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ABSTRACT

of the dissertation for the degree of Doctor of Philosophy

FORMATION OF SMALL STRUCTURES ON THE SURFACE IN THE CASE OF FIELD EMISSION

Specialty:	2203.01 - Electronics
Field of science:	Physics

Applicant: **Elchin Mammadhuseyn Akbarov**

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The work was performed at the Institute of Physics of Azerbaijan National Academy of Sciences, laboratory of "Infrared photoelectronics and plasma phenomenas".

Scientific supervisor:

Doctor of physical sciences, associate-professor
Ilham Soltan Hasanov

Official opponents:

Doctor of physical sciences, associate prof.
Ayaz Hidayat Bayramov

Doctor of physical sciences, associate prof.
Elchin Ahmed Kerimov

Ph.D. in physics, associate prof.
Elshan Fayaz Nasirov

Dissertation council BED 1.14 created on the basis of the dissertation council ED 1.14 of Supreme Attestation Commission under the President of the Republic of Azerbaijan operating at the Institute of Physics of Azerbaijan National Academy of Sciences.

Chairman of the Dissertation council:

Active member of ANAS,
Doctor of physical and mathematical science, prof.
Nazim Timur Mammadov

Scientific Secretary of the Dissertation council:

Doctor of Physical Sciences, associate prof.
Rafiga Zabil Mehdiyeva

Chairman of the scientific seminar:

Doctor of Physical Sciences, associate prof.
Tahir Djumshud Ibrahimov

GENERAL DESCRIPTION OF THE WORK

Relevance of the research topic. Long-term improvement of plasma ion sources has provided development in many scientific and technical areas, such as acceleration technique, electromagnetic separation of isotopes, ion-beam technology in solid state physics and microelectronics, plasma physics and controlled thermonuclear fusion, long-term operation of spacecraft, etc. In this type of device, ions are formed as a result of the collision of electrons with atoms and molecules in a gas-discharged plasma, and the concentration of ions in the formed beam is determined by the density of the plasma. Although it has long been desired to improve the ion-optical characteristics of plasma sources in various ways, this has not been possible.

In principle, the best method is the ion field emission method. This method allows to significantly increasing the current density of the ion beam, the emission of ions is carried out from the liquid condensate phase under the influence of a high electric field. Here, the high density of the ion beam current is due to the fact that under the influence of a high electric field, the surface of the liquid is stretched and sharpened, the value of the electric field at the sharp end increases many times, and thus the flow of all atoms becomes ionic beam. Of course, the beam current is small compared to the plasma emitter, but in liquid metal ion sources the beam brightness is several orders of magnitude larger than the others because the dimensions of the emission zone is extremely small.

Many peculiar physical phenomena occur in the conductive liquid emitter: the surface of the needle is wetted with the working substance, the liquid flows to the top in the needle heated by electron bombardment, the surface of the liquid is deformed under the influence of high electric field, ions are generated in the extremely small region, excited atoms radiate and a large expansion occurs in the spectral line.

At a certain value of the ion current along with ions, charged nanoparticles are also generated. When the metal stream is stretched long enough, the electric field breaks the tip of the stream and leads to the formation of the charged finely dispersed phase on the beam. The counter-impulse of the nanoparticle excites the surface of the liquid and causes capillary instability. As a result, the ion current is subjected to high-frequency oscillations.

Surface modification by means of liquid metal ion sources is mainly carried out by deposition of focused ion beams on the surface. Here, the beams are obtained by a liquid metal ion source and then focused using an electrostatic lens. This method is quite complicated, because the lenses are subject to various distortions. However, the conditions for short-range surface modification without the use of electrostatic lenses have not been studied.

We have studied both the deposition of charged nanoparticles and the modification of the surface without the use of ionic optics to create small-scale structures. At the same time, the physical processes that occur during the generation of charged nanoparticles in the beam as a result of their collision with ions were studied. Nanoparticles of various elements such as gold, silver, indium, tin, etc. were obtained and the processes of their deposition on the surface were considered.

Dissertation work fulfilled the scientific research plan of the Institute of Physics of Azerbaijan National Academy of Sciences.

Aims and purpose of the research:

The purpose of the dissertation is the generation of nanoparticles of various metal elements using the phenomenon of field ion emission and to determine the physical processes that occur during the formation of small-scale structures on the conductive surface.

In order to achieve the purpose of the dissertation, the following tasks were set:

- Determination of the technology of making needles, which is a key element of liquid metal ion sources, identification the differences and advantages of needles made by mechanical and electrochemical methods;
- Determining under what conditions the working substances wet the needle made of what material;

- Determination of the current-voltage characteristics of the source during the emission phenomenon, as well as the current of obtaining nanoparticles and their size;
- Investigation of collisions of fast ions with heavy nanoparticles;
- Preparation of small-scale structures on the conductive surface that can be moved by means of a remote-controlled piezo-table.

Research methods:

In the dissertation work generation of ions (In+, Sn+, Au+) and charged nanoparticles of these elements in a liquid metal source, narrow and long strips precipitated by a finely dispersed phase, the formation of a space charge of electrons by thermal emission in a Gabor lens were used as research objects.

Main provisions for the defense:

- Estimation of energy loss and free path in matter as a result of the passage of fast ions through charged nanoparticles in a multicomponent ion beam.
- Deposition of narrow and long strips on a moving substrate located in close distance and evaluation of the practical wqapplication of the method.
- Calculation of the accumulation time of compensating electrons in the electromagnetic trap, at focusing of the pulsed beam of heavy ions by the plasma lens.

The scientific novelty of the research:

- For the first time, the needle, the main element of the ion source, was made of tungsten material and soaked in a vacuum under a eutectic alloy of gold.
- Energy loss of ions was observed in the multicomponent beam and this phenomenon was explained as a result of the collision of the components.
- In and Sn strips of micrometer scale are deposited on a moving conductive substrate located close to the source needle.
- The space charge accumulation time of electrons in the plasma lens to focus pulsed heavy ion beams was calculated.

The teoretical and practical significance of the research: The interaction of different particles in complex ion beams and their consequent energy losses must be taken into account in spectrometers, energy analyzers, accelerators and other systems. In space charged lenses the duration of the electric field creation has a certain effect on the formation of pulsed ion beams. The deposition of thin and long strips on the surface by means of a liquid metal ion source can find application in microelectronics.

In the dissertation work generation of ions (In+, Sn+, Au+) and charged nanoparticles of these elements in a liquid metal source, narrow and long strips precipitated by a finely dispersed phase, the formation of a space charge of electrons by thermal emission in a Gabor lens were used as research objects.

Approbation and implementation:

The materials of the dissertation were discussed at the following international and national conferences:

- “Large-scale research projects-2012, “Materials science and informatics for high technologies” November 9-12, 2012, Baku;
- “Swift Heavy Ions in Matter” International Conference, May, 2015, Germany;
- “Materials of the XX Republican Scientific Conference of Doctoral Students and Young Researchers” , 2016, Baku;
- 2nd International Scientific and Technical Conference "Problems of Metallurgy and Materials Science", November 28-30, 2017, Baku;
- International Scientific Conference of Masters and Young Researchers "Problems of Physics and Astronomy", May 24-25, 2018, Baku.

Publications. According to the main results of the dissertation, 11 works, including 6 articles, 5 theses and conference materials were published abroad ("Science Citation Index") and in republican scientific journals, conference materials. The list of works is given at the end of the abstract.

Name of the organization the Dissertation has been performed:

The dissertation was performed at the laboratory “Infrared photoelectronics and plasma phenomena” of the Institute of Physics of the Azerbaijan National Academy of Sciences.

Volume, structure and main content of the dissertation:

The dissertation consists of an introduction, 5 chapters, results and a list of used sources of 99 items. The volume of work consists of 200548 characters, excluding figures, tables, graphs and a list of references, contains 7 tables, 60 figures.

CONTENT OF WORK

In the **introduction** of the work, the relevance of the topic is substantiated, the purpose of the work and the main provisions of the defense are indicated, scientific innovations and the scientific and practical significance of the obtained results are reflected.

The first chapter provides a comparative analysis of the scientific literature related to the dissertation. Here information is given on the physical processes occurring on the surface of a conductive liquid emitter, the emission of ions and nanoparticles from the surface of the liquid, the generation of charged particles and their size, the structure of various types of liquid metal ion sources, source life, angular intensity and distribution, emitter preparation technology and other topics. It has been shown that the equilibrium condition on the surface of a liquid in the system consisting of cone-shaped liquid electrode and extractor system with potential difference between them, depends on the relationship between the surface tension coefficient and the electric field intensity, and the physical processes that occur during the emission of ions during the increase in the value of the electric field are explained in detail.

The second chapter describes the working principle and preparation parameters of the ion source, as well as the methodology of experimental measurements and electrical circuits. Topics as the assembly of a container-type liquid metal ion source, placement in a vacuum device, technology for mechanical and chemical preparation of anode needles, principles for studying the composition of beams using a mass-analyzer, the principle of operation of MS2000 piezo-table for small surface etching and placement in a vacuum device has been widely described.

It has been shown that one of the main elements of liquid metal ion sources is the needle. Thus, the working substance is located on the needle and melts during heating and flows along the surface to the sharp end of the needle. Depending on the type of working substance, the material of the needle should be selected so that it is moistened by the working substance. At the same time, the melting point of the needle material must be greater than the melting point of the working substance. The voltage of the creation of emission phenomenon and the durability of the needle directly depend on the sharpness of the needle being made. Due to the high emission voltage during mechanical sharpening of the needle, it is necessary to make it sharper. For this purpose, the needles are sharpened chemically.

Once the sharpening process is complete, the needle is examined under a microscope. Figure 1 shows a tungsten needle moistened by eutectic alloy of gold. It is known that at the melting temperature of gold (1063 ^{o}C) the pressure of saturated steam is quite high. In this case, gas discharge occurs, and stable emission of ions is not obtained. Therefore, eutectic alloy of gold is used. For example, an alloy containing 88% Au and 12% Ge has a melting point of 361^{o}C. For experiments such a working substance was synthesized in the laboratory. Wetting the source needle by molten material is one of the most important conditions. A special technological operation has been developed for wetting the tungsten needle by a liquid alloy. The needle is placed in a narrow graphite boat and the working part is sprinkled with powder of the working substance. The boat is closed with a graphite cap and heated under vacuum until the substance melts. In this way, the wet end of the needle is placed in the oven and the working substance is added there.

Here also is provided information on plasma-optical systems, emphasizing that in some cases conventional optical systems are insufficient and therefore ion-optical systems are needed in order not to distort the initial distribution of the space charge potential of the beams. The advantage of the plasma-optical method in the focusing of high-current beams is substantiated, the peculiarities of focusing with the help of electromagnetic fields in the volume of the quasi-neutral beam are studied.

Figure 1. Tungsten needle wetted by Au + Ge alloy

The third chapter examines the energy losses that occur when fast ions in a beam collide with charged nanoparticles. Topics such as nuclear losses, electron losses and energy losses during the generation of charged nanoparticles have been widely discussed. In order to investigate the energy losses during the generation of charged nanoparticles, the dependence of the current recorded in the collector circuit at different values of the ion beam current on the value of the electric field applied between the analyzer jackets was investigated, graphical descriptions of the measurements are given. It has been explained that the ions moving outside the axis of the beam do not lose energy or that the energy of the ions moving in the center of the beam decreases due to their interaction with the charged nanoparticles as they propagate along the system axis.

In the liquid metal source operating in the mode of generation of charged nanoparticles (In, Sn, Au, Ge), energy losses of ions close to the axis and a decrease in the ion current at the center of the beam were observed. In the experiments, nanoparticles with a size of

2-20 nanometers and a characteristic specific charge of $5 \cdot 10^4$ C/kg were found. The energy spectra of the ions were determined using a velocity filter with transverse static electromagnetic fields. A 4% decrease in the energy of In^+ ions was observed under the conditions of the measurements. The flow of nanoparticles, unlike the ion beam, has a small radial dispersion; no change in the velocity of the ions was observed outside this flow. Energy losses of ions occur when they fly through small nanoparticles. The depth of penetration of accelerated ions in liquid indium was estimated using the Lindhard-Scharff-Schiott model. Similar interactions between components occur in complex ion-cluster systems where the relative motion of different charged particles exists.

The energy losses of accelerated ions occur, for example, during the interaction of ion beams with the plasma and the surface of the solid. The Coulomb collision model is used to determine energy losses in plasma. The results of these calculations are in good agreement with the experimental results. As accelerated ions pass through the condensed matter, their inelastic collisions with electrons and elastic ones with the nuclei of atoms are considered. When the energy of the ions is small, the depth of their penetration into the substance until they stop completely is determined mainly by the interaction with the nuclei. The evolution of the ion distribution function also takes place within a beam with a high concentration of particles. The transverse scattering of ionic energy increases under the influence of fluctuating electric fields, resulting in a decrease in the brightness of the beam.

Collisions can also occur between different fragments of the beam, during their relative movement. The same situation applies to different types of mass analyzers in the separation of complex ion beams. In this study, the energy losses of ions in a liquid metal ion source are considered. Under certain conditions, ions and charged nanoparticles are formed in such sources, which can be deposited on the surface of the solid. This is of interest for the formation of various quantum structures.

A container-type compact ion source was used to create the beams. The working substance (Sn, In, Au, Ge, BNiAl eutectic) together with a wetted needle (W, Fe, Ni) is placed in a graphite container heated from the back side by bombarding with electrons until reaching the melting point of the working substance. The voltage that accelerates the ions is measured directly between the needle and the extractor, i.e. after the limiting resistance. The composition of the beam and the energy spectra of the ions were determined using an analyzer with intersecting fields (for example, with Vine's velocity filter). The mass analyzer can be moved by micrometric screws relative to the axis of the beam at two intersection coordinates without breaking the vacuum. The oscillation spectrum of the beam current was recorded using an S4-25 analyzer with a frequency range of up to 60 MHz. The distribution of the ion current within the radius of the beam was determined using a small multi-channel probe. The measurement system was calibrated using standard devices and the physical measurements were repeated to collect statistical data.

The experimental system is based on the A700-Q Leybold-Heraeus vacuum device, which provides a final vacuum of $5\cdot10^{-6}$ Torr.

It is known that emissions from liquid metal ion sources are stable at small ion currents. At a certain threshold beam current (approximately 40 μA) high-frequency oscillations occur, which is observed with the formation of charged nanoparticles with dimensions of 2-20 nanometers and a specific charge e/m = $5\cdot10^{4}$ C/ kg (In, Sn). The dimensional distribution of nanoparticles is characterized by a decrease in decreasing exponential function; the amount of particles of minimum size is 3 orders of magnitude greater than the amount of particles of maximum size. Calculations show that an average one elemental charge is required for 16 nanoparticle atoms.

The oscillations of the beam current are due to the formation of capillary instability of the Taylor cone with a system of standing waves on its surface. The discrete form of the spectrum of oscillations is related to this. Experiments have shown that during emitter instability, the density of the ion current in the center of the beam decreases slightly relative to the periphery of the beam.

At different values of the ion beam current, the dependence of the current recorded in the collector circuit on the value of the electric field applied between the analyzer jackets was measured.

A mechanically made needle made of 0.5 mm Ni wire was wetted by In at room temperature, then placed in a graphite bowl with the working substance and fastened to the container. The container was placed in an A700Q vacuum device. The analyzer was then placed on a table that could be moved mechanically from outside the chamber in two coordinates to investigate the composition of the beam. The width of the slit at the analyzer inlet was determined to be 50 μm. The vacuum device was activated and the experiment was performed when the chamber pressure was $2 \cdot 10^{-5}$ Torr. First, heat the needle, a current of $I_{cathode}$ = 20 A was applied to the tungsten cathode.

After about 5 minutes, a voltage of U=6 kV was applied between the needle and the extractor to obtain the emission, and the current in the beam was I_{beam} = 30 μA. Under these conditions, the current in the collector circuit was measured at different values of the voltage between the analyzer jackets. Then a voltage of U=6.2 kV was applied again between the needle and the extractor, in this case, the beam current was I_{beam}= 50 μA, and the current in the collector circuit was measured at different values of the voltage between the analyzer jackets.

Thus, while maintaining the conditions of the experiment, the repetitive energy spectra of the ions were measured at the center of the beam and outside its axis. The latter was obtained by moving the mass analyzer along the beam axis. The spectrum was obtained in two modes: without and with the formation of nanoparticles (curve 1, I_b = 30 μA and curve 2, I_b = 50 μA, respectively). The electric field intensity of 140.5 V/cm in the analyzer corresponds to ions with an energy of 6 keV (Figure 2).

As can be seen, with the formation of nanoparticles, the spectrum at the center of the beam shifts towards small energies at a maximum of 250 eV, and outside the beam axis, it moves towards maximum energies. The latter shows that in order to increase the beam current, it is necessary to increase the output voltage U_b. It is known that charged nanoparticles in liquid metal ion sources propagate only in the form of clusters with a divergence angle of 3-4^o (ion cluster divergence is up to 90^o). Non-delaying of the ions moving outside the axis of the beam indicates that the decrease in the energy of the ions is due to their interaction with the charged nanoparticles as they propagate along the axis of the system. The relative velocities of ions and nanoparticles are 0.75 v_i, where v_i is the velocity of the ions under the conditions of our experiments. The interaction of ions with nanoparticles occurs at the inlet of the mass analyzer with a needle (at a distance of about 10 mm). The magnetic field of the analyzer then separates the various components of the beam.

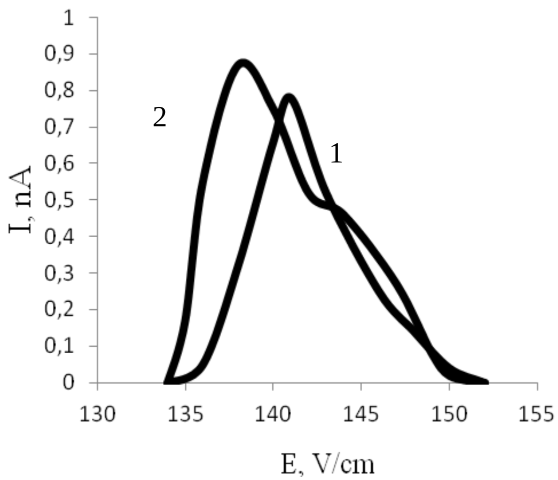


Figure 2. Dependence of the ion current passing through the analyzer at the center of the group on the intensity of the electric field":
In_1^+: 1 - I_b = 30 μA, U = 6 kV; 2 - I_b = 50 μA, U = 6.2 kV.

In the field emission of ions, the Rayleigh instability of the dispersed liquid stream occurs, which results in the separation of the nanoparticles. The period of development of instability is defined by the expression

$$t = \frac{1}{2\gamma_m}\left(ln\frac{\sigma}{Tk_{min}} + 2ln\frac{vk_{min}^2}{\gamma_m}\right) \qquad (1)$$

where σ is the coefficient of surface tension; γ_m is maximum increment of linear theory; T is temperature of the liquid; k_{min} is wave number corresponding to the maximum increment; υ is the kinematic viscosity coefficient. According to this formula, the calculation of the breakdown time gives a value of approximately $t=10^{-10}$ s. During this time, the early formed nanoparticles will cover a distance of 2.45 μm. Then, for the total number of nanoparticles in the ion scattering stream during the flight to the analyzer inlet, we will obtain an approximate value of $N=10^4$ particle in a cylinder with a radius of 130 μm and a height of 10 mm.

The penetration depth of the accelerated ions in condensed matter is considered in the theory of Coulomb collisions of atoms with electrons and nuclei. When the energy of ions is low, their stopping is determined by the elastic interaction with the nuclei and the penetration depth into the substance is calculated from the expression

$$R_n = 2kE_0 \qquad (2)$$

Here

$$k = \frac{1{,}8\left(Z_1^{\frac{2}{3}} + Z_2^{\frac{2}{3}}\right)^{\frac{1}{2}}}{NZ_1Z_2}\frac{M_1 + M_2}{M_2}\ nm\,(eV)^{-1},$$

Z_1, M_1 and Z_2, M_2 are the nuclear numbers of the initial ion and substance atoms, respectively; N is the concentration of atoms, nm^{-3}. For liquid indium at E_0 = 3.38 keV, the relative velocity $v_i - v_{np}$ for both nanoparticles and N = 34.1 nm^{-3}, the expression (2) gives R_n = 1.54 nm. The depth of penetration of ions is smaller than the observed minimum d_{np} = 2 nm of nanoparticles, so the ions must lose all energy. However, it should take into account that the probability of the ion flying along the diameter of the droplet is much smaller than that along all the shorter parts.

It is known that charged nanoparticles and clusters containing 30 atoms are intensively formed in liquid metal sources. The size of such clusters (approximately 1 nanometer) is smaller than the penetration depth calculated for ions in our conditions, R_n = 1.54 nm. Most likely, the resolution of the Tesla electron microscope we used was not enough to observe such small particles. Thus, the ions lose some of their energy as they pass through the small nanoparticles and leave them in the original direction.

A separate view of the charged state of the fast ion passing through the nanoparticle is required. Experiments is known in which a rapid flow of neutral atoms propagating along the beam axis is observed. The energy spectrum of these atoms is quite wide. Of course, it can be assumed that some of the ions are neutralized as they fly through the tiny nanoparticles.

From Figure 2 (curve 2) it can be seen that there is a part of the ions with a high enough energy. It is likely that this beam of ions was distributed outside the nanoparticle beam and did not interact with it. A similar shape of the peak in the energy spectrum is observed for diatomic ions, indicating that they participate in these processes along with single atomic ions.

The absorption of some of the ions close to the axis as a result of the collision with the nanoparticles and loss of their charge confirms the decrease in current in the center of the beam.

The fourth chapter examines the processes of deposition of nanoparticles to create surface structures. The process of deposition of In nanoparticles on tungsten, silicon, copper, molybdenum plates at different voltages, different values of emission current and different values of the movement speed of the piezo-table was studied, images of the obtained samples were given and explained.

In a certain mode of the source, ions (In, Sn, Au, Ge) and nanoparticles are generated simultaneously. The generation of nanoparticles is accompanied by the excitation of capillary instability over the liquid emitter, which leads to the modulation of the ion current.

Deposition of narrow strips can be achieved without complex ion optics, because a beam of nanoparticles has a very small separation angle of up to 20^o. If the transverse moving seat is placed close to the source needle, a deposited strip will be obtained. When the seat is placed hundreds of microns away from the needle and moved horizontally relative to the needle by the MS 2000 piezo-table, 20 μm wide indium strips are deposited. To obtain narrower strips, the seat should be placed at a closer distance and heat should be taken away from the heated area so that the rapid condensation of nanoparticles on the cooled surface does not stick to each other.

As we know, different technologies are used to create various small-dimension structures on the surface. Obtaining of structures usually consists of several stages and therefore requires considerable time. Placing nanoparticles, prepared in a certain way, directly on the surface simplifies the technology. It is possible to use a liquid metal ion source for this purpose. Such sources have been studied for a long time. Conducted theoretical and experimental studies have shown that electric field emission has the highest initial current density and brightness. This is due to the fact that the emission zone of ions is very small (~ 5 nm). The sharpening of the liquid surface is obtained as follows. The source emitter-needle is made of refractory metal. The radius of its sharp tip is a few microns. The working substance (pure metals, their compounds, semiconductors) with a relatively low melting point is in a container in the back. The container and the needle are heated to the melting point of the working substance and the liquid wets the needle (for this purpose the material of the needle must be selected according to the working substance).

When a voltage of a few kilovolts is applied between the extractor and the needle, the liquid at the tip of the needle stretches and a small protruding protrusion forms. As a result of tunneling at a certain threshold voltage, ions are released directly from the liquid into the vacuum (field emission) and accelerate in the electric field. As the voltage increases, the ion current also increases and the liquid protrusion becomes longer. At a certain value of the current (40 μA, Sn, In) the pressure of the electric field exceeds the surface tension pressure of the liquid and pulls the charged nanoparticles out of the emission region (Figure 3).

The distribution of nanoparticles in a narrow beam can be applied to the deposition of narrow strips on the surface. It is not necessary to use complex ion optics for this. If the flat conductive seat is placed too close to the needle, a narrow strip will form on the surface during its horizontal movement during emission. An MS 2000 (USA) piezo-table was used to move the seat in three directions with great precision. The ion source and piezo-table were located in a vacuum chamber, the working vacuum was $5{\cdot}10^{-6}$ Torr. When the distance between the needle and the seat is small, the working voltage is also somewhat lower. Keep in mind that as you approach the seat, the ion current density will increase and the seat will heat up significantly. A small distance between the needle and the seat could be expected to cause electrical discharges, but in all cases high electrical stability was observed.

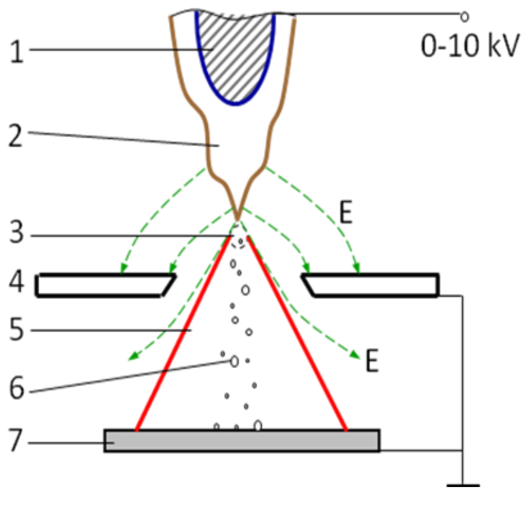
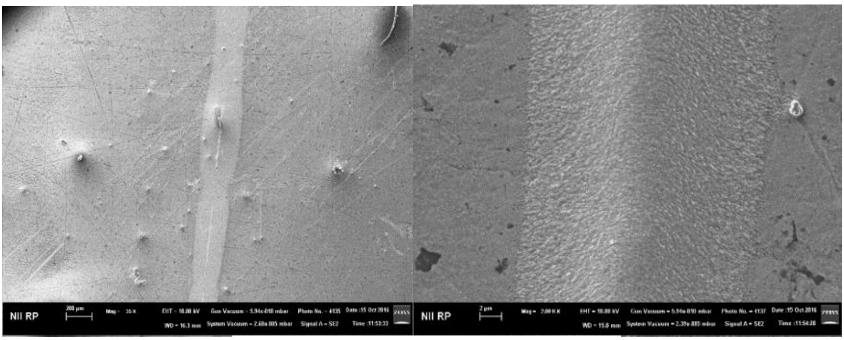


Figure 3. Emission phenomenon at the liquid metal ion source: 1- needle; 2 -Taylor liquid cone; 3 - illuminated area; 4 - extractor; 4 - ion beam; 6 - nanodrops; 7 - collector.

In experiments, indium nanoparticles were deposited on polished tungsten (W) plates. A needle chemically made of Ni wire with a diameter of 0.5 mm was wetted by In at room temperature, then placed in a graphite bowl with the working substance and fastened to the container. The container was placed in A700Q type vacuum installation. The polished tungsten plate was then placed on a piezo-table on a tube made of fluoroplastic-4 material at a distance of 2 mm from the needle. After determining the direction of movement of the piezo-table, the chamber door was closed and the experiment was carried out at a pressure of $2x10^{-5}$ mBar. To heat the needle, to the tungsten cathode a current of $I_{cathode}$ = 20 A was applied with incresing at a certain rate. After about 5 minutes, a voltage of U=4.5 kV was applied between the needle and the tungsten base to obtain the emission, and the current in the beam was I_{beam} = 50 µA. From the moment the current was occurred, the piezo-table began to move 10 mm at a speed of 0.5 mm/s, and a small size strip was obtained on the tungsten plate.

In Figure 4 wide strip about 200 microns is observed, which is a trace of ions. The narrow line in its center is clearly distinguished.

This line is a trace of nanoparticles of 20 µm wide and 1 mm long. At a larger magnification of the microscope, when examining the finely dispersed structure of this beam, it was observed that the size of the elongated grains is 100-200 nm, i.e. significantly larger than the size of the generated droplets.

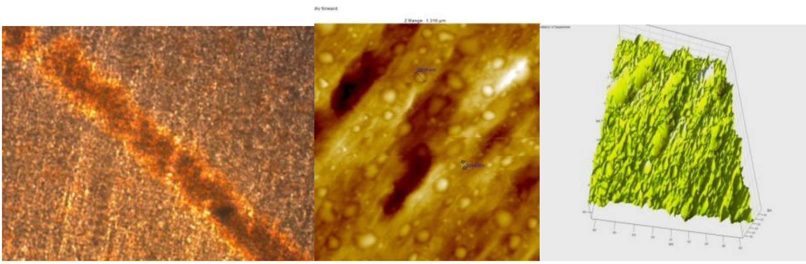


a) b)

Figure 4. a) Deposited strip on tungsten (W) plate: I_{beam} = 50 µA, U = 4.5 kV, $\nu = 0.5\frac{mm}{s}$; b) nanodroplets strip

Along with tungsten plates, strips were also deposited on silicon, copper and molybdenum plates. When examining the small strips obtained on the polished copper plates, it was decided to use Mo plates with a higher melting temperature, as it was observed that there were cases of melting in the substrate under the influence of the beam current.

The plates were first cut to 2x50x70 mm and polished, then mounted on a copper radiator, then was placed in special place made of fluoroplastic material on the fluoroplastic tube, the distance between the needle and the plate was initially set as 1mm, after the direction of movement of the table was determined the chamber door was closed and the vacuum pump was started. The experiment was performed when the pressure in the chamber was $2{\cdot}10^{-5}$ mBar. To heat the needle, to the tungsten cathode a current of $I_{cathode}$ = 20 A was applied with incresing at a certain rate. After about 5 minutes, a voltage of U = 500 kV was applied between the needle and the molybdenum substrate to obtain the emission. Then the substrate began to approach the needle, after a certain approach, the emission was obtained, and the current in the beam was I_{beam} = 40÷50 μA. From the moment the current was occurred, the piezo-table began to move 10 mm at a speed of 0.5 mm/s, and a small size strip was obtained on the molybdenum (Mo) plate (Figure 5).



a) b) c)

Figure 5. a) Deposited strip on molybdenum (Mo) plate, b) disperse structure; c) three-dimensional AFM image.

I_{beam} = 40÷50 μA, U = 500 V, $\nu = 0.1\frac{mm}{s}$

The fifth chapter examines the processes of space charge formation in the plasma lens during the focusing of heavy ion clusters. For pulsed beams, the duration of electric field formation in the lens was determined and calculated.

In the focusing of pulsed ion clusters by means of plasma lens, it was found that some time is required for an electric field to form inside the lens. Before an electric field can be created, a certain number of electrons must accumulate in the lens so that the magnetic field lines are equipotential. It should be noted that in the absence of electron emission from the wire (cold wire), the electrostatic field in the lens is created by the electrodes, but there are no electrons and the magnetic field lines are not equipotential.

It is also possible to focus the flow of charged nanoparticles formed in a liquid metal ion source by means of a plasma lens. Plasma lens, which is an effective ion-optical system, allows the creation of various structures on the surface by focusing nanoparticles. It should be noted that in this process the ion beam must be separated from the stream of nanoparticles. Otherwise, due to the high ion current density, the deposited trace of nanoparticles in focus will melt and deform. Separation of ions can be performed using a mass-spectrometer.

The duration of electron accumulation in the lens volume is determined in the initial approach from the following formula:

$$\rho V = \dot{I}\tau \qquad (3)$$

Here ρ is space charge density, V is lens volume, I is wire current strength, τ is accumulation time. We consider that the electron cloud inside the lens is cylindrical. But in reality this is not the case.

The density of the space charge of electrons in a lens is determined from the Poisson equation in cylindrical coordinates

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial U}{\partial r}\right) = -\frac{\rho}{\varepsilon} \qquad (4)$$

Here r is the radial coordinate, U is the potential of the point under consideration, ρ is the density of the space charge, ε is the electrical constant.

After integration (we consider the space charge constant) we obtain:

$$\rho = \frac{2\varepsilon E}{r} \qquad (5)$$

where $E = \frac{\partial U}{\partial r}$ is the intensity of the electric field. Just at a constant density of electrons the intensity of the electric field is directly proportional to the radius (or the electric potential depends on the square of the radius). Such dependence corresponds to ideal optics and is usually realized in experimental plasma lenses.

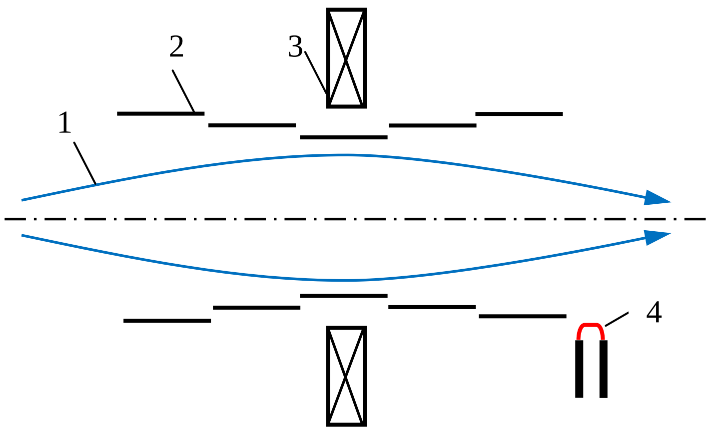


Figure 6. Scheme of the plasma lens with an incandescent wire compensator:
1- ion beam, 2 - lens electrodes, 3 - magnetic winding,
4 - compensator.

The current intensity of the electrons coming out of the wire is simply the current flowing through the plane diode:

$$\mathrm{i} = \frac{4\varepsilon}{9}\sqrt{\frac{2e}{m}}\frac{U^{\frac{3}{2}}}{d^{2}}S \qquad (6)$$

where *e/m* is the specific charge of an electron, *U* is the voltage applied to the electrode closest to incandescent wire, *d* is the distance between the wire and the electrode, and *S* is the effective area of the emission region of the wire.

Using the shown formulas in Equation (6), we obtain the following expression for the collection period:

$$\tau = \frac{9\pi r l d^2 E}{2\sqrt{2\frac{e}{m}}U^{3/2}S} \qquad (7)$$

where *l* is the length of the lens.

In our experiments, r = 2.5 cm, l = 10 cm, d = 0.5 cm, U = 50 V, S = 0.5 mm^2. Under such conditions, the following value is obtained for the collection period: τ = 29.8 μs. In the presented simple approach, the emission current of the wire was considered constant over time. However, as a space charge is created in the lens, the emission current will decrease. It should be noted that in experiments with cold compensators, the delay time of focusing the pulsed beam was also 20-30 μs.

MAIN RESULT PRESENTED FOR DEFENCE

1. For production of the beam of gold ions, the technology of preparation and vacuum wetting of the sharp-pointed emitter of the liquid metal ion source was developed, and as a result, stable emission of gold ions was provided.
2. In the source of the liquid metal ion, the energy loss of the ions in the central region of the beam was recorded (250 eV at 6 keV total energy of ions) and this phenomenon was explained by their passage through the charged nanoparticles.
3. The mean free path of fast ions in matter has been estimated based on the Lindhart, Sharf, and Shiott models. The

penetration depth for liquid indium was calculated to be R_n = 1,54 nm.
4. Sedimentation of micrometer-width strips on a moving and conducting seat at a distance (50 μm) from the emission point of the charged nanoparticles was obtained. At closer distances, the deposited trace melts due to the high density of the ion current. The seat must be sufficiently cooled for deposition narrow strips.
5. Focusing of a beam of nanoparticles is possible by means of plasma lens. For pulsed beams, the set value of the time of formation of the electric field in the lens (accumulation of electrons due to thermal emission) is 30 μs.

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Address: 131 H. Javid ave., AZ-1143, Baku

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