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Electronic dynamic behavior in inductively coupled plasmas with radio-frequency bias[*]

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The inflexion point of electron density and effective electron temperature curves versus radio-frequency (RF) bias voltage is observed in the H mode of inductively coupled plasmas (ICPs). The electron energy probability function (EEPF) evolves first from a Maxwellian to a Druyvesteyn-like distribution, and then to a Maxwellian distribution again as the RF bias voltage increases. This can be explained by the interaction of two distinct bias-induced mechanisms, that is: bias-induced electron heating and bias-induced ion acceleration loss and the decrease of the effective discharge volume due to the sheath expansion. Furthermore, the trend of electron density is verified by a fluid model combined with a sheath module.

Keywords: inductively coupled plasmas, radio-frequency bias, Langmuir probe, fluid model

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1. Introduction

Inductively coupled plasma (ICP) has been widely used in the semiconductor industry because of its perfect characteristics of reduced ion damage, independently controllable ion energy and plasma density.[1,2] As we all know, there are two discharge modes in inductive discharges, E mode (capacitive mode) and H mode (inductive mode).[3–6] In actual industrial etching processes, ICPs are always operated in the H mode. Besides, a radio-frequency (RF) bias source is always applied to the substrate electrode in order to control the ion bombardment, thereby increasing the etch rate.[7–15]

Recently, it has been found that the applied RF bias voltage cannot only control the ion energy independently but can also directly influence the bulk plasma parameters by means of heating mechanism and energy loss scheme.[16–20] For instance, Sobolewski *et al.*[16] and Lee *et al.*[17] observed experimentally that the electron density increased with the RF bias power in the E mode, but showed different dependence on the bias power when the discharge is in the H mode. In addition, Kwon *et al.*[18] verified the descending trend of electron density with RF bias power in the H mode with a self-consistent global model. Recently, Lee *et al.*[19,20] observed the skin effect on plasma uniformity and collisionless electron heating in ICP with a RF bias.

However, studies about the bias effect are still not completely clear. Besides, when the ICP power becomes higher, will the inflexion point of the electron density-bias curve appear at the same bias voltage value? Since the sheath becomes thinner under this discharge condition, the bias may have different influence on the plasma density. Therefore, in this paper, the bias effect on the electronic dynamic behavior was investigated in the H mode of ICP discharges by a Langmuir probe, especially in a wide bias voltage range. A novel electron behavior with RF bias source was observed, which is an un-monotonic evolution of electron density and temperature, as well as the vibration of EEPF shape between Maxwellian and Druyvesteyn types.

This paper is organized as follows. In Section 2, the schematic of the ICP reactor, a Langmuir probe and Z-Scan setup are described. In Section 3, the evolutions of electron density, effective electron temperature and EEPF with the RF bias voltage are presented. In addition, the trend of electron density and sheath thickness are calculated by a fluid model combined with a sheath module. Finally, a short summary is given.

2. Experimental setup

The measurement was carried out in a planar coil ICP with RF biased substrate in Ar. The experimental setup has been described in our previous papers (see Fig. 1).[21–24] Briefly, a RF field was generated by a two turn planar coupling coil, which included a water-cooled copper tubing, and a 13.56-MHz RF power was connected to the coil via a Γ-type matching network. The coil was placed on the top of the discharge chamber above a coupling quartz window. The discharge reactor had a cylindrical shape with an inner diameter of 30 cm and a height of 25 cm. An aluminum substrate of 26 cm in diameter was fixed 9 cm away from the power coupling quartz window. The secondary RF supply (13.56 MHz, 0–500 W) was connected to the substrate via another Γ-type match network, which served as the bias voltage in this experiment.

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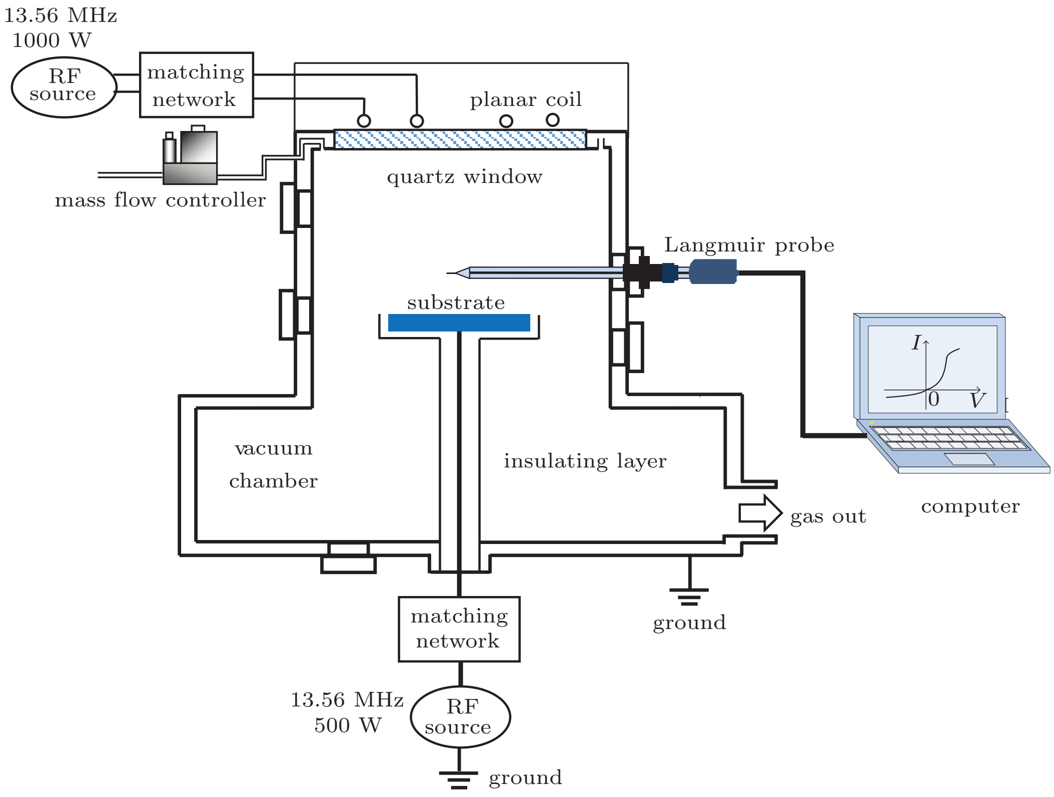

Fig. 1. (color online) Schematic diagram of planar-type ICP reactor in the experiment.

A Z-Scan (advanced energy RF measurement system) was connected to the substrate to measure the RF bias voltage. A Langmuir probe (Hiden probe Hiden Analytical Ltd) was fixed at the chamber center (6.0 cm away from the quartz window) to measure the electron density. The probe tip (0.2 mm in diameter, 10-mm long) is made of a tungsten wire. The electron density (n_e), effective electron temperature (T_{eff}), and the EEPF are obtained from the second derivative analysis of the I–V characteristics.[25]

3. Results and discussion

The measured n_e versus RF bias voltage at different ICP powers is shown in Fig. 2. The gas pressure is fixed at 20 mTorr. It is interesting to note that n_e decreases with RF bias when it is in the low range; however, as the bias voltage increases further, n_e has a remarkable increase, and the inflexion point appears at higher bias voltage when the ICP power is higher. The evolutions of n_e with RF bias voltage may be caused by the interaction of two distinct bias-induced mechanisms. In the low RF bias voltage range, the sheath near the substrate expands with increasing bias voltage, as shown in Fig. 3. Therefore, the effective discharge volume decreases due to the sheath expansion, whereas the effective area of the plasma loss is not changed due to the constant surface area around the chamber. Meanwhile, the number of ions in the bulk plasma that are accelerated and flow to the substrate increases with the bias voltage.[17,19] Hence, n_e decreases with the RF bias voltage. However, as the RF bias voltage increases further, the sheath above the substrate expands continuously (confer Fig. 3). Thus, the electrons are accelerated and gain more energy from the thicker sheath, and a large number of high-energy electrons start to play a dominant role, and consequently enhance the ionization of neutral gases in the bulk region. Although the plasma density becomes lower due to both the shrinking discharge volume and ion acceleration loss, the plasma generation caused by the energetic electrons is more prominent and this gives rise to the increasing n_e with bias voltage under this discharge condition.

To validate the evolution of n_e with the RF bias voltage, a two-dimensional (2D) self-consistent fluid model is employed to simulate the RF bias voltage effect, which has already been well described in Ref. [26]. The electromagnetic fields in the ICP reactor are governed by Maxwell equations, and are solved by the finite difference time domain technique. A sheath model is also included to illustrate the sheath more precisely.[27] The calculated n_e and sheath thickness as a function of RF bias voltage with the ICP coil current fixed at 10 A are presented in Fig. 3. It is clear that the trend of n_e with RF bias voltage qualitatively agrees well with the experimental results.

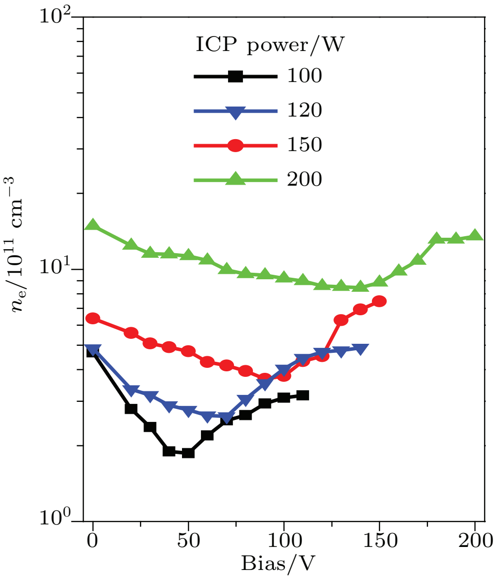

Fig. 2. (color online) The measured electron density with RF bias voltage at 20 mTorr.

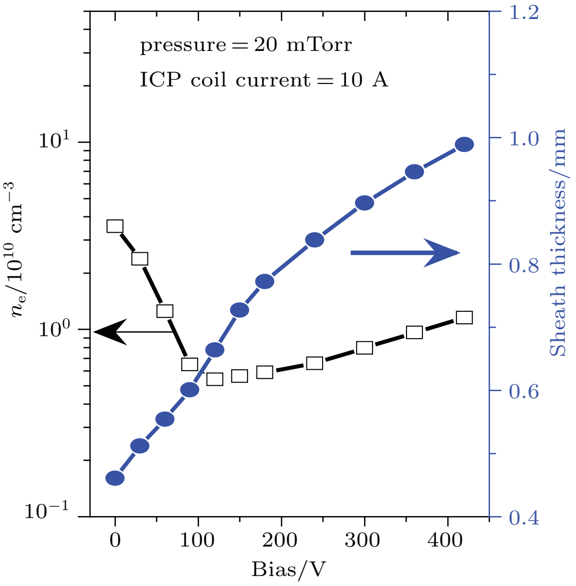

Fig. 3. (color online) The calculated electron density and sheath thickness with RF bias voltage at 20 mTorr.

The measured effective electron temperature, T_{eff}, as a function of RF bias voltage at various ICP powers is presented in Fig. 4. It is clear that T_{eff} increases first with RF bias voltage, and then decreases. The inflexion points of T_{eff} curves versus RF bias voltage at all the selected ICP powers (i.e., 100, 120, 150, and 200 W) correspond to those of n_e, except that they are minima in Fig. 2. Indeed, in the low RF bias voltage range, the sheath voltage rises with the RF bias voltage and the electrons can obtain more energy from the RF sheath oscillation (i.e., stochastic heating), and this gives rise to the higher electron temperature. Whereas, when the RF bias voltage increases further, the energetic electrons that were originally generated by the sheath oscillation at relatively high RF bias voltages are now substantially consumed due to the energy loss caused by the frequent ionization and excitation processes with neutral gases. Therefore, T_{eff} drops sharply in the high RF bias voltage range.

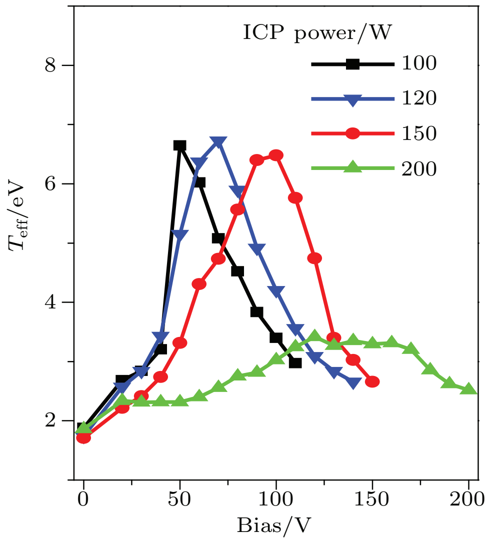

Fig. 4. (color online) Measured effective electron temperature with RF bias voltage at 20 mTorr.

It can also be noticed from Fig. 4 that, when the ICP power is lower (i.e., 100, 120, and 150 W) T_{eff} varies in the range 2–7 eV. However, at the ICP power of 200 W, T_{eff} is much lower; that is, varies from 2 eV to 3 eV. This is probably caused by the fact that when ICP power in the range of 100–150 W, the electron–electron (e–e) coulomb collision frequency is lower due to the low n_e. Therefore, high energy electrons heated by the capacitive bias sheath cannot be consumed by coulomb collisions and, hence, T_{eff} is as high as that of capacitive plasmas under this discharge condition. However, at an ICP power of 200 W, n_e is very high at all of the selected bias voltage values; that is, in the order of 10^{12} cm^{-3}. Although the electrons can be accelerated by the RF capacitive sheath, they lose more energy due to the frequent coulomb collision, which results in the low electron temperature around 3 eV.

Figure 5 demonstrates the evolution of EEPF with the RF bias voltages at 20 mTorr, 120 W. In the range of low RF bias voltage (i.e., lower than 70 V, Fig. 5(a)), the low-energy electron group of EEPF decreases and the high-energy electron tail increases with the RF bias voltage, and the EEPF shape varies from Maxwellian distribution to Druyvesteyn-like distribution. Indeed, when the bias voltage is switched off, the discharge is maintained by pure ICP power, the EEPF is a Maxwellian distribution because the high e–e coulomb collision frequency is caused by the high electron density ($\nu_{\text{ee}} \propto n_e/T_{\text{eff}}^{3/2}$).[28–30] When the RF bias voltage is switched on in the low range (i.e., around 10 V at low ICP power and 100 V at high ICP power), the electrons gain more energy due to the stochastic heating, and thus a large number of high-energy electrons are generated. Therefore, the high-energy electron tail of EEPF grows, while the low-energy electron group of EEPF declines. However, in the range of high RF bias voltage, the EEPF shape evolves backward with RF bias, and becomes a nearly Maxwellian distribution again at 130 V, as shown in Fig. 5(b). This happens because, when the RF bias voltage increases further, the energetic electrons lose energy due to the more frequent ionization and excitation processes with neutral gases, as mentioned above. Thereby, the high-energy electron tail of EEPF declines and the low-energy electron group of EEPF increases. The increasing n_e can also intensify the e–e coulomb collision, which accordingly returns the EEPF back to Maxwellian shape.[27–29]

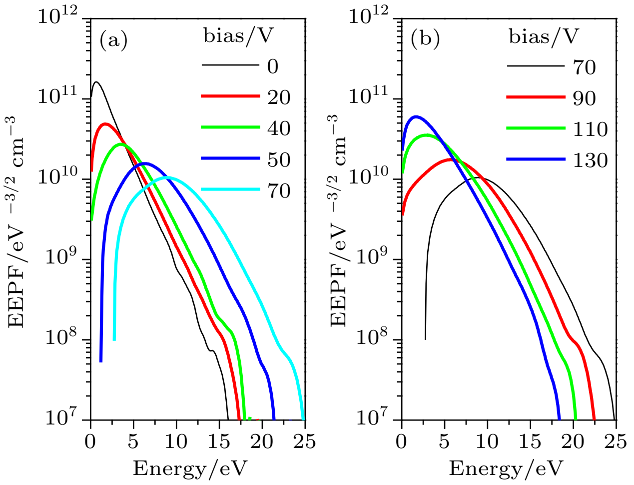

Fig. 5. (color online) Measured EEPFs with the RF bias voltage at 20 mTorr, 120 W in the range of low RF bias voltage (a) and in the range of high RF bias voltage (b).

4. Conclusions

In summary, it is found that the RF bias voltage has different effects on the bulk plasma characteristics when the value is sufficiently high in the H mode of ICP discharges. In the low RF bias voltage range, the n_e decreases, T_{eff} increases and the EEPF evolves from a Maxwellian to a Druyvesteyn-like distribution. However, in the range of high RF bias voltage, n_e reversely grows, T_{eff} declines, while the EEPF shifts back to Maxwellian distribution again. This phenomenon can be explained by the competition between bias-induced electron heating and bias-induced ion acceleration loss and the decrease in the effective discharge volume due to the sheath expansion at low pressure (i.e., 20 mTorr). In addition, the variation of n_e with RF bias voltage is verified by the fluid model. In our future work, the trends of the ion energy distributions, ion flux and averaged ion energy on the substrate electrode with the RF bias will be investigated by a retarding field energy analyzer.

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