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 (H_2-CH_4 or Ar-CH_4 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.[1]

So far, we have studied application feasibility of a magnetically filtered multicusp plasma source to a tandem *p*-CVD reactor.[2–5] 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.[6–9] 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., H_2-CH_4 and Ar-CH_4 plasmas).[5] Besides these, we also discuss the role of the magnetic filter in a weakly ionized plasma[10,11] and study further the control of neutral radicals.[12,13]

II. EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows a schematic drawing of the apparatus.[4,5,9] 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.

H_2, Ar, and CH_4 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[5] 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 $n_{fe}(E)$ with an energy higher than E was estimated, i.e., the density ratio of the fast to total plasma electrons n_{fe}/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,[4,5,9,12,13] 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 CH_4 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.[12,13]

Figure 2 shows the spatial variation of the two EEDF for two different CH_4 plasmas, i.e., (a) H_2-CH_4 plasmas and (b) Ar-CH_4 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

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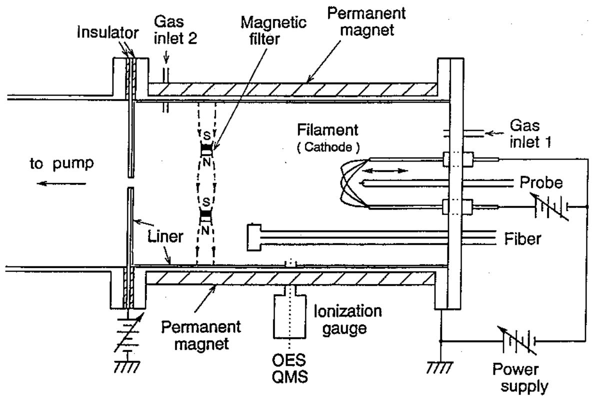

FIG. 1. Schematic diagram of the multicusp plasma source equipped with the movable magnetic filter and the plasma grid.

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_{fe}/n_e, corresponding to the EEDF of H_2 plasmas for two different L_f. Corresponding to the variation of the EEDF, n_{fe}/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 in the energy of the etching ions.

The present permanent magnetic filter of two rods produce 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.

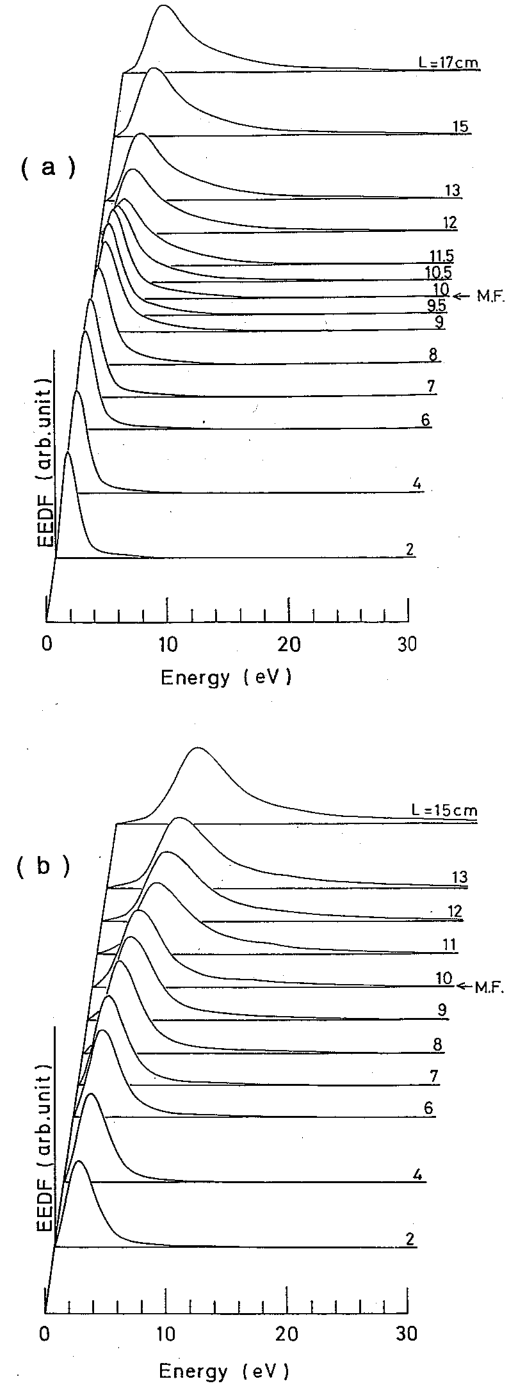

FIG. 2. Axial variations of the EEDF for two different cases, (a) H_2-CH_4 plasmas and (b) Ar-CH_4 plasmas, where filter position L_f=10 cm. Experimental conditions are as follows: discharge voltage V_d=80 V, discharge current I_d=2 A, and gas pressures $p(H_2\text{-}CH_4 \text{ gas})=p(\text{Ar-}CH_4 \text{ gas})$=2.9 mTorr. In both cases, the ratio of $p(CH_4)$ to the diluted gas is 30%.

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.[5,9] 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

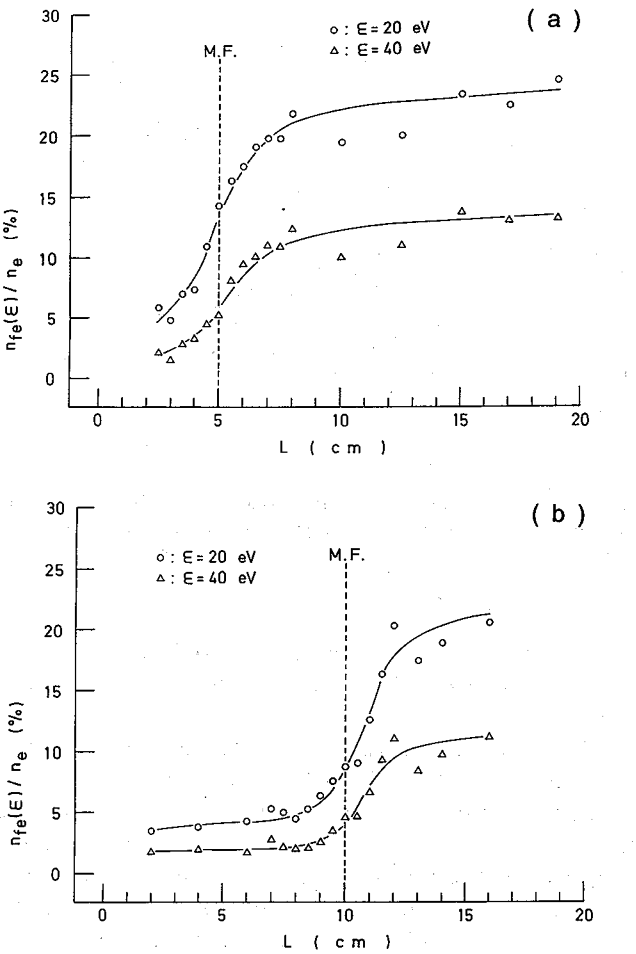

FIG. 3. Axial variations of density ratio n_{fe}/n_e corresponding to the axial variations of the EEDF for H_2 plasmas as shown in Fig. 2(a), where (a) $L_f=5$ cm and (b) $L_f=10$ cm. Experimental conditions are the same as ones in Fig. 2.

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

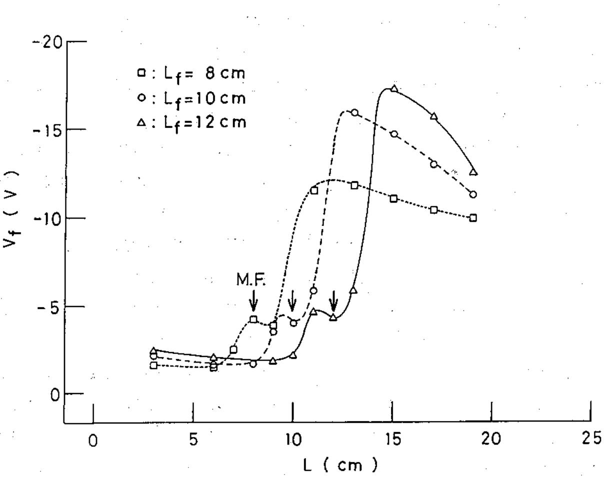

FIG. 4. Axial variations of V_f for different three filter positions in H_2-CH_4 plasmas. Experimental conditions are the same as ones in Fig. 2.

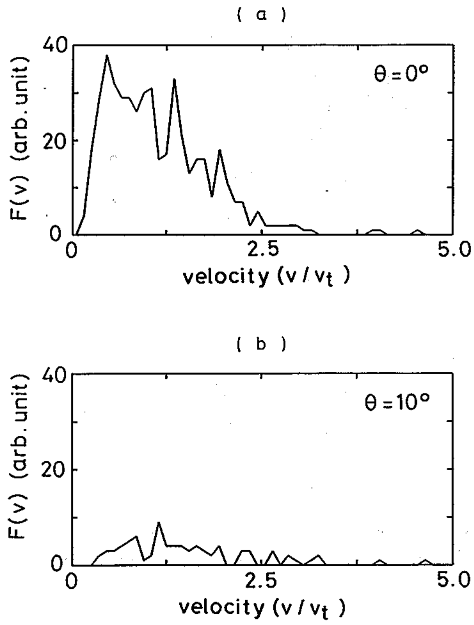

FIG. 5. Accumulated velocity distribution functions of passed electrons for magnetic field parallel to z in (a) and for the tilted magnetic field at an angle θ to z in (b), where $a_B/\rho_e=3.5$. Parameter a_B/ρ_e is the ratio of the characteristic width of the magnetic filter to the electron thermal Larmor radius for the maximum magnetic field.

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 $v^2=v_x^2+v_y^2$. 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, 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

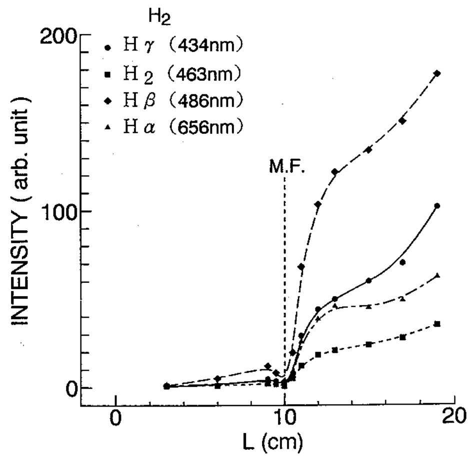

FIG. 6. Axial variations of the emission intensities in H_2 plasmas when $L_f = 10$ cm. Experimental conditions are as follows: $V_d = 80$ V, $I_d = 2$ A, and $p(H_2 \text{ gas}) = 2.9$ mTorr.

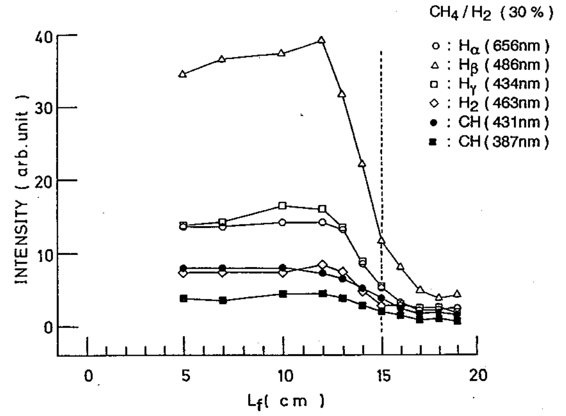

FIG. 8. Emission intensities for some species of radicals observed at the midpoint (i.e., $L = 15$ cm) vs L_f. Experimental conditions are as follows: $V_d = 80$ V, $I_d = 2$ A, and $p(H_2\text{-}CH_4 \text{ gas}) = 2.9$ mTorr.

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 $H_2\text{-}CH_4$ and $Ar\text{-}CH_4$ plasmas are also measured. There is a strong correlation between the emission intensity of CH radicals and n_e.

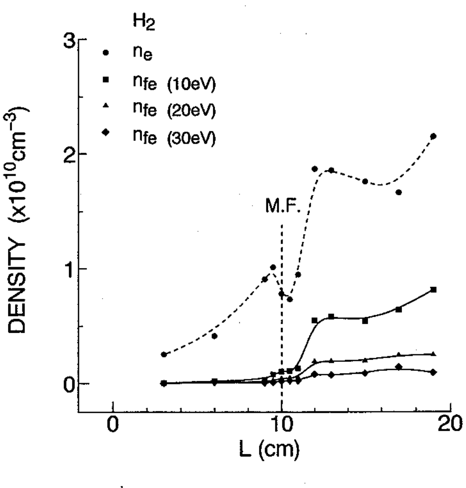

FIG. 7. Axial variations of energy-dependent electron densities in H_2 plasmas. They are corresponding to the results in Fig. 6.

The radical density n^* satisfies the relation, $n^* = n_0 n_e(E) \langle \sigma v \rangle \tau$, if the radicals are mainly produced by the electron impact dissociation process, where n_0 is source gas density, $n_e(E)$ is energy-dependent electron density, $\langle \sigma v \rangle$ is dissociation reaction rate, and τ is mean lifetime of the radical.[15] In particular, $n_e(E)$ and $\langle \sigma v \rangle$ 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_s, 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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