Plasma Characteristics of 450 mm Diameter Ferrite-Enhanced Inductively Coupled Plasma Source

Seung Pyo Hong, Jong Hyeuk Lim, Gwang Ho Gweon, and Geun Young Yeom[1]*

Department of Materials Science and Engineering, Sungkyunkwan University, Suwon, Kyunggi-do 440-746, Korea
[1] *Sungkyunkwan Advanced Institute of Nano Technology (NCRC), Suwon, Kyunggi-do 440-746, Korea*

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The effect of C-shaped ferrite modules installed above a spiral-type inductively coupled plasma (ICP) antenna coil and the plasma characteristics of an ICP source operated at 2 MHz were investigated in order to realize 450 mm wafer processing. The application of an appropriate amount of Ni–Zn ferrite modules to the antenna increased the plasma density slightly and decreased the plasma potential, while the application of the ferrite modules all over the antenna line decreased the plasma density and increased the plasma potential. In particular, by installing the ferrite modules locally in a low-plasma-density region, plasma uniformity was improved effectively.

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Wafer diameter has increased 1.5 times about every ten years. However, it is difficult to predict when a 450 mm wafer will be introduced because of the negative aspect of the excessive cost of the development of 450-mm-diameter processing systems in addition to the cost of 450 mm diameter silicon wafers.[1)] Among the processing tools using plasmas, capacitively coupled plasma (CCP) and inductively coupled plasma (ICP) sources are generally used in the semiconductor industry. However, there are some problems that must be solved in scaling up those plasma sources for 450-mm-diameter wafer processing.

First, in the case of CCP sources, increasing the excitation frequency causes standing wave effects that can affect processing uniformity. Yang and Kushner have suggested the formation of large-area uniform plasmas by using a segmented electrode CCP to suppress wave effects and by making the electrical distance between electrode feeds and sheath edges as uniform as possible.[2)] Similarly, Ellingboe *et al.* have studied a segmented discrete tile-type electrode that increases the rf frequency of an arbitrarily sized plasma source without causing wave effects.[3)] For the ICP sources, the scaling up of the sources for next-generation wafer processing also reveals the problems due to the thickness of the dielectric material and the large antenna impedance caused by the large antenna length.[4–6)]

In this study, the characteristics of an external ICP source for 450-mm-diameter wafer processing have been investigated. Ferrite modules installed above an ICP antenna can reinforce the induced time-varying magnetic field below the antenna and can change the plasma characteristics of the ICP source.[7)] The schematic diagram of the large-area ICP system used in this experiment is shown in Fig. 1(a). The processing chamber was made of an anodized aluminum with an inner diameter of 630 mm and housed a substrate with a diameter of 450 mm for next-generation wafer processing. A 30-mm-thick quartz window was used to cover the top side of the processing chamber and a 6-turn spiral external antenna made of 7 mm Cu tubing was placed on the quartz window. One end of the antenna was connected to a generator of 2 MHz rf power through an L-type matching network, while the other end was directly connected to the ground. To investigate the effects of the ferrite modules on the plasma characteristics and the electrical properties of the antenna, two ICP antenna configurations with different ferrite modules were used, as shown in Fig. 1(b).

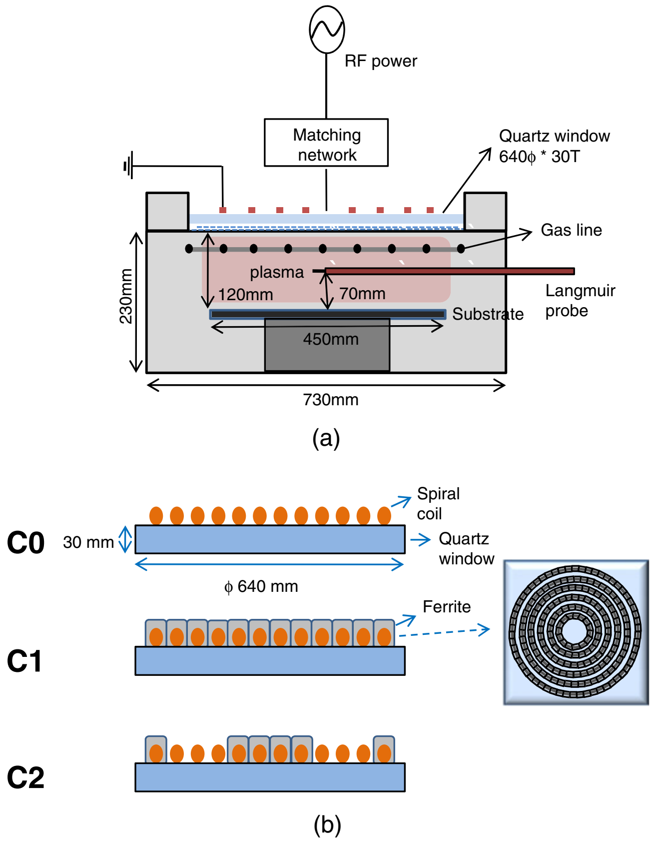

Fig. 1. (Color online) (a) Schematic diagram of 450 mm inductively coupled plasma system. (b) Three different antenna configurations with and without ferrite modules.

Figure 2 shows (a) the plasma density and (b) plasma potential and electron temperature measured using a double Langmuir probe (Plasmart Inc.) as a function of rf power at an Ar pressure of 20 mTorr. As shown in Fig. 2(a), the increase in rf power increased the plasma densities of all the antenna types; however, C2 showed the highest plasma density, while C1 showed the lowest plasma density. At an rf power of 2500 W and an Ar pressure of 20 mTorr, C2 showed 1.61×10^{12} cm^{-3}, while C0 and C1 showed 1.46×10^{12} and 1.40×10^{12} cm^{-3}, respectively. In the plasma

*E-mail address: gyyeom@skku.edu

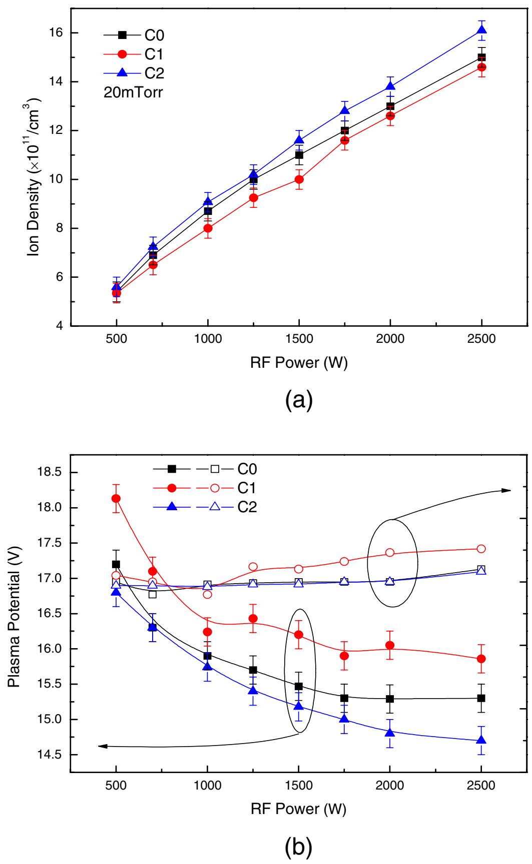

Fig. 2. (Color online) (a) Ion density and (b) plasma potential and electron temperature measured using a Langmuir probe at an Ar pressure of 20 mTorr as a function of rf power with three different antennas operated at 2 MHz.

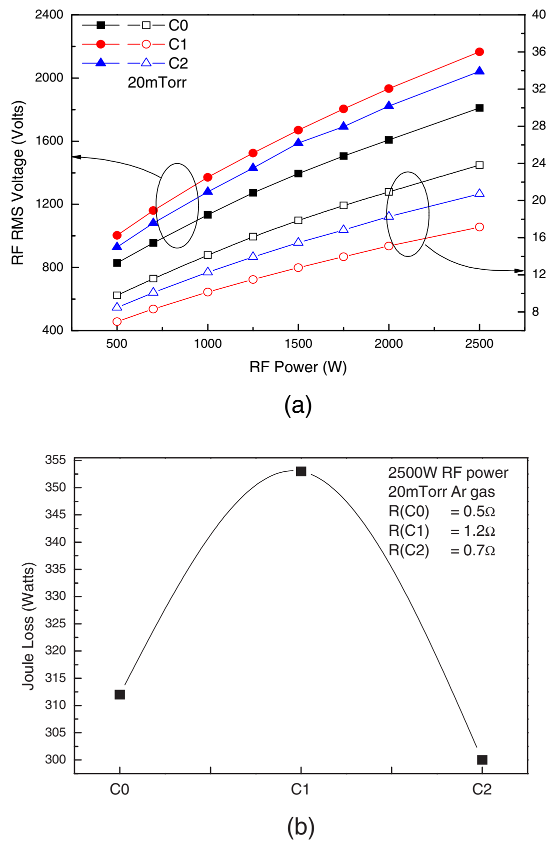

Fig. 3. (Color online) (a) Joule loss of four different antenna types at the pressure of 20 mTorr and at the RF power of 2000 W (b) RF rms voltage and current measured as a function of rf power at 20 mTorr Ar using an impedance analyzer installed at the power output of the matching network.

potential range of 14–18 V and in the electron temperature range of 2.0–2.3 eV, as shown in Fig. 2(b), no significant differences were obtained among the antenna types. However, C2 showed the lowest plasma potential at all rf powers. A low plasma potential decreases the possibility of contaminating the substrate by decreasing the sputtering possibility of the wall materials.[8] The installation of C-shaped ferrite modules above the ICP antenna line tends to increase the plasma density in the area between the antenna line and the substrate by reinforcing the time-varying magnetic field below the antenna line through the absorption and diversion of the time-varying magnetic field induced above the antenna line using the ferrite modules located above the antenna line. However, as shown in Fig. 2(a), the ICP source with the antenna line completely covered with C-type ferrite modules (C1) showed a lower plasma density than the ICP source with the antenna line without ferrite modules (C0), while the ICP source with the antenna line locally covered with ferrite modules (C2) showed a higher plasma density than the ICP source with the antenna line without ferrite modules (C0).

To understand the differences in plasma characteristics among the ICP sources with and without ferrite modules, the electrical characteristics of the ICP antenna for the ICP sources were investigated. As shown in Fig. 3(a), the rf rms voltage and current increased with the rf power in all the cases considered and the ICP antenna without ferrite modules (C0) showed a lower rf rms voltage and a higher rf rms current than those with ferrite modules (C1, C2). For the ICP antennas with ferrite modules, the ICP antenna partially covered with ferrite modules (C2) showed a lower rf rms voltage than that fully covered with ferrite modules (C1). The decrease in rf current and the increase in rf voltage at a given rf power for the ICP sources with ferrite modules are due to the resistance of the ferrite itself, and, with the increase in the ferrite content in the source, the resistance of the ICP source increases. When the resistance of the ICP antennas was measured using the impedance analyzer without striking a discharge, C1 showed the highest resistance of 1.2 Ω, while C0 and C2 showed 0.5 and 0.7 Ω, respectively.

The joule loss of the antenna, therefore, was calculated using the data in Fig. 3(a). As shown in Fig. 3(b), the ICP source fully covered with ferrite modules (C1) showed a higher joule loss than that without ferrite modules (C0); however, when the ICP was locally covered with ferrite modules, the source (C2) showed a lower joule loss than that without ferrite modules (C0). Therefore, the power delivered to the plasma was the lowest for the ICP source fully covered with ferrite modules (C1) and was the highest for the ICP source partially covered with ferrite modules (C2). The differences in plasma density obtained for the different ICP sources with and without ferrite modules shown in Fig. 2(a) are believed to be related to the power delivered to the source. Moreover, the lower plasma density obtained with C1 than that obtained with C0 is due to the more significant power loss to the ferrite itself, even though the

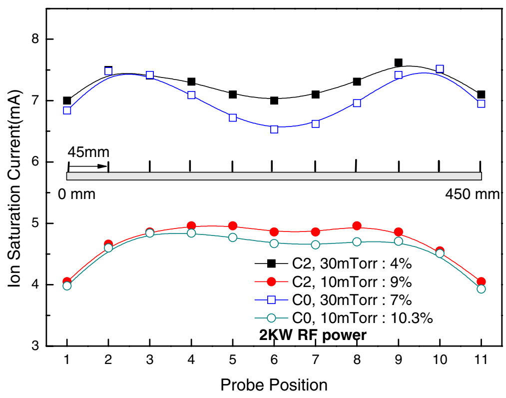

Fig. 4. (Color online) Plasma uniformities of the C0 and C2 antennas measured using a movable Langmuir probe system as a function of operating pressure at the rf power of 2000 W.

installation of ferrite modules is thought to increase the inductive coupling to the plasma via the magnetic field added by the ferrite modules.

For the 450-mm-diameter ICP source, the plasma uniformity may be more important than the plasma density. As shown in Fig. 4, the ICP source without ferrite modules showed a lower plasma uniformity of 7% than that with ferrite modules showing a plasma uniformity of 4% at an Ar pressure of 30 mTorr. The low operating pressure improved the plasma uniformities of both cases. The improvement of plasma uniformity at the low operating pressure was related to the increased diffusion of the charged particles toward the wall owing to decreased scattering, which decreased the ion density significantly near the chamber wall, even though the ion density uniformity at the center of the chamber was improved. Also, as shown in Fig. 4, the ion density showed a typical double-hump-type profile, which was caused by the higher induced magnetic field at a specific location below the source. However, the ICP source partially covered with ferrite modules (C2) showed a more uniform ion density profile by having a weaker hump-type ion current profile.

The improvement of the plasma uniformity was related to the reinforcement of the magnetic field by the ferrite modules. That is, as shown in Fig. 5(a), when no ferrite was applied to the spiral ICP antenna (C0), the highest time-varying magnetic field was induced between the power input location (center) and the ground location (edge). By applying ferrite modules at both the center and the periphery (C2), as shown in Fig. 5(b), a more uniform time-varying magnetic field was induced below the spiral ICP antenna, resulting in a more uniform ion density profile.

As shown in the Fig. 6, the SiO_2 etch depths measured along the centerline of the wafer.

The 450-mm-diameter ICP system was configured with and without the installation of C-shaped ferrite modules above the spiral antenna, and the electrical properties and plasma characteristics of the ICP source operated at 2 MHz were compared. The ferrite modules applied above the ICP antenna diverted the magnetic field above the antenna line to below the antenna line; therefore, it improved the power transfer efficiency and the plasma density. However, when a portion of the antenna was covered with ferrite modules, the improvement of plasma density with a lower plasma potential could be observed even though the improvement was not significantly high.

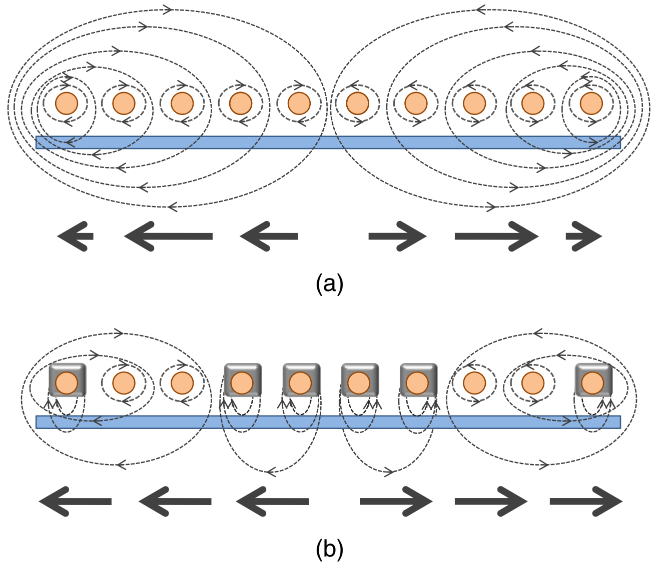

Fig. 5. (Color online) Schematic drawing of the induced magnetic field by the spiral ICP antenna for (a) without and (b) with ferrite modules installed locally at the center and edge of the antenna.

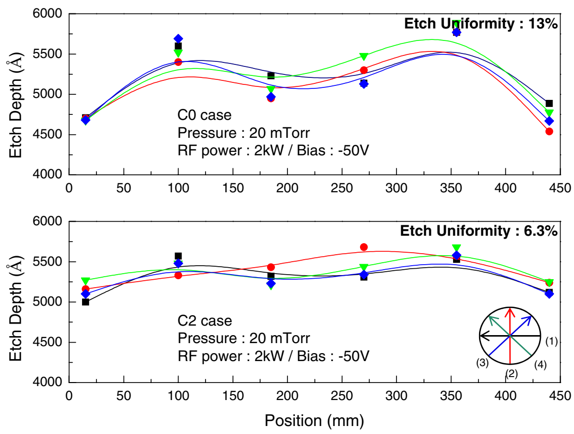

Fig. 6. (Color online) The etch uniformity of SiO_2 measured at the RF power of 2000 W, dc bias voltage of -50 V, and a C_2F_6 pressure of 20 mTorr.

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