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Study of the Regularities of Low- and Super-low-Energy High-intensity Metal Ion Beams Formation

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Introduction

The development of the low energy, high intensity ion implantation method made it possible to dope various structural materials with metal and gas ions at depths of tens and hundreds of micrometers[1,2]. At ultra-high doses of ion irradiation exceeding 10^{21} ion/cm^2, the ion-sputtered layer thickness can reach several hundred micrometers[3]. During sputtering of the sample surface layer, both matrix material and implanted dopant are sputtered, which leads to a decrease in the efficiency of dopant accumulation and a decrease in the ion-doped layer depth. One of the solutions to the problem of significant ion sputtering of the surface can be based on high-intensity implantation at ultra-low ion energy, when ion sputtering is minimized and provides only dynamic cleaning of the irradiated surface from contamination with oxides and carbides.

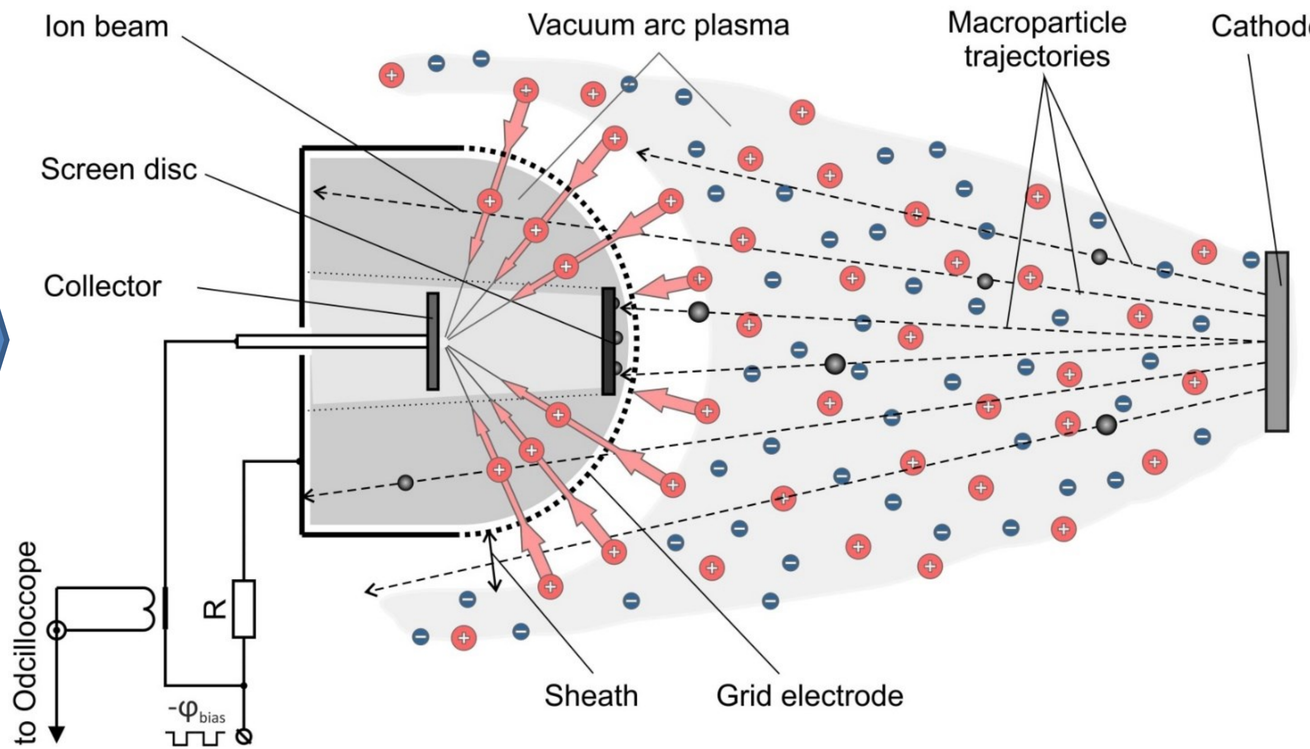
This work is devoted to the study of plasma-immersion and classical systems for the extraction of metal ions from vacuum arc plasma, their subsequent ballistic focusing in the drift space with its preliminary filling with plasma, as well as under conditions of additional formation of electronic “cloud” in order to effectively compensate for the spatial charge of the focused ionic beam.

[1]A.I. Ryabchikov, D.O. Sivin, O.S. Korneva, P.S. Ananyin, A.I. Ivanova, I.B. Stepanov, Vacuum, vol. 165, pp. 127-133, 2019.
[2] A.I. Ryabchikov, D.O. Sivin, O.S. Korneva, I.V. Lopatin, , P.S. Ananin, N.A. Prokopenko, Y.K. Akhmadeev, Nuclear Instruments and Methods in Physics Research, Section A, vol. 906, pp. 56-60, 2018.
[3] A.I. Ryabchikov, D.O. Sivin, P.S. Ananin, A.I. Ivanova, V.V. Uglov, O.S. Korneva, ” Russian Physics Journal, vol. 61, Issue 2, pp. 270-277, 2018.

Experimental Setup and Research Methodology

To form metal ion beams, axially symmetric vacuum-arc plasma generators were used, operating both with pulsed and continuous vacuum-arc discharge

Fig. 1. Scheme of plasma-immersion formation of high-intensity metal ion beams



Experimental Setup and Research Methodology

In contrast to the previous studies, when grid electrodes with a grid cell size of 1.8 × 1.8 mm[1] were used to form high-intensity beams at ultra-low energy, in these experiments, grid structures with a cell size of 100 and 500 μm with a transparency of about 40 and 50 %, respectively, were used

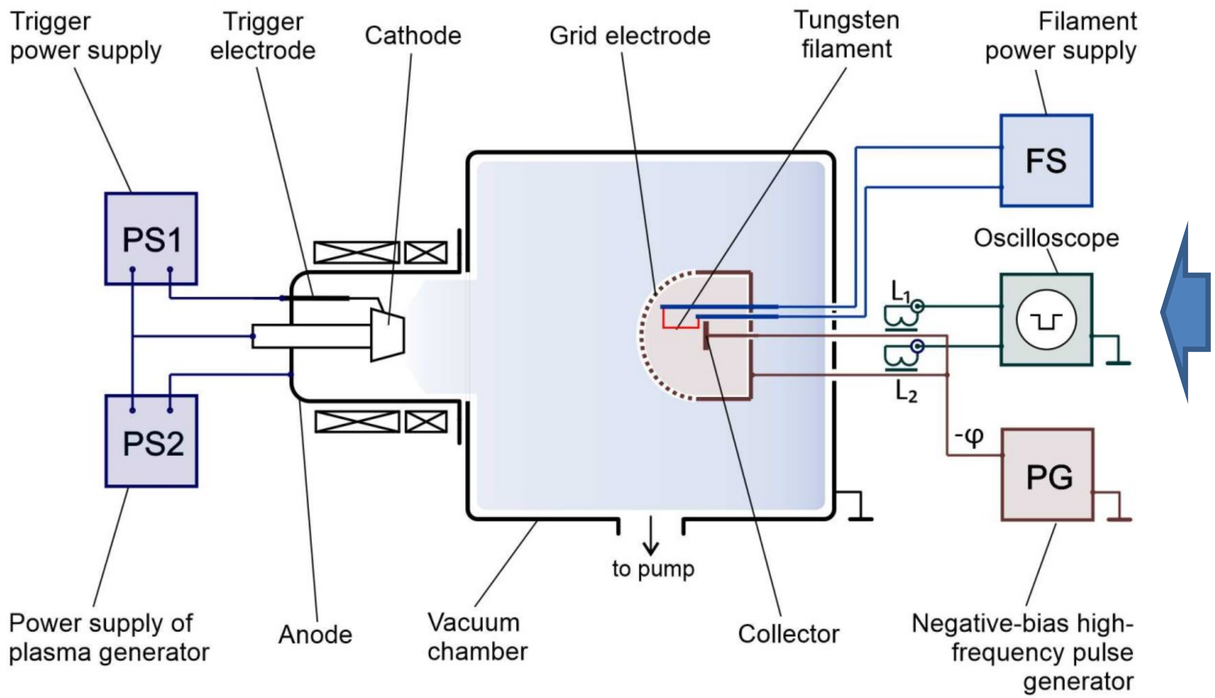


Fig. 2. Scheme of the classical formation of a high-intensity ion beam with a ballistic focusing system

[1] A.I. Ryabchikov, P.S. Ananin, S.V. Dektyarev, D.O. Sivin, A.E. Shevelev, “High intensity metal ion beam generation,” Vacuum, vol. 143, pp. 447–453, 2017

Experimental results with a grid cell size of 500 μm

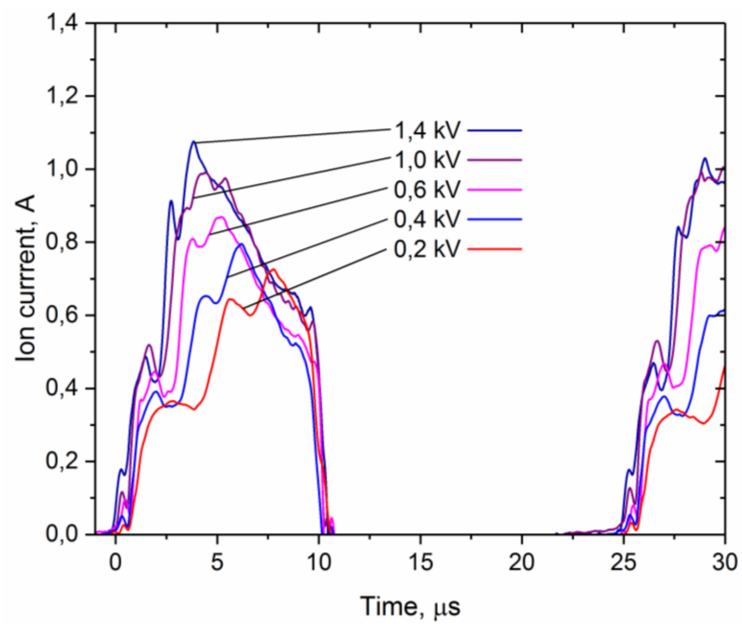


Fig. 3. Ion current to the collector with a diameter of 19 cm

At bias pulse duration of 10 μs, the ion beam transport to the collector was quite efficient even at bias voltage of 0.2 kV. Ion current of more than 1 A was recorded at voltage of 1.4 kV, and when the accelerating voltage decreased to 0.2 kV, the maximum amplitude of the recorded current of titanium ions decreased to 0.7 A.

Experimental results with a grid cell size of 500 μm

The experiments were carried out with a pulse duration of the bias potential of 30 μs.

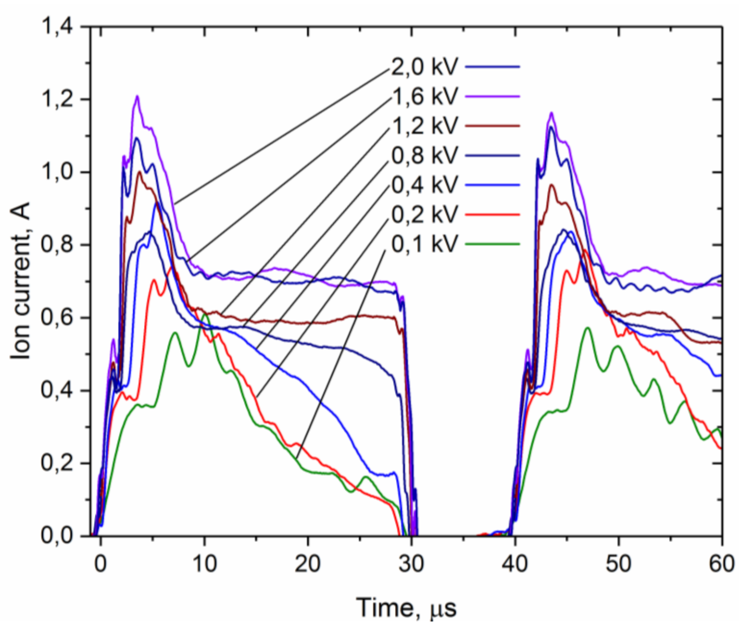


Fig. 4. Ion current to the collector with a diameter of 19 cm at a pulse duration of the bias potential of 30 μs

The oscillograms demonstrate a significant decrease in the ion current to the collector as the bias potential amplitude decreases at pulse durations exceeding 10 μs. Obviously, at large bias potential durations, the spatial charge of the ion beam in the drift space is decompensated due to the escape of electrons into the accelerating gap through the grid cells.

Experiments with a collector of 4.5 cm in diameter

Experiments at different bias potentials revealed a dramatic decrease in the ion current detected by the collector. At bias voltages of 1.2–1.4 kV, the ion current to the collector, stable in amplitude of about 0.45 A, is observed throughout the entire pulse duration. As the bias voltage decreases, both a decrease in the ion current amplitude is observed, and the dynamics of the increase in the ion current during the pulse changes. The latter indicates a significant influence of the spatial charge neutralization processes on the ion beam transport.

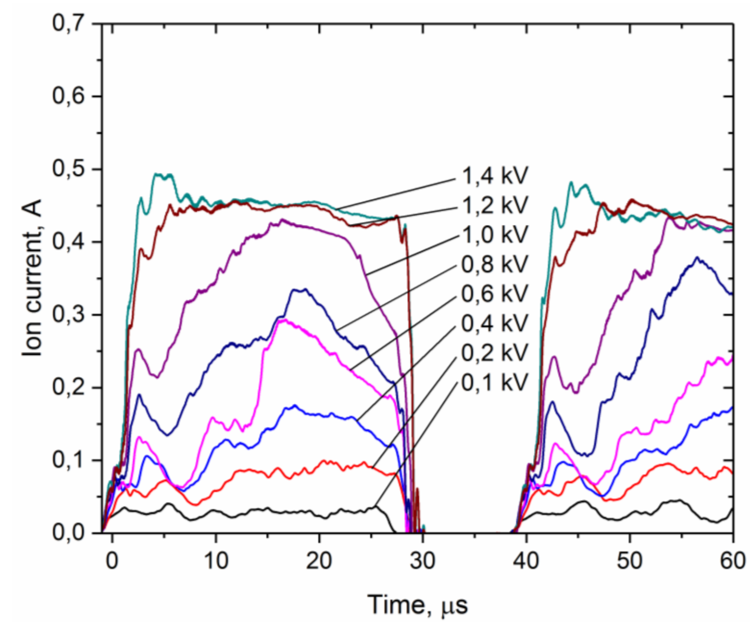


Fig. 5. Ion current to the collector d = 4.5 cm

Experimental results with a grid cell size of 100 μm

When using a grid electrode with a grid cell size of 100 μm, the ion beam transport efficiency was approximately 20% higher at low bias potentials of 200–400 V.

However, in the process of study, it turned out that the fine-structured grid electrode has two significant drawbacks.

Firstly, such a grid electrode poorly retains its shape, and at high repetition rate of bias potential pulses, as a result of heating the grid, there is a significant deformation and a change in the focusing properties of the spherical electrode.

Secondly, it turned out that even with titanium vacuum-arc plasma there is a rapid change in the grid electrode transparency due to the deposition of microdrops of the vacuum arc in sizes comparable to the sizes of the grid cells.

Qualitatively, the results of studies on grids with different cell sizes did not differ significantly.

Experiments with an additional electron cloud

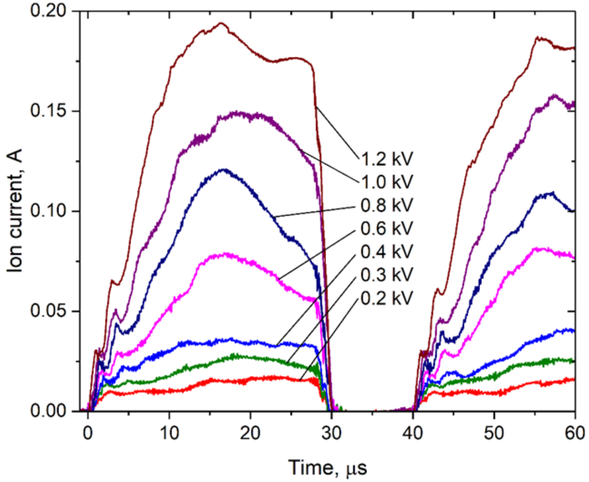


Fig. 6. Ion current to the collector d = 1,15 cm

A characteristic feature of the oscillograms is a significant tightening of the leading edge of the current pulse, which is determined by the processes of neutralization of the space charge of the ion beam and the dynamics of its focusing. With a bias potential of 0.6 kV, the maximum ion current density is about 75 mA/cm^2. Such a density is reached after 15 μs from the moment the potential is applied.

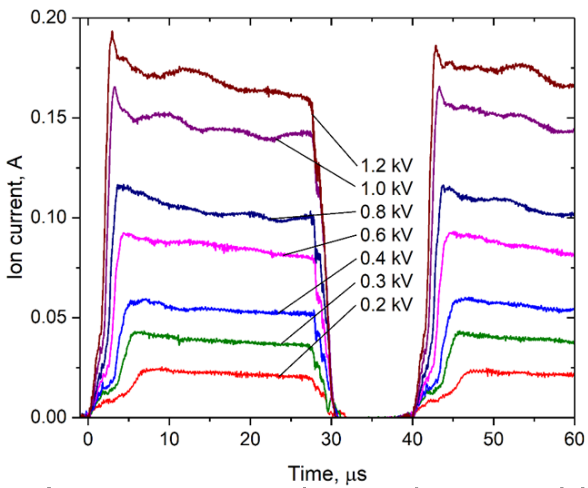


Fig. 7. Ion current to when using an additional electron thermal emitter

The maximum amplitude of the ion current does not differ significantly from the case when an additional electron thermal emitter was not used. At the same time, a comparison of the oscillograms indicates a significant increase in the integral of the beam current over the entire pulse duration. The maximum ion current density achieved with a bias potential of 0.6 kV and an arc current of 120 A exceeded 90 mA/cm^2.

Experiments with an additional electron cloud

Studies of the dependence of the ion current density on the collector at bias potentials of (0.4-0.6) kV on the arc discharge current in the range from 100 to 180 A showed the possibility of changing the ion current density during high-intensity implantation in the range from 40 to 180 mA/cm^2

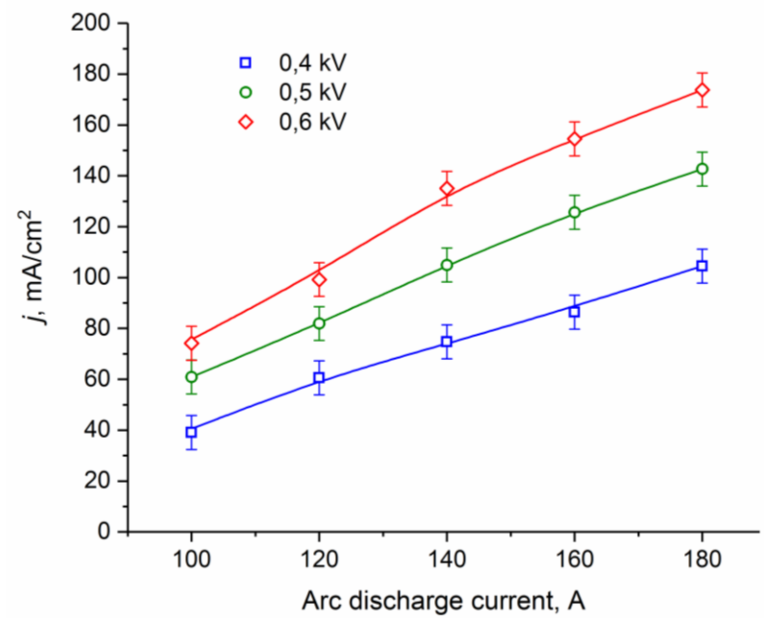


Fig. 8. Dependence of the ion current density on the collector on the arc discharge current

Conclusion

The studies on the formation of high-intensity beams of titanium ions using a single-grid plasma-immersion system showed that when using a focusing grid with a radius of 120 mm and a mesh cell size of 500×500 μm with amplitude bias potentials of about 0.5-0.6 kV, the maximum ion current density approaches 100 mA/cm^2. Compensation of the space charge of the ion beam using an additional electron emitter does not significantly change the maximum amplitudes achieved by the ion current density, but significantly improves the shape of the current pulse, providing significant increases in the fluence of ion irradiation during the pulse.

Changing the arc discharge current from 100 to 180 A provides the ability to control the current density on the target in the range from 40 to 180 mA/cm^2 while varying the amplitude of the bias potential in the range from 0.4 to 0.6 kV.

The use of a fine-grained mesh with a cell size of 100×100 μm did not provide a significant increase in the ion current density. At the same time, such a grid poorly retains its shape upon thermal heating by an ion beam. The use of such a grid for generating metal ion beams from a plasma of a vacuum arc is limited by a rapid change in the transparency of the grid structure due to the deposition of microparticles on it.