Self-Consistent Kinetic Modeling of Electron Distribution Function in a Low-Pressure Inductively Coupled Plasma*

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Based upon the spatially inhomogeneous Boltzmann equation in two-term approximation coupled with electromagnetic and fluid model analysis for the recently developed inductively coupled plasma sources, a self-consistent electron kinetic model is developed. The electron distribution function, spatial distributions of the electron density and ionization rate are calculated and discussed.

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Inductively coupled plasma (ICP), as one type of high density plasma source, is currently being investigated as plasma sources for material processing,[1] especially in the field of the semiconductor etching and deposition. For these low pressures (1–100 mTorr), the spatially dependent description of the electron kinetics plays an important role. Straightforward numerical simulation using Monte Carlo treatment of electrons is a computationally very demanding task.[2] Fluid model[3] or hydrodynamic approach[4] can give only a rather crude description of phenomena. Comparatively effective kinetic modeling of ICP has recently been developed.[5] Their model self-consistently calculated the electron distribution function (EDF) in plasma, however, leaves out important physics since it imposed an average process that all electrons are trapped in the plasma by a static space-charge electric field and imposed idealized boundary conditions.

We consider an ICP driven by the electric field from a spiral coil placed on the dielectric roof of a cylinder with metallic walls and bottom (Fig. 1). The plasma is generated and heated by an inductively coupled azimuthal electric field. For typical pressures, the electron energy relaxation length exceeds the discharge dimensions, it is useful to use the total energy of the electron $\varepsilon = w - e\phi(z,r)$, where w is the kinetic energy of electron, as an independent variable.[6] The Boltzmann equation is simplified by considering the case of small anisotropy of the EDF when the two-term approximation is applicable: $f = f_0(\varepsilon,z,r) + \boldsymbol{v}/v \cdot \boldsymbol{f}_1(\varepsilon,z,r,t)$, where $f_1 \ll f_0$. For the rf field $E_\theta(z,r,t) = E_0(z,r)e^{i\omega t}$, the kinetic equation can be written in the form:[7]

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\nu D_r(z,r,\varepsilon)\frac{\partial f_0}{\partial r}\right] + \frac{\partial}{\partial z}\left[\nu D_r(z,r,\varepsilon)\frac{\partial f_0}{\partial z}\right] + \frac{\partial}{\partial \varepsilon}\left[\nu D_\varepsilon(z,r,\varepsilon)\frac{\partial f_0}{\partial \varepsilon}\right]$$
$$= \sum_k \left[\nu v_k^*(w) f_0 - \sqrt{\nu^2 + \frac{2\varepsilon_k^*}{m}} v_k^*(w+\varepsilon_k^*) f_0(\varepsilon+\varepsilon_k^*)\right] + J_{\rm el} + J_{\rm ee}, \qquad (1)$$

where $D_r = \dfrac{\nu^2}{3v_{\rm m}}$ and $D_\varepsilon = \dfrac{e^2E_0^2(z,r)\nu^2 v_{\rm m}}{6(v_{\rm m}^2+\omega^2)}$ are the diffusion coefficients in space and energy respectively, $v_{\rm m}$ and v_k^* are the momentum transfer and inelastic collision frequencies. The first term in the right hand side of Eq. (1) representing the electrons which have suffered inelastic

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collisions is written for the excitation of level k with energy ε_k^*. The last two terms J_{el} and J_{ee} in the right hand side of Eq. (1) are the collision integrals for elastic and electron-electron interactions respectively.

The spatially dependent kinetic equation (1) represents an elliptic partial differential equation which can be solved numerically. The domain of integration is not rectangular but possesses an irregular boundary defined by the space potential $\varepsilon = -e\phi(z,r)$ where the kinetic energy is zero, i.e., $w(z,r) = 0$. The boundary condition on the discharge axis follows from the rotational symmetry: $\left.\frac{\partial f_0}{\partial r}\right|_{r=0} = 0$. In energy direction the boundary condition is: $\left.\frac{\partial f_0}{\partial \eta}\right|_{\varepsilon \le -e\phi_w} = 0$; $-D_r \left.\frac{\partial f_0}{\partial \eta}\right|_{\varepsilon \ge -e\phi_w} = \nu f_0 \frac{\Omega}{4\pi}$, where η denotes the direction normal to the wall and ϕ_w is the potential of the wall. The first equation is the boundary condition for trapped electrons corresponding to their reflection by the potential wall and the second equation expresses the boundary condition at $\varepsilon > -e\phi_w$ that is obtained by imposing equality of the normal component of the electron diffusive flux and the electron loss to the wall.[8] The solid angle Ω of the loss cone is given by $\Omega = 2\pi\left(1 - \sqrt{\frac{e\Delta\phi}{\varepsilon + e\phi_{sh}}}\right)$ where $\Delta\phi$ is the potential drop in the sheath and near the wall, the electrons having kinetic energy $w = \varepsilon + e\phi_{sh}$ after last scattering can overcome the potential drop $\Delta\phi$ and reach the absorbing wall. The boundary condition on the curve $w = 0$ is deduced from the validity of Eq. (1) on that curve: $-\frac{\partial\phi(z,r)}{\partial r} D_r \left.\frac{\partial f_0}{\partial r}\right|_{w=0} - \frac{\partial\phi(z,r)}{\partial z} D_r \left.\frac{\partial f_0}{\partial z}\right|_{w=0} = D_\varepsilon \left.\frac{\partial f_0}{\partial \varepsilon}\right|_{w=0}$, where neither a source nor a sink of electrons along this boundary exists and the divergence of a diffusive flux perpendicular to that boundary between the spatial and energy space must be continuous.[8]

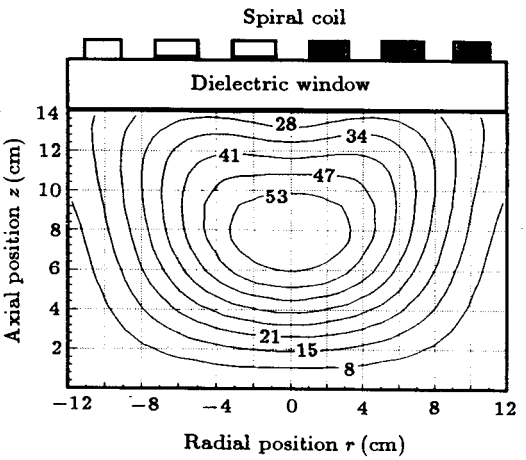

Fig. 1. Schematic of the discharge and contours of electron density (10^{10} cm^{-3}) for an argon pressure 20 mTorr and power 500 W.

The electromagnetic field in ICP reactor can be primarily divided in two parts: the inductively coupled electromagnetic field $\boldsymbol{E}_I$ and the plasma static electric field $\boldsymbol{E}_s$, $\boldsymbol{E} = \boldsymbol{E}_I + \boldsymbol{E}_s$, where $\boldsymbol{E}_s = -\nabla\phi$, ϕ is the static electric potential (plasma potential). The spatial distribution of the rf induction field $\boldsymbol{E}_I$ has the azimuthal component $E_{I\theta}$ only. Similar to Ref. 3, if the oscillating current through the coil is $I = I_0 \cos\omega t$, the corresponding inductive electric field $E_{I\theta} = E_1 \cos\omega t + E_2 \sin\omega t$ should satisfy following equations:

$$\nabla^2 E_1 - \frac{1}{r^2} E_1 + \left(\frac{\omega^2}{c^2} - \frac{\mu_0\omega^2\sigma}{\upsilon_m}\right) E_1 - \mu_0\sigma\omega E_2 = 0, \tag{2}$$

$$\nabla^2 E_2 - \frac{1}{r^2} E_2 + \left(\frac{\omega^2}{c^2} - \frac{\mu_0\omega^2\sigma}{\upsilon_m}\right) E_2 - \mu_0\sigma\omega E_1 = 0, \tag{3}$$

where $\mu_0 = 4\pi \times 10^{-7}$H/m, σ is the plasma electric conductivity derived from EDF:

$$\sigma(z,r) = -\frac{2e^2}{3m} \int_{-e\phi}^{\infty} \frac{1}{\upsilon_m + i\omega} \frac{\partial f_0}{\partial \varepsilon} (\varepsilon + e\phi)^{3/2} \mathrm{d}\varepsilon. \tag{4}$$

For the ICP reactor as shown in Fig. 1, on the metallic chamber wall and the reactor axis, $E_{I\theta} = 0$, while on the top surface, $E_{I\theta}$ is determined by the current I_0 in the coil and the inductive current in the plasma.[3]

Owing to the great importance of the space charge potential, we constitute it via fluid model. Assuming quasi-neutrality condition and neglecting the thermal energy of ions in comparison to that of the electrons as well as their inertia, the time average equations for ions can be written as[3,11]

$$\nabla \cdot [\mu_i n_i \nabla \phi(z,r)] = -R_i \ , \tag{5}$$

where $n_i = n_e, n_e$ is the density of electrons deduced from EDF:

$$n_e(z,r) = \int_{-e\phi(z,r)}^{\infty} f_0(z,r,\varepsilon)\sqrt{\varepsilon + e\phi(z,r)}\,\mathrm{d}\varepsilon, \tag{6}$$

μ_i is the mobility of ions. The ionization rate R_i is given by

$$R_i(z,r) = \int_{u_i - e\phi(z,r)}^{\infty} \sqrt{\varepsilon + e\phi(z,r)}\,v_i[\varepsilon + e\phi(z,r)]f_0(z,r,\varepsilon)\mathrm{d}\varepsilon, \tag{7}$$

and u_i is the ionization threshold.

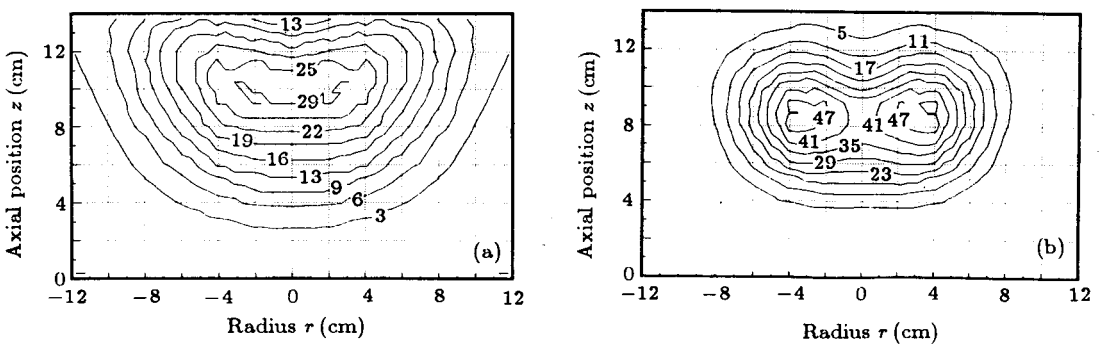

Fig. 2. Ionization rate (10^{15}/cm^{3}s) contours for argon pressure 20 mTorr (a), and 40 mTorr (b) with power 500 W.

The numerical treatment comprises a number of tasks which have to be solved self-consistently. A starting potential is assumed as a parabolic potential. With this starting potential and some starting values the spatially dependent EDF can be evaluated from Eq. (1) using some standard iterative method. Then the azimuthal component of rf electric field was calculated from Eqs. (2) and (3) for given coil current. A new potential was calculated from the solution of Eq. (5). Electron density was calculated from Eq. (6). With this new potential the procedure restarts iteratively.

The typical profiles for electron density n_e are shown in Fig. 1. The electron density gets its maximum in the vicinity of center and the results seem quite close to those obtained by experiment[9] and by the non-local simulation.[5] Figure 2 shows the calculated spatial distribution of the excitation rate R_i. When the pressure decreases, the maximum moves from off axis and is peaked where the electron density peaks, near the center of the discharge where the rf field is absent. It allows us to explain the difference between the experimentally observed shapes of the light emission for different pressures.[7,10] When the pressure increases, the fast electrons undergo inelastic collisions before reaching the region of the highest potential and the electron energy relaxation length becomes less than the discharge dimensions.

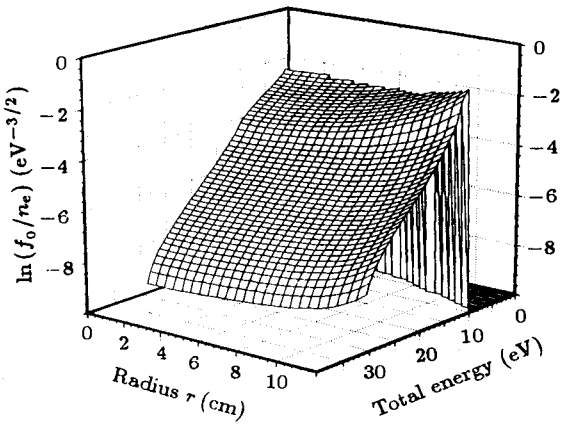

Fig. 3. Normalized EDF by solution of the spatially inhomogeneous kinetic equation (in radial direction $z = 5$ cm).

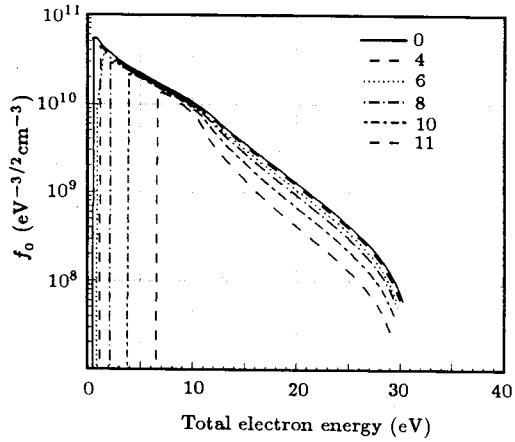

Fig. 4. Radial evolution of the EDF. Labels correspond to radial distance from the center at a fixed axial distance (4.4 cm) from the dielectric window.

In order to get an impression of the spatial inhomogeneity, in Fig. 3 EDF of total energy are presented as a function of the radius in radial position ($z = 5$ cm). This surface exactly represents onsets of the EDF of kinetic energy in different radial positions. The EDF reveals deviations from the spatial homogeneity, especially in the EDF tail where inelastic collisions occur. Depletion of the EDF tail is observed in the highest potential region, especially in the center region of the discharge. For a given total energy, the kinetic energy is maximal in the center and thus also the efficiency of inelastic collisions. In Fig. 4 the radial distributions of the EDF are showed which have the same features as those measured in the experiment.[7] The curves are matched to each other in center region and it seemed a non-local effect appears in this region where the EDF depends only on energy. From the axial and radial directions the EDF becomes more anisotropic for the majority of electrons. This results in a drop of the mean kinetic energy from the center towards the wall, where the trapped electrons perform many bounces in the wall and pass the heating region many times before being heated enough to be lost to the wall.

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