Atomic Hydrogen Output from the Source Based on Low-Pressure Gas Discharge

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Abstract – Comparative investigations of atomic hydrogen (AH) output from a source in which various types of a direct current low-pressure gas discharges were initiated are executed. It is shown, that the arc discharge with the heated cathode is preferable to AH generation as it functions at low voltage and higher discharge currents that generate of pure and intensive AH flows. It is established, that for increase AH output from the source due to increase of atoms generation rate and reduction of their recombination rate at discharge cell walls, plasma with the maximal concentration should be created near of emission orifice. In the source functioning mode with the plasma jet effusing from the emission aperture in vacuum, additional AH generation that led to increasing atoms output was observed.

1. Introduction

The most effective way of molecular gases atomization and neutral atoms flow generation is the dissociation of molecules by electronic impact in gas discharge plasma. For AH generation usually use RF and microwave discharges sources, ECR microwave discharge, and also direct current discharges. The volume of special experimental investigations of AH generation in a direct current gas discharge plasma is limited. In work [1] it has been shown, that in hydrogen plasma of negative hydrogen ions arc-discharge source with a direct-heated cathode concentration AH grows with increase of discharge current. In works [2, 3] it is established, that not only concentration, but also AH output from AH source on the basis of low pressure arc-discharge with the self-heated cathode (SC) grows with increase of discharge current and depends on the gas flow rate, and also from a position and the area of the emission orifice. It is shown, that effect of a position and the area of the emission orifice on AH output is caused by high recombination coefficient of atoms on discharge cell walls therefore on cell volume a non-uniform distribution of AH concentration [3] is established.

Till now a question on optimum type of the direct current gas discharge, allowing to obtain maximal AH output, practically it is not investigated and remains opened.

The present work is devoted to definition of optimum direct current discharge type and definition of working mode of such discharge, providing an effective atomization of hydrogen molecules and maximal AH output from the source.

2. Results and discussion

It is known [2], that basic atoms generation channel in low-temperature hydrogen plasma is reaction of a dissociation of molecules by electron impact

$$e + H_2 \rightarrow H + H + e. \qquad (1)$$

In connection with a low degree of plasma ionization and as consequence, with low ions concentration H^{2+} and H^{3+}, reaction of AH generation by the dissociative recombination of molecular ions H^{2+} and H^{3+} are characterized considerably smaller rate and it is possible to neglect. Then frequency of H_2 dissociation is

$$Z_1 = n_e n_{H_2} \int_0^\infty \sigma(E) v f(E) dE, \qquad (2)$$

where n_e – electrons concentration in discharge, n_{H_2} – molecular hydrogen concentration in discharge, $\sigma(E)$ – effective section of molecular hydrogen dissociation, v – electrons speed, $f(E)$ – function of electrons distribution on energy, E – electrons energy.

According to (2), for increase AH concentration in plasma it is necessary to increase electrons concentration and to optimize their energy. Considering, that AH concentration growth in plasma leads to increase AH output from the source [2], definition of maximal AH output conditions from the source can consist in a choice of optimum voltage and discharge current, and, considering works data [3], probably, and in a choice of optimum spatial distribution of electrons concentration on a cell volume.

In experiments AH source described in work [4] was used. The discharge cell of the source has been modified that allowed to initiate in it various types of discharges, functioning at various voltage and currents, and also having various spatial distribution of plasma on a cell volume. In a cell it was ignited or glow reflective discharge with the hollow cathode (voltage 400–600 V, discharge current 0.1–1 A) or arc discharge with SC (voltage 300–75 A, discharge current 0.5–3 A). Spatial distribution of plasma on a cell volume was changed by means of control of plasma penetration depth in the hollow cathode.

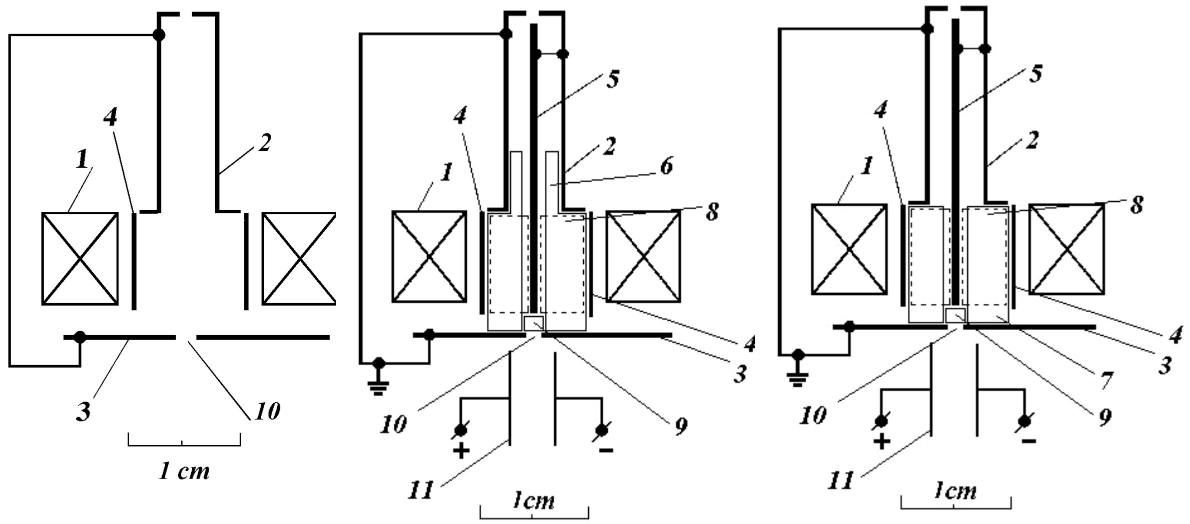

Fig. 1. The scheme of electrodes of a discharge cell of AH source with glow discharge (a) and with the combined arc discharge (b, c): 1 — permanent magnet, 2 — hollow cathode, 3 — cathode-reflector, 4 — anode, 5 — self-heated cathode, 6 — area of reflective discharge with the hollow cathode (continuous line), 7 — area of reflective discharge without the hollow cathode (continuous line), 8 — area magnetron discharge with the heated cathode (dashed line), 9 — area Penning discharge (continuous line), 10 — emission orifice, 11 — deflecting system

The discharge cell (Fig. 1) represented an axis-symmetric construction placed in a magnetic field of a permanent magnet 1. The hollow cathode 2, cathode-reflector 3 and the cylindrical anode 4 formed a cell of reflective glow discharge with the hollow cathode (Fig. 1, *a*) [5].

Electrodes 2, 3, 4 and the self-heated tungsten rod cathode 5 which are heating at switch on of discharge up to temperature thermionic emission, formed a cell of the combined arc discharge (Fig. 1, *b*) In the given configuration of a cell, discharges of three types simultaneously were initiated in it. The hollow cathode 2, the flat cathode-reflector 3 and the cylindrical anode 4 formed a cell of reflective discharge. At gas flow rate more ≅5 sccm plasma penetrate inside of the hollow cathode, and in a cell functioned the reflective discharge with the hollow cathode 6 (Fig. 1, *b*) [6]. At gas flow rate less ≅5 sccm plasma could not penetrate inside of the hollow cathode, and in a cell burned reflective discharge without the hollow cathode 7 (Fig. 1, *c*) [6]. The self-heated electrode 5 and the cylindrical anode 4 formed a cell magnetron discharge with the heated cathode 8. The flat end of SC 5, part of a surface of the flat cathode-reflector 3 and the cylindrical anode 4 formed a cell arc Penning discharge 9 functioning in the field of the emission aperture.

Modes of arc discharge with jet and without jet of the plasma effusing through the emission aperture 10 in vacuum have been investigated. Transition from the mode with plasma jet to mode without jet occurred at sharp reduction of plasma concentration near to the emission orifice which was realized at transition from the mode of discharge without the hollow cathode to the mode of discharge burning with the hollow cathode. In the first mode concentration of plasma near to the emission aperture was sufficient that the doubled thickness near-cathode layer $2h$ was less diameter of the emission orifice d, as a result plasma effusing through the emission aperture in vacuum.

Transition to the mode of discharge with the hollow cathode led to decreasing of plasma concentration near to the emission orifice, as a result $2h$ became more d and plasma did not get through the aperture. The plasma jet had length about 10–12 cm and thickness no more than 1 cm. In a number of experiments to minimize effect of the plasma jet on AH generation in a space of beam transportation of atoms the deflecting system 11 (DS) was used (Fig. 1, *b*, *c*). On DS electrodes applied bias 120 V which led to reduction of the plasma jet length up to 1 cm.

Purified hydrogen was introduce through the orifice in the hollow cathode 2. The continuous gas discharge was ignited in a cell at supply of electric power on it from the direct current stabilized source. Thus cathodes of a cell and the vacuum chamber have been earthed, and positive bias applied on the anode. Measurements of AH flow density in range $J=5\cdot10^{13}$–10^{16} at. $cm^{-2}s^{-1}$ were spent on the source axis by means of thin-film AH sensor specially developed by us [7]. Measurement of metal impurity concentration on Si samples surface before and after their exposition in AH flow was made by ToF SIMS.

In Table 1 results of comparative experiment on measurement of AH output from the source in which it was ignited or the glow reflective discharge with the hollow cathode or the combined arc discharge with the hollow cathode are presented. For equal discharges currents (0.8 A) AH output is more in case of the source in which the glow discharge was functioned. It testifies that higher voltage of glow discharge provided higher energy of electrons and as consequence, a lot of events of a dissociation made by one electron. In case of close powers of electric supplies (≅400 W) AH output is a little bit more in case of arc discharge. The lowered voltage (low energy of electrons), characteristic for arc discharge, were compensated by a greater discharge current (greater electrons concentration).

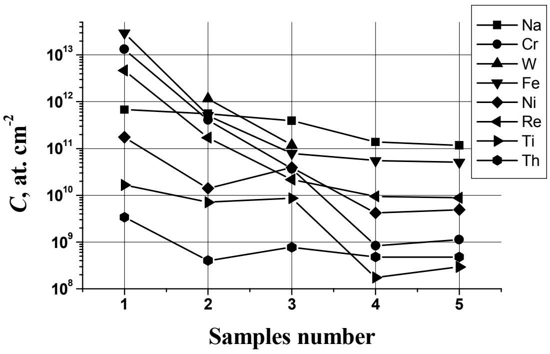

Fig. 2. Concentration of metal elements on Si samples surface before and after their exposition in AH flow; exposition time 10 min, voltage of arc discharge: sample № 1 – 230 V, sample № 2 – 180 V, sample № 3 – 120 V, sample № 4 – 75 V; sample № 5 – initial sample without an exposition in AH flow

Let's consider advantages and disadvantages of one discharge type in comparison with another. The disadvantages of glow discharge are restriction on the maximal discharge current and, hence, on maximal AH output at which the discharge burns without cathode spots. In case of a discharge cell used in experiments transition to discharge with a cathode spot occurs at currents more than 1.2–1.5 A. Occurrence of cathode spots increases pollution of AH flow by metal atoms of cathodes that prevents with practical use of such discharge mode. The arc discharge with SC is deprived this disadvantage, a current growth is limited only by temperature of material melt of SC. It speaks well for that arc discharge is more preferable for generation of intensive AH flows. Besides the arc discharge has low voltage which decreases with growth of a discharge current that was significantly reduces the maintenance of metal impurity in AH flow. In Fig. 2 dependence of metal atoms concentration on Si samples surface introduced on the surface during their exposition in AH flow, for a case of arc discharges functioning at various voltage is resulted. It is visible, that reduction of voltage of discharge leads to decrease in pollution of AH flow by metal impurity. Presence of such dependence testifies that the basic mechanism of AH flow pollution is ion sputtering of a cathodes material and that for reception of pure AH flow it is necessary to reduce voltage of discharge. Researches carried out by us have shown, that at voltage of discharge low 75 V a pollution degree of a flow by metal atoms becomes less than 10^{-6} % that is enough for practical use of such flow in technology of microelectronics [8].

All the further experiments were spent with the source in which various types of arc discharge were initiated. In Table 2 data on AH output from the source in which arc discharges with the hollow cathode or without the hollow cathode were ignited are presented. Thus in the second case experiment was spent with switched DS that minimized effect of the plasma jet on AH generation processes in space of atoms beam transportation. It is visible, that at equal power of electric supplies for arc discharge without the hollow cathode greater AH output, than in case of discharge with the hollow cathode is observed in 2.5 times. It is possible to explain higher AH output increase in plasma concentration, as on the average on cell volume, and near to the emission orifice which occurs owing to reduction of plasma volume. As a result, rate of AH generation increases on the one hand, and on the other hand the volume in which occurs AH generation, comes nearer to the emission orifice that reduces probability of atoms recombination on cell walls during their movement from a dissociative collision point to the emission orifice. In case of discharge without the hollow cathode it would be possible to explain higher AH output as well as effect of a DS electric field on AH generation processes in volume of a discharge cell. To be convinced of that action of this factor can be neglected, experiment has been executed in which the burning mode of arc discharge with the hollow cathode without a plasma jet was used. As the data resulted in Table 3 testify, effect of a DS field on AH output is not present and, hence, there is no its effect on AH generation in a discharge cell volume.

Table 1. AH output from the source in which discharges of various types were initiated

Parameter	Glow reflective discharge with the hollow cathode	Arc discharge with the hollow cathode	
I_p, A / U_p, V	0.8 / 560	0.8 / 195	2.4 / 160
AH output, at. cm^{-2} s^{-1}	$1.3 \cdot 10^{15}$	$0.74 \cdot 10^{15}$	$1.4 \cdot 10^{15}$

Table 2. AH output from a source in which arc discharges of various types were initiated

Parameter	Arc discharge with the hollow cathode	Arc discharge without the hollow cathode, DS switch on
I_p, A / U_p, V	2 / 190	2.4 / 160
AH output, at. cm^{-2} s^{-1}	$1.6 \cdot 10^{15}$	$4 \cdot 10^{15}$

In Table 4 are presented data on AH output from the source in which at equal currents arc discharges with hollow and without hollow cathode function, but voltage on DS did not apply. It led to that in case of discharge without hollow cathode the mode of discharge with a plasma jet effusing in vacuum was realized. At a current of discharge 2.4 A simultaneous action of two factors (reduction of plasma volume and existence of a plasma jet) leads to increase in AH output in 6 times. It in 2.4 times is more, than in case when effect of a jet was minimized by switching of DS. It is obvious, that the increase in AH output is connected with an additional dissociation of molecules in a jet which occurs under action of oscillating electrons in it.

Table 3. AH output from a source depending on the voltage applied or not applied on DS

Parameter	Arc discharge with the hollow cathode	
	DS switch on	DS switch off
I_p, A / U_p, V	2.4 / 160	2.4 / 163
AH output, at. cm^{-2} s^{-1}	$1.5 \cdot 10^{15}$	$1.5 \cdot 10^{15}$

Table 4. AH output from a source in which arc discharges of various types were initiated.

Parameter	Arc discharge without the hollow cathode		Arc discharge with the hollow cathode	
I_p, A / U_p, V	0.8 / 300	2.4 / 180	0.8 / 195	2.4 / 160
AH output, at. cm^{-2} s^{-1}	$1.8 \cdot 10^{15}$	$8.1 \cdot 10^{15}$	$0.75 \cdot 10^{15}$	$1.4 \cdot 10^{15}$

3. Conclusion

Thus, the arc form of discharge is preferable to AH generation in plasma of a direct current discharge that is connected with an opportunity of production of more intensive and pure AH flows. For increase in AH output from the source the maximal plasma density should be realized in the field of the emission orifice. For increase in a dissociation degree of a flow it is possible to use AH generation in a plasma jet effusing from the emission orifice in vacuum.

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