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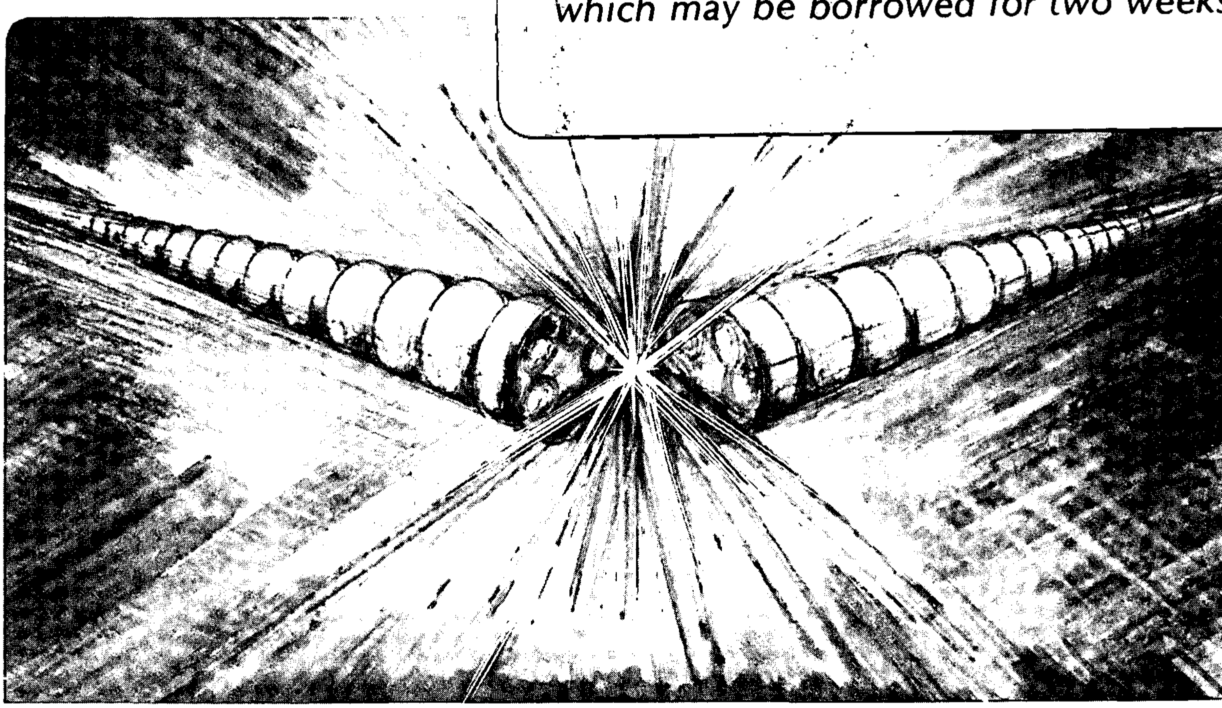

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H^- Formation in a Barium-Seeded Hydrogen Discharge*

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Abstract

It has been found that the H^- output current from a multicusp source can be substantially increased if the hydrogen plasma is seeded with cesium or barium. Experimental results demonstrate that, for a pure hydrogen discharge, the H^- ions extracted from a multicusp source are indeed produced in the plasma volume. However, if barium is mixed with hydrogen in the source discharge, the majority of the H^- ions are generated on the anode walls.

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H^- ions are being used in cyclotrons and tandem accelerators, in fueling storage rings of synchrotrons, and in generating high energy neutral beams for heating and for driving current in tokamak fusion reactors. There are two major types of H^- ion sources;[1] surface-production sources and volume-production sources. Unlike surface sources, volume H^- sources do not utilize a negatively biased converter electrode[2] and require no cesium for normal operation. The H^- ions formed by volume processes have lower average energy than those generated by surface conversion,[3] resulting in a lower emittance of the extracted beam. However, the discharge power and operating pressure of volume H^- sources are high and the amount of electrons accompanying the extracted H^- beam can be large. To address these problems, intensive research on volume sources is now being conducted in many accelerator and fusion laboratories.

The multicusp plasma generator can produce large volumes of uniform and quiescent plasmas[4] and has been used successfully as a positive hydrogen ion source in neutral beam systems.[5] In the past, attempts have also been made to extract H^- ions directly from the plasma of a multicusp source equipped with a permanent magnet filter.[1,6-8] The highest H^- current density achieved was about 250 mA/cm^2 and was obtained from a small multicusp source operated in a pulsed mode with relatively high gas pressure and high discharge power.[8] Experiments have been conducted to improve the H^- yield by optimizing the source geometry and by mixing various gases with hydrogen in the discharge.[9,10] These measures, however, enhanced the extractable H^- current density only by less than 50%.[10]

Surprisingly, recent experimental findings show that the H^- yield from a filter-equipped multicusp source can be increased substantially if the hydrogen discharge is seeded with cesium or barium.[11,12] As a result, H^- beams with current densities exceeding 1 A/cm^2 can now be easily obtained from a small multicusp source when cesium is introduced into the hydrogen discharge.[10] The large enhancement in the H^- output (> a factor of 5) can only be explained if there is a substantial change in the population of vibrationally excited H_2 molecules or positive ion species, which in turn favors the formation of H^- ions via electron-molecule or electron-ion collisional processes,[3,13-15] or if surface generation of H^- ions[16] on the chamber walls becomes significant. In this Letter, we report the first experimental investigation which identifies the source of H^- formation when the plasma is operated with and without barium.

The experiment was performed in a small multicusp H^- source which is shown schematically in Fig. 1. The source chamber was a thin-walled copper cylinder (7.5-cm-diam by 8-cm-long) surrounded by 14 columns of samarium-cobalt magnets for primary electron and plasma confinement.[17] The permanent magnets in turn, were enclosed by an outer anodized aluminum cylinder. During discharge operation, adequate cooling of the magnets was provided by water circulating in between the two cylinders.

The open end of the source chamber was enclosed by a two-electrode extraction system. A steady-state hydrogen plasma was produced by primary electrons emitted from one set of tungsten filaments, and the entire chamber wall served as the anode for the discharge. A second set of tungsten filaments was used to supply additional primary electrons into the source plasma. It has been demonstrated that a negative plasma potential can be formed in a multicusp ion source by the low-energy electron injection technique.[18] If the energies of the injected electrons are lower than the ionization energy of the background gases, then they cannot give rise to ionization process, but they can be confined very efficiently by the multicusp fields. The presence of a large quantity of these low energy primaries will produce a negative plasma potential well.

In order to enhance the H^- yield, a pair of water-cooled permanent magnet filter rods[6] was installed, it divided the entire source chamber into an arc discharge and an extraction region. This filter provided a narrow region of transverse magnetic field (B_{max} ~135 G) which was strong enough to prevent primary electrons from entering the extraction chamber. Excitation and ionization of the gas molecules were caused by the primaries in the discharge region. Both positive and negative ions, together with cold electrons, were present in the extraction region, and they formed a plasma with very low electron temperature ($T_e \leq 1$ eV), which is favorable for H^- formation and survival.[19]

Barium, instead of cesium, was employed in this experiment for several reasons. Due to the magnetic field generated by the filament, it is easier to inject primaries with energies below the ionization potential of barium (E_i = 5.2 eV), than primaries with energies below that of cesium (E_i = 3.9 eV), into the plasma. Secondly, barium has a much lower vapor pressure than cesium, so that much less of its vapor effuses from the source, and voltage-breakdown problems in the accelerator region can be minimized.

A thin molybdenum sheet liner was installed against the inner walls of the source chamber and around the filter rods (Fig. 1). During source operation, the liner, which was thermally isolated from the chamber walls, was heated by the plasma and by radiation from the tungsten filaments. Seeding of the source with barium was accomplished by placing some solid samples of barium on the liner. The barium evaporated during discharge operation and deposited on all surfaces of the liner.

Negative ions were extracted from the source through a small (0.1 x 1.0 cm^2) aperture. A compact magnetic deflection mass spectrometer,[20] located just outside the extractor, was used for relative measurement of the extracted H^- ions as well as their energy spectrum. Plasma parameters were obtained with a small Langmuir probe located near the center of the source chamber.

The source was initially operated with pure hydrogen at a pressure of 4 x 10^{-3} Torr. A background plasma with a density of 2 x 10^{11} cm^{-3} was maintained by a discharge voltage of 80 V and a discharge current of 0.5 A from filament set (1). Figure 2(a) shows the corresponding H^- signal as recorded by the mass spectrometer. The plasma potential V_p measured at the center of the source chamber was about 4 V positive with respect to the anode or chamber walls.

As more and more low-energy electrons were injected from the second set of filaments into the background plasma, Langmuir probe traces showed that the plasma potential V_p became less positive and eventually dropped below the anode potential. It was found that V_p was approximately 3 V negative relative to the anode walls when filament set (2) was operated with a discharge voltage of 12 V and a discharge current of 5 A. Under this dual-cathode discharge condition, the plasma density in the source was found to increase by 62 %. The H^- output signal, as shown in Fig. 2(b), also increased by about the same percentage. Thus, the enhancement in H^- output is directly proportional to the increase of the source plasma density.

The energy spectrum of Fig. 2 (b) also showed that the H^- ion peak has been shifted to the higher energy side. The increase in beam energy is due to the change in plasma potential before and after the injection of low energy electrons. The energy level diagram of Fig. 3 illustrates the relation between the energy of an H^- ion and the potential of the source plasma. If the plasma potential V_p is positive with respect to the anode and the H^- ion is generated in the plasma volume by a collisional process, then its energy $E = e(V_a - V_p)$ when it arrives at the detector, where e is the electronic charge and V_a is the extraction voltage. If the plasma potential V_p is negative, then the energy of the volume-produced H^- ion will become $e(V_a + |V_p|)$ and the H^- peak will appear farther to the right or to the higher energy side of the spectrum.

On the other hand, if the H^- ion is born on the anode surface and the potential of the plasma in the source chamber is positive, then the energy of the H^- ion when it arrives at the detector will be $E = eV_a + \Delta E$ where ΔE is the amount of energy possesed by the H^- ion just when it leaves the anode surface. The actual H^- formation process on the anode surface has not yet been identified. If the H^- ion is generated by reflection of the positive hydrogen ion species,[21-23] then $\Delta E \leq eV_p$. If the H^- ions are formed by reflection of the neutral hydrogen atoms which include the Franck-Condon neutrals, then ΔE can be as large as 2 eV.[24] H^- ions can also be generated by a desorption process[25,26] on surfaces and the incoming projectile can transfer some energy to the adsorbed hydrogen atom. In all these cases, the majority of the H^- ions produced on the anode surface cannot reach the plasma volume if the potential of the plasma is sufficiently negative with respect to the anode. The H^- will be confined or trapped on the surface by the potential barrier and therefore cannot be extracted from the ion source. Only the volume-produced H^- ions will be extracted and subsequently detected by the mass spectrometer.

For a pure hydrogen discharge, the H^- output signal shown in Fig. 2(b) increased with the plasma density when the plasma potential became negative. It is also found that the increase in H^- energy (~7 eV) is equal to the overall change in plasma potential. Based upon this analysis, one can conclude that for pure hydrogen operation, the H^- detected in Figs. 2(a) and (b) are produced in the bulk of the plasma volume, most probably by the dissociative attachment process.[27,28]

Seeding of the hydrogen discharge with barium was carried out by placing some barium pellets on the liner. For this measurement, the source pressure was maintained at 2×10^{-3} Torr and the background plasma was obtained with a discharge power of 80 V, 0.2 A from filament set (1). In this barium-seeded discharge operation, Langmuir probe characteristics showed that the plasma potential was ~1.5 V more positive than the anode. The spectrometer signal in Fig. 4 (a) demonstrates that the H^- output has increased by about a factor of 3 compared with pure hydrogen operation. A similar enhancement has previously been observed when H^- ions were extracted from a smaller multicusp source.[12]

In order to achieve a negative plasma potential, low-energy primary electrons were again injected into the barium-seeded plasma. With filament set (2) operated at a discharge voltage of 4 V and discharge current of 2 A, the plasma potential at the source center was changed to ~1 V negative with respect to the anode. Under this discharge condition, the H^- peak shown in Fig. 4(b) is shifted to the higher energy side, similar to the result obtained for pure hydrogen operation. However, the H^- output signal is now reduced by a factor of 2.4 even though the plasma density has increased by a factor of ~2. This reduction in H^- output signal indicates that the majority of H^- ions observed in Fig. 4(a) are formed on the anode surface. When V_p becomes negative, the surface-generated H^- ions are unable to enter the plasma and only the volume-produced H^- ions can be extracted and detected by the spectrometer. The H^- signal decreases and it is not until V_p becomes positive that the H^- output can recover its original value of Fig. 4(a).

The above observation demonstrates that surface-generated H^- ions are responsible for the large enhancement of the H^- output current when barium is added to a multicusp source. It should be noted that the energies of the H^- formed on the anode surface can be quite different from those generated from a self-extraction type negative ion source.[2] In the latter configuration, a converter electrode with bias potential of -100 V or higher is employed. As a result, the average transverse energy of the "self-extracted" H^- ions is high (>5 eV).[29,30] In principle, the tranverse energy of the H^- ions obtained from the barium-seeded source operation can be minimized by adjusting the potential difference between the plasma and the anode surface. If this can be accomplished, then this new type of surface-production source can be used to provide large currents of high brightness H^- beams.

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Figure Captions

Fig. 1 A schematic diagram of the multicusp H^- ion source.

Fig. 2 The H^- signal recorded by the mass spectrometer for pure hydrogen operation with (a) a positive plasma potential, and (b) a negative plasma potential produced by injecting low energy (12 eV) electrons.

Fig. 3 An energy level diagram illustrating the relationship between the energy of an extracted (surface- or volume-produced) H^- ion and the plasma potential of the ion source.

Fig. 4 The H^- signal recorded by the mass spectrometer for barium-seeded hydrogen operation with (a) a positive plasma potential, and (b) a negative plasma potential produced by injecting low energy (4 eV) electrons.

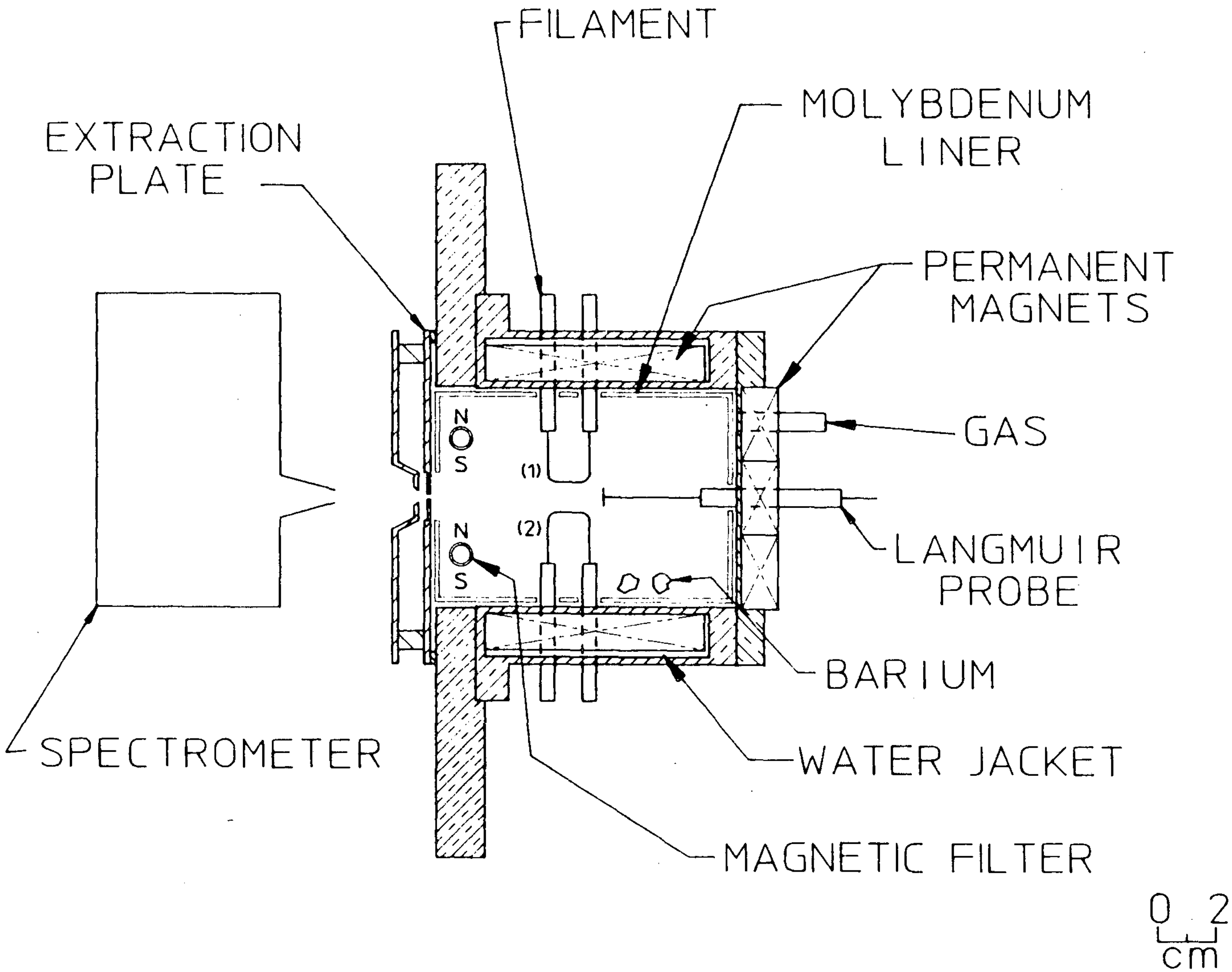

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Fig. 1

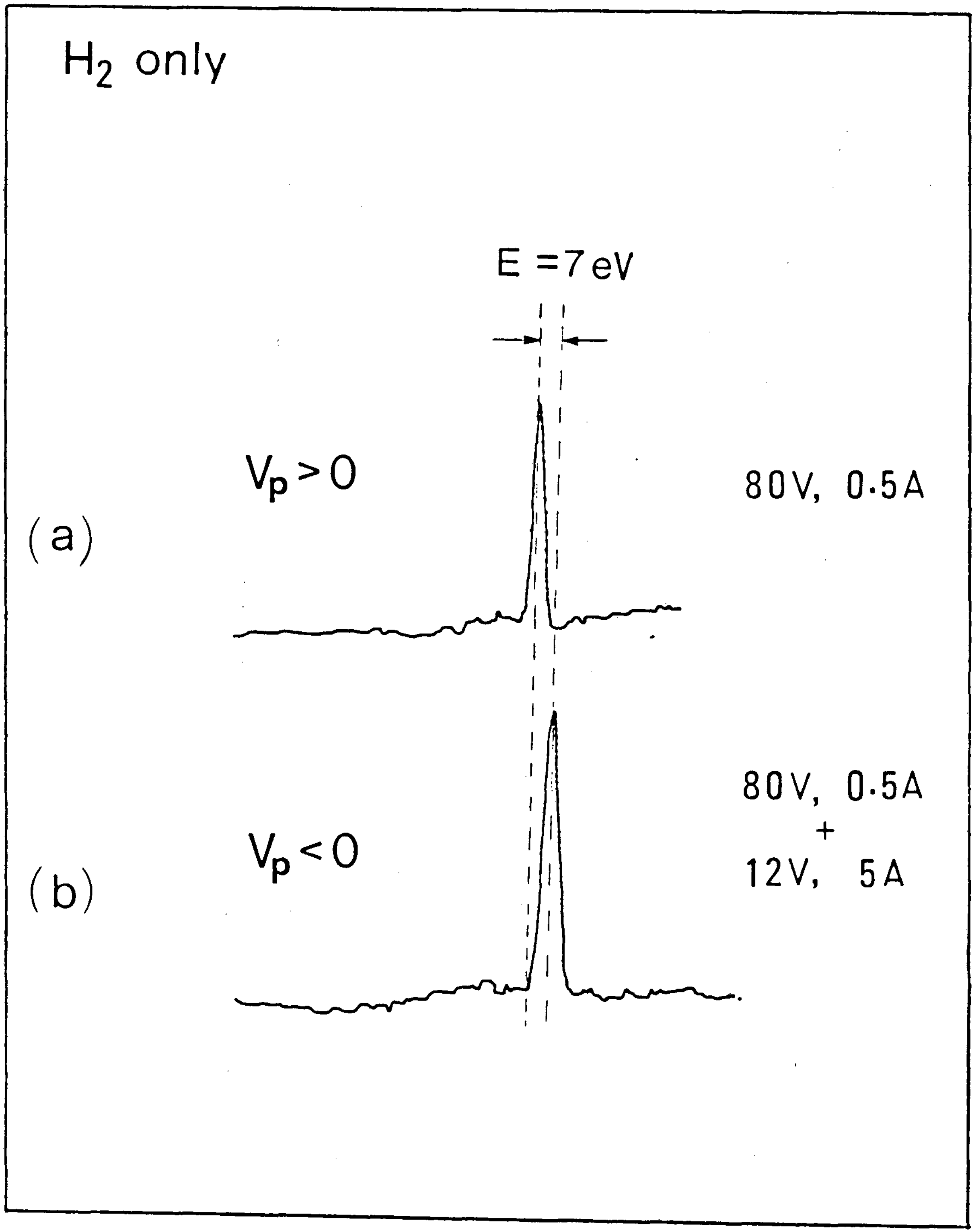

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Fig. 2

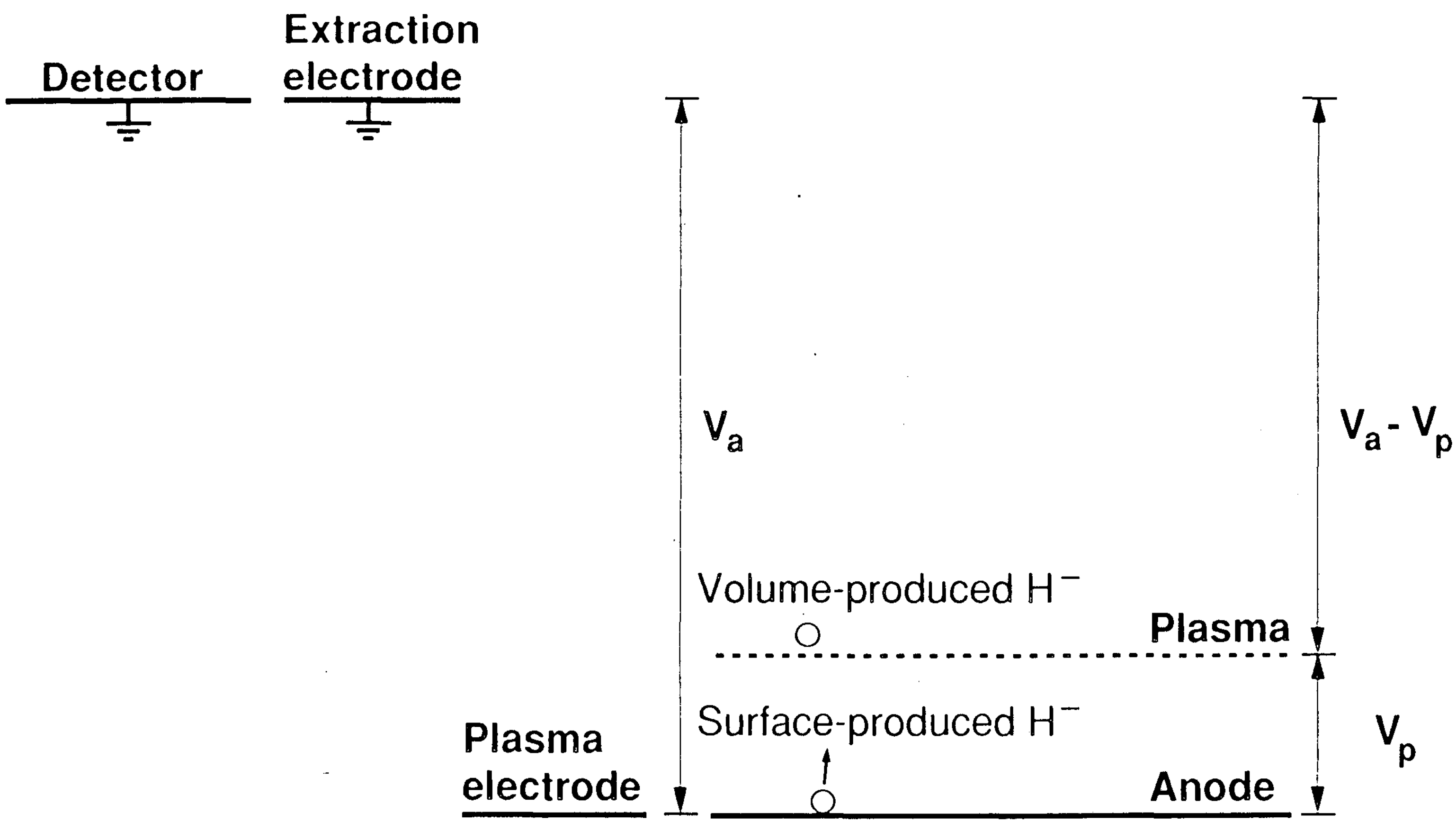

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Fig. 3

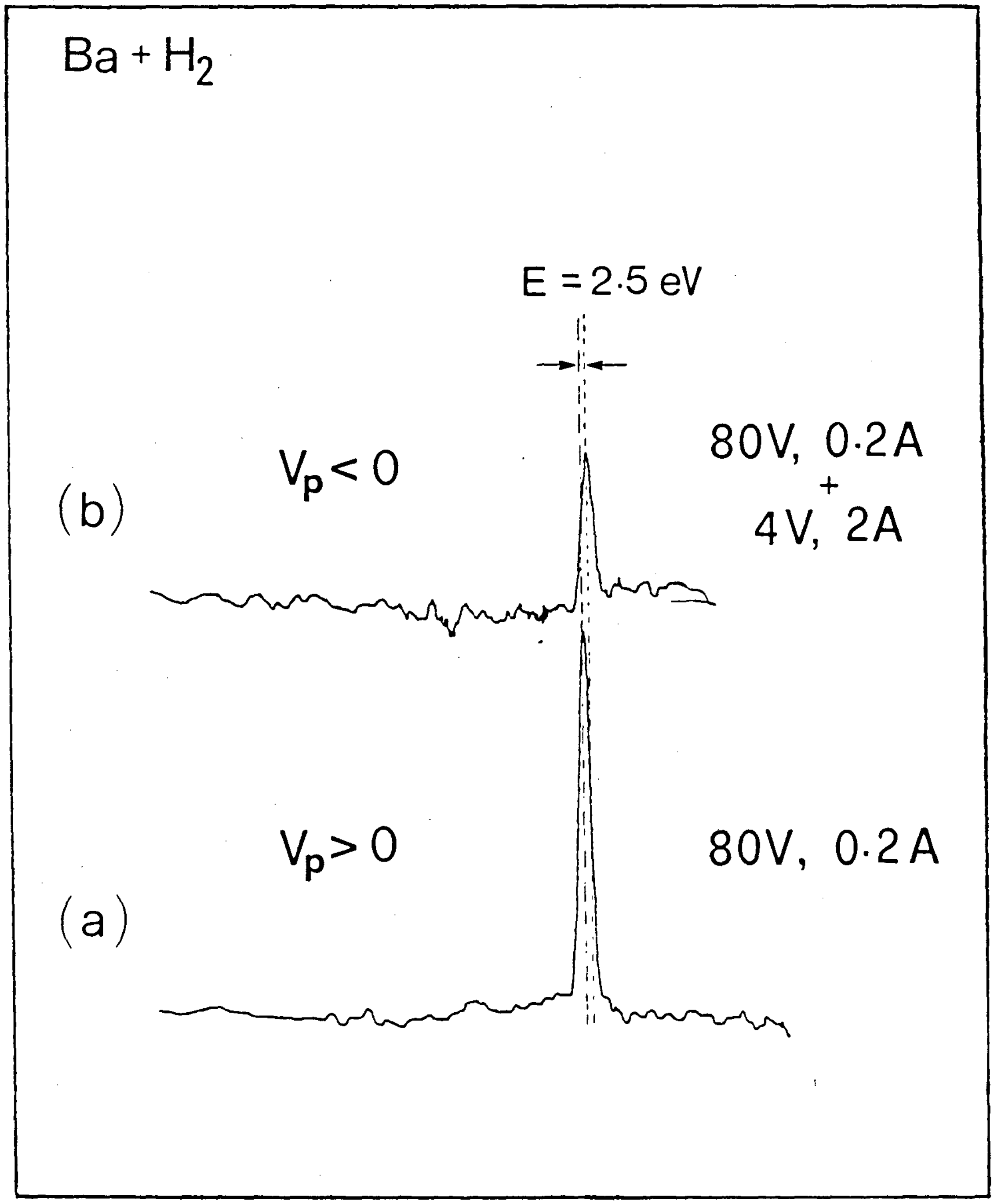

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Fig. 4

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