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FORMATION AND EXTRACTION OF H⁻ IONS FROM PENNING DISCHARGE WITH METAL HYDRIDE CATHODES IN LMF AND HMF MODES

Ihor Sereda[1]*, Yaroslav Hrechko[1], Kostyantyn Sereda[1], Oleh Vorobiov[2]
[1]V.N. Karazin Kharkiv National University, Kurchatov av. 31, 61108, Kharkiv, Ukraine
[2]Ivan Kozhedub Kharkiv National Air Force University, Kharkiv, Ukraine
**Corresponding author email: igorsereda@karazin.ua*
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The use of metal hydride cathodes in Penning discharges offers a promising approach to the efficient production of negative hydrogen ions under low- and ultralow-pressure conditions. In this work, we summarize and extend our experimental studies on the influence of metal hydride elements on the characteristics of Penning discharge with axial extraction of negative ions. At low residual pressure, the introduction of metal hydride cathodes enables plasma generation exclusively from hydrogen released by the cathode material, without any external gas injection. This feature opens the way to the development of compact, gas-feed-free ion sources with excellent gas utilization. The negative ions extraction mechanism is shown to depend strongly on the operating mode of the Penning discharge, determined by the magnetic field strength. In the low magnetic field mode, the expansion of the anode layer toward the discharge axis and the associated negative space charge suppresses efficient extraction, limiting it mainly to paraxial ions and those formed near the extraction aperture. In contrast, in the high magnetic field mode, the anode layer becomes thin, and the central plasma region is essentially field-free, enabling the extraction of negative ions from the entire discharge cross-section. Furthermore, the effect of increasing the anode diameter is investigated. Enlarging the anode diameter increases the plasma volume surrounding the metal hydride cathodes, leading to improved plasma uniformity, more homogeneous cathode heating, and a more uniform hydrogen release. These effects enhance the conditions for negative ions formation and result in a higher extracted current. The results demonstrate the feasibility and advantages of metal-hydride-based Penning ion sources for efficient production of negative ions under low-pressure operation.
Keywords: *Negative ions; Hydrogen; Penning discharge; Metal hydride; Volume source*
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Recent progress in high-energy hydrogen neutral beam technology has intensified interest in negative-ion sources, since efficient neutralization at energies above ~60 keV per nucleon is only feasible for H^- beams [1]. Negative ions can be produced either in plasma volume via dissociative attachment to rovibrationally excited $H_2(v)$ molecules or on low-work-function cesiated surfaces [2]. Although cesium greatly enhances H^- yield, its leakage degrades high-voltage insulation and limits long-term reliability, motivating the search for cesium-free alternatives [3].

Efforts to reduce cesium consumption have included the development of specialized cartridges based on Cs_2CrO_4 alloy combined with an St101 getter [4]. Although this approach improves source stability and operational reliability, it does not resolve the fundamental issue of identifying alternative materials that can deliver negative-ion yields comparable to those of cesium-coated surfaces. Subsequent experimental studies have demonstrated that tantalum surfaces in hydrogen plasma can enhance H^- production through the formation of highly rovibrationally excited $H_2(v)$ molecules generated by recombinative desorption [5]. Alkali-metal-based surface coatings have also been shown to increase negative-ion emission; however, their practical application is limited by high chemical reactivity and rapid sputtering under plasma exposure [6]. As a result, current research has increasingly focused on inorganic compounds and metal alloys as more robust candidates. In particular, LaB_6 cathodes have exhibited promising performance in cesium-free Penning discharges, indicating that suitable alternative materials may ultimately replace cesium in negative ion sources [7].

Among the most promising candidates for volume negative ion sources are stable hydrides formed from ZrV getter alloys, similar to St707, which are well known for their extremely low equilibrium hydrogen pressures, fast sorption–desorption kinetics, and pronounced thermal effects [8]. Ion bombardment of such hydrides induces the controllable release of rovibrationally excited $H_2(v)$ molecules into the plasma providing a substantial enhancement of volume H^- production. This concept opens the possibility of developing a compact, gas-feed-free ion source that operates at very low pressure and achieves high gas efficiency. It has recently been demonstrated that ZrV-based metal hydrides offer a significant advantage for H^- ion production, since hydrogen molecules are released from the hydride surface in a vibrationally excited state [9].

The extraction of negative ions is typically performed perpendicular to the magnetic field through the anode slit [2], but using high discharge voltages significantly simplifies the source design by modifying the discharge behavior [10]. Particularly, a flux of negative particles (ions and electrons), together with positive ions, is yielding along the magnetic field [17]. Therefore, replacing the cathode with a metal-hydride cathode and reversing the extraction electrode polarity can convert a conventional positive-ion source into a gas-feed-free negative-ion source.

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In this paper, we summarize our previous results on the impact of metal hydrides on the properties of a Penning discharge with axial extraction of H^- ions, and extend the analysis to different anode diameters. This approach is used to demonstrate the possibility of increasing the negative-ion current by enlarging the plasma volume in which the metal-hydride cathodes are immersed.

EXPERIMENTAL SETUP

The experiments were performed in a Penning-type discharge cell comprising two opposing flat cathodes (1 and 5) and a tubular anode (4) placed in an external longitudinal magnetic field of up to 0.1 T (Fig. 1). Discharge operation was achieved by applying a positive potential to the anode. The cathode (1) could be electrically biased up to −400 V, while the opposite cathode (5) was maintained at ground potential.

To increase the plasma-filled volume, the anode of 37 mm in diameter and 12 mm in length could be replaced by an enlarged anode with a diameter of 56 mm and a length of 30 mm. In both configurations, the cathodes were disk-shaped electrodes 20 mm in diameter and 5 mm thick, mounted coaxially at a distance of 15 mm from the respective anode ends.

Two cathode configurations were used: single metal hydride cathode (1MH) with cathode (1) made of metal hydride and cathode (5) made of copper and double metal hydride cathodes (2MH), with both cathodes made of metal hydride.

The cathode material captures and retains a large amount of hydrogen due to its multiphase structure, which includes tetragonal ε-ZrH_2 and the C15-type ZrV_2H_x intermetallic Laves phase with the metal type of hydrogen bond [8]. This intermetallic phase absorbs hydrogen efficiently already at room temperature and pressures of about 0.1 MPa, with a sorption rate that is 2 – 3 orders of magnitude higher than that of pure zirconium. In contrast, the formation of zirconium hydride ZrH_2 in pure zirconium requires temperatures of about 500 K and high pressures of 7 – 10 MPa. The intermetallic phase promotes rapid hydrogen uptake and diffusion, so that even zirconium becomes effectively hydrogenated at room temperature. As a result, a mixture of hydrides is formed, where both phases are highly saturated with hydrogen. Additionally, zirconium hydride has an extremely low equilibrium dissociation pressure (about 1.5×10^{-9} Pa at 500 K), which ensures strong hydrogen retention within the lattice, enabling operation under high-vacuum conditions.

Since the process of the alloy uptake with hydrogen is accompanied by the crystal lattice destruction, the obtained hydride powder was mixed with a copper binder and then pressed into a disk 2 cm in diameter with a thickness of 0.5 cm. Each cathode absorbed approximately 870 cm³ of hydrogen at atmospheric pressure and room temperature.

The main advantage of a metal hydride cathode is its ability to absorb hydrogen isotopes and release them into the plasma at low pressure via controlled thermal decomposition of the hydride phases. To avoid uncontrolled desorption and pressure spikes, the cathode temperature was monitored with thermocouples and maintained below 80 °C, well below the hydride decomposition threshold [8]. Under these conditions, hydrogen is released exclusively through ion-stimulated processes. Rovibrationally excited $H_2(v)$ molecules form by surface recombination of hydrogen atoms and are then converted to H^- via dissociative electron attachment, providing an energy-efficient, surface-driven pathway for enhanced negative-ion production.

The experiments were conducted at a residual pressure of 0.2 mPa in the vacuum chamber pumped by a diffusion pump, which went to approximately 0.6 mPa during discharge operation due to hydrogen release from the cathodes. Notably, no external gas injection was used under these conditions. The residual gas composition was not controlled in our experiment; however, it is assumed to be typical for such conditions, consisting mainly of N_2, CH-containing species, and water vapor. The partial pressures of molecular and atomic hydrogen under similar conditions of metal hydride application were measured in [9], and it was shown that the gases incapable of forming stable negative ions results in very low extracted negative currents, primarily composed of co-extracted electrons.

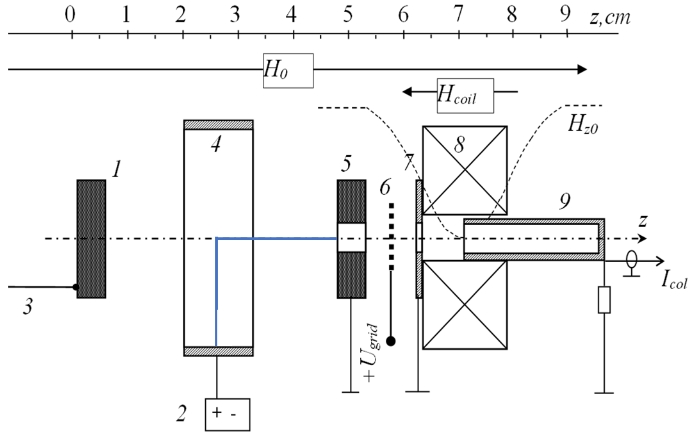

Figure 1. The scheme of the experiment.
1 – metal hydride cathode, 2 – power unit, 3 – thermocouple, 4 – anode, 5 – metal hydride/copper cathode with an aperture, 6 – reflecting grid $U_{grid} = +1.6$ kV, 7 – electrons collector, 8 – filter magnetic coil, 9 – H^- ion collector, H_0 – main axial Penning magnetic field ($H_0 = 0 - 0.1$ T), H_{coil} – reverse magnetic field of the filter.

During Penning discharge operation in high-voltage mode axial electrons oscillate between the cathode layers and could fall in the central region of the cathodes, which allows for the axial output of negatively charged particles including negative ions [10]. To suppress electrons and positive ions in the extracted axial beam, an electromagnetic filter was used. It was positioned behind the cathode (5) with the central aperture of 5 mm in diameter and consisted of a grid (6) for retarding positive ions, a magnetic coil (8) for deflecting electrons, an electron collector (7) for the diverted electrons, and a collector (9) for the extracted axial H^- ion beam. The required parameters for the filter operation were determined through numerical analysis of electron and H^- ion trajectories [11].

RESULTS AND DISCUSSION

The operation of volume sources of negative hydrogen ions relies on the interaction between low-energy (thermal) electrons and rovibrationally excited hydrogen molecules $H_2(v)$. In this process, an electron is temporarily captured, forming a short-lived resonant compound state H_2^-. The decay of this state can proceed through dissociative electron attachment, resulting in the production of a negative hydrogen ion (H^-) and a neutral hydrogen atom:

$$H_2(v) + e \rightarrow H_2^- \rightarrow H^- + H. \tag{1}$$

The intensity of resulted H^- ion beam is determined primarily by the concentration of rovibrationally excited $H_2(v)$ molecules, which generated in plasma by energetic electron impact with neutral hydrogen. In case of using a preliminary hydrogenated metal hydride, rovibrational excitation of hydrogen molecules are ensured by recombination of H-atoms at the metallic surface, which then can be converted to H^- ion by dissociative electron attachment. So, the challenge is to increase the concentration of rovibrationally excited $H_2(v)$ molecules keeping the working pressure below 0.3 Pa to eliminate the negative ion losses due to collisional destruction [16].

The concept of the source relies on a specific feature of Penning discharge operated at low pressure and high voltage. The electron current dominates in the central cathode region, enabling axial extraction of negatively charged particles, including negative ions. In contrast to the Ellers-type ion source operating in a high-current mode, H^- ions in this Penning discharge are generated in the central field-free plasma region via dissociative attachment of low-energy electrons (2 – 4 eV) to vibrationally excited hydrogen molecules $H_2(v)$, released from the metal hydride cathode. The produced negative ions then drift axially through the field-free plasma, confined by the anode layer, and can be easily extracted through a central aperture in the cathode [2, 10].

The characteristics of a Penning discharge are known to be strongly influenced by the experimental conditions. The discharge operating modes were identified as functions of the key physical parameters, namely the anode voltage, magnetic field strength, and working gas pressure [10]. Particularly under our experimental conditions (the pressure in the vacuum chamber of 0.6 mPa, the applied voltage of 5 kV and the discharge current of about 0.8 mA) the discharge burns between "low-magnetic field mode" (LMF -mode) at $H_0 = 0.06$ T and "high-magnetic field mode" (HMF-mode) at $H_0 = 0.1$ T. Graphically it can be described in Fig.2. In LMF-mode, the axial potential is distorted by a negative space charge distributed throughout the entire discharge volume resulting in the potential sag on the axis cell. In contrast, in the HMF-mode a field-free plasma region forms near the discharge axis, while the electron cloud is confined to a sheath adjacent to the anode. Due to the potential sag in LMF-mode, the energy spectrum of the emitted axial H_2^+ ions is strongly shifted to the low-energy region (Fig.3).

Since the transition from LMF-mode to HMF-mode is not abrupt because of its dependence on gas pressure, it is not possible to unambiguously define the point at which LMF-mode changes into HMF-mode. Instead, a regime of gradual transition exists in which effects characteristic of both LMF and HMF modes coexist and mutually influence each other.

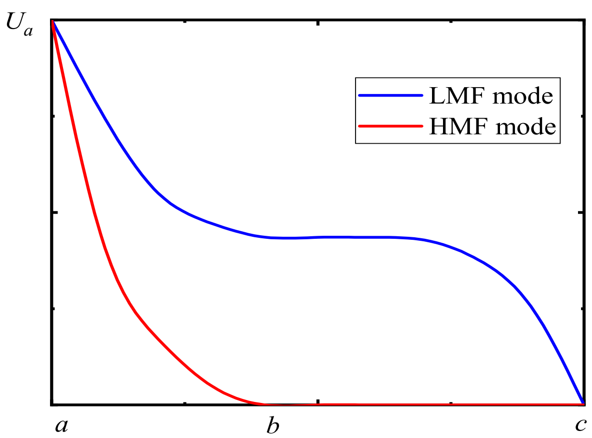

Figure 2. The schematic potential distribution curve inside the discharge cell when measuring the energy spectra of extracted ions. Dots a, b, c (see Fig. 1) designate: a – anode, b – cell center, c – cathode

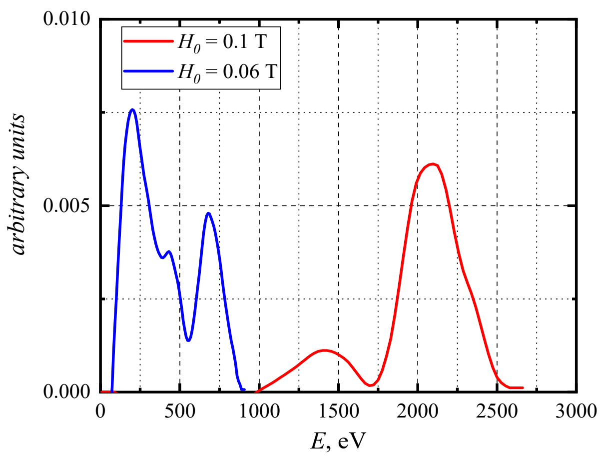

Figure 3. The H_2^+ ion energy distribution function axially emitted from Penning discharge with metal hydride cathode at $P = 0.6$ mPa and $U_d = 5$ kV

Using the relations between the magnitude of the potential sag and the discharge current for LMF-mode [10] one can obtain the following expressions for the discharge current:

$$I_d = 4\pi l \varepsilon_0 n_0 v_e \sigma_i (U_a - U_0) \tag{2}$$

Substituting the following parameters: anode length $l = 0.0015$ m, ionization cross section of the hydrogen molecule $\sigma_i \approx 10^{-20}$ m^2, electron velocity for ionization $v_e = 2.35 \times 10^6$ m/s, neutral particle density n_0 [m^{-3}] = $2.6 \times 10^{20} p$ [Pa], anode potential $U_a = 5$ kV, and assuming ($U_0 \sim E_{max}/e \approx 250$ V from Fig.3), Eq. (2) yields a local pressure in the cell of $p \approx 16$ mPa at $I_d = 0.8$ mA.

Thus, the release of hydrogen from metal-hydride leads to a local pressure increase from 0.6 mPa to 16 mPa near the cathode surface, and, when the rovibrational excitation of the released molecules is taken into account, results in a significant enhancement of negative ion formation according to Eq. (1).

The extraction mechanism of H^- ions depends on the mode of Penning discharge operation. In LMF-mode the anode layer expands toward the axis, and its negative space charge expels H^- ions from the plasma volume. In this case only ions formed near the extraction aperture in the cathode and paraxial ones could be efficiently extracted. In HMF-mode, the anode layer is thin, and the central plasma region is essentially field-free, enabling H^- ions to be extracted from the entire cross-section of the cell. It is demonstrated in Fig. 4 and Fig. 5.

Using single metal hydride cathode placed opposite the extraction region results in the poorest source performance, particularly for small anode radii. In LMF mode, the extraction of H^- ions generated near the metal hydride surface is hindered by a thick anode layer, which suppresses the extracted H^- current almost to zero. As the magnetic field increases, the anode layer contracts toward the anode, allowing paraxial negative ions to reach the extraction region and contribute to the extracted current, which rises to about 2.5 µA. Applying a negative bias to the metal-hydride cathode only weakly affects this behavior, increasing the extracted current to approximately 15 µA.

In HMF-mode, this effect becomes more pronounced. The anode layer is thin and only weakly affects the axial transport of H^- ions. As a result, the extracted H^- current increases by more than a factor of two due to the pushing effect of the negative potential applied to the metal hydride cathode, near which the main production of negative ions occurs.

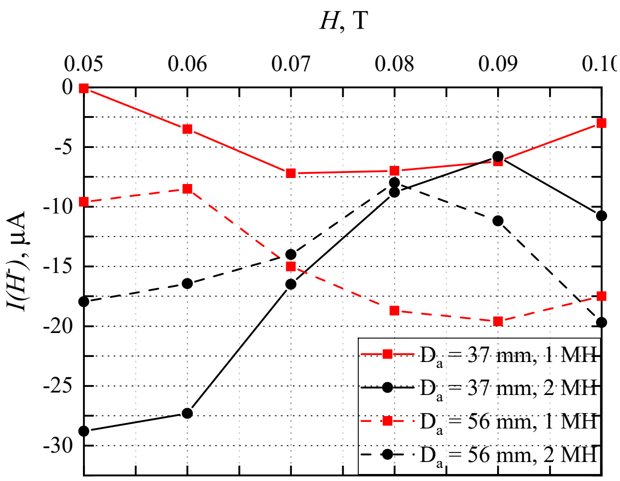

Figure 4. The current of extracted negative ions via magnetic fields at P = 0.6 mPa, U_d = 5 kV, I_d = 0.8 mA and grounded cathodes

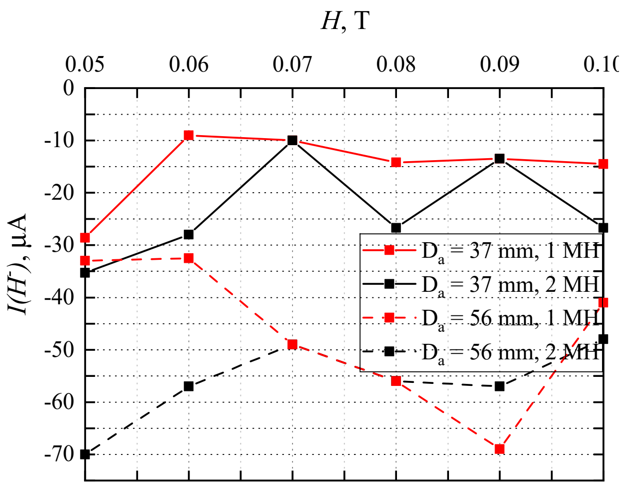

Figure 5. The current of extracted negative ions via magnetic fields at P = 0.6 mPa, U_d = 5 kV, I_d = 0.8 mA and electrically biased cathode (1) U_{bias} = -400 V in Fig.1.

The introduction of second metal-hydride cathode leads to much stronger increase in the extractable current. In this configuration, two spatially separated regions of efficient H^- ion production are formed, characterized by different extraction mechanisms. H^- ions generated near the cathode opposite the extraction region propagate along the discharge axis with thermal velocity when both cathodes are grounded, or are additionally accelerated toward the extraction region when a negative bias is applied. In contrast, H^- ions produced near the extraction region are directly extracted by the electromagnetic filter grid biased at a positive potential. The remaining ions, which are not affected by the grid potential, may be deflected toward the extraction grid by the negative space charge of the anode layer expanding toward the axis.

This effect is clearly pronounced in LMF mode, as shown in Fig. 4 and Fig. 5, both with and without the application of a negative bias. In the HMF mode, however, this difference becomes much less pronounced.

Increasing the anode diameter improves the utilization of the metal hydride cathode surface by enlarging the plasma volume in which the cathodes are immersed. The expansion of this region improves plasma uniformity and increases the effective plasma–cathode interaction area, resulting in more homogeneous cathode heating and a more uniform release of hydrogen from the metal hydride. Consequently, the conditions for negative-ion production are enhanced, leading to a higher extracted H^- current.

The transition from LMF to HMF mode is accompanied by the formation of a tenuous plasma region around the discharge axis, which can be distorted by potential sag [10]. This effect complicates the interpretation of the experimental results; nevertheless, the overall trends described above remain clearly observable.

CONCLUSIONS

The experimental results demonstrate the promising results of metal hydride elements using in plasma sources with efficient negative ion production. The key advantage of metal hydride lies in its ability to take up hydrogen isotopes in atomic form and release them into the plasma in a controlled manner under low-pressure conditions. Recombination of hydrogen atoms on the metal hydride surface directly produces rovibrationally excited hydrogen molecules. The feedback coupling between the discharge current and the hydrogen release rate provides efficient gas utilization, increases the density of rovibrationally excited molecules, and consequently enhances H^- ion production via dissociative electron attachment.

In a Penning discharge operated at low residual pressure, the introduction of metal-hydride cathodes enables plasma generation only on hydrogen released from the metal hydride, without any external gas injection. This opens the way to the development of a new type of compact, gas-feed-free ion source capable of operating at low and ultralow pressures with excellent gas utilization.

Formation of negative ions occurs via the dissociative mechanism of low-energy electron attachment near the surface of metal hydride cathodes, where the heightened density of rovibrationally excited hydrogen molecules is achieved. The extraction mechanism of negative ions depends on the operating mode of the Penning discharge. At low pressure, the determining factors are the electron drift within the anode layer and the presence of a practically field-free central zone, where axial electrons oscillate between the cathodes and may impinge on the central area, thereby opening the possibility of their extraction together with negative ions.

In the low magnetic field (LMF) mode, the anode layer expands toward the axis, and its negative space charge expels negative ions from the plasma volume. As a result, only ions formed near the extraction aperture in the cathode and paraxial ions can be efficiently extracted. In contrast, in the high magnetic field (HMF) mode the anode layer becomes thin, and the central plasma region is essentially field-free, allowing negative ions to be extracted from the entire cross-section of the discharge cell.

Increasing the anode diameter further enhances the efficiency of negative ions production by enlarging the plasma volume in which the metal hydride cathodes are immersed. The expansion of this region improves plasma uniformity and increases the effective plasma–cathode interaction area, leading to more homogeneous cathode heating and a more uniform release of hydrogen from the metal hydride. Consequently, the conditions for negative-ion formation are improved, resulting in a higher extracted negative-ion current.

ORCID
Ihor Sereda, https://orcid.org/0000-0002-9111-9853; **Yaroslav Hrechko**, https://orcid.org/0000-0001-9198-3660;
Kostyantyn Sereda, https://orcid.org/0000-0001-6934-2752; **Oleh Vorobiov**, https://orcid.org/0000-0001-5966-4037

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УТВОРЕННЯ ТА ЕКСТРАКЦІЯ ІОНІВ H^- З РОЗРЯДУ ПЕННІНГА В LMF ТА HMF РЕЖИМАХ

Ігор Середа[1], Ярослав Гречко[1], Костянтин Середа[1], Олег Воробйов[2]
[1]Харківський національний університет імені В.Н. Каразіна, просп. Курчатова, 31, 61108, Харків, Україна
[2]Харківський національний університет Повітряних Сил імені Івана Кожедуба, Харків, Україна

Використання металгідридних катодів у розрядах Пеннінга пропонує перспективний підхід до ефективного утворення негативних іонів водню в умовах низького та наднизького тиску. У цій роботі ми підсумовуємо та розширюємо наші

експериментальні дослідження впливу металогідридних елементів на характеристики розряду Пеннінга з аксіальною екстракцією негативних іонів. При низькому залишковому тиску введення металгідридних катодів дозволяє генерувати плазму виключно з водню, що виділяється матеріалом катода, без будь-якого зовнішнього напуску газу. Ця особливість відкриває шлях до розробки компактних джерел іонів без подачі газу, а також до ефективного використання газу. Показано, що механізм екстракції негативних іонів значною мірою залежить від режиму роботи розряду Пеннінга, який визначається напруженістю магнітного поля. У режимі низького магнітного поля розширення анодного шару до осі розряду та пов'язаний із ним негативний об'ємний заряд пригнічують ефективну екстракцію, обмежуючи її переважно параксіальними іонами та тими, що утворюються поблизу отвору екстракції. Навпаки, в режимі високого магнітного поля анодний шар стає тонким, а центральна область плазми практично вільна від поля, що дозволяє екстрагувати негативні іони з усього поперечного перерізу розряду. Крім того, досліджується вплив збільшення діаметра анода. Збільшення діаметра анода збільшує об'єм плазми, що оточує катоди з гідридів металу, що призводить до покращення однорідності плазми, більш однорідного нагрівання катода та більш рівномірного виділення водню. Ці ефекти покращують умови для утворення негативних іонів та призводять до вищого струму вилучення. Результати демонструють доцільність і переваги джерел іонів Пеннінга на основі гідридів металу для ефективної генерації негативних іонів за низького тиску.
Ключові слова: *негативні іони; водень; розряд Пеннінга; гідрид металу; об'ємне джерело*