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# ANALYSIS OF THE ION BEAM COMPOSITION OF InSb AND $(InSb)_{0.98}Bi_{0.02}$ OBTAINED BY LIQUID METAL ION SOURCE

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To investigate the mass composition of the ion beam obtained through field ion emission, a mass analyzer designed analogous to the Wien velocity filter was utilized. This Wien filter analyzer operates based on the principle of intersecting mutually perpendicular electric and magnetic fields (E×B) to classify charged particles according to their mass and charge. The ion beam was obtained using mInSb and $InSb_{0.98}Bi_{0.02}$ as the working materials. The mass composition of the ion group was analyzed using this method. In the experiments, it was found that the ion beam obtained using InSb as the working substance had a homogeneous composition, consisting solely of $(InSb)^+$ ions. However, in contrast, when the working substance was $(InSb)_{0.98}Bi_{0.02}$, it was determined that the ion beam had a miscellaneous composition. In addition to $(InSb)^+$ ions, the ion beam was found to contain $((InSb)_{0.98}Bi_{0.02})^+$ and $(Bi)^+$ ions.
**Key words:** *Liquid metal ion sources; LMIS; Sharp emitter; Ion beam; Mass analysis; InSb; InSbBi*
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## INTRODUCTION

A highly promising method for modification various surface structures is the deposition of nanodroplets on a conductive surface. Liquid metal ion sources (LMIS) or electrohydrodynamic ion sources (EHD emitters) with sharp emitters are commonly used for this purpose [1]. Sharp emitters exhibit the highest current density and a remarkably small emission area. They are capable of generating charged droplets of the working substance with nanoscale dimensions. The ability to focus the generated beams to submicron sizes makes them suitable for applications in microtechnology. Moreover, the generation of nanoparticles with diverse compositions is of great interest for thin film deposition and nanotechnology.

Under specific operating conditions, these sources also generate charged nanoparticles [2]. The determination of the emission area size in these sources has been the subject of extensive experimental and theoretical research. Theoretical estimates for the diameter of the emission area indicate a value of around 3-4 nm [3]. Based on this size, a high initial current density on the order of $10^8 A/cm^2$ is achieved.

Liquid metal ion sources have been the subject of intensive research in recent years, particularly for applications in submicrometer lithography, ion-stimulated chemical synthesis, implantation, and microanalysis. These sources are being studied for their capability to fabricate, analyze, and process surface relief with submicrometer resolution using focused ion beams. Initially, liquid metal ion sources relied on pure metals with low melting points as the working substances. However, addressing numerous contemporary technological tasks, including localized ion implantation, ion beam mixing, direct non-resistive ion lithography, and the fabrication of micro and nanoelectromechanical systems, necessitates the application of ion beams with various masses, charge states, and chemical properties [4]. This fact has stimulated the development of liquid metal ion sources using alloys, which allow for the generation of a wide range of different ions [5].

The purpose of the work is to obtain ion beams in liquid metal ion sources based on InSb and $(InSb)_{0.98}Bi_{0.02}$ working materials and to study their composition using an (E×B) Wien velocity filter [6].

## EXPERIMENT

The experiment was conducted in a vacuum chamber, specifically a Leybold-Heraeus type A700Q, and the overall schematic of the experiment is provided in Figure 1 [7,8]. A needle made of nickel-chromium (NiCr) with a diameter of 0.5 mm was used as the needle material. The needle was placed in a graphite container and heated to the melting temperature of the working substance (approximately 450°C) by the impact of thermo-electrons emitted from a heated cathode. Prior to the experiment, the needle tip was chemically treated and sharpened to ensure optimal wetting of the needle surface with the working substance.

It is known that Wien mass filters are mass and energy separators that operate by separating charged particles in crossed electric and magnetic fields perpendicular to each other. In our experiments, a mass analyzer similar to the Wien velocity filter was used for the mass analysis of ion beams, with crossed (E×B) fields. A homogeneous magnetic field in the analyzer was created by two smooth ferrite plates measuring (120×80×12) mm, positioned at a distance of 20 mm

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from each other. The magnetic field strength in the analyzer had a magnitude of $11.2\times10^4$ A/m. To generate the electric field, a specific controllable voltage was applied from a DC voltage source to the parallel electric plates (with a distance of 2 cm between them) resembling a capacitor configuration. The analyzer was positioned between the extractor and the collector. The collector is connected to ground through an ammeter, where the neutralization of positive ions occurs. In the experiments, the ion currents in the extractor and collector circuits were measured. Currents as low as $10^{-12}$A were detected in the collector circuit using a DC current amplifier, KEITHLER 6487.

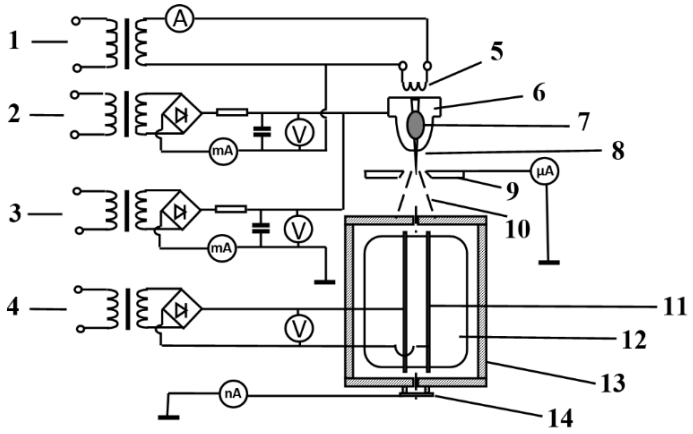


**Figure 1**. Experimental scheme of investigating the composition of the ion group using a Wien filter
1) electrical circuit of the heated cathode; 2) thermo-electron emission current circuit; 3) circuit of the extracting emission electric field; 4) circuit of constant voltage applied to the analyzer's electric plates; 5) filament; 6) container; 7) working substance; 8) needle; 9) extractor; 10) ion beam; 11) magnet; 12) frame; 13) plate; 14) collector.

The ion source was mounted on a Leybold-Heareus vacuum system, which provided vacuum of $6\times10^{-6}$mbar. The ion source was heated to the melting temperature of the working substance using therms-electrons emitted from the heated cathode [9]. To heat the working material to its melting temperature, the dependence of the container's temperature on the power supplied to the heater was used. At the same time, a high electric field is applied between the ion source and the extractor in advance. Once the source is heated and the working material melts, ion emission occurs, and the optimal power of the heater is maintained constant. In the experiments, the characteristics of the ion and nanoparticle phases were determined by gradually increasing the extraction voltage. Ion emission occurred above a threshold voltage of (5-6) kV between the source and the extractor (with a needle-extractor distance of approximately 0.5 mm) [10]. By applying a constant voltage to the plates of the analyzer, with emission currents ranging from 30-60 μA, the ion beam was separated based on the particles' mass and charge. The current in the collector circuit was measured using a picoammeter. Peaks in the current were observed in the collector circuit at specific constant voltage values on the analyzer, allowing for the determination of the mass composition of the ion beam.

## RESULTS AND DISCUSSION

Theoretical values of the fixed voltage applied to the plates generating the electric field of the analyzer were calculated in order to observe the current generated by the charged particles, which are potentially present in the ion beam obtained from InSb and $(InSb)_{0.98}Bi_{0.02}$ materials, in the collector circuit. For the current generated by particles of equal mass and charge to be observed in the collector circuit, it is essential for these particles to move in a straight trajectory inside the analyzer without sensing the electric and magnetic fields. To achieve this, the forces exerted on the particles by the electric and magnetic fields inside the analyzer must balance each other.

$$F_E = F_B; \mapsto qE = qvB \mapsto v = \frac{E}{B} = \frac{U}{Bd} \mapsto v = \sqrt{\frac{2qU_0}{m}}$$

In this case, $F_E$ and $F_B$ represent the forces exerted by the electric and magnetic fields, respectively, on the charged particles passing through the analyzer. By solving the last two equations simultaneously, we obtain the following expression for the fixed voltage applied to the plates creating the electric field of the analyzer [11]:

$$U = \sqrt{\frac{qN_A}{M} \cdot 2U_0 d^2 B^2}$$

Through this principle, we can find the voltage at which particles of different masses and charges in the beam can provide maximum collector current. Here, U represents the voltage applied to the plates generating the electric field of the analyzer, q is the charge of a singly ionized particle, $N_A$ is Avogadro's number, M is the molar mass, $U_0$ is the accelerating voltage applied to the extractor, d is the distance between the plates generating the electric field, and B is the

induction of the magnetic field. According to the above principle, theoretical calculations have been performed to determine the theoretical values of the fixed voltages at which different charged ions, whose presence is estimated in the composition of the ion beam entering the analyzer, can produce maximum collector current. The calculated values are given in Table 1 below.

**Table 1.** Voltage of the analyzer according to the value of mass and charge for different ions

| Ion species | U (V, DC) |
|---|---|
| $(InSb)_4^+$ | 95 |
| $(InSb)_3^+$ | 110 |
| $(InSb)_2^+$ | 130 |
| $(InSb)^+$ | 190 |
| $(InSbBi)^+$ | 140 |
| $(Bi)^+$ | 210 |

In the experiment conducted using InSb as the working material, the composition of the ion beam was investigated with an accelerating voltage of 6 kV and an emission current of 40 μA. The extractor was connected to ground through a microammeter. Only around a voltage of 190 V, a peak was observed (Figure 2). According to the table, this result corresponds to $(InSb)^+$ ions, which are singly ionized with a specific charge of $q/m_0 = 4.09 \cdot 10^5$C/kg. Therefore, the emitted ion beam consists exclusively of $(InSb)^+$ions. The same observation is obtained when the beam current is varied within the range of (30-50) μA.

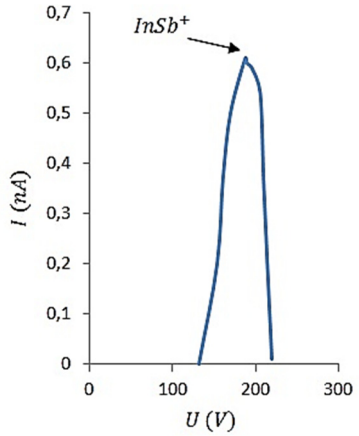


**Figure 2**. Composition analysis of the InSb ion beam ($U_0 = 6kV, I_b = 40\mu A$)

When the ion source based on $InSb_{0.98}Bi_{0.02}$working material was used, and the extractor voltage was 6 kV and 6.2 kV, with a beam current of 30 μA and 60 μA, the composition of the beam was investigated, and the results are presented in Figure 3. As observed in the figure, three distinct peaks are visible in both cases. These peaks correspond to ions with specific voltages: +190V for $(InSb)^+$, 142V for $((InSb)_{0.98}Bi_{0.02})^+$ and +210V for $Bi^+$ (Figure 3). The ion beam obtained from the combination of $InSb_{0.98}Bi_{0.02}$is not monatomic; instead, it consists of subclusters composed of ionized $(InSb)^+$, $((InSb)_{0.98}Bi_{0.02})^+$, and $Bi^+$ ions. The $((InSb)_{0.98}Bi_{0.02})$ ions have a specific charge of $q/m_0=2.16 \cdot 10^5$ C/kg. It is observed that as the beam current increases, the peak corresponding to Bi+ ions decreases in height. This is because of the higher accelerating voltage, which results in a larger portion of Bi atoms in the composition of $(InSb)_{0.98}Bi_{0.02}$semiconductor being emitted.

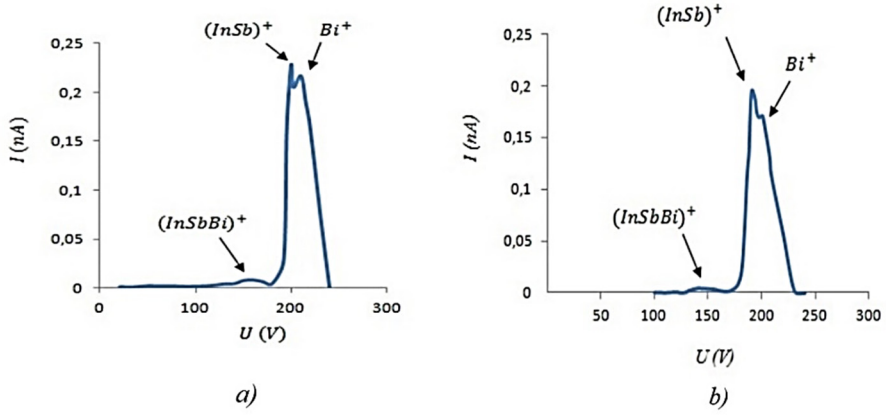


**Figure 3**. Composition analysis of the $(InSb)_{0.98}Bi_{0.02}$ ion beam: a) $U_0 = 6kV, I_b = 30\mu A$; b) $U_0 = 6.2kV, I_b = 60\mu A$

Thus, the results of the experiments conducted for the mass analysis of the ion groups obtained through the ion source of the considered compounds are in full agreement with the theoretically calculated values. The width of the slit at the entrance of the mass analyzer is 200 μm, and the diameter of the slit at the exit is 2 mm. These dimensions have been determined for analyzing the composition of a specific portion of the ion beam current, taking into account the resolving power of the analyzer.

## CONCLUSIONS

Composition analysis of ion beams was conducted using the field ion emission method for ion sources based on InSb and $(InSb)_{0.98}Bi_{0.02}$ as working materials. The ion beam obtained from the InSb substrate was monatomic and comprised solely of singly ionized $(InSb)^+$ ions. However, the beam obtained from the $(InSb)_{0.98}Bi_{0.02}$ material consisted of three subclusters, each consisting of singly ionized ions. The experimental results align with theoretical calculations.

**Data availability statement**

The manuscript was performed at the laboratory "Infrared photoelectronics and plasma phenomena" of the Institute of Physics Ministry of Science and Education of Azerbaijan Republic.

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## REFERENCES

[1] P.A. Mazharov, V.G. Dudnikov, and A.B. Tolstoguzov, "Electrohydrodynamic emitters of ion beams" UFN, **190**, 1293 (2020). https://doi.org/10.3367/UFNr.2020.09.038845
[2] C. Cruz, K. Paurezzaci, and A. Wagner, "Ion cluster emission and deposition from liquid gold ion sources," J. Appl. Phys. **58**, 2724–2730 (1985). https://doi.org/10.1116/1.570316
[3] D.R. Kingham, and L.W. Swanson, "A theoretical model of a liquid metal ion source," Vacuum, **34**(10-11), 941-945 (1984). https://doi.org/10.1016/0042-207X(84)90175-1
[4] L. Bruchhaus, *et. al*., "Comparison of technologies for nano device prototyping with a special focus on ion beams," J. Appl. Phys. Rev. **4**, 011302 (2017). https://doi.org/10.1063/1.4972262
[5] L. Bischoff, P. Mazarov, L. Bruchhaus, and, J. Gierak, "Liquid metal alloy ion sources—An alternative for focussed ion beam technology," Applied Physics Reviews, **3**(2), 021101 (2016). https://doi.org/10.1063/1.4947095
[6] L. Bischoff, N. Klingner, P. Mazarov, K. Lenz, R. Narkowicz, W. Pilz, and F. Meyer, "Dysprosium liquid metal alloy ion source for magnetic nanostructures," Journal of Vacuum Science & Technology B, **40**(5), 05282 (2022). https://doi.org/10.1116/6.0001837
[7] I.S. Gasanov, I.I. Gurbanov, and E.M. Akbarov, Eur. Phys. J. D, **69**, 75 (2015). https://doi.org/10.1140/epjd/e2015-50531-0
[8] I.S. Gasanov, I.I. Gurbanov, and E.M. Akbarov, ACTA Physica Polonica A, **134**(1), 119 (2018). https://doi.org/10.12693/APhysPolA.134.119
[9] S.A. Aliyev, F.E. Mammadov, E.M. Akberov, I.I. Gurbanov, A.A. Badalov, and Sh.O. Eminov, "Main elements and characteristics of electrohydrodynamic ion sources based on InSb," Azerbaijan J. of Physics, **XXIX**(3), section En, 19-23 (2023).
[10] L. Bischoff, N. Klingner, P. Mazarov, W. Pilz, and F. Meyer, "Boron liquid metal alloy ion sources for special focused ion beam applications," Journal of Vacuum Science & Technology B, **38**(4), (2020). https://doi.org/10.1116/6.0000073
[11] I.S. Gasanov, *Plasma and beam technology,* (Science, 2007), pp. 67-68. (in Russian)

## АНАЛІЗ СКЛАДУ ІОННОГО ПУЧКА InSb ТА $InSb_{0,98}Bi_{0,02}$, ОТРИМАНОГО З ВИКОРИСТАННЯМ РІДКИХ МЕТАЛІВ

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Для дослідження масового складу пучка іонів, отриманого за допомогою польової іонної емісії, використовувався мас-аналізатор, розроблений аналогічно фільтру швидкості Віна. Цей аналізатор фільтра Wien працює на основі принципу перетинання взаємно перпендикулярних електричного та магнітного полів (E×B) для класифікації заряджених частинок відповідно до їх маси та заряду. Іонний пучок отримано з використанням робочих матеріалів mInSb та $InSb_{0,98}Bi_{0,02}$. Цим методом аналізували масовий склад іонної групи. В експериментах було виявлено, що іонний пучок, отриманий з використанням InSb як робочої речовини, має однорідний склад, що складається виключно з іонів (InSb)+. Однак, на відміну від цього, коли робочою речовиною був $(InSb)_{0,98}Bi_{0,02}$, було визначено, що іонний пучок має різний склад. Крім іонів (InSb)+, було виявлено, що пучок іонів містить іони $((InSb)_{0,98}Bi_{0,02})$+ і (Bi)+.

**Ключові слова**: *рідкометалеві іонні джерела, LMIS, гострий емітер, іонний пучок, масовий аналіз, InSb, InSbBi*