Angular distributions of Ga^+ and In^+ ions emitted from a gallium–indium alloy liquid-metal ion source

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There is a pronounced difference between the angular distributions of the gallium and indium ions emitted from a gallium–indium alloy liquid-metal ion source. A qualitative explanation is offered for the effect on the basis of a difference between the evaporation fields for gallium and indium ions.

Liquid-metal ion sources are finding progressively wider use in ion-beam apparatus for the microanalysis and microprocessing of various materials.[1] Many such sources, some using single elements and some using alloys, have been developed. These sources can furnish essentially the entire list of ions of interest.[2] However, the operating mechanism of these sources is not totally clear. In particular, in the case of alloy liquid-metal sources there are uncertainties regarding the interaction of the different elements of the alloy in the ionization zone. In descriptions of these sources it is usually assumed that the ions of all the components of the alloy have the same angular distribution, so the ratios of the flux densities of the different ions measured in only a single direction, usually along the axis of the emission cone, are reported. In the present study it has been found that the angular distributions of the ions of the different elements emitted by an alloy liquid-metal source may actually be quite different.

Our experimental apparatus included an MI-1201T mass spectrometer. The liquid-metal ion source was a thin tantalum tube filled with the gallium–indium alloy (94 at.% Ga and 6 at.% In). A tungsten tip protruding from this tube was welded to holders through two tungsten filaments. The source was mounted on a drum which rotated in a vertical plane, in such a way that the end of the tip was on the rotation axis, opposite the middle of the entrance slit of the mass spectrometer. This slit was covered with a screen with a horizonal slit about 1 mm wide, opposite its middle. The effect was to achieve an angular resolution $< 1°$. The vacuum in the entrance part of the mass spectrometer during operation of the liquid-metal ion source was $10^{-6} - 10^{-7}$ Pa.

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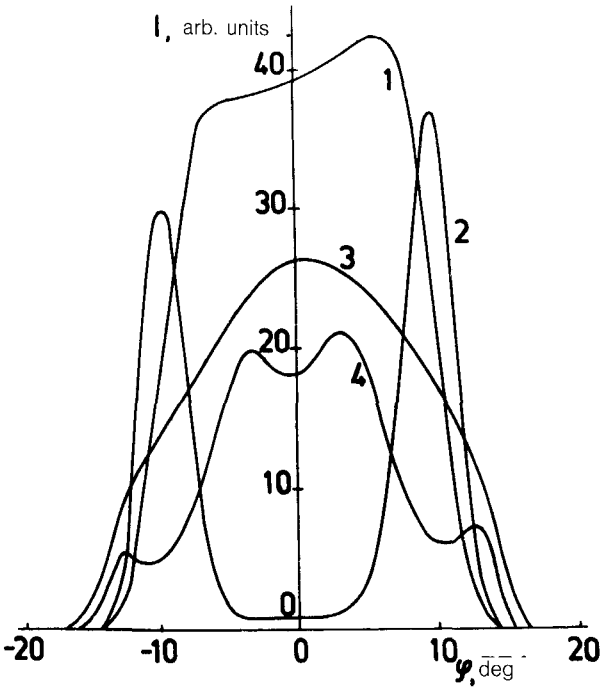

FIG. 1. Angular distributions of $^{69}Ga^+$ and $^{115}In^+$ ions emitted from a gallium–indium alloy liquid-metal ion source at an emission current of 2 μA and at various source temperatures. *1*—$^{69}Ga^+$, $T = 300$ K; *2*—$^{115}In^+$, $T = 300$ K; *3*—$^{69}Ga^+$, $T = 500$ K; *4*—$^{115}In^+$, $T = 520$ K. The vertical scale for the $^{115}In^+$ ions has been enlarged by a factor of 10.

Figure 1 shows angular distributions of $^{69}Ga^+$ and $^{115}In^+$ ions for a source at room temperature and for a low emission current, 2 μA, close to the threshold. We see that these distributions are completely different. That of $^{69}Ga^+$ is similar to the typical angular distribution of singly charged ions for a single-element source at low temperatures.[3]. This distribution is somewhat asymmetric, probably because of an asymmetric shape of the end of the tip. For the $^{115}In^+$ the angular distribution has clearly expressed maxima at angles of $\pm 10°$. The "angular density" of the indium ion current at these maxima is higher than that at the center of the emission cone by a factor of several tens. If a screen is placed in an orientation perpendicular to the axis of the emission cone, the mark left by the Ga^+ ions on the screen is found to be a circle, while that left by the In^+ ions is a ring.

As the source temperature is raised, the angular distribution of the $^{69}Ga^+$ ions, at $T \approx 350$ K, begins to smooth out and to broaden. At $T \approx 500$ K, it acquires the typical "high-temperature" shape, with a maximum at the center of the emission cone and with a sharp decay at the edge of the cone. On the angular distribution of the $^{115}In^+$ ions, the maxima begin to broaden and decrease in height as early as $T \approx 330$ K; the current at the center of the cone increases. At $T \approx 380$ K, each maximum splits in two. As the temperature is raised further, the inner maxima grow and move toward each other, while the outer maxima shrink and move away from each other.

To find a possible reason for the difference between the angular distributions of

the Ga^+ and In^+ ions for a source at room temperature, we consider the operation of an alloy liquid-metal source under stable conditions; stable conditions probably prevail when the source is at low temperature, and the emission current is low. The electric field causes the liquid metal to form a Taylor cone at the end of the tip. A thin protuberance (with a diameter less than[4] 10 nm) grows here. As the length of this protuberance increases, the electric field at its end increases, and an intense emission of ions begins. The length of the protuberance stabilizes in such a way that the electric field at its end, produced by the external potential and the ion space charge, becomes equal to the ion evaporation field. The field at which the evaporation energy of the singly charged ions reaches zero is proportional to the square of the heat of vaporization (q_i) of a singly charged ion, which is given by

$$q_i = q_a + v_i - \varphi.$$

The heat of sublimation q_a for In is about 0.4 eV, while the ionization potential v_i is 0.2 eV lower than that of Ga. As a result, for a work function φ of about 4 eV the evaporating field for In^+ is about 30% lower than that for Ga^+. While the evaporating field for Ga^+ is reached at the end of the protuberance in the In–Ga alloy source, for In^+ this field is reached at a certain distance from the end. The In^+ ions thus evaporate from the lateral surface of the protuberance, contributing to the side maxima (Fig. 2). Because of the small thickness of the protuberance, this process leads to the effective removal of In from the jet. The concentration of this element at the end of the protuberance thus becomes very low. Correspondingly, there is a sharp decrease in the In^+ current at the center of the emission cone.

As the temperature is raised, the operating regime of the source at a low emission current changes substantially. Detailed studies of a gallium liquid-metal ion source in Refs. 5 and 6 and also in our own laboratory (the results are to be published in *Ukrainskiĭ fizicheskiĭ zhurnal*) have shown that there is a pronounced change in the angular distribution of the Ga^+ ions here. The energy distribution of these ions becomes much wider, and the central part of the emission cone acquires a large number of slow ions. In the same part of the emission cone we find the appearance of Ga_2^+ ions

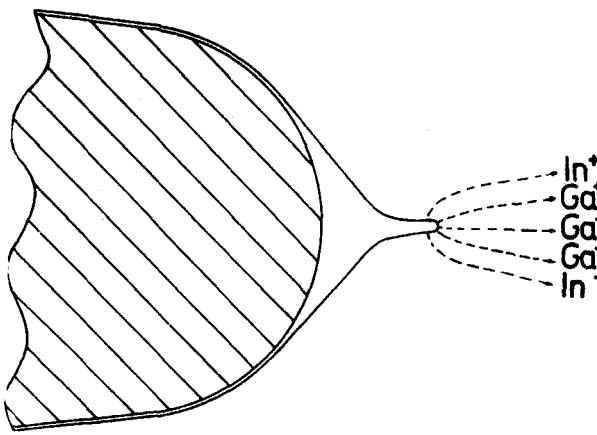

FIG. 2. Proposed mechanism for the spatial separation of gallium and indium ions in an alloy liquid-metal ion source operating under stable conditions.

with a large energy deficiency, while a minimum appears in the central part of the emission cone on the angular distribution of the doubly charged $Ga^{+\,+}$ ions. These results agree best with the model of Ref. 7, according to which the protuberance at the end of the Taylor cone becomes unstable at high source temperatures, and charged droplets as well as ions are emitted from the protuberance. Forming in a strong electric field, these droplets carry a significant positive charge, and they explode not far from the protuberance, creating a cloud of neutral atoms, singly charged diatomic ions, and charged clusters. The change in the angular distribution of the In^+ ions appears to reflect a change in emission mechanism. In addition to the evaporation from the lateral surface of the protuberance, In^+ ions evaporate from the exploding droplets and from the points at which the droplets detach from the protuberance at high source temperatures.

We wish to stress that the substantial difference observed between the angular distributions of ions of different elements in these experiments should be taken into consideration in theoretical work on the operating mechanism of alloy liquid-metal ion sources and also in the practical use of these sources.

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