Formation of high intensity ion beams with ballistic focusing

Koval T.V.1), Ryabchikov A.I.2), Shevelev A.E.3), Tran My Kim An4), Tarakanov V. P.5)

1 Professor, the Department of Software Engineering, the Institute of Cybernetics, National Research Tomsk Polytechnic University, Tomsk, Russia
2 Head of Laboratory, the Institute of Physics and Technology, National Research Tomsk Polytechnic University, Tomsk, Russia
3 Graduate student, the Institute of Physics and Technology, National Research Tomsk Polytechnic University, Tomsk, Russia
4 Graduate student, the Institute of Cybernetics, National Research Tomsk Polytechnic University, Tomsk, Russia
5 Lead researcher, the Joint Institute of High Temperatures of RAS, Moscow, Russia

E-mail: 1 tvkoval@mail.ru, 2 ralex@tpu.ru

Abstract. This investigation presents the results of experimental investigation and theoretical simulations of the influence of plasma and negative bias parameters on formation, transportation and focusing of high intensity ion beams of titanium and nitrogen (with an ion current density up to 1 A/cm$^2$ and pulsed power density up to 2.6 kW/cm$^2$). It was shown that the conditions of space charge neutralization of the focusing beam have a significant influence on the distribution and magnitude of the ion current at the collector.

1. Introduction

Ionimplantation provides an important tool for the surface modification of a wide range of materials for a broad array of applications in fundamental research and applied technology. Typically, ion implantation involves bombarding the sample surface with beams of metal or gaseous ions with energy in the $1 - 100$ keV range and at current density in the $1 - 100$ μA/cm$^2$ range to achieve modification of the ion-bombarded material surface to a depth of up to about $1$ μm. Traditionally the high ion energy beam is provided by an ion source with high extraction voltage or with post-acceleration of the extracted beam. In recent years an alternative approach called plasma immersion ion implantation (piii or pi3) has evolved [1,2] in which the ions are accelerated across the high voltage plasma sheath generated by a repetitively-pulsed or DC negative bias applied to the substrate immersed in the plasma.

In many ion implantation applications there are aneed for high implantation dose, in turn calling for high current density of metal and gaseous ions. Metal ion beams can be generated by vacuum arc ion sources. The vacuum arc discharge, however, as well as providing a copious flux of metal plasma also generates a significant component of cathode debris – solid, initially molten, particulates called "macroparticles" – that can lead to contamination of the implanted substrate. Here we describe a novel approach to the formation of high intensity beams of gaseous and metal ions with extremely high current density with the use of gas discharge plasma source with hot cathode, as well as metal plasma source based on DC vacuum arc discharge accompanied with the originally developed system, which excludes accumulation of macroparticles in the area of ion beam interaction with a target. The method of the formation of high intensity ion beam, investigated in Ref. [3,4] and based on plasma immersion
extraction and acceleration of ions and their subsequent ballistic focusing. The system is the combination of the grid electrode, made in the form of hemisphere, and a cylindrical section, providing a field-free drift space for ballistic focusing and transportation of the ion beam formed by the grid. The hemispherical grid, in the certain conditions, can provide ballistic focusing of the beam, however, the efficiency of focusing and transportation is substantially depends on neutralization of the beam space charge in the drift space.

This work is devoted on experimental investigations and theoretical simulations of the influence of plasma and negative bias parameters on formation, transportation and focusing of high intensity ion beams of titanium and nitrogen.

2. Experimental results
A DC vacuum arc discharge is used to form dense metal plasma. We used a water-cooled titanium cathode located within a modest axial magnetic field (about 60 G); the arc discharge current was 160 A. A hemispherical metal grid is positioned on-axis some 40 cm from the cathode. Nitrogen plasma was generated with the use of arc discharge source with hot cathode PINK [5], the discharge current was 20 A. The hemisphere grid with radius of 7.5 cm is mounted on and electrically attached to cylindrical section, providing equipotential drift space for ballistic focusing and transportation of the ion beam formed by the grid. A current collector plate is positioned at the geometric focus of the system and is connected to a repetitively pulsed negative bias generator with amplitude varied from 1.2 kV to 2.6 kV; pulse duration from 1 to 8 μs, with the fixed pulse repetition rate of 10^5 p.p.s. A Rogowski coil is used to monitor the collector current. Macroparticles in the plasma flux incident upon the hemispherical grid are blocked from viewing the sample holder by a metal plate mounted on-axis; we used a disk of radius 2 cm.

Typical oscillograms of the ion current of titanium and nitrogen beams with the amplitude of negative bias of -2.6 kV, pulse durations of 2, 4, 6 and 8 μs are presented in Fig. 1a,b. The oscillograms of titanium ion beam current (Fig. 1a) shows a significant influence of pulse duration on the formation of ion beam. With the pulse duration of 2 and 4 μs, an ion beam current reaches up to 0.8 A. It should be noted that the amplitude of the spike at the beginning of a pulse is conditioned by inductive and capacitive characteristics of Rogowski coil and has no relations with the measured ion current. The delay of the ion current pulse, in comparison with a bias pulse, is related to the time of sheath formation near the grid electrode and ion time-of-flight through the drift space. The increase in bias pulse duration up to 6 μs leads both to the manifold decrease of an ion current amplitude at the beginning of the pulse and to the delay in the ion beam formation (Fig. 1a).

![Figure 1. Typical oscillograms of titanium (a) and nitrogen (b) ion beam currents](image-url)
The distribution of titanium ion current at bias pulse duration of 4 μs and bias pulse frequency of 100 kHz was defined with the use of thermographic camera by analyzing the temperature changes of rapidly heated thin tungsten foil and presented in Fig. 2. The obtained distribution reveals the substantial influence of the beam space charge on the efficiency of beam focusing.

In case of a plasma flow, formed by the PINK source, the high stability of the nitrogen ion current pulses and the similarities in their shape at different negative pulse durations were observed (Fig. 1b). With the increase of chamber gas pressure up to 0.4 Pa, the ion beam is forming and focusing even at pulse duration of 8 μs.

Figure 2. The relative distribution of the temperature of tungsten target after its irradiation by titanium ions

3. Simulation results

If the pulse repetition rate is large, the off-bias time can be small enough to fill equipotential drift space with plasma. The propagation velocity of vacuum arc plasma usually amounts to approximately 1.5·10^6 cm/s and with the off-bias time 2 μs, the plasma flux can penetrate through drift space only 3 cm from the grid electrode. The distribution of plasma in drift space is defined by its velocity and diffusion process tightened with the concentration gradient.

The simulations of the ion beam formation were performed using PIC code KARAT [6].

Near the entrance of the drift space plasma concentration is almost one order of magnitude larger than ion beam concentration; however, in the spherical geometry the density of fully neutralized ion beam is increasing as 1/r^2 with the distance from the grid electrode to the current collector plate. Thus, the focusing of ion beam is accompanied with the formation of inhomogeneous potential well, which defines the movement of charged particles of plasma (ions and electrons). Fig. 3 demonstrates the

Figure 3. The calculated distribution of beam (a) and plasma ions (b); E – the grid electrode, C – collector
calculated distributions of ions in beam (a) and plasma (b), where the arrows designate the direction of ion velocity. The ion energy at the entrance of the drift space corresponds to the accelerating voltage of 2.6 kV, the plasma density $n = 2 \times 10^{10} \text{ cm}^{-3}$. With the off-bias time $t > 4 \mu \text{s}$, focused ion beam is forming. Fig. 4 shows simulation results on the current distribution of such beam.

![Figure 4](image)

**Figure 4.** The ion beam current density distribution on the collector

With $t < 4 \mu \text{s}$, the number of plasma electrons in the drift space during the formation of the beam, may be insufficient to neutralize its charge. In this case, the beam formation is accompanied by redistribution of the nonuniform plasma density and the formation of a virtual anode. Fig. 5 shows the dynamics of the number of plasma particles and ions beam (increased 2-fold) in time. Fig. 6 shows the configuration portraits of the beam at different moments, plasma concentration $n = 10^{10} \text{ cm}^{-3}$. The part of the reflected ions from the potential well minimum falls on the grid, increasing its current. The other part passes into the sheath, reducing the current density in the ion layer, which leads to fluctuations in the emission plasma boundary and beam current. As the calculations show, the lower the plasma density, the greater the time of the emission of plasma ions, and a correspondingly longer time to form the beam and the less current, that is observed in experiment (Fig. 1).

![Figure 5](image)

**Figure 5.** The dynamics of the number of charged particles in the drift space: $g$ and $r$ – plasma electrons and ions, $y$ – beam ions
In addition, the formation of the beam and the dynamics of the collector current are influenced by the ionization of residual gas by ions, plasma and the secondary electrons captured in the potential well. Secondary electrons formed as a result of ion-electron emission from the collector surface, also compensate the space charge of the transported ion beam.

4. Conclusions
The experimental and theoretical studies have shown that the formation of ion beam of a very high density, and the ion current at the collector are significantly depends on conditions of space charge neutralization of the focusing beam. The beam formation may be accompanied by the appearance of a virtual anode, if the drift space does’t fill with plasma or residual gas.

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