Resource-Efficient Technologies 2 (2019) 29–35

TOMSK POLYTECHNIC UNIVERSITY

Resource-Efficient Technologies

journal homepage: http://ojs.tpu.ru/index.php/res-eff

COMPARISON OF GLOW, ARC, AND MAGNETRON DIRECT CURRENT DISCHARGES

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Abstract

Glow discharge (GD) in a tube, arc discharge (AD) without cathode heating from an external source, and magnetron discharge (MD) in a planar magnetron are compared. In each of the discharges, characteristic areas are distinguished.
In MD, electrons trapped in the near-cathode region are not directly involved in ionization processes, but "wake" acceleration of slow ions by electrons that move along Larmor orbits is possible, which gives additional energy to ions moving toward the cathode.
In GD in the near-cathode region, the average energy of the ejected electrons is on the order of several electron volts, and the energy of the ions and neutrals is less than 0.1 eV. In MD in the near-cathode region, the average energy of knocked-out electrons, ions, and neutrals is on the order of tens of electron volts.
The differential resistance of GD is negative, that of AD is usually negative, and that of MD is positive.
The energy of ions in the magnetron plasma can be greater than that of electrons, which gives new possibilities for acoustoplasma control of MD and the creation of appropriate instruments and devices.

Key words: glow discharge, arc discharge, magnetron discharge, direct current

1. Introduction

For technical purposes, in creating thin-film coatings and plasma chemistry, glow discharge (GD), arc discharge (AD), and magnetron discharge (MD) are frequently used. It is advisable to compare different types of discharges from a single point of view and investigate the power modes of discharges with direct current, radio frequency discharges, and acoustoplasma mode. In the acoustoplasma mode, the discharge current has a constant and low-frequency variable component [1, 2]. In all types of discharge – except for the AD with a cathode, which is heated from an external source – the mechanism of cathode emission is associated with the bombardment of the cathode surface by positive ions.

This is the first of a series of works dedicated to the comparison of different types of discharges that are powered by direct current. This article describes the various discharges and different methods of their power from a unified standpoint. This work is the result of both the authors' research and a review of work performed by other authors. It is based on five main works [3–7].

2. Discharge Types

The sections that follow consider in detail each of the discharges.

2.1. Glow discharge

Figure 1 shows a GD in a long tube with flat electrodes and of sufficiently large diameter (such that

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☆ Peer review under responsibility of Tomsk Polytechnic University.
https://doi.org/10.18799/24056537/2019/2/237

the destruction of charged particles on the walls can be neglected). Distributions of the luminous intensity and discharge parameters are also given. The data for Figure 1 are taken from [4, 7].

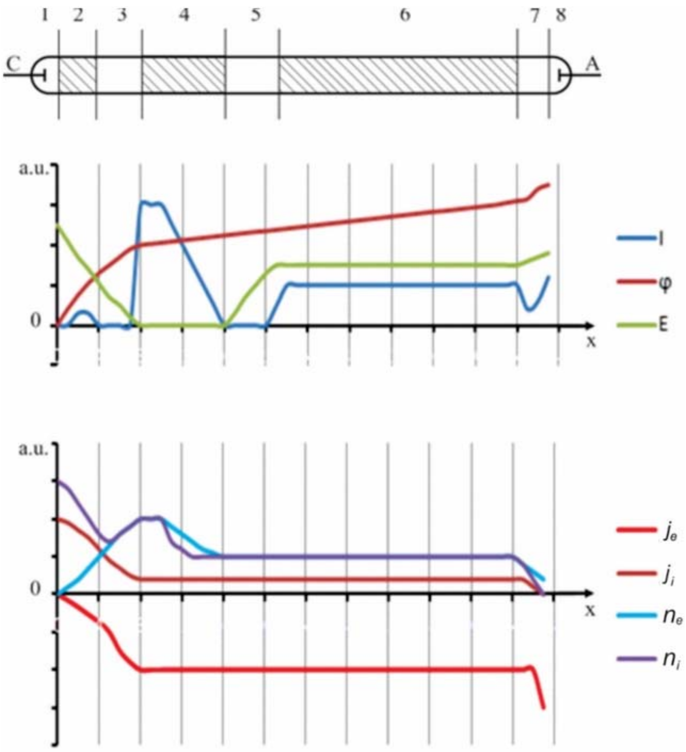

Fig. 1. Glow discharge in a long tube with flat electrodes. In the upper part of the figure, the discharge is shown with the luminescence region shaded. The Figure shows the distribution of luminous intensity I, potential φ, electric field strength E, and electron and ion current densities j_e and j_i and charges n_e and n_i, respectively. Index e refers to the electronic component, and index i refers to the ionic component

In GD, electrons fly out of the cathode with an energy of ~1 eV, which is not enough to excite atoms. To maintain its existence, a dark Aston space is created in the plasma (narrow area 1 in Figure 1). In the Aston space, there is a large positive space charge and a strong electric field that drops to zero only on the border of the region of negative glow (area 4, Figure 1). The thickness of the Aston space is comparable with the mean free path of electrons; all other areas are wider. The acceleration of electrons in the Aston space is enough to excite the glow of atoms. Thus, an area of cathode glow arises (area 2). With further acceleration of electrons by the electric field, the electrons' energy becomes greater than the energy of excitation of the glow during electron impact. As a result, an area of dark cathode space appears (area 3). In this region, the atoms are ionized, and electrons and ions multiply. Due to the slower ion velocity, the positive space charge increases slightly toward the end of the dark cathode space, but because of electron avalanches that create fast electrons, negative and positive charge compensation occurs. As a result, the electric field weakens to zero, and there is no electron acceleration. Because of collisions, the electron energy becomes less than the maximum excitation energy of the emission of atoms. Thus, an area of negative glow arises (area 4). There is a negative space charge in this area, i.e., electron concentration is higher than ion concentration. Because of further collisions, the electron energy becomes less than the lower limit of the excitation energy of the luminescence, and an area of dark Faraday space (area 5) arises. In Faraday space, the longitudinal electric field increases to an intensity that is characteristic of a positive column. The positive column (area 6) is usually the longest part of the discharge and extends to the anode area, which consists of a dark anode space (area 7) and an anode glow film at the anode surface (area 8).

Thus, the GD consists of a cathode layer (Aston dark space, cathode luminescence, and dark cathode space), a transition layer (negative luminescence and dark Faraday space), a positive column, and an anode layer (dark anode space and a film of the anode glow). The cathode layer is an autonomous, self-consistent system in which the conditions for self-maintenance of current are fulfilled. With external control of this system, it is possible to change the conditions for self-maintenance of current. The length of the cathode layer (*pd*, where *p* is the pressure and *d* is the layer thickness in the direction of the tube axis) at room temperature is ~30 - 100 Pa · cm. The length of the transition layer is ~1 kPa · cm. The length of the anode layer is ~1 mm. The length of the positive column depends on the length of the tube. If the tube length is equal to the sum of the lengths of the cathode and transition layers, then the positive column may not exist. If the length of the tube is shorter than the sum of the lengths of the cathode and transition layers, then the discharge is distorted. It becomes unstable, experiences parameter strong fluctuations, and can disappear.

At a pressure of ~10 Pa, the length of the cathode layer d_{cat} is ~3–10 cm. The length of the transition layer d_{trans} is ~100 cm, i.e., at low pressures and short distances, the cathode–anode region is dominated by a negative space charge, and instead of a positive column, we see an area of negative luminescence (glow). This effect gave this type of discharge its name.

In the positive column of a GD, the average electron energy is ~1–2 eV. This energy is not enough to excite the glow of atoms. Still, it exists due to the stepwise excitation of atoms and the presence of a small fraction of fast electrons, which were born at the cathode and reached the positive column without collisions.

In a long tube with a diameter of several centimeters and a direct current supply, the probability for an electron to die on the walls in the positive column is ~$7\cdot10^{-4}$ per centimeter of tube length. Ambipolar diffusion does not affect the electroneutrality of the positive column.

The current density j can be written as

$$j_k = q_k n_k \nu_k \tag{1}$$

where index k refers to electrons (e) and ions (i), q_k is the particle charge, n_k is the density of charged particles per unit of volume, and v_k is the velocity of charged particles in the direction of the tube axis (drift under the influence of an external electric field).

The current density is often represented by the expression [8]

$$j = \rho E = n_e q_e k_e E \tag{2}$$

where index e refers to electrons, E is the electric field strength, and k_e is the electron mobility. In (2), it is assumed that in the GD, the ion mobility is less than the electron mobility, and the drift velocity is determined by the expression $v_e = k_e E$.

We consider diffusion flows to the walls of the tube to be insignificant. With electroneutrality, $n_e \approx n_i$. In this case, it follows from Figure 1 that the ionic component of current density has a speed in the direction of the tube axis that is less than the electron velocity but is still noticeable. Thus, instead of (2), the expression will be

$$j = n_e e E(k_e + k_i^*) \tag{3}$$

where k_i^* is determined not only by transport phenomena but also by ion charge exchange and is not a small quantity. Thus, it is impossible to neglect the part of the current in the plasma, which is caused by the ion charge exchange, not the motion of free electrons.

In the region from the surface of the cathode to the area of negative luminescence, the current is mainly transported by ions. In the rest region (area 5–8 in Figure 1) of the GD, the current is bipolar. Thus, in GD, the distributions of the applied potential difference and of the density of charged particles of different signs are nonuniform along the length of the cathode and transition layers. One of the main properties of GD is low sensitivity to changes in the discharge burning conditions and the negative differential resistance of the discharge.

2.2. Arc discharge

We mainly consider a low pressure arc p of ~1–100 Pa. The knocking out of ions from the cathode can be considered a sputtering process, which is characterized by a sputtering coefficient S (the number of particles knocked out of the cathode per particle falling on the cathode). In a hot cathode AD, if the cathode is heated not from an external source but from ion bombardment, then thermionic emission gives S ~ 0.7–0.9 of total current, but electron knockout during ion bombardment $(1 - S)$ ~ 0.1–0.3. Because the cathode is heated during ion bombardment, not just during direct knockout of electrons by the ion, one incident ion leads to emission of $S/(1-S)$ ~ 2–9 electrons.

Figure 2 presents the picture of the AD and the change of the discharge parameters along the arc (from the cathode to the anode). The collisionless layer and the quasineutral layer together form the cathode layer (or the cathode fall region). Ions are mostly born not from the cathode but in the cathode layer. Then, the ions carry their energy to the cathode and heat it. In a short arc, almost all current in the positive column is electron current. The fraction of ion current is ~1%.

Consider the processes that occur in the cathode layer. For a direct current discharge, the current density and particle concentration are only interesting in the cathode layer, so the corresponding curves in Figure 2 do not continue further into the positive column.

A positive space charge creates in the collisionless layer a sharp drop in the electric field strength (area 1, Figure 2). The size of this region is less than the mean free path of electrons and ions.

The collisionless layer is separated from the positive column by a quasineutral layer, in which the plasma is quasineutral. The quasineutral layer is the main source of ions, which rush to the cathode. The electric field strength in the quasineutral layer is less than that of the cathode, but in the quasineutral layer, there is enhanced ionization of atoms by electrons, which were accelerated in the collisionless layer. In the collisionless layer, there are no sources of charges; therefore, the concentrations of electrons and ions should not change even though their speed changes. As a result, in the discharge current, the fraction of the electronic component increases, and that of the ionic component decreases. The ratio of the ion current to the total current in a collisionless layer $j_i/(j_i + j_e) \approx 0.2–0.4$. This leads the fraction of the electronic component of the current to be ~100% in the quasineutral layer and the ionic component to drop almost to zero. However, in the quasineutral layer, due to intensive production of density charges $n_e \approx n_i$, they increase in the direction of the positive column.

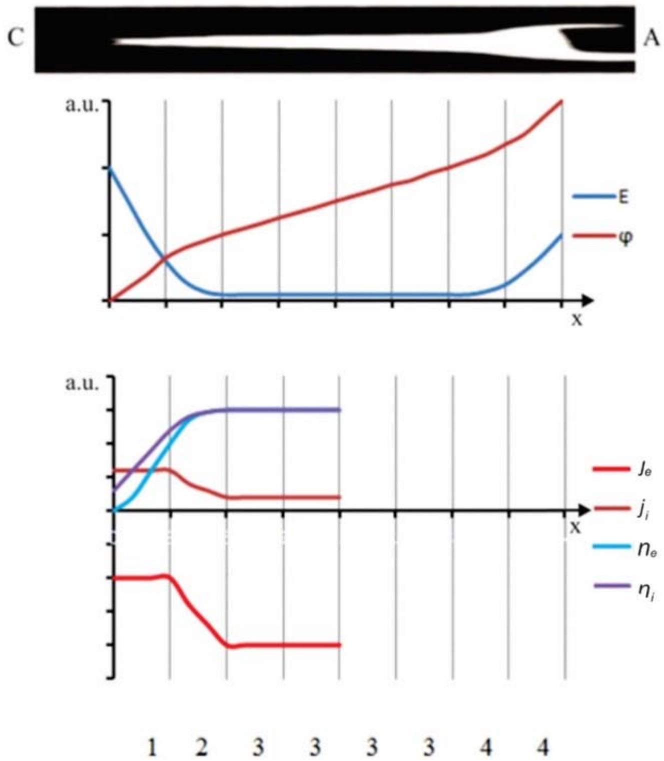

Fig. 2. Arc discharge pattern, with the distribution of electric field strength E, potential φ, electron and ion current densities j_e and j_i along the discharge, n_e and n_i electron and ion particles density: 1– collisionless layer; 2–quasineutral layer; 3– positive column region; 4–anode region

In an AD with a long positive column - e.g., in a compact fluorescent lamp (CFL) - most processes in the positive column of the AD and the GD are similar. The size of the cathode spot in a CFL is ~1 mm, and the cathode layer is almost indistinguishable. The cathode spot moves to adjacent points on the cathode surface, with a decrease in the emission of a given cathode point. Modern CFL does not operate on direct current but instead on alternating current of increased frequency (~30…60 kHz).

For AD with a short arc, the differential resistance is positive. For AD with a long positive column, the differential resistance is negative.

2.3. Magnetron discharge

Figure 3 presents a planar magnetron. Two permanent cylindrical magnets in the center and one annular magnet create a magnetic field above the cathode. The magnetic field is chosen such that in the region of maximum intensity, it captures electrons but barely acts on ions. Ions bombard the cathode and knock out neutral atoms, secondary ions, and secondary electrons. These particles on the path to the anode ionize the atoms of the buffer gas. But if the energy of the formed ions is small and they return to the cathode, then they are accelerated in the anode – cathode gap.

The region of a strong magnetic field is localized near the cathode, and at 1–2 cm from the cathode, it usually becomes close to zero. In our experiments, the magnetic field 3–5 mm from the cathode was so small that with increasing distance from the magnet to the cathode by this value, the discharge became unstable. Thus, the magnetic field strength was not enough to hold the electrons, and pulsation of the space charge began.

MD has four main areas (Figure 3). Area 1 is the cathode layer, where the ions are accelerated and bombard the cathode. Area 2 is the electron trap or torus, where trapped electrons are localized. Area 3 is the area of generation of ions in the buffer gas. Area 4 is the anode area, where the processes of deposition on the substrate and the clustering of atoms and ions occur.

In a collision, an electron can transfer only a small part of its energy to an atom. Therefore, the electron energy must significantly exceed the ionization potential of the atom. The voltage in area 2 is on the order of several volts. The voltage in area 3 is only a few tens of volts, and the main energy of the ions is obtained in a narrow cathode layer. Our experiments have shown that both in the cathode layer and area 3, the voltage drop in the MD can significantly exceed the voltage drop in the cathode layer of the AD. But the thickness of the cathode layer in the MD is greater, so the electric field intensity will be less.

The cathode layer thickness is 0.1–0.3 mm, if the current in the MD corresponds to the saturation current density (~10 mA/cm^2). This is less than the free path length of ions (a few centimeters) in a buffer gas with a pressure of several pascals, and the ions pass this layer without collisions. The electric field strength in the cathode layer is $E > 10^3$ V/cm. If the discharge current density is greater than the saturation current density, then the voltage drop across the cathode layer increases and does not depend on the current, and the layer thickness decreases. As a result, the field strength in the cathode layer is $>10^4$ V/cm. Thus, it may exceed the value in the AD.

The current–voltage characteristic was experimentally obtained as [3, 9]

$$U = \alpha \vartheta^{\delta} \tag{4}$$

where U is the voltage, α is the coefficient, ϑ is the discharge current, and δ is the power ratio (usually $\delta < 0.2$).

In our studies, we use the mathematical theory of catastrophes [2, 10–12]. Therefore, it is advisable to present (4) in the form of a catastrophe equation as

$$U = \alpha \vartheta^{m} + \beta \vartheta^{m-2} + \gamma \vartheta^{m-3} + \ldots + \text{Const} \tag{5}$$

where m is a whole number > 2, α, β, γ and *Const* are the expansion coefficients of U in a row.

If the anode is brought nearer to the cathode, then in position 3*a* (Figure 3), the pulsation of the space charge begins, and the magnetron goes into the acoustoplasma mode without external modulation of current or voltage.

In [3], the empirical dependence of the kinetic energy of ions ε_i on the voltage U in the cathode - anode region is given as follows:

$$\varepsilon_i \approx 0.73U \tag{6}$$

Thus, the kinetic energy of ions in an MD can reach up to 300–500 eV.

Ion energies > 200 eV have a sputtering coefficient $S > 1$. The same energy has knocked-out neutral atoms. With a further increase in voltage, the energy of the knocked-out atoms and value of the sputtering coefficient S increase.

Because the average velocity of sputtered cathode atoms is higher than the thermal velocity of the buffer gas atoms, as a result of elastic collisions, their energy varies only slightly, and thermalization of atoms of the cathode material requires a large number of collisions. In the calculations, it can be assumed that the atoms of the buffer gas are stationary.

The kinetic energy of ions in the magnetron plasma can be greater than the kinetic energy of electrons, and this gives new possibilities for acoustoplasma control of MD and the creation of corresponding devices and facilities – e.g., as realized in [13]. Acoustics act on ions and atoms.

The torus or electron trap region is formed due to the electron drift in crossed electric and magnetic fields [14]. This is an area of high conductivity of plasma due to the high concentration of electrons. The electric field strength in the torus region is $E \sim 0.1$–0.5 V/cm. The cathode erosion profile repeats the torus profile.

Because of the magnetic field H, directed parallel to the cathode surface, a potential well is formed with a depth of [3]

$$\Delta U = \mu H = eEr/2 \tag{7}$$

where $\mu = JS/c$ is the magnetic moment of all trapped electrons, c is velocity of light, $J = ev_e/2\pi r$ is the electric current of a single electron, v_e is its drift speed, r is the radius of the torus, and $S = \pi r^2$ is the area of a circle bounded by the trajectories of the trapped electrons. From (6), it can be seen that the depth of the potential well for trapped electrons depends not on the magnetic but on the electric field strength in the torus. Modulation of the discharge current can lead to modulation of the depth of the potential well and modulation of the space negative charge. This effect is used in the acoustoplasma magnetron [13]. Moreover, the electronic component is modulated, which has an energy close to the height of the potential barrier walls, i.e., on the border of areas 2 and 3 (Figure 3). That is, an additional component of low-energy electrons appears. These are then accelerated along the path to the anode and cause additional ionization.

The potential well depth at a constant discharge current (with a wall height of ~10–20 eV) is significantly greater than the energy of thermalized electrons (~1–2 eV). Therefore, thermal electrons are captured in the torus region.

Larmor frequency of electrons in the torus (in the plane perpendicular to the cathode surface) is $\omega_H = eH/m_e$, where e is the electron charge, m_e is the electron mass, $H \sim 10^{-1}$ T, and $\omega_H \sim 10^{10}$ Hz. If we neglect the interaction with surrounding electrons and ions, then for the stationary case and the quasistationary case (in which the electron rotation frequency in the torus, in the plane parallel to the cathode, is less than the modulation frequency of the electric field), the electron drift velocity in the direction perpendicular to E and H is as follows [13, 15]:

$$v_e = [\vec{E} \times \vec{H}] / H^2 \approx E / H \approx eE / m_e \omega_H \tag{8}$$

Then, at $H \sim 10^{-1}$ T and $E \sim 10^{-3}$ V/m, the drift speed is $\sim 10^4$ m/s with a torus radius of 1.5 cm, and the track frequency is $\sim 10^5$ Hz.

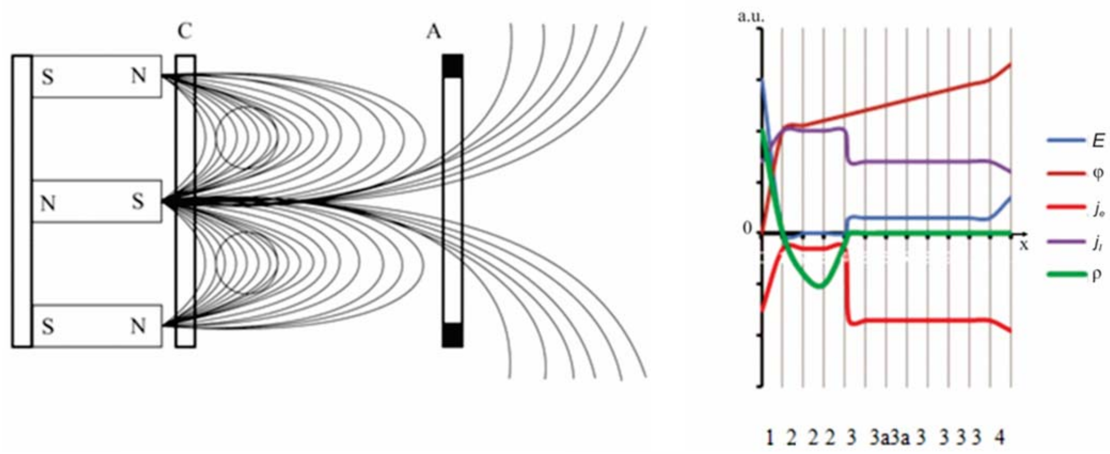

Fig. 3. Magnetron discharge, with the distribution in the cathode –- anode section of the electric field strength E, potential φ, densities of electronic j_e and ionic j_i components of current, and space charge ρ: 1– cathode layer; 2– torus region; 3–generation region in the buffer gas; 4– anode region.

Thus, during the motion along the torus circle inside the potential well, the electron will experience ~10^4 reflections from the walls of the potential well. Therefore, the movement of electrons is random and does not affect fast ions passing through the cross section of the torus. For slow ions, the random nature of the electrons moving in the direction of the torus radius is preserved, but because the Larmor electron trajectory has a certain direction, "wake" acceleration [16–18] of slow ions in a plane parallel to the plane cathode is possible.

A region is formed near the anode, which is often defined as "like a positive column," that is also electrically neutral. Because the anode is usually located close to the cathode, there is no positive column. However, there is a stream of fast ions, electrons, and neutral atoms. In addition, only a few centimeters after the anode region, the structure of a classical plasma with Debye screening is restored. I.e., where the thermalization of electrons occurs and their energy, as a result of collisions, becomes comparable with the thermal energy. In the anode region in the anode field, electrons are decelerated, and ions are accelerated, i.e., a quasineutral flow of charged particles is created that is more uniform in velocity.

3. Conclusion

From a unified standpoint, the cathode regions of the GD, AD, and MD are considered in detail. Distributions along the discharge axis of the longitudinal electric field, potential, charges, and electron and ion current densities are given.

In GD, the ion charge exchange current must be taken into account, which can make a significant contribution to the total current.

In MD, when the magnetic field decreases, instability arises, and the pulsations of the space charge begin. As a result, the magnetron goes into the acoustoplasma mode of operation without using external modulation of current or voltage.

In the MD, electrons trapped in the cathode region are not directly involved in ionization processes, but it is possible to wake acceleration of slow ions on electrons that move along Larmor orbits. These ions will cause enhanced ionization.

The ion energy in the magnetron plasma can be greater than the energy of electrons. This gives new possibilities for acoustoplasma control of the MD and the creation of corresponding instruments and devices.

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Received: 12.05.2019