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BEHAVIOR OF AXIAL ELECTRON DISTRIBUTION FUNCTION DEPENDING ON THE DIMENSION OF THE PENNING CELL WITH METAL HYDRIDE CATHODES

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The behavior of axial electron distribution function is experimentally studied at different anode radius in the hydrogen plasma of Penning discharge in case of single or double metal hydride cathodes using. A significant decrease in axial electron energy was discovered at a larger anode radius and at the double metal hydride cathodes using. The influence of changes in the energy of oscillating electrons on the efficiency of negative ions formation has been considered.

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INTRODUCTION

The introduction of metal hydride cathode in Penning ion source causes a number of interesting phenomena [1, 4, 5]. This is mainly due to the ability of metal hydride material to uptake hydrogen in chemically bound atomic state and to release it at ion flow impact from plasma. The desorption process is nonequilibrium and entails to the formation of vibrationally excited H_2* molecules, which have the ionization potential on 0.5 eV lower and ionization cross-section in 1.5 times higher than molecular hydrogen fed from balloon [1]. So, the efficiency of positive and negative hydrogen ions formation substantially increases. Positive ions generated basically in the anode layer of negative space charge, where the vast majority of supplied potential drops. The cathode layers are still present, but with low voltage drop. So, the plasma of a Penning discharge forms two regions: the central field-free plasma region, containing electrons oscillating between the cathodes, and the anode layer region between the field-free plasma column and the inner cylindrical anode of the source [2].

When the discharge operates at low pressure and high magnetic field, the current of oscillating electrons predominates in the central region of the cathodes [3]. These electrons are heated ($\varepsilon \approx 100$ eV) by the instability in the anode layer and overcome the cathode potential barrier. In case of metal hydride cathode using the additional reduction in cathode potential barrier was observed, that facilitates the axial extraction of negatively charged particles including negative ions [4].

Negative ions are formed in the volume of central field-free plasma due to the dissociative attachment of slow electrons to pre-excited hydrogen molecules H_2* released from the cathode. The efficiency of H^- ions formation by the mechanism of dissociative attachment depends on the high level of the vibrational excitation of hydrogen molecules (for the reduction of the cross section of the process) and low electron energy (for efficient dissociative attachment). Obviously, H^- ions efficiently generated near the surface of metal hydride cathodes, where the above conditions are satisfied [5]. Therefore, the energy of oscillating axial electrons plays an important role in the processes of H^- ions formation.

The goal of this work is to investigate the behavior of axial electron energy distribution function depending on dimensions of used Penning cell.

1. EXPERIMENTAL SETUP

The experimental investigations were carried out in discharge cell of penning configuration set in longitudinal magnetic field (Fig. 1). The electrode system was fixed inside the quartz cylinder. Two different cells were used in experiments. The first one consists the cylindrical anode (1) 4 cm in diameter and 1 cm in length. The second one has an anode 5.6 cm in diameter and 3 cm in length. The anode was installed on the center position between the cathodes of 12 mm.

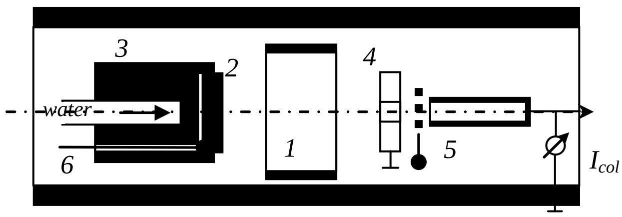

Fig. 1. The scheme of discharge cell: 1 – anode; 2 – metal hydride cathode; 3 – cathode-holder; 4 – cathode-reflector; 5 – energy analyzer; 6 – thermocouple

Metal hydride cathodes (2) and (4) were the same and were a disks 2 cm in diameter and 0.5 cm in thick. It was pressed from powder mixture of saturated with hydrogen $Zr_{50}V_{50}H_x$ alloy and copper stuff. The initial saturation of material with hydrogen was about 860 cm^3 at normal conditions.

For pressure stabilization during the discharge burning the metal hydride cathode was placed in water-cooled copper cathode-holder (3). Temperature stabilization of metal hydride at a level which is lower than the temperature of the thermal destruction of hydride phases ensures activated hydrogen H_2* desorbtion mainly by ion-stimulated processes from the surface of metal hydride locally to the near-cathode region.

Due the predomination of the current of oscillating electrons in the central region of the cathodes it was possible to measure their energy distribution by an electrostatic energy-analyzer (5), which was set behind the central aperture in the cathode.

In check experiments metal hydride cathode (4) was changed with copper one of the same form and dimensions. The investigations were caried out at residual pressure, which do not exceed 3×10^{-6} Torr. During the discharge burning, the pressure increased to $5\cdot10^{-6}$ Torr due to hydrogen releasing from metal hydride.

2. RESULTS AND DISCUSSION

The design features of the Penning cell implies that the distribution of spatial potential for electrons in the axial direction has the form of a potential well [2], where the electrons oscillate between reflective electrodes (cathodes) in an axially symmetric magnetic field. In the radial direction, the retention of electrons in the Penning trap is ensured by a magnetic field. For these reasons, their extraction is difficult both in the longitudinal and transverse directions to the magnetic field lines. In the first case, extraction through the cathode aperture is limited by the cathode potential drop, and in the second case, by the presence of a transverse magnetic field. However, due to the predomination of electron current on the central region of the cathodes at low pressure and high magnetic field, and despite the cathode potential drop, an electron current could be registered behind the cathode, if the cathode has an aperture [3].

The formation of negative ions in the hydrogen plasma occurs mainly as a result of the reaction of dissociative attachment of low-energy electrons with an energy of about 1…2 eV to the hydrogen molecules, excited on a high vibrational level ($v > 5$) [6]. Therefore, for the efficient generation of negative hydrogen ions in a volume source, it is necessary to have a system for the formation of low-energy electrons.

In addition, in order to increase the probability of the process of capturing low-energy electrons by vibrationally excited molecules and, as a consequence, increase the current efficiency of the negative ion source, it is necessary to increase the time that low-energy electrons are retained in the interaction region. In case of a Penning cell, such a region is the cathode region, where the oscillating axial electrons have a minimum energy due to the rotation of their trajectories.

The falling of electrons to the cathodes in a Penning discharge occurs, as a rule, from the region which is adjacent to the anode layer. This region is characterized by a minimum (down to zero) value of the space potential and usually formed at high discharge voltage and magnetic field. Usually, it also depends on the cell dimension and the gas plasma formed on.

The distribution functions of axial electrons in the cell for different anode diameters and in the presence of one or two metal hydride cathodes are shown in Fig. 2.

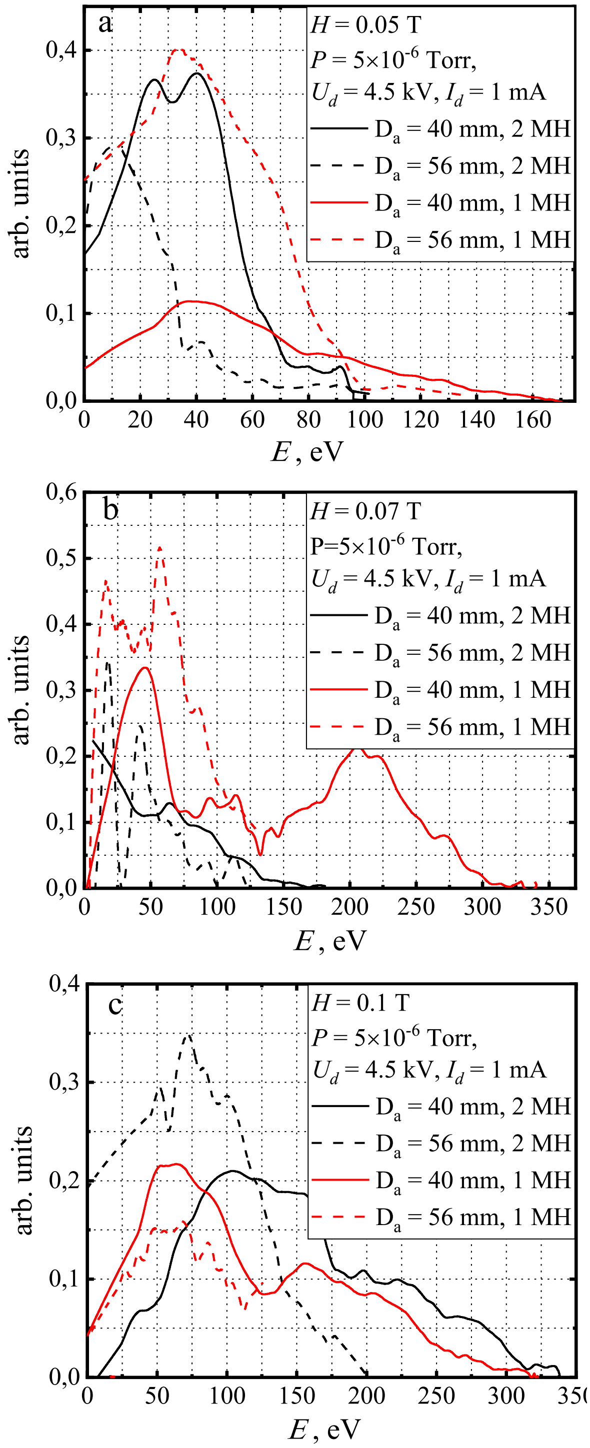

Fig. 2. The energy distribution function of axial electrons at different magnetic fields and the anode radius

At weak magnetic fields, the area of the anode layer of negative space charge occupies almost all the space inside the anode [2]. At the same time, the electrons oscillating along the axis move in a narrow area limited by the anode layer and the spread of their energy is not so large (see Fig. 2,a). On the contrary, at strong magnetic fields the anode layer is thin, the area of movement of oscillating electrons expands, and the spread of their energy increases (see Fig. 2,c). The instability of the anode layer, in which electrons acquire additional energy, also plays an important role.

It can explain the presence of several less pronounced subgroups of electrons in addition to the main group of the highest intensity. It is more noticeable at high magnetic fields, when the amplitude of oscillations is large [7].

In this mode, regardless of the cathode material, intensive high-frequency drift oscillations are always observed in the frequency range from 40 to 100 MHz. The frequency of drift oscillations is inversely proportional to the magnetic field strength and linearly depends on the anode voltage. The azimuthal mode of these oscillations is usually equal to $m = 1$. The perturbation of the potential and density caused by the rotational oscillations which propagates in the azimuthal direction toward the drift of the electron component in crossed E×H-fields [7].

When using a metal hydride cathode, the oscillation frequency increases abruptly when the discharge switches to the axial electron output mode [4]. The jump of the frequency of drift oscillations can be explained by a decrease of the potential in the central region of the discharge. From the relationship for the frequency ν of drift oscillations (1)

$$\nu = nc\frac{V_a - V_o}{\pi H R_a^2}, \quad n = 1, 2, ..., \tag{1}$$

it follows, that a fall of the potential V_o in the center of the discharge cell leads to an increase in the radial electric field in the region of the anode layer and, as a consequence, to an increase of the frequency of drift oscillations. Here V_a is the anode voltage; V_o is the potential of the cell center; H is the magnetic field strength; R_a is the anode radius, c is the light speed.

Another feature is that the electron beam current is modulated by similar oscillations with a modulation depth of up to 80%. With the increase of the anode voltage, the amplitude of the oscillations rises as well.

The anode diameter, as well as the use of one or two metal hydride cathodes, do not significantly impacted the most probable energy of oscillating electrons at all other things being equal. But it is worth noting the narrowing of the electron distribution function in case of two metal hydride cathodes using, which is observed in the all studied range of magnetic fields. In case of weak magnetic fields, a noticeable decrease of the electron energy is noted as well.

The presence of a hydrogen-saturated metal hydride cathode plays a decisive role here. Ions which are primarily generated in the anode layer fall on the cathode at different angles and facilitate the desorption of hydrogen into the near-cathode region. A local increase of the pressure occurs self-consistently [8]. The desorption rate (local pressure) is determined by the ion flux to the surface and is set in such a way, as to ensure the required plasma density [9].

Then, the decline of electron energy along the increase of pressure can be explained by the fact, that the escape of electrons to the anode is facilitated due to collisions with the gas molecules under pressure increasing. The original ions move toward the axis and help to neutralize the negative space charge, which leads to the decrease of the spread of electron energy. As can be seen, this effect is more pronounced when using two metal hydride cathodes, and when hydrogen desorption into the cell occurs from both sides simultaneously.

Additional reduction in cathode potential barrier (1) makes it even easier the axial extraction of negatively charged particles including negative ions [4].

This can be explained as follows. High-energy electrons that move and gain additional energy in the direction of the aperture in the cathode-reflector have an energy of approximately from 100 to 200 eV depending on the magnetic field. The second group is formed from the reflected electrons. These electrons gain additional energy in the direction from the cathode-reflector with an aperture. They are reflected from the potential drop near the metal hydride cathode and exit through the aperture passing through the discharge cell again. The energy of the group of reflected electrons is approximately 10 - 50 eV depending on the magnetic field and is determined by the value of the potential barrier.

While the emission of a high-energy group of electrons has a periodic character, then during the emission the electron density in the cathode region falls due to the outflow of the high-energy component, and the cathode potential decreases. As a result, a current of electrons with lower energies is recorded.

Thus, the decrease in the value of the potential barrier, which occurs due to the pulsed output of the fast electrons and a local increase of pressure during hydrogen desorption ensures the unimpeded outflow of negative ions in the axial direction.

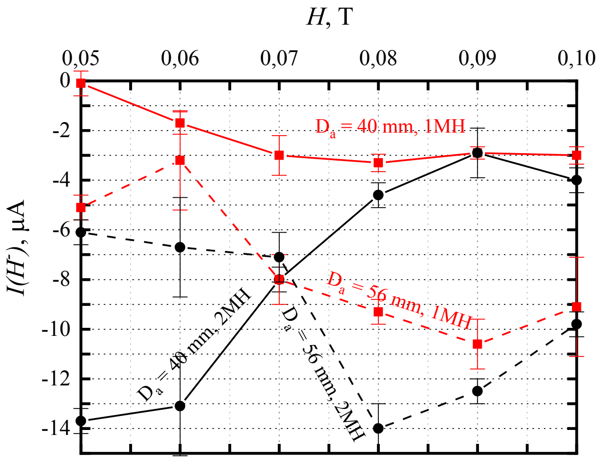

Fig. 3. The current of H^- ions depending on the magnetic fields at different anode radius, at $P = 5 \cdot 10^{-6}$ Torr, $U_d = 4.5$ kV, $I_d \approx 1$ mA

Fig. 3 shows the dependence of the negative ion current on the magnetic field for different anode diameters and the use of one or two metal hydride cathodes. In this case instead of collector (5) in Fig. 1 the electromagnetic filter was installed for H^- ions separation from outgoing flux of charged particles [5].

Although the formation and yield of negative ions depends on many processes in the Penning discharge, a general trend can be traced. The greater the spread in electron energies, the lower the H^- ion current. An increase of the anode diameter leads to a narrowing of the electron distribution function with a cutoff of the proportion of high-energy particles. Accordingly, the contribution of the processes of de-excitation of hydrogen molecules and the destruction of negative ions decreases, and the negative ion current becomes higher.

CONCLUSIONS

Thus, the presence of a hydrogen-saturated metal hydride cathode plays a decisive role in the formation of electron energy distribution function and in the generation of negative ions. The decrease in the value of the potential barrier, which occurs due to the pulsed output of the fast electrons and a local increase of pressure during hydrogen desorption ensures the unimpeded outflow of negative ions in the axial direction. The greater the spread in electron energies, the lower the H^- ion current. The increase of the anode diameter leads to a narrowing of the electron distribution function with a cutoff of the proportion of high-energy particles, and the negative ion current becomes higher.

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ПОВЕДІНКА ФУНКЦІЇ РОЗПОДІЛУ ОСЬОВИХ ЕЛЕКТРОНІВ ЗАЛЕЖНО ВІД РОЗМІРУ КОМІРКИ ПЕННІНГА З МЕТАЛОГІДРИДНИМИ КАТОДАМИ

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Експериментально досліджено поведінку функції розподілу аксіальних електронів при різному радіусі анода у водневій плазмі пеннінгівського розряду при використанні одного або двох металогідридних катодів. Було виявлено значне зменшення аксіальної енергії електронів при більшому радіусі анода та використанні двох металогідридних катодів. Розглянуто вплив зміни енергії коливальних електронів на ефективність утворення негативних іонів.