Physical Characteristics of the Modified Glow Discharge Ion Source

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This work is concerned with a study on the operating characteristics of a self-axial extraction-type glow-discharge ion source. This compact ion source, with conical anode of various divergence angle Θ, can work under different operating conditions. An output ion beam currents I_b were measured at a distance $d_{cc} = 5$ cm from the plane cathode, and were found to be dependent upon the gas pressure p, angle Θ and the discharge current I_d. High ion beam currents of 85 μA and 410 μA were obtained at the optimum angle $\Theta = 30°$ for discharges: [N_2 gas, $p = 2.9 \times 10^{-2}$ mbar, $I_d = 2$ mA] and [H_2 gas, $p = 7.7 \times 10^{-2}$ mbar, $I_d = 2$ mA], respectively.

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1. Introduction

Different applications of ion sources can be mentioned as well: cleaning, etching, coating, sputtering process, ion implantation, fusion research, isotope separators, mass spectrometers, etc. [1–4]. Glow discharge (GD) ion sources offer the particular attraction of being free from neither magnetic fields nor filaments with a restricted lifetime. Ions of GD sources are produced principally by electron-gas molecule impact at pressure in the range of $10^{-2} \leq p \leq 10^{-3}$ mbar [5–14].

Efficiency of a GD ion sources for delivering intense beams depend on voltages across the discharge, gas pressure, gap distance between electrodes, size of the ion exit aperture, geometry and surface properties of the electrodes set. Efficient and reliable GD ion sources operation at low pressures is achieved by maximizing the electron path in the ion source region through the use of magnetic fields or by mechanical confinement created in a peculiar geometry of cathode-anode sets.

In our paper we describe the ion GD source construction and its characteristics using N_2 and H_2 gases. The electromechanical confinement in the internal space of a conical anode plays a large role in the operation of the source at lower pressures, where the ion density could be increased by electron oscillations in the confined plasma as well as "focusing" of ions on the central place of cathode.

2. Design features and physical idea of ions source work

A schematic diagram of the modified glow discharge ion source and its associated electrical circuit are shown in Fig. 1.

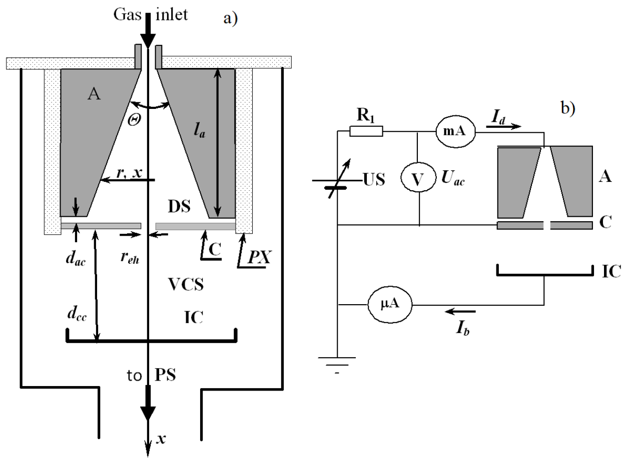

Fig. 1. (a) Mechanical structure of the ion source, where: A — anode, C — cathode, DS — discharge space, IC — collector of ions, PX — Perspex housing of discharge electrodes set, VCS — vacuum chamber space, PS —- pumping system. (b) Associated electrical circuit, where: US — regulated high voltage supply, R_l — limiting resistance. This ion source consists of conical Cu anode of different angles θ of their divergence and plane Al cathode arranged at a distance of $d_{ac} = 3$ mm.

A pumping system PS is used for initial evacuation and cleaning the ion source chamber and maintenance of needed pressures in the ion source during its run. This system consists of by: 450 l/min rotary pump allowing ultimate pressure of $10^{-2}-^{-3}$ mbar, diffusion pump of speed 270 l/s allowing ultimate pressure of 10^{-5} mbar and nitrogen trap that fixed between the ion source chamber and the diffusion pump. The working gas is transmitted to the ion source through a needle valve to regulate the rate of its consumption Q. High efficiency of gas consumption and its being trouble free are two typical features where this ion source could be operated in a vacuum region (p_v<than 1×10^{-3} mbar) for a long time (2 h) without any breakdown problems, and in a stable mode. Working gas pressures p_d in the discharge space

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are assessed in the light of fundamental principles of gas flows and on the base of corresponding measured parameters: gas consumption Q and pressure p_v in the VCS region.

The power supply US of the regulated voltage (0–10 kV) is used for initiating and maintenance the glow discharge between the anode and the cathode.

The ion density increased by electron oscillations in the confined plasma. Therefore, higher output I_b could be produced due to this "mechanical" confinement of ions stream at discharge axes x. This choice of the anode angle geometry is a unique feature of our modified ion source.

Some ions produced in the anode–cathode space pass the extracting hole of $r_{eh} = 1.5$ mm in radius, arriving at the flat Faraday cup situated at a distance $d_{cc} = 5$ cm from the plane cathode. Electric signal on this collector IC is assumed to be a measure of an intensity I_b of the ion beam.

The operating principle of our ion source is based on the molecule ionization by electrons roaming and oscillate ion in gas and energized by an electric field of the conical anode-cathode space, see Ref. [6]. This type of discharge was proved for its stability, simplicity, and ability to operate at the low gas pressures. Therefore high output ion beam current can be self-extracted axially from the "cylindrical" discharge region. The ion density increased by electron oscillations in the plasma confined in the interior of conical anode and flat cathode. Therefore, higher output I_b could be produced due to this "mechanical" confinement. The possibility of change of the anode angle geometry was a unique feature of our modified ion source.

3. Experimental study of ion source

The ion source was cleaned before putting inside the vacuum system. The polishing of the electrode parts should remove the impurities parts from their surfaces and the contamination due to the erode materials of the discharge.

3.1. Experimental $I_d = f(U_{ac})$ characteristics of discharges in the GD source of ions

In the following, measurements of the discharge voltage U_{ac} and discharge current, I_d with different nitrogen pressures and different anode angles θ are shown in Fig. 2a–d. From these figures, it was found that an increase of the discharge voltage was accompanied by an increase of the discharge current, where the characteristics of such discharge is characterized by abnormal glow [7]. Indeed, an angle $\theta = 30°$ needs higher voltage than other angles, which means that maximum high output ion beam current could be obtained.

Shapes of the above characteristics $I_d = f(U_{ac})$ suggest our ion source to work at the mode of abnormal one-dimension glow discharge. However, our discharges are specific because a conical shape of anode.

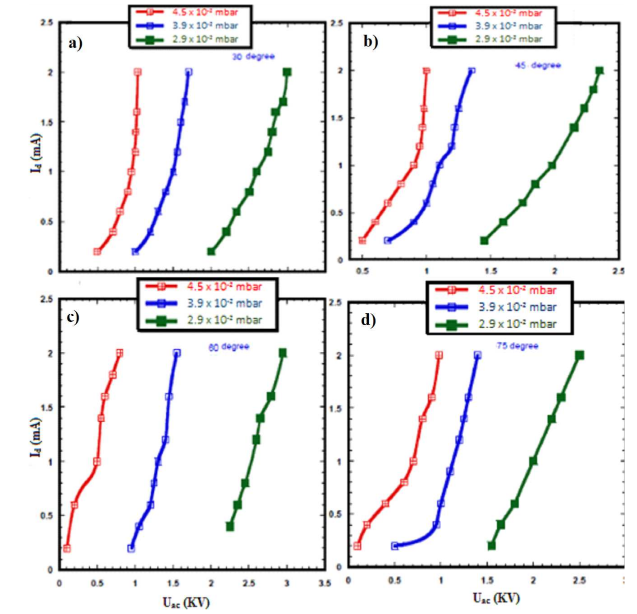

Fig. 2. The discharge current I_d vs. discharge voltage U_{ac} for different angles Θ of anode at various pressures p_d of the N_2 gas.

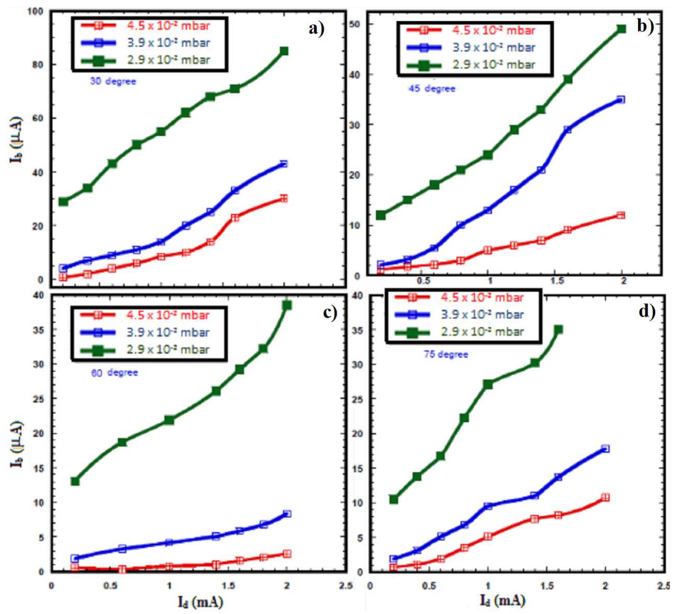

Fig. 3. The ion beam current I_b vs. the discharge current I_d at different angles Θ of anode divergence and at different pressures p_d of N_2 gas.

3.2. Measurements of output ion beam parameters

Figure 3a–d shows the output ion beam characteristics, i.e. the relation between the output ion beam current I_b and the discharge current I_d for different values of the anode angles at various gas pressures using N_2 gas. From these figures, it is clear that, when the discharge current increases, the output ion beam current increases and reaches its maximum value at anode angle of 30° at pressure of 2.9×10^{-2} mbar. Therefore, it is clear that this angle is the optimum value, where maximum output ion current can be obtained with maximum ion energy.

This ion source exhibits a favourite confined behaviour due to a mechanical constriction for the anode angle geometry. High electric field strength for angle $\Theta = 30°$ was obtained and hence, high ion beam current could be obtained.

4. Effect of AC voltage on ion beam current

Measured $I_b = f(U_{ac})$ characteristics of the discharge in nitrogen are presented in Fig. 4a–d.

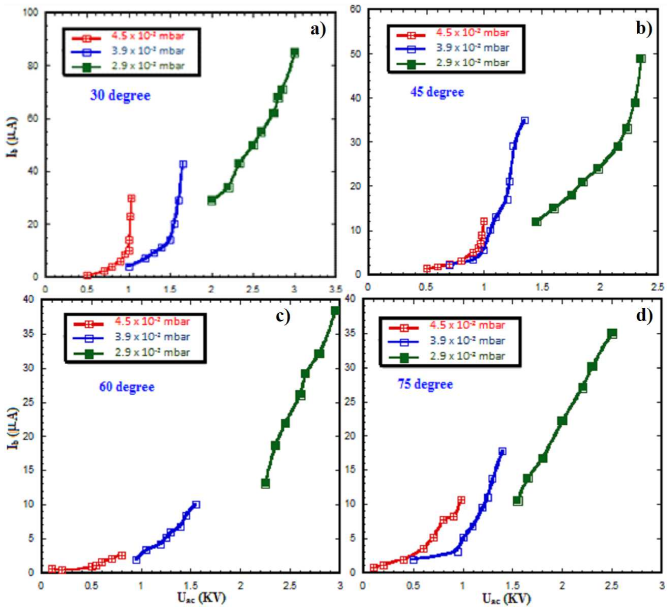

Fig. 4. The discharge voltage U_{ac} — ion beam current I_b characteristics using N_2 gas with various anode angle Θ.

We can see strong effect of the U_{ac} voltage on the current I_b. Relative change $\Delta U_{ac}/\bar{U}_{ac} \approx 0.4$ of the discharge voltage, products high change relative $\Delta I_{ac}/\bar{I}_{ac}1$ of the beam current, see Fig. 4a, [30°, 2.9×10^2 mbar].

5. Quantitative characteristics of "mechanical" confinement of discharge

Figure 5 shows the relation between the output ion beam current and the discharge current at pressure of 2.9×10^{-2} mbar and at the optimum anode angle by using H_2 and N_2 gases.

From this figure, it is clear that rates

$$4.71 < \frac{I_{bH_2}}{I_{bN_2}} < 5.24 \tag{1}$$

of beam intensities of both extracted ions are of almost constant over large range of discharge currents. Moreover we observe that the most confined discharge is that of H_2

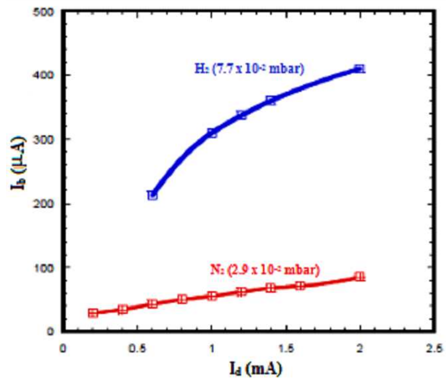

Fig. 5. The ion beam current I_b vs. the discharge current I_d using H_2 and N_2 gases at anode angle $\Theta = 30°$.

gas. Above results are surprising in the light of the facts: discharges in H_2 gas work at pressures much higher than those in N_2 gas; beam intensities of N_2^+ ions run down with increasing N_2 pressures, see Fig. 4a.

Figure 6 repeats the relation $I_b = f(I_d)$ of the discharge in N_2 gas with various anode divergence Θ and at most optimal gas pressure.

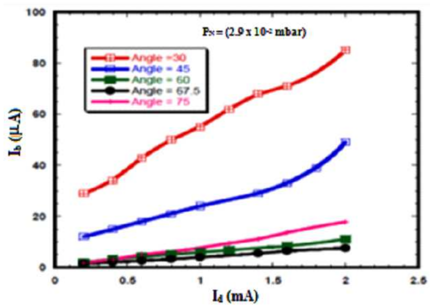

Fig. 6. The ion beam current vs. the discharge current intensity at different anode angles Θ.

It is clear that both the output ion beam current and the discharge voltage increase at the optimum angle 30° and also by decrease of the pressure. The rate of eventual etching of any specimen exposed to the output ion beam of any gas increases by decrease of the pressure [15]. It is also clear that the maximum output ion beam current and discharge voltage were obtained at optimum pressure $p \approx 2.9 \times 10^{-2}$ mbar where the etching rate is maximum due to the ion beam extracted from a stable discharge.

The dependences of both the source discharge power P and source efficiency I_b/I_d on the discharge current intensity are presented in Fig. 7.

Surprising "linear" character of the dependence $P = f(I_d)$ has simple explanation. In the case of metallic conductors some change ΔU_{mc} of supplying voltage creates only some change Δu_e of mobility of electrons at their constant concentration n_e, finally it creates an increase ΔI_c of current. In the case of glow discharges some change ΔU_d creates changes $(\Delta n_e,\ \Delta n_i)$ of car-

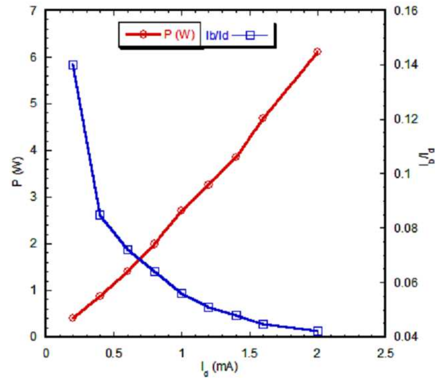

Fig. 7. Variation of the discharge power P and the efficiency ε_{ib} vs. the current intensity I_d at $p_{N_2} = 2.9 \times 10^{-2}$ mbar and $\theta = 30°$.

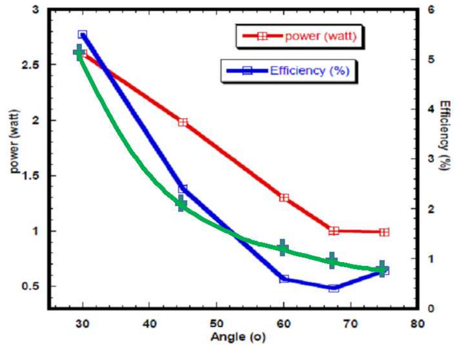

Fig. 8. The discharge power and the measured ion source efficiency vs. the anode divergence Θ, at $p_{N_2} = 2.9 \times 10^{-2}$ mbar and $I_d = 1$ mA. Both green symbols and line — theoretical efficiency ε_{ip} calculated with Eq. (2).

riers densities as well as their mobility (Δu_e, Δu_i), finally creates increase ΔI_d of current. Total change of discharge current ΔI_d affected by $\Delta U_d = \Delta U$ change is higher than change ΔI_c of metallic conductor affected by corresponding voltage change $\Delta U_d = \Delta U$. Reversal consideration allows conclusion: some change of discharge current $\Delta I_d = \Delta I_c$ needs a voltage change ΔU_d smaller than corresponding a voltage change $\Delta U_{mc} = \Delta U$. Finally we can conclude: energy deposition into discharge space is carried out with a power $P = I_d U_d^k$ at $k < 2$. In our source the power P increases linearly with the increase of U_{ac}, i.e. at $k \approx 1$.

Due to gas heating its concentrations n_{go} at the geometric discharge axes are lower than concentration n_{ga} averaged over the discharge cross S_c. This heating increases with the increasing discharge power. Because of this fact an ion production efficiency at axial subspace is lower than that averaged over cross S_c. Ion beam current densities i_b at the discharge axis are lower than those i_d averaged over the cathode cross S_c! Finally, the efficiency $\varepsilon_{ip} \approx i_b S_{ex}/(i_d S_c)$ can be concluded to fall with increase of both a current intensity and a power of the studied discharge.

Exact explanation of above problems can be carried out only on the base of the theory of the cathode fall plasma, however this aim exceeds the frame of this paper which is rather an experimental work.

Figure 8 shows the relation between the anode angle geometry and both the discharge power $P_d = U_{ac} I_d$ and the ion source efficiency $\varepsilon_{ip} = I_b/I_d$.

Specific character of the dependence $\varepsilon_{ip} = f(\theta)$ has a simple quantitative explanation. Let us assume the active surface of cathode as $S_c = \pi l_a^2 \cot^2(\theta/2)$. There is commonly known fact that glow discharges tend to develop their cathode spot surface over the all cathode. If we assume a discharge current density to be constant over all cathode surface then we can write

$$\varepsilon_{ip} = \frac{I_b}{I_d} = \frac{i_d S_{ex}}{i_d S_c} = \dots \frac{r_{ex}^2}{l_a^2} \cot^2 \frac{\theta}{2}. \quad (2)$$

Diagrams of Fig. 8 suggest that both calculated and measured efficiencies ε_{ip} are similar.

Exact explanation of above problems can be carried out on the base of the theory of the cathode fall plasma. However this aim exceeds the frame of this paper which is rather some experimental work.

The minima of both power P_d and efficiency ε_{ip}, observed at some peculiar angle $\Theta_m \approx 67.5°$, have not any simple explanation actually.

In the practical use of ion sources the right way is to adjust all ion source parameters to achieve: a maximum extracted ion beam current (A_1), a minimum of its angular divergence (A_2) after its pass through extraction hole and a mono-energy spectrum of extracted ions (A_3). Problems of the achievement A_1 can be successfully considered in the light of our studies reported above. However the both A_2 and A_3 problems could be resolved on the base of both analytical or numerical modellings. These modellings are intended for our future scientific activity.

6. Conclusion

To the best of our knowledge, this is the first time that compact low-pressure gaseous ion source based on a DC glow discharge with the conical anode was designed, made, operated and studied.

This ion source has a compact size and is featured by easy and long-time stable operation in a wide range of pressure, no heated parts (such as filaments) are present, and simple construction. From the obtained results and their discussions, it can be concluded that: the presented ion source produces a reasonable amount of ion beams using N_2 and H_2 gases. This configuration (electrostatic confinement) of different anode angle divergence ($30° \leq \theta \leq 75°$) was found to be the essential part for discharge confinement therefore, a higher output ion beam current could be obtained. This electro-mechanical confinement of plasma created in a conical interior space of the anode, plays a major role in the source at low pressures, where the ion density could be increased by electron oscillations in the confined plasma. It has been also concluded that the ion beam current can be increased greatly when using an anode with angle of 30°. An extremal ion beam of $I_b \approx 85$ μA and 410 μA can be obtained at source parameters [N_2 gas, $p = 2.9 \times 10^{-2}$ mbar, $U_{ac} = 2.5$ kV and $I_d = 2$ mA] and [H_2 gas, $p = 7.7 \times 10^{-2}$ mbar, $U_{ac} = 2.55$ kV and $I_d = 2$ mA]. Currents I_b of extracted ions increased linearly with discharge currents I_d even at optimal other source parameters. However the efficiency I_b/I_d decreased "hyperbolically" with the increasing I_d currents. Considerable experience has been required for controlling these parameters in order to obtain the optimum performance from the source. The presented results show that this ion source can be used in various applications as surface cleaning, etching, sputtering and in particular, for polymers treatment. Modest theoretical studies of ion production characteristics allowed us to understand positive and negative features of the studied ion source.

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