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A hollow cathode discharge modification as a source of sputtered atoms and their ions

D. ZHECHEV*[1], S. TILEVA[1], G.V. MISHINSKY[2], and V.I. ZHEMENIK[2]

[1]Institute of Solid State Physics, Bulgarian Academy of Sciences
72 Tzarigradsko Chaussee Blvd., BG-1784 Sofia, Bulgaria
[2]Joint Institute for Nuclear Research, Flerov Laboratory of Nuclear Reactions, 141980, Russia

A nonconventional hollow cathode discharge (HCD) modification grounded on a conical bottom (CB) cylindrical cathode is reported. This CBHCD enhances the main HCD property, i.e., the sputtering of the cathode surface/probe inserted. Comparative polarisation measurements with a conventional flat bottom HCD show a stronger narrowing of the Hanle signal width for the sputtered Cu atoms in CBHCD. Thus their density is higher in CBHCD. This result is specified by the radial optogalvanic profile. It contains two peaks of the mentioned density, i.e., near the cylindrical cathode surface and over the cone peak. Some preliminary examinations of CBHCD as an ion source in three arrangements are performed and discussed.

Keywords: hollow cathode discharge, self-alignment, optogalvanic effect, ion source.

1. Introduction

The hollow cathode discharge (HCD) is known to combine two important processes, i.e., sputtering and excitation/ionisation realised separately elsewhere. This *a priori* combination presents the main spectroscopic advantage of HCD. From the very beginning these properties are being improved by using various geometric, magnetic field and operating mode modifications [1]. Often the problem is how this prospective combination to be used out of the cathode cavity. The arrangement of HCD as an ion source (IS) puts the same specific problem [2]. Indeed, intensive atomisation of the cathode surface/probe inserted via sputtering process allows various ions including those of refractory elements to be produced as an ion beam. Its cross-section may be of a large enough value. On the other side, the electrons oscillating within the cathode dark space (CDS) boundary form uniform enough plasma. There are no limitations radioactive ions to be also generated in HCD. In this case the radioactive substance may be a component of the cathode surface or inserted as a probe. These features also impart a new importance to HCD within the frames of a modern problem, i.e., generation of beams of accelerated fission fragments at bombardment of ^{238}U target by cyclotron accelerated electrons. In this case the bremsstrahlung spectra of γ-rays turns out producing ^{238}U fission fragments [3].

The main difficulty in this HCD-IS aspect is the low efficiency of the extracted ions yield. It is because the radial component of the ion velocity dominates that along the direction cathode-anode. The physical conditions needed for the both ion producing and extraction/transportation distinguish strongly in two orders related to the gas pressure. Their combination is a nontrivial problem. Thus each contribution to this field extends the HCD-IS application.

In this communication, the sputtering and ionising properties of a nonconventional modification of HCD are studied and analysed within the frames of an IS. The pressure difference between the HCD and the extractor region is sustained by the pressure drop across a small aperture. A precursory test of this HCD modification as an IS is performed.

2. Conical bottom hollow cathode discharge

The used HCD modification distinguishes by its conical bottom (Fig. 1) instead of the conventional flat one. The conical bottom CBHCD idea is increasing of the inner cathode surface within the same size of the cathode cavity.

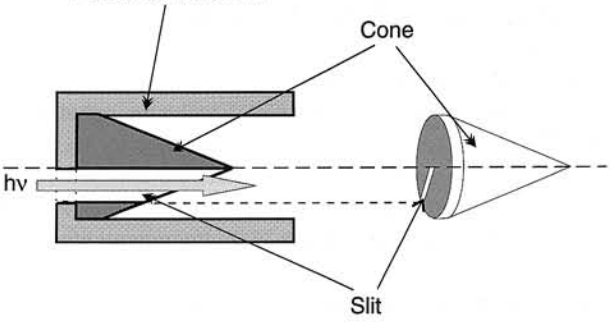

Fig. 1. Dismountable cylindrical hollow cathode with conical bottom (length 30 mm, radius 3 mm, cone height 20 mm).

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*e-mail: spectron@issp.bas.bg

Generally, this means a higher density of the sputtered atoms and of their ions. The cathodes from Al, Mo, Fe, and Cu are used for comparison of the spectral intensities I in the two kinds of cathodes, i.e., I^c in CBHCD and I^f in flat bottom HCD (FBHCD).

At the same stable state discharge current an increase in the spectral intensities I^c was observed in the cathodes of 6 mm and 3 mm diameters. Ne and He were used as buffer gasses. The ratio I^c/I^f was found to be varying around 3 for Al I 309.3 nm, within (2.0–10.0) for Al II 466.6 nm, (1.9–4.3) for Mo I 379.8 nm, (1.2–2.5) for Fe I 372 nm, (2.6–4.2) for Si I 251.6 nm.

This increase exceeds essentially the change of the inner cathode surface due to the conical one. Therefore the cathode surface is not the main reason for the observed I^c effect. Another possible explanation might be looked for in the higher rate of excitation/ionisation in CBHCD. However, the I-V-curves in Fig. 2 do not support directly this reason because of their closeness. The I-V-curves suggest that the CB decreases the voltage across the HCD. It means that the balance between the primary processes shifts to those developing at lower energy. This shift is confirmed by the observed decreasing of the buffers (atoms and ions) spectral emission contrary to that of the sputtered particles. That is why a hypothesis for intensification of the cathode surface sputtering seems to be plausible. In this case, a higher density N of the sputtered atoms should be detected in the cathode cavity of CBHCD.

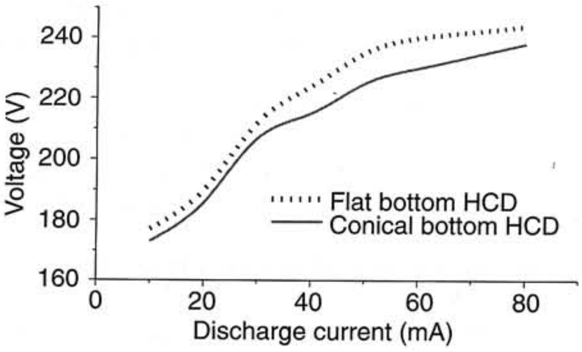

Fig. 2. Volt-Ampere characteristics of flat and conical bottomed HCDs.

3. Self-alignment of the excited atoms and optogalvanic effect in CBHCD

As a sensitive probe of the sputtered atoms, the width $2\Delta H_{1/2}$ of the Hanle-signal is used. Earlier the coherent effect of self-alignment type was established in HCD [4]. The effect arises due to the characteristic nonthermalised electrons and manifests itself in the polarsation of the spontaneous emission. The density N is known to broad the value $2\Delta H_{1/2}$ for a resonant transition due to the trapping effect [4]. In our experiment, the polarisation of the resonant line CuI 324.7 nm was measured in a scanning magnetic field H_0.

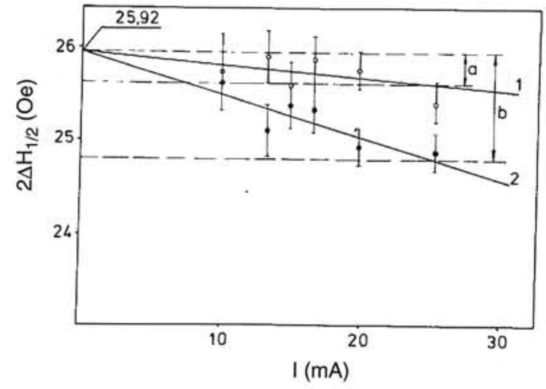

Fig. 3. Hanle-signal width $2\Delta H_{1/2}$ of the CuI ($4^2P_{3/2}$–$4^2S_{1/2}$) transition: line 1 – flat-bottomed cathode, line 2 – conical-bottomed cathode.

Figure 3 illustrates Hanle signal widths measured at low current value I. Line 2 lies systematically below than line 1. This behaviour manifests stronger trapping of the CuI 324.7nm in CBHCD, therefore the higher N_c (in factor 3) in CBHCD. Indeed, if N_0^c andN_0^f are the densities of Cu atoms in ground state, because of the linearity of the function $N_0^{c,f}$ (I) the ratio a/b depends on the ratio of the concentrations. At a = 0.37 G and b = 1.12 G (i = 0.25 mA) the ratio $N_0^f / N_0^c = 0.33$ gives a three times higher concentration in the CBHCD. This result shows the more intensive sputtering as the main contribution to the enhanced spectral line intensities of the sputtered atoms.

The character of the sputtered atoms radial profile is an essential property of every sputtering source. The radial distribution of the sputtered atoms in CBHCD was established by measuring the optogalvanic signal (OGS) ΔU(R) at irradiation of a home made Ne/Cu CBHCD tube by CuI 587.2 nm. In a good approach, the OGS may be considered as an optogalvanic probe of the irradiated level population. The radial slit (Fig. 1) allows plasma irradiation through the bottom. In this way no photoelectrons are generated in the OG measurements. The slit is also used for ion extraction. Figure 4 illustrates the comparison between the sput-

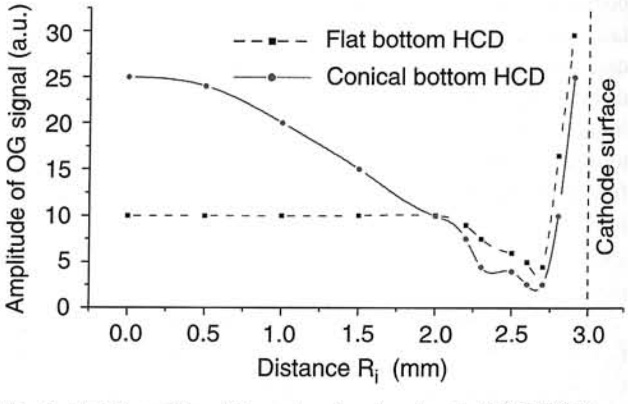

Fig. 4. Radial profile of the optogalvanic signal of CuI 587.2 nm (pulsed Cu laser of 10 kHz, 10 ns, 0.6 mm, 3 W).

tered atoms radial profiles in the HCD. Obviously the CBHCD contains a second maximum of the distribution $\Delta U(R)\ l_{R=0}$. It means that the optical density $\kappa_0\ l_{R=0}$ for the irradiated transition reaches its maximum at the laser path $l_{R=0}$. However, this path is the shortest one in this region. Thus, near the cone peak the absorption coefficient $\kappa_0(N_0^c)$ is maximum as well the sputtered atom density N_0^c. This fact is taken in mind in the arrangement of HCD-IS.

Earlier we estimated the contribution of the positive ion to the yield of sputtered atoms in HCD [5]. This contribution suggests the importance of discharge current as a parameter for sputtering intensification. A pulsed mode of operation was used in CBHCD. The yield of sputtered particles increases by using pulsed mode of the CBHCD (current 4A), combined with a separate dc power supply (15 mA).

4. CBHCD as an ion source

The above-mentioned CBHCD spectral advantages are transferred to a scheme of IS. A cylindrical HC (2R = 15 mm, length 30 mm) and Cu conical bottom (length 15 mm) are used in three IS modifications and modes of operation. Figure 5 gives a schematic general description of two IS-arrangement variants, i.e., (a) and (b) of CBHCD application as a IS. The flowing gas Ar is used as buffer one. Only preliminary testing of these CBHCD-IS combinations was performed.

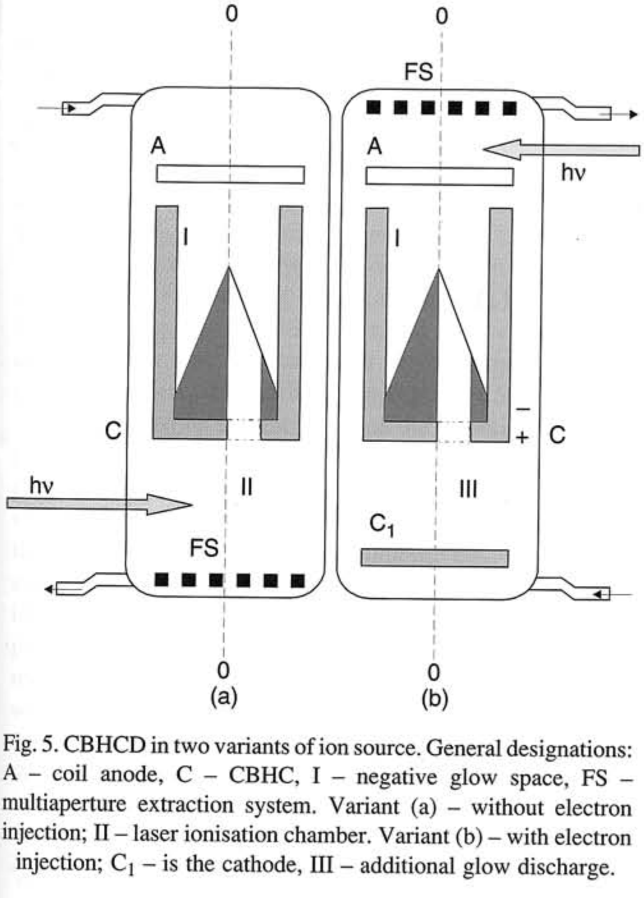

Fig. 5. CBHCD in two variants of ion source. General designations: A – coil anode, C – CBHC, I – negative glow space, FS – multiaperture extraction system. Variant (a) – without electron injection; II – laser ionisation chamber. Variant (b) – with electron injection; C_1 – is the cathode, III – additional glow discharge.

The CBHCD is connected spatially with the extracting vessel II in the variant (a). The pressure difference between the gas discharge medium I (0.4 Torr) and the vessel II [$10^{-(3\div4)}$ Torr] is sustained by the pressure drop across the hole 0.5 mm diameter (not displayed in Fig. 5) centred on the CB peak along the axis OO. Thus, beam of buffers and sputtered particles forms itself penetrating to vessel II. Here, the atoms of interest are ionised selectively by a suitable laser frequency. As the ions of sputtered particles their maximal density above the cone peak predetermines their higher beam like efficiency in CBHCD. An accel-decel multiaperture system extracts the ions. In these preliminary experiments the presence of sputtered Cu atoms in the chamber II was only tested by their fluorescence. The efficiency of this type IS arrangement may be enhanced by using a radial slit through the cone instead of the axial hole (Figs. 1 and 5). This HCD-IS arrangement limits the working gas pressure no less than the critical one about 10^{-2} Torr. It is determined by the geometric sizes of the anode-cathode system and the used conical bottom. The CBHCD turned out operating at lower gas pressure in relation to the conventional flat bottom HCD. The most probable reason seems to be the higher density of the sputtered atoms of lower potential of ionisation.

Another idea is developed in the variant (b). In order to minimise the critical low working gas pressure p an additional ionising factor is needed. An external injection of electrons maintains the CBHCD at subcritical gas pressure, Fig. 5(b). The electron beam is generated by an additional discharge II and injected through the hole/slit to the CBHCD (I). Here, the cathode C is used as an anode in relation to the additional cathode C_1.

The electron injection is found to shift the pressure operating range to lower values. It is due to the same behaviour of the ignition voltage U_0. The ignition curve $U_0(p)$ of CBHCD covers a pressure-range of 1.5 orders lower in relation to the case without electron injection. The increased fluorescence observed in this CBHCD-IS variant is manifestation of its higher ion beam generating efficiency.

A following essential enhancement of this efficiency turned out to be the periodic changing of the power polarity. In this case being at inverted polarity, the negative anode extracts the prepared positive ions in the NG (I). The maximum yield of ions was found to be strongly depending on the front steep and frequency of changing power polarity. As for the duration, the inverted power is to be in factor 4–10 longer than the normal one. This relation depends on the gas pressure and discharge current in CBHCD and might be ascribed to the ion path to the anode-extraction system.

4.1. Some additional considerations concerning the HCD usage as a source of radioactive ions

According to the general idea presented in Ref. 3, an accelerated beam of electrons bombards the ^{238}U target. The colliding electrons emit brumsstralhung and its energy turns out to be enough for target fission. The next step is the ionisation of the fission fragments. Within the frames of the previous HCD-IS arrangement the both fission and ionisation might be combined in CBHCD where the cathode or its cone is the bombarded ^{238}U target. Then, the fission fragments turn out additional ionised by the electron beam. Thus, this scheme is of higher efficiency related to the radioactive ions.

5. Conclusions

A new HCD modification, based on conical bottom, is studied by using electrical, spectroscopic, and optogalvanic measurements. In CBHCD, the balance of the primary processes turns out shifted to those running at lower energy. The yield of sputtered atoms is found to be increased in relation to that in a conventional flat bottom cathode. It is because of a second maximum in the radial profile of the sputtered atoms distribution. This peak is localised under the cone peak.

The enhanced sputtering in CBHCD is applied in a scheme of IS. Three arrangements and modes of operation of the CBHCD-IS combination are exposed. The injection of an additional electron beam allows both the CBHCD to operate at lower buffer gas pressure and to form the ion beam at the same pressure.

The operation mode of changing power circuit polarity improves the extraction of the ions from the negative glow. This operation mode modification promises to be suitable in forming beams of accelerated fission fragments at bombardment of ^{238}U target by cyclotron accelerated electrons.

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