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# Development of a Highly-Efficient Cold-Cathode Ion Source for Ion Implantation

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This article describes the design of a highly-efficient ion source with a Penning-system cold cathode for ion implantation. The ion source is intended for receiving large currents (> 10 μA) from solid materials whose boiling point is higher than the melting point. The ion source on the BALZERS MPB-202 ion implanter is also tested.

**Key words:** ion implantation, ion source, ion implanter, metal ions, semiconductor structures.

В даній статті описано конструкцію високоефективного джерела йонів із холодною катодою Пеннінґової системи для йонної імплантації. Джерело йонів призначене для одержання великих струмів (> 10 μA) з твердих матеріялів, температура кипіння яких вище за температуру топлення. Також проведено апробацію джерела йонів на йонному імплантері BALZERS MPB-202.

**Ключові слова:** йонна імплантація, джерело йонів, йонний імплантер, йони металів, напівпровідникові структури.

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## 1. INTRODUCTION

One of the main methods of introducing impurities for the production of semiconductor devices is ion implantation using a gaseous or solid-state source of ions. Ion implantation systems use hot and cold cathode sources (Penning source). The hot cathode ion source allows implantation of ions from gases and solids. However, such a source cannot be used to implant elements with melting points lower than the boiling point. Such elements include Fe, Cu, Mo, Al, Ti, Be and others. In this regard, doping of the specified elements must be carried out using an ion source with a cold cathode [1–3].

The principle of operation of the source consists in atomization of a solid substance by plasma in a longitudinal magnetic field. However, such ion sources do not provide ion currents greater than 10 μA when spraying a solid-phase substance. That is why there was a need to develop an effective source of ions with a cold cathode of the Penning system, which would provide significantly larger ion currents [4].

## 2. CONSTRUCTION OF THE ION SOURCE

The design of the ion source was carried out using mathematical modelling of individual elements of the source, in particular the configuration of the magnetic field. An available type of magnet was selected, the dimensions of the source and its power supply system were calculated for further integration into the MVR-202 ion implanter of the 'BALZERS' company of the V. Lashkaryov Institute of Semiconductor Physics of the National Academy of Sciences of Ukraine. The implanter is used to work out the operating modes of the source during the generation of beryllium ions and demonstration implantation of beryllium ions into a plate made of indium antimonide [5, 6].

The physical and technical features of the development of plasma ion sources are fundamentally similar. However, the development requirements in the case of beryllium ion generation are specific and are regulated by the 'Sanitary rules for working with beryllium and its compounds' [7]. The latter requires specially equipped premises and imposes some restrictions on the use of standard methods of organizing work with ion sources. It is known that beryllium is similar to aluminium in many ways (diagonal similarity in Mendeleev's periodic system of elements). Therefore, at the development stage, the ion source was tested in the aluminium ion generation mode.

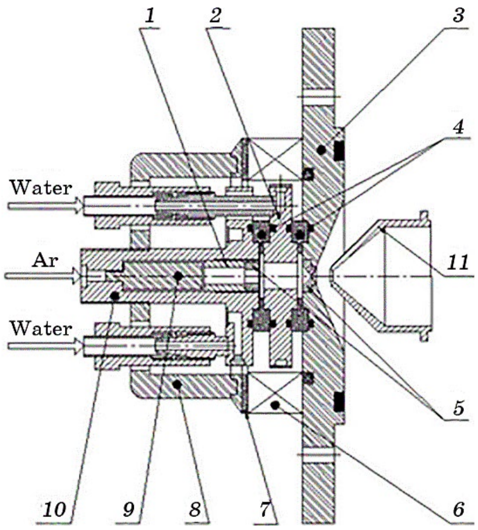


**Fig. 1.** Construction of the source of metal ions: *1*—hollow cathode; *2*—anode; *3*—anticathode; *4*, *7*—insulators; *5*—sputter inserts; *6*—NdFeB magnet; *8*—ion source case; *9*—ferromagnetic insert; *10*—cathode unit; *11*—extracting electrode.

Modern sources of metal ions require a stable plasma discharge of the working gas, effective atomization and ionization of the atoms of the implanted substance, acceleration of the formed ions and formation of an ion beam [8]. The design of such a source is schematically shown in Fig. 1.

The gas discharge chamber of the source consists of a hollow cathode (*1*), anode (*2*), anticathode (*3*) and body (*8*), which form the Penning discharge geometry. A uniform magnetic field in the gas discharge chamber is created by an NdFeB magnet (*6*) and magnetic conductors (*3*), (*8*), (*9*). The magnetic wire is highlighted in the figure with dashed lines.

The construction of the source is based on the formation of a plasma ion emitter using a Penning glow discharge. Ionization of sputtered atoms is ensured by the oscillation of electrons in the discharge chamber at low pressure. Modelling of the magnetic field of the ion source was carried out using the TRUCK program [9, 10]. The magnetic field in the cathode–anticathode gap was set in the range of 0.1–0.2 T. The simulation showed that when using a permanent NdFeB magnet (ring size $100\times70\times20$ mm), the magnetic field strength ($B$) in the middle of the hollow cathode (*1*), anode (*2*) and the anticathode (*3*) reaches values of 0.16–0.2 T. These are acceptable values for the created ion source.

The supply of gas (Ar) for the formation of stable gas-discharge plasma is carried out through a hole in the back of the cathode (*1*). To avoid discharge burning near the cathode hole in the source, a gas distribution cavity is provided. Gas supply to the discharge chamber is carried out through a narrow gap with a diameter of 0.5 mm in the peripheral area of the cathode assembly (*10*). Overheating of the electrodes in contact with the discharge can lead to a change in the burning mode of the discharge. To exclude this phenomenon, the cathode assembly (*10*) and the anode (*2*) of the ion source are cooled with water. For effective ionization of atoms in the gas discharge chamber, the atomized solid substance in the form of inserts (*5*) is pressed into the middle of the hollow cathode and anticathode. Spray inserts are made from the material whose ions need to be obtained. At the stage of working out the design of the source and its modes of operation, the insert was made of aluminium. The cathode (*1*) is made of molybdenum.

When voltage is applied to the electrodes of the source between the cathode (*1*), anode (*2*) and anticathode (*3*), a glow discharge with a voltage of ≅400 V and a current in the range of 100–400 mA (Ir) ignites. Accelerated ions of the working gas (Ar) spray the aluminium inserts, creating an environment of Al atoms in the emission region of the gas discharge chamber. Fast oscillating electrons concentrated along the discharge axis provide ionization of aluminium atoms. Under the action of an external electric field, aluminium ions are extracted into the region of the ion–optical path of the source and form an ion beam. An external electric field is formed in the middle of the emission hole with a diameter of 1.5 mm, when a voltage of 30 kV is applied between the anticathode (*3*) and the extracting electrode (*11*).

After testing the work of the source with aluminium ions and ensuring sanitary and technical conditions for work with beryllium, the ion source was used to obtain Be ions. For this, sprayed inserts made of beryllium and aluminium alloys with a beryllium content of 20% and more were used.

## 3. APPROBATION OF THE ION SOURCE

The ion source was tested on the BALZERS MPB-202 ion implanter. The beryllium (Be) used to form the inserts in the cathode and anticathode has a high ionization energy of 9.32 eV. This energy is greater than that of Fe (7.89 eV), Cu (7.72 eV), Mo (7.1 eV), Al (5.98 eV), Ti (6.8 eV). In addition, Be has two electrons in the outer orbital, which complicates the ionization process. Accordingly, most ion sources with a cold cathode are not capable of providing an ion beam current of more than 0.07 μA. In our case, providing large ionic currents of beryllium ions will allow a priori to obtain large ionic currents for elements with lower ionization energy of atoms. The dependence of the $Be^+$ current on the discharge current is shown in Table 1. It can be seen that, with a discharge current of 400 milliamps, the implanter is able to provide a beryllium ion current at the level of 0.35 μA. The resulting beryllium ion current was used to implant beryllium ions into the InSb matrix for 1 hour. The ion implantation energy was 20 KeV.

Using the Atomika 4000 instrument, secondary ion mass spectrometry (VIMS) profiles of the $Be^{+}$ impurity distribution along the depth were measured. The measurements were carried out using a beam of primary $O^{2+}$ ions with energy of 7 keV. The depth of the crater formed during sputtering was measured using a DEKTAK 3030 contact profilometer. Along with this, a simulation of the implanted beryllium profile in the InSb matrix with energy of 20 keV was carried out using the SRIM (The Stopping and Range of Ions in Matter) program. Since the used program quite accurately predicts the distribution profiles of implanted ions in a solid body, the comparison of the measured beryllium profile and the simulated one will allow assessing qualitatively the effectiveness of the coordinated work of the created source and the BALZERS MPB-202 ion implanter.

Figure 2 shows the measured and modelled profiles of the beryllium impurity distribution along the depth. It can be seen that, within 1 hour, the beryllium source in the BALZERS MPB-202 implanter is able to provide a concentration of beryllium in the distribution maximum at the level of $10^{19}$ atoms/cm$^3$. The shapes of the measured and calculated distribution profiles are similar, which confirms the formation of a hidden layer for the used materials.

In this way, we can talk about the successful design of the developed source for this type of implanters. In addition, a 'lifetime' study of a beryllium-cathode ion source was conducted. The obtained 'lifetime' of

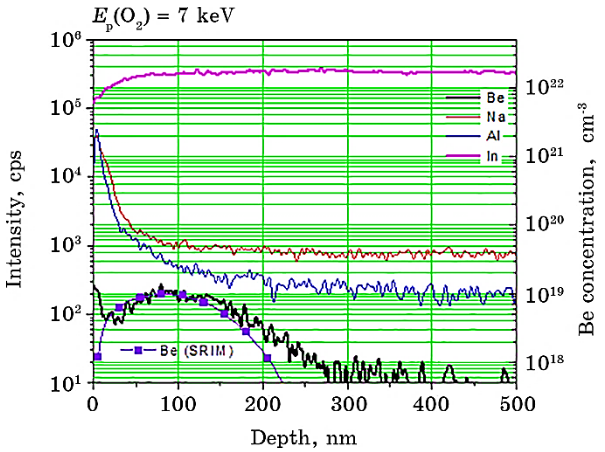


**Fig. 2.** Profile of the distribution of $Be^{+}$ implanted with $E$ = 20 keV along the depth in the InSb matrix.

**TABLE 1.** Dependence of the beryllium beam current on the discharge current.

| $I_p$, μA | 100 | 150 | 200 | 250 | 300 | 350 | 400 |
|---|---|---|---|---|---|---|---|
| $I_{Be^+}$, μA | 0.07 | 0.08 | 0.1 | 0.13 | 0.16 | 0.2 | 0.35 |

the ion source was of 16 hours at a discharge current of 400 mA. The measured profile of impurity distribution in depth and simulated using the SRIM 2018 program are presented in Fig. 1.

As shown in Fig. 1, the real profile of the implanted impurity coincides with the theoretically calculated one.

## 4. CONCLUSION

A study of the 'lifetime' of an ion source with a beryllium cathode was carried out. The 'lifetime' of the ion source was of 16 hours at a discharge current of 400 mA.

The developed highly-efficient source with a cold cathode of the Penning system is capable of providing high currents of the ion beam from the following materials: Fe (9.6 μA), Cu (11 μA), Mo (9.7 μA), Al (23 μA), Ti (12 μA), Be (0.3 μA). No source with a cold cathode can provide the currents for the above-mentioned elements.

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