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Processing Uniformity Improvement by Magnetic Field Distribution Control in Electron Cyclotron Resonance Plasma Chamber

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A novel ECR processing apparatus has been developed. Processing uniformity can be improved by controlling the magnetic field distribution in the ECR plasma chamber. Excellent uniformity of ±1% on six-inch wafers and ±2% on eight-inch wafers has been obtained for SiO_2 deposition. The conditions required for the specimen processing, such as ion perpendicular incidence, can be decided independently of uniformity control because the uniformity is controlled only in the plasma generation region. This method can be also applied to ECR ion-stream etching.

1. Introduction

ECR plasma technology has become important for VLSI processes such as etching and deposition. Using this technology, a highly ionized plasma of reactive gases can be stably generated at low gas pressures of 10^{-2} Pa and can be effectively transported to the specimen by a divergent magnetic field method. Anisotropic etching is achieved with excellent selectivity.[1] Also, high-quality thin films such as SiO_2 can be deposited without substrate heating.[2] To cope with the VLSI processes in which wafers larger than six inches in diameters will be used, uniformity improvement of the ECR plasma process is an important subject. However, an ECR plasma apparatus designed to improve uniformity must satisfy two requirements. One is that plasma uniformity should be decided independently from the conditions for the specimen region because additional control procedures can be taken to achieve the optimum condition for the process, such as perpendicular ion incidence. The other is that the advantages of separating the plasma generation section from the process section, such as less dissociation probability of reaction products, should not be lost.

Our new ECR plasma apparatus meets both of these requirements. To improve plasma uniformity, we disperse microwaves by controlling magnetic field distribution in the ECR plasma chamber. We were able to achieve this by analyzing microwave propagation characteristics in the plasma when a magnetic field is applied.

In this work, we first analyzed the microwave propagation characteristics and then measured the dependence of the ion current uniformity on magnetic field distribution, to verify results of the analysis. Based on these findings, we developed a novel ECR plasma processing apparatus and measured the uniformity and the deposition rate of SiO_2.

2. Propagation Characteristics of Microwaves

Figure 1 shows the magnetic configuration of a standard ECR plasma apparatus.[1] The calculated equi-magnetic-field-strength surfaces are shown by the dashed lines. To generate the ECR plasma, an external magnetic field is generated by the upper and lower coils and microwaves (frequency 2.45 GHz) are aimed at the ECR plasma chamber from the high-magnetic-field region through the quartz window. The ECR surface (875 G) forms in the proper region in the ECR plasma chamber.

The dispersion relation of microwaves in a uniform plasma under the influence of a uniform magnetic field was analyzed assuming that microwaves propagate parallel to the external magnetic field and that the plasma is surrounded by a cylindrical conductor. The influence of the chamber wall is included in the analysis. The equivalent plasma refractive index is calculated from the dispersion relation. Figure 2 shows the dependence of the equivalent plasma refractive index on frequency. The horizontal axis is the ratio of the microwave frequency ω to the electron cyclotron frequency ω_c. The ratio of the plasma

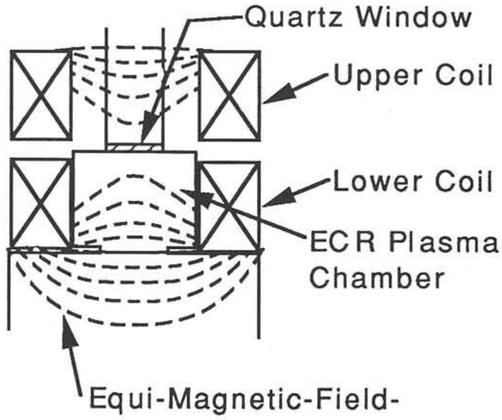

Fig. 1 Magnetic configuration and the equi-magnetic-field-strength surfaces of a standard ECR plasma apparatus.

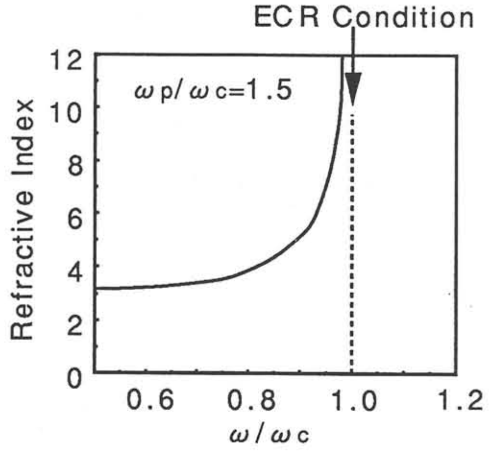

Fig. 2 Dependence of the equivalent refractive index of the plasma frequency . The horizontal axis is the ratio of the microwave frequency ω to the cyclotron frequency ω_c (=eB/m).

frequency ω_p to ω_c is assumed to be 1.5, which corresponds to typical plasma density. This figure shows that the equivalent plasma refractive index increases monotonically as ω/ω_c increases, when ω/ω_c is less than 1.0. During ECR plasma generation, microwave frequency ω is fixed and microwaves propagate from the high-magnetic-field region to the ECR surface, *i.e.*, ω/ω_c increases up to 1.0 as the microwaves propagate. Therefore, the equivalent plasma refractive index increases monotonically and diverges at the ECR surface as the microwaves propagate.

In the case of the standard ECR plasma apparatus, equi-magnetic-field-strength surfaces are convex with a small curvature near the quartz window as shown in Fig. 1 because the peripheral magnetic field is stronger than the central magnetic field in the ECR plasma chamber. Therefore, the equivalent plasma refractive index is larger at the center of the ECR plasma chamber than at the periphery.

Based on these facts, it appears that the plasma acts as a "convex lens" that focuses the microwaves on the center of the ECR plasma chamber as the microwaves propagate towards the ECR surface (convex lens effect). This results in non-uniform plasma generation, especially when the ECR surface is formed near the quartz window. When the central magnetic field is stronger than the peripheral magnetic field, it is highly probable that there is no "convex lens effect" and that microwave power is uniform. This indicates that the equi-magnetic-field-strength surface near the quartz window becomes concave. The dependence of the ion-current uniformity on magnetic field distribution is measured to verify this claim.

3. Experimental Results and Discussion

3.1 Ion Current Measurement

In a preliminary experiment, a sub coil was placed over the quartz window to change the magnetic field distribution near the quartz window, as shown in Fig. 3. The radial distribution of the ion current in the specimen chamber was measured with a Langmuir probe biased at −60 V. The magnetic field generated by the sub coil is so weak that only the magnetic field near the quartz window is changed. Therefore, to increase the effect of the magnetic field distribution upon the ion current uniformity, the upper and lower coil currents were fixed at 23 A and 16 A to form the ECR surface near the quartz window. When the sub coil current is 0 A, the ECR surface is slightly convex and is about 2 cm from the quartz window.

The measured ion current uniformity of Ar plasma is shown in Fig. 3. When the sub-coil current is 0 A, the uniformity is poor because the ECR surface is formed near the quartz window. However, the ion current uniformity improves as the sub coil current increases. The equi-magnetic-field-strength surface near the quartz window changes from slightly convex to slightly concave as the sub coil current is increased. This result shows that the "convex lens effect" disappears and that microwaves are distributed in the ECR plasma chamber by making the equi-magnetic-field-strength surface concave.

Figure 4 shows the practical magnetic configuration for achieving such a magnetic field distribution. Assuming that the coil currents are equal, the equi-magnetic-field-strength surfaces are calculated

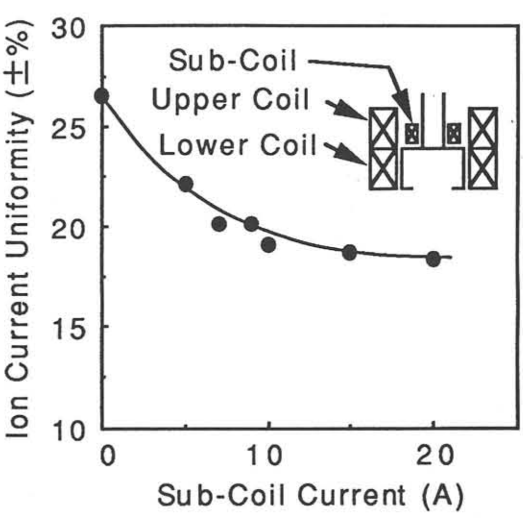

Fig. 3 Dependence of the ion-current uniformity on sub-coil current. The upper coil current is 23 A and the lower coil current is 6 A. The sub-coil is placed over the quartz window.

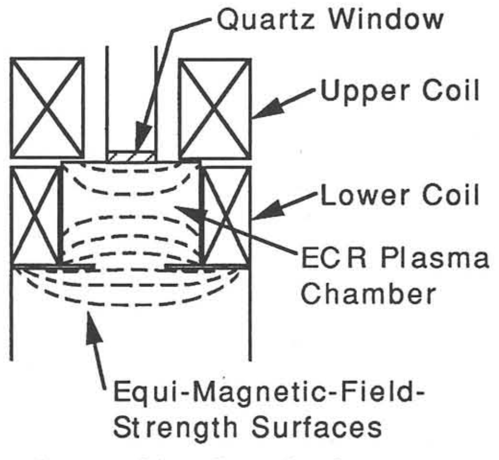

Fig. 4 Novel magnetic configuration for a concave equi-magnetic-field-strength surface near the quartz window.

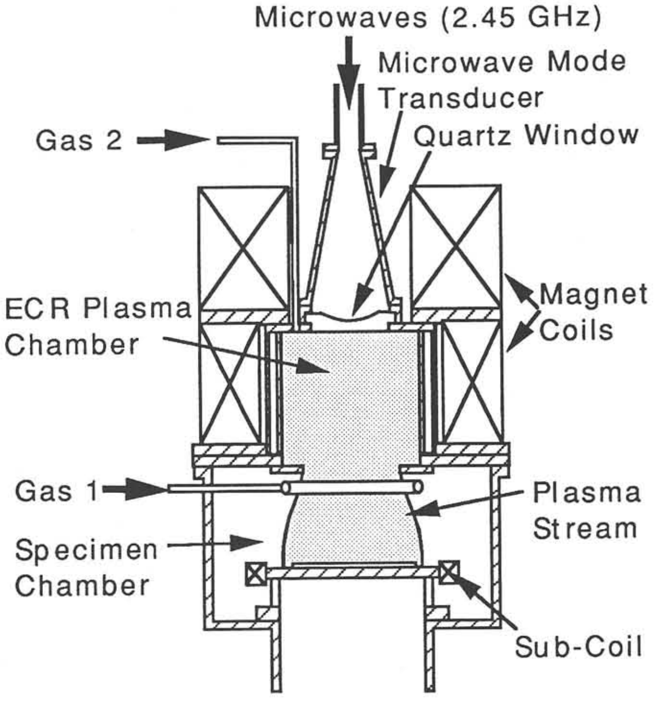

Fig. 5 Novel ECR plasma processing apparatus using the new magnetic configuration.

to be the dashed lines in Fig. 4. The concave surface near the quartz window is easily achieved even when the coil currents are equal because the inner diameter of the upper coil is smaller than that of the lower coil.

3.2 Uniformity of SiO_2 Deposition Rate

Based on the above results, we developed the novel ECR plasma processing apparatus shown in Fig. 5. The inner diameter of the lower coil is enlarged with no enlargement of the outer diameter of the coils compared with the standard ECR plasma processing apparatus. Moreover, a concave quartz window and a sub coil are added to the standard ECR apparatus. The sub coil is placed around the specimen and is used to achieve optimum process conditions around the specimen. The deposition rate of SiO_2 is measured by the ellipsometric method.

Figure 6 shows the radial distribution of the SiO_2 deposition rate for various magnet coil currents. This varies between convex and concave as the coil current is increased, *i.e.*, the ECR surface is moved from the quartz window toward the plasma extraction window. Concave distribution has never been achieved with an ordinary magnetic configuration. Excellent uniformity of ±1% on ±7 cm is obtained when the coil current is 250 A.

The dependence of the uniformity and deposition rate of SiO_2 on coil current is shown in Fig. 7. The uniformity of a six-inch wafer (±7 cm) depends on the coil current, but the deposition rate has little dependence on coil current. The coil current at which the distribution changes from convex to concave depends on the microwave power and gas flow rates of SiH_4 and O_2. The radial distribution is convex below 250 A and concave above 250 A (dashed line) under these conditions. The effect of the shape of the quartz window is also shown in Fig. 7. Uniformity is also improved by using a concave window instead of the plate window. The concave window subsequently improves uniformity.

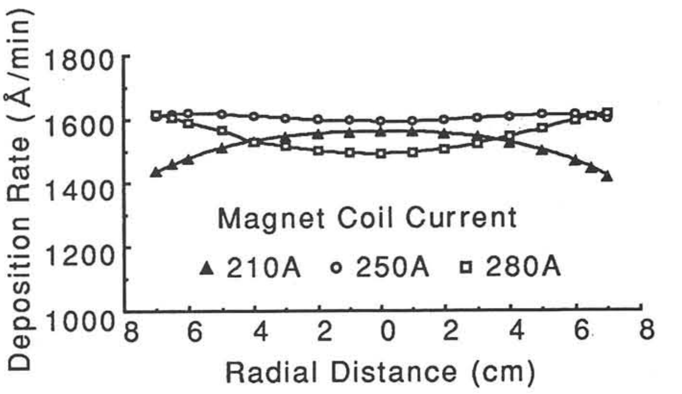

Fig. 6 Radial distribution of SiO_2 deposition rate. The deposition conditions are SiH_4 30 SCCM, O_2 30 SCCM with a microwave power of 300 W.

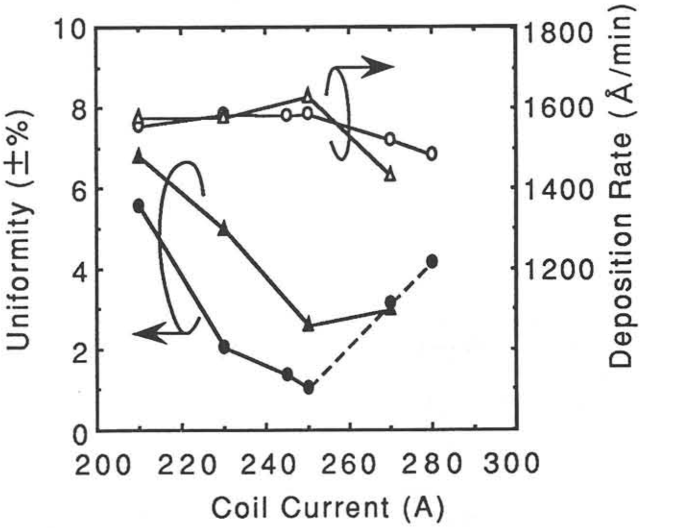

Fig. 7 Dependence of uniformity and deposition rate of SiO_2 on coil current. The deposition conditions are SiH_4 30 SCCM, O_2 30 SCCM, with a microwave power of 300W. Shape of the quartz window is plate (▲,△) and concave (●,○).

4. Conclusion

Changing the equi-magnetic-field-strength surface near the quartz window from convex to concave eliminates the "convex lens effect" and allows the microwaves to distribute in the ECR plasma chamber. A novel ECR plasma processing apparatus has been developed using this concept. Excellent uniformity of ±1% for six-inch wafers and ±2% for eight-inch wafers has been obtained for SiO_2 deposition. The conditions for the specimen can be decided independently of uniformity because uniformity is controlled only at the plasma generation region. This method can be applied to other ECR techniques such as ECR ion-stream etching.

References

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2) S. Matsuo *et al.*: Jpn. J. Appl. Phys. **22**(1983) L210.