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Plasma Ion Source with an Internal Evaporator

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A new construction of a hollow cathode ion source equipped with an internal evaporator heated by a spiral cathode filament and arc discharge is presented. The source is especially suitable for production of ions from solids. The proximity of arc discharge region and extraction opening enables production of intense ion beams even for very low discharge current ($I_a = 1.2$ A). The currents of 50 μA (Al^+) and 70 μA (Bi^+) were obtained using the extraction voltage of 25 kV. The source is able to work for several tens of hours without maintenance breaks, giving possibility of high dose implantations. The paper presents the detailed description of the ion source as well as its experimental characteristics like dependences of extracted currents and anode voltage on anode and cathode currents.

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1. Introduction

Ion implantation, offering precise control of the dopant depth profile, is one of the most important techniques enabling modification of optical and electronic properties of solids. One of the clues of this well-established method is obtaining intense and stable ion beams. This is a challenge especially in the case of refractory substance, like rare earths, which are of great interest due to their specific electronic, optical and magnetic properties [1, 2].

There are several ways [3] enabling production of ions of non-gaseous elements by feeding vapors into the ionization chamber, each having its advantages and drawbacks. The very popular method is using an external oven producing vapor for hollow cathode, electron cyclotron or any other kind of ion source. The weak spot of such solution is an effective vapor transport, as well as low vapor pressure of non-volatile substances. The second difficulty could be overcome by using alloys of low melting point [4]. Another popular group of feeding material are volatile compounds like halides or organometallic compounds [5]. One should, however, have in mind that they are highly reactive and toxic. Sputtering of feeding material placed in the source could be done by ions [6, 7] or electrons [8]. Mechanical sputtering of metals was also employed [9], but the main drawback of this approach was a poor stability of extracted current. The great advantage of laser ablation ion sources [10, 11] is the fact that they can ionize any solid material and give possibility of effective production of multiply charged ions. Finally, vapors of high melting point materials could be produced using discharge plasma for heating a container placed inside the ionization chamber.

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This approach was successfully applied in our previous design [12, 13], combining features of Nielsen [3] and metal vapor arc discharge (MEVVA [14]) ion sources. The molybdenum crucible, often called an evaporator, is surrounded by a spiral cathode. The arc discharge between the cathode and cylindrical anode heats the ionizer, making the feeding substance vaporize. Atoms are ionized in the discharge by energetic electrons. Ion source of that kind provides high extracted currents of solid ions, e.g. 80 μA of Al^+, 10 μA of Cr^+, 100 μA of As^+. The current values were obtained using 25 kV extraction voltage and measured approximately half an hour after the discharge is initialized — in many cases (like Mn and In) extracted currents grow even twice as large with the source operation time. It is worth mentioning that the source is able to produce ≈ 25 μA of Eu^+ using $EuCl_3$ and H_2 to prevent formation of EuOCl.

The paper presents a new construction based on the idea of an internal evaporator. The evaporator is placed inside a hollow cathode and surrounded by a spiral filament. The arc discharge region, where ion production takes place, is as close as possible to the extraction opening. That factor could lead to the increase of extracted currents, compared to the cylindrical anode source [12, 13]. Additionally, the front part of the source, being an anode, is negatively biased and attracts positive ions. Another modification is funnel-like shape of the extraction opening, making the penetration of the extraction field easier.

The detailed description of the ion source construction is given in the paper. The preliminary results obtained for Al, In and noble gases are presented — namely the dependences of extracted ion currents on anode and cathode currents as well as on the magnetic field of the electromagnet that surrounds the source. The changes of anode voltage due to these factors are also shown and discussed.

2. Construction of the source

The cross-section of the source is shown in Fig. 1. The hollow cathode chamber, made of molybdenum, has an inner diameter of 14 mm and the length of 20 mm. The chamber consists of two cylindrical parts separated by an insulator made of boron nitride. The two parts of the hollow cathode chamber are also mounts of the spiral cathode filament. The filament has an external diameter of 7 mm and is made of tungsten wire. A cathode current I_c may be varied up to $\approx$ 38 A. The typical lifetime of the cathode is 50 h and depends on the filament material (it is extended e.g. for thorium enriched tungsten). The molybdenum evaporator is placed inside the cathode, surrounded by a spiral filament. It has a form of a long ($\approx$ 30 mm) slim tube. The external diameter is 3 mm. The crucible is filled with a feeding substance (powder or small lumps). The evaporator is heated mainly by the cathode filament. Discharge also provides heat, but the distance between the region of arc discharge and the evaporator is significantly larger than in our previous design. The evaporator temperature is also controlled (depending on the melting point of the feeding substance) by changing the depth of the crucible's insertion in the chamber.

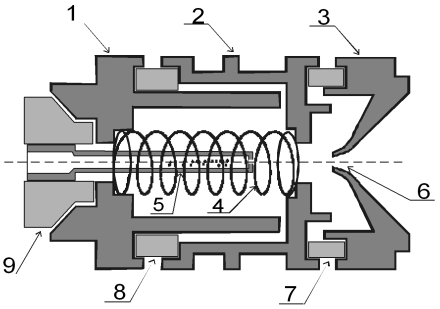

Fig. 1. Schematic view of the ion source: 1, 2 — cathode chamber parts, 3 — anode, 4 — filament, 5 — evaporator, 6 — extraction hole in the anode, 7, 8, 9 — insulators.

The arc discharge burns in the region between a tip of funnel-shaped anode and a front part of cathode mount. The discharge ignition is done by applying a voltage of approximately 90–110 V. It should be mentioned that later on, when the discharge is established, the anode voltage U_a is lower (20–60 V). Vapors of the feeding substance reach the discharge, where neutral atoms are ionized by electrons. The whole chamber of the source is surrounded by an axial electromagnet coil compensating the field from the spiral filament. When the ions produced by electron impact ionization arrive near the anode, they are caught by the electric field and pulled out of the source through the extraction hole of 1 mm diameter. The shape of the anode makes the penetration of extraction field easier. Due to this (and small distance between the discharge and extraction hole) one may expect that the extracted currents could be larger than in the case of our earlier construction [12, 13].

3. Experimental results

During the development stage the source was tested mainly using noble gases. Current vs. voltage characteristics were measured for He, Xe and Kr using the Faraday cup attached to the extraction electrode. Total extracted currents are shown in Fig. 2. The results were obtained for the discharge current $I_a = 1$ A. In all cases I_{tot} grows fast with U_{ext}, as predicted by the Child–Langmuir formula. For U_{ext} larger than 12 kV (Ne) or 17 kV (He and Xe) saturation is observed, meaning that the I_{tot} is limited by the rate of ion production in the source. The clue is that currents are approximately 2 or 3 times larger than those obtained for the Nielsen-like type ion source, which was the base for the construction described in [12, 13]. It should be mentioned here that during the presented experiments I_a was limited to 1.2 A.

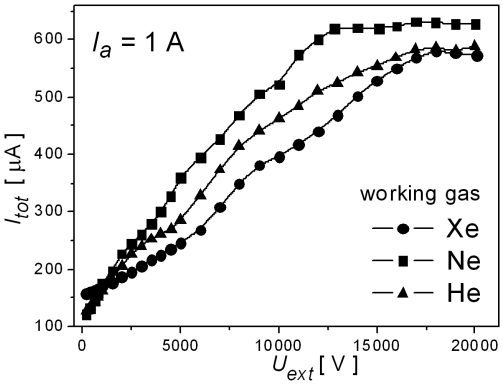

Fig. 2. Current vs. voltage curves for noble gases.

The currents of separated beams I_{ion} (after passing an electromagnet and accelerating system) were determined for $I_a = 1.1$ A and the accelerating voltage $U_{acc} = 75$ kV. Ion currents were 80 μA (He^+), 55 μA (Xe^+) and 110 μA (Ar^+). The values of I_{ion} yielded by our previous construction (the same conditions) were 15 μA, 20 μA and 40 μA, respectively. The vantage of the novel design with arc discharge near the extraction opening is clear.

The source was also tested using *n*-butane, in order to check whether ions with two or more C atoms could be obtained. The result was 80 μA for the ions having mass of 30 a.m.u. (most probably $C_2H_6^+$).

During the tests with solids the evaporator was loaded with $\approx$ 100 mg of Al or 250 mg of In. The influence of I_a, I_c and magnetic field B of the electromagnet on I_{ion} was under investigation (see Fig. 3). For both substances there is a fast increase of I_{ion} with I_a due to the increasing plasma density, which leads to more effective ionization. Moreover, the arc discharge takes part in the heating of the evaporator — the larger is I_a, the higher is the evaporator's temperature. Let us note that I_a values are too small to observe saturation of $I_{ion}(I_a)$ curves, which were observed during the tests of our earlier construction. This effect was due to the decrease of U_a with the increasing I_a and less effective electron ionization.

In the considered case there is rather an increase of U_a with I_a. It is expected that for larger I_a (3 or 4 A) both the reduction of U_a and saturation of $I_{ion}(I_a)$ curves will be observed.

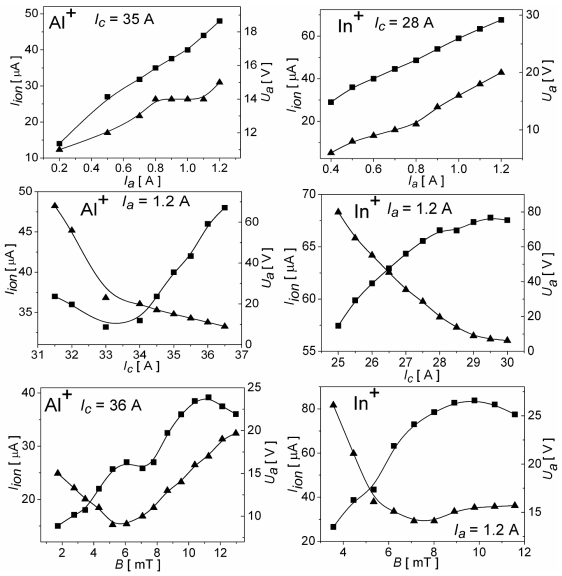

Fig. 3. Ion current (squares) and anode voltage (triangles) for Al^+ and In^+ as functions of discharge current I_a, cathode current I_c and magnetic field flux B.

The evaporator is heated mainly by a cathode filament. Hence, I_{ion} should rise with I_c. This is confirmed by the experimental data — currents rise very fast with I_c. Let us note that Al (melting point 933 K) requires much higher I_c than indium (430 K). In that case one can see saturation of $I_{ion}(I_c)$ curve, which may be explained by the fact that the filament is a source of primary electrons. Increasing concentration of electrons has two consequences: it enhances the ionization probability but also causes the reduction of U_a. As previously, the reduction of U_a and, consequently, decrease of electron energy, leads to the saturation of $I_{ion}(I_a)$. This is seen for indium — U_a is just above the ionization potential (5.786 eV [15]) for larger I_c.

Dependence of I_{ion} on the magnetic field was tested in order to find its optimal values. Both curves have their maxima near 10 mT. Let us note that the curve for the more volatile substance In has a broader peak than that for Al — such behavior was also observed for our previous type of ion source. Magnetic field from the external coil is used to compensate the field of spiral filament. It increases efficiency but only up to some level — this effect is hindered by the reduction of U_a, as could be seen for indium.

Characteristics of the source were also determined for noble gases (Xe, Ne and He). As one can see in Fig. 4, the trends of the curves are similar to those for solids. The total extracted currents grow almost linearly with I_a, the increase of U_a is also visible. High I_c is required to provide enough primary electrons. There is a rise of I_{tot} with I_c in the case of He and Ne. Once again increasing I_c leads to the reduction of U_a and deterioration of ionization efficiency due to lowering energy of electrons. This effect is well pronounced in the case of Xe. In order to optimize performance of the source, the optimal electromagnet current has to be chosen for each gas — the curves have much broader peaks than in the case of solid feeding substances.

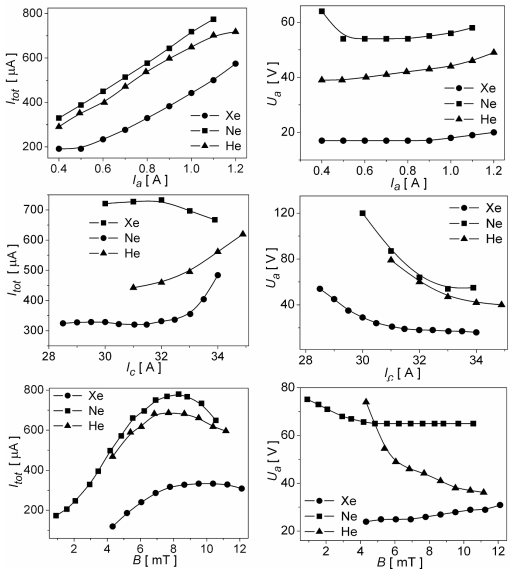

Fig. 4. Total extracted currents and U_a as functions of I_a, I_c and B. Case of noble gases.

Other feeding substances, like Bi, As, Sb and the like were also used. The ion currents (e.g. 90 μA of Bi^+, 35 μA of Sb) were comparable or even better to those obtained using the cylindrical anode source [12] despite very low I_a. It should be mentioned here that the source under some conditions (e.g. high U_a) is capable of producing reasonable amounts of doubly charged ions — e.g. a current of 15 μA of Bi^{++} ions was measured when U_a was approximately 120 V. High currents of molecular ions were also observed. In the case of antimony the current of Sb_2^+ ion (25–30 μA) was comparable to that of Sb^+ ions, giving opportunity of high dose implantations in a reasonable time.

4. Conclusions

A novel design of ion source with an internal evaporator heated by a spiral cathode filament and arc discharge has been presented. The source is able to produce much higher ion current intensities than in the case of our previous construction, due to the fact that the arc discharge region is as close as possible to the extraction orifice. The extracted Al^+ and In^+ and Sb^+ current intensities are 50 μA, 70 μA and 35 μA, respectively. Despite the fact that very low anode currents were used (up to 1.2 A) these values are comparable with the parameters of a commercial hollow cathode source (HighVoltage

Engineering model SO-55) [16]. One may expect that using an anode power supply capable of providing a current of 3–4 A will result in ion currents at least twice or three times larger than those presented in this paper.

The source is able to provide beams of molecular (like Sb_2^+) and doubly charged ions. Other advantages of this sources are: simple maintenance and low power consumption (approximately 350–400 W). The hollow cathode ion source with internal evaporators enables high dose (up to 10^{17} ions per cm^2) implantations with a variety of metallic and non-metallic solids.

Acknowledgments

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