Pulse modulation for plasma parameter control and optimization of volume H^- ion source

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Pulse modulation of a negative ion volume source was investigated, both with and without a magnetic filter for various operating conditions. Without a magnetic filter, afterglow negative ion peak is observed, which was reported by some authors. Variation of afterglow peak was discussed as a function of gas pressure, discharge power, and extraction voltage. With a magnetic filter, on the other hand, there is no remarkable afterglow peak and the negative ion current during the discharge pulse exceeds all the afterglow currents for the present experimental conditions. Finally, comparison of afterglow negative ion peak (no magnetic filter case, i.e., temporal filter) with negative ion current during the discharge pulse (with magnetic filter case, i.e., spatial filter) was discussed. © *1998 American Institute of Physics.* [S0034-6748(98)58902-2]

I. INTRODUCTION

It has been proposed to separate the two-step volume production of the negative hydrogen ions (the vibrational excitation of molecules due to primary fast electron collisions and dissociative slow electron attachment to these molecules) in time rather than in space, the so-called "temporal filter." [1,2] In this type of source, without magnetic filter, the discharge current is rapidly pulsed on and off. Reported experimental results indicate that the extracted H^- current in the afterglow is larger than that during the discharge period by a factor of 3.[1] Recently, in the field of plasma processing, a pulse modulation technology for etching plasmas with negative ions has been strongly attracted to overcome local side-wall etching (notching) and low etch selectivity to underlying materials.[3-5]

It is important to clarify basic physics for enhancement of negative ions due to pulse modulation. The purpose of this work is to verify whether the H^- current is enhanced when the source discharge is switched on and off for various operating conditions, i.e., discharge current, gas pressure, extraction voltage, and modulation frequency.[6] Effect of superposing a magnetic filter on pulse modulation is also tested for an additional enhancement of H^- production.

II. EXPERIMENTAL SETUP AND PROCEDURE

The source is a conventional multicusp tandem volume source shown in Fig. 1. A stainless steel cylinder (30 cm long, 16 cm in diameter) contains tungsten filaments maintained on the right-hand side flange. The multicusp magnetic field configuration is produced by Sm–Co magnets located in a line configuration on the cylindrical wall (eight rows of magnets) and on the right-hand side flange.

The magnetic filter (MF) is created by two water-cooled Sm–Co magnets rods which provide a limited region of transverse magnetic field of about 70 G on the axis. This field divedes the entire chamber into the source region (with filaments) and the extraction region. Namely, the MF is strong enough to prevent all energetic primary electrons in the source region from entering into the extraction ergion. Cold electrons, however, together with positive ions can penetrate the filter and form a diffused plasmas.

The source was operated with a continuous flow of pure hydrogen. Figure 1 presents a schematic diagram of the experimental setup, including the discharge direct current (dc) power supply, V_d, and the switch which pulses the discharge on and off. The switch interrupts the discharge current, as shown in Fig. 1. The filament heating and the voltages applied to the other electrodes (including the plasma electrode and the plasma grid) were not pulsed. The frequency and duty cycle of discharge modulation were varied in the range of 100 Hz–20 kHz and 20%–50%.

Plasma parameters are measured by Langumuir probes. The left-end plate, i.e., the plasma grid, has a single hole (10 mm diameter) through which negative currents were extracted from the source. A Faraday cup with deflection mag-

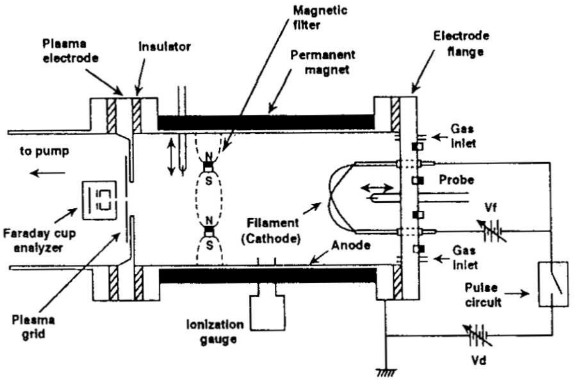

FIG. 1. Schematic diagram of the negative ion source. The discharge dc power supply, V_d, and the switch which pulses the discharge current on and off are also shown.

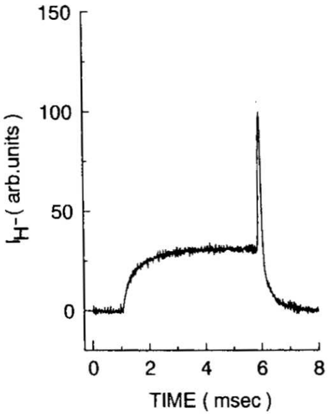

FIG. 2. Time evolution of the extracted H$^-$ current from a pulse discharge without a MF. Discharge conditions are as follows: discharge voltage $V_d = 80$ V, discharge current $I_d = 8$ A, hydrogen gas pressure $p(H_2) = 2$ mTorr, extraction voltage $V_{ex} = 600$ V, modulation frequency $f = 100$ Hz and modulation duty cycle $D = 50\%$.

net was used for relative measurement of the extracted H$^-$ ions.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Pulse discharge without magnetic filter

The time variation of the extracted H$^-$ current from a pulse discharge is shown in Fig. 2. The time variation of plasma parameters (electron density n_e and electron temperature T_e), corresponding to the H$^-$ current in Fig. 2, is shown in Fig. 3. At a time of 1 ms, the discharge is switched on. The extracted H$^-$ current reaches a steady-state value at a time of 2.5 ms. At a time of 6 ms the discharge is switched off. As the fast electrons are lost and the bulk electrons cool, the extracted H$^-$ current increases reflecting the enhanced production of H$^-$ by dissociative attachment and the lower losses than during the discharge.[1] The enhanced production is only sustained for a short period and a peak in extracted H$^-$ current is reached 75 μs after the discharge is switched off. For times greater than 100 μs the H$^-$ current decays exponentially with a decay rate $\tau_- = 130$ μs.

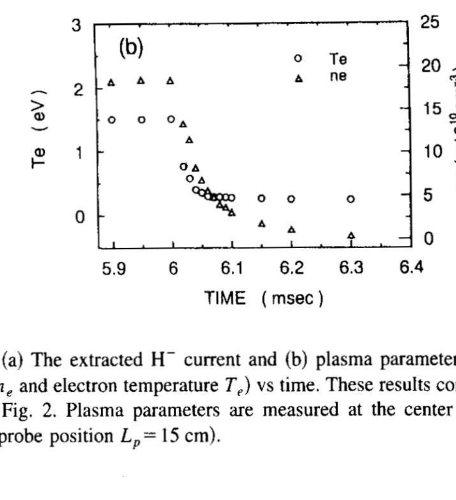

FIG. 3. (a) The extracted H$^-$ current and (b) plasma parameters (electron density n_e and electron temperature T_e) vs time. These results correspond to ones in Fig. 2. Plasma parameters are measured at the center of the ion source (probe position $L_p = 15$ cm).

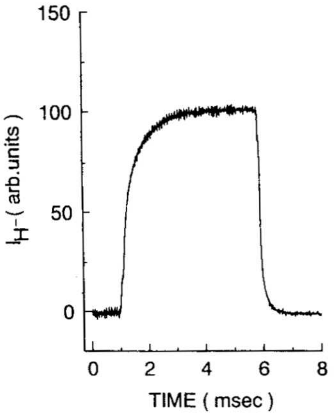

FIG. 4. Time evolution of the extracted H$^-$ current from a pulse discharge with the MF. Discharge conditions are the same as ones in Fig. 2 except that magnetic filter position $L_f = 3$ cm.

B. Pulse discharge with magnetic filter

The time variation of the extracted H$^-$ current from a pulse discharge with the MF is shown in Fig. 4. The extracted H$^-$ current reaches a steady-state value at a time of 3 ms. At a time of 6 ms, the discharge is switched off. In this case, however, there is no afterglow H$^-$ current peak. Furthermore, the steady-state value of H$^-$ current during the discharge pulse goes up comparable to the afterglow peak in Fig. 2.

Plasma parameters (n_e and T_e) in the source region ($L = 15$ cm) and in the extraction ergion ($L = 0.5$ cm) were measured. It is reconfirmed clearly that by using the MF, n_e and T_e are already optimized for H$^-$ volume production in the discharge period.

For various operating conditions, i.e., varying gas pressure p, discharge voltage V_d and discharge current I_d, the extracted H$^-$ current has no remarkable afterglow peak. Therefore, there is no additional effect for enhancement of H$^-$ production due to combining the MF with pulse modulation.

With increasing modulation frequency f up to 20 kHz, however, the extraction current from a modulated discharge is higher than the current from an unmodulated (dc) discharge. Typical example is shown in Fig. 5. This feature indicates pumping the vibrational density and H$^-$ ions when the MF is present. Details are now under study.

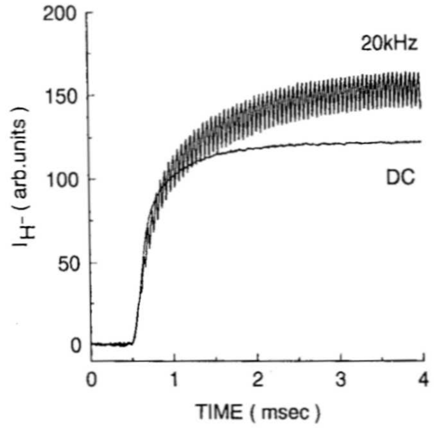

FIG. 5. The extracted H^- currents from an unmodulated (dc) and modulated (20 kHz) discharge with the MF. Discharge conditions are $V_d = 80$ V, $I_d = 8$ A, $p = 3$ mTorr, $L_f = 2$ cm, and $D = 60\%$.

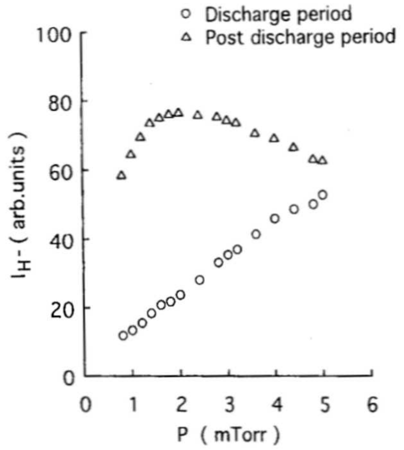

FIG. 7. Pressure dependence of the extracted H^- current in a pulse discharge source without the MF. Open triangle and circle correspond to the afterglow peak and the steady-state value of the H^- current. Discharge conditions are $V_d = 80$ V, $I_d = 5$ A, $f = 100$ Hz, $D = 50\%$, and $V_{ex} = 600$ V.

C. Characteristic features of a pulse modulated ion source

Here, we show two characteristic features concerning extraction of H^- current from the pulse modulated ion source without the MF.

Figure 6 shows the extracted H^- current versus extraction voltage, where two symbols (i.e., dotted circle and open diamond) correspond to the afterglow peak and to the steady-state value in the discharge period. Current–voltage ($I-V$) characteristics for the afterglow peak is very similar to the Child–Langmuir law, i.e., $I \propto V^{3/2}$. These results indicate that pulse modulation is effective to extract negative ion current.

Figure 7 shows pressure dependence of the extraction of H^- current. Two symbols (triangle and circle) correspond to the afterglow peak and to the steady-state value in the discharge period. The H^- current in the discharge period increases linearly with p. On the other hand, the afterglow peak is much enhanced in low pressure region and reaches the maximum at some optimum pressure (i.e., $p = 2$ mTorr). Namely, this type of operation is effective at low gas pressure. Therefore, an additional advantage would be obtained due to the reduction of stripping loss in the high voltage accelerator and in ion beam processing.

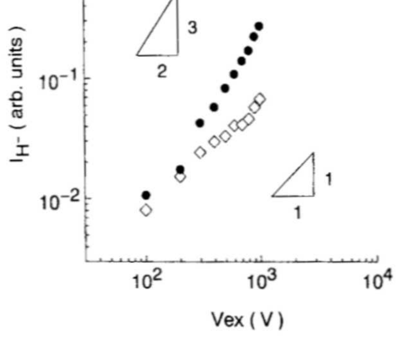

FIG. 6. $I-V$ characteristics in a pulse discharge source without the MF. Dotted circle and open diamond correspond to the afterglow peak and the steady-state value of the H^- current. Discharge conditions are $V_d = 80$ V, $I_d = 10$ A, $p = 2$ mTorr, $f = 100$ Hz, and $D = 20\%$.

IV. CONCLUSIONS

The pulsed operation of the negative ion volume source has been investigated. As a result, we reached the following conclusions:

(1) Without the MF, we have reconfirmed the peak in the negative ion current extracted during the afterglow period.

(2) With the MF, there is no afterglow peak and the negative ion current during the discharge pulse exceeds the afterglow current.

(3) With increasing modulation frequency up to 20 kHz, an additional enhancement of H^- current is observed due to combination of the MF with pulse operation.

(4) Pulse modulation is effective for operating the negative ion source in a low pressure region.

ACKNOWLEDGMENTS

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