Control of reactive plasmas in a multicusp plasma source equipped with a movable magnetic filter

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With the use of both a movable magnetic filter and a plasma grid, plasma parameters (H₂-CH₄ or Ar-CH₄ plasmas) are spatially well controlled. At any filter position, plasma parameters change steeply across the magnetic filter. Then, a plasma source is divided into the two parts, i.e., the source plasma region (high density plasma with energetic electrons) and the diffused plasma region (low density and low-temperature plasma without energetic electrons). Plasma parameters in the diffused plasma are well controlled by changing the plasma grid potential. The role of the magnetic filter (i.e., preferential reflection of energetic electrons) is well clarified by computer simulation. The relation between plasma parameters and some species of neutral radicals is also briefly discussed.

I. INTRODUCTION

The plasma chemical vapor deposition (p-CVD) method has been successfully used in the preparation of various kinds of thin films. As the initial processes, i.e., the decomposition of source gas molecules or production of reactive species, are triggered by electron collisions, plasma parameters, especially energy distribution and density of electrons, must initially be carefully controlled.

So far, we have studied application feasibility of a magnetically filtered multicusp plasma source to a tandem p-CVD reactor. These type of plasma sources are widely used and investigated to be promising sources of high current H⁻ or D⁻ ions for the preparation of neutral beams in the fusion community. In this article, we show that the addition of a movable magnetic filter and a plasma grid can spatially control well an electron energy distribution function (EEDF) and plasma parameters in reactive plasmas (i.e., H₂-CH₄ and Ar-CH₄ plasmas). Besides these, we also discuss the role of the magnetic filter in a weakly ionized plasma and study further the control of neutral radicals.

II. EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows a schematic drawing of the apparatus. The source chamber (16 cm diameter, 30 cm long) is made of stainless steel and the outside wall of the chamber is lined with 16 rows of ferrite magnets arranged in an alternating north pole-south pole geometry. A line-cusp surface magnetic field layer is thus established around the central volume with a magnetic field density of 1 kG just inside the wall, decreasing rapidly to a few Gauss 3-4 cm further inside. The central field-free volume is approximately 8 cm in diameter. This surface magnetic field layer confines primary electrons and produced plasmas well.

H₂, Ar, and CH₄ gases were introduced into the source chamber continuously. The source pressure p was measured by an ionization gauge. Steady-state plasmas were produced by primary electrons emitted from 4 tungsten filaments (0.27 mm diameter, 10 cm long). These filaments were biased negatively to a discharge voltage V_d with respect to the grounded chamber wall to provide a primary electron emission discharge current I_d.

A samarium-cobalt magnetic filter divides the entire chamber into an arc discharge (the right hand side, region I) and a diffused plasma (the left hand side, region II). This filter provides a limited region of transverse magnetic field that is strong enough to prevent all energetic primary electrons in region I entering into region II. However, cold electrons, together with positive ions, can penetrate the filter and form a diffused plasma. Concerning this point, a new mechanism will be discussed later. Besides, potential of a plasma grid equipped in region II is variable.

Plasma parameters were measured by two cylindrical Langmuir probes (0.5 mm diameter, 2 mm long). To obtain the EEDF by using the Druyvesteyn method, the second derivative of the probe characteristic was also measured. From these data, the density of fast electrons n_f(E) with an energy higher than $E$ was estimated, i.e., the density ratio of the fast to total plasma electrons $n_f/n_e$. Information for neutral particles was obtained by both emission spectroscopy and a quadrupole mass spectrometer.

III. RESULTS AND DISCUSSION

A. Effect of the magnetic filter on controlling plasma parameters

According to the recent experimental results, a remarkable change in plasma parameters (i.e., EEDF, electron density $n_e$, electron temperature $T_e$, floating potential $V_f$, etc.) across the magnetic filter is clearly observed. Even if CH₄ gas is introduced into hydrogen or argon plasma, in both cases, the magnetic filter can spatially control well the EEDF and the related plasma parameters.

Figure 2 shows the spatial variation of the two EEDF for two different CH₄ plasmas, i.e., (a) H₂-CH₄ plasmas and (b) Ar-CH₄ plasmas, where a filter position $L_f$=10 cm. The EEDF varies remarkably across the filter. In the diffused plasma region (i.e., region II), there is little of the
high-energy component of electrons. Namely, the magnetic filter prevents only the high-energy electrons from entering into region II. This feature is the most remarkable point on controlling the EEDF. In general, when the EEDF is controlled by using an electrostatic mesh grid, a retarding field is applied usually. Then, on the contrary, only slow electrons are reflected preferentially.

Figure 3 shows spatial variations of the high-energy component of electrons, i.e., \( n_b/n_e \), corresponding to the EEDF of H\(_2\) plasmas for two different \( L_f \). Corresponding to the variation of the EEDF, \( n_b/n_e \) in region II decreases remarkably across the filter.

Figure 4 shows spatial variations of \( V_f \) for three different \( L_f \). This is another example of the effects of the magnetic filter as \( V_f \) depends on high energy tail of the EEDF, and there is a remarkable difference in \( V_f \) across the filter. Controlling \( V_f \) is important in processing plasmas. In plasma etching, for example, \( V_f \) is essential because it is directly related to the energy of the etching ions.

The present permanent magnetic filter of two rods produces an integrated magnetic field of about 130 G cm, where only electrons are magnetized. With increasing \( p \), electron-neutral collisions may reduce the effects of the magnetic filter on controlling plasma parameters. Up to 10 mTorr at least, we have tested that this magnetic field is strong enough to prevent primary electrons from passing although optimum field strength depends on plasma conditions.

**B. Effect of plasma grid potential on controlling plasma parameters**

We note that plasma parameters in region II strongly depend on the plasma grid potential \( V_b \). With increasing \( V_b \) (> 0), as a whole, \( n_e \) decreases monotonically. On the other hand, \( T_e, V_s \), and \( V_f \) increase monotonically. Furthermore, it is interesting that effect of changing \( V_b \) appears not only in front of the plasma grid but also in the whole region of the diffused plasma.

**C. Particle simulation on the role of magnetic filter**

According to the results shown in Figs. 2–4, the magnetic filter prevents only high-energy electrons entering into region II. Although one of the explanations for preferential electron penetration across the filter has been given by Coulomb collisions for high density plasmas,\(^{14}\) this is not the case of the present experiment and the role of the
magnetic filter is not well clarified. To understand a physical mechanism underlying this phenomena, i.e., the velocity-dependent diffusion across the filter, we have undertaken two-dimensional (x-y plane) electrostatic particle simulation.\(^{10,11}\) The magnetic field is parallel to z and its magnitude has a Gaussian dependence on x. Full dynamics of particles are followed selfconsistently. Here, we simply point out a new mechanism, although detailed discussion will be reported elsewhere.

The velocity-dependent diffusion coefficient \(D_x(v)\) obtained from test particle diffusions decreases as electron velocity \(v\) increases, where \(v^2=v_0^2+v_F^2\). These results suggest that most electrons cross the magnetic filter due to \(E\times B\) drift where \(E\) and \(B\) are thermally excited low frequency electrostatic fluctuations and filter fields. Therefore, \(E\times B\) drift for electrons decreases with the increase of \(v_0\) because fluctuating electric fields are averaged over their finite Larmor radii. Namely, high-energy electrons diffuse more slowly than low energy electrons.

Figure 5 shows the accumulated velocity distributions of electrons. They are the electrons that are on one side at \(t=0\), cross the filter, and reach the other side before the given time. When the magnetic field is tilted to the z axis, low frequency fluctuations are suppressed, and the number of electrons crossing the filter reduces significantly.

We have also studied experimentally the characteristics of plasma fluctuation.\(^5\) Plasma fluctuation with a well-defined frequency (i.e., 1–2 MHz, a frequency range of lower hybrid waves) was observed. Apparently, fluctuation fields are localized near the magnetic filter. These results support the physical picture of the magnetic filter described above.

D. Relationship between plasma parameters and neutral radicals

So far, we have successfully confirmed that plasma parameters are spatially well controlled by using the movable
magnetic filter and by changing potential of the plasma grid. Next, we will show the experimental results on controlling neutral particles and discuss the application feasibility of our plasma source to plasma processing.

In Figs. 6 and 7, emission intensities for some excited species of hydrogen plasmas and energy dependent electron densities are plotted as a function of $L$, respectively. In Fig. 7, the parameter is an electron density, i.e., the total electron density $n_e$ and the density of fast electrons $n_{fe}(E)$. As a whole, axial distribution patterns of not $n_e$ but $n_{fe}(E)$ have good correlation with that of emission intensities.

Figure 8 shows light intensities for some excited species observed at the midpoint, i.e., $L = 15$ cm, as a function of filter position $L_f$. When $L_f < 15$ cm observed emission spectra are from the source plasma, i.e., high density region. When $L_f > 15$ cm, on the contrary, observed spectra are from the diffused plasma, i.e., low density region. Apparently, light intensities depend on the EEDF. Axial variations of the emission intensity for CH radicals in H$_2$-CH$_4$ and Ar-CH$_4$ plasmas are also measured. There is a strong correlation between the emission intensity of CH radicals and $n_e$.

The radical density $n^*$ satisfies the relation, $n^* = n_0 n_t(E) \langle \alpha v \rangle \tau$, if the radicals are mainly produced by the electron impact dissociation process, where $n_0$ is source gas density, $n_t(E)$ is energy-dependent electron density, $\langle \alpha v \rangle$ is dissociation reaction rate, and $\tau$ is mean lifetime of the radical. In particular, $n_t(E)$ and $\langle \alpha v \rangle$ are strong functions of the EEDF. On the other hand, we have also obtained the same features of emission intensities shown in Figs. 6 and 8 even if we introduce gases into the chamber from the gas inlet 1 or 2 (see Fig. 1). Namely, there is no change in the ground state population. Therefore, it means, according to the results shown in Figs. 6–8, that spatial distribution of excited molecules or radicals can be controlled by changing plasma parameters (i.e., EEDF, $n_e$, and $T_e$), although detailed measurement and discussion are now under study.

**IV. CONCLUSIONS**

It is confirmed that the EEDF and other plasma parameters ($n_e, T_e, V_e, V_f$, etc.) in reactive plasmas change steeply across the magnetic filter, and that the entire plasma is divided into two distinct regions (i.e., the source plasma with high-energy electrons and the diffused plasma without high-energy electrons). With the use of a movable magnetic filter and a plasma grid, plasma parameters in reactive plasmas are spatially well controlled. Furthermore, with the change of plasma parameters, radical densities could be spatially controlled. It is interesting that the present technique will be applicable to any other plasma source, for example, ECR plasma source. The particle simulation has also clarified the physical picture of the magnetic filter, i.e., preferential reflection of energetic electrons. In the future, we study further the relationship between the control of reactive plasmas (i.e., CH$_4$ plasma) and the formation of thin films.
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