Experimental test of H^- volume production process in a hydrogen discharge

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To investigate electron energy dependence of pure H^- volume production, we have recently designed a double-plasma-type negative ion source. In this source, both energy and density of fast electrons are well controlled. With the use of this source, the effect of fast electrons on H^- production, i.e., the so-called two-step process of H^- production, is discussed.

I. INTRODUCTION

According to our recent simulation results,[1-3] most of the H^- ions are produced by a two-step process.[4] Namely, H^- ions are generated by dissociative attachment of slow plasma electrons e (with an electron temperature $\kappa T_e \sim 1$ eV) to highly vibrationally excited molecules $H_2(v'')$ (effective vibrational levels $v'' \geqslant 5$–6), and these $H_2(v'')$ are mainly produced by the collisional excitation of fast electrons e_f with energies in excess of 35–40 eV. Although different techniques (i.e., optimizing the magnetic filter and the plasma grid potential, and introducing cesium vapor) to increase the H^- yield in a multicusp source have been investigated by many authors, there are a few reports on studying physically the two-step process of H^- production or its enhancement.[5-7]

Recently, we have developed a double-plasma DP-negative ion source.[8] In this paper, we show that fast electron energy distribution and its density n_{fe} are well controlled with the use of this source. We also report the results on the relation between the n_{fe} and H^- current, and between fast electron energy E_{fe} and the H^- current.

II. EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows a schematic diagram of the DP-type negative ion source. The source chamber is made of stainless steel, and is divided by a mesh grid into two regions, i.e., a driver plasma region (the right-hand side) and a target plasma region (the left-hand side). The target plasma region is a conventional volume production type of the negative ion source equipped with a magnetic filter and a plasma grid.[5,7] Electrons in the driver plasma are extracted and injected into the target plasma region as an electron beam with acceleration voltage V_B (i.e., the potential difference between two chambers) and the beam current I_B. With the change of V_B and I_B, e_f in the target plasma region [i.e., the source region of the ion source or the region of $H_2(v'')$ production caused by e_f] are well controlled.[8]

Plasma parameters are measured by Langmuir probes. To obtain an electron energy distribution function (EEDF) using the Druyvesteyn method, the second derivative of the probe characteristics was also measured. From those data, the density of fast electrons $n_{fe}(E)$ with an energy higher than E was estimated.[7,8]

The left-end plate, i.e., the plasma grid, has a single hole (10 mm diameter) through which ions were extracted from the source. A magnetic-deflection-type ion analyzer was used for relative measurement of the extracted H^- ions.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Throughout the present experiment plasma production in the target plasma region is carried out only by beam-plasma discharge of the injected electron beam. The electron beam is injected at $z=0$ cm, i.e., the position of the mesh grid, and plasma is produced. There is a spatial variation in electron density n_e (n_e increases gradually with z and then saturates near $z=15$–17 cm), although electron temperature T_e is kept at a nearly constant value. Both n_e and T_e change remarkably across the magnetic filter in the same manner of the usual volume source, where filter position $z_f=20$ cm.

Figure 2 shows the dependence of plasma parameters on V_B. They are measured at $z=15$ cm in the source region and at $z=21$ cm in the extraction region, where the plasma grid is set at $z=22$ cm. As I_B is kept constant at 1 A in this case, the discharge power in the target plasma region becomes high with increasing V_B. Although T_e keeps nearly constant value with increasing $V_B(\geqslant 30$ V), n_e increases linearly and then saturates.

Figure 3 shows the dependence of the EEDF on V_B in the source region, corresponding to the results in Fig. 2. They are also measured at $z=15$ cm. With increasing V_B,

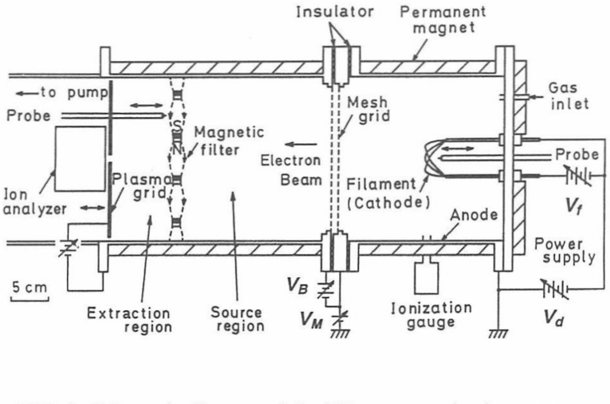

FIG. 1. Schematic diagram of the DP-type negative ion source.

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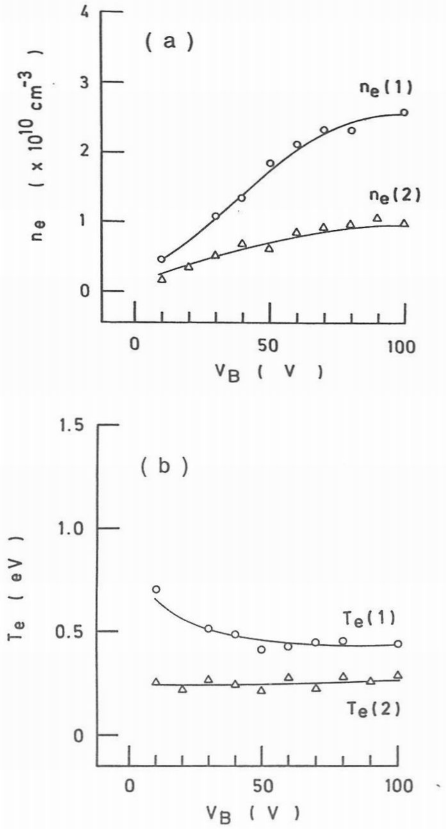

FIG. 2. Plasma parameters in the source and extraction regions vs V_B, i.e., (a) $n_e(1)$ and $n_e(2)$, and (b) $T_e(1)$ and $T_e(2)$. They are measured at $z=15$ cm in the source region and $z=21$ cm in the extraction region, respectively. Here, the electron beam is injected into the target plasma at $z=0$, and the magnetic filter and the plasma grid are set at $z=20$ and 22 cm. Experimental conditions are as follows: Discharge voltage in the driver plasma $Vd=45$ V, gas pressure $p(H_2 \text{ gas})=4$ mTorr and injected beam current $I_B=1$ A.

the EEDF increases in magnitude, particularly its high energy tail [see Fig. 3(b)]. It is, therefore, expected that, e.g., $n_{fe}(E_{fe} \geqslant 20\text{–}30$ eV) in the source region will be controlled by changing V_B and I_B.

We will show later the dependence of $n_{fe}(E)$ on V_B for some different electron energies. These $n_{fe}(E)$ are derived from the EEDF shown in Fig. 3 and the n_e in Fig. 2. In order to study the electron energy dependence of H^- production, i.e., to compare the behavior of energetic electrons with H^- production, $n_{fe}(E)$ for four different energies are plotted as a function of V_B in Fig. 5.

Figure 4 shows the dependence of H^- current on V_B. As the plasma grid is set at $z=22$ cm in this case, the distance between the plasma grid and the magnetic filter is 2 cm. The plasma grid potential V_b is kept at the same potential of the chamber anode, and is not optimized to extract the highest H^- current at every V_B. It is quite interesting that the H^- current increases steeply when V_B is higher than 30 eV. On the other hand, electron densities in both the source and the extraction regions increase linearly with V_B. The plasma characteristics shown in Figs. 2 and 3 correspond to the H^- current in Fig. 4. According to the results in Fig. 3, with increasing V_B, the EEDF changes its shape. At the same time, fast electron density,

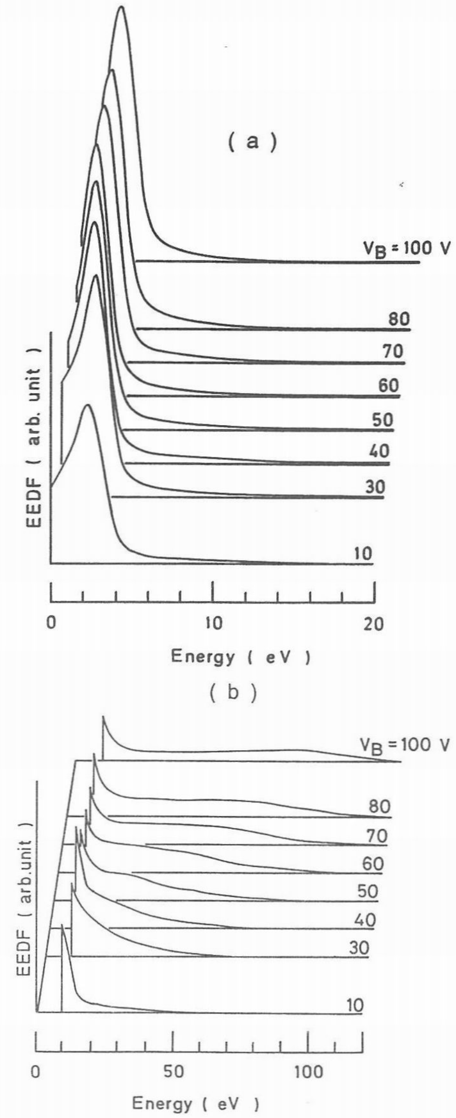

FIG. 3. EEDF in the source region vs V_B, i.e., (a) bulk plasma electrons and (b) high energy tail. They are measured at $z=15$ cm. Experimental conditions are the same as ones in Fig. 2.

e.g., $n_{fe}(E \geqslant 30$ eV), increases markedly when V_B becomes higher than 30 eV. It can be said that $H_2(v'')$ and then H^- production hardly depend on the shape of the energy distribution of e_f, if e_f with energies in excess of 30–40 eV are present.[3]

When H^- ions are produced by the so-called two-step process, where $H_2(v'')$ are produced in the source region and H^- ions are formed in the extraction region, H^- density is written briefly as follows:

$$H^- \text{ density} = n_{fe}(1) n_e(2) N_{H_2} \langle \sigma v \rangle_{v''} \langle \sigma v \rangle_{DA} \tau_{v''} \tau_- ,$$

where $n_{fe}(1)$ is e_f density in the source region, $n_e(2)$ is n_e in the extraction region, N_{H_2} is density of hydrogen molecules, $\langle \sigma v \rangle_{v''}$ is reaction rate of vibrational excitation by e_f in the source region, $\langle \sigma v \rangle_{DA}$ is reaction rate of dissociative attachment in the extraction region, $\tau_{v''}$ is the lifetime of $H_2(v'')$, and τ_- is the lifetime of H^- ions. Roughly speaking, H^- density is proportional to the product of $n_{fe}(1)$

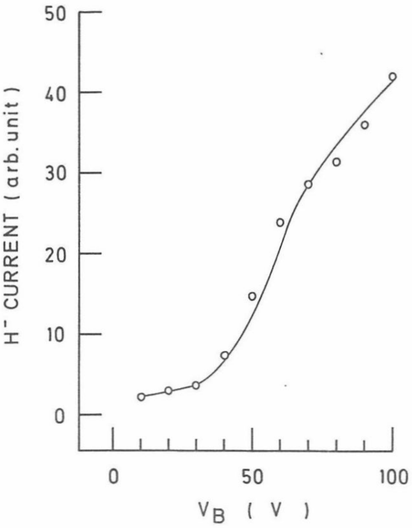

FIG. 4. Extracted H$^-$ current vs V_B, where plasma grid potential V_b is not optimized but equal to the anode potential. Experimental conditions are the same as ones in Fig. 2.

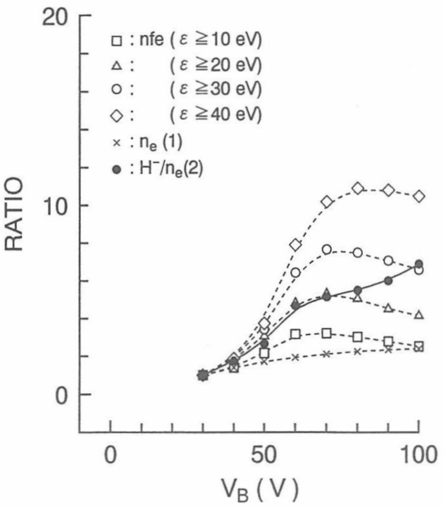

FIG. 5. Normalized H$^-$ current and fast electron densities $n_{fe}(E)$ with an energy higher than E vs V_B.

and $n_e(2)$, if T_e keeps a certain constant value during the change of electron densities—because reaction rates and lifetimes depend on T_e.

The present experimental results qualitatively support the above-mentioned feature. We will test this point in the following: In Fig. 2 variations of plasma parameters in the extraction region, i.e., $n_e(2)$ and $T_e(2)$ are shown as a function of V_B. With increasing V_B, $n_e(2)$ increases gradually while $T_e(2)$ keeps nearly the constant value. Then, $\langle \sigma v \rangle_{\mathrm{DA}}$ would be kept at a certain constant value. By using the experimental results shown in Figs. 2–4, we can discuss the relationship between the increase in H$^-$ current and key parameters, i.e., $n_{fe}(1)$ and $n_e(2)$. Figure 5 shows the ratio H$^-/n_e(2)$ and $n_{fe}(1)$ as a function of V_B. As H$^-$ current is proportional to $n_e(2)$, H$^-/n_e(2)$ represents directly the effects of plasma parameters in the source region. Here, all data points are normalized by the value at V_B=30 V. Namely, we treat the values of H$^-$, $n_{fe}(1)$, and $n_e(2)$ at V_B=30 V as reference levels, respectively. Because the H$^-$ current increases steeply when V_B is equal or higher than 30 V. At the same time, as $n_{fe}(1)$ is a function of electron energy, we plot the five examples of $n_{fe}(1)$ for five different electron energies, i.e., E=40, 30, 20, 10, and 0 eV. When E=0 eV, $n_{fe}(0)$ means $n_e(1)$. To get a good correspondence between H$^-/n_e(2)$ and $n_{fe}(1)$, energy of fast electrons must be at least higher than 20 eV. This is a typical example of electron energy dependence of H$^-$ production. It also means that e_f is essential to H$^-$ volume production.

At a certain value of V_B (i.e., higher than 30–40 V), densities $n_{fe}(1)$ and $n_e(2)$ increase with I_B, and then H$^-$ also increases markedly. According to these results, it would be possible to enhance H$^-$ production by optimizing beam parameters V_B and I_B, i.e., increasing $n_{fe}(1)$ with efficient high energy.

IV. CONCLUSIONS

We have recently developed the DP-type negative ion source. Plasma parameters, especially the energy and density of e_f are well controlled by changing the injected beam parameters (i.e., V_B and I_B). By using this source, the effect of e_f on H$^-$ production is investigated, and the present results support qualitatively the two-step process of H$^-$ production. Optimization of the DP source for H$^-$ production is now under study. In the future, we will also study D$^-$ production and its isotope effect.

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