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Some parameters dependency on the effective secondary emission coefficient (ESEC)in microdischarge

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Abstract

The relations between the applied potential and electron current density, ion concentration near the cathode, field due to space charge and current multiplication factor are studied in microdischarge for noble gases. So, all these parameters studied at different values of the effective secondary emission coefficient γ for Argon gas. We found that all these parameters proportional inversely with ionization energy and increase with γ .

1. Introduction

Microdischarge is defined as the discharge has gap length between electrodes less than 1 mm [1]. Micro-plasma is introduced by the reducing the dimension of the gab length between electrodes to the sub- millimeter range[1,2]. When a device has gap length between electrodes less than 1

The research is a part of Ph.D. dissertation in the case of the first researcher.

mm, the device called micro-plasma device [2].

When the distance between electrodes less than 10 μm, this lead to breakdown at applied voltage less than predicated by Paschen's law (relationship between breakdown voltage and gas pressure×distance between electrodes). At this scale, it is unclear how the field emission affects other fundamental plasma properties, therefore the Paschen's law fails at this scale due to the electron field emission [1].

Microdischarge has many applications including lighting, advantageous environmental of sensing, gas sensor, chemical synthesis and material processing [2,3].

An analytical calculation was carried out to calculate the Electron current density, ion concentration near the cathode, field due to space charge and current multiplication factor depended on Rumbach and Go model[1]. We are studied the variation of these parameters with deferent values of the effective secondary emission coefficient which can be define as the number of the secondary electrons leave the cathode surface per positive ions bombarded the cathode surface[4].

2. Theory

The electron current density j_e, inside vessel which is containing two electrodes with gap distance x , can be written by an ordinary differential equation, which is a study state equation[5]

$$\frac{dj_e}{dx} = \alpha\, j_e \qquad \dots (1)$$

where α is the Townsend's first ionization coefficient.

the total current j_{tot} is sum of the electron current density j_e and ion current density j_i

$$j_{tot} = j_e + j_i \qquad \dots (2)$$

at the study state, the total current is constant at any point between the electrodes, therefore we can write

$$\frac{dj_e}{dx} = -\frac{dj_i}{dx} \qquad \dots (3)$$

the current density for either species (electron and ion) is related with the number density n and the applied electric field by[6]

$$j = -qn\mu E \qquad \dots (4)$$

where q and μ are the charge and the mobility of the species, respectively.

from Maxwell's equation, the electric field can be described by

$$\vec{\nabla} \cdot \vec{E} = -\frac{\rho}{\varepsilon_\circ} \quad \ldots (5)$$

where $\varepsilon_\circ$ is the permittivity of free space and ρ is the charge density which is given by

$$\rho = qn = q(n_i - n_e) \quad \ldots (6)$$

so in one dimension equation (5) will take the form

$$\frac{dE}{dx} = -\frac{q}{\varepsilon_\circ}(n_i - n_e) \quad \ldots (7)$$

Equations (1), (3) and (7)are formed a system of three first order ordinary differential equations that required three boundary conditions to solve it.

The first condition: Is that the cathode is at $x = 0$ and the anode at $x = d$" where d is the gap length". Therefore, the total voltage between the electrodes must be

$$V_A = \int_o^d -E(x)dx = \Phi(d) - \Phi(0) \quad \ldots (8)$$

where $\Phi(d)$ is the electric potential at the anode and $\Phi(0)$ is the electric potential at the cathode.

The second condition: Is that the net ions flux is zero at the anode. Therefore, the total current at the anode is due to the electron current , or

$$j_{tot} = j_e(d) \quad \ldots (9)$$

The third condition: Is that the electron current density at the cathode $(x = 0)$ is defined as

$$j_e(0) = \gamma\, j_i + j_{FE}(E_\circ) + j_\circ \quad \ldots (10)$$

where γ is the ESEC, $j_\circ$ is the background current density and j_{FE} is the current density due to the field emission which is a function of the electric field at $(x = 0)$,

$$E_\circ = E(0) \quad \ldots (11)$$

The field emission current density is given by Fowler-Nordheim equation at $E_\circ = E(0)$ [7]

$$j_{FE}(E_\circ) = C_{FN}(\beta E_\circ)^2 \exp\left(-\frac{D_{FN}}{\beta|E_\circ|}\right) \quad \ldots (12)$$

where β is the local geometric field enhancement factor and C_{FN} and D_{FN} are constant dependent on the work function of the cathode material and given by the following equations [8]

$$C_{FN} = \frac{e^3}{8\pi h\phi} \quad \ldots (13)$$

and

$$D_{FN} = \frac{4}{3}\left(\frac{2m}{\hbar^2}\right)^{1/2} \frac{(\phi - E_F)^{1/2}}{e} \quad \ldots (14)$$

where m is the electron mass and E_F is the Fermi energy of the cathode material.

2.1 The analytic solution

From equation (1), we can write

$$\frac{dj_e}{j_e} = \alpha\, dx \quad \ldots (15)$$

By integrate equation (15), we get

$$\ln \frac{j_e}{c} = \alpha x$$

Take the exponential to the both side of above equation, we get

$$j_e = c e^{\alpha x} \quad \ldots (16)$$

In the same way, we can prove that

$$j_i = c\left(e^{\alpha d} - e^{\alpha x}\right) \quad \ldots (17)$$

where c is constant and can be determined by using the boundary condition at the cathode.

From the definitions of the drift relationship for electrons and ions "equation (4)" one can estimate the density of electrons and ions such that,

$$n_e = -\frac{j_e}{q\mu_e E} \quad \ldots (18)$$

and

$$n_i = -\frac{j_i}{q\mu_i E} \quad \ldots (19)$$

By using equation (18) and equation (19) into equation (7), the Maxwell equation will be

$$\frac{dE}{dx} = -\frac{q}{\varepsilon_\circ}\left(-\frac{j_i}{q\mu_i E} + \frac{j_e}{q\mu_e E}\right) \quad \ldots (20)$$

But $\mu_e \rangle\rangle \mu_i$ $\left(\mu_e = 1000\mu_i\right)$, therefore, we can neglect the second term in equation (20), then

$$\frac{dE}{dx} = \frac{j_i}{\varepsilon_\circ \mu_i E} \quad \ldots (21)$$

rewrite equation (21) by using $E = V_A/d$ and equation (17)

$$\frac{dE}{dx} = \frac{c}{\varepsilon_\circ \mu_i (V_A/d)}\left(e^{\alpha d} - e^{\alpha x}\right) \quad \ldots (22)$$

Integrating equation (22) as the following

$$\int_{E_\circ}^{E(x)} dE = \int_0^x \left[\frac{c}{\varepsilon_\circ \mu_i (V_A/d)}\left(e^{\alpha d} - e^{\alpha x}\right)\right] dx$$

or

$$E(x) - E_\circ = \frac{c}{\varepsilon_\circ \mu_i (V_A/d)}\left[x e^{\alpha d} - \frac{1}{\alpha}\left(e^{\alpha x} - 1\right)\right]$$

, therefore

$$E(x) = \frac{c}{\varepsilon_\circ \mu_i (V_A/d)}\left[x e^{\alpha d} - \frac{1}{\alpha}\left(e^{\alpha x} - 1\right)\right] + E_\circ$$

… (23)

In order to calculate the total voltage between the tow electrodes we use equation (23) into equation (8), taken x to be change from 0 to d (the gap length)

$$V_A = -\int_0^d \left\{ \frac{c}{\varepsilon_\circ \mu_i \left(V_A / d \right)} \left[x e^{\alpha d} - \frac{1}{\alpha} \left(e^{\alpha x} - 1 \right) \right] + E_\circ \right\} dx$$

$$= -\frac{c}{\varepsilon_\circ \mu_i \left(V_A / d \right)} \left[\frac{d^2}{2} e^{\alpha d} + \frac{1}{\alpha^2} \left(1 - e^{\alpha x} \right) + \frac{d}{\alpha} \right] + E_\circ d$$

, therefore

$$E_\circ = \frac{V_A}{d} + \frac{c}{\varepsilon_\circ \mu_i V_A} \left[\frac{d^2}{2} e^{\alpha d} + \frac{1}{\alpha^2} \left(1 - e^{\alpha x} \right) + \frac{d}{\alpha} \right] \quad \ldots (24)$$

Let

$$A = \frac{1}{\varepsilon_\circ \mu_i V_A} \left[\frac{d^2}{2} e^{\alpha d} + \frac{1}{\alpha^2} \left(1 - e^{\alpha x} \right) + \frac{d}{\alpha} \right] \quad \ldots (25)$$

we get

$$E_\circ = \frac{V_A}{d} + cA \quad \ldots (26)$$

But the field at the cathode is equal to the sum of applied electric field, E, and the field emission due to the space charge E_{sc}, such that

$$E_\circ = \frac{V_A}{d} + E_{sc} \quad \ldots (27)$$

By making a simple comparison between equation (26) and equation (27), we fined that

$$E_{sc} = cA \quad \ldots (28)$$

where E_{sc} is the field due to the space charge, we not that A (equation 25) is depend on the first Townsend's ionization coefficient α which can be taken from the following empirical formula [9]

$$\alpha = D_1 p e^{-D_2 \sqrt{\frac{p}{E}}} \quad \ldots (29)$$

where p is the gas pressure, E is the applied electric field and D_1 and D_2 are empirical constants taken from the table (1)[9].

The electron current density j_e at the cathode (boundary condition $x = 0$) could be hold from equation (16), since

$$j_e(0) = c \quad \ldots (30)$$

And for the ion current density j_i from equation (17), where

$$j_i(0) = c\left(e^{\alpha d} - 1 \right) \quad \ldots (31)$$

By using equation (26) into equation (12), the current density due to the field emission will be

$$j_{FE}(E_\circ) = C_{FN} \left[\beta \left(\frac{V_A}{d} + cA \right) \right]^2 \exp \left(-\frac{D_{FN}}{\beta \left(\frac{V_A}{d} + cA \right)} \right) \quad \ldots (32)$$

Table (1) The values of empirical constants D_1 and D_2 values for the analytical model of the first Townsend ionization coefficient for noble gases[9].

Gas	D_1 $m^{-1}Pa^{-1}$	D_2 $V^{1/2}m^{-1/2}Pa^{-1/2}$	D_1 $cm^{-1}torr^{-1}$	D_2 $V^{1/2}cm^{-1/2}torr^{-1/2}$
He	3.3	12.1	4.4	14.0
Ne	6.2	14.7	8.2	17.0
Ar	21.92	23.01	29.22	26.64
Kr	26.76	24.43	35.69	28.21
Xe	48.98	31.25	65.30	36.08

Using the definitions in equations (30), (31) and (32) into equation (10), we get

$$c=\gamma\left[c\left(e^{\alpha d}-1\right)\right]+C_{FN}\left[\beta\left(\frac{V_A}{d}+cA\right)\right]^2\times$$
$$\exp\left(-\frac{D_{FN}}{\beta\left(\frac{V_A}{d}+cA\right)}\right)+j_{\circ} \quad ...(33)$$

if the field due to the space charge less than the applied field ($E_{sc}=cA \langle\langle \frac{V_A}{d}$) , then equation (33) will take the form

$$c=\gamma\left[c\left(e^{\alpha d}-1\right)\right]+C_{FN}\left[\beta\left(\frac{V_A}{d}\right)\right]^2\times$$
$$\exp\left(-\frac{D_{FN}}{\beta\left(\frac{V_A}{d}\right)}\right)+j_{\circ} \quad ...(34)$$

Or

$$c\left[1-\gamma\left(e^{\alpha d}-1\right)\right]=j_{FE}\left(\frac{V_A}{d}\right)+j_{\circ} \quad \ldots (35)$$

Or

$$c=\frac{j_{FE}\left(\frac{V_A}{d}\right)+j_{\circ}}{1-\gamma\left(e^{\alpha d}-1\right)} \quad \ldots (36)$$

where

$$j_{FE}\left(\frac{V_A}{d}\right)=C_{FN}\left[\beta\left(\frac{V_A}{d}\right)\right]^2\exp\left(-\frac{D_{FN}}{\beta\left(\frac{V_A}{d}\right)}\right)$$
… (37)

So the electron current density $\left(j_{tot}\right)$ can be estimated by equation (36) into equation (16),

$$j_{tot}=j_e=\frac{e^{\alpha d}\left[j_{FE}\left(\frac{V_A}{d}\right)+j_{\circ}\right]}{1-\gamma\left(e^{\alpha d}-1\right)} \quad \ldots (38)$$

And by using equation (36) into equation (17), to obtain the ion current density is

$$j_i=-\frac{\left(e^{\alpha d}-e^{\alpha x}\right)\left[j_{FE}\left(\frac{V_A}{d}\right)+j_{\circ}\right]}{1-\gamma\left(e^{\alpha d}-1\right)}$$
… (39)

inserting equation (39) into equation (19), ion concentration has been given by

$$n_i = -\frac{\left(e^{\alpha d} - e^{\alpha x}\right)\left[j_{FE}\left(\frac{V_A}{d}\right) + j_{\circ}\right]}{q\mu_i\left(\frac{V_A}{d}\right)\left[1-\gamma\left(e^{\alpha d}-1\right)\right]} \quad \dots (40)$$

put equation (36) into equation (17), we get the field emission due to the space charge E_{sc} such that

$$E_{sc} = \frac{j_{FE}\left(\frac{V_A}{d}\right) + j_{\circ}}{1-\gamma\left(e^{\alpha d}-1\right)} A \quad \dots (41)$$

use equation (25) into equation (41), E_{sc} can be expressed as the
follows,

$$E_{sc} = \frac{j_{FE}\left(\frac{V_A}{d}\right) + j_{\circ}}{1-\gamma\left(e^{\alpha d}-1\right)} \times \left\{ \frac{1}{\varepsilon_{\circ}\mu_i V_A}\left[\frac{d^2}{2}e^{\alpha d} + \frac{1}{\alpha^2}\left(1-e^{\alpha x}\right) + \frac{d}{\alpha}\right]\right\}$$
$\dots (42)$

The multiplication factor M is defined as the ratio between the total electron current density j_{tot} to the current density due to the field emission j_{FE}, therefore we can write

$$M = \frac{j_{tot}}{j_{FE}} \quad \dots (43)$$

getting use of equation (38) and equation (43), the current multiplication factor take it the formula,

$$M = \frac{e^{\alpha d}}{1-\gamma\left(e^{\alpha d}-1\right)} \quad \dots (44)$$

Where $j_{FE} \rangle\rangle j_{\circ}$

3. Results and Discussion

The results have been estimated by using $4.65eV$ work function for copper electrodes. Electron current density, ion concentration, field due to space charge and multiplication factor have been calculated as a function of applied voltage for all noble gases (He, Ne, Ar, Kr and Xe).

Figure (1) shows the relation between electron current density and applied potential (voltage) for noble gases with $3\mu m$ gap between electrodes, it shows that the atom with less mass has less current density because the first Townsend's coefficient (α) has a large value for lighter mass atom. The figure also shows no current density when the applied voltage less than (120 v), the current density increase as the voltage increase.

In figure (2) the ion concentration near the cathode has been calculated from equation (40), is plotted as a function of potential applied on the electrodes , this figure shows the same tendency as in figure (1).

Figure (3) illustrated the field emission due to the space charge as a function to the applied potential for different noble gases. Also the field emission due to the space charge increase as the voltage increase.

Figure (4) shows the current multiplication factor versus the applied potential for noble gases at distance between electrodes $3\mu m$ for gas pressure $760 Torr$.

We found that all thesparameters proportional inversely with the ionization energy of the gas.

Figures (5), (6), (7) and (8) are represent the electron current density, the ion concentration near the cathode, the field emission due to the space charge and the current multiplication factor as a function of applied potential for different values of ESEC, respectively. It has been found that all these parameters increase with the ESEC increasing.

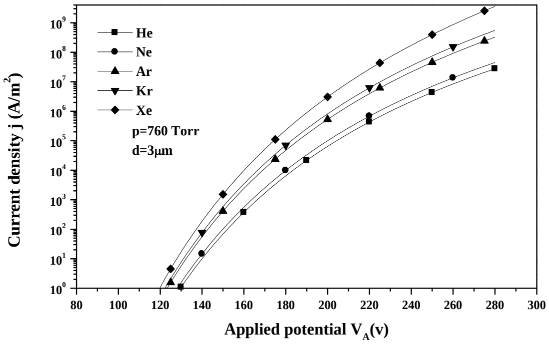

Figure (1): The electron current density versus the applied potential for noble gases at distance between electrodes $3\mu m$ with gas pressure $760 Torr$.

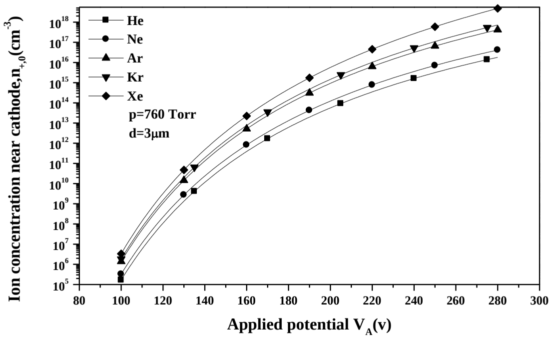

Figure (2): The ion concentration near the cathode versus the applied potential for noble gases at distance between electrodes $3\mu m$ for gas pressure $760 Torr$.

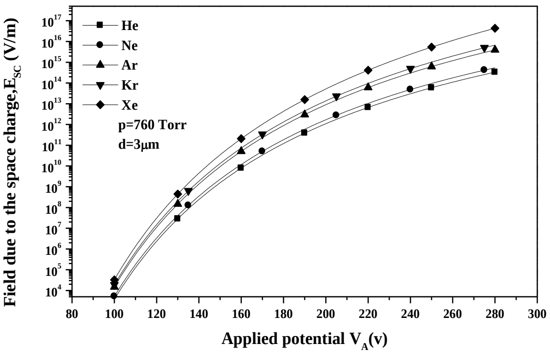

Figure (3): The field emission due to the space charge as a function to the applied potential noble gases at distance between electrodes $3\mu m$ for gas pressure $760 Torr$.

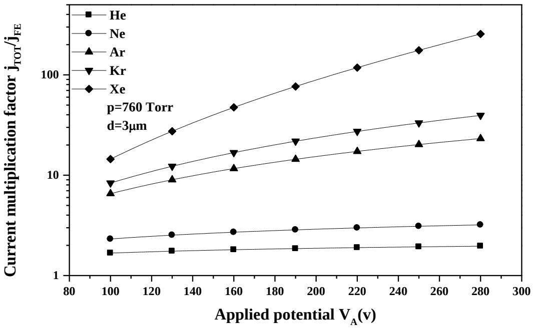

Figure (4): The current multiplication factor versus to the applied potential for noble gases at distance between electrodes $3\mu m$ for gas pressure $760 Torr$.

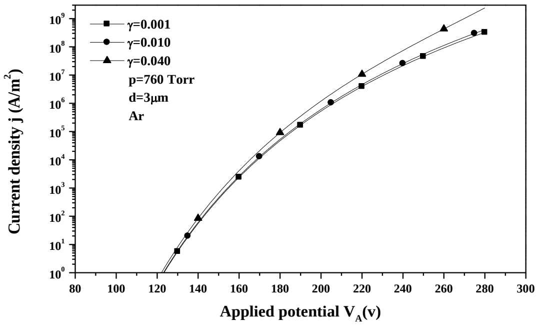

Figure (5): The electron current density versus the applied potential for Argon for $\gamma = (0.001, 0.010\, and\, 0.040)$ at distance between electrodes $3\mu m$ for gas pressure $760 Torr$.

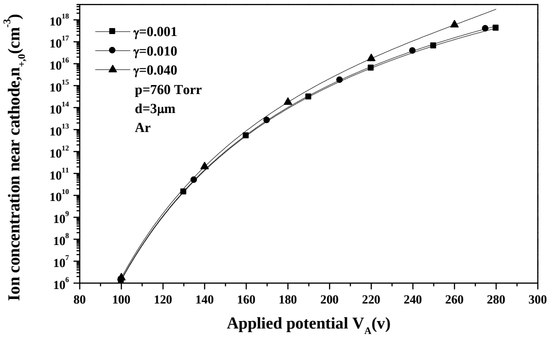

Figure (6): The ion concentration near the cathode versus the applied potential for Argon for $\gamma = (0.001, 0.010\, and\, 0.040)$ at distance between electrodes $3\mu m$ for gas pressure $760 Torr$.

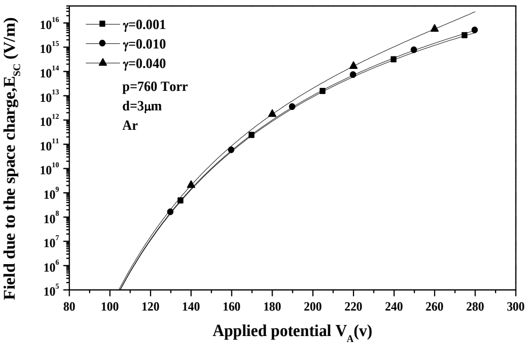

Figure (7): The field emission due to the space charge versus the applied potential for Argon for $\gamma = (0.001, 0.010\, and\, 0.040)$ at distance between electrodes $3\mu m$ for gas pressure $760 Torr$.

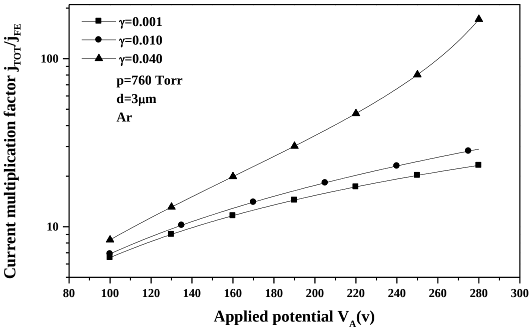

Figure (8): The current multiplication factor versus the applied potential for Argon for $\gamma = (0.001, 0.010\, and\, 0.040)$ at distance between electrodes $3\mu m$ for gas pressure $760 Torr$.

Conclusions

1- The number of electrons emission, the ion concentration near the cathode, the field emission due to the space chargeand the current multiplication factor equation from the cathode surface due to impact positive ions increase with decreasing of the ionization energy of noble gases.

2- All these parameters increase with the effective secondary emission coefficient γ.

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دراسة اعتمادية بعض العوامل على عامل الانبعاث الثانوي المؤثر في التفريغ المايكروي

تاريخ الاستلام : ٢٠١٥\٢\٨ تاريخ القبول : ٢٠١٥\٦\٢٣

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الخلاصة

تم دراسة العلاقة بين الجهد المسلط بين قطبين وكثافة تيار الالكترونات و تركيز الايونات قرب سطح الكاثود والمجال الناتج عن شحنة الايونات وعامل التكبير في التفريغ المايكروي للغازات النبيلة. كذلك درست هذه العوامل مع تغير عامل الانبعاث الثانوي المؤثر γ. وجدنا بان جميع هذه العوامل تتناسب عكسيا مع طاقة التأين للغازات النبيلة وتزداد بزيادة γ.

كلمات مفتاحيه: عامل الانبعاث الثانوي المؤثر، التفريغ الميكروي، معاملات تاونسند

Physics classification : QC717.6-718.8

البحث مستل من أطروحة دكتوراه للباحث الأول