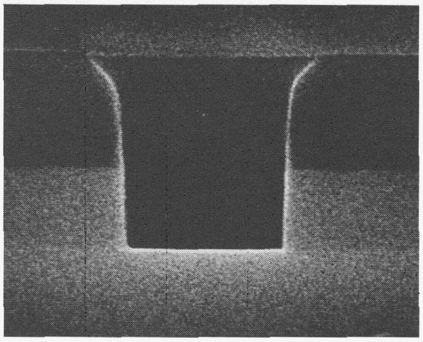

Fig. 12. Etching profile of SiO_2 contact hall.
Pressure 0.2 Pa
Microwave power 1 kW
RF power 400 W
Etching gas CHF_3+CF_4

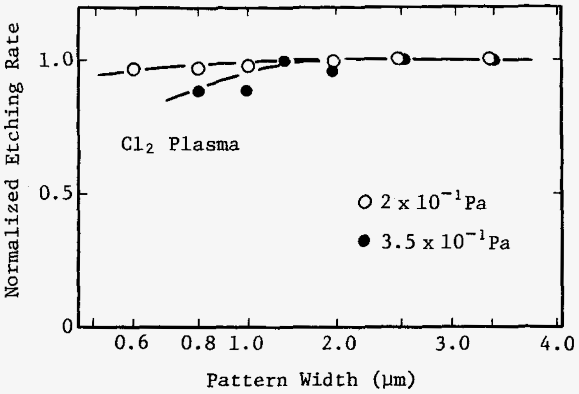

Fig. 13. Micro loading effect in Al-Si(1%) film etching.
Microwave power 800W, RF power 140W

Fig. 13. Micro loading effect in Al-Si (1%) film etching.
Microwave power 800 W
RF power 140 W

6 CONCLUSION

The uniformity and the throughput of ECR plasma equipment are remarkably improved by using a dual magnetic coil, a high power microwave generator and a large capacity exhaust. The improved equipment is suitable for various kinds of application. The ECR plasma will play an important role in VLSI processes.

REFERENCES

1. S. Matsuo and Y. Adachi, Jpn. J. Appl. Phys., 21, L4 (1982).
2. S. Matsuo and M. Kiuchi, Jpn. J. Appl. Phys., 22, L210 (1983).
3. K. Machida and H. Oikawa, J. Vac. Sci. Technol., B4, 818 (1986).
4. K. Kobayashi, M. Hayama and S. Kawamoto, J. Appl. Phys., 26, 202 (1987).
5. T. Akahori, T. Suehiro, T. Tani and S. Nakayama, Microprocess Conf., '88, 130 (1988).
6. T. Ono, M. Oda, C. Takahashi and S. Matsuo, J. Vac. Sci. Technol., B4, 696 (1986).
7. Y. Tobinaga, N. Hayashi, H. Araki and S. Nakayama, J. Vac. Sci. Technol., B6 (1), 272 (1988).
8. S. Nakamura and S. Nakayama, Proc. Symp. on SiN and SiO_2 Thin Insulating Films, 285 (1989).