# THE RADIAL DISTRIBUTION OF CURRENT DENSITY IN AN ELECTROHYDRODYNAMIC ION SOURCE BASED ON THE InSn ALLOY

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The radial distribution of current density from the center of the beam to the edges across the radius of the emission field was investigated using a miniature probe target placed at a specific distance from the emission point at various beam current values from a liquid metal ion source with InSb as the working substance. It has been observed that despite the consistent geometric dimensions of the emission area at various emission current values, the current density decreases at measurement points from the center of the beam towards the edges. The experimental results provide the maximum opportunity to adjust the dimensions of thin layers deposited on various substrates using the ion source, as well as to ensure uniform thickness distribution across the surface of the samples.

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**Keywords:** ion source, working substance, ion beam, radial distribution, emission.

## INTRODUCTION

Presently, the deposition of thin layers of various elements and compounds onto surfaces is one of the most pertinent areas of research, and, of course, various methods known to science and technology are employed for this purpose. For example, magnetron sputtering, thermal evaporation, electron-beam evaporation, and others. Certainly electrohydrodynamic ion sources or ion sources from metal-liquid alloy (LMAIS) [1,2] are increasingly being used to obtain charged particles from various substances and alloys and deposit them onto different surfaces. The reason for this is that this method allows obtaining an intensive ion beam, requires a smaller amount of working substance for the ion source, allows for the control of the charged particle's exit velocity, the possibility of separating the particle beam based on their charge and mass, and so on. All of these provide additional capabilities to achieve the desired quality in the acquired delicate layers. However, the uneven distribution of current density in the emitted ion beam, which is highest at the center and decreases as you move away from the center, naturally leads to the formation of areas with varying thickness on the surface of the deposited layer, creating thin layers. Therefore, there is a need to study the radial distribution of current density in the beam [3,4]. Measuring the radial distribution of current in the beam provides the maximum opportunity to control the thickness of thin layers deposited on various substrates using ion sources. It helps in finding the optimal deposition mode when they are placed within the emission field. In this way, it is possible to achieve a uniform layer thickness across the entire surface of the samples.

InSb was used as the working material in the ion source. InSb is a widely studied semiconductor compound. The ease of synthesis and purification, as well as the high electron mobility at room temperature (which facilitates ionization), encourage the use of InSb. The energy bandgap of InSb at a temperature of 77 K is 0.27 eV, while at room temperature, it is 0.17 eV. The small bandgap of InSb allows it to be used as a photodetector in the near and mid-infrared range (3-5 μm). At the same time, this compound is used in the manufacturing of photodiodes, thermoelectric generators, as a Hall effect sensor, in devices that measure resistance changes in a magnetic field, and in various other applications. The deposition of ion compound layers based on InSb in an ion source allows for the creation of thin films and various surface structures, thereby expanding its range of applications.

## EXPERIMENT

The experiment was conducted in a Leybold-Heraus A700Q vacuum system at a pressure of $5x10^{-6}$ mbar. The overall structural diagram of the ion source is presented in Figure 1 [5].

Initially, the needles, which are the primary components of the ion source, were manufactured using a special method from NiCr material and coated with InSb material in a vacuum environment. Afterward, the InSb-coated needle is placed inside a graphite container containing the working material and is installed in the ion source. To set up the experiment, a piezostage MC-2000 was placed inside the vacuum chamber, while the table control system was positioned outside the chamber. The connection is established between the table and the control panel, as well as between the control panel and the computer. All wiring and the table are shielded to prevent the impact of high voltage on the table control system. Additionally, a special collector with a diameter of 5 mm was prepared and installed on the piezostage to register the batch current (Figure 2). After taking all the necessary precautions, the experiment was conducted in a vacuum environment.



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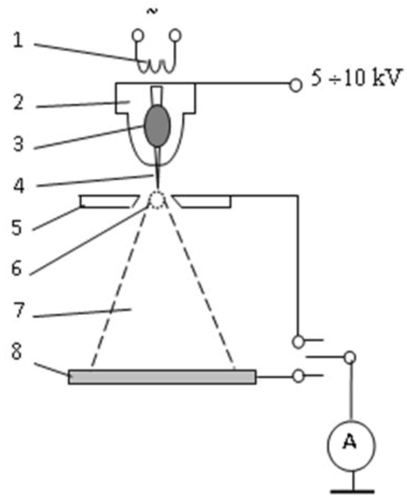


*Fig. 1.* Ion source diagram: 1 - cathode, 2 - container, 3 - working material, 4 - needle, 5 - extractor, 6 - bright field, 7 - ion beam, 8 – collector

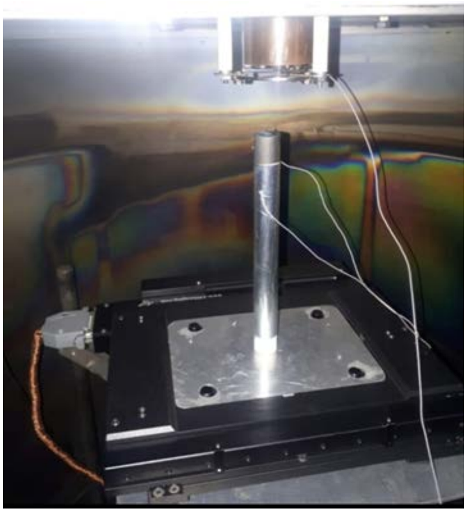

*Fig. 2.* Ion source in the vacuum chamber and the collector circuit located on the piezo stage.

The ion source was heated to the melting temperature of the working material using a tungsten cathode and then via thermionic emission. Subsequently, an accelerating voltage was applied between the extractor and the cathode, and ion emission occurred at a specific threshold voltage. When measuring the beam current in the collector circuit, the collector was displaced using the piezostage from the control panel located outside the chamber.

The most important characteristic of any ion column is the focusing of the ion beam to the smallest possible quasi-point dimensions [6]. The minimum diameter of the ion beam d at the target is determined by the formula

$$d = \sqrt{\left(Md_q\right)^2 + d_s^2 + d_c^2 + d_b^2} \qquad (1)$$

Where M is the optical magnification of the ion column, $d_q -$ is the virtual (imaginary) size of the source, $d_s -$ is the spot size due to spherical aberration, $d_c -$ the spot size due to chromatic aberration, and $d_b$ is the diffraction spot.

Accordingly, $d_q$ $d_c$ and $d_b$ are calculated using the following formulas:

$$d_s = \frac{1}{2} C_s \alpha^3, \;\; d_c = C_c \left(\frac{\Delta E}{E}\right)\alpha, \quad d_b = 0{,}6\,\frac{\lambda}{\alpha}, \qquad (2)$$

where $\alpha -$ is the angle of ion entry into the target, $C_s -$is the coefficient of spherical aberration, $C_c -$ is the coefficient of chromatic aberration, $E -$ is the ion energy, $\Delta E -$is its energy spread, and $\lambda -$ is the de Broglie wavelength of ions, which is calculated by the formula

$$\alpha^2 = \frac{I}{\pi M^2 (\frac{dI}{d\Omega})} \qquad (3)$$

where $I -$is the primary ion current, and $'\Omega -$ is the angular spread of ions in the beam.

Analyzing equations (1) - (3), it can be concluded that the optical magnification of the ion column is initially determined by the size and design of the column, and its value can vary within small limits by adjusting the potential on the condenser lens. It's important to consider that the de Broglie wavelength for ions is negligibly small compared to that of electrons, which is why the impact of diffraction on blurred spots is typically disregarded. The angle of ion entry (acceptance) is determined by the choice of the aperture limiting the ion current. At high ion currents (1-100 nA), spherical aberration makes the main contribution to the diameter of the ion beam, while in the range of moderate currents (10-50 pA), its influence becomes insignificant. At currents below 10 pA, the virtual size of the source becomes the primary contributor. Therefore, from a practical standpoint, the beam diameter is significantly influenced by the accelerating voltage, the total ion current, the energy spread of ions, and the virtual size of the source. In the future, we will examine in more detail the relationship between these parameters and the type of ions used in EHD sources. As an example, Figure 3 shows the dependence of the gallium beam diameter on the ion current in comparison with the most well-known sources used in modern Focused Ion Beam (FIB) systems [7].

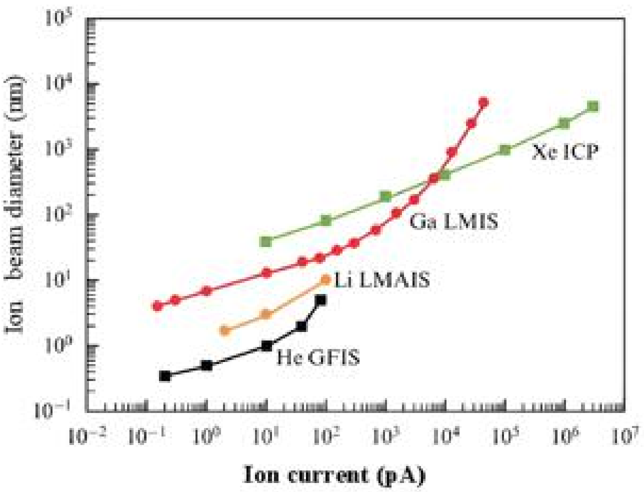


*Fig. 3.* The dependence of the ion beam diameter on the ion current for various sources used in modern Focused Ion Beam (FIB) systems [7].

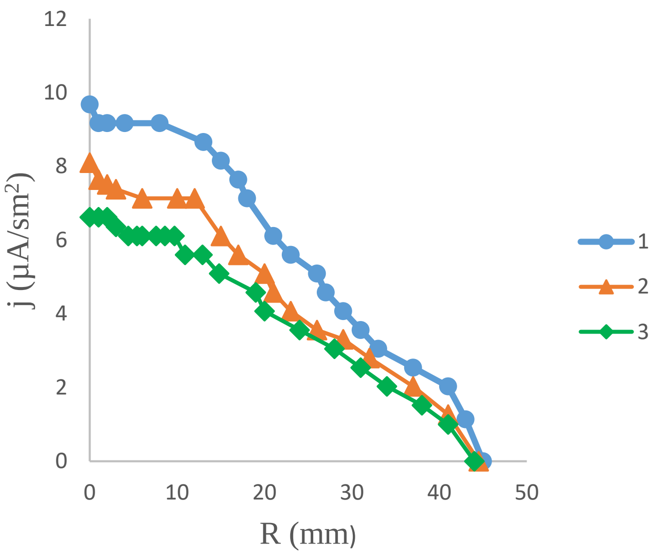


*Fig. 4.* Radial distribution of current density of the ion beam.
1) $I_{beam}$=30μA, U=6,3kV; 2) $I_{beam}$=50μA, U=6,5kV; 3) $I_{beam}$=70μA, U=6,5kV

The experiment was repeated at three different cluster current values (30 μA, 50 μA, 70 μA), and the radial distribution in the collector circuit was measured. The graphs of the radial current density distribution for each cluster current value are shown in Figure 4. When measuring the radial current distribution, if the beam radius is known, it allows for the calculation of the total divergence angle of the ion beam. In our experiments, the distance between the collector and the ion source was approximately 42 mm, while the beam current radius was about 44 mm.

$$\alpha = 2\ \mathrm{arctg}\frac{l}{r} = 2\ \cot\frac{42}{44} = 2\ \mathrm{arctg}\,(1{,}04) \approx 2\ \cdot 46° \approx 92°$$

Here, $l-$ represents the distance between the collector and the ion source, $r-$ is the radius of the current beam, and $\alpha-$ is the emission angle. In scientific literature, it has been demonstrated using transparent electron microscopes with electron energies of 1 MeV that the total scattering angle from the Taylor cone at the tip of the needle for materials such as Au, AuSi, CoGe, CoNd, In, Pb, and others during the ion emission process is in the range of 90° to 100° [8,9]. Clearly, the calculated emission angle in our experiments matches the values stated in the literature. This once again serves as strong evidence that we accurately determined the center of the ion beam during our measurements.

## RESULTS

Measurements were conducted at three different cluster current values (30 μA, 50 μA, 70 μA). In all three cases, a point in the collector circuit where the cluster current had the maximum value was identified and taken as the center of the ion cluster. Then, the piezostage was set in motion, and the beam current magnitude was measured at intervals of approximately 1 mm. The current density value at each point was calculated based on the recorded beam current values. The calculated scattering angle, based on the dimensions of the ion source and the ion beam from the emitter, corresponds to the sizes obtained by other authors and accepted in the literature.


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