Ion current density distribution in a pulsed non-self-sustained glow discharge with a large hollow cathode

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Abstract. The paper reports on azimuthal and radial distributions of the ion saturation current density measured with a single cylindrical and a plane probe in the plasma of a low-pressure (≈ 1 Pa) pulsed non-self-sustained glow discharge with a large (0.21 m³) hollow cathode at discharge currents higher than 100 A. It is shown that increasing the discharge operating voltage and decreasing the operating pressure in the range 0.4–1 Pa improves the uniformity of the ion current density distribution.

1. Introduction

Anomalous glow discharges are widely used for thermochemical surface treatment of metals and alloys [1], including nitriding, cementing, diffusion surface saturation with boron or other elements [2]. The volume of working chambers can reach several cubic meters, and the charge weight more than ten tons [3]. However, there are series shortcomings that affect the treatment time. Among them are relatively high pressures ranging from several tens to several hundreds of pascals. This factor does not allow efficient surface cleaning from oxides, which can lengthen the treatment time in an anomalous glow discharge to 50 h. In the last two decades, it has been shown that low-pressure (≈ 1 Pa) discharges with surface cleaning by high-energy ions can provide a several-fold decrease in nitriding time and higher nitriding efficiency [4–6]. Today, however, such discharges are hardly used in industry because it is difficult to provide plasma uniformity in large (≥0.5 m³) vacuum volumes. A way to increase the plasma uniformity is to use several plasma sources around the periphery of a chamber whose walls will serve as an anode, but this greatly increases the cost of equipment and decreases the efficiency and reliability of the entire system. One of the most promising methods for plasma generation at low pressure is to use a hollow-cathode glow discharge. In this type of discharge, the azimuthal distribution of ion current density is symmetric about the center [7] and allows one to obtain currents of 30 A in a volume of 0.2 m³ at a voltage of ~600 V. In the plasma of this discharge, the ion current density reaches ~2–3 mA/cm². Recent research demonstrates that steels and titanium are most efficiently nitrided at an ion current density of about 4 mA/cm² and higher [8]. To attain the so high ion current density in a large volume, it is required that the discharge current in this volume be greater than 100 A. The discharge current can be increased through injection of additional electrons which, when arrived in the plasma of a glow discharge, are accelerated in the region of potential fall near the hollow cathode, oscillate inside the hollow, and efficiently ionize the gas [9]. This allows one to obtain discharge currents of about 100 A in continuous modes and up to several hundred
amperes in pulsed modes at a discharge operating voltage of ≈200 V [10]. In a non-self-sustained glow discharge, electrons are normally injected from a small area of an emission electrode separating the regions of main and auxiliary discharges [9, 11]. As a result, the current density of these electrons is two or three orders of magnitude higher than that of γ-electrons formed at the hollow cathode walls via secondary ion-electron emission. Therefore, the plasma density and hence the ion saturation current density to a probe locally increases in the direction of electron emission from the auxiliary discharge at about the free path from the face of the grid electrode. The aim of our study was to determine how the operating conditions and parameters of a low-pressure pulsed non-self-sustained glow discharge with a large (= 0.2 m³) hollow cathode influence the azimuthal and radial ion current density distributions.

2. Material and research techniques

The azimuthal and radial distributions of ion saturation current densities in a hollow-cathode pulsed non-self-sustained glow discharge were studied on an experimental test bench shown schematically in Fig. 1. The inner walls of a vacuum chamber of dimensions 600×600×600 mm formed a hollow cathode of volume 0.21 m³ for the main glow discharge. The chamber was pumped with a TMN-500 turbomolecular pump to an ultimate pressure of 5·10⁻³ Pa. The operating pressure was controlled in the range 0.4–1 Pa through gas supply (nitrogen).

The main glow discharge was ignited between hollow cathode 1 (chamber wall) with a surface area \( S_\text{c} = 2.3⋅10^4 \text{ cm}^2 \) and uncooled plane anode 2 with a surface area \( S_\text{a} = 310 \text{ cm}^2 \). The chamber material was stainless steel (12Cr18Ni10Ti). The anode was arranged through the side flange of the chamber. The anode to cathode area ratio was \( S_\text{a}/S_\text{c} = 1/74 \). The glow discharge was powered from an inverter dc/pulse voltage source with the following parameters: voltage amplitude \( U_\text{d} = 30–300 \text{ V} \), pulse current \( I_\text{d} = 0–550 \text{ A} \) at maximum average output current \( I_{\text{d,av}} = 120 \text{ A} \), maximum average power \( P = 30 \text{ kW} \), pulse repetition frequency \( f = 1–1000 \text{ Hz} \), and pulse duty factor \( \gamma = 1–100 \% \). For decreasing the drop in voltage amplitude during a discharge pulse, a capacitor bank with \( C = 7.2 \text{ mF} \) was installed at the output of the glow discharge power supply. The power supply prevented from microarcs at the surface of the hollow cathode. The discharge current \( I_d(t) \) was measured using a Honeywell CSNJ481 Hall probe with data transmission to a Tektronix TDS2014C oscilloscope. The discharge voltage \( U_d(t) \) was measured with an oscillographic probe (1:100) between the glow discharge anode and cathode.

For stable operation of a steady glow discharge at voltages of several tens of volts and ignition of a pulsed discharge, an arc electron source with an integrally cold hollow cathode was used [12]. The arc was ignited via a dielectric flashover when nitrogen was supplied through gas inlet 4 and a high-voltage pulse was applied between trigger electrode 5 and cylindrical hollow cathode 6. The auxiliary arc discharge operated between cylindrical hollow cathode 7 and conical anode 8 covered with a fine grid of geometric transparency 45% (mesh size 0.4×0.4 mm). Such a conical shape deflects electrons emitted in the main discharge from the axis of the plasma source, thus improving the plasma uniformity in the hollow cathode. Conical grid anode 8 with its concave central part was at the potential of the glow discharge hollow cathode and was an emission electrode through which electrons from the auxiliary arc discharge were injected to the main glow discharge. The cathode spot moved over the inner surface of the cylindrical hollow cathode at the maximum tangential component of an axial magnetic field induced by coil 3. The auxiliary arc steadily operated through a hole in arc arrester 8 and a high-voltage pulse was applied to it. The auxiliary arc discharge was ignited via a dielectric flashover when nitrogen was supplied through gas inlet 4. The auxiliary arc current was the nearest site of conical grid anode 8. The arc source was powered from an ARC150 stabilized current source [13] which provided an arc current of up to \( I_a = 150 \text{ A} \) at a voltage of up to \( U_a = 60 \text{ V} \). In all experiments, the magnetic induction on the axis of the electron source was \( B = 3.8 \text{ mT} \).
Figure 1. Experimental test bench (a) and current and voltage of non-self-sustained glow discharge at $I_a = 150 A$, $p (N_2) = 1 Pa$ (b). In test bench: 1 – cathode of glow discharge, 2 – anode of glow discharge, 3 – magnetic coil, 4 – gas inlet, 5 – trigger electrode, 6 – hollow cathode of auxiliary arc, 7 – arc arrester, 8 – conical grid anode of auxiliary arc, 9 – cylindrical Langmuir probe, 10 – grid, 11 – plane probe with guard ring.

The azimuthal distribution of ion current densities was measured using plane probe 11 of diameter 5 mm with a guard ring; the probe had the potential of the glow discharge hollow cathode. The radial distribution was measured using cylindrical Langmuir probe 9. For measuring the azimuthal distribution, the probe was rotated about the center of the chamber at a distance of 18 cm from its axis, being positioned at the height of the axis of the auxiliary plasma source from which electrons were emitted. The probe was fixed in a flange with a rotary feedthrough at the chamber bottom. The radial and azimuthal distributions of ion current densities were analyzed at different pressures and different discharge voltages and currents. The parameter characterizing the azimuthal nonuniformity of ion current density was the ratio of maximum density deviation from average to average ion current density:

$$k = \frac{|j_n - j_{av}|_{max}}{j_{av}} \times 100\%,$$

where $j_n$ is the ion saturation current density for rotation through a certain angle $n = 1–18$, and $j_{av}$ is the ion current density averaged over all measurements.

3. Results and discussion

The radial distribution of ion saturation current densities is presented in Fig. 2; plane $A–A$ in which the probe moved is shown in Fig. 3. Almost in all cases, the maximum ion current density falls on the chamber center, i.e., $j_i = 11 mA/m^2$ at $I_d = 90 A$, and at the edges, it decreases. This is because the probability of nitrogen ionization is higher near the chamber center than at the periphery. The plasma density calculated by Bohm’s formula is $\approx 10^{13} cm^3$ at $T_e = 1 eV$. If we neglect the extreme points of radial distributions near the chamber walls, the distribution nonuniformity is up to 20 %. Varying the operating pressure in the range 0.4–1 Pa can cause plasma density redistribution in the chamber: local maxima appear in the radial distribution (Fig. 2a, curve 2), which can be due a change in the free path such that regions with a higher ionization probability, compared to others, arise at this distance from the chamber walls.
Figure 2. Radial distributions of ion saturation current density to probe, chamber center 0 cm: (a) for \( U_d = 182 \) V, \( I_d = 90 \) A at \( p(N_2) \) equal to 1 Pa (1), 0.65 Pa (2), and 0.4 Pa (3); (b) for \( U_d = 182 \) V, \( p(N_2) = 0.65 \) Pa at \( I_d \) equal to 125 A (1), 90 A (2), and 60 A (3); and (c) for \( p(N_2) = 0.65 \) Pa, \( I_d = 90 \) A at \( U_d \) equal to 130 V (1) and 182 V (2).

As Fig. 3a suggests, decreasing the operating pressure in the range from 1 Pa to 0.4 Pa improves the uniformity of azimuthal current density distributions by more than 50 %, which is also confirmed by calculations of \( k \) in Table 3. Increasing the glow discharge current from 60 A to 125 A increases the ion current density but the nonuniformity parameter \( k \), in this case, remains almost unchanged. Increasing the discharge operating voltage from 130 V to 235 V decreases the nonuniformity by 20 %, all other things being equal.

![Figure 2](image1.png)

Figure 3. Azimuthal distributions of ion saturation current density to probe, chamber center 0 cm: (a) for \( U_d = 182 \) V, \( I_d = 90 \) A at \( p(N_2) \) equal to 1 Pa (1), 0.65 Pa (2), and 0.4 Pa (3); (b) for \( U_d = 182 \) V, \( p(N_2) = 0.65 \) Pa at \( I_d \) equal to 125 A (1), 90 A (2), and 60 A (3); and (c) for \( p(N_2) = 0.65 \) Pa, \( I_d = 90 \) A at \( U_d \) equal to 130 V (1), 182 V (2), and 235 V (3).

Varying the anode area \( S_a \) from 300 cm\(^2\) to 600 cm\(^2\) does not provide any noticeable change in the azimuthal ion current density distribution and its parameter \( k \).

Table 1. Nonuniformity \( k \) for azimuthal distribution of ion saturation current density in low-pressure non-self-sustained discharge with hollow cathode

| Mode No | Mode | Key parameter | Nonuniformity \( k \), % |
|---------|------|---------------|------------------------|
| 1       | \( U_d = 182 \) V, \( I_d = 90 \) A | \( p(N_2) = 1 \) Pa | 89                     |
4. Conclusion

Thus, almost in all modes studied, the radial plasma density peaks at the chamber center and decreases at the chamber walls. The key factors that influence the uniformity of ion saturation current densities in a non-self-sustained glow discharge are the operating pressure and the discharge operating voltage. Decreasing the operating pressure from 1 Pa to 0.4 Pa decreases the azimuthal nonuniformity of ion current density by 50 %, and increasing the discharge operating voltage from 130 V to 235 V decreases the factor $k$ by 20 %. Increasing the glow discharge current in in the range 60 – 125 A and increasing in the anode area from 300 cm$^2$ to 600 cm$^2$ fails to provide any considerable change in the azimuthal distribution and its nonuniformity factor. By varying the gas pressure and the discharge operating voltage, it is possible to provide ion saturation current densities nonuniform to about $\approx 30\%$ even with a single electron source and to form nitrided layers of acceptable uniformity in bulky products.

Acknowledgments

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