5

Egypt. J. Phys. **Vol. 48,** pp. 37- 43 (2020)

Egyptian Journal of Physics

https://ejphysics.journals.ekb.eg/

Simulator of Planar Electrodes Plasma Characteristics Using Different Gases

S. I. Radwan[1], H. Saleh[2], H. El-Khabeary[1*] and A. G. Helal[1]

[1]*Accelerators & Ion Sources Department, Nuclear Research Center, Atomic Energy Authority P. N. 13759, Cairo, Egypt*

[2]*Radiation Engineering Department, National Center for Radiation Research and Technology, Atomic Energy Authority, P. N. 11787, Cairo, Egypt*

SIMULATOR Plasma Source for Planar Electrodes, SPSPE, was designed to verify the experimental results of planar anode and cathode which were obtained previously using nitrogen gas. Experimentally, the glow discharge was carried out at operating pressure values in the range of 0.1 - 0.6 Torr and the distance between the disc anode - disc cathode distance equal to 10 cm using nitrogen gas. The comparison between SPSPE and the experimental values at different product of pressure and distance values for breakdown voltage, discharge current and the second Townsend coefficient using nitrogen gas was made. It was found a good match between SPSPE and the experimental values. Also, the first Townsend coefficient was calculated by SPSPE at different product of pressure and distance values using nitrogen gas, while breakdown voltage and discharge current were calculated by SPSPE at different product of pressure and distance values using nitrogen, argon and carbon dioxide gases. It was found that the minimum breakdown voltage values equal to 472.77, 232.26 and 349.27 volts at minimum product of pressure and distance values equal to 1.5, 1 and 0.75 Torr.cm using nitrogen, argon and carbon dioxide gases, respectively. Also, it was found that the minimum discharge current values equal to 0.5228 mA and 3.65 mA at minimum product of pressure and distance value equal to 1 Torr. cmusing nitrogen and argon gases, respectively. While minimum discharge current value equal to 7.8 mA was obtained at minimum product of pressure and distance value equal to 0.75 Torr.cm using carbon dioxide gas.

Keywords: Simulator plasma source, First and second townsend coefficients, Paschen's law, Breakdown voltage, Discharge current

Introduction

Plasma is the fourth state of matter that contains the electrons, neutral atoms, excited molecules, free radicals, positive and negative ions [1,2]. To generate the plasma, there is a gas discharge that can be carried out by direct current, alternating current as radio-frequency or microwave. These plasma sources have many applications used in deposition of thin and thick films, materials treatment including surface modifications, light sources, semiconductor processing and treatment of waste [3-10]. The plasma can be classified into low and high temperature, where the low temperature, cold plasma, is divided into two types that are low and atmospheric pressures [11-14].

Technologies of plasma processing have been developed for different applications especially the surface modification of many materials [15-19]. The plasma generation at atmospheric pressure has a lot of applications in space technology that need a high voltage for the gas discharge to be formed [20]. The plasma can be maintained between two electrodes in the gas medium by applying a voltage exceeding the breakdown voltage of the used gas. This breakdown voltage relays on the product of gas pressure, P, and the gap distance, d, between the electrodes which is called the Paschen's law [21,22]. The minimum Paschen condition can be observed when the electrodes distance is less than a millimeter under the atmospheric pressure. The expected applied voltage for the working gas breakdown is a few hundred volts. On the other

*Corresponding author : helkhabeary@yahoo.co.uk
Received : 9 / 7 / 2019 ; accepted : 24 / 8 / 2019
DOI :10.21608/EJPHYSICS.2019.19108.1025
©2020 National Information and Documentaion Center (NIDOC)

hand, at the atmospheric pressure and the distance between electrodes equal to 5 mm the breakdown voltage for argon gas is raised a few kilo volts [20].

The aim of this study is to design a simulator based on the gas discharge equations to form a plasma. This is necessary for establishing and working for any plasma source that is suitable for obtaining the best operating conditions. In this work, SPSPE is designed to compare the simulated results with the previous experimental results for parallel disc anode - disc cathode plasma source characteristics [23]. The comparison between SPSPE and the experimental values was made at different product of pressure and distance, Pd, values for breakdown voltage,V_b, discharge current, I_d, and second Townsend coefficient, γ, using nitrogen gas. Also, V_b and I_d for plasma source using nitrogen, N_2, argon, Ar and carbon dioxide, CO_2, gases were studied. While the first Townsend coefficient, α, is calculated by SPSPE at different Pd values using nitrogen gas. The importance of this simulator is to reduce and save the efforts, time and the materials used to produce good discharge characteristics for different applications.

Simulator Study

Electrical discharge at low pressure

In d.c. gas discharge, when a potential is applied between two electrodes in a gas then the current flows through the gas between these electrodes and converts it from insulating dielectric to conducting gas. The breakdown voltage in planar geometry of glow discharges, Vb = E.d, where E is the electric field and d is the gap distance between two electrodes. Paschen found that the breakdown voltage can be described by the equation [24]:

$$V_b = \frac{BPd}{\ln(APd) - \ln[\ln(1+\frac{1}{\gamma})]} \quad (1)$$

where A and B are gas constants and equal to (13, 413), (16, 240) and (27, 621) for N_2, Ar and CO_2 gases, respectively, P is the gas pressure, d is the gap distance between two electrodes and γ is the second Townsend coefficient(the number of secondary electrons produced per incident positive ion). At large Pd, V_b increases which means high-pressure insulation. At some critical value of Pd, V_b goes infinite that called vacuum insulation and in between, there is a minimum.

Simulator plasma source for planar electrodes (SPSPE)

SPSPE is used to carry out the suitable experiment needed to various applications and economize the used materials with definite conditions. In which, the different parameters with different input variables as the gas type, the electrodes geometries, distance between electrodes, and gas pressure are designed [25]. One relation can be studied by SPSPE is the Paschen's lawas in the equation [26]:

$$V_b = f\,(P\times d) \quad (2)$$

The minimum value for breakdown voltage, $(V_b)_{min}$, is constant for the given electrodes in a definite gas. The V_b versus Pd curve is found by applying a voltage across two electrodes in a vacuum chamber [27]. When the applied voltage between anode and cathode increases, the discharge current increase. From Child - Langmuir equation, the maximum current density, I_{max} (A/cm^2), can be calculated by the relation [26, 27]:

$$I = 2.334\ x\ 10^{-6}\frac{V^{3/2}}{d^2}\left(\frac{A}{cm^2}\right) \quad (3)$$

Where V is the potential drop across the gap distance between two electrodes in volts and d is the gap distance between two electrodes in meter.

Figure 1 shows an example of the Simulator Graphical User Interface (GUI) for planar geometry plasma source. This work introduces a verification of V_b, I_d and γ versus different Pd values for disc anode - disc cathode which are previously determined experimentally [23]. In addition, α versus different Pd values is calculated by SPSPE using N_2 gas. Also, the error percentage between experimental and SPSPE values for V_b, I_d and γ is calculated using N_2 gas. Finally, V_b and I_d versus different Pd values are calculated by SPSPE using N_2, Ar and CO_2 gases.

SPSPE discharge characteristics

From the experimental results for parallel disc anode - disc cathode plasmasource [23], the discharge characteristics were verified and compared using SPSPE. The SPSPE values of V_b, I_d, and γ versus different Pd values for disc anode –disc cathode distance equal to 10 cm were determined using N_2 gas. Figures 2, 3 and 4 show the comparison between SPSPE and the experimental values for V_b, I_d, and γ versus different Pd values using N_2 gas.

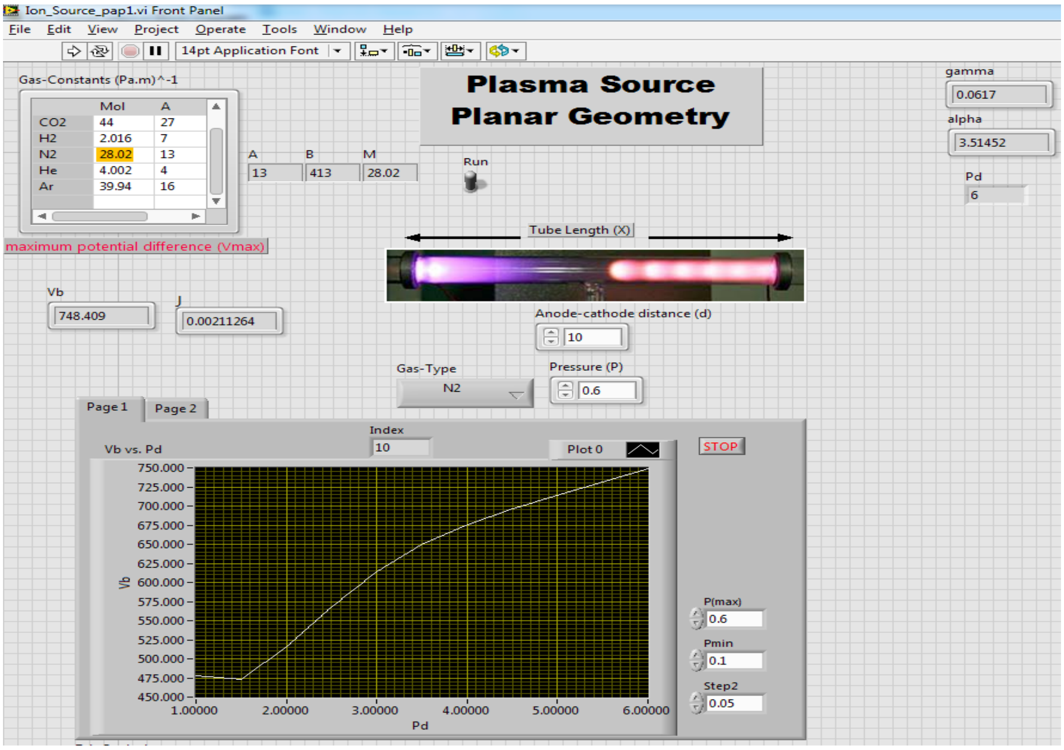

Fig. 1. Simulator Graphical User Interface (GUI) for planar geometry plasma source.

Figure 2 shows V_b versus different Pd values calculated by SPSPE values and compared with the experimental values for planar anode - cathode using nitrogen gas [23]. It was clear that as gas pressure increased, V_b is increased linearly. The increase of V_b at low Pd values can be explained by the need to compensate for a small number of collisions. While at high Pd values due to a large number of collisions,V_b is increased in order to enhance energy gain between collisions, when mean free path is getting shorter and the energy gained between two collisions becomes smaller. In the range of the Paschen minimum, the production of charges by ionization and secondary electrone mission are well balanced with losses by attachment, diffusion and drift. Also, there is matching between the experimental and simulated values at low Pd, while at high Pd values the experimental values are higher than the simulation values. This is due to the experimental error of the measuring instrumentations used in the experiment. Table 1 shows the simulator and experimental values of V_b with its error percentage.

Figure 3 shows SPSPE values compared with the experimental values of I_d versus different Pd using N_2 gas. It is found that I_d increases with increasinggas pressure. Also, it is clear that there is matching between the experimental and simulated values. Table 2 shows the simulator and experimental values with its error percentage.

Figure 4 shows γ calculated by SPSPE versus different Pd valuesusing N_2 gas and compared withthe experimental values. It is found that at low pressure, γ increases slowly with increasing gas pressure. This is due to long electrons mean free path between collisions which lead to few ionizing collisions. While at high pressure, γ increases rapidly with increasing gas pressure. This is due to the increase in the number of ion collisions on the cathode with increasing gas pressure. Also, it is clear that there is matching between the experimental and simulated values. Table 3 shows the simulator and experimental values of γ with its error percentage.

Figure 5 shows α calculated by SPSPE versus different Pd values using N_2 gas It was clear that α (the number of first electrons produced per incident positive ion) values decreases with increasing gas pressure. When the gas pressure increases, the electronsmean free path between collisionsdecrease and therefore the ionization decreases and as a result α decreases. Table 4 shows the simulator values of α using N_2 gas.

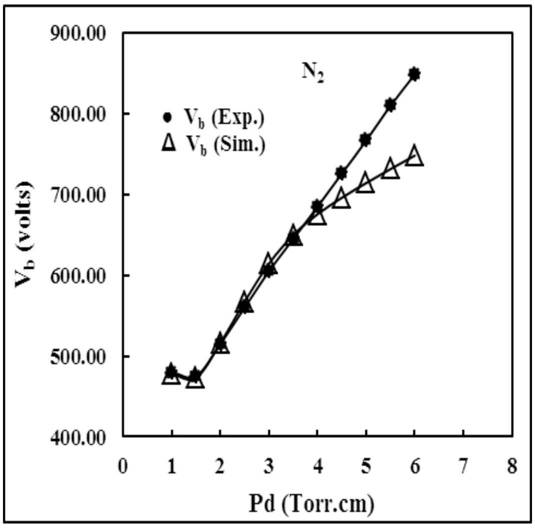

Fig. 2. SPSPE and experimental values of V_b versus Pd using N_2. of V_b with its error percentage.

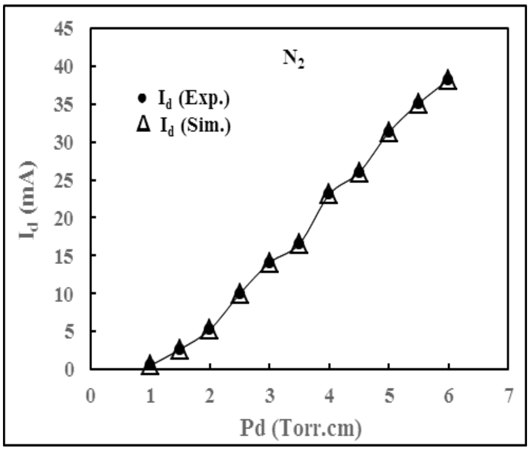

Fig. 3. SPSPE and experimental values of Idversus Pd using N_2 gas. of Id with its error percentage.

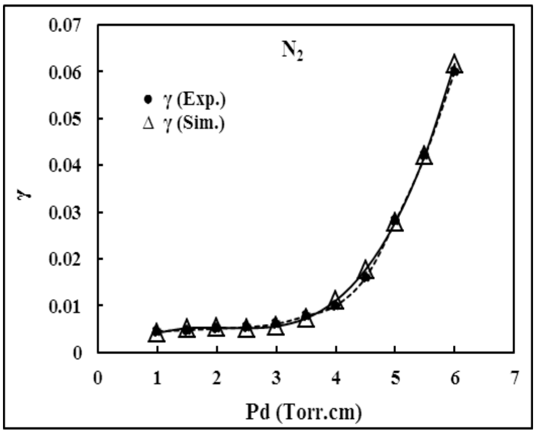

Fig. 4. SPSPE and experimental values of γ versus Pd using N_2 gas.of γ with its error percentage.

TABLE 1. Simulator and experimental values of V_b with its error percentage.

Pd (Torr.cm)	$V_{b\,(Sim.)}$ (volts)	$V_{b\,(Exp.)}$ (volts)	error %
1	477.78	480	0.4646
1.5	472.77	475	0.4717
2	516.01	515	0.1957
2.5	567.50	560	1.3216
3	614.37	605	1.5251
3.5	650.06	645	0.7784
4	675.79	685	1.3628
4.5	696.19	726	4.2818
5	714.37	767	7.3673
5.5	731.65	810	10.709
6	748.41	849	13.441

TABLE 2. Simulator and experimental values of I_d with its error percentage

Pd (Torr.cm)	$I_{d\,(Sim.)}$ (mA)	$I_{d\,(Exp.)}$ (mA)	error %
1	0.5228	0.55	5.203
1.5	2.6728	2.7	1.018
2	5.2728	5.3	0.5159
2.5	9.9728	10	0.2727
3	14.0728	14.1	0.1933
3.5	16.5728	16.6	0.1641
4	23.0728	23.1	0.1179
4.5	25.9728	26	0.1047
5	31.2728	31.3	0.087
5.5	35.0728	35.1	0.0776
6	38.1728	38.2	0.0713

TABLE 3.Simulator and experimental values of γ with its error percentage.

Pd	$\gamma_{(Sim.)}$	$\gamma_{(Exp.)}$	error %
1	0.0042	0.0045	7.143
1.5	0.0052	0.0047	9.615
2	0.0053	0.00512	3.396
2.5	0.0052	0.0054	3.846
3	0.0056	0.0061	8.929
3.5	0.0073	0.0078	6.849
4	0.0111	0.01	9.910
4.5	0.0177	0.016	9.605
5	0.0278	0.028	0.719
5.5	0.0422	0.042	0.474
6	0.0617	0.06	2.755

Figure 6 shows V_b calculated by SPSPE versus different Pd values using N_2, Ar and CO_2 gases. It was obvious that as gas pressure increased, V_b is decreased until reaching a minimum value and after that V_b is increased. It is found that $(V_b)_{min.}$ values are equal to 472.77, 232.26 and 349.27 volts at $(Pd)_{min.}$ equal to 1.5, 1 and 0.75 Torr.cm using N_2, Ar and CO_2 gases, respectively. It is deduced that $(V_b)_{min.}$ of higher molecular weight gas occurs at lower $(Pd)_{min.}$ value. Table 5 shows the simulator values of V_b versus Pd using N2, Ar and CO_2 gases.

Figure 7 shows I_d calculated by SPSPE versus different Pd values using N_2, Ar and CO_2 gases. It was obvious that as gas pressure increased, I_d decreased until reaching a minimum I_d value and after that I_d was increased. It was found that $(I_d)_{min.}$ values are equal to 0.5228 mA and 3.65 mA at $(Pd)_{min.}$ equal to 1 Torr.cm using N_2 and Ar gases, respectively. While $(I_d)_{min.}$ value is equal to 7.8 mA at $(Pd)_{min.}$ equal to 0.75 Torr.cm using CO_2 gas. Table 6 shows the simulator values of I_d using N_2, Ar and Co_2 gases.

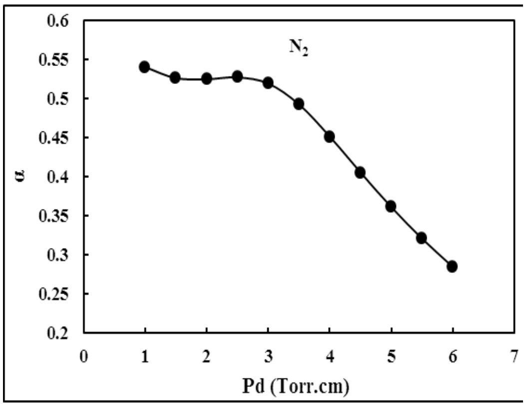

Fig.5. Simulator values of α versus Pd using N2 gas.

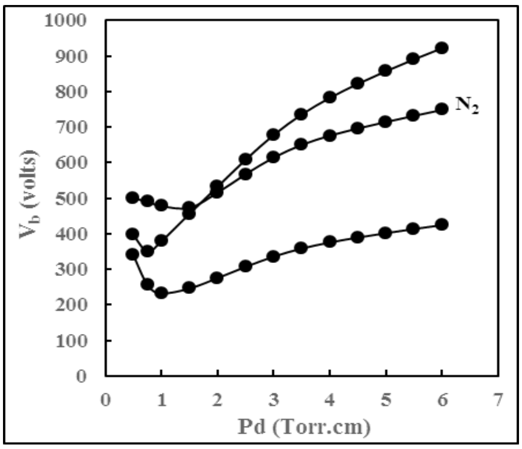

Fig. 6. Simulator values of V_b versus Pd using N_2, Ar and Co_2 gases.

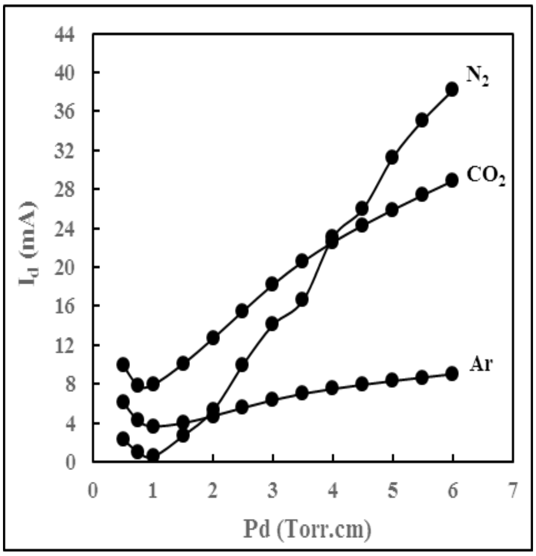

Fig.7. Simulator values of Id versus Pd using N2, Ar and Co_2 gases.

TABLE 4. Simulator values of α using N2 gas.

Pd	α
1	0.547
1.5	0.525
2	0.5245
2.5	0.5269
3	0.519
3.5	0.4923
4	0.4511
4.5	0.40531
5	0.361
5.5	0.32061
6	0.28453

TABLE 5. Simulator values of V_b using N_2, Ar and Co_2 gases.

Pd (Torr. cm)	$V_{b(Sim.)}$ N_2(volts)	$V_{b(Sim.)}$Ar (volts)	$V_{b(Sim.)}$ CO_2(volts)
0.5	499.8	359.53	357.09
0.75	490.03	255.91	349.27
1	477.78	232.26	389.27
1.5	472.77	246.19	456.54
2	516.01	275.38	532.67
2.5	567.5	306.96	608.54
3	614.37	335.83	678.05
3.5	650.06	358.55	735.82
4	675.79	375.54	782.26
4.5	696.19	389.4	821.73
5	714.37	401.84	857.37
5.5	731.65	413.48	890.53
6	748.41	424.59	921.84

TABLE 6. Simulator values of I_d using N_2, Ar and Co_2 gases.

Pd (Torr.cm)	$I_{d(Sim.)}$ N_2 (mA)	$I_{d(Sim.)}$ Ar (mA)	$I_{d(Sim.)}$ CO_2(mA)
0.5	2.32	6.13	9.96
0.75	1	4.22	7.8
1	0.5228	3.65	7.92
1.5	2.6728	3.98	10.06
2	5.2728	4.71	12.68
2.5	9.9728	5.55	15.48
3	14.0728	6.35	18.21
3.5	16.5728	7	20.58
4	23.0728	7.5	22.56
4.5	25.9728	7.92	24.29
5	31.2728	8.31	25.89
5.5	35.0728	8.67	27.4
6	38.1728	9.02	28.86

Conclusion

In this work, SPSPE was utilized to evaluate the gas discharge characteristics between the planar electrodes with a definite value of each parameter for different gases to produce plasma that is necessary for suitable application. A good match was found between SPSPE values and the experimental values obtained previously using nitrogen gas. It is concluded that $(V_b)_{min}$ values were equal to 472.77, 232.26 and 349.27 volts at $(Pd)_{min}$values equal to 1.5, 1 and 0.75 Torr.cm using N_2, Ar and CO_2, gases, respectively. Also, it was concluded $(I_d)_{min.}$ values equal to 0.5228 mA and 3.65 mA at $(Pd)_{min.}$ value equal to 1Torr.cm using N_2 and Ar gases, respectively. While $(I_d)_{min}$value equal to 7.8 mAat $(Pd)_{min}$value equal to 0.75 Torr.cm using CO_2 gas. This simulator is the first version for planar electrodes and nowadays we will complete it for cylindrical electrodes, spherical electrodes and other geometries suitable for the ion thruster, ion gun and different applications in nano-technology space science.

References

1. Bittencourt, J. A. *"Fundamentals of Plasma Physics"*, 3rd ed., Springer, New York (2017)
2. Morozov, A. I. *"Introduction to Plasma Dynamics"*, 1st ed., CRC Press, Taylor& Francis Group, New York (2012)
3. Lundin,D., Jensen, J., Pedersen, H., *J. Vac. Sci. Technol.* A, 32 (3), 030602-(1-5) (2014)
4. El-Hossary, F.M., Negm, N.Z., Abd El-Rahman, A.M., Hammad, M. and Templier, C., *Surface & Coatings Technology,* 202, 1392-1400(2008)
5. Alajlania, Y.,Placido, F., H. On. Chu, R. De Bold, Fleming, L. and Gibson, D., *Thin Solid Films,* 642, 45-50 (2017)
6. Liu, SC, Dai, GM and Chang, EY., *IEEE 22nd international symposium on the physical and failure analysis of integrated circuits,* 378-380 (2015)
7. Yakut,S., Ulutas, K. and Deger, D., *Thin Solid Films,* 645, 269-277 (2018)
8. Paosawatyanyong, B., Tapaneeyakorn, K. and Bhanthumnavin, W., *Surface & Coatings Technology,* 204, 3069-3072 (2010)
9. Miller, K. K.,Gottfried, J. L.,Walck, S. D.,Pantoya, M. L. and Chi-Chin, Wu, *Combustion and Flame,* 206, 211–213 (2019)
10. P. Slepička, et al, *Separation and Purification Technology,* 220, 52-60 (2019)
11. Thirumdas, R., Trimukhe, A., Deshmukh, R. R. and Annapure,U. S., *Carbohydrate Polymers,* 157, 1723-1731 (2017)
12. Bardos, L. and H. Barankova, *Thin Solid Films,* 518, 6705-6713 (2010)
13. Setsuhara, Y., *Archives of Biochemistry and Biophysics,* 605, 3-10 (2016)
14. Demkin,V. P., Melnichuk, S. V. and Postnikov, A. V., *Physics of Plasmas,* **25**, 083502 (2018)
15. Conrads, H. and Schmidt, M., *Plasma Sources Sci. Technol.,* 9, 441- 454 (2000)
16. Mayrhofer, H., Mitterer, C., Hultman, L. and Clemens, H., *Prog. Mater. Sci.,*51, 1032-1114 (2006)
17. Goetzbergera, A., Heblinga, C. and Schock, H.W., *Mat. Sci. Eng. R.,* 40, 1- 46 (2003)
18. Lieberman, M.A. and Lichtenberg, A.J., Wiley, New York (1994)
19. Choi,M. C., Kim, Y. and Ha, C.S., *Prog. Polym. Sci.,* 33, 581 (2008)
20. Schutze, A., Jeong, J.Y., Babayan, S.E., Park, J. , Selwyn, G.S. and Hicks, R.F., *IEEE Trans. Plasma Sci.,* 26, 1685 (1998)
21. Paschen, F., *Ann. Phys. Chem.,* 37, 69-96(1889)
22. Heng Chen, C., Andrew Yeh, J. and Jen Wang, P. *Journal of Micromechanics and Microengineering,*

16 (7), 1366-1373 (2006)

23. Samah I. Radwan, El-Khabeary, H. and Helal, A.G., *Can. J. Phys.,* 94, 1275–1281 (2016)

24. Lieberman, A. M. and Lichtenberg, A.J. *"Principles if Plasma Discharges and Materials Processing",* 2nd ed., John Wiley & Sons, Inc., Hoboken, New Jersey (2005)

25. Radwan, S., Saleh, H., and Bourham, M., I*OP Conf. Series: Materials Science and Engineering,* 610, 012043(2019)

26. Child, C. D., *Phys. Rev. Ser. I,* 32 (5), 492 (1911)

27. Langmuir, I., *Phys. Rev.,* 2, 450 - 486 (1913)

محاكاة خصائص بلازما الأقطاب المستوية بإستخدام غازات مختلفة

سماح إبراهيم رضوان[1]، حسن صالح[2]، هشام الخبيرى[1] و عادل جمعه هلال[1]
[1]قسم المعجلات والمصادر الأيونية – مركز البحوث النووية – هيئة الطاقة الذرية (رقم بريدى ١٣٧٥٩) القاهرة – مصر
[2]قسم الهندسة الأشعاعية – المركز القومى لبحوث وتكنولوجيا الإشعاع – هيئة الطاقة الذرية (رقم بريدى١١٧٨٧) القاهرة – مصر

تم تصميم برنامج محاكاة لمصدر بلازما الأقطاب المستوية وذلك للتحقق من النتائج التجريبية لأنود و كاثود مستويان والتى تم الحصول عليها سابقًا باستخدام غاز النيتروجين. من الناحية التجريبية، تم إجراء التفريغ التوهجى عند قيم ضغوط تشغيل فى المدى من1,0إلى6,0 توروالمسافة بين أنود قرص –كاثود قرص تساوى 10 سم بإستخدام غاز النيتروجين. كما تم عمل مقارنة بين المحاكاة والقيم التجريبية عند قيم مختلفة لمضروب الضغط والمسافة وذلك لكل من جهدالإنهيار ، تيار التفريغ ومعامل تاونسند الثانى بإستخدام غاز النيتروجين. وقد وجد تطابق جيد بين المحاكاة و القيم التجريبية. أيضا، تم إستخدام برنامج المحاكاة لحساب معامل تاونسند الأول عند قيم مختلفة لمضروب الضغط والمسافة بإستخدام غاز النيتروجين ، بينما تم حساب جهد الأنهيار و تيار التفريغ عند قيم مختلفة لمضروب الضغط و المسافة بإستخدام غاز اتالنيتروجين والأرجون وثانى أكسيدالكربون. وقد وجد أن الحد الأدنى لقيم جهدا لإنهيار يساوى 77,472،26,232،27,349 فولت وذلك عند الحد الأدنى لقيم مضروب الضغط والمسافة يساوى5,1، 1 ،75,0 تور.سم بإستخدام غازات النيتروجين والأرجون وثانى أكسيدالكربون، على التوالى. كما وجد أيضا أن الحد الأدنى لقيم تيار التفريغ يساوى5228,0،65,3 ميللى أمبير وذلك عندالحد الأدنى لقيمة مضروب الضغط والمسافة يساوى1 تور.سم بإستخدام غازات النيتروجين والأرجون، على التوالى. كذلك تم الحصول على الحد الأدنى لقيمة تيار التفريغ يساوى8,7 ميللى أمبير وذلك عندالحد الأدنى لقيمة مضروب الضغط والمسافة يساوى75,0 تور.سم بإستخدام غاز ثانى أكسيدالكربون.