

PHYSICAL PROCESSES IN THE NEGATIVE ION SOURCE WITH REFLECTED DISCHARGE

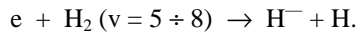
V.P.Goretskii, A.V.Ryabtsev, I.A.Soloshenko, A.F.Tarasenko, A.I.Tshedrin

Institute of Physics of NAS of Ukraine

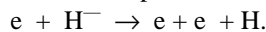
INTRODUCTION

In this article the results of experimental and theoretical investigations of the physical processes in the negative ion source with reflected discharge are represented. This source was developed at the Institute of Physics of NAS of Ukraine. It is naturally, that for optimal utilization of the source one should know the mechanisms of formation and destruction of negative ions, mechanisms of small admixture influence on emission characteristics of the source and space-time evaluation of source plasma in the direction of extracted slit. All these problems were studied in the present work in detail.

It was shown, that main mechanism of negative hydrogen ion formation is a dissociative attachment of electrons to oscillatory excited molecules H_2 :



The destruction of H^- ions is mainly determined by detachment under the influence of H^- ion collisions with hot electrons of plasma:



The rate of the last process drops dramatically with electron temperature decrease, this explains the presence of maximum for H^- concentration in the region between discharge column and anode, where electron temperature is low.

The problem with mechanism of small admixture influence of Cs on emission characteristics of H^- ion source was solved. It was shown that the increase of extracted H^- ion current with Cs vapor added, is not due to volume processes with Cs participation, but due

to conversion of H to H^- on the anode surface covered with cesium having low work function.

EXPERIMENTS

The scheme of the ions source under study is shown in Fig.1. Incandescent tungsten cathode 1 with a diameter of 2 mm serves as an electron source. Before anode chamber 3, aperture 2 is placed which limits the radial size of plasma column 6. Reflection of electrons providing gas ionization is realized by anticathode 7 with potential equal to that of the cathode. Gas feed is performed through the holes in anode 5 placed at the equal distance from each other. Magnetic field with the strength of up to 2 kOe is directed along the system axis. Extraction of ions is accomplished through the slit by field electrode 4. Diameter of the discharge chamber comprises 5 mm, diameter of the aperture comprises 2.5 mm. Exactly with this configuration, the maximum ion yield is observed in a range of $2 \cdot 10^{-2} \div 2 \cdot 10^{-1}$ Torr; discharge voltage – in a range of 100 ÷ 200 V; discharge current – in a range of 1 ÷ 10 A; extracting voltage – in a range of 8 ÷ 14 keV. For a thorough comparison of experimental and calculated results, measurements of the plasma parameters have been accomplished. Plasma density values, averaged along the plasma column radius, which have been obtained from measurements of the ions flux on the anticathode, grow up proportionally to the discharge current and reach 10^{14} cm^{-3} . (Temperature of electrons in the discharge column varied from 2 up to 6 eV accordingly at a pressure variation from $2 \cdot 10^{-1}$ up to $2 \cdot 10^{-2}$ Torr). Plasma parameters outside the column can be measured by a thin cylindrical probe introduced into plasma through the emission slit perpendicularly to the magnetic field direction. The plasma concentration on a rim is lower approximately by an order than that in a column, and the temperature of electrons at $p \approx 1 \cdot 10^{-1}$ Torr is about 1 eV. It is visible already from these data that the researched discharge is an analog of the known two-chamber systems developed for injectors of neutral particles. In this discharge, fast electrons create dense plasma and turn out oscillatory excited molecules H_2 . Outside a column, there are optimum conditions for H^- ion formation. In this case, the cooling of electrons is carried out during diffusion across a magnetic field.

Introduction of cesium was accomplished by sputtering of a dichromate cesium tablet 8 (see Fig.1) placed on the reflector 7. When the discharge was glowing with the tablet installed, its voltage fell down to 50 V, and current of negative ions, extracted from the source, decreased. After several hours of operation, the voltage returned back to a value typical of the pure hydrogen regime and the current of H^- ions rose dramatically. Subsequent measurements were performed in this regime.

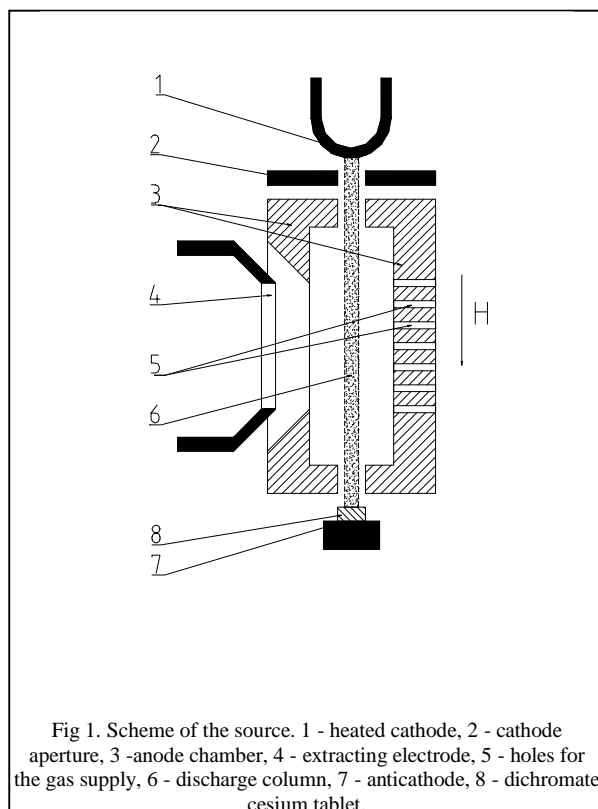


Fig 1. Scheme of the source. 1 - heated cathode, 2 - cathode aperture, 3 - anode chamber, 4 - extracting electrode, 5 - holes for the gas supply, 6 - discharge column, 7 - anticathode, 8 - dichromate cesium tablet.

NUMERIC SIMULATION

For determining the current density of H^- ions and calculating the concentrations of both charged ($n_e, N_{H^-}, N_{H_2^+}, N_{H^+}, N_{Cs^+}$) and neutral ($N_{H_2}, N_H, N_{H_2(v)}, N_{Cs}$) mixture components the system of kinetic equations [1] was solved together with the Boltzman equation [2, 3].

The plasma distribution along the discharge chamber and radius was supposed to be homogenous.

The spatial distribution of neutral components was assumed to be uniform, since their free run paths were comparable or more than the chamber radius under experimental conditions. The electron energy distribution function (EEDF) in the discharge column was determined from the Boltzman equation with the assumption of weak dependencies of the charged component concentrations on a radius. The last was proved by probe measurements. As it was shown in the previous proceedings [4-7], EEDF in the discharge column region possesses a flat plateau shaped dependence on the input beam energy ranging from ~ 100 eV down to ~ 20 eV, and has practically the Maxwellian shape at low energies ($T_e = 3-5$ eV). A high-energy part of EEDF was absent between the cathode and anode due to the strong magnetizing of electrons along a radius, and the electron temperature was essentially smaller than that in the column region ($T_e \leq 1$ eV). Due to this, EEDF was assumed to be practically the Maxwellian f_{0m} with radial dependent

temperature, which was determined from the equation of energy balance.

Mobilities and diffusion coefficients were calculated taking magnetizing into account. It was assumed that, in the whole discharge chamber, ions possessed the Maxwellian distribution. The principal mechanism determining the transfer coefficients at a pressure $p \sim 0.1$ Torr and the plasma concentration $n \sim 10^{13} - 10^{14} \text{ cm}^{-3}$ for electrons consisted in scattering on ions. It was assumed, like in [5], that the temperature of atomic hydrogen T_H and that of negative ions T_{H^-} were equal to $4 \cdot 10^3$ K.

While solving the system of kinetic equations and the Boltzman equation elementary processes listed in Table were taken into consideration.

RESULTS OF NUMERICAL SIMULATIONS AND COMPARISON WITH EXPERIMENTS

Fig.2 represent calculated radial distributions of charged components in the discharge chamber of the negative ion source scheme of which is shown on Fig.1. As one can see from Fig.2, the gradients of all component concentrations are negligible in the central part of the plasma column. The gradients increase by absolute value at the column boundary and in the drift part of the source. While the electron and positive ion concentrations are almost monotonically decrease with radius, the radius distribution of negative ion concentration has the pronounced non-monotone character. In addition, the concentration N_{H^-} in the maximum region is more then three orders high then N_{H^-} in the region of the plasma column. This important for experiments fact may be explained as follow. As it was mention above, the processes of H^- formation and destruction, determine the value of N_{H^-} in the column region, where the main mechanism of destruction is electron detachment in collisions of H^- with plasma fast electrons (see Table, reaction 17). The cross-section for this process has threshold character: σ_{-0} equals zero when electron energy $\varepsilon_{th} \leq 1.25$ eV and it reaches value of $\sigma_{-0} \approx 2 \cdot 10^{-15} \text{ cm}^2$ when electron energy $\varepsilon \approx 10$ eV. As the electron temperature beyond column decreases along a radius, the rate of the process slumps, which leads to increase of H^- concentration despite of some decrease of their formation. The same reason causes the presence of a maximum of negative ion current density j_{H^-} to the anode depending on the distance between the discharge column and the anode (see Fig.2) (the maximum

Table.

1	$H_2(v) + e \rightarrow H_2^+ + e + e, v = 0, \dots, 14$
2	$H + e \rightarrow H^+ + e + e$
3	$H_2 + e \rightarrow H + H + e$
4	$H + H (wall) \rightarrow H_2$
5	$H_2^+ + e \rightarrow H + H$
6	$H_2 + e \leftrightarrow H_2(v) + e, v = 1, 2, 3$
7	$H_2 + e \rightarrow H_2^*(B^1\Sigma_u^+, c^1\Pi_u) + e \rightarrow H_2(v) + e + \hbar\omega, v = 0, \dots, 14$
8	$H_2(v) + H \rightarrow H_2(v') + H$
9	$H_2(v) + wall \rightarrow H_2(v'), v = 1, \dots, 14, v' = 0, \dots, v$
10	$H_2(v) + e \rightarrow H^- + H, v = 1, \dots, 14$
11	$H + e \rightarrow H^-$
12	$H_2^+ + e \rightarrow H^- + H^+$
13	$H^- + H_2^+ \rightarrow H + H_2$
14	$H^- + H^+ \rightarrow H + H$
15	$H^- + H_2 \rightarrow H + H_2 + e$
16	$H^- + H \rightarrow H + H + e$
17	$H^- + e \rightarrow H + e + e$
18	$H_2^+ + e (wall) \rightarrow H_2$
19	$H^+ + e (wall) \rightarrow H$
20	$Cs + e \rightarrow Cs^+ + e$
21	$Cs^+ + Cs + M \rightarrow Cs_2^+ + M$
22	$Cs_2^+ + e \rightarrow Cs + Cs$
23	$Cs^+ + H^- \rightarrow Cs + H$
24	$Cs_2^+ + H^- \rightarrow Cs + Cs + H$
25	$Cs^+ + e (wall) \rightarrow Cs$
26	$H + e (wall) \rightarrow H^-$

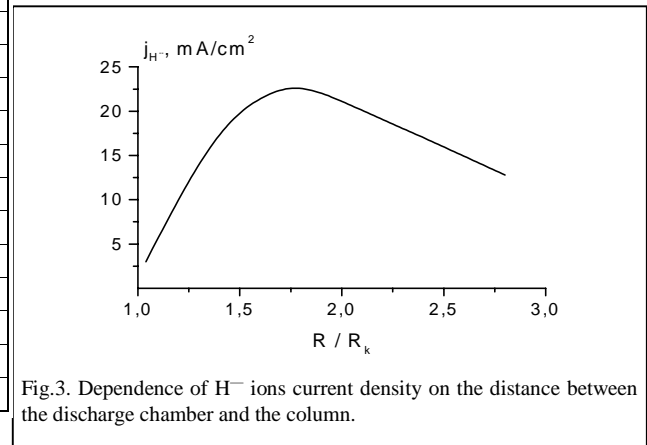


Fig.3. Dependence of H^- ions current density on the distance between the discharge chamber and the column.

disappear if the rate of the 17th process is artificially supposed to be constant along a radius). As one can see from Fig.4, for the discharge column radius $R_c = 0.125$ cm, an optimum reaches when $R/R_c = 1.8$. The optimal value of j_{H^-} for this case exceed that for $R/R_c = 1$ in 7.5 times. The results of experiments carried out with different diameters of the anode chamber are in good agreement with calculated results: the optimum is reached when $R/R_c \approx 2$; the optimal value of extracted current is approximately in 6 times higher than for $R = R_c$.

Fig.4 exhibits the dependence of the H^- ion current, extracted from the source, on pressure with the extracting voltage of 14 kV. One can see from the figure that the introduction of cesium results in significant changes of emission properties of the source. Principal changes are the following: 1) increase of the maximum value of H^- ions current density; 2) increase of a gas economy, especially at a low pressure (Fig.5); 3) influence of the cesium adding decreases with an increase of the slit width. Attention should be paid to changes in the mentioned dependencies: in the pure hydrogen regime, the optimal pressure value exists providing the best gas economy of the source ($p \approx 10^{-1}$ Torr), whereas the economy is inversely proportional to H_2 pressure in the regime with cesium added. The maximum achieved value of the gas economy comprises $\sim 2\%$, which exceeds the value in the pure hydrogen regime by one order of magnitude.

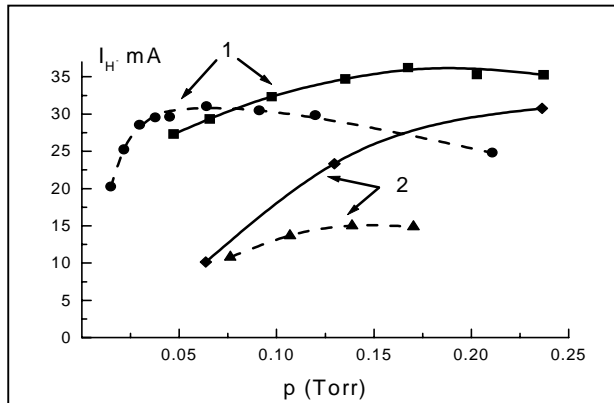


Fig.4. Dependence of extracted current of H^- ions on pressure in the source chamber at $U_0 = 14$ kV (1 - with Cs, 2 - without Cs, solid curve for emission slit 1.5×40 mm², dash curve - 0.7×40 mm²).

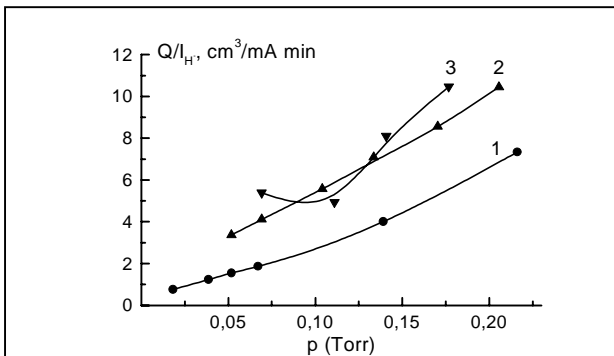


Fig.5. Dependence of a gas flow per the H^- ions extracted current on pressure. (1, 2 source with Cs for the emission slit of 0.7×40 and 1.5×40 mm², respectively; 3 - source without Cs, emission slit of 0.7×40 mm²)

It should be noted that even these experimental results point to the mostly surface character of the cesium influence. First and foremost, it is evident from the fact that, in the cesium regime, an increase of the slit width does not lead to a proportional rise of the extracted H^- current (see curves 1). While without cesium, the magnitude of the extracted current is always proportional to the slit width (see curves 2). Two more facts indicate the surface character of the effect: 1) cesium influence is most effective at a low gas pressure, when the role of volume processes is less important; 2) in the cesium regime, the current of extracted H^- ions depends more weakly on pressure, than in the case of pure hydrogen discharge.

Fig.6 shows the dependencies of the current density for hydrogen negative ions j_{H^-} at the anode on pressure for three cases: 1 - pure hydrogen discharge (considered processes are 1 - 19 in Table); 2 - cesium is present only in a volume of the discharge chamber (processes 1 - 25); 3 - cesium is present only at the surface (processes 1 - 19, 26). One can see from Fig. 4 (curve 2) that introducing Cs vapor into the discharge chamber volume, under the condition of an artificial maintaining of the discharge voltage, results only in an inessential increase of j_{H^-} at high pressure as compared to the case of the pure hydrogen regime (curve 1). The principal mechanism of the hydrogen negative ions formation in this case, as well as in the case of the pure hydrogen discharge, consists in the dissociate attachment of electrons to vibrationally excited hydrogen molecules (process 10). A weak increase of the negative ions current with addition of cesium is caused by the following reasons. Cesium performs both appropriate and inappropriate roles in volume processes. Due to low energies of electron excitation and ionization of Cs, the number of electrons with energy exceeding the Cs excitation energy is decreased. The electron temperature T_e ($T_e = -1/(d \ln f_0/d\epsilon)$) makes sense only for energy ≤ 20 eV) falls down in agreement with the experimental data. On the one hand, a decrease of the amount of fast electrons and the temperature of the electrons majority causes a decrease of the rate of formation of vibration-

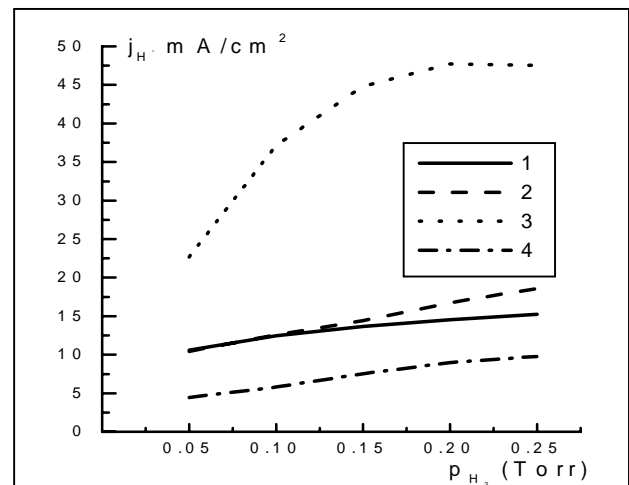


Fig.6. Calculated dependence of H^- ions current density on pressure. 1 - pure hydrogen discharge; 2,4 - discharge in mixture H_2/Cs , $N_{Cs} = 1.6 \cdot 10^{13}$ cm⁻³, processes 1-25 are considered; 3 - discharge in hydrogen with taking into account conversion H to H^- at cesium doped surface. Discharge voltage 120 V (1-3); 50 V (4).

ally excited molecules and, consequently, H^- ions. On the other hand, a decrease of T_e leads to lowering the rate of electrons detachment (process 17; cross section of this process depends on temperature) and, as well, to lowering the H_2 dissociation rate and, respectively, to a decrease of the atomic hydrogen concentration, which participates actively in taking off H_2 vibration excitation. The last two factors promote an increase of the H^- ions concentration. The mentioned appropriate and inappropriate effects resulting from the Cs introduction into discharge practically compensate each other (Fig.6). However, under the condition of an artificial maintaining of the discharge voltage at the same level, appropriate effects slightly overcome inappropriate ones. Decrease of a calculated value of the discharge voltage down to 50 V (which is practically observed in experiments with Cs introduced into the volume) leads to a diminishing of the H^- ions current. Thus, in accordance with the experiment, the theory shows that Cs in the volume cannot increase the current density of H^- ions extracted from the source.

On the contrary, considering the H to H^- conversion at the anode with adsorbed cesium leads to an increase of the H^- ions current (Fig.6, curve 3) and volume concentration of H^- by a factor of 2-4 even with the conversion coefficient $\gamma = 10^{-3}$. We shall not proceed with a detailed comparison now, but mention that this increase is in agreement with an increase of the H^- current observed experimentally (Fig.4). We also mention that, under conditions of experiments, no special care was taken for a checking or optimization of the Cs coating. However, as it was mentioned in [8], conversion coefficients under conditions of ion sources are usually in a range of 10^{-3} to 10^{-1} , depending on the hydrogen atom temperature and a degree of the surface coating by cesium. One can see from the calculation, that already at a rather low conversion coefficient, an essential increase of the negative ion yield at source surface is observed.

CONCLUSIONS

Based on the theoretical and experimental results obtained in the present work we may draw the following conclusions.

The optimal conditions for obtaining of the record value of the current density are realized in the stationer plasma source of negative hydrogen ions with reflected discharge. It was achieved at the expense of the source geometry, which assume two zones – a plasma column and a drift region where efficient cooling of plasma electrons is realized.

In the plasma sources, the limiting value for specific power which allow the maximum output of the H^- ions, is about 500 W/cm^3 .

The addition of cesium to initially plasma source of H^- ions may lead to a significant increase of the gas economy of the source and the current density. This effect is connected to the fact that the recharge of positive ions and fast atoms on the edge of the emission slit became the main mechanism for the H^- ions formation. That is, the cesium addition changes the plasma source to the surface-plasma source with the anode generation of ions.

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