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MEASUREMENTS OF THE BREAKDOWN POTENTIALS FOR DIFFERENT CATHODE MATERIALS IN THE TOWNSEND DISCHARGE

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The breakdown potentials have been measured for argon and helium discharges using three different cathode materials: aluminium, silver and magnesium. The measurements show that lower breakdown potentials are associated with lower work function of the cathode material. For the three different cathodes, the secondary ionization coefficients have been estimated using the measured values of the breakdown potentials and the first ionization coefficient, in the range 0.60 to 2.25 V/[Pa cm] (80 to 300 V/[torr cm]) for Ar discharge and in the range of 0.15 to 1.80 V/[Pa cm] (20 to 240 V/[torr cm]) for He discharge. The minimum breakdown potential has been found at $(pd)_{\min} = 80$ Pa cm (0.6 torr cm) in Ar discharge and at 530 Pa cm (4.0 torr cm) in He discharge.

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1. Introduction

Electrical breakdown of gases is the transition from an insulator to a conducting state and the minimum voltage at which this transition occurs is called the breakdown voltage V_{Br}. The physics of the electrical breakdown has a great significance because of its wide applications in electronics and technology [1].

Low pressure electrical discharges are a very useful tool for understanding and predicting the properties of discharges used for plasma processing, deposition of thin films by sputtering, plasma polymerization, etching, welding and cutting, plasma spraying, plasma display panels and light sources [2].

The interest in studying the properties of Townsend discharge is motivated by the necessity of extending knowledge in the field of gas discharge physics and to help to solve practical problems associated with the use of this kind of discharge in technical devices [3].

The emission of secondary electrons as a result of collisions of ion beams with metallic surfaces has been studied by many authors [4]. References [4] represent only a small part of recent work devoted to practical use of discharge in gases.

The aim of the present work is to investigate and measure the breakdown potentials in Ar and He for three different cathode materials in the Townsend region. Also, to determine the generalized secondary ionization coefficient, ω/α, necessary for self-sustaining the gas discharges.

2. *Experimental setup*

The discharge in He and Ar was studied in a Pyrex glass tube of 10 cm diameter and 40 cm long. The anode is an Al disk, while the cathode was made of three different materials, Al, Mg and Ag. The diameter of the electrodes was 5 cm and the cathode-to-anode separation was fixed at 1.0 cm.

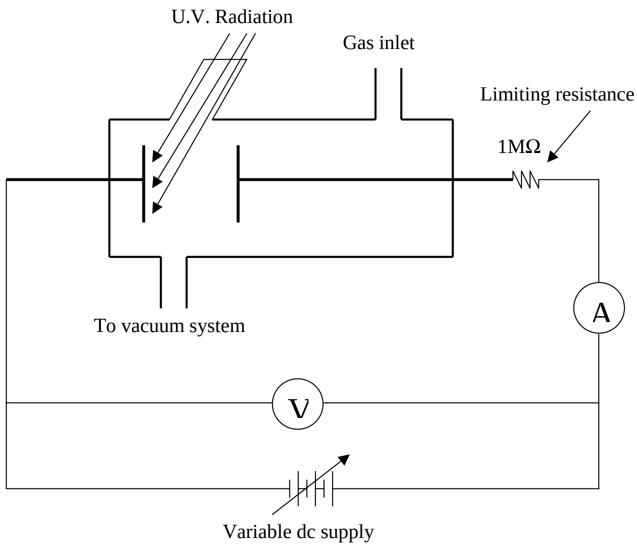

Fig. 1. The electric circuit for measurement of breakdown potential.

By means of a rotary and a diffusion pump, the discharge system (Pyrex tube) could be evacuated down to about 1.3 mPa (10^{-5} torr). During all measurements, a continuous gas flow through the discharge vessel was maintained. High purity argon and helium gases were used as the working gases and they were fed to the discharge tube through a needle valve. The pressures of the gases were varied from 13 to 650 Pa (0.1 to 5 torr) and measured using a dial gauge (Edward Model CG3).

The discharge tube is provided with a quartz window on its side so that UV radiation passing through it strikes the cathode at its center and so provides an efficient source of photoelectric current.

Figure 1 shows the circuit used for the determination of the breakdown potential. The external resistance R_L was used to limit the discharge current, to protect the current meter and to ensure that the discharge would be limited to the Townsend region and would not step up to the glow discharge region. The current flow in through the discharge tube was measured by a nanoampermeter (Mutlipreci Model MN 5121) connected in series with the cathode.

3. *Results and discussion*

3.1. *Measurements of the gas breakdown potential*

The gas breakdown voltage $V_{\rm Br}$ was determined as a function of the product of the gas pressure p and the interelectrode distance d. The breakdown potentials have been measured for Ar discharge in the range between *pd* 26 and 530 Pa cm (0.2 to 4.0 torr cm) while for He discharge from 133 to 2400 Pa cm (1.0 to 18 [torr cm]) for the three different cathodes.

3.1.1. **Argon breakdown potential**

Figure 2 shows the Paschen curves for Ar gas using the three cathodes. The minimum breakdown potential $(V_{\rm Br})_{\rm min}$ for the three cathodes occurs at the value of $(pd)_{\rm min}$ = 80 Pa cm (0.6 torr cm). The minimum breakdown potential $(V_{\rm Br})_{\rm min}$ was found to depend upon the type of the cathode material. This can be related to the difference in the work function of the different cathodes. On the left-hand side of the Paschen curve, $V_{\rm Br}$ decreases when increasing *pd* which can be attributed to the increases in the collision frequency, hence the increase of the number of collisions between electrons and neutral atoms. However, on the right-hand side, the breakdown voltage increases gradually when increasing *pd*, which can be attributed to the decrease in the ionization cross-section. Therefore, electrons need more energy to break down the discharge gap, resulting in an increase of $V_{\rm Br}$ [5].

Mari [6] measured breakdown potentials in Ar discharge using Ag cathode. The minimum breakdown voltage $(V_{\rm Br})_{\rm min}$ was found to be 170 V at $(pd)_{\rm min}$ = 163 Pa cm (0.7 torr cm), while in the present work $(V_{\rm Br})_{\rm min}$ was found to be 213 V at $(pd)_{\rm min}$ = 80 Pa cm (0.6 torr cm) for the same type of cathode.

3.1.2. **Helium breakdown potential**

Figure 3 shows the typical Paschen curves for He discharge using the three cathodes. The minimum breakdown potential, $(V_{\rm Br})_{\rm min}$, for the three cathodes, occurs at a value of $(pd)_{\rm min}$ = 530 Pa cm (4 torr cm). $(V_{\rm Br})_{\rm min}$ has been found for He discharge at 168, 162 and 152 V for Ag, Mg and Al cathodes, respectively. One can

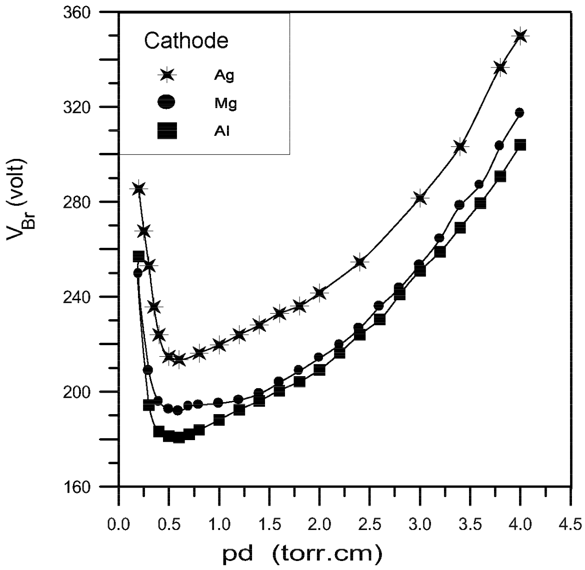

Fig. 2. Breakdown voltage vs. pd for Ar *discharge.*

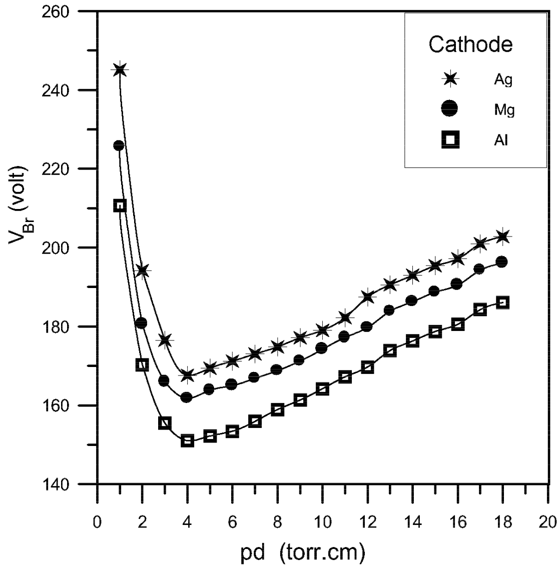

Fig. 3. Breakdown voltage vs. pd for He *discharge.*

notice that the minimum breakdown potential increases for the larger work functions of the cathode materials.

Table 1 shows the values of $(V_{\rm Br})_{\rm min}$ in Ar and He discharges and the work functions of the used cathodes for comparison.

TABLE 1. The work function ϕ and the minimum breakdown potential $(V_{\rm Br})_{\rm min}$ for different cathode type and different gases.

Cathode material	ϕ (eV)	$(V_{\rm Br})_{\rm min}$ (Volt) [Ar gas]	$(V_{\rm Br})_{\rm min}$ (Volt) [He gas]
Silver (Ag)	4.26 – 4.74	213	168
Magnesium (Mg)	3.66	192	162
Aluminium (Al)	3.6	182	152

Figure 4 shows the Paschen curves for Ar and He gases, using Mg cathode. It is clear that the minimum breakdown voltage $(V_{\rm Br})_{\rm min}$ of He is lower than that of Ar, in spite of the higher ionization potential of He (24.5 eV) than that of Ar (15.67 eV). This can be attributed to the higher efficiency of the secondary ionization processes in He discharge as compared to Ar discharge. Hagstrom [7] determined

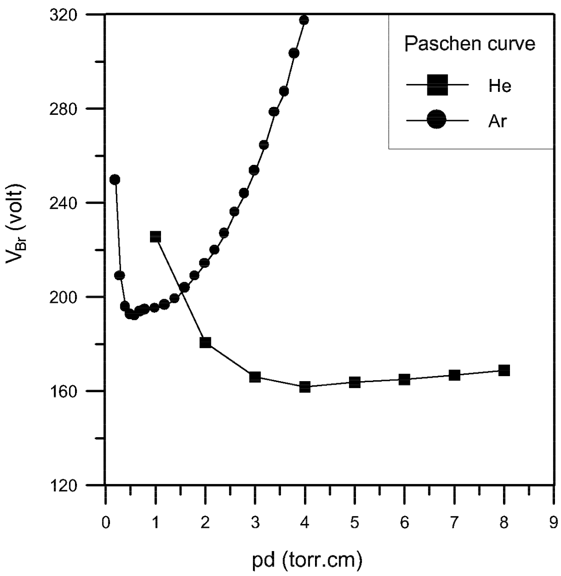

Fig. 4. Breakdown voltage vs. pd for Ar *and* He *gases by using* Mg *cathode.*

the effect of bombarding clean metal with positive ions of rare gases. He reported that the efficiency of the process increases by decreasing the ion mass, increasing the ionization potential of the gas and decreasing the work function of the cathode material. He concluded that the secondary Townsend ionization coefficient γ_i of He is higher that that of Ar, hence, lower breakdown potentials occur in He discharge rather than in Ar discharge. Figure 4 also shows that $(V_{\rm Br})_{\rm min}$ of Ar occurs at $(pd)_{\rm min}$ of 80 Pa cm (0.6 torr cm), while that for He occurs at $(pd)_{\rm min}$ of 530 Pa cm (4 torr cm). Since

$$\lambda_{\rm e-n} = \frac{1}{N_n Q_i}\,, \tag{1}$$

and

$$\nu_{\mathrm{e-n}} = N_n Q_i v_{\mathrm{e}} \,, \tag{2}$$

where $\lambda_{\mathrm{e-n}}$ is the mean free path, $\nu_{\mathrm{e-n}}$ the collision frequency (number of collision per sec), N_{n} the density of the gas atoms, v_{e} the velocity of electrons and Q_{i} is the ionization cross-section.

At the same E/p, the ionization cross-section of He [Q_i (He)] is lower than that of Ar [Q_i (Ar)] by a factor of ten [8]. Hence, the mean free path for He [$\lambda_{\mathrm{e-n}}$(He)] is larger than that of Ar [$\lambda_{\mathrm{e-n}}$(Ar)] at the same E/p by nearly ten times. Therefore, the probability of ionizing He gas is expected to be lower than that of Ar gas by the same order of magnitude. This can explain the higher values of $(pd)_{\mathrm{min}}$ in He than in Ar even though V_{Br} in He is lower than that in Ar.

Table 2 shows the values of mean free path $\lambda_{\mathrm{e-n}}$ and the collision frequency $\nu_{\mathrm{e-n}}$ of the two gases at different values of E/p.

TABLE 2. Mean free path and the collision frequency at different E/p for He *and* Ar *gases. (1 torr corresponds to 133.3 Pa.)*

	He gas			Ar gas		
E/p (V/[torr cm])	p (torr)	$\lambda_{\mathrm{e-n}}$ (cm)	$\nu_{\mathrm{e-n}}$ $\times 10^5 \mathrm{s}^{-1}$	p (torr)	$\lambda_{\mathrm{e-n}}$ (cm)	$\nu_{\mathrm{e-n}}$ $\times 10^6 \mathrm{s}^{-1}$
50	3	0.23	30	***	***	***
100	1.8	0.39	46	2.2	3.9×10^{-2}	46
150	1.6	0.440	45	1.4	4.4×10^{-2}	45
200	1	0.704	31	0.9	7.9×10^{-2}	27
250	***	***	***	0.5	0.14	16

It is clear from Table 2 that $\lambda_{\mathrm{e-n}}$(Ar) is lower than $\lambda_{\mathrm{e-n}}$(He) by a factor of ten and $\nu_{\mathrm{e-n}}$(Ar) is larger than $\nu_{\mathrm{e-n}}$(He) by the same factor at any value of E/p.

3.2. Secondary ionization coefficients

The number of secondary electrons emitted in the discharge by the various secondary electron processes per ion pair produced in the discharge is known as the total secondary Townsend electron coefficient, ω/α. Values of the secondary ionization coefficient ω/α are estimated using the following equation [9]

$$\frac{\omega}{\alpha} = \frac{1}{e^{\eta V_{\mathrm{Br}}} - 1} \,. \tag{3}$$

In the case of large ηV_{Br}, i.e., $\exp(\eta V_{\mathrm{Br}}) \geq 1$, this equation can be written as

$$\frac{\omega}{\alpha} = \frac{1}{e^{\eta V_{\mathrm{Br}}}} \,. \tag{4}$$

ω/α at a certain value of E/p is determined using the values of η (η is the first Townsend ionization coefficient). Values of η were taken from the results of Kirthouf [10]. V_{Br} at a certain E/p was obtained from the present results for the Paschen curves, by dividing V_{Br} with the corresponding value of pd.

3.2.1. Secondary emission in argon

Figure 5 shows curves of ω/α as functions of E/p in argon gas using Ag, Mg and Al cathodes. The three curves have the same general behaviour. At low values of E/p, ω/α increases rapidly to a maximum value, then decreases very slowly, followed by an slow increase. Also, Fig. 5 confirms that the cathodes, which have a lower work function (e.g., Al), are associated with a higher secondary ionization coefficient, while Ag, which has the highest work function, has lower secondary ionization coefficient.

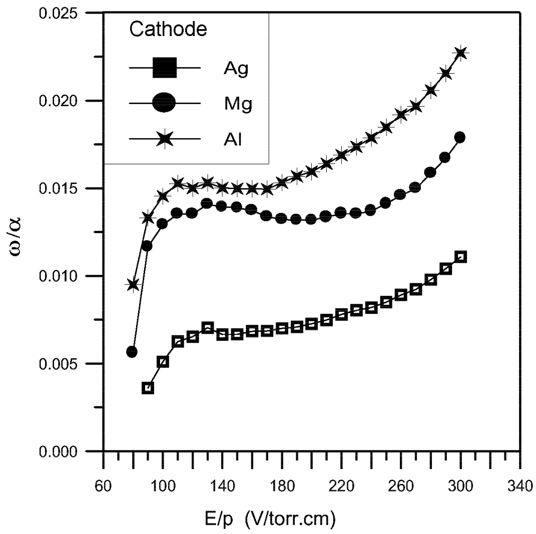

Fig. 5. Relation between the secondary ionization coefficient ω/α and E/p for Ar *gas.*

The secondary ionization coefficient curves can be subdivided into three regions. In the first region, E/p between 0.60 and 0.90 V/[Pa cm] (80 to 120 V/[torr cm]), ω/α rises sharply. This may be attributed to the photoelectric emission by photon bombardment of the cathode surface [11].

In the second region, E/p between 0.90 and 1.50 V/[Pa cm] (120 to 200 V/[torr cm]), ω/α decreases slowly when increasing E/p. This can be due to the decrease in the photoelectric effect as a result of the decrease in the number of excited atoms in this region.

In the third region, E/p above 0.90 V/[Pa cm] (120 V/[torr cm]), ω/α increases when increasing E/p. This may be due to the increase in the contribution of ions where the dominant secondary process is mainly due to the impact of ions on the cathode at high E/p [11].

Phelps and Petrović [5] showed that, as E/p increases in the range from 0.26 to 7.50 V/[Pa cm] (35 to 1000 V/[torr cm]), the photoelectric effect decreases, the contribution of the ion bombardment increases, while metastable states have a small influence in this range of E/p. These results are in agreement with the conclusion of the present work, where at low E/p the photoelectric emission from the cathode is dominant, while at high E/p, the ion bombardment is dominating as a secondary electron process.

3.2.2. **Secondary emission in helium**

Figure 6 shows the values of ω/α for helium gas, using Mg, Al and Ag cathodes. Values of ω/α are deduced from the measured breakdown potential of the Paschen curves, which were measured in the pressure range of 133 to 2400 Pa (1 to 18 torr). From the same figure, it is also clear that ω/α decreases sharply for Al, Mg, and Ag cathodes in the narrow range of E/p from 0.15 to 0.60 V/[Pa cm] (20 to 80 V/[torr cm]), and then it tends to be nearly stable in the range of E/p above 0.60 V/[Pa cm] (80 V/[torr cm]).

In the range of E/p below 0.60 V/[Pa cm] (80 V/[torr cm]), it is well known that the secondary electron emission from the cathode is mainly due to the incidence of either photons and/or metastable excited atoms onto the cathode [5].

However, in the range of E/p above 0.60 V/[Pa cm] (80 V/[torr cm]), ω/α is nearly constant for each cathode material. Identification of the secondary processes

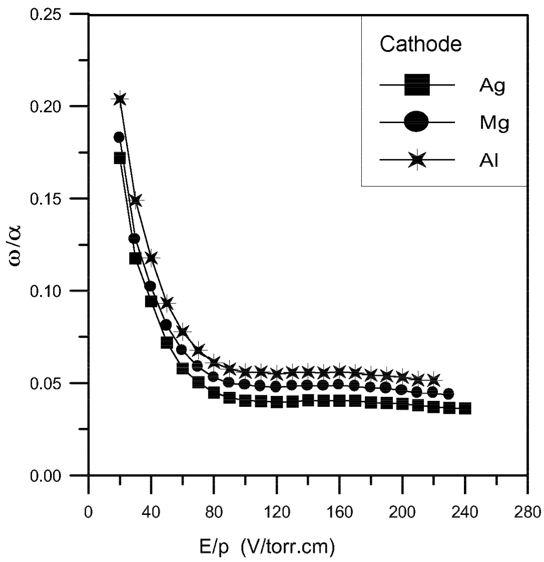

Fig. 6. Relation between the secondary ionization coefficient ω/α and E/p for He *gas.*

in that region is possible by the technique of formative time lag [9]. However, it is well known that the secondary emission by the positive ions is the most probable process in that region due to the values of ω/α which are nearly constant.

Figure 7 shows the values of ω/α for the two gases (Ar and He) as functions of E/p for the Mg cathode. It is clear that values of ω/α for He gas are higher than those of Ar. This may be related (as mentioned above) to the fact that the efficiency of electron emission by the incidence of the gas ions onto the cathode increases whem using a smaller ion mass, i.e., $\gamma_{\mathrm{He}} > \gamma_{\mathrm{Ar}}$ [7]. This proves that, the positive-ion contribution to ω/α is very significant as a secondary ionization process from the cathode.

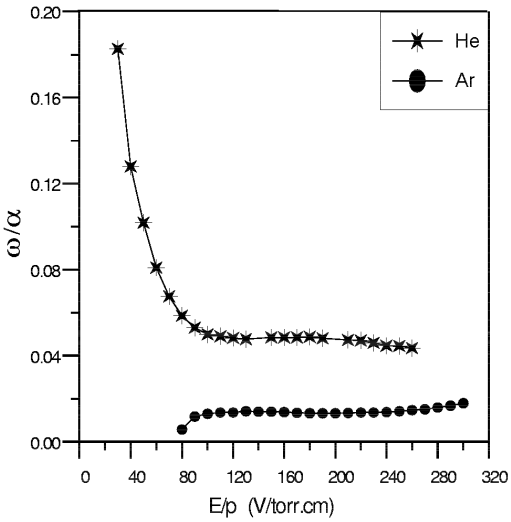

Fig. 7. Relation between the secondary ionization coefficient ω/α and E/p for Ar *and* He *gas using* Mg *cathode.*

4. Conclusions

The breakdown potentials have been measured for Ar and He discharges using three different cathode materials: aluminium, silver and magnesium. The minimum breakdown potential for the three different cathodes occurs at the value of pd_{min} equal to 80 Pa cm (0.6 torr cm) for Ar discharge and at pd_{min} 530 Pa cm (4 torr cm) for He discharge. It is concluded that the minimum breakdown potential increases with the increase of the work function of the cathode materials.

From the Paschen curves for Ar and He gases, it is clear that the minimum breakdown voltage of He gas is lower than that of Ar gas. This can be attributed to the higher efficiency of secondary ionization processes in He discharge rather than in Ar discharge.

The secondary ionization coefficients, (ω/α), have been estimated using the measured values of the breakdown potentials and the first ionization coefficients, for the three cathodes. The values were made in the range of E/p from 0.60 to 2.25 V/[Pa cm] (80 to 300 V/[torr cm]) for the Ar discharge and in the range 0.15 to 1.80 V/[Pa cm] (20 to 240 V/[torr cm]) for the He discharge. It is concluded that the values of (ω/α) for He gas are higher than for Ar gas. Various secondary processes of the discharge for the three cathode materials are discussed.

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References

[1] V. Lj. Marković, S. R. Gocić and M. K. Radović, Eur. Phys. J.: Appl. Phys. **6** (1999) 303.

[2] A. Bogaerts and R. Gijbels, J. Appl. Phys. **79** (1996) 1279.

[3] B.G. Salamov, S. Bykakkas, M. Ozer and K. Colokoglu, Eur. Phys. J.: Appl. Phys. **2** (1998) 275.

[4] See for example A. Rostagni, Z. Phys. **88** (1934) 55; H. C. Hayden and N. G. Utterbach, Phys. Rev. A **135** (1964) 1575. K. H. Krebs, Fortschr. d. Phys. **16** (1968) 419; K. H. Krebs, Vacuum **33** (1983) 555. Yu. P. Raizer, High Temp. **24** (1983) 984.

[5] A. V. Phelps and Z. Lj. Petrović, Plasma Source Sci. Technol. **8** (1999) R21.

[6] T. Mari, 9th ICPG (1974) p. 85.

[7] H. D. Hagstrom, Phys. Rev. **104** (1956) 309.

[8] H. S. W. Massey, E. H. S. Burhop and H. B. Gilbody, *Electronic and Ionic Impact Phenomena*, Oxford, Claredon Press (1969).

[9] F. Llewellyn-Jones, *Ionization and Breakdown in Gases*, London, Methuen Co. (1956).

[10] A. A. Kruithof and F. M. Penning, Physica **4** (1937) 430.

[11] G. Auday, Ph. Guillot, J. Galy and H. Brunet, J. Appl. Phys. **83** (1998) 5917.

MJERENJE PROBOJNIH NAPONA ZA VIŠE KATODNIH MATERIJALA U TOWNSENDOVOM IZBOJU

Mjerili smo probojne potencijale za izboj u argonu i heliju s trima katodnim materijalima: aluminijem, srebrom i magnezijem. Mjerenja pokazuju da su niži probojni naponi povezani s nižim radnim funkcijama. Odredili smo sekundarne ionizacijske koeficijente za te tri vrste katoda na osnovi izmjerenih probojnih napona i prvih ionizacijskih koeficijenata, u području 0.60 to 2.25 V/[Pa cm] za izboj u Ar i u području 0.15 to 1.80 V/[Pa cm] za izboj u He. Najniži probojni napon za izboj u Ar iznosi $(pd)_{\min} = 80$ Pa cm, a za izboj u He 530 Pa cm (4.0 torr cm).