Bull. Inst. Chem. Res., Kyoto Univ., Vol. 70, No. 1, 1992

The Effect of Biasing the Plasma Electrode on Hydrogen Ion Formations in a Multicusp Ion Source

Hiroyasu EGO, Yoshihisa IWASHITA and Hidekuni TAKEKOSHI*

Received February 17, 1992

The plasma electrode covered with magnetic cusp fields acting as a magnetic filter was installed in a multicusp ion source. The formation processes of the negative and positive hydrogen ions in this source have been investigated when an electrostatic positive bias is applied to the plasma electrode with respect to the anode chamber. The dominant H^- volume–production process is the recombinational attachment rather than the dissociative attachment when the bias voltage is more than +3V. This recombinational attachment improves the H^+ ratio in the extracted positive beam, keeping its current value.

KEY WORDS : Volume–produced H^- source/Plasma electrode biasing/Dissociative attachment/Recombinational attachment/Electron suppression

INTRODUCTION

The efforts towards extracting the volume–produced negative ions from various multicusp configurations with a magnetic filter have been made successfully.[1)–26)] It has been indicated[20)–21)] that the majority of extracted H^- ions is formed in the filter region by the dissociative attachment of low–energy electrons to vibrationally excited hydrogen molecules $H_2(v'')$,

$$e+H_2(v'') \rightarrow H^-+H.$$

The purposes of this work are to study the generation processes of hydrogen ions near the plasma electrode (PE) and to find the relationship between the plasma characteristics and the extracted ion currents. An ion source used in our experiment does not have a conventional magnetic filter but the beam extraction aperture is covered with cusp fields generated by permanent magnets installed in the PE. This magnetic field is named as the PE cusp. It is shown that this field configuration acts as a magnetic filter to enhance the H^- volume–production near the PE. We have investigated the PE bias effect on the generation processes in the presence of this cusp magnetic filter.

EXPERIMENTAL SET–UP

A schematic diagram of the experimental apparatus is shown in Fig. 1. The ion source

恵郷博文, 岩下芳久 : Accelerator Laboratory, The Institute for Chemical Research, Kyoto University, Gokanosho, Uji, Kyoto, Japan.
* 竹腰秀邦 : Hiroshima Denki Institute of Technology, 6–20 Nakano Aki Hiroshima Japan.

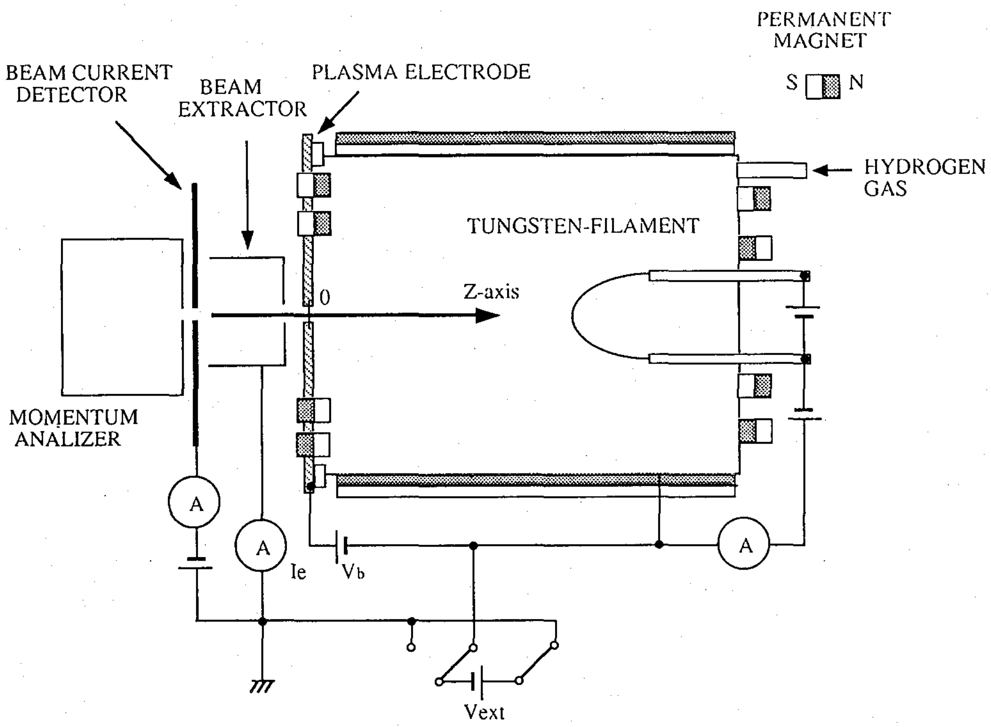


Fig. 1. *A schematic diagram of the multicusp ion source equipped with the cusp PE. The z–axis of the coordinate system used in the profile measurement is shown and its origin is at the center of the extraction aperture.*

chamber is a cylindrical copper vessel (15cm in diameter by 22cm long) surrounded externally by ten columns of Sr–Ferrite magnets (B_{max}~1kG). These magnets from continuous line cusps parallel to the source axis and cusps are connected at the end plate by four extra rows of magnets. The open end of the chamber is enclosed by the two–electrodes extraction system. The first electrode (the PE) connected to the chamber is electrically isolated from the chamber wall to apply a bias voltage and has a beam extraction aperture (3mm in diameter). The chamber is biased at −10kV relative to the second electrode (the beam extractor) at the earth potential when the negative ions generated in the discharge plasma are extracted. The polarity is reversed when the positive ions are extracted.

The ion source vessel, beam extraction systems and beam diagnostics are fabricated in a big vacuum chamber which is evacuated by a *1500l/s turbo–molecular pump*. The chamber can be evacuated to less than 5×10^{-6} Torr before a neutral hydrogen gas is admitted to the system. The gas pressure in the chamber is monitored with a Penning Ion Gauge (PIG). A negatively biased 1mm in diameter and 100mm long tungsten filament is heated up with the current of about 60A. The filament power is adjusted to keep the arc current of 3A at the discharge voltage of 80V even if the neutral H_2 gas pressure is changed. A quiescent plasma with medium densities is obtained in a range of the pressure from 0.1m Torr to 10m Torr.

Pairs of Sr–Ferrite permanent magnets installed in the PE make magnetic cusp fields over

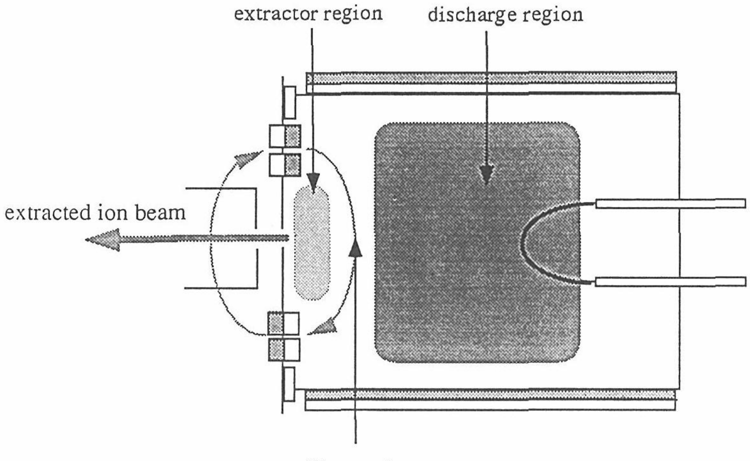


Fig. 2. The magnetic cusp field configuration near the PE.

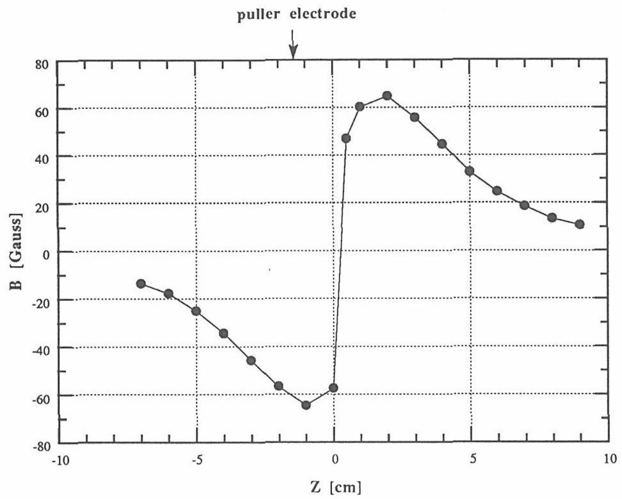


Fig. 3. The profile of the transverse magnetic field induction on the z–axis near the PE. The arrow indicates the location of the beam extractor.

the beam extraction aperture (Fig. 2). Figure 3 shows the dependence of the magnetic field induction, **B**, transverse to the beam axis (z–axis) on the distance from the center of the beam extraction aperture. The magnetic field is measured with a Hall probe. This magnet configuration provides an anti–symmetric profile of the magnetic field. It has a maximum value, about 70 Gauss, at z=2cm and vanishes around the beam extraction region. The magnetic cusp field is strong enough to keep the primary and energetic electrons from getting into the extraction region and the plasma is cold in this region. Thus, the field has the same effect as the conventional magnetic filter used to enhance the H^- volume–production. It divides the entire chamber into three regions as shown in Fig. 2. They are the extraction region (z∼0 cm), the filter region (z~2cm) around the maximum cusp field, and the discharge region (z ≥4cm) where most energetic electrons are confined and the electron temperature is rather high as described in the next section.

By means of an electron suppressor with permanent magnets, a reduction in the electron current extracted from an ion source has been reported[20)-22)]. The stray magnetic field over the beam extractor is strong enough to damp only electrons from the extracted beam while the ions are slightly deflected. The magnetic field configuration adopted here can eliminate the use of an electron suppressor.

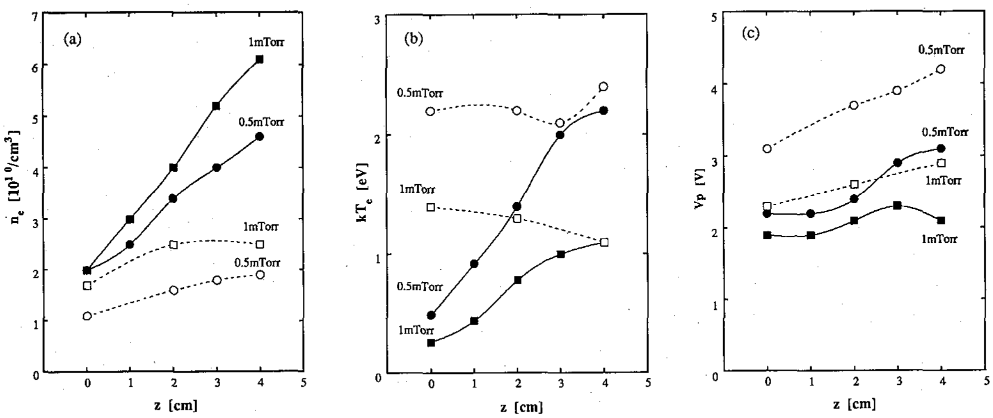
The total extracted ion beam current is measured by a current detector of 200mm in diameter which has a 1mm wide and 20mm long slit in the center. After passing through the slit, a small fraction of charged particles enters a magnetic-deflection momentum analyzer and the mass distribution of the beam is obtained. It should be noted that a value of a specific ion beam current quoted in this paper is the product value of the total current and the ratio of the ion species.

We measure plasma characteristics by a movable cylindrical Langmuire probe[43-46)] (which is 3mm long and 1mm in diameter) to obtain profiles of the plasma electron density n_e, the plasma electron temperature kT_e, and the plasma potential V_p. This probe is inserted into the chamber from the extraction aperture.

EXPERIMENTAL RESULT

A. The effect of the PE cusp on plasma parameters

Fugure 4 shows the measured profile of the plasma parameters at two neutral gas pressures. The density of the discharge region (z~4cm) with the PE cusp is two-times larger than that without the PE cusp since the magnetic cusp field over the PE confines the plasma effectively. Figure 4(a) also shows that the cusp field disturbs the plasma near the PE and causes



(a) Plasma electron density (b) Electron temperature (c) Plasma potential

Fig. 4. The profiles of plasma parameters with the cusp field (solid lines) and without the cusp field (dotted lines) near the PE.

the electron density gradient.

Figure 4(b) shows that the plasma electron temperature around the PE cusp is lower and the plasma is cold ($kT_e \sim 1eV$) in the extraction region. Most of these cold electrons are attributed to diffusion processes across the magnetic field. The suitable plasma condition for the dissociative attachment process of $H_2(v'')$ is attained near the extraction aperture by this magnetic configuration.

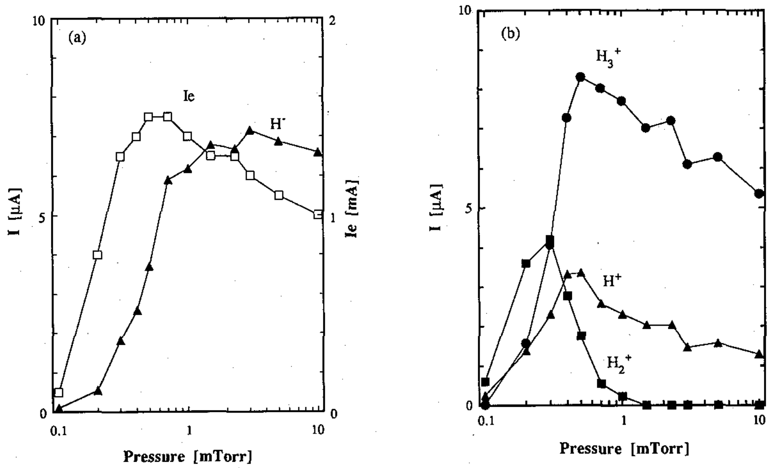
B. The dependence of extracted currents on the pressure

The dependence of hydrogen ion yield on gas pressure is measured and the results are presented in Fig. 5. Figure 5(a) shows that the H^- yield increases rapidly with the source pressure up to 3mTorr. Above 3mTorr, the H^- current decreases slightly. The electron current exhibits a broad peak around the pressure of 0.5mTorr.

Figure 5(b) represents the variation of extracted positive ion currents. The dependence of the H^+ and H_3^+ currents on the gas pressure in similar to that of the electron current. The H_2^+ current, however, has a peak of about 4μA at 0.3mTorr and decreases rapidly. This pronounced drop of H_2^+ with the increase of H_3^+ and H^+ is probably caused by the higher rate of the resolution process of H_2^+,

$$H_2^+ + H_2 \rightarrow H_3^+ + H,$$
$$H + e \rightarrow H^+ + 2e.$$

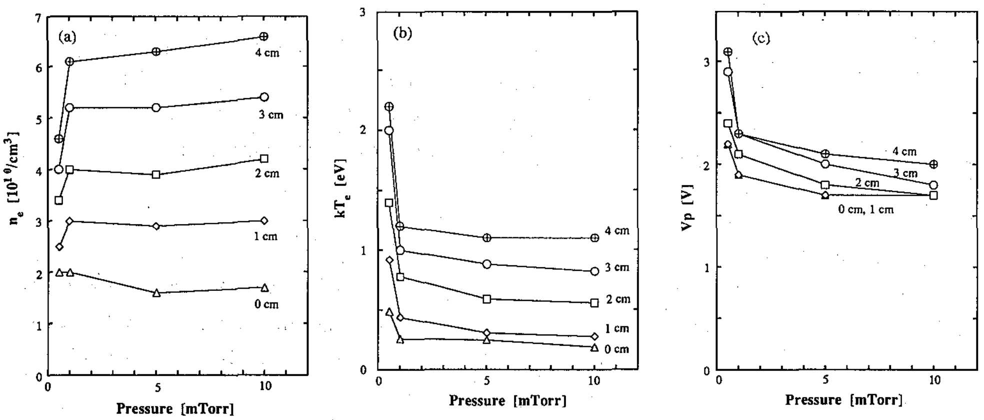
Figure 6(a) shows that the plasma density near the extraction aperture (z=0cm) is almost constant, while n_e in the filter and discharge region increases rapidly. The kT_e, however, decreases remarkably at the pressure of 1mTorr and becomes almost constant ($\sim$1eV) above 1mTorr (Fig. 6(b)). The increase of H^- ion current may be due to the drop of the electron temperature and the increase of the plasma density in the filter region. The results show that the optimum pressure is approximately 0.5mTorr for the H^+ extraction and 3mTorr



(a) Extracted H^- ion current and electron current

(b) Positive ion currents

Fig. 5. The dependence of extracted beam currents on the neutral H_2 gas pressure.



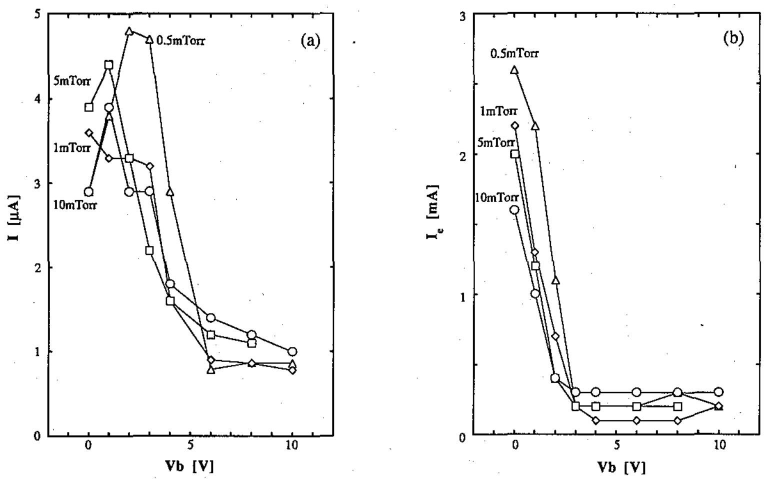
(a) Plasma electron density (b) Electron temperature (c) Plasma potential

Fig. 6. The dependence of plasma parameters on the H_2 gas pressure.

for the H^- extraction with the arc power of 80V 3A.

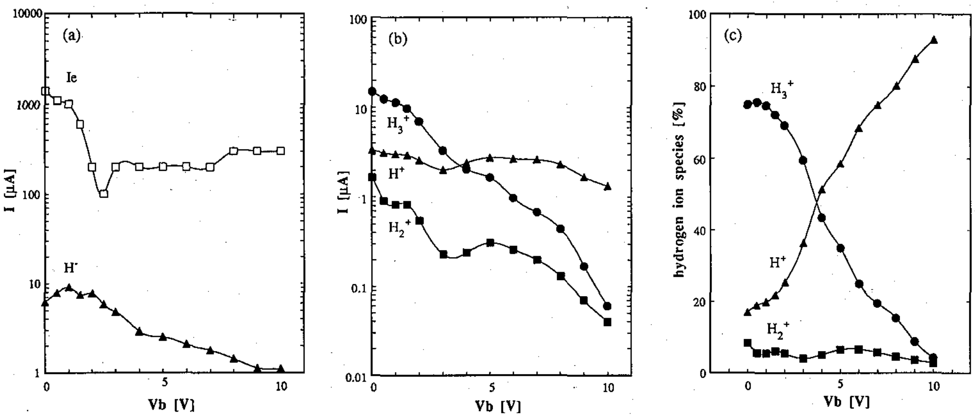
C. The extracted current as a function of the PE bias voltage V_b

The H^- yields as a function of the PE bias voltage at four neutral gas pressure are shown in Fig. 7. A small positive bias potential relative to the anode enhances the H^- yield accompanied with a reduction of the electron current. At each pressure, an optimum H^- yield is obtained at the PE bias between +1V and +3V relative to the anode. The enhancement of the H^- yield is more noticeable when the pressure is about 0.5mTorr. The dependence of the



(a) Extracted H^- ion current (b) Electron current

Fig. 7. The extracted beam currents as a function of the PE bias voltage for several H_2 gas pressures.



(a) H^- current and electron current (b) Positive ion currents (c) Ratios of extracted positive hydrogen ion species

Fig. 8. The dependence of extracted beam currents upon the PE bias voltage.

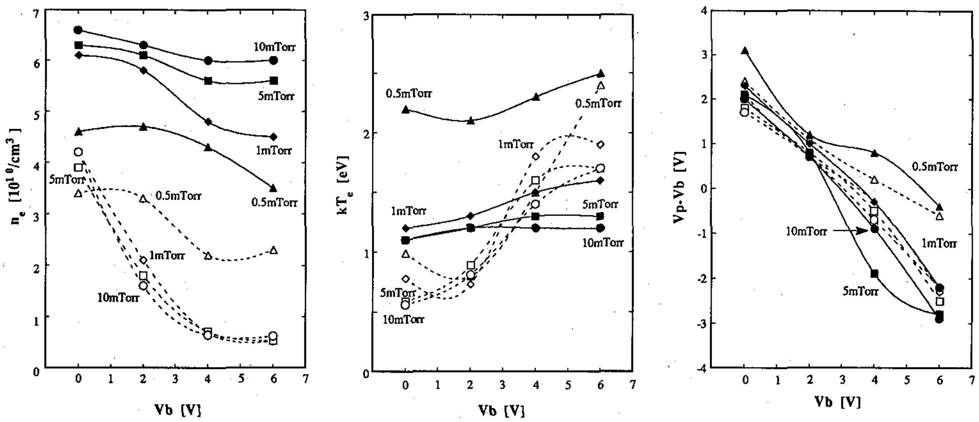
H^- current on V_b was examined at the pressure of 0.7mTorr at which the H^- yield exhibits the most enhancement and the result is shown in Fig. 8.

The extracted H^- current, I^-, has a peak of 9μA at $V_b = +1$V. The extracted electron current I_e is about 1.5mA at $V_b = 0$V and it decreases to about 0.1mA at $V_b = +2.5$V. Thus, by employing the PE cusp and biasing the plasma electrode at +2.5V, the ratio of I^-/I_e was improved from 1/250 to 1/15.

Figure 8(b) shows the ratio of positive ion species as a function of V_b. The H_3^+ and H_2^+ currents decrease steeply as V_b is increased. Figure 8(b) shows that the rather high H^+ ion percentage is obtained at higher V_b than +4V with slight decrease of its current value.

The plasma electron density n_e, the plasma potential V_p and the electron temperature kT_e are measured as a function of V_b and the results are shown in Fig. 9. It is illustrated in Fig. 9 (a) that n_e in the filter region decreases more rapidly than that in the discharge region. With the small positive bias, there is a large drop in density at the filter region. This corresponds to the decrease of the extracted electron current. Figure 9(b) shows that kT_e increases with V_b particularly in the filter region. These variations of n_e and kT_e reduce the rate of the dissociative attachment and decrease the H^- current. Comparing Fig. 9(b) and Fig. 7, it is found that kT_e in the filter region ($z \sim 2$cm) is always about 0.8eV when I^- exhibits the maximum current. It can be also seen in Fig. 9(b) that kT_e in the filter region becomes close to or higher than that in the discharge region when the H^+ ion is the dominant component in the extracted positive ion current. This phenomenon is related to the recombinational attachment and the detail discussion is shown in the next section.

The important result is that the negative ion production is enhanced when the electron temperature in the filter region is about 0.8eV with either change of the neutral gas pressure or V_b. The effect of V_b on the electron density n_e and the electron temperature kT_e is weak at the discharge region ($z \geq 4$cm). The major part of the plasma volume is not affected by V_b. The extracted ions are strongly affected by the plasma condition of the filter region. These results indicate that most of the extracted ions are produced in the filter region.



(a) Plasma electron density (b) Electron temperature (c) Plasma potential

Fig. 9. The dependence of plasma parameters on the PE bias voltage in the filter region (z=2cm; dotted lines) and discharge region (z=4cm; solid lines).

DISCUSSION

The observed H^- yield at a low electron temperature is consistent with either the dissociative attachment of $H_2(v'')$ or the recombinational attachment of molecular hydrogen ions.[15] It has, however, reported[8] that the dominant H^- production process in filter–equipped multi–cusp sources is the dissociative attachment. In our experiments, the optimum H^- production is obtained when the plasma electron temperature in the filter region is about 0.8 eV. The same result has been reported in Ref. 2.

It has been also indicated[5] that the elimination of a potential gradient between the PE and the source plasma plays an important role in the H^- yield when a small positive bias is applyed to the PE. Figure 9(c) shows that the difference between the plasma potential and the PE bias, $V_p - V_b$, is reduced from about 2V (for V_b=0V) to about 1V (for V_b=2V). The plasma potential is almost constant throughout the extraction region and the discharge region at this V_b value. The enhanced H^- yield by the small PE bias can be explained by both effects.

Figure 9(b) shows that the electron temperatures in the fiter region increase up to 1.5eV with V_b. Energetic electrons mainly emitted from the filament are winding around magnetic cusp field lines.[49] When the PE bias is applied, those electrons will $\mathbf{E} \times \mathbf{B}$ drift vertically in a cycroidal motion and electrons trapped in the filter field becomes more energetic. These electrons may contribute to the rise in electron temperatures which decreases the rate of the dissociative attachment. Figure 8(a), however, shows that the remarkable tail of the H^- yield at higher V_b. The rate of the recombinational attachment,

$$e + H_2^+ \rightarrow H^- + H^+,$$
$$e + H_3^+ \rightarrow H^- + H_2^+,$$

increases gradually as the electron temperature becomes high because this process has a maximum cross section in the energy range of 4eV to 10eV. Most of H^- ions seems to be formed by the recombinational attachment when V_b is more than +3V.

Figure 8 shows that the extracted H^+ ion current is comparable to the H^- current with decrease of the H_2^+ and H_3^+ ions when V_b is more than +4V. The H^+ yield probably comes from the dissociation of molecular ions, H_2^+ and H_3^+. This also indicates that the recombinational attachment is predominant over the dissociative attachment at V_b higher than +3V.

Summarizing the above results, it is shown that the dominant H^- formation process changes with PE bias and the ratio of positive ion species is sensitive to the PE bias values.

ACKNOWLEDGMENTS

We would like to thank Professors M. Inoue and A. Noda for continuous encouragement and useful discussions.

REFERENCES

1) M. Bacal and G. W. Hamilton, *Phys. Rev. Lett.*, **42**, 1538 (1979).
2) M. Bacal et al., *J. Appl. Phys.*, **52**, 1247 (1981).
3) M. Bacal et al., *J. Appl. Phys.*, **55**, 15 (1984).
4) M. Bacal et al., *Rev. Sci. Instrum.*, **56**, 649 (1985).
5) M. Bacal et al., *Rev. Sci. Instrum.*, **59**, 2152 (1988).
6) A. J. T. Holmes et al., *Rev. Sci. Instrum.*, **56**, 1697 (1985).
7) L. M. Lea et al., *Rev. Sci. Instrum.*, **61**, 409 (1990).
8) K. N. Leung and W. B. Kunkel, *Phys. Rev. Lett.*, **59**, 787 (1987).
9) K. N. Leung et al., *Phys. Rev. Lett.*, **62**, 764 (1989).
10) K. N. Leung et al., *Appl. Phys. Lett.*, **47**, 227 (1985).
11) K. N. Leung, K. W. Ehlers and M. Bacal, *Rev. Sci. Instrum.*, **54**, 56 (1983).
12) K. N. Leung and M. Bacal, *Rev. Sci. Instrum.*, **55**, 339 (1984).
13) K. N. Leung et al., *Rev. Sci. Instrum.*, **56**, 364 (1985).
14) K. N. Leung et al., *Rev. Sci. Instrum.*, **56**, 2097 (1985).
15) K. N. Leung et al., *Rev. Sci. Instrum.*, **57**, 321 (1986).
16) K. N. Leung et al., *Rev. Sci. Instrum.*, **59**, 453 (1988).
17) K. N. Leung et al., *Rev. Sci. Instrum.*, **60**, 531 (1989).
18) K. N. Leung et al., *Rev. Sci. Instrum.*, **61**, 1110 (1990).
19) K. N. Leung et al., *Rev. Sci. Instrum.*, **61**, 2378 (1990).
20) R. McAdams et al., *Rev. Sci. Instrum.*, **59**, 895 (1988).
21) R. McAdams et al., *Rev. Sci. Instrum.*, **61**, 2177 (1990).
22) M. P. Nightingale and A. J. T. Holmas, *Rev. Sci. Instrum.*, **57**, 2396 (1986).
23) R. L. York and R. R. Stevens Jr., *Rev. Sci. Instrum.*, **55**, 681 (1984).
24) M. Bacal and F. Hillion, *Rev. Sci. Instrum.*, **56**, 2274 (1985).
25) C. Chan, T. Intrator and N. Hershkowitz, *Phys. Lett.*, **A91**, 167 (1982).
26) O. Fukumoto et al., *Phys. Lett.*, **A100**, 186 (1984).
27) W. L. Stirling et al., *Rev. Sci. Instrum.*, **50**, 103 (1979).
28) K. W. Ehlers and K. N. Leung, *Rev. Sci. Instrum.*, **52**, 1452 (1981).
29) K. W. Ehlers and K. N. Leung, *Rev. Sci. Instrum.*, **53**, 1423 (1982).
30) K. W. Ehlers and K. N. Leung, *Rev. Sci. Instrum.*, **53**, 1429 (1982).
31) K. W. Ehlers et al., *Rev. Sci. Instrum.*, **50**, 1031 (1979).
32) N. Hershkowitz et al., *J. Appl. Phys.*, **53**, 4105 (1982).
33) K. N. Leung et al., *Phys. Lett.*, **51A**, 490 (1975).
34) K. N. Leung et al., *Phys. Lett.*, **60A**, 203 (1977).
35) M. Tamba and H. Amemiya, *Rev. Sci. Instrum.*, **61**, 247 (1990).

36) C. Chan, T. Intrator and N. Hershkowitz, *Phys. Lett.*, **A91**, 167 (1982).
37) O. Fukumoto et al., *Phys. Lett.*, **A100**, 186 (1984).
38) J. M. Wadehra and J. N. Bardsley, *Phys. Rev. Lett.*, **41**, 1794 (1978).
39) M. Allan and S. F. Wong, *Phys. Rev. Lett.*, **41**, 1791 (1978).
40) J. R. Hiskes and A. M. Karo, *J. Appl. Phys.*, **56**, 1927 (1984).
41) J. Rd Hiskes, *J. Appl. Phys.*, **55**, 15 (1984).
42) R. Hiskes and A. M. Karo, *J. Appl. Phys.*, **53**, 3469 (1982).
43) F. F. Chen in "PLASMA DIAGTNOSTIC TECHNIQUES" (R. H. Huddlestone and S. L. Leonard, eds.), p 113 ACADEMIC PRESS, New York, London (1965).
44) G. J. Schultz and S. C. Brown, *Phys. Rev.*, **98**, 1642 (1955).
45) B. Hopkins and W. G. Graham, *Rev. Sci. Instrum.*, **57**, 2210 (1986).
46) E. Mravlag and P. Krumm, *Rev. Sci. Instrum.*, **61**, 2164 (1990).
47) K. W. Ehlers and K. N. Leung, *Rev. Sci. Instrum.*, **51**, 721 (1980).
48) R. Limpaecher and K. R. Mackenzie, *Rev. Sci. Instrum.*, **44**, 726 (1973).
49) O. Kaneko et al., *Rev. Sci. Instrum.*, **57**, 67 (1986).
50) H. Matsuzawa and T. Akitsu, *Rev. Sci. Instrum.*, **58**, 141 (1987).
51) J. H. Whealton and J. C. Whitson, *Particle Accelerators*, **10**, 235 (1980).
52) E. Surrey and A. J. T. Holmes, *Rev. Sci. Instrum.*, **61**, 2171 (1990).