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Introduction

Treatment of materials by accelerated ions causes considerable changes in the microstructure and properties of the surface layer of these materials. Results of numerous laboratory studies show that ion beams are highly efficient in surface modification of materials. However, development and commercial use of ion beam technologies is hampered due to the lack of inexpensive, reliable and efficient ion sources. One of the promising directions in development of commercial ion sources is the use of cold-cathode discharges for producing ion emitting plasma. This approach permits eliminating components heated to high temperatures. As a result, ion sources have a simpler design, are more reliable, and live longer. Since ion sources with cold cathodes are less demanding to pressure and chemical composition of the working medium, they may find a wider field of application. Main difficulties involved in creation of this type of ion sources call for the study and solution of some problems related to the properties of cold-cathode discharges. Conditions should be provided for generation of dense, stable and homogeneous plasma at a low gas pressure, an efficient extraction of ions from the plasma, and formation of a homogeneous beam with a large cross-sectional area. Ion sources employing glow discharges with a high operating voltage call for improved energy performance, which is achieved by decreasing the initiating and operating voltage of the discharge. Special attention should be attached to examination of the mass-charge composition of plasma and the content of impurities, because high-energy particles produced in the glow discharge may largely change the plasma composition as opposed to the thermionic-cathode discharge. For example, glow-discharge cathodes are intensively sputtered by high-energy ions, accelerated in cathodic fall of potential. High-energy electrons present in plasma favor generation of highly charged and atomic ions.

The main objectives of the contract works were as follows:

- Analyze discharge characteristics in the electrode system of the inverted magnetron type, parameters and emission properties of the discharge plasma, and formation of broad beams in an ion optics system.
- Create a laboratory prototype ion source, deliver the prototype ion source to Los Alamos, and perform joint experiments on ion beam surface modification of materials.
- Use results of the investigations and tests of the laboratory ion source as the basis for development of a commercial ion source with the beam up to 1000 cm^2 in cross-sectional area.

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Tasks and Main Results

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Task 2.1. Specific features of the charge initiation in a coaxial electrode system employing a hollow cathode and a thin-wire anode with a weak magnetic field applied.

Configurations of the electrodes and fields in the coaxial electrode system with a hollow cathode and an axial thin-wire anode, which is placed in a longitudinal magnetic field, ensure oscillatory motion of fast electrons in the volume. As a result, electron avalanches quickly develop at the stage of the discharge initiation and the efficient energy relaxation of primary electrons takes place at the stage of the discharge operation. Consequently, the static

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breakdown voltage, the discharge operating voltage, and the working pressure of the gas decrease. The glow discharge initiation time in the chamber having the characteristic dimension of 0.1 to 0.5 m is a few tens of microseconds. It decreases with increasing magnetic field, gas pressure, and voltage applied to the gap.

The study of the discharge initiation dynamics revealed a new effect: the pulse repetition rate strongly affected the discharge delay time. The analysis showed that the observed effect was not reduced to the decrease in the statistical delay time of the discharge initiation (which was detected earlier by many researchers) caused by the growth of the rate of appearance of primary electrons with increasing pulse repetition rate f . In our experiments, when f was increased, the statistical spread of the delay time dropped almost to zero. If f was increased further, the discharge formation time was reduced, too. According to our analysis, the observed effect can be explained as follows: When the discharge is produced at a large hollow cathode, the ion current density at the cathode proves to be insufficient for conditioning of the cathode surface. Under incomplete vacuum thin non-conductive films are formed and preserved for a long time on the surface of the glow-discharge cathode. These films affect the secondary ion-electron emission and cause the post-discharge electron emission of the cathode. The post-discharge emission of electrons is due to the surface charge of the thin films and is characterized by an abrupt drop of the current with time. Therefore, when the pulse repetition rate is increased and the pause between pulses is shortened, the generation rate of primary electrons grows. If the frequency f is high enough, the generation rate of primary electrons grows so large that it provides the multi-electron mechanism of the discharge initiation and the corresponding decrease in the discharge formation time.

This new effect appeared and was detected thanks to specific experimental conditions. The large surface area of the cathode provided the proportional increase in the generation rate of primary electrons and the corresponding decrease in the statistical spread of the discharge delay time. The increase in the pulse repetition rate also caused growth of the rate of appearance of primary electrons and the decrease in the time spread. Increasing the surface area by ~ 1000 times and the frequency by ~ 100 times as compared to the values usually used in such experiments, we managed to minimize the contribution from the static delay time almost to zero. It was also possible to determine the discharge formation time at a low current density of the post-discharge emission and analyze how the discharge development depends on the cathode processes. The electron post-emission intensity of the cathode was found to be very high after the discharge quenching and drop abruptly with time.

The detected effect accounts for the large difference between the calculated and experimental discharge initiation time. This effect ensures reliable and efficient initiation of discharge and provides conditions for generation of ion beams at a high pulse repetition frequency even using a large-size cathodic chamber, inspite of the large values of the calculated discharge formation time (~ 0.1 -1 ms).

Task 2.2. The study of the conditions and the regimes of the discharge operation.

Application of a magnetic field altered operating conditions of the hollow-cathode discharge. Depending on the magnetic induction value, three main regimes of the discharge operation were observed in our experiments with the 150-mm in diameter discharge system.

1) Magnetic field induction of 0-2 mT

The discharge operating voltage decreased with growing field as a result of the increase in the energy relaxation of fast electrons in plasma. Moreover, the magnetic field altered the conditions of generation and transport of charged particles. Due to the ionization frequency increase at the discharge periphery, the radial profile of plasma becomes more homogeneous.

2) Magnetic field induction of 2-8 mT

As the magnetic field induction was increased within this interval, the discharge operating voltage increased, harmonic plasma oscillations with the frequency of a few tens of kHz appeared, ions were extracted from plasma less efficiently, and plasma got less homogeneous. Probe measurements showed that growth of the operating voltage and emergence of the oscillations were due to the formation of a near-anode layer of space charge. The potential drop in that layer could reach ~ 1 kV with growing magnetic induction and discharge current and decreasing pressure. The accompanying instability was not a rotation one. The analysis showed that the said layer resulted from the impaired transfer of slow plasma electrons across the magnetic field to the small-size anode.

3) Magnetic field induction exceeding 8 mT

At a certain value of the magnetic field induction the discharge operating voltage dropped abruptly. Simultaneously the plasma noise increased dramatically. The fact that in a strong magnetic field the discharge switched to the low-voltage mode of operation with a high level of noise was explained by disruption of the classical diffusion of electrons across the magnetic field. The classical diffusion was replaced by an anomalous diffusion providing an efficient transfer of charges at a low pressure and a low applied voltage. However, in the latter case the plasma density distribution was highly inhomogeneous and therefore this regime is inapplicable for generation of wide ion beams when ions are extracted along the field lines.

Thus, the near-anode layer prevented extending the range of stable operation of the discharge to lower pressures by increasing the magnetic field induction. The analysis showed that the electron transfer was impeded most near the anode where the density of slow plasma electrons was a maximum. To improve stability of the high-current discharge at a low gas pressure, it was proposed to use an inhomogeneous magnetic field whose induction would have been a minimum near the cathode and close to zero at the center of the system (at the anode). A multipole magnetic system served to provide such distribution of the magnetic induction. The experiments showed that the magnetic multipole prevented development of plasma oscillations and growth of the discharge operating voltage even when the magnetic induction near the cathode was one order of magnitude higher than the critical induction of the homogeneous field, at which the discharge lost stability. The discharge got unstable when the noncompensated field at the axis was equal to the critical inhomogeneous field. The magnetic multipole discharge produced a homogeneous stable plasma at lower pressures and higher discharge currents.

Task 2.3. Ion emission properties of the glow-discharge plasma and the influence of ion extraction on discharge properties.

A homogeneous discharge plasma was produced in weak magnetic fields. A highest plasma density was obtained at high operating voltages of the discharge, i.e. at minimum values of the field induction and the gas pressure. The analysis of the physical model of the discharge showed that the effective coefficient of the ion-electron emission decreased and the discharge operating voltage increased with increasing fraction of ions extracted from plasma. As a result, when the extraction efficiency of ions was high, the condition of discharge self-consistency was fulfilled at higher gas pressures. However, this effect was significant only at high ion extraction efficiency. Considering that the ion extraction efficiency of the sources being developed does not exceed 10% of the cathode current, the influence of ion extraction on discharge characteristics can be neglected. The use of a magnetic field to control the plasma density

distribution makes it possible to change the radial profile of the plasma density from the maximum at the axis to the homogeneous one and, when the field is increased, to obtain a dip at the center. Note that the distribution with a minimum of the current density at the axis is preferable for formation of beams with a large angular divergence, because it partially compensates the effect of the beam blurring in the drift space and improves the beam current density distribution at the target.

Task 2.4. Analysis of the specific features of ion extraction and formation of ion beams in the presence of a layer of space charge near the first electrode of the IOS.

The screen electrode (SE) of the ion optics represents a component of the hollow cathode. The SE surface accounts for a considerable portion of the cathode surface. The SE potential cannot be changed at will for the hollow-cathode discharge. Otherwise, the loss of fast electrons is increased and the high-current discharge gets unstable at low gas pressures. When a cathodic potential is applied to the SE, a cathodic layer of space charge appears between the SE and plasma. The potential drop across this layer is close to the discharge operating voltage. The said layer affects the shape of the plasma emission surface near the IOS apertures. The presence of the layer means that the plasma boundary is displaced at the aperture periphery. The position of the plasma boundary at the aperture periphery depends on the layer thickness, i.e. the plasma density and the potential drop across the layer. On the other hand the position of the plasma boundary at the center of the aperture is determined by the electric field intensity and the plasma density. Therefore, the field intensity in the accelerating gap should be higher in order to obtain the concave surface of plasma. This results in impediment of the beam formation and a lower limiting density of the beam current achievable in such systems. One more aftermath of the presence of the cathodic layer is the influence of edge effects in the IOS apertures on the efficiency of ion extraction from plasma to the beam. When the plasma boundary is positioned improperly, a large fraction of the ion current from the plasma can be intercepted at the screen electrode of the IOS. The mathematical modeling and the experiments show that the effect of the current density limitation is most significant in high-perveance systems with a low energy of ions (1 keV). The extraction efficiency is strongly affected by the cathodic layer in high-voltage systems too. As a consequence, the beam current can decrease to 50% if the ion optics configuration and the optics operating mode are chosen improperly.

Task 2.5. Examination of the mass-charge composition of the ion beam.

Bombardment of the glow-discharge cathode with high-energy ions leads not only to the electron emission but also to heating and sputtering of the cathode. It was shown that the glow-discharge plasma can have two kinds of impurities: gas and metal ions. Contamination with gas impurities occurs after replacement of the working gas. The contamination intensity and duration depend on the cathode surface condition and chemical activity of the gas. High temperature favors diffusion of impurity atoms and encourages formation of a near-surface layer with an altered structure and a different chemical composition. Replacement of the gas and subsequent sputtering of the cathode lead to contamination with gas impurities. If diffusion is blocked owing to a low temperature of the cathode or the presence of a layer, where diffusion of impurity atoms is hampered, contamination with gas impurities is insignificant.

Contamination with metal ions depends on the gas type and the discharge current. When the cathode temperature is high, this type of contamination is small. It may be conceived that, as with the specific features of the discharge ignition, the condition of the cathode surface is decisive for contamination of plasma with metal ions. The films are removed and the metal is sputtered effectively only when the mean current density at the cathode is high. Despite a high

sputtering rate of the cathode surface, plasma contains an insignificant amount (less than 10%) of metal ions. This is due to the fact that the metal is sputtered predominantly as neutral atoms. Ionization of these atoms is possible only if they are ionized during their travel from one to the other wall of the chamber. The time during which particles stay in plasma is short owing to the small traveling length (the chamber diameter) and a high energy of the sputtered particles (1-10 eV). Therefore the probability of their ionization is little. As a result, metal atoms condense on the opposite walls of the cathodic chamber.

Task 2.6. Development and manufacture of the laboratory version of the source, its delivery to Los Alamos. Start-up and joint experiments.

An ion source running in the pulsed-periodic mode and generating beams of gas ions with the cross-sectional area of 100 cm^2 , the energy up to 50 keV, and the mean current up to 50 mA was fabricated. The pulsed mode parameters were as follows: pulse length of 0.4 ms; pulse repetition frequency of 50 - 200 Hz; pulsed current density of the ion beam being $\sim 5 \text{ mA/cm}^2$. The source provided a high rate of dose accumulation equal to $\sim 10^{17} \text{ 1/min}$. After the source was started up in Los Alamos, the beam was certified and conditions of formation of a wide homogeneous ion beam were determined. Joint experiments were performed on high-dose implantation of nitrogen and carbon ions in metals (chromium and aluminum), and also on deposition of DLC's on the ceramic surface. It was shown that the growth of temperature, which takes place under the action of a high-power ion beam, leads to the increase in the thickness and changes in the microhardness of the modified surface layer.

Task 2.7. Development of the commercial version of the source.

A full-scale mock-up of the discharge system of the ion source having the cathodic chamber 0.5 m in diameter was fabricated. Experiments concerned with the study of the initiation conditions and stability of the discharge and examination of ion-emission properties of plasma were performed. It was shown that the working gas pressure could be reduced nearly in proportion to the increase in dimensions of the discharge system. The optimal value of the magnetic induction providing a uniform distribution of the plasma density also decreased proportionally. The discharge initiation time did not exceed 50 μs . The region of the homogeneous plasma generation ($\sim 10\%$) accounted for 2/3 the diameter of the cathodic chamber. Therefore a chamber 0.5 m in diameter is needed to generate beams with the cross-sectional area of 1000 cm^2 . An ion-source was designed with the following ratings: voltage of 50 kV, the mean beam current of 200 mA, and the cross-sectional area of the beam equal to 1000 cm^2 .

Conclusion

Characteristics of the low-pressure glow discharge in the system of the inverted magnetron type underwent a comprehensive study. Ion-emission properties of the discharge plasma in a weak magnetic field were analyzed. Provisions for the use of this type of discharge in sources of large-cross-section beams were determined. Specific features of formation of ion beams in electrostatic ion optics in the presence of a layer of space charge were examined. Main sources of possible plasma contamination and conditions necessary for reducing the level of the contamination were determined. The successful solution of the aforementioned problems made it possible to use this type of discharge as the plasma emitter of ions in sources generating large-cross-section beams.

A laboratory version of the source was fabricated, delivered to and started up at the LANL. The source provided high dose accumulation rates. Joint experiments were performed concerning specific features of high-dose and high-temperature implantation of ions in metals and dielectrics.

The electrode system lends itself to scaling and can be used as the basis for creation of commercial ion sources. A commercial ion source with the ion beam 1000 cm^2 in cross-sectional area was designed.

Papers Published on Results of the Contractual Works

1	Characterization and performance of a high-current density implanter with a magnetized hollow-cathode plasma source	12 Intern. Conference on High-Power Particle Beams "BEAMS'98" Haifa, Israel, June 7-12, 1998. Book of Abstracts, p.399	Zoran Falkenstein, Donald J. Rej, N.V.Gavrilov,
2	Characteristics of the initiation and operation of a repetitive pulsed hollow-cathode glow discharge	Proc. XXIII Internation. Conf. on Phenomena in Ionized Gases, Toulouse, France, July 17-22, 1977. Vol. 2, p. 32-33	N.V.Gavrilov, Mesyats G.A.
3	High-Current Broad Beam Pulsed Gaseous and Metal Ion Sources for Surface Treatment Applications	12 Intern. Conference on High-Power Particle Beams "BEAMS'98" Haifa, Israel, June 7-12, 1998. Book of Abstracts, p.54	N.V.Gavrilov, Nikulin S.P., Oks E.M., Schanin P.M.
4	Influence of magnetic field on ion emission of plasma and parameters of a hollow-cathode glow discharge	12 Intern. Conference on High-Power Particle Beams "BEAMS'98" Haifa, Israel, June 7-12, 1998. Book of Abstracts, p.360	N.V.Gavrilov, D.R. Emlin
5	Influence of a plasma potential to the characteristics of a beam formed by electrostatic ion optics	12 Intern. Conference on High-Power Particle Beams "BEAMS'98" Haifa, Israel, June 7-12, 1998. Book of Abstracts, p.361	N.V.Gavrilov, D.R. Emlin, V.V. Bersenev
6	Effect of the electrode surface condition on characteristics of the pulsed hollow-cathode glow discharge	Zh. Tekhn. Fiziki (in press) (In Russian)	N.V.Gavrilov, S.E. Romanov