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RF plasma sheath in an oblique magnetic field

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Abstract

A sheath model in an oblique magnetic field is build, which has one-dimension coordinate space and three-dimension speed space. The effects of magnetic field on the structure of RF sheath and parameter characteristics are discussed. The numerical simulation result shows that magnetic field has great effects on the sheath structure, especially in the region near the edge of sheath. Also, the magnetic field affects ion energy in the direction vertically to the board and incidence departure angle.
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Keywords: Radio frequency; Magnetized sheath

1. Introduction

RF discharge is more widely used than DC discharge. The characteristic of RF plasma sheath and the behavior of electrons and ions are to decide the quality of plasma processing products. Since 1988, when Lieberman [1] began to study RF plasma sheath, more research work about this field has been developed. And now the research work of RF plasma sheath is quite understood in the absence of magnetic field.

Introducing the magnetic field does make sheath problems more complex. Until now there are seldom research works about plasma RF magnetic sheath, and this field does not enjoy a well-established solution yet. In some sense, the effects of the magnetic field cannot be ignored, such as magnetically enhanced reactive ion etching; a weak magnetic field parallel to the board applied to lighten the plasma diffuse would obtain high density plasma, as well as Helicon Wave Plasma. Recently Hou [2] numerically simulated two dimension non-flat plasma RF sheath in a vertical magnetic field. In this paper, we reported the flat plasma RF sheath in an oblique sheath and discuss the characteristic of parameters in the magnetized sheath.

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2. Mathematical formulation and basic equations

We consider a collisionless plasma sheath in the presence of an oblique magnetic field. The magnetic field, which is spatially uniform and constant in time, lies in the (x, z) plane and makes an angle θ with the x-axis in the negative direction (Fig. 1). We use a one-dimensional model in space—only the variations along the x-coordinate. At the edge of sheath and plasma, the electron potential $\phi = 0$. Generally, photoemission from metallic surfaces has been ignored, the RF voltage added on the board makes a periodicity cosine change with the time.

$$\phi(0, t) = \phi_{dc} + \phi_{rf}\cos(\omega t), \tag{1}$$

where ϕ_{rf} is swing of radio frequency voltage, ω is RF frequency, ϕ_{dc} is direct current bias voltage.

Considering the confection effects of electron density distribution on potential density, electrons are thought to answer the sheath potential instantaneously. We assume electrons obey the Boltzmann distribution without considering the effects of magnetic field. The reason is, the respond time of electrons is much shorter than other charged particles, electrons can reach new equilibrium state soon and set as background of other particles. On the other hand, many researches involved in this field [3–8] adopt

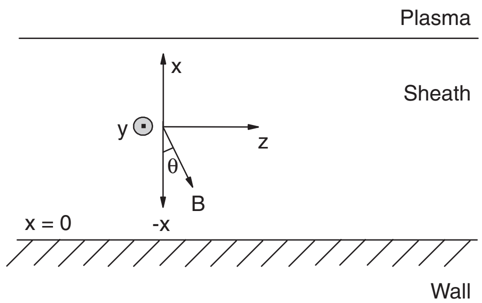

Fig. 1. Model geometry of RF magnetic sheath.

Boltzmann distribution to describe electrons to make the simple model.

$$n_e = n_{e0} \exp\left(\frac{e\phi}{T_e}\right), \tag{2}$$

where n_e, ϕ, T_e are electron number density, electrostatic potential and electrostatic temperature. Ions accelerate from the edge of sheath and obey the continuity equation and momentum equation,

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{v}_i) = 0, \tag{3}$$

$$m_i\left[\frac{\partial \mathbf{v}_i}{\partial t} + (\mathbf{v}_i \cdot \nabla)\mathbf{v}_i\right] = -e\nabla\phi\hat{x} + e\,\frac{\mathbf{v}_i \times \mathbf{B}}{c}, \tag{4}$$

where n_i, m_i, $\mathbf{v}_i$ are ion number density, mass and velocity.

The system is completed with the Poisson equation

$$\frac{\partial^2 \phi}{\partial x^2} = -4\pi e(n_i - n_e). \tag{5}$$

We define $c_{is} = (T_e/m_i)^{1/2}$ is ion sound speed, $\omega_{ic} = eB/m_i c$ is ion cyclotron frequency, λ_D is electron Debye length. For simplicity, introduce dimensionless parameters as follows:

$$\Phi = \frac{e\phi}{T_e}, \quad \xi = \frac{x}{\lambda_D}, \quad \tau = \frac{t}{\tau_0}, \quad \tau_0 = \frac{\lambda_D}{c_{is}}, \quad \mathbf{u}_i = \frac{\mathbf{v}_i}{c_{is}},$$
$$N_e = \frac{n_e}{n_{e0}}, \quad N_i = \frac{n_i}{n_{i0}}.$$

At the edge of sheath and plasma region, from the equal neutral condition, $\delta_i = n_{i0}/n_{e0} = 1$. Putting the oblique magnetic field $\hat{B}_0 = -\cos\theta\hat{x} + \sin\theta\hat{z}$, we get

$$N_e = \exp(\Phi), \tag{6}$$

$$\frac{\partial N_i}{\partial \tau} + u_{ix}\,\frac{\partial N_i}{\partial \xi} + N_i\,\frac{\partial u_{ix}}{\partial \xi} = 0, \tag{7}$$

$$\frac{\partial u_{ix}}{\partial \tau} + u_{ix}\,\frac{\partial u_{ix}}{\partial \xi} = -\frac{\partial \Phi}{\partial \xi} + \gamma_i u_{iy} \sin\theta, \tag{8}$$

$$\frac{\partial u_{iy}}{\partial \tau} + u_{ix}\,\frac{\partial u_{iy}}{\partial \xi} = \gamma_i(-u_{iz}\cos\theta - u_{ix}\sin\theta), \tag{9}$$

$$\frac{\partial u_{iz}}{\partial \tau} + u_{ix}\,\frac{\partial u_{iz}}{\partial \xi} = \gamma_i u_{iy}\cos\theta, \tag{10}$$

$$\frac{\mathrm{d}^2 \Phi}{\mathrm{d}\xi^2} = -(N_i - N_e), \tag{11}$$

where $\gamma_i = \omega_{ic}/\omega_{pi}$ is the ratio of ion cyclotron frequency and ion plasma frequency, ω_{pi} is the ion plasma frequency. From the above equations, every parameter in the RF plasma sheath, including electron, ion density and potential, can be numerically simulated.

3. Numerical results and discussion

We assume that the ions enter the sheath with velocity only in x direction. Under this condition, the sheath edge condition is the same with the Bohm criterion. Applied potential drop $\phi_{rf} = 48$ V and $\phi_{dc} = -50$ V. Fig. 2 shows ion density distribution under the external magnetic field ($B = 0.1$ T, $\theta = 20°$) when the RF frequency is much larger than plasma frequency ($\omega = 10.0\omega_{pi}$). The results show that ion density distribution of the whole sheath still average of the RF field does not change with time, in the case of without external magnetic field. But the ion density distribution increases for a little in the region near the plasma.

Fig. 3 indicates the ion density distribution under the external magnetic field ($B = 0.1$ T, $\theta = 20°$), when the RF frequency is much smaller than plasma frequency ($\omega = 0.1\omega_{pi}$). The ion density distribution of the whole sheath makes the RF field instantaneous. In the region near the electrode, potential of the RF sheath makes a periodicity cosine change with time, in the case of without external magnetic field. Hence, ion density distribution increases a little in the region near the plasma, compared to the case without magnetic field.

Both the group figures reflect that sheath answers the external magnetic field more obviously with the increase of ion density distribution. Because plasma has coercivity, if the plasma density value is lower, the effects of magnetic field become weak; when the plasma density value is higher, the effects of magnetic field become strong. From the two group figures, we observed that the ratio of RF frequency and the ion plasma frequency is different and grade of sheath that answers the magnetic field is also different. The region and the magnitude of effects are different.

For example, $\omega = 0.1\omega_{pi}$; Fig. 4 shows ion density distribution and velocity in x direction, in comparison with and without magnetic field at time $t = 0.5\tau_0$ and $1.0\tau_0$. The figures show that the convolute effect of magnetic field slows down the ion flow velocity in x direction at the edge of sheath. The decrease of the ion flow velocity brings the increase of the ion density distribution. The potential distribution is the same as that without magnetic field and the change of ion density distribution and velocity in x direction is not obvious because of confection of RF voltage, near the electrode.

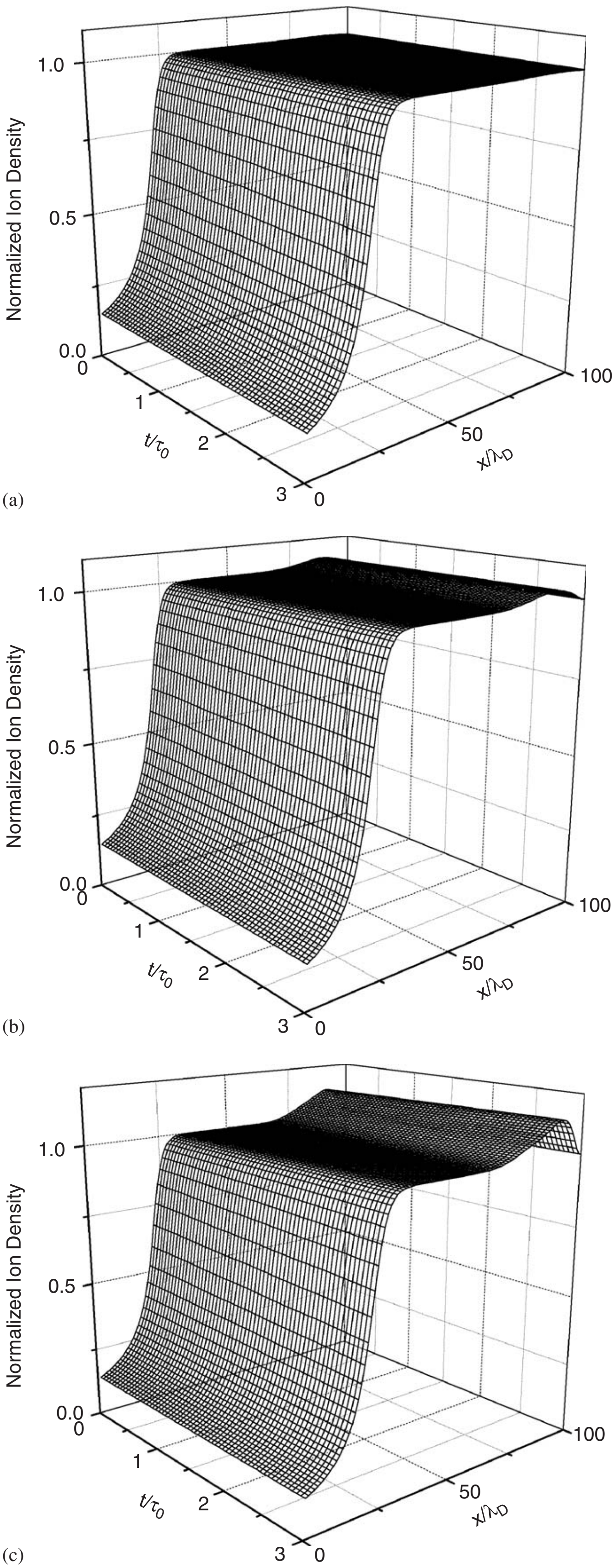

Fig. 2. Normalized ion density distribution of RF plasma sheath with magnetic field, $\omega = 10.0\omega_{pi}$, (a) $n_0 = 5 \times 10^9$, (b) $n_0 = 5 \times 10^8$, (c) $n_0 = 5 \times 10^7$.

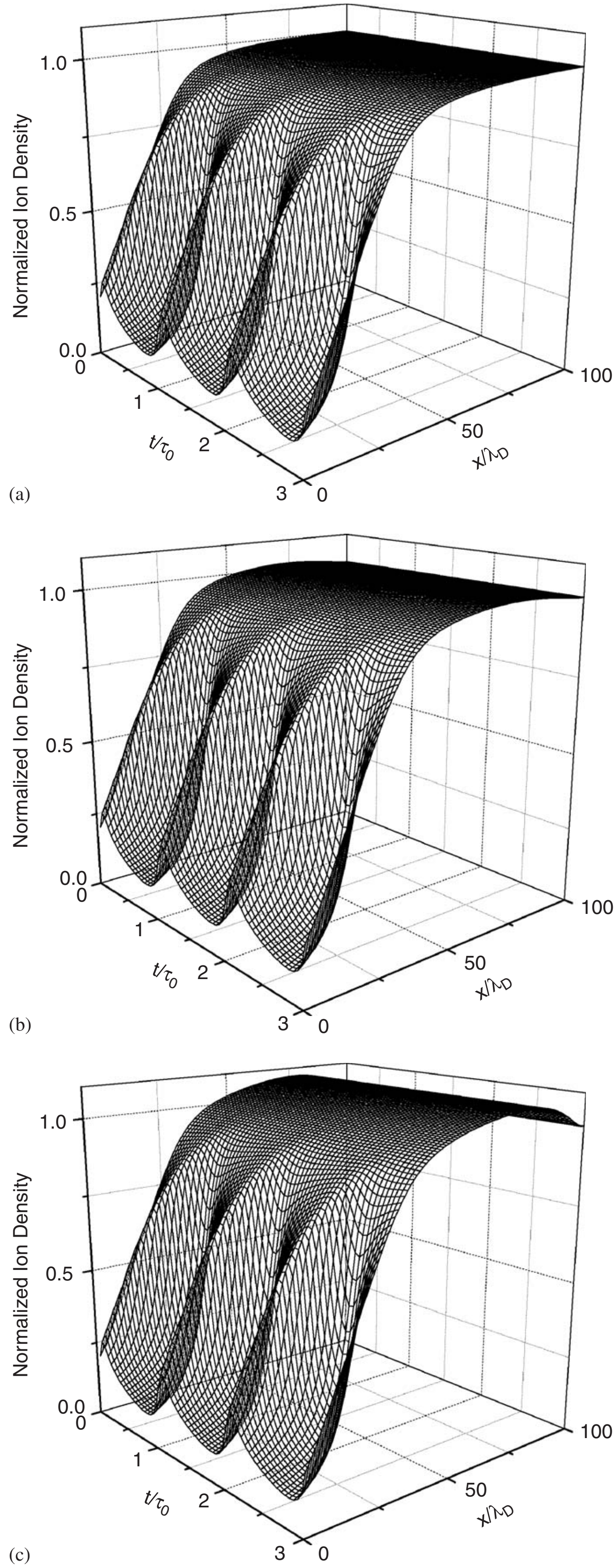

Fig. 3. Normalized ion density distribution of RF plasma sheath with magnetic field, $\omega = 0.10\omega_{pi}$, (a) $n_0 = 5 \times 10^{11}$, (b) $n_0 = 5 \times 10^{10}$, (c) $n_0 = 5 \times 10^9$.

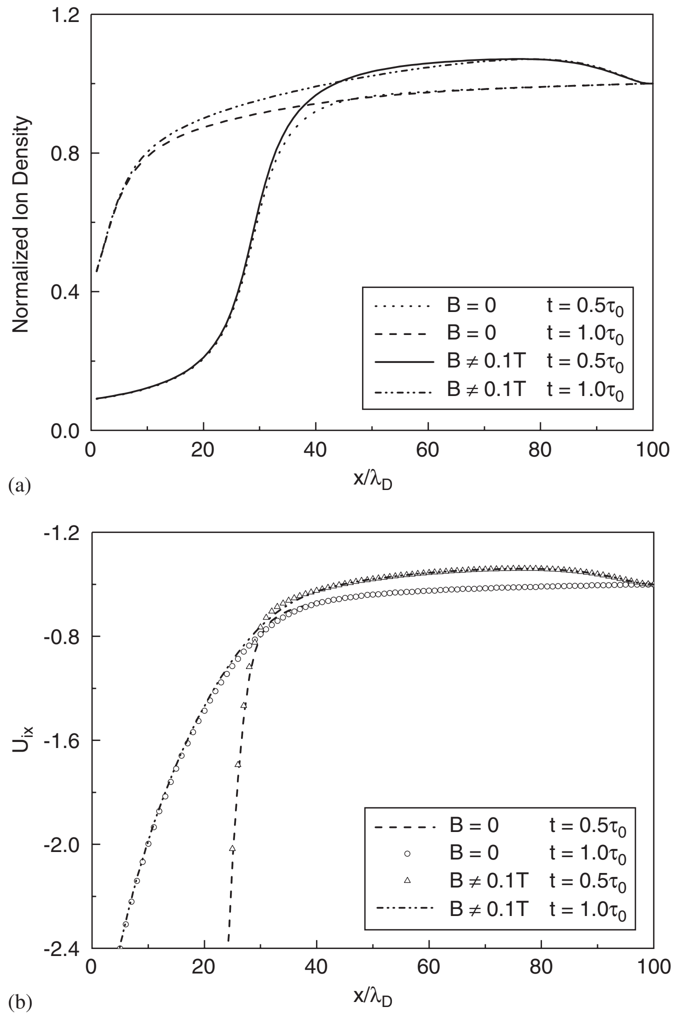

Fig. 4. $\omega = 0.10\omega_{pi}$: (a) normalized ion density distribution; (b) normalized ion velocity in x direction.

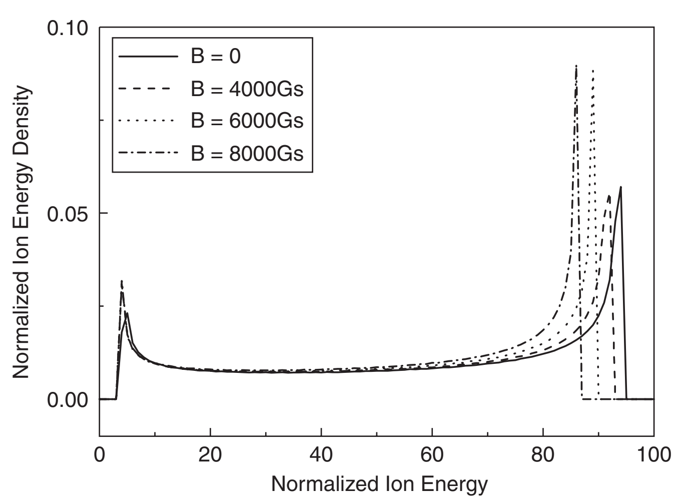

Fig. 5. The effect of magnetic field on the ion energy distribution in x direction.

Finally, we concluded that the effects of magnetic field on plasma RF sheath is similar to the effects on the plasma DC sheath [9,10]. The difference is that in RF sheath,

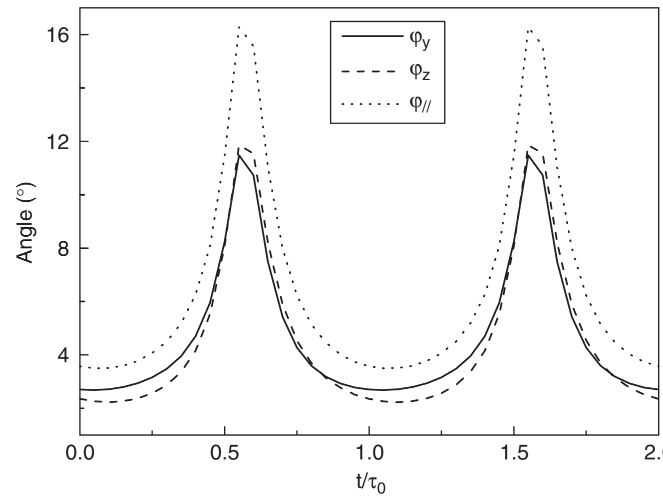

Fig. 6. Variation of ion incidence departure angle with time.

electrode has been added in the case of negative bias voltage, so ions enter the sheath and the acceleration is higher than the case without bias voltage. This leads to control of ion movement states.

Although the existence of magnetic field cannot change ion gross energy, it makes ions depart from their initial move direction, in the case that magnetic field can change ion energy in x direction. Fig. 5 shows the effects of magnetic field on the ion energy in x direction at $\omega = 0.1\omega_{pi}$. It shows that the apex of higher energy moves to the side of low energy with the increase of magnetic field. In other words, more energy transfers to the direction parallel to the board. Magnetic field has no obvious effects on the apex of lower energy. Because ion speed is fast, the Lorantz force produced is strong and the effects of magnetic field are also strong.

We define $\varphi_y, \varphi_z, \varphi_{//}$ as ion incidence departure angle in y direction, z direction and direction parallel to the board. Fig. 6 indicates ion incidence departure angle with the magnetic field, $B = 0.4\,\mathrm{T}$, $\theta = 30^\circ$ at $\omega = 0.10\omega_{pi}$. Fig. 7 shows the effects of magnetic field on the ion incidence departure angle $\varphi_{//}$. Because of electrode, the voltage changes periodically with the time and ion incidence departure changes periodically with the time too. When the angle of magnetic field is zero, ions do not change their move direction and ion incidence departure angle is also zero. With the increase of the angle of magnetic field, ion incidence departure angle also increases.

4. Conclusion

Ion density distribution indicates the instantaneous RF field depends on the ratio of frequency with magnetic field in the region near the electrode. If the RF frequency is much larger than plasma frequency, ion density distribution of the whole sheath still indicates the average RF field does not change with time, in the case of without external magnetic field. If the RF frequency is much smaller than

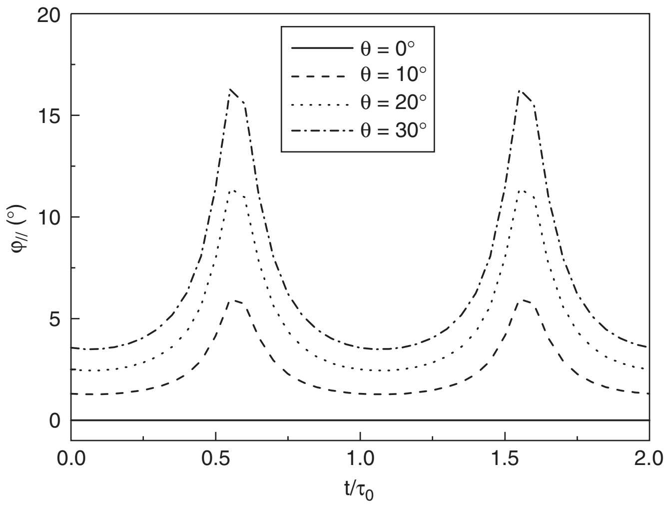

Fig. 7. Ion incidence departure angle in parallel direction of the board.

plasma frequency, the ion density distribution of the whole sheath indicates the RF field instantaneous. While in the region near the plasma of the RF sheath, the change of ion density distribution is similar to the solution of DC sheath. The convolute effect of magnetic field slows down the ion flow velocity in x direction. The decrease of the ion flow velocity brings the increase of the ion density distribution. Ion departure angle changes periodicity, and increases with the magnetic field which is parallel to board direction.

Acknowledgements

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