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Electron energy dependence of vacuum ultraviolet emission and H^- production in a low-pressure hydrogen plasma

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A two-step process of pure H^- volume production via vibrationally excited ground state molecules $H_2(v''\geqslant 5)$ is discussed. The principal source of this vibrational excitation is through singlet excitation by fast primary electrons followed by vacuum ultraviolet (VUV) emission. The VUV emission from a low-pressure hydrogen plasma has been used to study the production mechanism of $H_2(v''\geqslant 5)$ molecules and its electron energy dependence, in a double plasma source where both energy and density of fast electrons are well controlled. The fast electron energy and density strongly affect the VUV emission intensity at wave lengths of, for example, 123 and 124.9 nm. There exists a certain threshold in fast electron energy for singlet excitation and then for $H_2(v'')$ excitation. Fast electrons with energy in excess of 15–20 eV mainly contribute to the VUV emission intensity and are sufficient to increase H^- production. © *1998 American Institute of Physics.* [S0034-6748(98)62102-X]

I. INTRODUCTION

Sources of H^-/D^- ions are required to generate efficient neutral beams with energies in excess of 150 keV. In pure hydrogen discharge plasmas, most of the H^- ions are produced by the two-step process.[1] Namely, H^- ions are generated by dissociative attachment of thermal plasma electrons e (with electron temperature $\kappa T_e \sim 1$ eV) to highly vibrationally excited molecules $H_2(v'')$ (effective vibrational level $v''\geqslant 5-6$), i.e.,

$$H_2(v'')+e\rightarrow H^-+H. \tag{1}$$

These $H_2(v'')$ are mainly produced by collisional excitation of fast electrons e_f with energies in excess of 20–30 eV,[1–3] i.e.,

$$e_f+H_2(X\ {}^1\Sigma_g, v''=0)\rightarrow e_f+H_2^*(B\ {}^1\Sigma_u, C\ {}^1\Pi_u) \tag{2a}$$

$$H_2^*(B\ {}^1\Sigma_u, C\ {}^1\Pi_u)\rightarrow H_2(X\ {}^1\Sigma_g, v'')+h\nu. \tag{2b}$$

There is considerable interest in measuring the density of highly vibrationally excited molecules in these plasmas.[4,5] An alternative approach is to study the production mechanism for $H_2(v'')$ by observing the photon emission associated with process (2).[6]

Recently, we have developed a double plasma (DP) negative ion source,[7] where plasma parameters, especially the energy and density of e_f are well controlled by changing the injected beam parameters. In this paper, with the use of this DP ion source, we will further study the VUV emission from a hydrogen plasma and enhancement of negative ion production, i.e., enhancement due to optimization of e_f distribution achieved by double plasma operation.[8,9]

II. EXPERIMENTAL SET-UP AND PROCEDURE

Figure 1 shows a schematic diagram of the DP negative ion source.[7–9] The source chamber made of stainless steel is divided by a mesh grid into two regions, i.e., a driver plasma region (the left-hand side) and a target plasma region (the right-hand side). The target plasma region is a conventional multicusp volume source of negative ions equipped with both a magnetic filter and a plasma grid.

In both chambers, a steady-state H_2 plasma is produced by primary electrons emitted from hairpin tungsten filaments. The chamber walls serve as the anode for the discharge. Single plasma operation is obtained using two different techniques: In the first technique electrons in the driver plasma are extracted and injected into the target chamber as an electron beam with beam energy eV_B. Here, V_B is the potential difference between two chambers. Plasma in the source region is produced by this injected beam (i.e., beam discharge). Here, we refer to this plasma as an electron beam excited (EBE) plasma.[10] In the other technique the ion source plasma is produced directly by a dc discharge (i.e., filament discharge) with voltage V_t and current I_t. Double plasma operation is the superposition of beam discharge and filament discharge. In this case, with the change of V_B and the

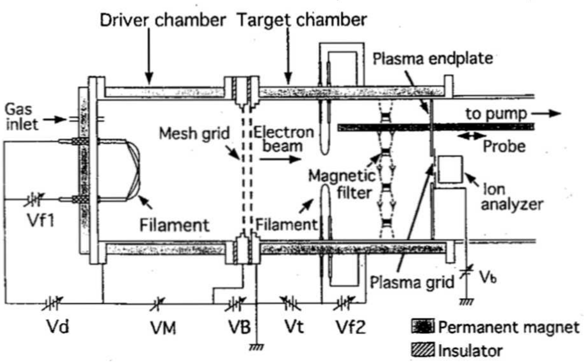

FIG. 1. Schematic diagram of the double plasma negative ion source.

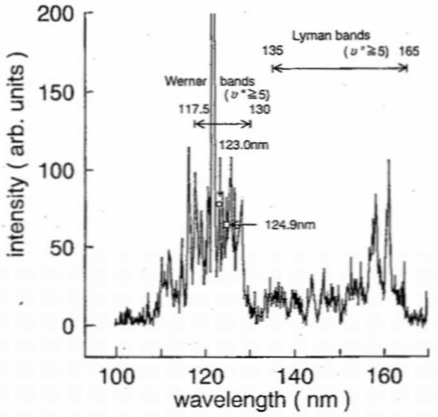

FIG. 2. Typical vacuum ultraviolet spectrum from the EBE hydrogen plasma. Experimental conditions are as follows: discharge voltage of driver plasma $V_d=40$ V, discharge current $I_d=4.3$ A, hydrogen gas pressure p (H_2)$=4$ mTorr, beam acceleration voltage $V_B=100$ V and beam current $I_B=2$ A.

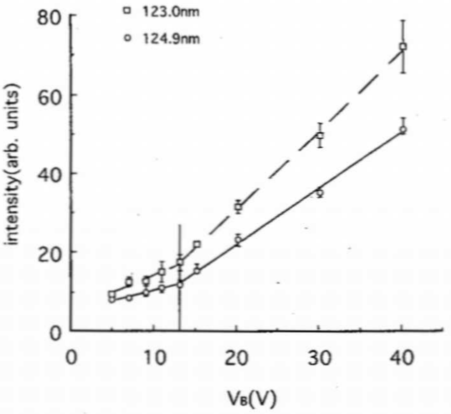

FIG. 3. The variation of the emission intensity at wavelengths (nm), □123 and ○124.9, versus V_B. In this experiment, I_B is varied from 1.23 to 1.45 A with changing V_B. Other experimental conditions are $V_d=40$ V, $I_d=5$ A and p (H_2)$=4$ mTorr.

beam current I_B, e_f in the target plasma [the source region of the ion source, i.e., the region of $H_2(\upsilon'')$ production caused by e_f] is well controlled.[7-10] In this region, light emission measurements were also made by the VUV spectrometer.

Plasma parameters (electron density n_e, electron temperature T_e, plasma space potential V_s and floating potential V_f) are measured using Langmuir probes. To obtain the electron energy distribution function (EEDF), the Druyvesteyn method was used. From the EEDF data, the density of fast electrons $n_{\mathrm{fe}}(E)$ with an energy higher than E was estimated. The right end plate, the plasma grid, has a single hole (5 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

A. VUV emission

An electron beam is injected at $z=0$ cm, which corresponds to the position of the mesh grid, and the EBE plasma is produced. Both n_e and T_e change markedly across the magnetic filter, where filter position $z_f=20$ cm. 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.

At first, we will show the experimental results on the VUV emission as a function of electron beam energy V_B.

Figure 2 shows typical vacuum ultraviolet spectrum from the hydrogen plasma. The transition from the $B\ {}^1\Sigma_u$ and $C\ {}^1\Pi_u$ levels to the ground state $X\ {}^1\Sigma_g$ of H_2 are termed the Lyman and Werner bands, respectively, and they are found in the vacuum ultraviolet region of the emission spectra. The intervals of the Lyman and Werner bands, and regions in which strong transitions leading to $H_2(\upsilon''\gtrsim 5)$ are expected, are indicated in Fig. 2.

As shown in Fig. 3, the emission intensity of the $C-X$ series (123 and 124.9 nm) were found to increase linearly with V_B. However, a rate of increase (i.e., the slope) is changed abruptly at about $V_B=13$ V. Namely, the intensities of these two lines are well enhanced when V_B is higher than about 13 V. These two lines (123 and 124.9 nm) correspond to the $C-X$ transitions (3,7) and (5,9). The rate of production of hydrogen molecules in particular vibrational levels through process (2) is equal to the rate of emission of photons of the appropriate wavelengths. A measurement of the photon emission at 123 and 124.9 nm would therefore provide an estimate of the production rate of $H_2(\upsilon''=7)$ and $H_2(\upsilon''=9)$.

B. Enhancement of H^- volume production

Recently, we have confirmed that the extracted H^- current in the double plasma operation is higher than that in the single plasma operation when observed under the same discharge power.[8,9]

Figure 4 shows the EEDF in the source region as a function of discharge power P_d. They are measured at $z=15$ cm in the source region, where the plasma grid is set at $z=22$ cm. In the case of the single plasma, $P_d=V_B\cdot I_B$. Here, I_B is the current collected by the mesh grid. Since the geometric factor of the mesh grid for permeability is about 50%, we assume that the injected beam current is equal to I_B. In the case of the double plasma $P_d=V_B\cdot I_B+V_t\cdot I_t$, where $V_t=50$ V and $I_t=2$ A. To obtain the data shown in Fig. 4, in the single plasma operation I_B is varied from 1 to 2.5 A at constant $V_B\doteq 100$ V. On the other hand, in the double plasma operation, I_B is varied from 0.63 to 2.5 A at constant $V_B=80$ V.

With increasing P_d, the EEDF increases in magnitude, especially in the high-energy tail. The EEDF shows marked difference between single and double plasmas. Namely, the EEDF in the single plasma is apparently lower than that in the double plasma. The aim of applying double plasma operation is to synthesize an optimum EEDF for negative ion formation.

We measured, for example, the intensity of the $C-X$ transitions (5,9) as a function of P_d. The photon emission at wavelength 124.9 nm in the double plasma is higher than that in the single plasma. This confirms that the double

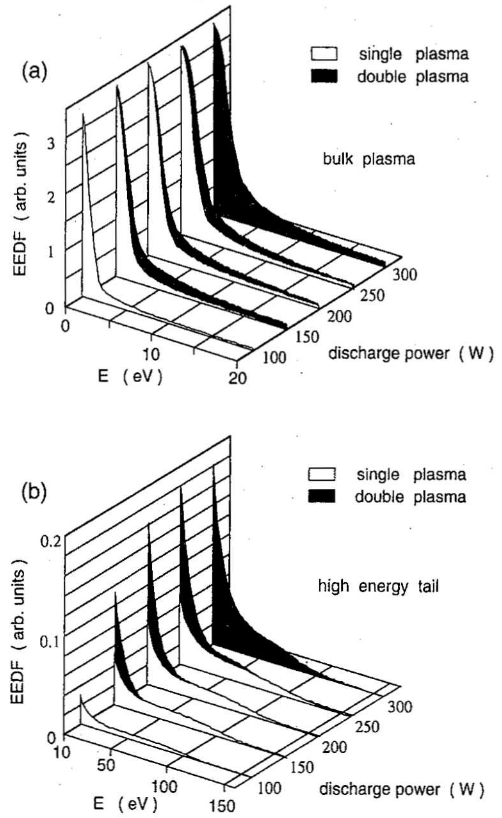

FIG. 4. Electron energy distribution function (EEDF) for H_2 plasmas in the source region versus discharge power P_d, (a) bulk plasma electrons and (b) high-energy tail. Here, $P_d = V_B \cdot I_B$ in the single plasma operation and $P_d = V_B \cdot I_B + V_t \cdot I_t$ in the double plasma operation. Experimental conditions are as follows: $V_d = 40$ V, $p(H_2) = 4$ mTorr, and $V_B = 80$ V in the double plasma operation and 100 V in the single plasma operation.

plasma operation can contribute significantly to the production of highly vibrationally excited states of the hydrogen molecule.

Figure 5 shows the dependence of negative ion currents on P_d. The plasma grid potential V_b is kept at ground potential, which is the potential of the chamber. Under the present operating conditions, the plasma grid is nearly optimal for extraction of the highest H^- current at every P_d although in general optimum grid potential varies with plasma conditions. The negative ion currents in the double plasma are much higher than those in the single plasma.

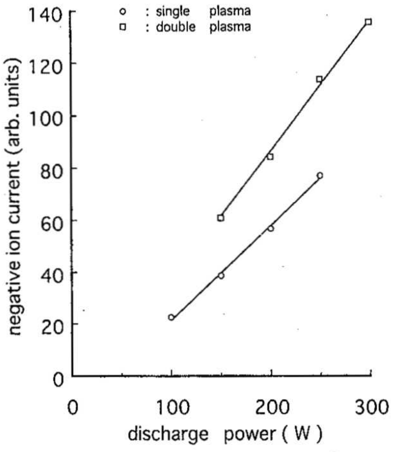

FIG. 5. Extracted H^- current versus P_d, where plasma grid potential V_b is set to be equal to anode potential. The experimental conditions are the same as those in Fig. 4, and extraction voltage $V_{ex} = 600$ V.

As is discussed elsewhere,[7–10] 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 as follows:

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

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 the reaction rate of vibrational excitation by e_f in the source region, $\langle \sigma v \rangle_{DA}$ is the 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 $n_{fe}(1)$ and $n_e(2)$, if T_e maintains certain constant during the change of electron densities. Reaction rates and lifetimes depend on T_e. Fortunately, in the present experiment, T_e is kept nearly constant value.

Enhancement of H^- production in the double plasma operation can be explained by examining the plasma parameters presented here. The key parameters for the two-step negative ion production process, $n_{fe}(1)$, $T_e(1)$, $n_e(2)$ and $T_e(2)$, are optimized better in the double plasma operation than in the single plasma operation.

IV. CONCLUSIONS

We have studied the enhancement of H^- production achieved by controlling the EEDF. Measurements of the basic plasma parameters including the VUV emission have been made in the source and extraction regions of single plasma and the double plasma. From the VUV emission intensity, it is confirmed that excitation of $H_2(v'')$ depends on fast electrons with energy in excess of 15–20 eV. For the same discharge power, H^- production in the double plasma operation is higher than that in the single plasma operation.

ACKNOWLEDGMENT

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