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Multicharged metal ions generation in a self-magnetically insulated ion diode

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A self-magnetically insulated ion diode was used to produce a pulsed beam of metallic ions from explosion emission plasma. The ratio of integral transferred charge for the Al, Ti and Mo ions amounted to at least 63% to the total beam charge. The ion diode had design features, which consisted in a bladed cathode and a removable perforated anode overlay made of VT-8 alloy. Analysis of the charge to mass characteristics of beam ions and the ion current density waveforms by the time of flight methodic with use of a Faraday cup showed the content of aluminum and titanium ions in the third to fourth states of ionization.

Keywords: ion diode, metal ions, magnetic spectrometer, track detector CR-39.

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The use of pulsed beams of metal ions for implantation into semiconductors is a promising method of their doping [1,2]. Ion implantation in the pulsed mode is associated with simultaneous annealing of the produced defects by virtue of a relatively high current density in a pulse and pulsed heating of the implanted layer in semiconductors and metallic materials [3]. The adjustability of the energy flux carried by a pulse also makes it possible to use beams of metal ions for surface doping and modification of metallic materials and thus enhance their corrosion and heat resistance and mechanical properties [4].

However, the production of pulsed beams of metal ions is subject to considerable physical limitations and technical difficulties. The ratio of current carried by pulsed beams of metal ions to the total ion-beam current does not normally exceed 20−30% [5–8]. The authors of certain studies have even concluded that it is essentially impossible to produce beams of ions of heavy metals in pulsed systems with a passive anode, since the velocity of light ions in an external electric field grows faster; as a result, these ions start screening heavier ions, which are located in the inner regions of plasma, by their intrinsic electric field, thus interfering with the acceleration of heavier ions [9]. However, there are several known approaches to raising the fraction of heavy ions in pulsed ion beams: the use of special systems for magnetic insulation of plasma in accelerating gaps, long pulses for separation of plasma components due to the difference in their thermal expansion rates, additional plasma sources, etc. For example, the production of high-current pulsed beams of metal ions in an ion diode with external radial magnetic insulation has been demonstrated in [10]. The fraction of metal ions was approximately 90% for lead and 20−50% for aluminum and copper. This substantial enhancement of the fraction of lead ions in a beam relative to beams of aluminum and copper ions was attributed, among other factors, to the difference in rates of propagation of metal ions and lighter ions (hydrogen, oxygen, carbon) in the accelerating gap. The authors of this study have also concluded that the accelerating pulse length should be raised to 2 μs to remove light ions from the accelerating gap prior to the primary acceleration cycle.

The use of a plasma gun [11] in a diode with external magnetic insulation did also provide an opportunity to raise the ion current to a level above 200 A/cm^2 at an $Al^{(1-3)+}$ ion concentration up to 89%. However, both an external source of a pulsed magnetic field and an additional plasma source were applied in this case.

The aim of the present study is to produce pulsed ion beams with the fraction of current carried by metal ions exceeding 50% in a self-magnetically insulated diode with a passive anode [12]. Two approaches to reaching this goal were used: the emissivity of a passive anode was enhanced by virtue of perforation and introduction of a bladed cathode, and the pause between plasma-forming and accelerating pulses was extended to ensure the removal of lighter plasma components from the acceleration region by force of their higher thermal expansion rate.

Experiments were performed at the TEMP-4M accelerator [13]. The anode of a vacuum diode was fabricated from aluminum, which features a low resistivity and a high thermal conductivity coefficient, and was fitted with a removable perforated overlay made of a titanium-based alloy (VT8: Ti — 88−90%, Al — 6−7%, Mo — 3−4%). The diameter of perforations in the overlay was 1 mm; they were arranged in several rows with a distance of 4 mm between them and a distance of 5 mm between the adjacent perforations in a row. These perforations at the anode and the bladed cathode configuration [14] intensified local uniformities of the electric field in the gap, thus exerting a

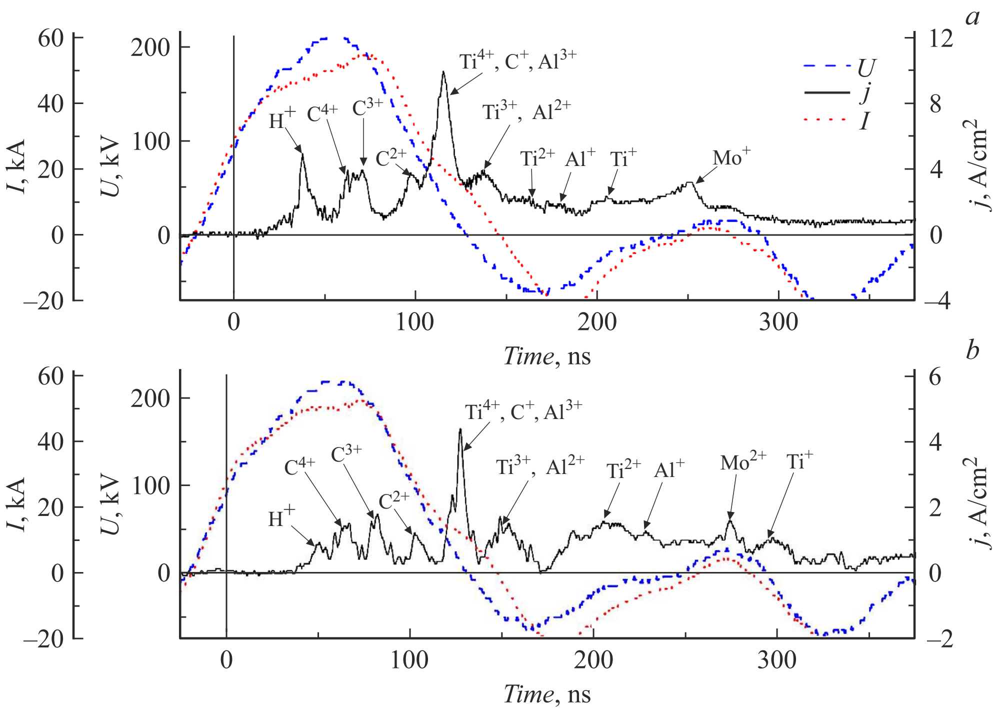

Figure 1. Oscilloscope records of U, I , and j for the distances of (a) 150 mm and (b) 250 mm.

positive effect on plasma formation on the anode surface. The amplitude of the accelerating voltage pulse in the diode was 200 kV, and its duration was 100 ns; the delay between the starting points of plasma-forming and accelerating pulses was up to 650 ns.

Accelerating voltage U across the anode–cathode gap, total diode current I, and ion current density j at distances of 150 and 250 mm from the anode were measured in the course of experiments. A time-of-flight procedure and a collimated Faraday cup (CFC) were used to estimate the elemental composition of the ion beam. Current j signals recorded at two distances were analyzed and compared with the data from track diagnostics performed with a magnetic spectrometer and a CR-39 track detector [14].

A peak in the oscilloscope record of j corresponding to the maximum proton current $j^{H\,\max}$ was chosen as a reference point for determining the ion-beam composition in accordance with the time-of-flight procedure. The reason for this is that protons are the lightest of all ionic beam components; therefore, they acquire the highest velocity, are the first to reach the sensor, and are always present in the ion beam.

One may identify characteristic peaks for groups of H^+, C^{n+}, Al^{n+}, Ti^{n+}, and Mo^+ ions in Fig. 1, a. The peaks for H^+ and groups of Ti^{4+}, C^+, and Al^{3+} ions have the highest intensity. The ions in these groups have a relatively insignificant velocity difference and reach the CFC almost simultaneously; as a result, j remains maximized here throughout the entire ion-current pulse. A more pronounced separation of the ion beam into groups is seen in the oscilloscope record made with the CFC mounted at a distance of 250 mm from the anode (see Fig. 1, b). Having integrated the j signal over time, we determined the quantitative ratios of carried charge and particle numbers for $C^{(2-4)+}$ and H^+. The results of calculations are presented in the table.

According to these data, groups of $C^{(2-4)+}$ and H^+ ions account for no more than $\sim 17\%$ of the total charge carried by the ion beam. The net fraction of charge carried by groups of Ti^{4+}, C^+, and Al^{3+} ions is $\sim 11\%$, while Ti^{3+} and Al^{2+} $\sim 9\%$. Ions Mo^+, Ti^+, Ti^{2+}, and Al^+ could not be separated reliably in the oscilloscope record of j, but they account for no less than 63% of the total charge carried by the beam. It should be noted that oxygen and nitrogen ions, which are close in mass to carbon ions and are always present both in the residual atmosphere of the vacuum chamber and in gases adsorbed onto the metal anode surface, may also enter the region of detection of carbon. However, published data on this matter (see, e.g., [15,16]) suggest that their number is insignificant relative to the amount of hydrogen and carbon in the atmosphere of the vacuum chamber. The amount of adsorbed nitrogen is also expected to be small, since the chemical activity of molecular nitrogen is low and its fraction in the beam should, just as the one of oxygen, be limited due to the fact that its ionization potential is higher than the corresponding potential of carbon or any metal in the VT8 alloy. Whatever the case might be, gas ions contribute to CFC and track detector signals in the region of light ions and do not reduce the calculated fraction of metal ions.

Figure 2 presents photographic images of the plate of a CR-39 track detector that was used in the magnetic

Number of particles and fraction of charge carried

Ion type	Ratio of carried charge to the total ion-beam charge, %	Particle concentration, $10^9\,cm^{-2}$
H^+	~ 3	~ 59
C^{2+}	~ 4	~ 40
C^{3+}	~ 5	~ 39
C^{4+}	~ 5	~ 28

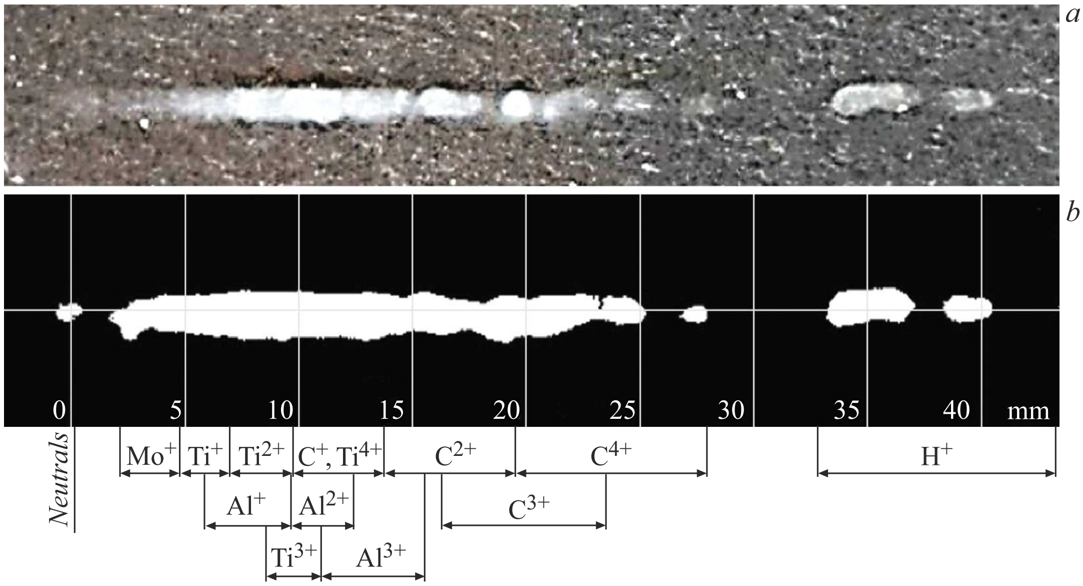

Figure 2. Photographic image of the CR-39 plate after etching. *a* — Without any graphical processing, *b* — after sharpness and contrast adjustments.

spectrometer. This CR-39 plate was subjected to etching in a NaOH solution to visualize ion tracks.

The photographic image of the track detector after etching without any graphical processing is shown in Fig. 2, *a*. The image in Fig. 2, *b* was processed to reveal more clearly all the tracks at CR-39. The calculated ranges of deflection of specific groups of ions within an energy interval of 100−200 keV by the magnetic field are indicated below.

The data obtained using the time-of-flight method for analysis of oscilloscope records and the results of track diagnostics with the magnetic spectrometer were mutually consistent. The calculated shifts of peaks in the j oscilloscope record relative to each other and relative to the proton group agreed closely with the experimental data in the indicated energy range. It follows from the analysis of the track spectrogram that the spectrum width was 135−180 keV for the proton group and at least 100 keV (in regard to the lower bound) for C^{4+} ions. The range of regions of Ti^{4+}, C^+, and Al^{3+} ion groups at the track detector in noteworthy (Fig. 2, *a*). Continuous and the most distinct tracks are located in this region, which is explained easily by the fact that ion-current density j in the oscilloscope record for the same groups of ions is the highest. According to [17], the diameters of pores after etching under the same conditions depend to a considerable extent on the particle energy. Figure 3, *a* shows the enlarged image of the track detector region where groups of Ti^{4+}, C^+, and Al^{3+} ions overlap.

The presence of pores with different diameters in this region is indicative of differences between the energy spectra of particles, which are typical of overlapping groups of ions with varied energies and masses. The histogram in Fig. 3, *b* reveals three groups of tracks of different diameters. The largest of these diameters correspond to ions with the highest energy deflected into this region (Ti^{4+}). Since pores with the smallest diameter correspond to C^+ ions in the histogram in Fig. 3, *b*, the fraction of charge carried by Ti^{4+} and Al^{3+} ions is on the order of 9%. Therefore, groups of multicharged ions of metals Ti^{4+}, Ti^{3+}, Al^{3+}, and Al^{2+} may account for as much as 18% of current carried by the ion beam.

Thus, the possibility of generation of ion beams with the majority of their charge carried by metal ions was demonstrated. The results of theoretical and experimental analysis and calculations revealed that the overall fraction of charge carried by ions of Al, Ti, and Mo metals was no

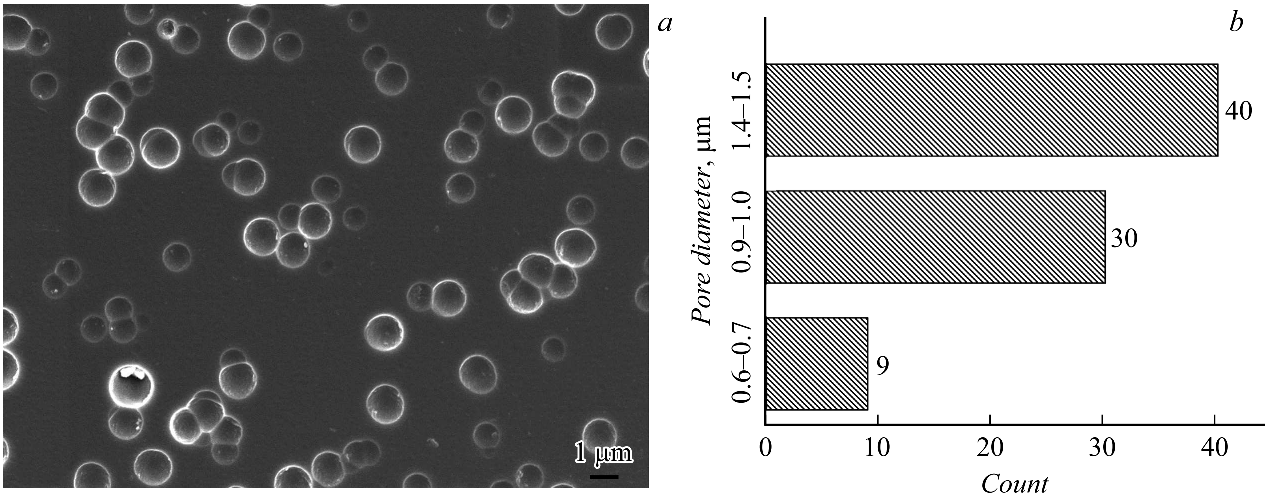

Figure 3. Enlarged image of the CR-39 plate surface after etching (*a*) and histogram of the diameter distribution of pores (*b*).

smaller than 63% of the total ion-beam charge. The fraction of charge carried by protons is fairly small due to the fact that the charge contribution of other ions in plasma is relatively significant and the pause between plasma-forming and accelerating pulses for the used gap in the diode is set to be sufficiently long for lighter and more mobile plasma components to largely leave (by virtue of thermal expansion) the region of acceleration in the diode [10]. A high degree of plasma ionization may also be attributed to a significant enhancement of the electric-field intensity at perforations of a removable anode overlay and to the use of a bladed cathode.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] A.D. Pogrebnyak, V.S. Lopatin, A.S. Vorobyev, Zh. Tekh. Fiz., **53** (6), 1186 (1983) (in Russian). https://www.mathnet.ru/rus/jtf/v53/i6/p1186
[2] J.M. Neri, D.A. Hammer, G. Ginet, R.N. Sudan, Appl. Phys. Lett., **37** (1), 101 (1980). DOI: 10.1063/1.91677
[3] G.E. Remnev, Yu.F. Ivanov, M.S. Opekunov, A.G. Puzyrevich, Pis'ma Zh. Tekh. Fiz., **21** (24), 60 (1995) (in Russian). https://journals.ioffe.ru/articles/20300
[4] G.E. Remnev, I.F. Isakov, M.S. Opekounov, G.I. Kotlyarevsky, V.L. Kutuzov, V.S. Lopatin, V. Matvienko, M. Ovsyannikov, A.V. Potyomkin, V.A. Tarbokov, Surf. Coat. Technol., **96** (1), 103 (1997). DOI: 0.1016/S0257-8972(97)00116-3
[5] A. Kitamura, K. Mitsuhashi, S. Yano, Laser Part. Beams, **5** (4), 683 (1987). DOI: 10.1017/S0263034600003190
[6] E.J.T. Bums, J.R. Woodworth, K.W. Bieg, T.A. Mehlhorn, W.A. Stygar, M.A. Sweeney, J. Appl. Phys., **63** (1), 11 (1988). DOI: 10.1063/1.340501
[7] Yu.L. Bakshaev P.I. Blinov, G.I. Dolgachev, V.A. Skoryupin, Sov. J. Plasma Phys., **5** (5), 583 (1979). https://www.scopus.com/inward/record.uri?eid=2-s2.0-0018512029&partnerID=40&md5=51bb2fb831353f5c02e4fdbe14591ae3.
[8] M. Sato, Jpn. J. Appl. Phys., **26** (6R), 927 (1987). DOI: 10.1143/JJAP.26.927
[9] A.I. Pushkarev, X.P. Zhu, Yu.I. Egorova, A. Prima, S.S. Polisadov, M.K. Lei, Plasma Phys. Rep., **48** (11), 1244 (2022). DOI: 10.1134/S1063780X22700350.
[10] Y. Nakagawa, T. Ariyoshi, IEEE Trans. Plasma Sci., **16** (4), 459 (1988). DOI: 10.1109/27.3860
[11] H. Ito, K. Fujikawa, H. Miyake, K. Masugata, IEEE Trans. Plasma Sci., **37** (10), 1879 (2009). DOI: 10.1109/TPS.2009.2022967
[12] I.F. Isakov, E.I. Logachev, V.S. Lppatin, S.A. Pechenkin, G.E. Remnev, Y.P. Usov, IEEE Trans. Electr. Insul., **EI-20** (4), 797 (1985). DOI: 10.1109/TEI.1985.348713
[13] G. Remnev, I. Isakov, M.S. Opekounov, V. Matvienko, V. Ryzhkov, V. Struts, I. Grushin, A.N. Zakoutayev, A.V. Potyomkin, V.A. Tarbokov, A.N. Pushkaryov, V.L. Kutuzov, M. Ovsyannikov, Surf. Coat. Technol., **114** (2-3), 206 (1999). DOI: 10.1016/S0257-8972(99)00058-4
[14] V.I. Shamanin, G.E. Remnev, V.A. Tarbokov, Instrum. Exp. Tech., **63** (4), 472 (2020). DOI: 10.1134/s002044122004017x.
[15] V.S. Tomal', N.K. Kasinskii, T.I. Demidovich, I.A. Ivanov, Kontenant, No. 2, 11 (2014) (in Russian). http://contenant.ru/1electron_mag/pdf/80.pdf

[16] A.E. Mikheev, V.A. Kharlamov, S.D. Kryuchek, A.A. Chernyatina, I.I. Khomenko, Vestn. Sib. Gos. Aerokosm. Univ., No. 2 (48), 216 (2013) (in Russian). https://readera.org/148177063
[17] T.W. Jeong, P.K. Singh, C. Scullion, H. Ahmed, P. Hadjisolomou, C. Jeon, H. Yun, K.F. Kakolee, M. Borghesi, S. Ter-Avetisyan., Sci. Rep., **7**, 2152 (2017). DOI: 10.1038/s41598-017-02331-w

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