International Journal of Scientific & Engineering Research, Volume 5, Issue 1, January-2014 1492
ISSN 2229-5518

Effect of the Hollow Cathode Geometry on Nitrogen Glow Discharge Plasma

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Abstract— An experimental study of DC hollow cathode glow discharge plasma at different nitrogen pressures ranged from (0.015 to 0.75Torr) has been proposed.Investigated was carried out under the influence of the hollow cathode geometry such as diameter and depth of hollow cathode at fixed discharge current (I_d=1.88 mA). Langmuir double probe method has been used to measure and calculate the plasma parameters as well as a computer MATLAB program is performed for this purpose. The results shows that the electron temperature increased with the increasing both inter-cathode distance and depth of hollow cathode for the low range of pressure (0.015, 0.038, 0.06) torr, while this behavior is inversed in high pressure ranges (0.15, 0.375, 0.6, 0.75) torr, due to the hollow cathode effect. Electron density tends to increase by decreasing hollow cathode geometry. On the other hand both floating and plasma potential increases with the increasing geometrical factor. It's observed that the results have satisfactory agreement with previous work reported in this field of hollow cathode.

Index Terms— Hollow Cathode ,Hollow Cathode depth,Cathode Geometry, Glow Discharge Plasma,Double Langmuir Probes,Electron temperature and Plasma Potential

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1 INTRODUCTION

When a planar cathode in a glow discharge replaced by a cathode with some hollow structure, in a specific range of operating pressure, the negative glow which has the highest electron density moves inside the hollow structure, and discharge takes place almost entirely inside the hollow [1], in these regions electron are caught and oscillate, causing additional ionization and excitation of atoms. This is known as the hollow cathode effect (HCE). Much higher current densities and much higher emitted light intensities can be achieved in hollow cathode discharges compared to a planar cathode discharge [2].

The hollow cathode effect (HCE) was first described by paschen in 1916. this effect occurs in cathode presenting cavities, hollow or even parallel faces, when the discharge fills the cavity under given conditions governed by the inter - cathode spacing and gas pressure [3].Owing to the hollow cathode effect the voltage in a hollow cathode discharge (HCD)is lower at equal current density and the, current density islarger at a given voltage than from similar direct current discharge with a planar cathode. There are two main reasons for these differences. The First is of geometric origin and is connected simply with reduction of charged particle losses in a closed space of a cavity.The second reason is connected with a higher efficiency of ionization in the hollow cathode cavity [4].The hollow cathode glow discharge plasma have been investigated both theoretically and experimentally in many works considering the effect of the discharge voltage, gas pressure, magnetic filed as well as the product of the inter diameter by the gas pressure which is an important parameters to describe the behavior of hollow cathode discharge, Wang and Cohen [5] studied the dependence of magnetron operational parameters on the inner - diameter d and length L of a cylindrical hollow cathode structure.A hollow cathode magnetron that built by surrounding a planar sputtering-magnetron cathode with a hollow cathode structure, was operable at substantially lower pressures than its planar-magnetron counterpart. Brunatto et al. [6], Investigated the influence of the radial spacing between cathodes on the iron sintering by hollow cathode electrical discharge, with surface enrichment of the alloying elements Cr and Ni.

Chin and Wong [7], expressed the dependence of the electron temperature, electron density and plasma potential of a D.C. helium hollow cathode discharge with product of the hollow cathode diameter and gas pressure.

Gomes et al. [8], studied the electrical characteristics of microhollow cathode discharges (MHCD) at high pressure of argon and air for different geometrical configuration. Experiments have been performed to determine the so-called Panchen's curves, i.e. the dependence of the breakdown voltage on the product electrode gap and gaspressure. Current-voltage characteristic curves were obtained as a function of the pressure and hole diameter. MHCD has stable direct current discharges that ignited at pressures ranging from 12 to 800 Torre, and a wide range of current densities and electrodes materials.Evidence of electron field emission wasobserved for several ranges of gap spacing.

The influence of the inter-cathode distance and the pressure on the surface morphology's changes in pressed iron samples and in the internal surface of the external cathodes was investigated in HCD by Brunatto [9]. It was verified a sputtering mechanism in promotes significant surface of different finishing between the pressed and sintered samples. The effect of the inter-cathode distance was not so evident probably as a consequence of the high sintering time specified for this study

Eizaldeen and Ashwaq [10] represent a study of some physical characteristics of argon plasma product by hollow cathode discharge with and without magnetic field achieved in the negative glow region of hollow cathode discharge. Results of the electron temperature T_e are smaller in the case of applied magnetic field than without magnetic field. On the other hand, Parra-Rojas et al. [11] studied low pressure DC air discharge produced in a hollow cathode reactor by emission spectroscopy in the near UV- near IR spectral range , quadrupole mass spectroscopy , and double Langmuir probes are used to obtain the plasma parameters .Later Abdelrahman and Abdebagi [12] designed and built a copper hollow cathode discharge laser to utilize copper transitions parameters for laser investigation .A suitable DC pulse power was constructed particularly to operate the system . The relation between gas pressure and discharge current was investigated and the optimum values obtained at 1.96A for the discharge current and 28mbar for the gas pressure of the discharge regime .A model to predict the plasma properties inside a thermionic hollow cathodeas a function of operational conditions and geometry is presentedby Pedrini et al. [13]. The hollow cathode features a lanthanum hex boride (LaB6) insert, which is capable of emitting current densitiesas high as $10^5 Am^{-2}$at temperatures of about 1900 K, along with a tantalum orifice platelocated at the downstream end of the cathode tube.The model self-consistently computesthe plasma parameterin both the emitter and orifice regions.

The objective of the present work is to obtain experimental observation of the hollow cathode Nitrogen glow discharge at various gas pressure and different hollow cathode geometry (inter–diameterand depth of hollow).The experimental work of this study is to design a hollow cathode of different inter diameter and various depth of hollow. The study will be adopted to investigate the influence of the geometrical configuration of the concerned hollow cathode on the plasma parameters such as electron temperature, electron density and both floating and plasma potential at different working pressure of nitrogen gas.

2 EXPERIMENTAL EQUIPMENT

The discharge tube is made of a cylindrical Pyrex glass of 5 cm diameter and 25 cm length. As shown in figure (1). The tube is opened in both sides in such a way that one can move the electrodes through them or closing them in order to get a good vacuum and homogenous discharge. The pressure in the chamber is measured by vacuum gauge head [Thermovac TM21], the range about 10 mbar. About 0.5 cm of the rims on the two sides of the tube are folded to about 80 degree angle with the tube wall to form a plate form for the cylindrical rubber which is used to prevent gas leakage. The distance between electrodes is fixed to 14 cm. The tube was provided with two pipe connection,the first one was connected with the double needle valve which, the first valve is a gas inlet that is rotatable and the another valve for rotary vacuum pump, and the second pipe is to input the Langmuir double probe and has a diameter 2.95 cm and 2.5 cm length. The discharge tube was filled with N_2 gas to produce nitrogen glow discharge, in such away by filling and evacuating the system many time to ensure that the chamber container is the nitrogen gas. Figure (2) shows the actual system of the present work and for more details see [14].

The hollow cathodes are made of metal (brass) of the hollow cylindrical shape. The purpose behind using hollow cathode is to get more stable and denser plasma at the center of the discharge. Hollow cathodes has been covered on the outer shell by an insulator (Teflon) and back sides and edges by an insulator in order to get the discharge inside the hole of the cathodes, as shown figure (3). The hollow cathode is connected to external electric circuit through the copper rode fixed at one end of the discharge chamber by vacuum seal to prevent leakage.

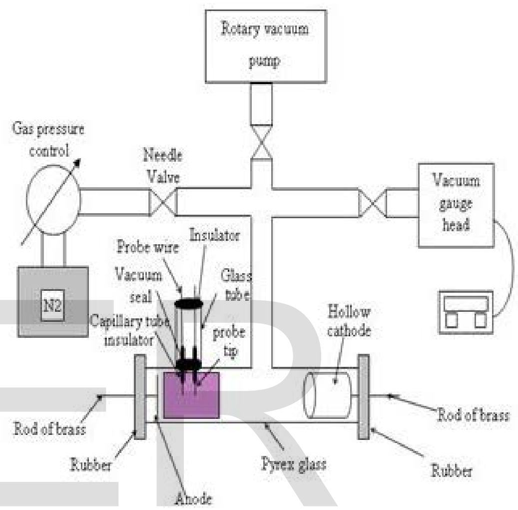

Fig.1. Schematic diagram of the discharge system

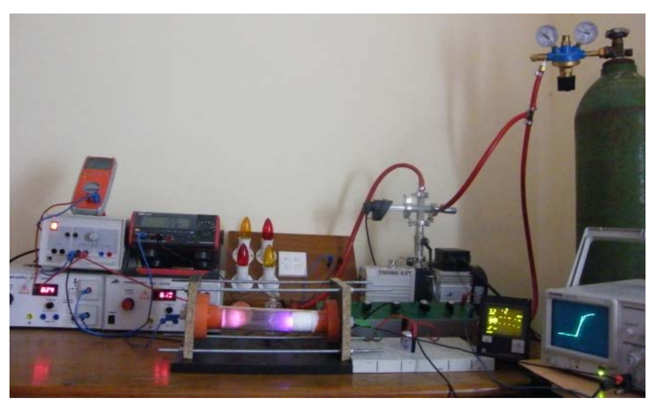

Fig.2. Image of the system

The present work deals with two different cases concerning the geometrical configuration of hollow cathodes design *First Case*: Hollow cathodes which used are in different inner diameters with (4, 3.5, 3, 2.5, 2, 1.5, 1 cm), all with thickness (0.5 cm) and depth (3 cm) and (4 cm) in length, figure (3).*Second Case*: This case was adopted for different depth of hollow cathode of (3.5, 3, 2.5, 2, 1.5, 1 cm), all with inter- diameter 3.5 cm, as well as used one anode of same diameter and thickness.

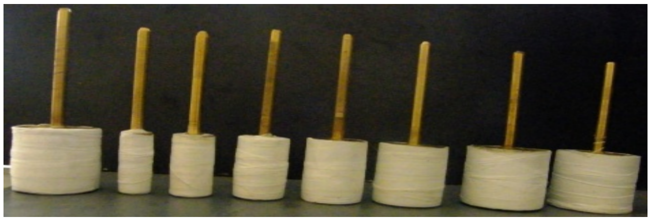

Fig.3. Cathode with different diameters

The anodes are made also from a copper metal (brass) of disk shape. In the first case used seven anodes with different diameters of (4, 3.5, 3, 2.5, 2, 1.5, 1 cm), and all of thickness (0.5 cm)as shown in figure (4). The anode is connected to external electric circuit through the copper rode fixed at one end of the discharge chamber by vacuum seal to prevent leakage.

Fig.4. Anode with deferent diameter

Discharge voltage has been supplied to the electrodes system by a DC power supply [3B power supply U21060], it is a variable power supply of range (0-6000V) and the maximum output current (2mA), two power supply have been connected in series to provides a (12KV) and current (2mA).this voltage is sufficient to occurring breakdown and generating glow discharge at different gas pressure. A digital multi meter [Mastech M9803R True RMS MULTIMETER] is used to measure the discharge current (I_d). The non-linear protective resistor (lamp) is used to limit the discharge current and avoid the streamer to pass through the chamber to make the spark breakdown [15]. This type of non-linear resistors is choosing because it provides a relatively high power of 25 watt out cooling process [16]. Langmuir double probe is constructed from a copper wire of radius (0.235mm). The probes are fixed within a capillary tube of glass and shielded by a plastic insulator to prevent their connection. The distance between the probes was (9.9 mm), the length is (6 mm) and passed through a glass tube to the discharge chamber.

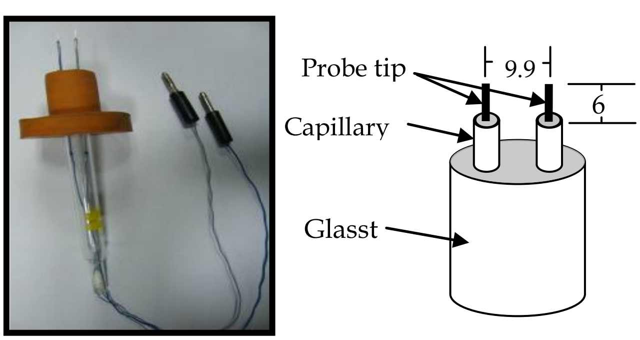

Fig.5. Construction of double probe and schematic diagram of cylindrical double probes

The double probe voltage about 10V is obtained from (220-50 HZ) an A.Cpower supply [LYBOLD DIDACTIC GMHZ 52135 WR00001888]. A direct resistance (100 KΩ) is used to convert the voltage to real value of current through the MATLAB program. The capacitor [C50 SAMER 29539] was used to reduce the phase difference in (I_p-V_p) characteristic of double probe. The x-y recorder (oscillogram) traces the(I_p-V_p)characteristic of the probes, the voltage on the probes is recorded on the x-axis, while the current through the probes is recorded on the y-axis, as the voltage drop across the resistance of value (100 KΩ),figure (6) represents the electric circuit of plasma system.

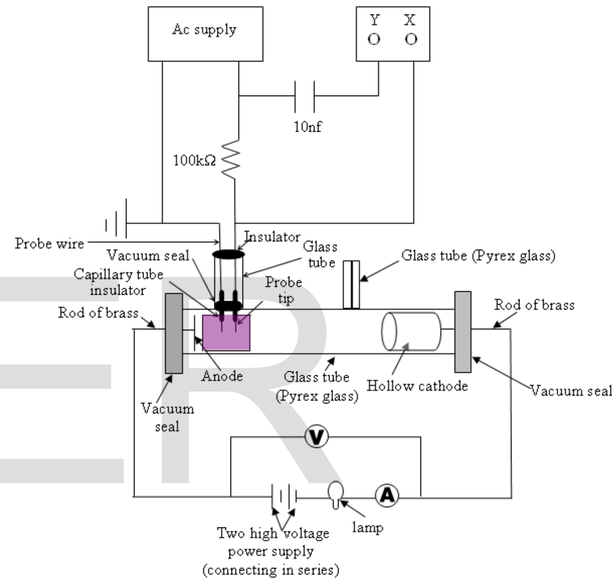

Fig.6. Electrical circuit of plasma system

3 Results and Discussions

Investigation of the effect of both diameter and depth of hollow on the electron temperature and its density as well as on the both floating and plasma parameters is reported. Plasma parameters have been obtained from the double probes characteristics and MATLAB computer program is used to determine the electron temperature and its electron density for different diameter and depth of hollow cathode [17].The double probes (I_p-V_p) characteristics are measured at different pressure, diameter and depth of hollow cathode at fixed discharge current (I_d=1.88 mA) are shown in figure (7).

In the present work, the lower and upper limit of operation Pd is used where P is the pressure and d is the diameter of the hollow cathode ranged between (0.06 Torr.cm ≤Pd≤ 3 Torr.cm) for nitrogen gas. Outside this range, the glow is observed either outside the cathode cavity or did not develop voltage-current characteristics [15]. These effects illustrate in figure (7)) at low pressure for small diameter and depth. If the pressure is low the mean free path of the electron will be large at this di-

ISSN 2229-5518

ameter and depth then the glow will not go inside [18]. At large HC we must used very low pressure and it is necessary to reduce the diameter of HC at higher pressure [19], [20].

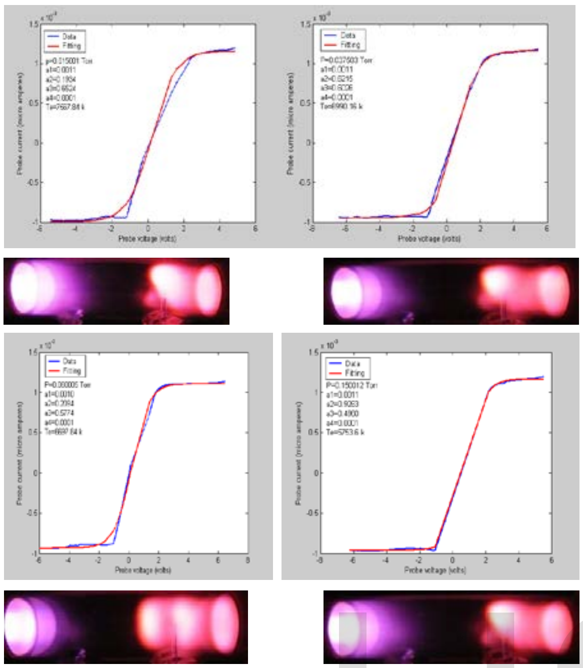

Fig.7. Double probe (I_p-V_p) characteristics of HC diameter (4 cm) and glow discharge image of each characteristic at different pressure

3.1 Hollow Cathode Geometry Dependence of the Plasma Parameters

Determination of the electron temperature in the hollow cathode discharge is based on the analysis of the (I_p-V_p) characteristics. The effect of the gas pressure on the discharge properties is expected since the increase of the collision by increasing the pressure tends to enhance the hollow cathode effects being possible to reach an optimized reduced Pd [21]. The hollow cathode discharge operation is in general, restricted to a certain range of Pd (0.1 Torr.cm <Pd< 10 Torr.cm) [22], [23]. The pd used ranged from (0.06 ≤ 3 Torr.cm). It is well known that the product (Pd) of the diameter (d) by pressure (P) is an important parameter to describe the behavior of the hollow cathode discharge.

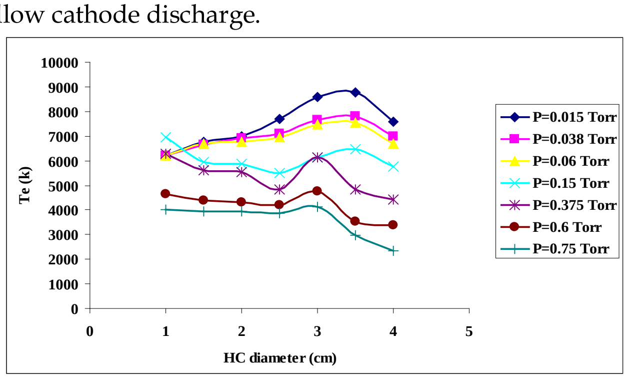

Fig.8. Electron temperature as a function of HC diameter at different pressure

Usually, the electron-atom inelastic collisions rate is increased by the decrease of the diameter with a large effect on the plasma density and electron temperature [21]. This effect is observed in figure (8) for the pressure (0.015, 0.038 and 0.06) torr. Since decreasing the diameter will increase the inelastic collision rate of electrons with the atoms and therefore the electron temperature will be decreased according to that. However this behavior is inversed for high pressures (0.15, 0.375, 0.6 and 0.75) torr, in this case, increasing the diameter will decreases the electron temperature; because the hollow cathode effect began to appear at this range of pressure, i.e the hollow cathode discharge promote oscillation of hot electrons inside the cathode. There by enhancing ionization, ion bombardment of inner wall and other subsequent processes, therefore electrons loss more energy during these ionizing collisions to the atoms - molecules of gas [21], [7], [9]. On the other hand the dependence of electron temperature on the depth of hollow cathode as shown in figure (9),is similar to that variation with the diameter of hollow cathode for both low and high pressures investigated due to the same reasons.

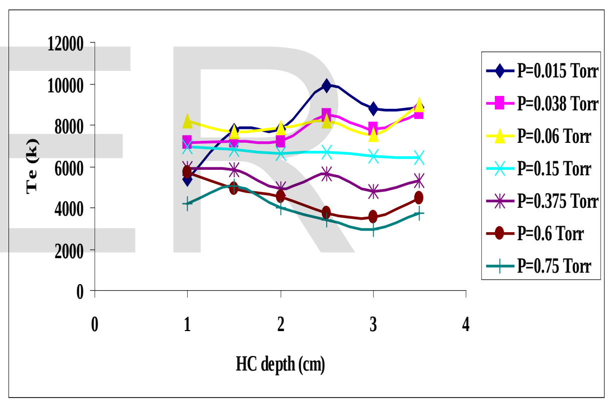

Fig.9. Electron temperature as a function of HC depth at different pressure

The electron density is important parameters in plasma processing due to the efficiency of the processes occurring in the plasma and their reaction rates are generally dependent directly on the density of the charged particles [24].

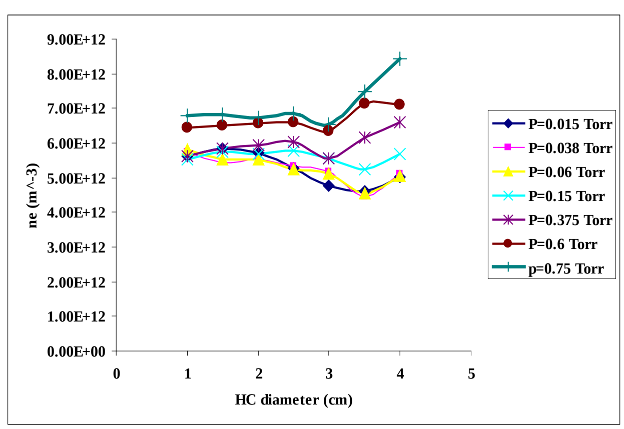

Fig.10. Electron density versus (HC) diameter for fixed discharge current (I_d=1.88 mA)

Figure (10) represent the variation of electron density with the HC diameter under different gas pressure. For increasing the cathode diameter the electron density reduce for the pressures (0.015, 0.038 and 0.06) Torre, due to a little inelastic ionization collisions of electron with atoms - molecules of gas. However for the pressure (0.15, 0.375, 0.6 and 0.75) torr enhancing the diameter in this branch of pressure, the electron density increase for constant pressure because the high energy electrons which are emitted by the cathode, oscillate between repelling potential of the sheath at the opposite cathode wall, these electrons enhance ionization in the negative glow and in the sheath. Thus due to the effect of electrostatic electron confinement at these values of Pd, the plasma assumes high values of electron and ion density [21].

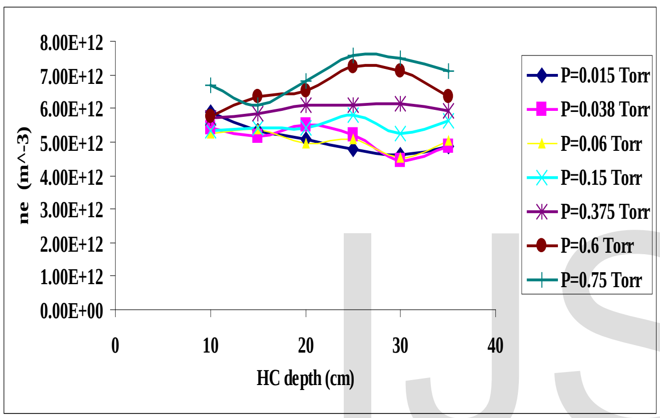

Fig.11.Density versus (HC) depth at different pressure.

Figure (11) shows the dependence of electron density on the depth of hollow cathode for different values of gas pressure. The figure showed the same effect observed in figure (10) with the increased hollow cathode discharge due to the same reasons of the inelastic collision rate with the atoms - molecules of the gas. The floating potential is calculated using equation [14], At this potential the number of ions and electrons reaching the probe are balanced so no net current is sensed in the probe circuit. The variation of floating potential versus geometrical factor of hollow cathode (HC diameter and HC depth) at different working pressure is shown in figures (12 and13) respectively.

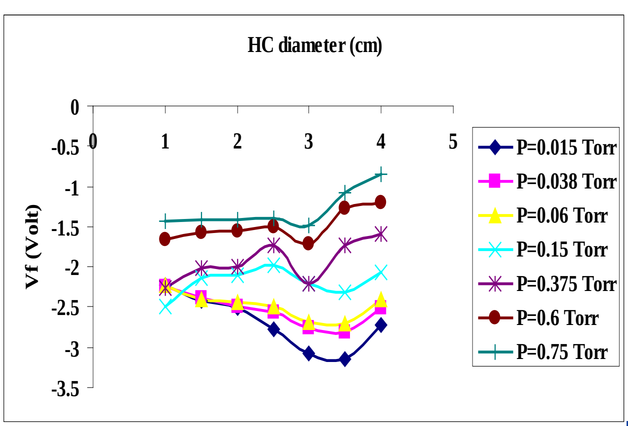

Fig.12. Floating potential versus (HC) diameter at different pressure.

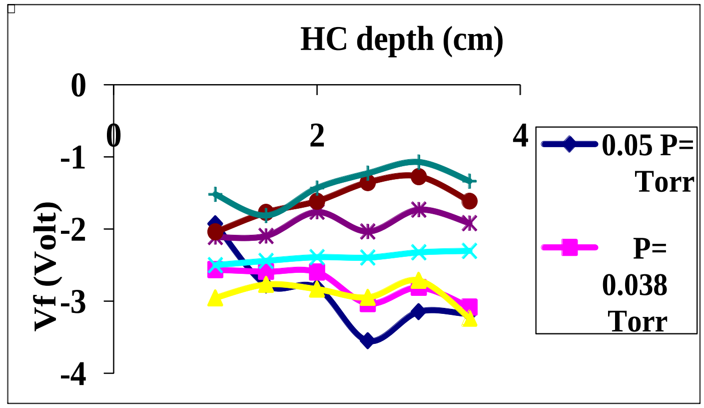

Fig .13 .Floating potential versus (HC) depth at different pressure.

It is appear from figures (12 and 13) that the floating potential increases with the increasing both diameter and depth of hollow cathode for the lower pressure (0.015, 0.038 and 0.06) torr, because this increase of the hollow cathode geometry is equivalent to the decreasing gas pressure, this in turn decrease the rate of inelastic collision with the other particle of gas because of large mean free path of electron at low pressure later more electron can reach the probe and the sheath becomes perfect [25]. Contrary to this behavior the floating potential decreases with the increasing geometrical factor of hollow cathode at higher pressure (0.15, 0.375, 0.6 and 0.75) torr. This is due to the oscillation of hot electron inside the cathode, there by enhancing ionization, ion bombardment of inner wall and other subsequent processes. Therefore a less number of electrons will reach the probe and the sheath around it becomes partially, i.e less floating potential.Plasmapotential always positive with respect to the body with it is contact. In many cases, the plasma potential provides a good indication of the energy of positive ions incident on surface of interest [26].The calculated plasma potential is plotted versus diameter and depth of hollow cathode in figures (14 and 15) respectively. As illustrated from figures the plasma potential is positive and varies with the hollow cathodegeometry of, the observed behavior close to that of the floating potential, because the plasma potential proportional linearly with the floating potential [14].

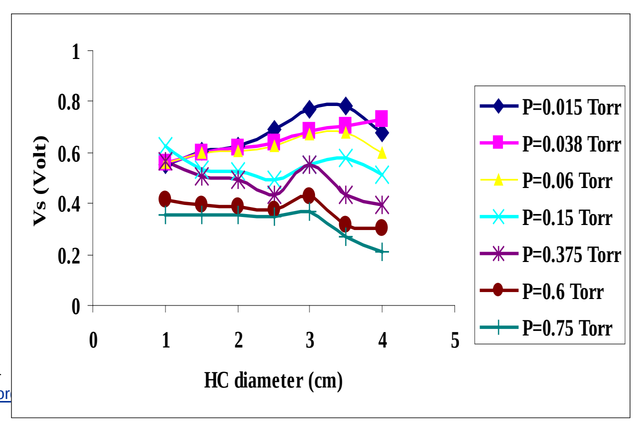

Fig. 14. plasma potential versus (HC) diameter at different pressure.

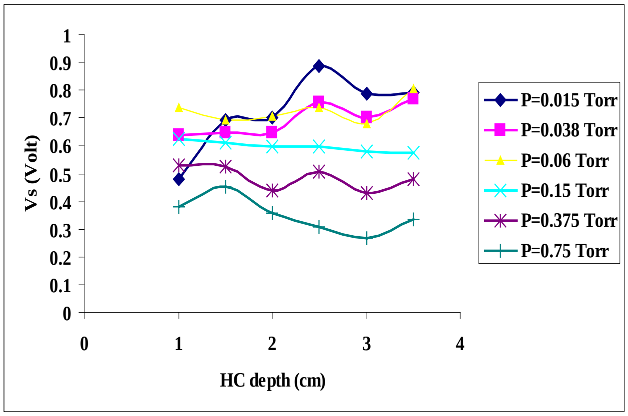

Fig. 15. plasma potential as a function of HC depth at different pressure.

3.1 Pressure Dependence of the Plasma Parameters

The electron temperature as a function of working pressure at different HC diameter is shown in figure (16). The increase of electron temperature with decreasing gas pressure was caused by lower rate of electron-heavy particle collisions enhancing electron losses to the wall [27]. As the pressure increase the mean free path and energy acquired by the electron decreases, since the electron lost all of it's during collisions with others gas particles [28].

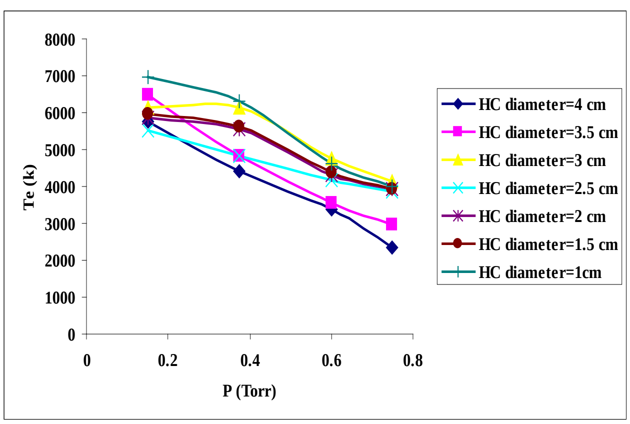

Fig. 16. Electron temperatures versus pressure at different HC diameter.

The electron density as a function of different working pressure at different HC diameter is shown in figure (17). The variation of electron density with the gas pressure close to linear relation, because of increasing number of ionization collision at this range of pressure [29]. The increase of plasma density with higher gas pressure resulted from the higher rate of electron impact ionization and the lower rate of ion diffusion to the reactor wall [27].

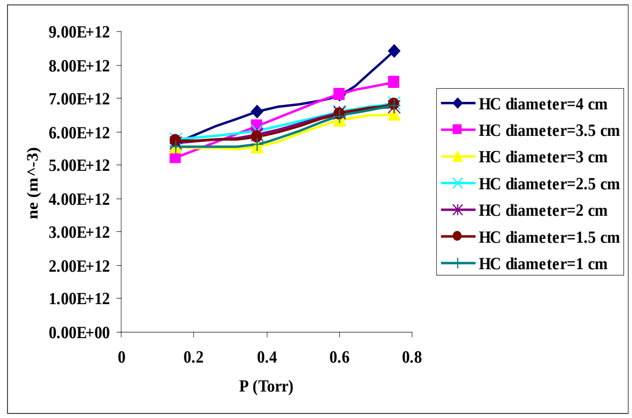

Fig. 17. Electron density versus pressure at different HC diameter.

The floating potential as a function of pressure at different hollow cathode diameter is shown in figure (18).

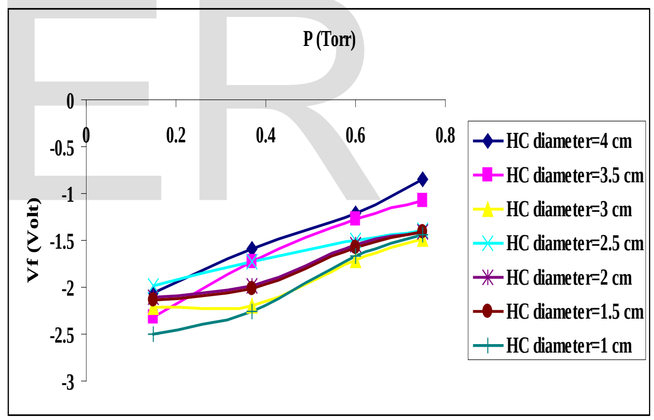

Fig. 18. Floating potential versus pressure at different HC diameter.

As indicated from figures ,that the floating potential changes inversely with the gas pressure, since at high pressure some electrons can reach the probe due to collisions of electrons with atoms - molecules of gas, therefore the sheath is partial, while at low pressure more electron can reach the probe and the sheath is perfect. One of most important plasma parameters is the plasma potential,Since potential can only determined with respect to a certain reference potential, in a plasma device usually the wall or plasma is used for this purpose, therefore the floating potential is more negative than the plasma potential [30].Plasma potential as a function of gas pressure for different hollow cathode diameter and depth as shown in figure (19). As illustrate from figures the plasma potential is positive and varies inversely with gas pressure.

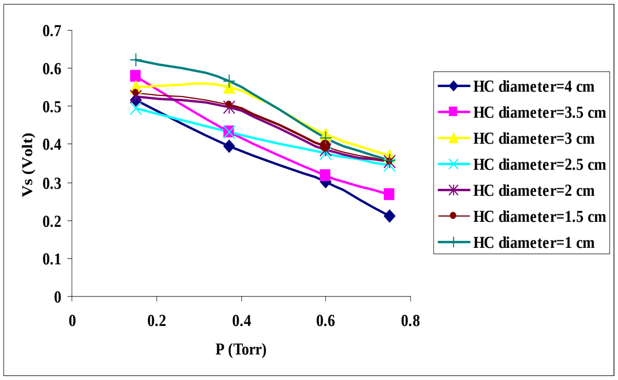

Fig. 19. Plasma potential versus pressure at different HC diameter.

4 Conclusions

A cylindrical hollow cathode DC glow discharge was studied experimentally as well as using double probes has very useful formation about the plasma parameters, such as electron temperatures, electron densities, plasma potential and floating potential which are correlated with the elementary processes involved in the discharge. All these parameters have been determined experimentally, the dependence of these parameters on the gas pressure, hollow cathode diameter and depth are experimentally investigated.

Important conclusions of the present work are summarized as follows:

1. The double probes techniques have been proven to be very valuable to determine the behavior of plasma parameters in glow discharge.
2. It is necessary to reduce the diameter of hollow cathode at higher pressure.
3. The electron temperature, electron density, floating and plasma potentials measured agree reasonable well with those from previous studies.
4. Increasing the geometrical factor of hollow cathode is equivalent to the decreasing of the gas pressure.
5. The observed effect of hollow cathode diameter is similar to that of hollow cathode depth on the plasma parameters.

References

[1] H. kirkici,"hollow cathode discharges for plasma light sources", ELECO'99 International Conference on Electrical and Electronics Engineering, Auburn University, Auburn AL 36849, USA, P.145-148, 1999.

[2] S. Janosi, Z. Kolozsvary and A. kis,"Controlled Hollow Cathode Effect: New Possibilities for Heating Low-Pressure Furnaces", Metal Science and Heat Treatment, Vol.49, Nos.7-8, P.310-316, 2004.

[3] S. F. Brunatto, A. N. Klein and J. L. Muzart,"Hollow Cathode Discharge Application of a Deposition Treatment in the Iron Sintering", Journal of the Braz. Soc. of Mech. Sci. & Eng., Vol. 30, No.2, P.145-151, 2008.

[4] V. I.Kolobov and L. D. Tsendin,"Analytic Model of the Hollow Cathode Effect", Plasma Sources Sci. Technol. 4, P.551-560, 1995.

[5] [5] Z. Wang, S. A. Cohen,"Geometrical Aspects of a Hollow Cathode Magnetron (HCM)", PACS No.52.80.-s, 52.40.Hf, 52.50.Dg, 52.75.Rx, 1999.

[6] S. F. Brunatto, I. Kuhn and J. L. R. Muzart,"Influence of the Radial Spacing Between Cathodes on the Surface Composition of Iron Samples Sintered by Hollow Cathode Electric Discharge", Materials Research, Vol.4, No.4, P.245-250, 2001.

[7] O. H. Chin and C. S. Wong,"Dependence of Some Plasma Parameters on a ap in a DC Helium hollow cathode discharge", Journal Fizik Malaysia, Vol.33, No.1-4, P.54-59, 2002.

[8] M. P. Gomes, B. N. Sismanoglu and J. Amorim,"Characterization of Microhollow Cathode Discharges", Brazilian Journal of Physics, Vol.39, No.1, P.25-30, 2009.

[9] S. F. Brunatto,"Plasma Assisted Parts Manufacturing: Sintering and Surface Texturing- part II -Influence of Inter-Cathode Distance and Gas Pressure", Technical Editor: Anselmo Eduardo Diniz, Vol.XXXII, No.2.P.136-145, 2012.

[10] Eizaldeen F . Kotp and AshwaqA.Al- Ojeery, " Studies The Effect of Magnetic Field on Argon Plasma Characteristics ", Australian Journal of Basic and Applied Sciences , 6(3): 817-825, 2012.

[11] F. C. Para – Rojas , E. Carrasco, A. Luque, F. J. Gordillo – Vazquez, V. J . Herrero, I. Tanarro," Diagnostics of Hollow Cathode Low Pressure Air Discharge as a Tool for Understanding Halo Spectral Features in the Earth Mesosphere ", 1st TEA – IS Summer School 17th – June22n Malaga , Spain, 2012.

[12] Wafa Salih Abdelrahman and Abdelrazig Mohamed Abdelbagi, " A study and Evaluation on a Homemade Copper Hollow Cathode Discharge Laser and Designed Pulsed Power Supply Parameters ", Indian Journal of Science and Tecnology, Vol. 6, Issue:2 February, ISSN: 0.974 – 6846, 2013.

[13] Daniela Pedrini, Riccardo Albertoni,FabrizioPaganucci andMariano Andrenucci, "Theoretical Model of a Lanthanum Hexaboride Hollow Cathode".Presented at the 33rdInternational Electric Propulsion Conference,The George Washington University, Washington, D.C., USA, 2013.

[14] SH. Muhamed, " Effect of Geometrical Factor on Nitrogen Glow Discharge Plasma " M.Sc, Thesis ,College of Science , University of Zakho . Kurdistan Region of Iraq, 2011.

[15] W. Lochet-Holtgreven,"plasma diagnostics", ed., Ch.11, North Holland, Amsterdam, Holland, 1968.

[16] A. J. Salim,"Study the Properties of Glow Discharge Helium Plasma Using Langmuir Single Probe and Data Acquisition System", M.Sc. Thesis, College of Science, University of Mosul, Iraq, 2007.

[17] A.A .Abul Kreem, " Langmuir probe data analysis code", File Exchange, MATLAB Center, 2013.

[18] E. M. Van veldhuizen,"The Hollow Cathode Glow Discharge Analyzed by Optogalvanic and other Studies", PhD Thesis,Eindhoven University of Technology, Eindhoven, 1983.

[19] J. Chen, S. Jin Park, Z. Fan, J. G. Eden and C. Liu,"Development and Characterization of Micromachined Hollow Cathode Plasma Display Devices", Journal of Microelectro mechanical Systems, Vol.11, No.5, P.536-543, 2002.

[20] V. Nehra, A. kumar and H. K. Dwivedi,"Atmospheric Non-Thermal

Plasma Sources", International Journal of Engineering, Vol.2, Issue.1, P.53-68, 2007.

[21] D. Soderstrom,"Modelling and Applications of the Hollow Cathode Plasma", PhD Thesis, Digital Comprehensive Summaries of Uppsala Dissertation from the Faculty of Science and Technology 433, Acta Uppsala University, Sweden, 2008.

[22] H. Goktas,"Construction of Double Discharge Pulsed Electron Beam Generator and its Applications", PhD Thesis, the GraduateSchool of Natural and Applied Sciences of the Middle EastTechnicalUniversity, 2001.

[23] E. B. Sozer,"Gaseous Discharge and there Applications as High Power Plasma Switches for Compact Pulsed Power Systems", M.SC Thesis, the Graduate Faculty of Auburn University, Auburn, Alabama, 2008.

[24] A. Grill,"Cold Plasma in Materials Fabrication From Fundamentals to Application", Institute of Electrical and Electronic Engineers, Inc, New York, USA, 1993.

[25] A. M. Daltrini, S. A. Moshkalev, L. Swart, P. B. Verdonck,"Plasma Parameters Obtained with Planar Probe and Optical Emission Spectroscopy", Journal Integrated Circuit and System, Vol.2, No.2, P.67-73, 2007.

[26] Hidden Analytical, "Plasma Diagnostics–Plasma characterization using a Langmuir Probe",2013.

[27] C. Koo Kim, "Analysis of Langmuir Probe Data in High Density Plasmas", Korean Journal Chemical Engineering, Vol.21, No.3, P.746-751, 2004.

[28] T. Grinys, S. Tamulevicius, I. Mockevicius, M. Andrulevicius,"Probe Temperature Measurement and Optical Emission Spectroscopy in Vacuum Plasma Spraying Process Control", ISSN 1392-1320 Materials science (Medziagotyra), Vol.13, No.4, P.346-350, 2007.

[29] M. Swarnalatha, C. Sravani, K. R. Gunaskhar, G. K. Muralidhar and S. Mohan,"Estimation of Density of Charge Species in a Triode Discharge System Vacuum", Vol.48, No.10, P.845-848, 1997.

[30] Swarnalatha, C. Sravani, K. R. Gunaskhar, G. K. Muralidhar and S. Mohan, "Probe Methods for Direct Measurements of the Plasma Potential", Romania Journal Physics, Vol.50, Nos.7-8, P.723-739, 1997.