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MEASUREMENTS OF THE ELECTRON ENERGY DISTRIBUTION FUNCTION IN TWO DIFFERENT REGIONS OF DC-MAGNETRON SPUTTERING DEVICE

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The electron energy distribution function (EEDF) at the edge of the cathode fall and positive column regions of Ar and He glow discharge were measured using a single Langmuir probe. The EEDF in the cathode fall region was found to be non-Maxwellian where two groups of electrons were detected. The two groups have no chance to be thermalized since they leave the cathode fall region fast. Sources of the two groups of electrons are discussed. Moreover, EEDF in the positive column region was found to be Maxwellian for both gases. Electrons have a chance to thermalize themselves due to the long plasma lifetime in this region.

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1. Introduction

In a cold cathode discharge, ions of the gas species are produced by electron-impact ionization, and most of these ions are accelerated into the cathode, causing atoms of the cathode material to be sputtered and secondary electrons to be emitted. These secondary electrons enter the trapping region and cause sufficient ionization to maintain the discharge. Most of the discharge voltage causing the ion and electron acceleration is across the cathode fall region. Cathode fall plays an essential role in controlling the power and stability of the glow discharge, particularly in the planar DC-magnetron sputtering device. Thus, there has been a considerable interest to understand the physical processes in the cathode fall region. Carman and Maitland [1] computed the distribution functions of the electron flux across the cathode sheath of helium discharge. Wendt et al. [2] reported that the impact of the formed ions into the cathode surface produces secondary-electron emission and the electrons are accelerated towards the plasma and confined near the cathode because of their small Larmor radius. Therefore, magnetron can be operated at pressures lower than the unmagnetized devices. Because of the inhomogeneous and strong electric field in this region, few experiments were carried out to measure the important parameters. Bowden et al. [3] measured the sheath thickness, which was found to be equal to the maximum displacement of secondary electrons from the cathode surface. Behringer and Fantz [4] measured the electron energy distribution function in argon and helium glow discharges using spectroscopic technique. They found that EEDFs were far from Maxwellian.

The positive column is the best understood region of the DC discharge. However, recently published investigations (e.g. Refs. [5] and [6]) were devoted to a description of the mechanism of the positive column on the basis of the consequent kinetic treatment of the electron velocity components.

Planar DC-magnetron sputtering devices are commonly used for thin film deposition and sputter etching. Investigation of the characteristics of the gas discharge between the two electrodes would help in understanding the mechanism of operation of the devices. However, experimental measurement of EEDF, particularly in DC-magnetron discharge received little attention in the literature (see Refs. [7] and [8]).

In the present work, EEDFs at the edge of the cathode fall and positive column regions in a DC-magnetron discharge were measured using a single Langmuir probe. The experimental data are discussed with the aim to explain the sources of fast electrons.

2. Experimental setup

A stationary DC-glow discharge was generated between two electrodes of metallic discs of about 5 cm in diameter. The anode was made of copper and the cathode of aluminium or another metal according to the sputtering purposes. A permanent circular magnet was fixed under the cathode surface. Since the radius of ion orbits $r_{\rm iL}$ in the present work is in the range of 8 – 10 cm (the magnetic filed was about 5 mT (50 gauss), the ion orbits are almost two orders of magnitude larger than the probe radius, so the ions can be considered to be fully free. Thus the effect of the magnetic field on the probe measurements can be neglected.

The electrodes were placed inside the metallic chamber of 15 cm diameter which was evacuated down to about 13 mPa (10^{-5} torr) using a large rotary pump and two stages of diffusion pumps. Argon and helium gases were introduced into the system via a needle valve. The discharge current was varied between 4 and 30 mA and the gas pressure was in the range 65 to 700 Pa (0.5 to 6 torr) for each of the gases. The device was operated using 300 – 800 V DC, whereas the current density was between 2 and 15 mA/m^2. Figure 1a is a schematic drawing of the apparatus used in this study.

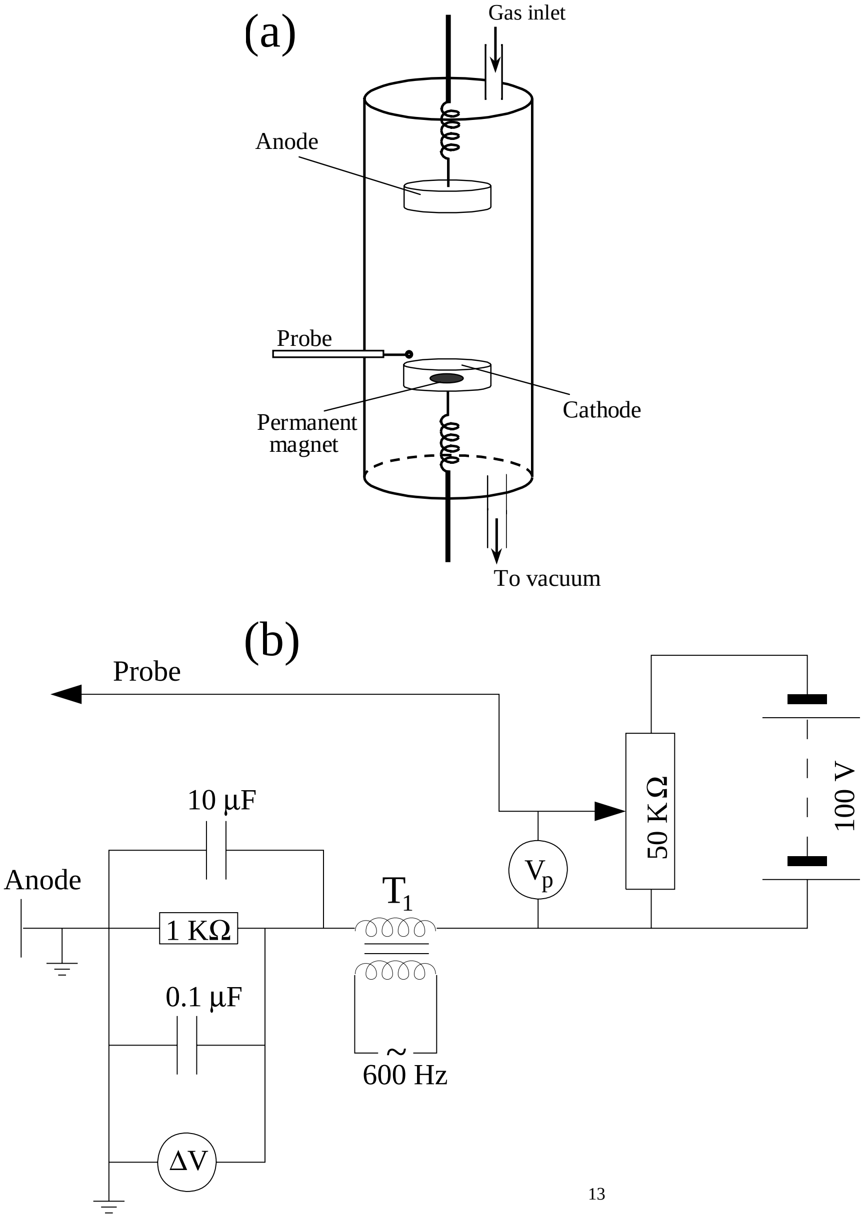


Fig. 1. a) Schematic drawing of the DC magnetron used in the measurements. b) Block diagram of the electronic circuit.

A single spherical Langmuir probe, made of phosphor bronze, of a radius of 0.15 cm was used to determine the plasma parameters. The probe can be moved in different regions of the plasma discharge. It is estimated that the Debye shielding length λ_0 varied from 0.095 to 0.12 cm in our experimental conditions. That was less than the probe radius. Also, the electron mean free path λ_e varied from 0.13 to 0.29 cm, which was larger than the probe radius. Therefore, the probe theory for high-pressure plasma could be used for the analysis of the measurements (see Ref. [9b]).

3. *Results and discussion*

When a small AC voltage signal ($e = A_a \sin \omega t$) is superimposed on the DC current of the electric probe, the probe current will change by $\Delta I(t)$. Sloane and MacGregor [9a] found that $I(t)$ depends on the second, fourth and higher even-order derivatives of the probe DC current with respect to the retarding potential. If the amplitude A_a of the alternating voltage is made so small that higher-order derivatives are negligible, $I(t)$ will be

$$\Delta I(t) = \frac{A_a}{4} \frac{\mathrm{d}^2 I}{\mathrm{d}V_p^2}\,, \tag{1}$$

where $\mathrm{d}^2 I/\mathrm{d}V_p^2$ is the second derivative of the probe current. This derivative may be measured at any point of the $I-V$ characteristic curve of the probe, by keeping A_a constant and small, and by measuring directly the variable current $\Delta I(t)$. The circuit for this measurement is shown in Fig. 1b.

The electron energy distribution function was computed using the expression [9b]

$$F(\epsilon) = -\frac{4}{Ae^2} \sqrt{\frac{mV_p}{2e}}\, \frac{\mathrm{d}^2 I_e}{\mathrm{d}V_p^2}\,, \tag{2}$$

where ϵ is the electron energy, A the probe area, I_e the electron current, V_p the probe voltage, and e and m are the electron charge and mass, respectively.

The electron-energy probability function EEPE is given by

$$f(\epsilon) = \frac{F(\epsilon)}{\sqrt{\epsilon}}\,. \tag{3}$$

For the Maxwellian energy distribution

$$\frac{\mathrm{d}^2 I_e}{\mathrm{d}V_p^2} \propto \exp\left(-\frac{eV_p}{kT_e}\right)\,. \tag{4}$$

Thus,

$$F(\epsilon) = const\ \sqrt{V_p}\ \exp\left(-\frac{eV_p}{kT_e}\right)\,, \tag{5}$$

where k is the Boltzmann constant and T_e the electron temperature.

The presence of a Maxwellian distribution was tested by plotting the semi-log curves of the second derivative against V_p. Equations (2) and (4) show that a plot of $\ln \mathrm{d}^2 I_e/\mathrm{d}V_p^2$ as a function of V_p would show a straight line of a slope $-e/(kT_e)$ whenever the distribution function is Maxwellian. Figures 2 and 3 show the semi-log plots of the second derivative of the electron current, $\ln \mathrm{d}^2 I_e/\mathrm{d}V_p^2$, for the cathode

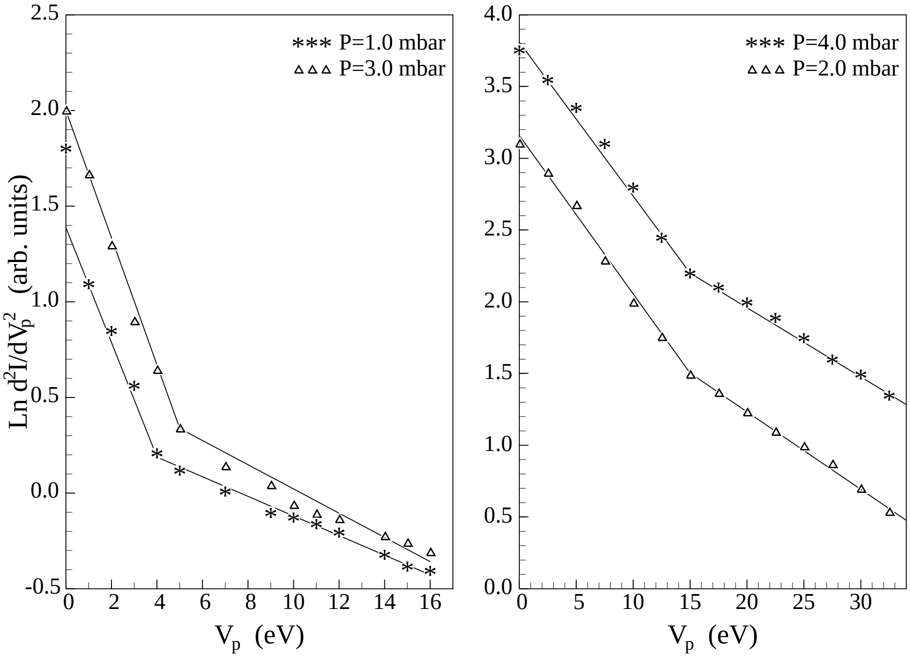


Fig. 2. Dependence of the second derivative of the electron current on the probe voltage, discharge in the cathode fall region in Ar, *anode current* 10 mA.

Fig. 3 (right). Dependence of the second derivative of the electron current on the probe voltage, discharge in the cathode fall region in He, *anode current* 20 mA.

fall regions of Ar and He discharges. It can be clearly seen that the curves have two linear parts of different slopes. This is related to the existence of two groups of electrons of different temperature [10]. The presence of the two groups of electrons was confirmed by calculating $F(\epsilon)$ using Eq. (5). Two well defined maxima were observed for Ar discharge at about 4 – 5 eV with a plasma density $(2.3-4)\times 10^8$ cm^{-3}, and 13 – 15 eV with a plasma density $(0.7-1.4)\times 10^8$ cm^{-3}, and also two for He glow discharge at about 7 – 9 eV with a plasma density $(3.9-5.3)\times 10^8$ cm^{-3}, and 19 – 21 eV with a plasma density $(1.6-2.2)\times 10^8$ cm^{-3} (see Figs. 4 and 5).

The presence of two groups of electrons at the edge of the cathode fall region can be explained as follows. The primary electrons emitted from the cathode are accelerated by the electric field before entering the negative glow region, forming what is called "runaway (escape) electrons". As these accelerated electrons enter the negative glow region, majority of them will be subjected to electron – atom collisions (inelastic collisions), loosing most of their energy and forming the low-energy group. However, a smaller number of these electrons will escape the region without inelastic collisions and they form the higher-energy group.

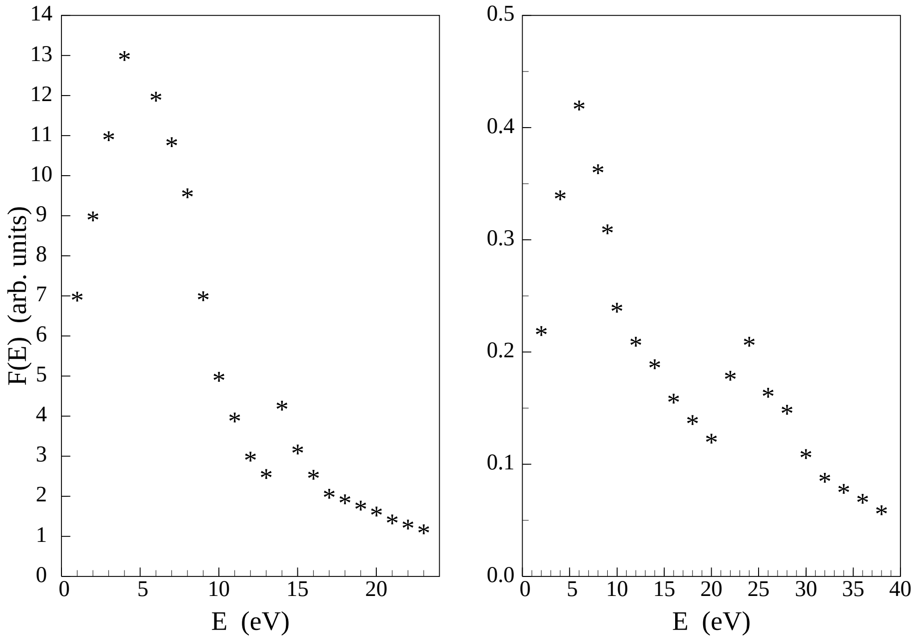


Fig. 4. Electron energy distribution function in the cathode fall region, discharge in Ar, $P = 130$ Pa *(*1.0 torr*) and* $I_A = 10$ mA.

Fig. 5 (right). Electron energy distribution function in the cathode fall region, discharge in He, $P = 270$ Pa *(*2.0 torr*) and* $I_A = 20$ mA.

Ecker and Müller [11] found that electrons can run away in a partially ionized gas as a result of the applied field E. The product of the ratio of the electric field and pressure (E/P) and of the gas temperature, T_g, $[(E/P)\,T_g]$ must exceed a critical value which depends upon the electron velocity, v_e, and the electron – atom collision cross-section, $Q_{e-n}(v_e)$. $[(E/P)\,T_g]_c$ corresponds to the maximum of the term $\{0.55 \times 10^4\ v_e^2\, Q_{e-n}(v_e)\}$, which is determined graphically when plotted against v_e^2]. When the applied value of $[(E/P)\,T_g]$ is larger, electrons can run away from the region. Values of Q_{e-n} were taken from Ref. [12].

In the present work with Ar discharge, the applied value of $[(E/P)\,T_g]$ in the cathode fall region was higher than the critical value $[(E/P)\,T_g]_c$ by at least an order of magnitude, as shown in Table 1. This confirms that some of the accelerated electrons could "run away" and gain high energy as a result of the formed electric field.

For He discharge, the applied value of $[(E/P)\,T_g]$ in the cathode fall region was higher than the critical value $[(E/P)\,T_g]_c$ by an order of magnitude for the pressure range about 300 to 600 Pa (3 – 6 torr), and by a factor of about 30 at the pressure of about 270 Pa (2 torr), as shown in Table 2.

Table 1. Applied and critical values of $(E/P) \times T_g$ *as functions of the gas pressure for* Ar *discharge at a constant dischagre current* $I_a = 10$ mA (1 torr = 133 Pa).

P (torr)	$[(E/P)\,T_g]_{\rm appl.}$ (Volt K/(cm torr))	$[(E/P)\,T_g]_{\rm crit.}$ (Volt K/(cm torr))
0.5	42×10^5	30×10^4
1.0	19×10^5	12×10^4
2.0	10×10^5	11×10^4
3.0	6×10^5	10×10^4
4.0	3.5×10^5	9.2×10^4

Table 2. Applied and critical values of $(E/P) \times T_g$ *as functions of the gas pressure for* He *discharge at a constant dischagre current* $I_a = 20$ mA (1 torr = 133 Pa).

P (torr)	$[(E/P)\,T_g]_{\rm applied}$ (Volt K/(cm torr))	$[(E/P)\,T_g]_{\rm crit.}$ (Volt K/(cm torr))
2.0	27×10^5	7×10^5
3.0	13×10^5	6.2×10^5
4.0	7.5×10^5	5.5×10^5
5.0	4.4×10^5	4.7×10^5
6.0	2.8×10^5	3.9×10^5

Under such conditions, electrons gain on energy in the electric field and escape (runaway) the cathode region before making an inelastic collision. Moreover, the time required in which fast electrons form a displaced Maxwellian distribution (self-collision time) is given by [13]

$$t_c = 0.266 \left(\frac{T_e^{3/2}}{N_e \, \ln(\lambda_D/\rho_0)} \right) , \qquad (6)$$

where λ_D is the Debye length, ρ_0 the average impact parameter for a 90° Coulomb deflection, N_e the electron density and T_e is the electron temperature. The values of $\ln(\lambda_D/\rho_0)$ were taken from Ref. [13]. The values of t_c in the present work (our pressure range) were in the range $(2.4 - 4) \times 10^{-9}$ s. The thickness of the cathode fall region was derived from the potential and electric field distributions of the glow discharge, and have been found in the range of 0.15 to 0.2 cm for pressures between 130 and 530 Pa (1.0 and 4.0 torr) and for a discharge current of 10 mA. The average electron velocity was estimated at about $(1.5 - 2) \times 10^8$ cm/s. The time needed in the present work that electrons leave the cathode fall region $t_{\rm electrons}$ was in the range of $(0.74 - 1.3) \times 10^{-9}$ s, which is about three times less than t_c. So, fast electrons did not have a considerable chance to redistribute themselves in a displaced Maxwellian distribution before leaving the cathode fall region.

There was also no chance for the formation of equilibrium between the two groups of electrons. The time required to approach equilibrium between the two electron groups is given by [13]

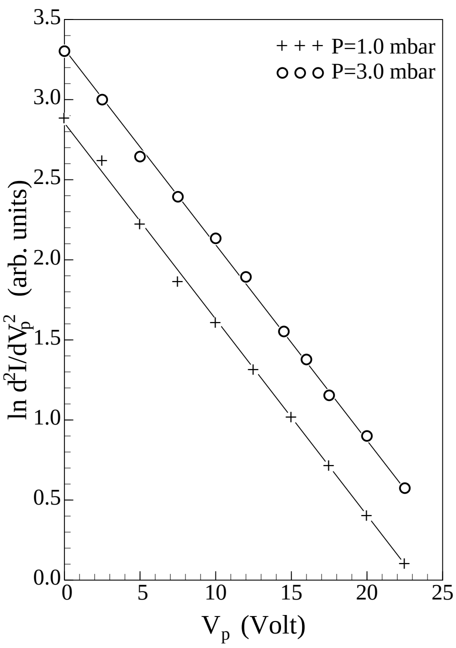
$$t_{\rm eq} = \frac{t_{\rm el}}{1 + N_{e_1}/N_{e_2}} \,, \tag{7}$$

where

$$t_{\rm el} = 17 \times 10^4 \left(\frac{(T_{e_l} + T_{e_2})^{3/2}}{N_{e_1} \, \ln(\lambda_D/\rho_0)} \right) . \tag{8}$$

$t_{\rm el}$ is the time at which equipartition of energy is established between the two groups of electrons, and T_{e_1}, T_{e_2}, N_{e_1} and N_{e_2} are the electron temperatures and densities of the two groups, respectively. In the present work (for our pressure range), $t_{\rm eq}$ was in the range of $(4 - 8.7) \times 10^{-7}$ s, which was about 100 times longer than that taken by the electrons to leave the cathode fall region. Consequently, the two groups were leaving the cathode fall region before reaching equilibrium with each other.

Figures 6 and 7 show the semi-log plots of the second derivatives of the elec-



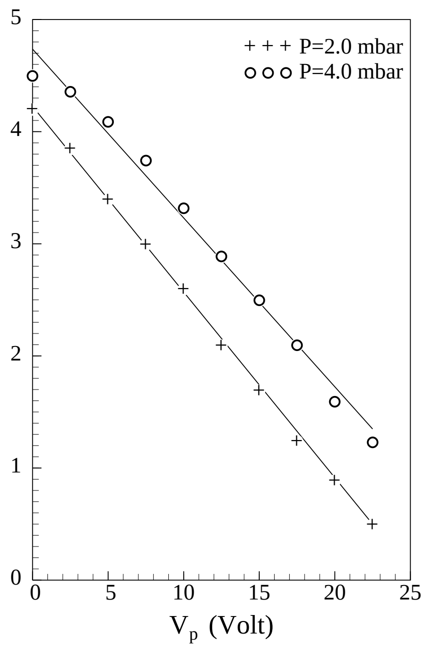


Fig. 6. Dependence of the second derivative of the electron current on the probe voltage, discharge in the positive column region in Ar, *anode current* 10 mA.

Fig. 7. Dependence of the second derivative of the electron current on the probe voltage, discharge in the positive column region in He, *anode current* 20 mA.

tron current $\ln \mathrm{d}^2 I_e/\mathrm{d}V_p^2$ in the positive column region of Ar and He discharges, respectively.

A comparison between the experimental data and the Maxwellian curves for $F(\epsilon)$ of the two gases is shown in Figs. 8 and 9. A good agreement has been obtained, indicating the presence of the Maxwellian distribution in the positive column region of the Ar and He glow discharges. This may be related to the fact that the length of the positive column region is at least one order of magnitude greater than the cathode fall thickness. So, electrons had a longer time to redistribute (i.e., to thermalize) themselves to form a Maxwellian distribution ($t_c = 2.4 \times 10^{-9}$ and $t_e = 10^{-8}$ s). It was found that the electron temperatures in the positive column (in our pressure range) are between 5.8 and 8.3 eV and from 4.8 to 7.4 eV for Ar and He discharges, respectively.

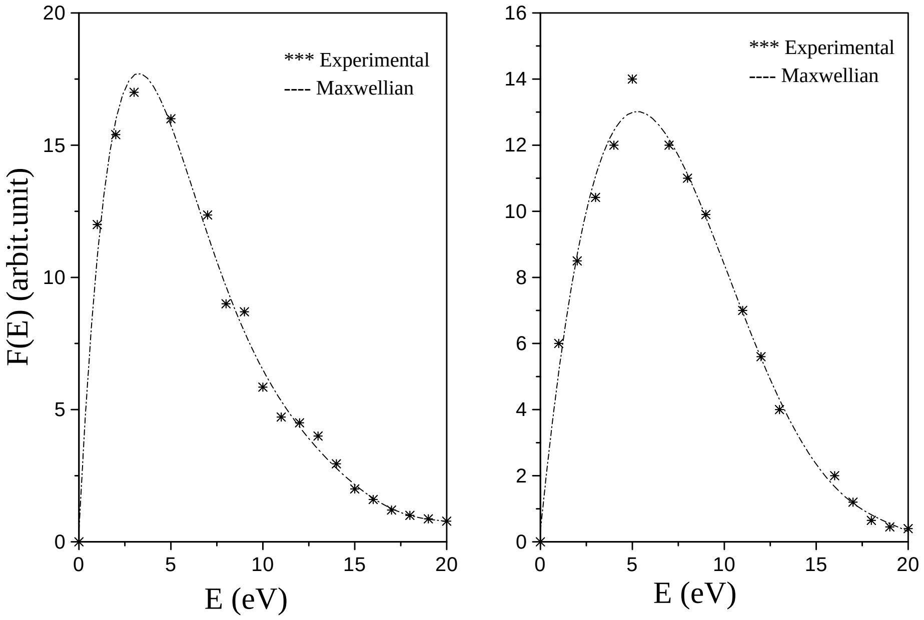


Fig. 8. Electron energy distribution function in the positive column region, discharge in Ar, $P = 130$ Pa *(*1.0 torr*) and* $I_A = 10$ mA.

Fig. 9 (right). Electron energy distribution function in the positive column region, discharge in He, $P = 270$ Pa *(*2.0 torr*) and* $I_A = 20$ mA.

4. Conclusion

The electron energy distribution functions in two regions of the Ar and He glow discharge were measured using a single Langmuir probe. Two groups of electrons having different temperatures were detected in the cathode fall region for both gases. The presence of these two groups was attributed to a “runaway” process in the weakly ionized gas in which the conditions for electron acceleration without inelastic collisions were well satisfied. The electrons collide with neutral atoms in the negative glow region and produce secondary electrons of different temperatures. The thermalization time between the two groups of electrons was longer than the time required for electrons to leave the cathode fall region. Therefore, electrons did not have time to redistribute themselves in one Maxwellian group.

In the positive column, only one velocity group of electrons was observed for both gases in the used pressure range. In that region, the thermalization time was short enough that electrons did redistribute themselves in one Maxwellian group.

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MJERENJE RASPODJELE ELEKTRONSKE ENERGIJE U DVAMA PODRUČJIMA ISTOSMJERNOG MAGNETRONA ZA RASPRAŠIVANJE

Primjenom Langmuirove sonde mjerili smo funkciju raspodjele elektronske energije (EEDF) na rubu katodnog tamnog prostora i u pozitivnom stupcu tinjavog izboja u Ar i He. U katodnom tamnom prostoru našli smo ne-Maxwellov EEDF s dvjema grupama elektrona. Ove dvije grupe ne mogu se termalizirati jer brzo napuštaju prostor tinjavog izboja. Raspravljamo uzroke dviju grupa. Međutim, u pozitivnom stupcu smo našli Maxwellovu EEDF. U tom je području trajanje plazme dugo i elektroni se mogu termalizirati.