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Design and Construction of Plasma Hollow Cathode Jet in Cylindrical Shape

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Abstract

A low pressure pulsed DC hollow cathode plasma jet system has been investigated. The design is developed to have a high density of plasma jet stream for plasma application. Experiments were carried out at charge voltage 4 KV, argon gas pressure 10^{-2} torr. The discharge current was measured by Rogoviski coil while the discharge voltage was measured by a resistive potential divider. The results indicated that the current voltage characteristics of hollow cathode discharge was dumping oscillation and was found to have breakdown voltage 1.92 KV, and maximum current 6.7 KA at argon pressure 10^{-2} torr. The photograph of light emission from pulsed DC hollow cathode plasma jet showed the expanding discharge with the densest plasma at the outlet of the nozzle. The time evolution of electron density and temperature were presented using I-V characteristic of single electric probe along the central axis of plasma jet system. The electron temperature and density were around 6.2 eV and (7×10^{-17} m^{-3}) to 3.8 eV (2.3×10^{-19} m^{-3}) respectively near the nozzle. The growth of electron temperature is related to the cathode voltage, and the electron temperature decreases at the end of the pulse time. The density variations synchronized with the discharge current because of the Lorentz force.

Keywords: Plasma physics, hollow cathode plasma jet, High voltage physics, copper sputtered

Introduction

Hollow cathode glow discharges have widely applications from surface metal properties to produce pulsed mixed metals gas ions and atoms seen for thin film preparation, ion implantation and ion injection into the substrate. In Cylindrical hollow cathode, the discharge takes place almost entirely inside the hollow cathode. In this regime electron are generated and oscillated, causing additional ionization and excitation of atoms. This is known as the hollow cathode effect (HCE) [1-9]. Much higher current density and much higher emitted light intensities are being achieved [9-11]. In the hollow cathode discharge itself as the origin of ions that can bombard the cathode surface. This bombardment causes secondary electron emission. Also, a high energy photon radiation from the plasma can cause secondary electrons from the cathode. These emissions of electron contribute to the total electron density. If the energy of ions is high enough sputter and or evaporation can occur and the cathode acts a source of material for the film deposition [6]. The hollow cathode discharge have been investigated in many works considering the effect of the discharge voltage, gas pressure and the product of the inter diameter of the hollow cathode by the gas pressure which is important parameter to describe the behavior of hollow cathode. The Hollow cathode discharge operation in general is restricted to a certain range of Pd. Where $0.01 < Pd < 10$ torr cm. where the d is internal diameter of the hollow cathode electrode and p is gas pressure. The minimum value of Pd for argon gas is 0.026 Torr cm [10-11]. The interest of DC pulsed hollow cathode plasma jet rises due to continuous reduction of plasma equipment cost, high quality of the plasma treatment and increase of plasma equipment productivity [9-16]. The aim of the present work is to obtain experimental measurements of the hollow cathode argon glow discharge at different positions on the axial axis of the hollow cathode tube; the study will be concerned on the `measurements of the plasma parameter such as electron temperature, electron density using single electric Langmuir probe.

Experimental Setup

The schematic diagram of the experimental setup is showing in figure (1). The hollow cathode is made of metal copper of the cylindrical shape of diameter 25 mm to absorb the produced heat by ions sputtering in the cathode. There is a hole of diameter 5 mm in the H.C. axis. The anode ring made of copper and has an inner diameter 40 mm, outer diameter 60mm and with a wall thickness of 5 mm, as shown in figure (1). The typical distance from the nozzle outlet to the anode is 10 mm, The H.C. chamber made from Pyrex glass with diameter of 75 mm and height 150 mm. The purpose behind using cylindrical hollow cathode is to get denser plasma at the axis of the discharge. The gas inlet is situated in the axis of the tube to obtain homogenous gas distribution along the tube. The hollow cathode is covered on the outer surface by insulate Pyrex glass tube in order to prevent the discharge from the rest of the system, as shown (Figure 1).

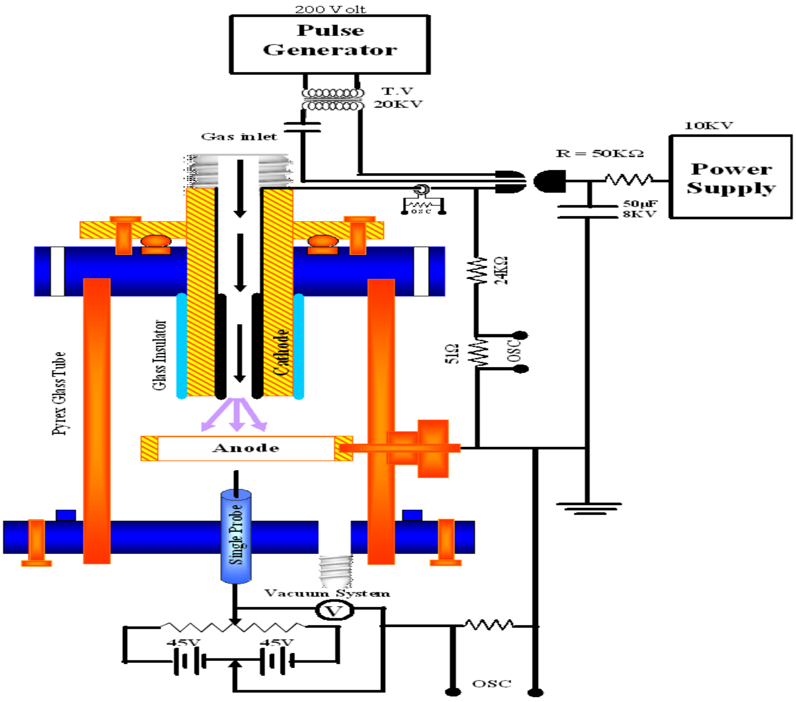

Figure 1: The schematic diagram of the Hollow cathode plasma Jet

The substrate can be fixed by a holder in the axis of the tube. The substrate is movable in vertical direction. The experimental chamber is continuously pumped by a rotary pump and an oil diffusion pump. The residual pressure of the vacuum apparatus reaches the order of 10^{-4} torr. The accurate pressure inside the reactor chamber is adjusted by a needle valve and a mass flow rate meter this pressure is measured by a penning gauge. All the results were performed in argon gas at pressure 10^{-2} torr. The discharge can be powered by a negative pulsed DC system to decrease over heating of the nozzle. The power system consists of a source of a half wave rectifier voltage 4 KV, spark gap switch, condenser bank (50 μF, 8 KV) and pulse generator of SCR circuit to switch on the spark gap by a signal of 10 KV with rise time 2 μs. Our diagnostic techniques are the Rogoviski coil for measuring the discharge current and the high voltage resistance potential divider for measuring the discharge voltage. The probe was made from molybdenum wire and was put in a Pyrex glass tube. The wire has 0.5 mm diameter and the length 3 mm, the probe was axially movable to measure plasma parameters at different positions. All the experimental results were recorded by a storage double beam oscilloscope. Langmuir probe diagnostic methods are ideally suitable for plasma parameters encountered in low pressure gas discharges. The term ‘low pressure’ as referred to Langmuir probe applications implies a ‘collisionless probe’ regime [10-11]. A very general requirement for Langmuir probe application and validity of the Druyvesteyn formula is collisionless electron motion about the probe $r_b, \lambda_D << \lambda_e$

Where r_b is the probe tip radius, λ_D is the Debye length and λ_e is the electron mean free path [4]. In the present work assuming the plasma generated by the hollow cathode discharge has electron temperature and electron density approximately (1-50 eV), (10^{15} – 10^{18} m^{-3}) respectively [2, 5]. r_b=0.25 mm, λ_D=22x10^{-3} mm, and λ_e=10 mm for argon pressure 10^{-2} torr. The single electric probe was used to measure the electron temperature and density of the plasma.

Results and discussions

The results were taken at low pressure about 10^{-2} torr, in chamber of the hollow cathode plasma jet, while the pressure in the nozzle is always higher than 25x10^{-2} torr. This means that the flow speed of the sputtered ions and atoms has critical sonic velocity at the nozzle outlet was reasonable [3]. So, the hollow cathode discharge is ignited the inner surface of the nozzle is being sputtered since nearly all the power is dissipated inside the hollow cathode.

Figure (2) shows the photograph of light emission from pulsed DC hollow cathode plasma jet at charging voltage 4 KV, an argon gas pressure 10^{-2} torr. The photo shows the expanding discharge with the densest plasma at the outlet of the nozzle. The emission plasma of the outlet nozzle works as a positive column of the DC glow discharge [2,5].

Figure 2: The photograph of light emission from pulsed DC hollow cathode plasma jet

The discharge current has been measured by Rogoviski coil [7]. The discharge current was measured by the relation.

I_d=n/r V_{osc} =1420 V_{osc} Amp. Where n is number of turns per unit length, I is output resistance, and V_{osc} is the measured voltage on oscilloscope.

The discharge voltage was measured by a resistive potential divider [7]. Using this relation:

V_d=K V_{osc} volts. Where K is constant and equal 480.

Figure (3) shows the typical waveform of the discharge current and discharge voltage for (Ar) at charging voltage 4 kV and gas pressure of 10^{-2} torr. It is remarkable from experimental results that the breakdown voltage is 1.92 kV and maximum discharge current is approximately 6.7 kA. The discharge current is dumped oscillation. The dumping oscillation in V-I waveform is mainly caused by the inductance in the discharge loop[2,5]. The half period of the discharge current is about 40 µs, and the rise time of discharge current is 20 µs.

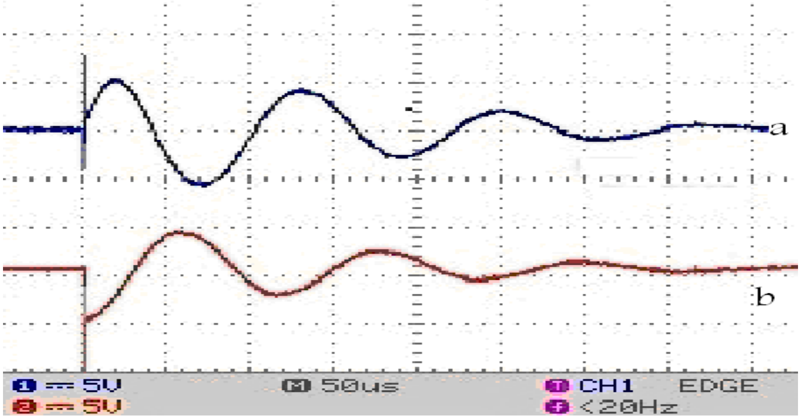

Figure 3: The typical waveform of (a) discharge current and (b) discharge voltage.

The single eclectic probe surface was cleaned from deposited films by applying high negative voltage on the probe in between probe characteristics measurements. This high negative voltage caused ion bombardment and consequent sputtering of material deposition the probe surface. The experimental measurements of the probe characteristics were performed many times and the results show that there are some errors in the range of 10%. Determination of the electron temperature in the Hollow cathode discharge is based on analysis of the (Ip – Vp) characteristics of the electric single probe.

The electron current in the retarding region (region between floating potential V_F and plasma potential V_s) when the distribution is Maxwellian can be calculated using the equation (1):

$$I_e = I_{re} \exp\left[-\frac{eV_p}{kT_e} \right] \tag{1}$$

Where: I_{re} is the probe current when the probe voltage reaches to the plasma potential, V_p is the probe voltage, T_e is the electron temperature, e is the electron charge, and K is the Boltezman constant (M. Cada et al. 2003). Figure (4) shows the I-V characteristics of the probe at z=3 cm, t=40 μs, and P=10^{-2} torr.

By plotting the semi-log curve of the electron current I_e as a function of the probe voltage V_p .

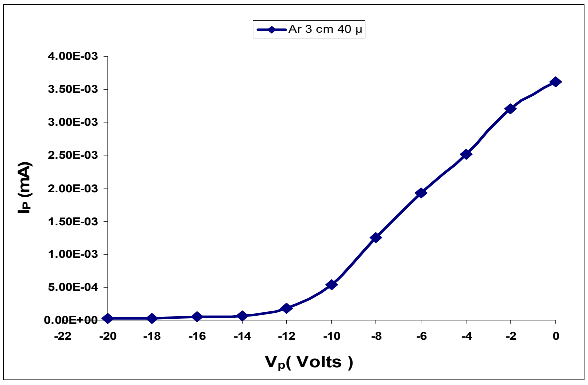

Figure 4: I-V characteristics of the probe at z=3 cm, t=40 μs, and P=10^{-2} torr

Electron temperature T_e can be calculated from the flowing equation (2):

$$\ln(I_e) = \ln(I_{re})\left[-\frac{eV_p}{kT_e} \right] \tag{2}$$

Figure (5) shows the variation of electron temperature with time at three positions 1 cm, 2 cm, and 3 cm, from the nozzle outlet on the nozzle axis for (Ar) at charging voltage 4 kV and gas pressure of 10^{-2} torr.

The electron temperature at beginning of the power at Z=1 cm was 7 eV. The growth of electron temperature is related to the cathode voltage. A rapid fall of electron temperature to about 3.9 eV at 40 μs at the end of the half period pulse was observed. Also the electron temperature decreases slightly after the end of the pulse time. This could be explained by the higher concentration of sputtered particles. As copper has lower

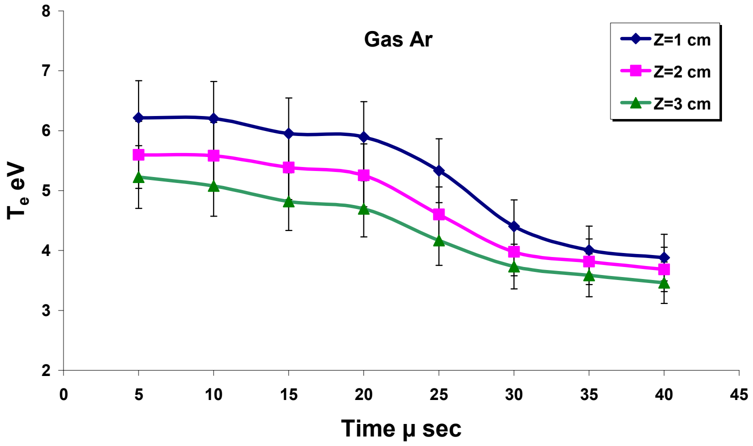

Figure 5: Electron temperature of plasma jet as a function of time at different distance from the nozzle (z)

Ionization potential than argon, the electron could be effectively cooled by ionization process. It is confirmed by the observation that the decay of electron temperature lost longer at greater distances from the nozzle axis, which can be achieved by the propagation particle later [1-5]. The ionization of working gas takes place almost in the plasma jet nozzle during the first pulse creating ions leave the nozzle outlet and they propagate through the reactor chamber together with the neutral gas particles. If there no electric field outside the nozzle their movements is affected by natural collision and by the diffusion processes. These two effects decelerate ions and neutrals in the direction of the plasma jet axis.

The electron density can be determined by I-V characteristics of probe [5] using the following equation (3):

$$I_{est} = \frac{1}{4} n_e e (\frac{8kT_e}{\pi m_e})^{1/2} A_p \qquad (3)$$

Where $A_P(m^2)$ is probe area, and $I_{est}(amps)$ is electron current saturation.

$$n_e = 0.76x10^{19} \frac{I_{est}(amps)}{\sqrt{T_e(eV)}} \qquad (4)$$

Figure (6) shows the time evolution of electron density for argon and nitrogen at charging voltage 4kv and gas pressure 10^{-2} torr. At different distances from the nozzle on the nozzle axis.

Electron density at beginning of the power at Z=1cm was ($7x10^{-17}$ m^{-3}). And a decrease of electron density to about ($1.3x10^{-17}$ m^{-3}) at 40μs at the end of the half period pulse was observed.

The plasma density is noticeably higher at the outlet of the nozzle than at the substrate. This effect comes from higher ionization coefficient during the first pulse time. It means that we can expect many electron – electron collision. The density variations synchronized with the discharge current because the Lorentz force increases with increasing the self-magnetic field, and the plasma accelerates due to the Lorentz force and thermo dynamic force [6].

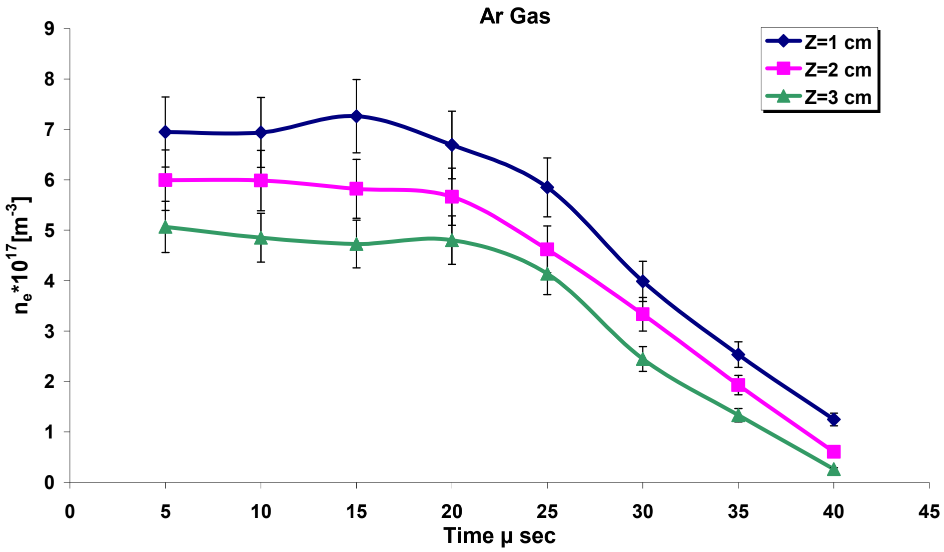

Figure 6: Electron Density of Hollow Cathode plasma jet as a function of time at different distance from the nozzle (z)

Conclusions

Several discharge current and voltage waveform were measured in the Argon plasma generated by pulsed DC power supply in hollow cathode plasma jet system. Experiments were per formed at typical gas pressure 10^{-2} and at charging voltage 4 KV. The photograph of light emission from pulsed DC hollow cathode plasma jet showed the expanding discharge with the densest plasma at the outlet of the nozzle. It was found that the breakdown voltage is 1.92KV and maximum discharge current is 6.7 KA, at 10^{-2} torr. The discharge current is dumped oscillation, related the inductance of the discharge circuit. Using I-V characteristics of single electric probe to estimate electron temperature and density which were around 6.2 eV and ($7x10^{-17}$ m^{-3}) to 3.8 eV ($2.3x10^{-19}.m^{-3}$) respectively near the nozzle. The growth of electron temperature is related to the cathode voltage, and the electron temperature decreases at the end of the pulse time. This could be explained by the higher concentration of copper sputtered particles. The density variations synchronized with the discharge current because of the Lorentz force. The hollow cathode plasma jet may be used for many purposes such as surface modification, thin film deposition and etching.

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