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Effect of Magnetic-Mirror Confinement on Electron Temperature Control in ECR Plasma

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Abstract

The effect of magnetic-mirror confinement on the decrease in the electron temperature was confirmed by both of the calculation of particle and power balance and the electron temperature measurements. It was found from the calculated results that this effect strongly depends on the collisional cross section between electrons and neutral particles. Furthermore, we succeeded in producing an ECR plasma with very low electron temperature (< 2 eV) and high electron density (~ 10^{12} cm^{-3}) by applying the mirror magnetic field for Ar gas diluted with N_2.

Keywords:

ECR plasma, magnetic mirror, low electron temperature plasma, electron impact cross section

1. Introduction

In semiconductor processing, high-density and low-electron-temperature plasma sources are required for a progress of microelectronic devices and a minimization of substrate damage. An electron cyclotron resonance (ECR) plasma source has attracted much attention for its high electron density that can be achieved at low gas pressure, however, its electron temperature is relatively high and need to be controlled. Recently, we have succeeded in reduction of the electron temperature in Ar diluted with N_2 plasma and H_2 plasma by applying the mirror magnetic field. Since the electron density was observed to increase at the same time, the decrease in the electron temperature is considered to be due to the reason that the loss of plasma was controlled by the magnetic-mirror confinement. However, the mirror magnetic field had no effect on Ar plasma, and the production mechanism of low-electron-temperature plasma is not still clear. In this study, we investigated this effect in detail by calculating the particle and energy balance including the magnetic mirror confinement of electrons for Ar, N_2 or H_2 plasma. Furthermore, we measured the electron temperature and density under various experimental conditions in comparison with the calculated results.

2. Experimental

The details of the experimental setup and an ECR plasma source were described in reference [1]. The microwave was introduced through a quartz window and a substrate holder was set around 550 mm from the window. Ar, N_2 and H_2 gasses were introduced into the chamber at a total flow rate of 50~70 sccm, and the pressure was kept at 2×10^{-3}, 5×10^{-3} or 8×10^{-3} Torr. Six magnetic coils with a width of 100 mm and an inner diameter of 320 mm were placed adjacent to the chamber to control the magnetic field distribution. The frequency and power of microwaves were 2.45 GHz and 0.7–2.5 kW, respectively. The plasma parameters were

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measured with a 1-mm-diameter Langumuir probe at 520 mm from the window.

3. Basic Equations

The particle balance equation for electrons is given approximately by [2]

$$\frac{\mathrm{d}n_e}{\mathrm{d}t} = n_e n_0 \langle \sigma v_e \rangle_i - \frac{n_e}{\tau_e}, \quad (1)$$

where n_e and n_0 are the local values of electron and neutral gas densities, $\langle \sigma v_e \rangle_i$ is the ionization rate coefficient averaged over the electron distribution, which is assumed to be Maxwellian in our calculation, and τ_e is the electron confinement time. On the other hand, the power balance for electrons is given approximately by

$$\frac{\mathrm{d}(1.5 n_e T_e)}{\mathrm{d}t} = \hat{P}_\mu - \hat{P}_x - \hat{P}_i - \hat{P}_d - \hat{P}_a - \frac{1.5 n_e T_e}{\tau_E},$$
$$\hat{P}_{x,i,d,a} = n_e n_0 \langle \sigma v_e \rangle_{x,i,d,a} E_{x,i,d,a}. \quad (2)$$

Here T_e is the electron temperature, $\hat{P}_\mu$, $\hat{P}_x$, $\hat{P}_i$, $\hat{P}_d$ and $\hat{P}_a$ are power densities associated with the absorption of microwave power, which is roughly estimated to be the incident power density, and the excitation, ionization, dissociation and electron attachment of gas atoms, and τ_E is the energy confinement time, $E_{x,i,d,a}$ is the excitation, ionization, dissociation (for molecules) and electron attachment energies, respectively. Assuming that the electron loss is caused by the ambipolar diffusion and the recombination at the chamber wall, τ_e and τ_E are given approximately by

$$\tau_e \approx 2\tau_E \approx L/c_s, \; c_s = \sqrt{2T_e/M_i} \quad (3)$$

where L is the plasma characteristic length, c_s is the ion acoustic speed, and M_i is the ion mass. In steady state, the left-hand side of eqs. (1) and (2) is equal to zero, and the relationship among T_e, n_0 and n_e can be obtained. On the other hand, the magnetic-mirror confinement of electrons is assumed to be governed by Coulomb scattering into a loss cone.

$$\tau_{em} = 3.5 \times 10^5 T_e^{3/2} \cdot n_e^{-1} \cdot (\ln \Lambda)^{-1} \cdot (1 - 2\theta_{lc}/\pi)^2,$$
$$\tan\theta_{lc} = (R-1)^{-1/2} \quad (4)$$

where θ_{lc} is the loss-cone angle. Particle and power balance in the mirror magnetic field is expressed by adding the term of τ_{em}, which is equal to zero at $R = 1$ (the magnetic configuration is flat type), to the electron and energy confinement times given by Eqs. (3).

4. Results and Discussion

The equilibrium relationship between T_e and n_0 obtained from Eqs. (1)–(4) for different magnetic field configurations is illustrated in Fig. 1. The value of n_e is also plotted against the electron temperature in Fig. 2. Both of T_e and n_e change little in the Ar plasma, on the other hand, T_e decreases and n_e increases for fixed value of the gas density in the N_2 plasma when the magnetic-

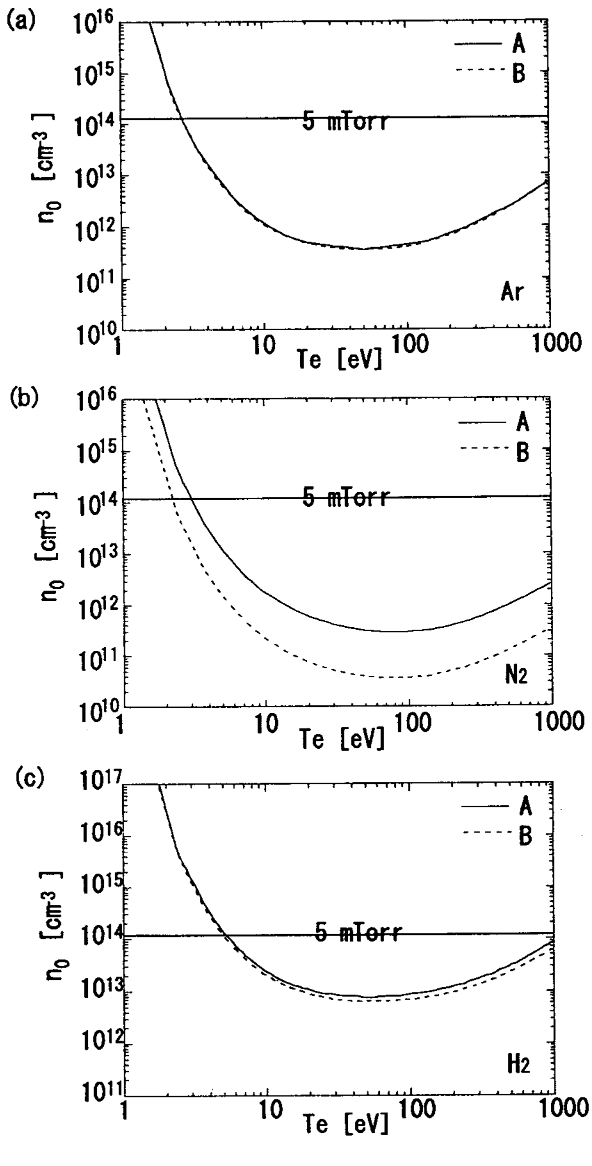

Fig. 1 The equilibrium relationship between the electron temperature and the gas density at the microwave power of 1 kW. Curve A: without magnetic-mirror confinement of electrons. Curve B: with magnetic-mirror confinement of electrons at the mirror ratio of 2.

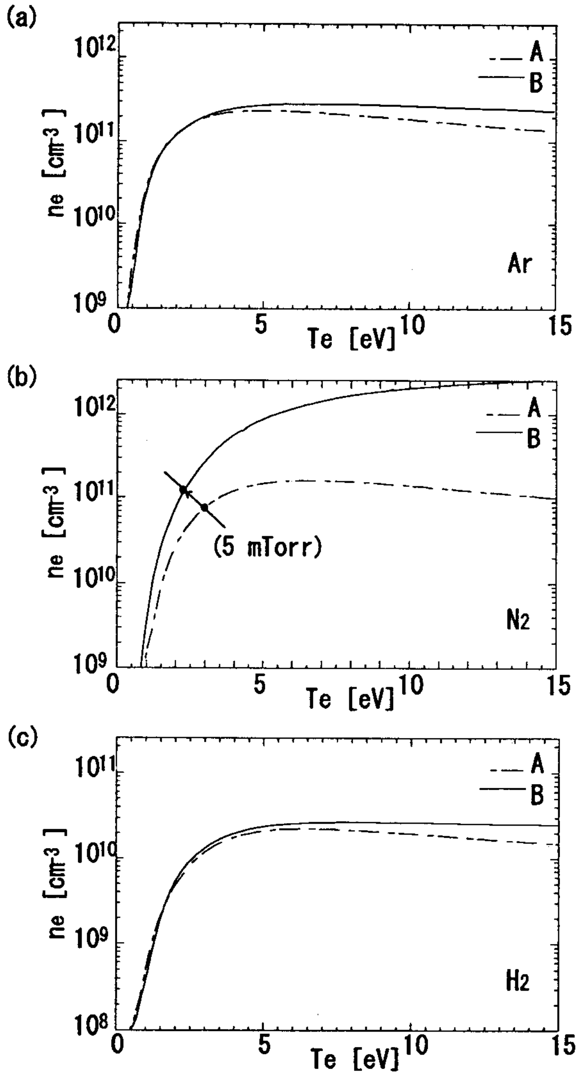

Fig. 2 The equilibrium relationship between the electron temperature and the electron density at the microwave power of 1 kW. Curve A: without magnetic-mirror confinement of electrons. Curve B: with magnetic-mirror confinement of electrons at the mirror ratio of 2.

mirror confinement of electrons is taken into consideration. This difference of the magnetic-miror effect between the Ar gas and the N_2 gas is considered to come from the difference in their electron impact cross section. The various excitation cross sections for N_2 peak at low electron energy of several eV, especially, the vibrational excitation cross section peaks strongly at 2 eV, whose maximum is about 7×10^{-16} cm^2. On the other hand, all the collisional cross sections for Ar peaks at high electron energy of 10^{1-2} eV. As mentioned above, we assumed that the magnetic-mirror

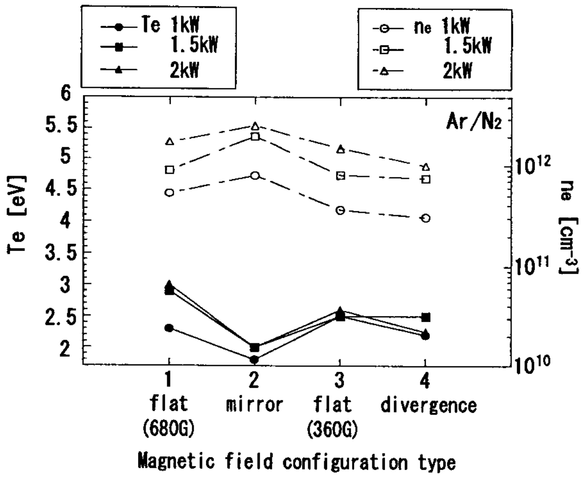

Fig. 3 The dependence of electron temperature and density on the magnetic field configuration for different microwave powers in Ar plasma diluted with N_2.

confinement of electrons is governed by Coulomb scattering into a loss cone. In weekly-ionized plasma such as ECR plasma, the Coulomb collision is generally considered to be negligible, however, the collision frequency is in inverse proportion to $T_e^{3/2}$, so that the frequency becomes higher as T_e decrease. In our experimental conditions, the Coulomb collision frequency is comparable to the collision frequency between electrons and neutral particles at T_e of several eV. This is why the magnetic-mirror confinement has an effect on the N_2 gas whose cross section peaks strongly where the Coulomb collision frequency is high and little effect on the Ar gas. A reasonably good agreement between these calculated results and the results of experiment on plasma parameter measurement was obtained. Furthermore, it was also found that T_e in Ar plasma could be reduced by diluting N_2 gas. Figure 3 shows the dependence of T_e and n_e on the magnetic field configuration in the Ar (91 %) diluted with N_2 (9 %) plasma, where the gas pressure was 5 mTorr. It was observed that T_e decreases and n_e increases when the mirror magnetic field is applied, especially, T_e was observed to be less than 2 eV at the microwave power of 1 kW. On the other hand, the relationship between T_e and n_0 or n_e for H_2 gas varies little in the case where the magnetic-mirror confinement of electrons in particle and power balance are included, as shown in Figs 1 (c) and 2 (c). This is understood from that the cross sections in the H_2 gas that peaks at low electron energy is very small (~7×10^{-17} cm^2) in comparison with that in the N_2

gas, however, this numerical results is different from the experimental results. In the experiment on plasma parameter measurement, it was observed that T_e decreases and n_e increases when the mirror magnetic field is applied in the H_2 plasma as well as in the N_2 plasma. It is necessary to clarify the mechanism of low-electron-temperature plasma production in the H_2 plasma, which is under investigation.

5. Conclusion

The effect of magnetic-mirror confinement on the decrease in the electron temperature was investigated in detail by calculating the particle and energy balance including the magnetic mirror confinement of electrons and plasma parameter measurement. It was confirmed that the magnetic-mirror confinement has an effect on the N_2 gas and little effect on the Ar gas. From the calculated results, this difference of the magnetic-mirror effect between the Ar gas and the N_2 gas is considered to come from the difference in their electron impact cross section. Furthermore, it was found from the experimental results that the electron temperature in Ar plasma could be also reduced by diluting N_2 gas in the mirror magnetic field.

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