Effects of assistant anode on planar inductively coupled magnetized argon plasma in plasma immersion ion implantation

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The enhancement of planar radio frequency (RF) inductively coupled argon plasma is studied in the presence of an assistant anode and an external magnetic field at low pressure. The influence of the assistant anode and magnetic field on the efficiency of RF power absorption and plasma parameters is investigated. An external axial magnetic field is coupled into the plasma discharge region by an external electromagnetic coil outside the discharge chamber and an assistant cylindrical anode is inserted into the discharge chamber to enhance the plasma discharge. The plasma parameters and density profile are measured by an electrostatic Langmuir probe at different magnetic fields and anode voltages. The RF power absorption by the plasma can be effectively enhanced by the external magnetic field compared with the nonmagnetized discharge. The plasma density can be further increased by the application of a voltage to the assistant anode. Owing to the effective power absorption and enhanced plasma discharge by the assistant anode in a longitudinal magnetic field, the plasma density can be enhanced by more than a factor of two. Meanwhile, the nonuniformity of the plasma density is less than 10% and it can be achieved in a process chamber with a diameter of 600 mm.

I. INTRODUCTION

Inductively coupled plasma sources have been used to produce high density plasma at low pressure for thin film deposition and etching in the microelectronics and optics industry. A high-plasma density at low pressure has been achieved with electron cyclotron resonance source and helicon wave source and helicon resonator. The inductively coupled plasma source is the most widely used in modern materials processing due to its excellent radical uniformity over diameters exceeding 20 cm and relatively simple source configuration. This design is also commonly used in plasma immersion ion implantation (PIII) related semiconductor processing applications. The inductively coupled plasma source can easily be scaled to a large diameter while maintaining high plasma density. Different methods including antenna configuration and external magnetic field design have been employed to increase the processed area and to improve the plasma density uniformity at high plasma density. Different configurations of radio frequency (RF) inductively coupled plasma sources have also been introduced to plasma immersion ion implantation.

It is well known that plasma sources are usually operated with static electric (DC discharge) or alternating electromagnetic (RF, microwave) fields. An additional static magnetic field is usually introduced into the plasma discharge system to achieve higher-density plasma. The mobility of charged particles across the magnetic field is confined in the plasma in the presence of an external magnetic field. In the $E \times B$ field used in magnetron discharge, the electric field increases the energy and mobility of electrons across the magnetic field while the magnetic field achieves plasma confinement.

In this paper, we present an enhanced magnetized radio frequency (RF) inductively coupled PIII process utilizing a separate plasma discharge chamber and processing chamber, in which an assistant anode enhances the plasma discharge and the absorption of RF power in the magnetized plasma. The effects of the assistant anode in magnetized plasmas on the characteristics of argon plasma are investigated. A Langmuir probe is used to characterize the electron temperature, plasma potential, and ion density of the argon plasma across the chamber.

II. EXPERIMENT

The schematic diagram of the enhanced magnetized RF planar inductively coupled PIII equipment is shown in Fig. 1. In order to cater to the demands of PIII processes, it consists of a plasma discharge chamber ($φ 600 \text{mm} \times 300 \text{mm}$) and a material process chamber ($φ 760 \text{mm} \times 1030 \text{mm}$), both made of stainless steel and pumped by a turbo pump and a mechanical pump. A cylindrical stainless steel sheet is inserted into the plasma discharge chamber to serve as an assistant anode with a diameter of 260 mm. Cylindrical coordinates are used to locate the position in the plasma discharge and processing chambers. $Z = 0 \text{mm}$ designates the top of plasma discharge chamber as shown in Fig. 1.

With increasing discharge chamber diameter, a spiral planar coil gives rise to inherent nonuniformity in the magnetic induction field because of the difference between the center and the periphery of the coil. In our study, in order to produce high-density and high-uniformity plasmas, four RF planar inductive coils are placed on four planar quartz windows on top of the plasma discharge region, each of which being about 120 mm in diameter. The four inductive coils are located symmetrically above the plasma discharge region and connected to a matching box. 13.56 MHz RF
power (0–2000 W) is coupled to the plasma by the four pancake inductive antennae through the quartz windows. An external axial magnetic field is introduced into the plasma discharge region by external Helmholtz type electromagnetic coils outside the discharge chamber. The magnetic field strengths in the plasma discharge and processing regions are monitored using different magnetic coil current \( I_c \). The axial magnetic field can be adjusted from 0 to 100 G by changing the coil current. The axial magnetic field profile at \( r=0 \) is described in Fig. 2. The axial magnetic field \( B_z \) is about 6.5 G at \( Z=150 \) mm when the magnetic coil current \( I_c \) is 0.2 A. A divergent magnetic field is also introduced into the processing chamber as a dashed line in Fig. 1. The cylindrical assistant anode is mounted close to the underside wall of discharge chamber, to which a 0–70 V positive anode voltage is applied. Some free electrons in the skin layer produced by RF discharge can be accelerated across the magnetic line to the anode. The DC discharge is sustained between the plasma cathode and assistant anode due to additional electron-neutral collisional ionization by energetic electrons.

To investigate the effects of the assistant anode and the external magnetic field on the characteristics of the RF inductively coupled plasma discharge, the plasma parameters were monitored by an electrostatic Langmuir probe. A cylindrical tungsten probe 10 mm long and 0.2 mm in diameter was swept across the plasma discharge and processing chamber along the axial and longitudinal directions to determine the electron temperature, plasma potential, and ion density profile. In our experiments, the axial magnetic field is about 0–100 G. The minimum electron gyro radius is about 0.76 mm (\( B_z = 100 \) G, \( T_e = 4 \) eV) and this means that the probe radius is smaller than the electron gyro radius. As shown previously by Chen,\(^{24}\) Lafframboise’s theory can even be used in magnetized plasma, if the probe radius is small compared to the electron gyro radius. Therefore, the plasma parameters of weakly magnetized plasma can be calculated by using the theory for unmagnetized plasma with small probe radius.\(^{25}\) The ion density \( n_i \) is determined according to the numerical results of Lafframboise,\(^{26}\) in which it is assumed that the ion temperature \( T_i \) is smaller than the electron temperature \( T_e \), and the electron and ion energy distribution functions are isotropic and Maxwellian. The ion density can be written as

\[
n_i = \frac{l_i}{er_p l_p \left( \frac{8e(V_p - V_b)}{m_i} \right)}^{1/2},
\]

where \( l_i \) is the ion saturation current, \( m_i \) is the ion mass, \( r_p \) is the probe tip radius, \( L_p \) is the probe tip length, \( V_p \) is plasma potential, and \( V_b \) is the probe bias voltage. We can plot the \( I_i^2 - V \) curve and fit to this straight line \( I_i^2 = AV_b + B \).\(^{27}\) The ion density \( n_i \) can be obtained by substituting the slope A into Eq. (1). The electron temperature is defined by\(^{28}\)

\[
e = \frac{d \ln I_e}{dV_b},
\]

where \( I_e \) and \( k \) are the electron current and Boltzmann constant, respectively. The plasma potential is solved according to\(^{29}\)

\[
V_p - V_f = \frac{T_e}{2} \left[ 1 + \ln \left( \frac{m_i}{2\pi mk_e} \right) \right],
\]

where \( V_f \) is the floating potential and \( m_e \) is the electron mass.

### III. RESULTS AND DISCUSSION

The effects of the assistant anode on the characteristics of the RF inductively coupled argon plasma are investigated with and without the external axial magnetic field. The ion density, electron temperature, and plasma potential can all be
calculated according to the equations described in the previous section. The ion density profiles with different external magnetic field \( B_z \) and the anode voltage \( V_a \) at \( r=0 \) are shown in Fig. 3. Here, the RF input power is 1000 W and the pressure is \( 5 \times 10^{-4} \) Torr. It can be observed that the ion densities in the plasma discharge region \( (Z=0-300 \text{ mm}) \) are larger than those in the processing chamber and the maximum ion density is about \( 7 \times 10^{15} \text{ m}^{-3} \) when no anode voltage and the external magnetic field are applied. In this situation, the argon plasma produced in the discharge region diffuses to the processing chamber due to the density gradient. The ion densities at different axial positions are improved more than 40\% when only the anode voltage \( (I_c = 0, V_a = 70 \text{ V}) \) is applied to the assistant anode. This is because the plasma discharge is enhanced by the additional DC discharge and the plasma produced by the RF discharge serves as a cathode. When the anode voltage is supplied, electrons will be forced by the external electric field. Electron-neutral collisional ionization can be enhanced due to the higher mobility and energy of free electrons introduced by the anode potential. The ion density can also be increased more than 55\% in the processing chamber when only the external magnetic field \( (I_c = 0.6 \text{ A}, V_a = 0) \) is applied. This means that the RF power absorption can be enhanced in the inductively coupled magnetized plasma by the longitudinal external magnetic field.\(^{14,30}\) It is also seen that the ion density increases with the axial position in the discharge chamber, implying that the maximum plasma density occurs downstream in the discharge region and that substantial RF power deposition also occurs downstream. This may be because the right-hand polarized whistler wave can propagate in an overly dense plasma\(^{31,32}\) where the plasma electron density is greater than the critical density. For a radio frequency \( f = 13.56 \text{ MHz} \), the critical density is approximately equal to \( 2.3 \times 10^{12} \text{ m}^{-3} \).

When the assistant anode and external axial magnetic field are both introduced into the discharge region, greater enhancement of the ion density is observed as illustrated in Fig. 3. The largest increase in the ion density by a factor of about three and a half occurs in the center of discharge chamber. The ion density in the processing chamber is also increased by over 100\%. The enhanced collisional damping of DC glow discharge in the presence of the external magnetic field may contribute to the huge jump in the ion density. The free electrons in the plasma produced by RF discharge are affected not only by the electric field forces but also the external magnetic field when the assistant anode and external magnetic field are adopted simultaneously. The Lorentz force \( \mathbf{F} \) acting on an electron in the presence of both electric field \( \mathbf{E} \) and the magnetic flux \( \mathbf{B} \) is given by

\[
\mathbf{F} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = m_e \frac{d\mathbf{v}}{dt},
\]

where \( e \) is the electron charge and \( \mathbf{v} \) is the velocity of electron. The electron energy is only affected by the electric field and the magnetic field does not work on the electrons. However, the magnetic field will change the electron motion direction and prolong the track of the electrons due to the circular motion of an electron in magnetic field, which may improve the electron-neutral collision frequency when the assistant anode voltage is sufficient. The ionization coefficient \( \alpha \) in this cross-field is given by\(^{33}\)

\[
\alpha = A p \sqrt{1 + \omega_e^2 \tau_e^2 \exp \left( \frac{-C p}{E \sqrt{1 + \omega_e^2 \tau_e^2}} \right)},
\]

where \( p \) is the gas pressure, \( A \) and \( C \) are constants, \( E \) is the electric field strength, \( \omega_e \) is the electron cyclotron frequency, and \( \tau_e \) is the duration between collisions for loss of the momentum. The ionization coefficient will increase with the electric field strength. In cylindrical coordinates, the cutoff voltage of electrons motion from cathode to anode in a cross-field is described as\(^{34}\)

\[
V_c = \frac{eB^2}{8m_e b^2} \left( 1 - \frac{a^2}{b^2} \right)^{1/2},
\]

where \( B \) is the magnetic flux density, \( a \) is the cathode radius and \( b \) is the anode radius. This means that if the anode voltage \( V < V_c \) for a given \( B \), the electrons (no initial energy) emitted from the cathode will not reach the anode. In our experiments, the DC discharge current will increase with the anode voltage as shown in Fig. 4. However, it is found that a
higher-anode voltage causes unstable discharge in a small magnetic field. This may be due to electric breakdown when the anode sheet is inserted into the discharge plasma. Conversely, the cutoff magnetic field can be calculated in terms of a given \( V \)

\[
B_c = \left( \frac{8V m_e/e}{b \left( 1 - \frac{a^2}{b^2} \right)} \right)^{1/2}.
\]  

(7)

This implies that if \( B > B_c \) for a given \( V \), electrons will not reach the anode. Therefore, the DC discharge current will decrease when the magnetic field is larger than a certain value. It can be concluded from the ion density versus magnetic coil current plot displayed in Fig. 5. The ion density peak occurs at about \( I_c = 0.6 \) A when a 70 V anode voltage is applied.

The radial ion density profile above the substrate is monitored in order to evaluate the plasma density uniformity for a large area. The density profiles at \( Z = 600 \) mm with and without the assistant anode and external magnetic field are depicted in Fig. 6. The nonuniformity in the radial ion density at \( Z = 600 \) mm can be decreased from \( \pm 12\% \) without the assistant anode and external magnetic field to \( \pm 6.7\% \) with 70 V anode voltage and 0.6 A external magnetic coil current. The plasma transportation originates not only from diffusion but also from the \( \nabla B \) drift and curvature drift arising from the magnetic field gradient and divergent magnetic field configuration in the process chamber in the presence of axial magnetic field. Meanwhile, the multi-polar cusp magnetic field around the inner wall of processing chamber may mitigate the plasma loss to the wall and improve the plasma uniformity.

The assistant anode and external magnetic field change the electron temperature and plasma potential somewhat. The measurements of the electron temperature and plasma potential are performed above the sample chuck at \( Z = 600 \) mm and \( r = 0 \) mm. The electron temperature versus magnetic coil current behavior with and without the anode voltage is plotted in Fig. 7. It can be observed that the electron temperature \( T_e \) diminishes with increasing of magnetic coil current. This may be partly due to secondary electron suppression.\(^{35}\) For the enhancement of mobility and electron energy, the electron temperature will increase when the anode voltage is applied, as shown in Fig. 7. The trends of plasma potential with respect to the external magnetic field and assistant anode are shown in Fig. 8. Because of the assistant anode sheet inserted into the plasma, the plasma potential is increased with the anode voltage, and due to the decrease of the floating potential with higher-external magnetic field, the plasma potential will retard with increasing of magnetic coil current.

**IV. CONCLUSION**

The enhanced effects on planar radio frequency inductively coupled argon plasma are studied in the presence of an assistant anode and an external magnetic field at low pressure. The influence of the assistant anode and external magnetic field on the characteristics of argon plasma is investigated. The ion density in the processing chamber can be enhanced by a factor of two when the anode voltage and magnetic coil current are simultaneously applied, and the improvement is about 50% when only one of them is used.
This is primarily due to enhanced DC discharge in the presence of an external magnetic field. The ion density uniformity can also be improved by the divergent magnetic field and multipolar cusp magnetic field in the processing chamber. The observed nonuniformity of the plasma density is less than 7% and can be achieved in a processing chamber with a diameter of 600 mm. The electron temperature and plasma potential are somewhat altered by the introduction of an external magnetic field. The ion density uniformity can also be improved by the divergent magnetic field of an assistant anode in a planar inductively coupled magnetized argon plasma.

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