Production of highly uniform electron cyclotron resonance plasmas by distribution control of the microwave electric field*

Muneo Furuse[a] and Seiichi Watanabe
Kasado Works, Hitachi Ltd. 794 Higashitoyoi, Kudamatsu 744=8601, Japan

Hitoshi Tamura
Mechanical Engineering Research Laboratory, Hitachi Ltd. 501 Kandatsu-Machi, Tsuchiura 300-0013, Japan

Osamu Fukumasa
Department of Electrical and Electronic Engineering, Faculty of Engineering, Yamaguchi University, 2557 Tokiwadai, Ube 755-0031, Japan

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We have developed the apparatus that can measure the three-dimensional distribution of microwave electric field intensity in electron cyclotron resonance (ECR) plasmas to investigate production and control of ECR plasmas. The relationship between the plasma properties of ECR plasmas and the microwave electric field intensity in plasmas is studied. We have confirmed that the pattern of the radial distribution of the ion saturation current at the electrode is the same as that of the microwave electric field intensity at the ECR zone. If the distribution of microwave electric field intensity at the ECR zone is uniform, the distribution of plasma density on the electrode becomes uniform, even if the distribution of microwave electric field intensity of the other zone is not uniform. Therefore, in order to obtain the optimum distribution of plasma density on the electrode, the distribution of microwave electric field intensity at the ECR zone must be controlled. © *1999 American Vacuum Society.* [S0734-2101(99)05806-6]

I. INTRODUCTION

In fabrication of ultralarge-scale integrated circuits (ULSI) such as 64-Mbit DRAMs, while are the representative semiconductor chips, manufacturing at the scale of quarter micron should be done. In addition, the etching process of the semiconductor requires high selectivity with high aspect ratio over a large area. Therefore, it is required that the plasma source of the etching apparatus not only generates plasmas efficiently in the low pressure condition but also produces plasmas with high uniformity and high stability. Plasma controllability is also necessary whereby plasma could be varied both in density and in spatial distribution. The area, which is satisfied with the above three conditions (i.e., uniformity, stability, and controllability) simultaneously, is called a process window.

A few types of the plasma sources[1] have been investigated for the next generation etching apparatus. Among them, it is possible for electron cyclotron resonance (ECR) plasmas to realize the wide process window in low pressure region. In ECR discharge, plasmas can be well controlled to optimize etching process by changing the resonance magnetic field condition and microwave power. For example, Suzuki *et al.* reported[2] that ECR discharge could produced plasmas with high density in the low pressure area. Watanabe *et al.* reported[3] the relationship between the distribution of plasma density and the distribution of microwave electric field (MWEF) intensity. They investigated various levels of microwave power by introducing only the dominant-mode microwave: either the circular TE_{11} mode or the rectangular TE_{10} mode. However, the relationship between the spatial distribution of MWEF intensity in the plasmas and the distribution of plasma density are not yet clear. It suggests that the MWEF intensity in the cavity and MWEF intensity in plasmas should be measured to clarify production and control of ECR plasmas. Many authors have investigated the relationship between plasma production and microwave. The topics investigated are plasma uniformity and microwave propagation,[4–8] plasma uniformity and the mode selection of the microwave,[9–11] and plasma uniformity and etching uniformity.[12]

We have also investigated the relationship between the distribution of ion saturation current and MWEF in the cavity resonator,[10] and the relationship between the distribution of ion saturation current and spatial distribution of MWEF intensity in plasmas.[13,14] In this article, we further discuss the relationship between the distribution of ion saturation current at the position of the electrode and the spatial distribution of MWEF or ECR zone in plasmas.

II. EXPERIMENT

Figure 1 shows a schematic view of the experimental apparatus. The apparatus is designed to investigate a microwave etching system, and the overall specifications are the same as a mass production etching system. The microwave power (2.45 GHz, 1.5 kW) is transferred to the cavity resonator through a waveguide, an isolator, a power monitor, and a three-stab tuner. A slot antenna is mounted at the bottom of the cavity resonator. Microwave is launched from the slot

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[a] Electronic mail: mune-furuse@Kasado.hitachi.co.jp

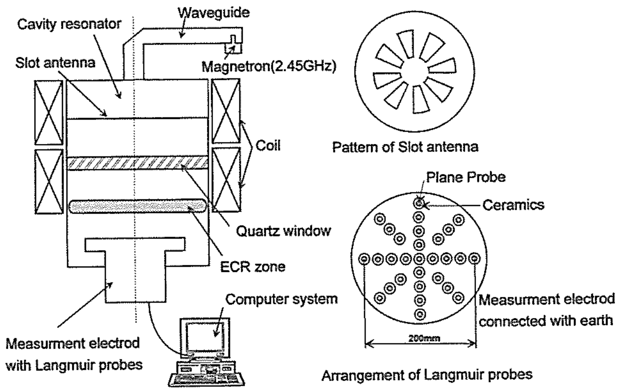

FIG. 1. Schematic view of the experimental apparatus.

antenna into the etching chamber through a quartz window. The etching chamber was evacuated to a base pressure under 1.3×10^{-5} Pa. Gases (Cl_2, BCl_3, O_2, Ar, and He) used for experiments were fed into the etching chamber through a mass flow meter.

Since the ion saturation current is proportional to the electron density of plasmas, the ion saturation current is measured to study the plasma properties. We have also investigated the correlation between the distribution of the ion saturation current and the distribution of the MWEF intensity. The radial distribution of ion saturation currents was measured by the measurement electrode where 29 plane type Langmuir probes are mounted. Each measurement probe diameter is 4 mm, and each probe is insulated electrically from the electrode. These probes are arranged in the area of diameter 200 mm, as shown in Fig. 1. The ion saturation current obtained by each probe is fed into the computer system.

Figure 2 shows a schematic view of the experimental setup used to measure the distribution of the MWEF intensity. In this case, instead of the electrode with 29 plane Langmuir probes, the three-dimensional stage where an MWEF probe could be moved is mounted. This MWEF probe system consists of two fluoroptic temperature sensors (Luxtron, Model-755). MWEF intensity is estimated calorimetrically from the temperature difference ΔT between the two thermometers. One fluoroptic temperature sensor measures the temperature of resistive susceptor, and the other measures the temperature in the vicinity of quartz pipe (i.e., the reference temperature). The temperature of resistive susceptor increases in the presence of the MWEF. When the MWEF probe is used in plasmas, the influence of light irradiation from plasma must be eliminated. Light irradiation markedly affects the value of ΔT. Heat transfer from plasmas also changes ΔT. In this experiment, therefore, light irradiation and the heat transfer to the temperature sensors from plasmas were prevented by setting light shield cover and by cooling the quartz pipe with air.

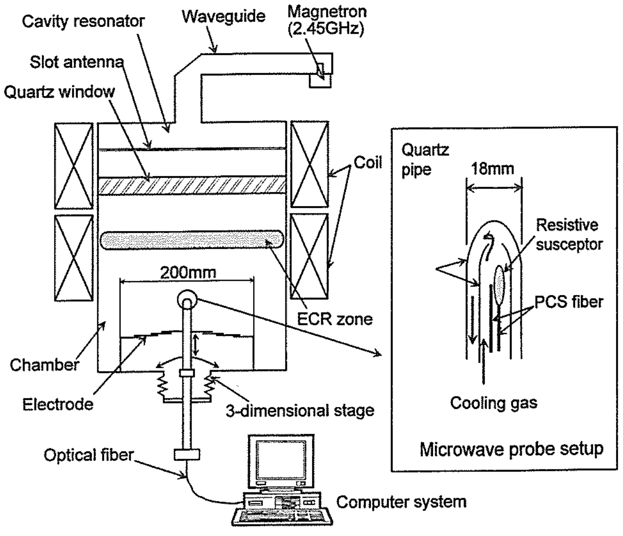

FIG. 2. Schematic view of the microwave electric field measurement apparatus.

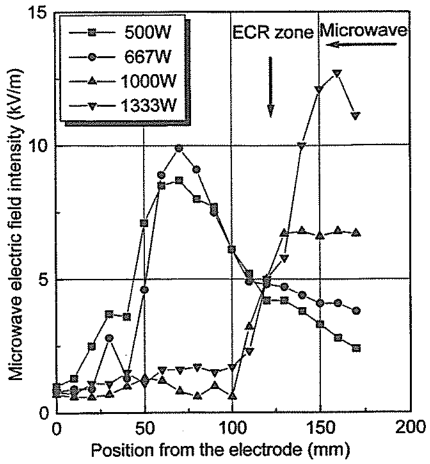

FIG. 3. Axial distribution of microwave electric field intensity as a function of probe position Z for various microwave powers, where the electrode is set at $Z=0$ mm. Experimental conditions are as follows: The ECR zone is set at 120 mm from the electrode. Gas flow rate of Cl_2 is 100 sccm and gas pressure is kept at 0.67 Pa.

III. RESULTS AND DISCUSSION

At first, the relationship between the distribution of MWEF intensity and the microwave power is studied. Cl_2

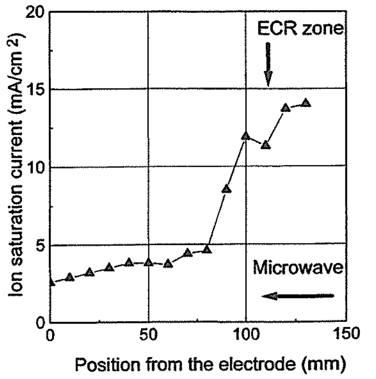

FIG. 4. Axial distribution of ion saturation current as a function of probe position, where the electrode is set at 0 mm. Experimental conditions are as follows: The ECR zone is set at 110 mm from the electrode. Gas flow rate of Cl_2 is 100 sccm and gas pressure is kept at 0.67 Pa.

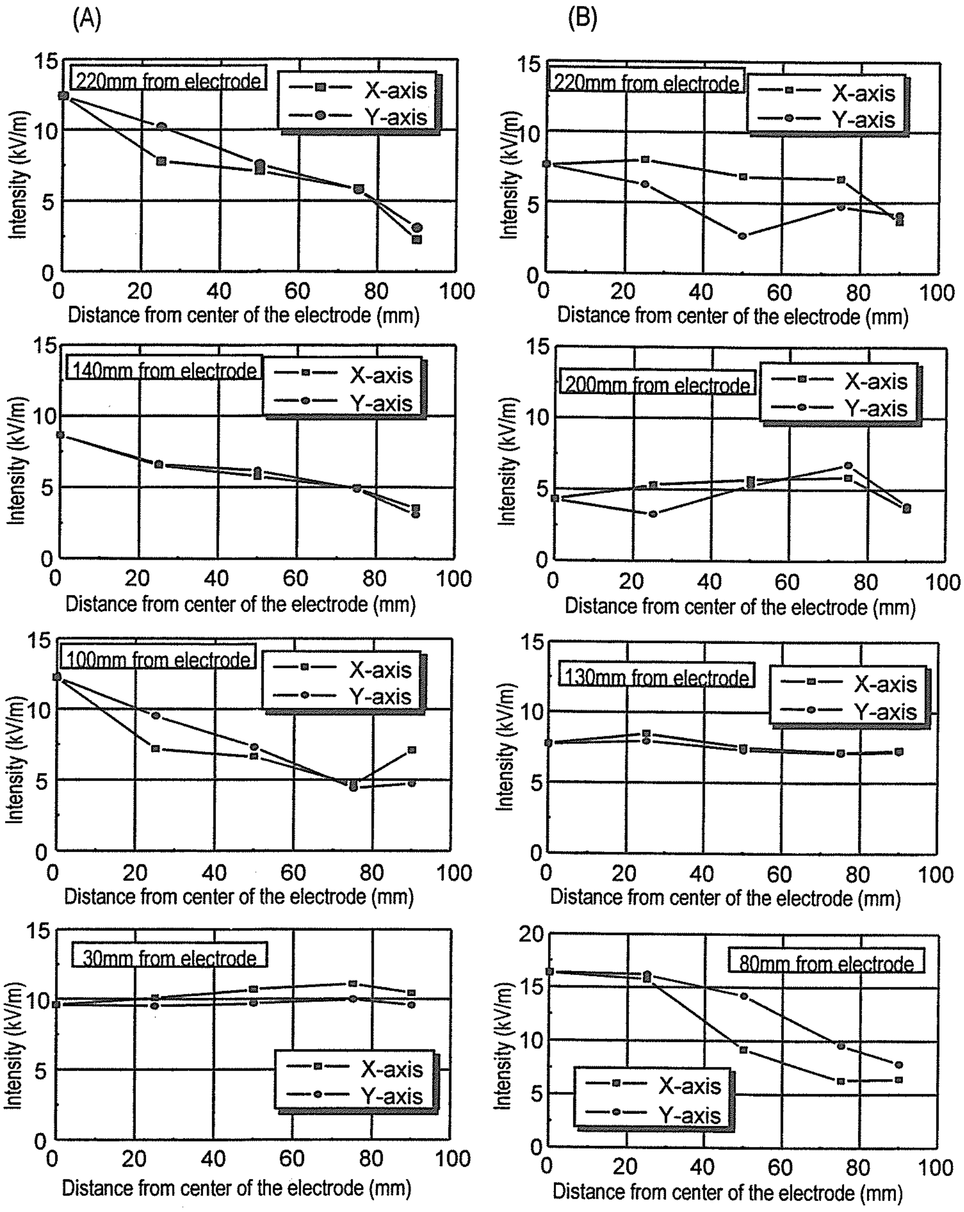

FIG. 5. Spatial distribution of microwave electric field intensity for various axial positions. Experimental conditions are as follows: The ECR zone is set at 30 mm in (A) and 80 mm in (B) from the electrode. Gas flow rate of Cl_2 and BCl_3 mixture is 150 sccm and gas pressure is kept at 1.6 Pa. Microwave power is 1.3 kW.

plasma was produced at a gas pressure of 0.67 Pa and the flow rate was 100 sccm. The power of microwave was changed from 500 to 1333 W.

A typical example of the axial distribution of the MWEF intensity is shown in Fig. 3. The microwave propagates in the plasma from right to left. In this figure, the electrode position is at 0 mm, and the ECR zone is located at about 120 mm from the electrode. The spatial distribution of the MWEF intensity in plasmas depends strongly on the microwave power. For high power case (>1000 W), the MWEF intensity decreases markedly near the ECR point. On the other hand, for low power case (<1000 W), the microwave penetrates further across the ECR point and has a maximum intensity at about $z = 70$ mm. These results suggest that, in low power case (<1000 W), there is formation of a standing wave with the electrode as the reflection edge. When the microwave power is above 1000 W, however, a standing wave is formed between the ECR zone and the quartz window due to repeated reflections. For high microwave power, electron density ne is higher than 1×10^{11} cm^{-3}, and for low microwave power, ne is lower than 1×10^{11} cm^{-3}.

The axial distribution of the ion saturation current was measured by the Langmuir probes. A typical example of the profile is shown in Fig. 4, where the power of microwave was 1000 W. According to the results shown in Figs. 3 and 4, the distribution of the ion saturation current has a maximum value in the ECR zone and is the same as the axial distribution of the MWEF intensity. Therefore, it suggests that the ECR zone is a main region of plasma production.

By taking into account the axial profiles of the MWEF and plasmas, we have studied the radial profile of the microwave plasmas.[13,14] Figure 5 shows the radial distribution of the MWEF intensity for various axial positions. Figure 6 shows the radial distribution of the ion saturation current at the electrode corresponding to the results in Fig. 5. In this experiment, the gas used was a mixture of Cl_2 and BCl_3 at

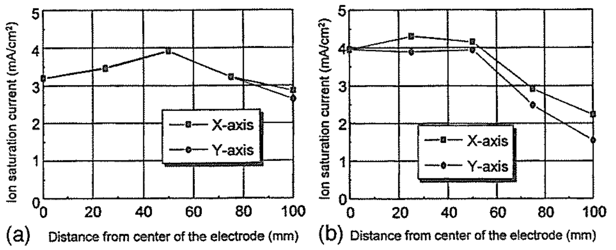

FIG. 6. Radial distribution of ion saturation current corresponding to the MWEF shown in Fig. 5. Experimental conditions are as follows: (a) The ECR zone is set at 30 mm, and (b) 80 mm from the electrode. Gas flow rate of Cl_2 and BCl_3 mixture is 150 sccm and gas pressure is kept at 1.6 Pa. Microwave power is 1.3 kW.

the pressure of 1.6 Pa (mixture gas flow rate: 150 sccm). The ECR zone was located 30 and 80 mm, and the microwave power was 1333 W.

The distributions of the MWEF intensity, both the ring shaped case and the center peak case are shown in Fig. 5. The result in Fig. 5 indicates that the radial distribution of MWEF intensity changes along the axial position. There is a strong correlation in the distribution of the MWEF intensity at ECR zone with the distribution of ion saturation current in Fig. 6. When the distribution of the MWEF intensity at ECR zone has the radial profile with the peak at the center, the distribution of ion saturation current also has the same profile. Even though the radial distribution of the MWEF intensity is uniform, the distribution of ion saturation current on the electrode is not uniform. Therefore, controlling the distribution of the MWEF intensity at the ECR zone, the distribution of ion saturation current on the electrode can be optimized for etching processes.

Based on these results, by changing the distance between the electrode and the ECR zone, it may be possible to control the MWEF intensity in the ECR zone, and hence control the plasma properties on electrode. Furthermore, the distribution of the ion saturation current could be optimized by varying the ECR position in the chamber. Here, we demonstrate the effect of the distance between the electrode and the ECR zone on the ion saturation current at the electrode. The working gas is the gas mixture of Cl_2 and BCl_3, at the pressure of 0.67 Pa (mixture gas flow rate: 150 sccm). The ECR zone was varied from 30 to 140 mm from the electrode, where microwave power was 1333 W.

Typical example is shown in Fig. 7. Distribution of the ion saturation current at the electrode is affected by the distance between the electrode and the ECR zone. By increasing the distance, the distribution of plasmas at the electrode is varied from the ring shaped model to the center peak model.

Finally, we discuss the relationship between the distribution of ion saturation current and the microwave power. In this experiment, the position of ECR zone, total gas flow rate and pressure are fixed at values, where the distribution of the MWEF is ring shaped. The results are shown in Fig. 8. The distribution of the ion saturation current on the electrode is always ring shaped even if the microwave power is changed.

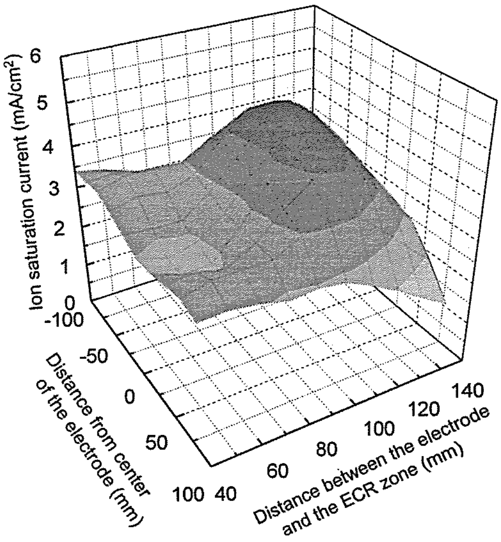

FIG. 7. Relationship between the distribution of ion saturation current and the distance from electrode to ECR zone. Experimental conditions are as follows: Gas flow rate of Cl_2 and BCl_3 mixture is 150 sccm and gas pressure is kept at 1.6 Pa. The microwave power is 1.3 kW.

On the other hand, the distribution of the ion saturation current on the electrode is always peaked at the center, when the MWEF has also center peak distribution.

With changing microwave power, the value of ion saturation current changes but the distribution of ion saturation current remains the same. The distribution of the ion saturation current on the electrode is decided by the distribution of the MWEF intensity at the ECR zone.

IV. CONCLUSIONS

We have developed an apparatus which can measure the three-dimensional distribution of MWEF intensity in ECR plasmas. With the use of this apparatus, we have investigated

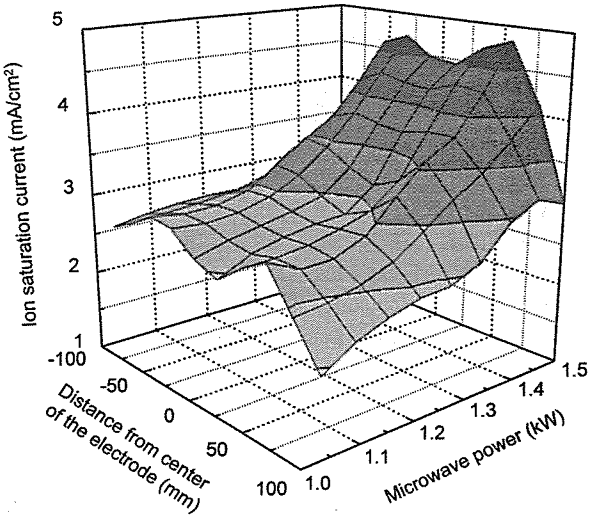

FIG. 8. Relationship between the distribution of ion saturation current and the microwave power. Experimental conditions are as follows: The ECR zone is set at 30 mm from the electrode. Gas flow rate of Cl_2 and BCl_3 mixture is 150 sccm and gas pressure is kept at 1.6 Pa.

the production and the control of the ECR plasmas. We have confirmed that the area of plasma production is mainly in the ECR zone. By measuring the spatial distribution of both ion saturation current and MWEF, a correlation in the distribution of plasma density at the electrode and the distribution of MWEF intensity at ECR zone has been established. In order to realize uniform distribution of ion saturation current on the electrode, the distribution of MWEF intensity at ECR zone should be kept uniform.

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