Generation of a High-Current, Very-Low-Energy Ion Beam with Unconventional Space Charge Neutralization

M.V. Shandrikov, A.V. Vizir, G.Yu. Yushkov, E.M. Oks*, A. Anders**, D.A. Baldwin***

Institute of High Current Electronics Russian Academy of Sciences, Tomsk, 634055,Russia
phone (3822)- 491776, fax (3822)- 492410, e-mail: shandrikov@opee.hcei.tsc.ru
** State University of Control Systems and Radioelectronics, Tomsk, 634055, Russia*
***Lawrence Berkeley National Laboratory, Berkeley, California 94720*
****4Wave, Inc., Sterling, Virginia 20166*

Abstract – A high-current, mixed ion-electron flux with space charge compensation has been produced without using a traditional dedicated source of space-charge-neutralizing electrons. The source employs a dual stage discharge and extraction concept. The main gas discharge plasma was generated in the cavity of a hollow cathode, representing a non-self-sustained glow discharge supported by electrons injected from the plasma of an auxiliary glow discharge. An ion beam was extracted from the plasma of the main discharge by a single grid extractor. Beam ions were later decelerated to a required energy in the layer between the grid and the beam plasma. The ion beam current was measured using a collector located 30–60 cm away from the discharge system. For the electron component of the main discharge plasma to penetrate into the ion beam drift space through the grid, the potential barrier was reduced under the conditions of the optimal extractor potential with respect to the hollow cathode. The space charge neutralization of the low-energy ion beam lead to a decrease in the plasma potential in the drift space and an increase in ion beam current. At a main discharge current of 1 A and a main discharge voltage of 300 V, an ion beam current of up to 100 mA and an ion energy of 20–100 eV was obtained. An increase in the distance between the collector and the discharge system necessitated a corresponding increase in the initial ion energy if the ion beam current needed to be kept constant. The formation of an ion beam with the desired energy was confirmed by time-of-flight measurements.

1. Introduction

Low-energy ion beams are increasingly finding applications in various fields, particularly, in ion-assisted thin film deposition for a number of new devices [1–3]. It is well established that the ion energy distribution affects the properties of the deposited coatings [4], and that the control of energy distribution allows specific physical and chemical processes to occur on the surface of the growing film [5]. The lowering of the ion energy to less than 100 eV enables one to eliminate undesirable sputtering of components of the vacuum chamber and electrodes of the discharge system, thereby drastically reducing contamination of substrates in the deposition process [6]. Additionally, if the energy is lowered below the displacement energy of typically 40 eV, so-called "ion-damage" can be avoided that critical in the growth of crystalline films as used in the semiconductor industry. Therefore, on the one hand, a decrease in ion energy is often highly desirable.

On the other hand, an increase in ion beam current is a competing, usually incompatible requirement. A high ion current would allow an increase in processing rate and a reduction in processing time and cost. In the traditional way of producing low-energy ion beams without positive space charge neutralization, the beam current is limited to a few milliampere. To neutralize the positive space charge of an ion beam, a dedicated neutralizer used, which is a source of electrons using a hot (thermionic) cathode [7] or plasma cathode [8].

In this paper we present the results of experimental research on the generation of a low-energy ion and electron flux such that the space charge is neutralized by discharge plasma electrons, as opposed to electrons from a dedicated neutralizer.

2. Experimental procedure

A schematic of the experimental arrangement is shown in Fig. 1. Plasma was produced in a two-stage discharge system operating in the continuous mode. The two-stage discharge consisted of a non-self-sustained glow discharge (the main discharge), supported by an auxiliary glow discharge (the emitter discharge). The latter ensured electron injection into the cathode cavity. The plasma-forming gas was supplied into cathode cavity 1 of the emitter discharge with a flow rate of 10÷20 sccm. The pressure in the cathode cavity 1 was 1 Pa. The emitter discharge was ignited by a high-current gas discharge on application of a high-voltage pulse (5 kV, 20 μs) between the trigger electrode (not shown in Fig. 1) and the cathode 1. The positive terminal of the emitter discharge power supply U_{inj} was connected to the negative terminal of the main discharge power supply U_{mn}. The hollow cathode 3 had a hole of dimensions 1×7 cm^2 which was aligned with the outlets of the cathode 1 and the intermediate electrode 2 and covered with a fine tungsten mesh of geometric transparency ~70 %.

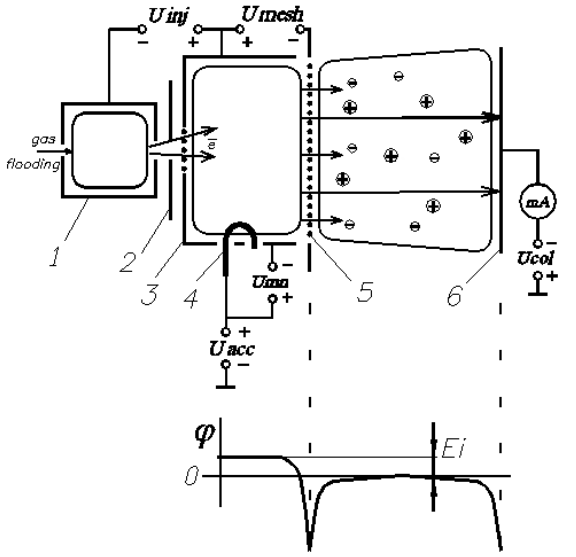

Fig. 1. Experimental arrangement of the discharge system: 1 – cathode of the emitter discharge, 2 – intermediate electrode, 3 – cathode of the main discharge (= anode of the emitter discharge), 4 – anode of the main discharge, 5 – extractor, 6 – collector. The power supplies: U_{inj} – emitter discharge, U_{mn} – main discharge, U_{mesh} – extractor, U_{acc} – accelerating voltage, U_{col} – collector

The electrons of the emitter discharge plasma that passed through the mesh were additionally accelerated in the cathode layer of the main discharge. The injection of additional electrons enabled operating the main glow discharge at low operating pressure and low operating voltage.

The cathode of the main discharge was a stainless steel cylinder of height 13 cm and diameter 25 cm. The anode of the main discharge was a water-cooled copper tube, 4, located in the cathode cavity. The area of the main discharge anode was chosen from the conditions of the optimal area ratio S_a/S_k=0.37 % (for argon) found earlier for a similar discharge system [9]. These conditions allowed us to decrease the operating pressure and the main discharge operating voltage. The pressure in the hollow cathode was approximately equal to the pressure in the drift space of the ion beam of about $(2{\div}4)\cdot10^{-2}$ Pa.

The ion beam was extracted through the extractor 5, which was aligned to the electrode 4. The extractor was a single mesh made of stretched molybdenum wires. The extractor design compensated for thermal expansion of the filaments during operation by individual stretchers. The geometric transparency of the extractor was 85 %. The extractor had a negative potential with respect to the cathode of the main discharge, which was given by the power supply U_{mesh}. This voltage controlled the output of high-energy electrons delivered from the main discharge plasma into the drift space of the ion beam through the barrier as determined by the grid potential.

Extraction of a low-energy high-current ion beam requires a grid with sufficient transmittance and with a small mesh size, since the positive space charge layer determined from the Child-Langmuir law is small. For this reason we used a high-voltage acceleration-deceleration system which ensured extraction of ions and their further deceleration to the required energy in the layer between the grid and the beam plasma. This made it possible to use a grid with a sufficiently large mesh (1.5 mm) and with a wire thickness of 0.2 mm.

In [9] it was shown that the potential of the main discharge plasma is about the same as that of the main discharge anode. Therefore, the resulting energy of ions upstream of the collector was determined by the potential difference between the main discharge anode and the plasma in the drift space (Fig. 1). The power supplies U_{inj}, U_{mn} and U_{mesh} were ground-free. Thus, as the beam plasma potential was kept at a specified level, the resulting energy of low-energy ions E_i could be varied by shifting the potential of the anode 4 with respect to the ground by a corresponding change in the power supply voltage U_{acc}.

The ion collector 6 of dimensions 40×50 cm^2 was placed 30–60 cm from the discharge system. A negative bias was applied from the power supply U_{col} to the collector to reflect high-energy electrons which escaped from the main discharge plasma through the potential barrier. The beam plasma potential was measured with a movable emissive probe.

3. Experimental results and discussion

As shown earlier [10], a low-energy ion beam can be transported in the space-charge-limited mode through filling the drift space with plasma.

The negative bias of the extractor with respect to the cathode of the main discharge (Fig. 2) prevented the electrons from entering into the drift space. As a result, a high positive potential, which precluded the passage of ions, was established in the beam transport region. The collector current was just a few milliampere. In contrast, the escape of some high-energy electrons due to a corresponding decrease in potential barrier led to a decrease of the ion beam potential and an increase of the ion current to the collector. In this case, the ion beam propagated through the beam plasma which originated from gas ionization by high-energy electrons. Thermalized electrons oscillated between the extractor and the collector, whereby neutralizing the positive space charge of low-energy ions. In doing so, the loss of high-energy electrons streaming from the hollow cathode of the main discharge could be compensated by a modest increase in the injected electron current from the emitter discharge plasma. The experiments have shown that the required increase in emitter discharge current is of the order of the collector current.

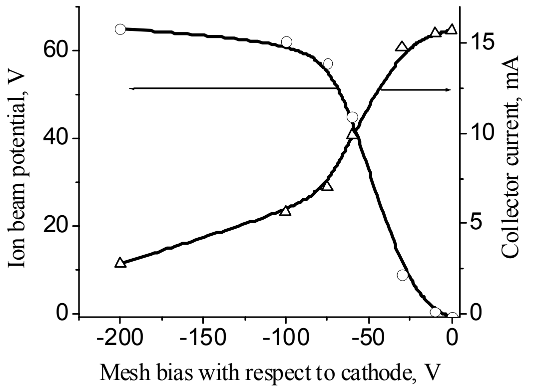

Fig. 2. Influence of discharge plasma electrons injection on beam plasma potential and ion collector current: I_{inj}=70 mA, U_{mn}=300 V, I_{mn}=250 mA, U_{acc}=75 V, U_{col}=–50 V, p=3·10^{-2} Pa

It is important to realize that electrons can escape from the hollow cathode plasma of the main discharge even with a negative extractor bias of –50 V. This effect can be associated with the presence of high-energy electrons from the tail of the Maxwell distribution in the main discharge plasma as well as with the penetration of electrons into the spacing between the extractor wires in which the potential barrier shows an increase. Because of the high-energy electrons that are present in the ion beam drift space, correct measurements of the ion current requires that the collector potential be higher than the potential of the main discharge cathode.

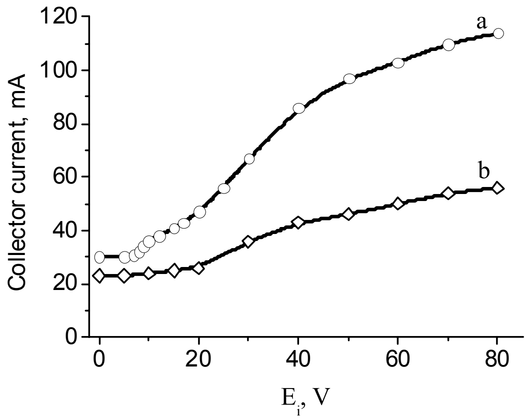

Fig. 3. Collector current versus the energy of accelerated ions: I_{inj}=500 mA, U_{mn}=300 V, U_{col}=–250 V, p= 3·10^{-2} Pa. The distance to the collector was 30 cm (a) and 60 cm (b)

In further experiments, the extractor was connected to the cathode of the main discharge. With this system, the dependence of the collector current on the ion energy was determined for the range from 0 to 80 eV (Fig. 3). The measurements show that the plasma potential in the drift space increases by no more than 1–2 V.

The independence of the collector current on the accelerated ion energy in the range from 0 to 10 eV indicates that the collector current is made up mainly of beam plasma ions created by ionization of the gas by high-energy electrons which escaped from the hollow cathode plasma. A further increase in ion beam energy caused the current of low-energy ions to the collector to dominate. Thus, the current of the accelerated ions at a certain accelerating voltage is equal to the collector current at this voltage, minus the collector current at zero accelerating voltage. Notice that the beam plasma potential was not higher than 10 % of the accelerating voltage and, hence, exerted only a slight effect on the ion paths.

To confirm the fact of the formation of the low-energy high-current beam, simple time-of-flight measurements have been made. For these measurements, the positive terminal of the power supply U_{acc} was switched to ground for a time of about 400 ns. Since the energy of the beam ions thus decreased to zero, the flux of accelerated ions to the collector also decreased after a time. The response time differentiation of the signal from the collector made it possible to determine the kinetic energy of the ions streaming to the collector. The results of the experiment are presented in Fig. 4.

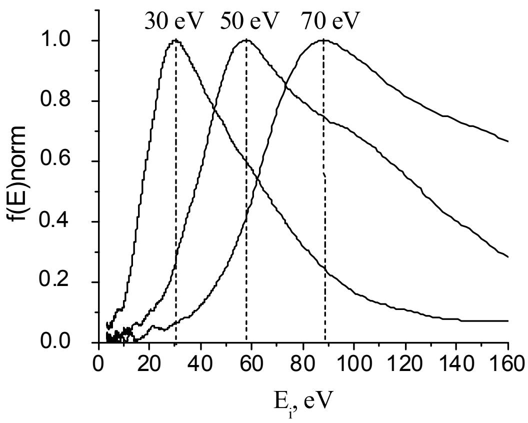

Fig. 4. Energy spectra for different ion beam energies: I_{inj}=500 mA, U_{mn}=250 V, U_{col}=–250 V, p=2·10^{-2} Pa. The distance to the collector was 30 cm

The position of the distribution maximum correlates closely with the specified energies of the ion beam. A small divergence can be attributed to the experimental inaccuracy. It should be noted that the presence of the high-energy "tail" in the ion spectra does not reflect the actual situation which is associated with the fact that when grounding the power supply Uacc, the collector current did not decrease to zero because the ions from the beam plasma continued their motion to the collector.

4. Conclusions

A discharges system for the formation of neutralized gas ion beams with energies in the range 20÷100 eV has been proposed and investigated. The special feature of this system is that no separate space charge neutralizer was used. Instead, the space charge of the beam was neutralized by electrons of the discharge plasma. Injection of the electrons into the drift space caused a decrease in the beam plasma potential and an increase in the ion current measured at the collector by about one order of magnitude.

In the system proposed, a directed Ar ion beam with a current of 110 mA and an energy of 80 eV has been obtained on the collector located 30 cm from the discharge system, with the accelerated ion current 3÷4 times greater than the beam plasma ion current.

Acknowledgment

This work was supported in part by the U.S. Department of Energy, Initiatives of Proliferation Prevention, project IPP-LBNL-T2-196, under Contract No. DE-AC02-05CH11231.

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