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New Inductive rf Discharge Using an Internal Metal Antenna

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In conventional ICP (or TCP) reactors, a rf power is inductively coupled to an antenna placed outside a plasma vessel. Such an external coupling system is known to have several disadvantages. In order to avoid these disadvantages, a new internal coupling system has been developed in which a bare metal antenna is directly immersed in a plasma, thus forming a full metal reactor. This is accomplished by generating magnetic field lines around an antenna conductor, which effectively suppress the electron loss at the antenna and hence suppress the anomalous rise of plasma potential. Magnetic fields near the antenna are formed by superposing a dc current on a rf current along the antenna. This type of ICP enables rf discharges at rather low pressures such as $\sim 3\times10^{-4}$ Torr due to the magnetron effect. Other characteristics of internal metal antennas are also discussed.

KEYWORDS: inductively coupled plasma, transformer coupled plasma, internal metal antenna, dielectric window, electrostatic coupling, plasma potential rise, magnetic field effect

Recently, much effort has been made to develop low-pressure high-density plasma sources for next-generation ULSI processes. For example, various types of inductively coupled plasmas (ICPs) have been developed as well as helicon sources and ECR plasma sources.[1)] In these sources, electromagnetic energies are externally coupled to a plasma through dielectric materials and the plasma potential is commonly as low as 20–30 V. In ICPs, a helical or spiral antenna is placed outside a dielectric cylinder, hemisphere or disk (transformer coupled plasma, TCP).

The use of dielectrics in a plasma reactor has several disadvantages. First, the dielectric materials are easily sputtered by the electrostatic coupling from antenna to plasma,[2,3)] resulting in impurities. Second, electrically conducting materials cannot be processed in this system: once the dielectric window is covered with conducting thin films, they prevent electromagnetic coupling with the plasma and eventually interrupt the discharge. Third, the dielectric materials are mechanically weak and cause difficulties in maintenance. Finally, a recent trend toward large reactors will require the use of a very thick dielectric disk in TCP to withstand a huge force against the atmospheric pressure.

Thus, it is desirable to develop a high-density plasma in a metal reactor without a dielectric window. To realize such ICPs, one may insert a bare metal antenna in a plasma with one end of the rf coil grounded. In this case, however, the electrostatic coupling from the antenna to the plasma leads to an anomalous rise in the plasma potential ($\sim$ 100 V at 100 W rf power), which in turn causes frequent unipolar arcs and unstable discharges. Dielectric coating of the metal antenna lowers the plasma potential and yields a stable high-density plasma.[2,4)] However, the dielectric coating will be sputtered due to a large self-bias voltage unless a Faraday shield of the antenna is used. On the other hand, one can modify external rf circuits, with a bare metal antenna immersed in a plasma. To float the antenna against the ground potential, two blocking capacitors are inserted in a circuit between the rf source and both ends of the antenna coil. In this case, a stable high-density ICP is obtained with a low plasma potential. However, a high negative dc self-bias (-300 V–-700 V) appears on the metal antenna and hence considerable metal sputtering may occur. If such sputtering is allowable, then this method is usable for device fabrication processes.

In this paper, we report a novel internal rf coupling system which enables us to produce a high-density low-pressure plasma using a grounded bare metal coil. A key point of the concept is schematically illustrated in Fig. 1(a). Suppose a metal cylinder along the ζ axis is immersed in a plasma which carries a rf current $I_{\rm RF}$ and oscillates with a rf potential $\phi_{\rm RF}$. Since electrons can instantaneously respond to the rf potential, a number of electrons are absorbed onto the antenna at the positive phase of $\phi_{\rm RF}$. This huge loss of electrons is the cause of an anomalous rise in the plasma potential. To suppress the electron loss on the antenna, we introduce a magnetic field as shown in Fig. 1(a): a dc current $I_{\rm DC}$ is superposed on the rf current, thus generating an azimuthal magnetic field B_θ around the antenna. When B_θ is sufficiently large, slow electrons approaching the antenna are reflected before entering the rf sheath. This phenomenon is essentially the same as the well-known effect of surface magnetic confinement.[4)] Fast electrons can enter the ion sheath region and drift azimuthally ($\boldsymbol{E}\times\boldsymbol{B}$ drift), which is the so-called magnetron effect. As a consequence, the localized magnetic field can considerably reduce the loss of electrons.

Such magnetic fields can be formed not only by a current but also by a permanent magnet. In fact, the effect of magnetic fields was first tested using a rf coil with a permanent magnet array. The experimental results are satisfactory but we report here only the results obtained using a dc current because of the flexibility and the small size.

Figure 1(b) shows a schematic diagram of the internal antenna system using a dc current. A 14-cm-diameter one-turn loop metal coupler is coaxially set in a cylindrical stainless steel vacuum vessel 36 cm in diameter and

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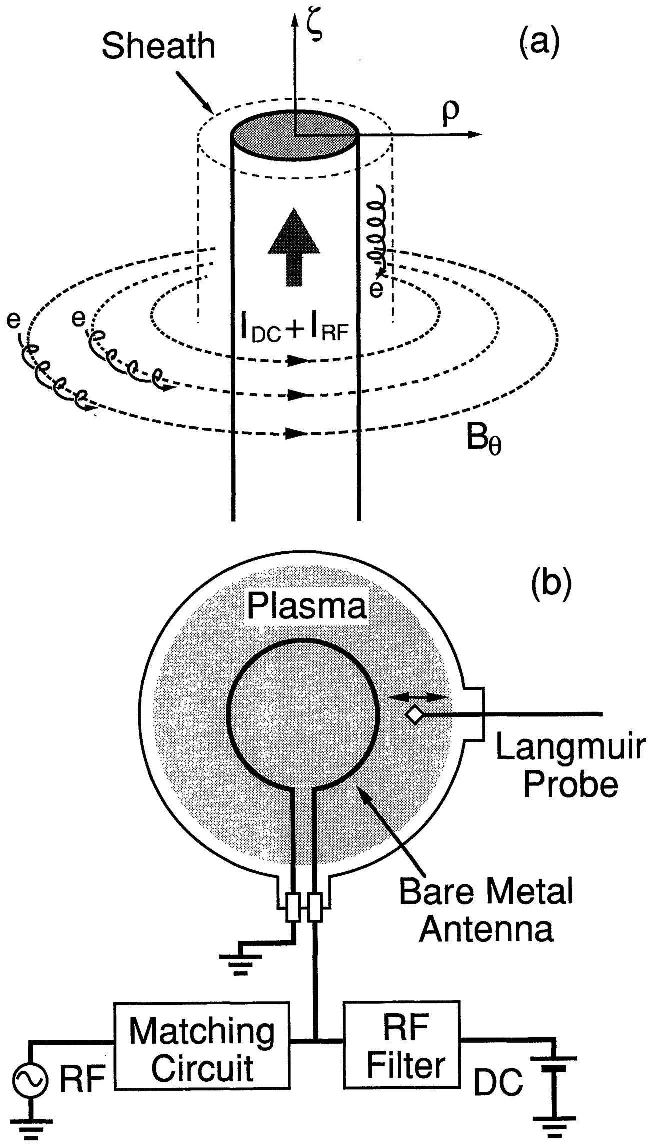

Fig. 1. (a)Electron motions under the azimuthal magnetic field generated by a dc current along a metal antenna in a plasma. (b)Internal metal antenna ICP apparatus.

47 cm in length. The antenna coupler is made of hollow copper conductor of outer diameter 3 mm through which cooling water flows. Hydrogen or argon is supplied through a mass flow controller at a pressure of 0.6–10 mTorr. A 13.56 MHz rf power of up to 1 kW is supplied to the antenna where peak-to-peak voltage reaches 1500–1800 V. A magnetic field localized around the antenna is formed by superposing a dc current (<250 A) on a rf current (<10 A) along the antenna. The dc power source (<7 V) and the rf source are isolated from each other by a rf filter and a matching circuit. Time-averaged plasma parameters are measured by a small Langmuir probe located on the chamber axis, 3 cm from the antenna plane.

Figure 2 shows an example of the current-voltage characteristics of the Langmuir probe with the magnetic field around the antenna as a parameter. The magnetic field B_θ at the distance ρ from the center of a cylinder carrying the dc current $I_{\rm DC}$ is given by $B_\theta = \mu_0 I_{\rm DC}/2\pi\rho$, for

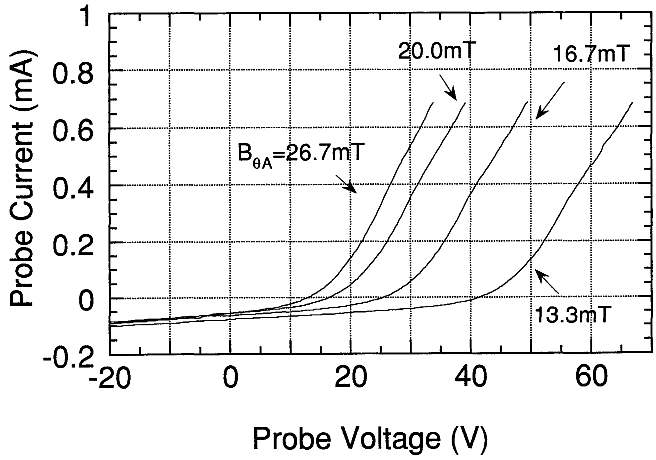

Fig. 2. The probe characteristics for different magnetic fields $B_{\theta \rm A}$ in 100 W rf discharges in 0.6 mTorr hydrogen.

the vacuum permeability μ_0. Substituting the radius a of the antenna conductor approximately yields the magnetic field on the surface $B_{\theta \rm A}$: for example, $I_{\rm DC} = 100$ A gives $B_{\theta \rm A} = 13.3$ mT (1 mT=10 G) in the present experiment ($2a = 3$ mm). However, a calculation of $B_{\theta \rm A}$ in the actual loop antenna with curvature effects taken into account reveals slight nonuniformity around the conductor. In comparison with the "straight cylinder model", $B_{\theta \rm A}$ increases by 6.4% inside the loop of the antenna and decreases by 6.4% outside. Henceforth, the value of $B_{\theta \rm A}$ in the "straight line model" is used as a measure of surface magnetic field. When no dc current was superposed on the antenna rf current, the plasma potential was anomalously high (>100 V) even at rf power as low as 100 W.

At the same time, unipolar arcs were frequently observed and the unstable discharge disturbed the probe measurements. However, dc antenna current over 100 A stabilizes the discharge and the plasma potential decreases from 55 V to 22 V as $B_{\theta \rm A}$ is increased from 13.3 mT to 26.7 mT, as shown in Fig. 2. It is also notable that this internal antenna system enables inductive rf discharge even at pressures as low as $\sim 3 \times 10^{-4}$ Torr.

The influence of $B_{\theta \rm A}$ on the plasma potential $V_{\rm p}$ is shown in Fig. 3 with hydrogen pressure as a parameter. The data are not shown in the low $B_{\theta \rm A}$ region where plasma potential is higher than ~100 V since unipolar arcs disturbed the measurement as described above. At all pressures, the plasma potential decreases with an increase in $B_{\theta \rm A}$ and reaches an almost saturated level of 25–30 V, which is slightly higher than the calculated floating potential, $(\kappa T_{\rm e}/e)\ln(M/2\pi m)^{1/2} \approx 13$ V, for $M = 2$ a.m.u. and the measured value of $\kappa T_{\rm e} \approx 4$ eV. Since a terminal of the metal antenna is grounded, the self-bias dc voltage is zero in the present case. For instance, the magnetic field of 10 mT gives the electron cyclotron frequency of 280 MHz and the electron Larmor radius of 0.7 mm. The measured electron temperature gives the electron-molecule collision frequency $\nu_{\rm e} \sim 0.5$ MHz in 6 mTorr hydrogen. Since the electron cyclotron frequency is much higher than $\nu_{\rm e}$, the plasma in the vicinity of the antenna are well magnetized and

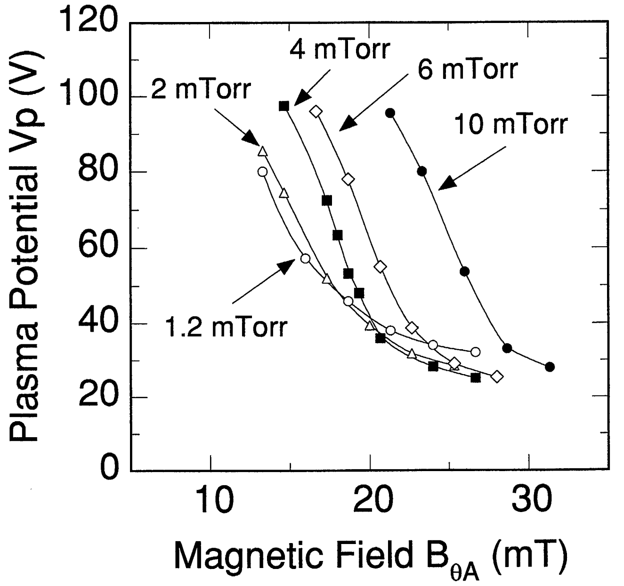

Fig. 3. Plasma potential V_p as a function of antenna magnetic field $B_{\theta A}$ at constant rf power (200 W) for different hydrogen pressures.

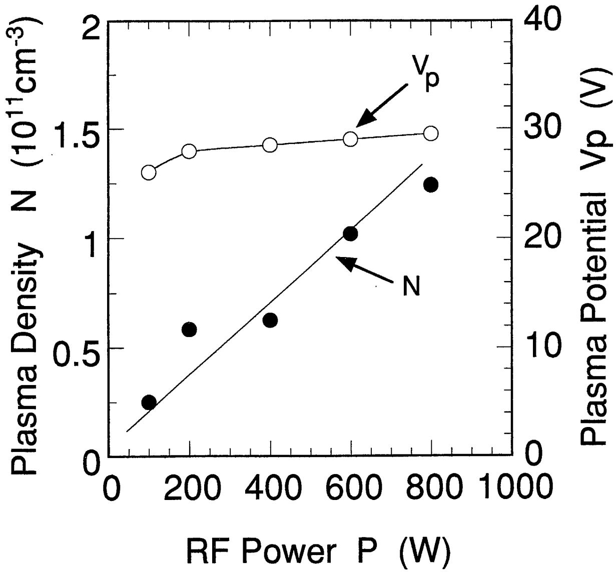

Fig. 4. Plasma density N and plasma potential V_p as a function of rf power P for 2 mTorr argon discharge at $B_{\theta A} = 30$ mT.

the electrons are considered to drift around the antenna conductor under the magnetic field B_θ and the radial rf electric field, and hence the electron loss to the antenna is considerably suppressed.

However, as seen in Fig. 3, the higher the discharge pressure is, the stronger is the magnetic field required to obtain the low plasma potential (~30 V). This result can be interpreted qualitatively as a result of collisional disturbance of electron cyclotron motions. Moreover, the rf power dependence of the magnetic suppression of plasma potential shows that a stronger magnetic field is required for higher-power discharge. For example, in order to obtain the plasma potential of ~30 V at 2 mTorr, the magnetic field should be increased by 15–25% when the discharge power is increased from 200 W to 1 kW. This is because the high power enhances the electrostatic antenna coupling, increasing the electron loss.

In general, molecular gases such as hydrogen yield relatively low plasma densities compared with argon, probably due to large energy losses in dissociation processes. In fact, the plasma density obtained in hydrogen discharge is $\sim 10^{10}$ cm^{-3} in the case of 500 W rf power and 0.6 mTorr. In the case of argon discharge, much higher densities were obtained as shown in Fig. 4. Almost the same magnetic effects on the plasma potential were observed in the argon plasma. The plasma densities, the plasma potential (~30 V) and the electron temperature ($\kappa T_e \sim 3$ eV) are similar to the parameters of a conventional ICP with external antenna. The spatial uniformity of plasma density has not been investigated in detail but the radial density profile in the downstream ~10 cm away from the antenna appears fairly flat at pressures lower than a few mTorr. In the magnetized antenna, the ion-induced sputtering of the antenna metal was observed to be considerably suppressed. The metal deposition caused by antenna sputtering was reduced by at least two orders of magnitude, compared with the case of a metal antenna floated by two blocking capacitors. The steady circular current I_{DC} generates a dipole magnetic field in the plasma. Its axial component B_z (normal to the antenna plane) reaches 1.8 mT at the coil center ($z = 0$) for I_{DC}=200 A ($B_{\theta A} = 26.6$ mT). This field is not strong but may be sufficient to support an $m = 0$ helicon wave excited by the rf current at 13.56 MHz.[5] However, this magnetic field decreases rapidly with the axial distance z as $B_z = 0.34$ mT at $z = 10$ cm, so that very careful measurements are necessary to investigate the existence of helicon waves in the present case. The presence of magnetic fields at the substrate position is not favored for some applications, *e.g.*, in dry etching, due to charge-up problems. In such cases, the use of permanent magnets instead of dc currents is recommended since this results in a strong magnetic field which quickly decreases with distance.

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