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Study the Effect of Electrodes Types on the Properties of DBD Plasma using Optical Emission Spectroscopy

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Abstract: ***The design of the Dielectric Barrier Discharge plasma system (DBD) which operates at the atmospheric pressure to generate cold plasma. This system consists of a high voltage power supply of up to (20 kV) and a current discharge of up to (mA) and a frequency of about (35 kHz). Two electrodes, made of copper and aluminum, with a diameter of (5 cm). The electrodes are surrounded by a Teflon dielectric material with thickness (2.5 cm) and (2 mm) thickness of dielectric material made of glass is placed between the electrodes to ensure electrical discharge and plasma generation. These electrodes are connected to the power supply. Plasma parameters (electron temperature, electron density, plasma frequency, Debye length, and Debye number) generated from the dielectric barrier discharge system by Optical Emission Spectroscopy for the nitrogen gas spectrum using the Boltzmann plot method for plasma parameters were calculated. In this work also it was studied the effect of the electrodes made of (copper and aluminum), the effect of the applied voltage (12 kV to 20 kV) on the properties of the generated plasma when the stability of the distance between poles (3 mm), the applied frequency (25.91 kHz), and the dielectric material thickness made of glass. From studying (current-voltage) curve note it was that, the discharge current increases when the voltage applied for both (copper and aluminum) electrodes increase. In addition, the disparity in the values of plasma parameters when the voltage applied increase***.

1. Introduction

The plasma is produced by subjecting a gas to an electric field between two electrodes with alternative current (high-frequency field), hence their designation as electrical discharges. The electric field accelerates the charged particles, essentially the electrons since the ions are much heavier, and the electric field energy is ultimately communicated to the plasma through collisions of the electrons with the heavy particles[1]. Therefore, it is the electrons that break molecules, and ionize atoms and molecules of the discharge gas without requiring the heavy particles to be as energetic, hence a lower energy cost and the possibility of using glass and metal discharge vessels without a heavy cooling. With some kinds of discharges, the gas temperature can even be as low as room temperature. The temperature of the discharge gas increases with pressure because of the increasing number of elastic collisions of electrons with heavy particles and depending on the gas, can exceed a few thousand degrees at atmospheric pressure unless a discharge is used[2].

In this research, will be studied the properties of plasma generated laboratory and the effect of each plasma parameter such as Voltage applied and Electrodes on the system and plasma generated. In this system, two types of electrodes (Copper and Aluminum) were used and change of the voltage applied to a given range (12–20 kV) was determined. The frequency, distance between the two electrodes and the dielectric were constant. In this work, OES and Boltzmann Plot were used to study plasma spectroscopy and compare results to obtain the best properties of plasma that can be used medically and in surface modification. However, studies are still passed on the practical aspect of applications and lack theoretical understanding of such discharges which would enable researchers to change operation parameters in the system to determine results detailed of plasma parameters. This is due to the chemical and physical properties which depend on the dynamics of the power dissipation and the mechanisms of the electron heating, whereby the plasma parameters are highly sensitive and affected by instabilities, process transitions and the variations associated electron heating for plasma[3]. It is therefore necessary to understand electron heating mechanisms in (DBD) system that working by atmospheric pressure to compensate for the theoretical aspect of the studies that are used this applications.

2. Dielectric Barrier Discharge (DBD)

A dielectric barrier discharge (DBD) plasma is an electrical discharge between two electrodes separated by a dielectric material. It used firstly as a new method of ozone generation. Also, it was called the silent discharge in contrast with a spark discharge, which is accompanied by substantial heating and generation of audible noise [4]. From a fundamental point of view, the main difference between DBD and spark discharges is the presence of the dielectric barrier which precludes dc operation of the DBD[5].

DBD plasma is usually driven by an applied voltage at frequencies between (0.05 and 500) kHz or by high voltage pulses. When the applied voltage reaches breakdown value, the electric current deposits surface charge onto the dielectric and the discharge self-terminates [6]. To improve the discharge parameters can be used to adjust various external parameters, for example:

1) The applied voltage affects the quantity of the electric field, hence on the energy of the charged particles.
2) The power controls the ionization density, hence is an approximate variable for the plasma density. Also, it is a probable variable to control for the energy of the plasma.

3) The pressure of the gas controls the collisions of electron frequency, that means a free path of plasma constituents.
4) The gas sort controls the ionization, thus the energy of necessary to produce an ion-electron pair in the plasma was controlled.
5) The electrodes form can affect the energy input by changing the electric field and change the shape of the electrodes.
6) Cathode properties can affect the discharge properties, such as the emission coefficient, or the able to the emission of thermal ions[7].

The types of electrodes configurations of DBD Plasma can be shown in Figure 1.

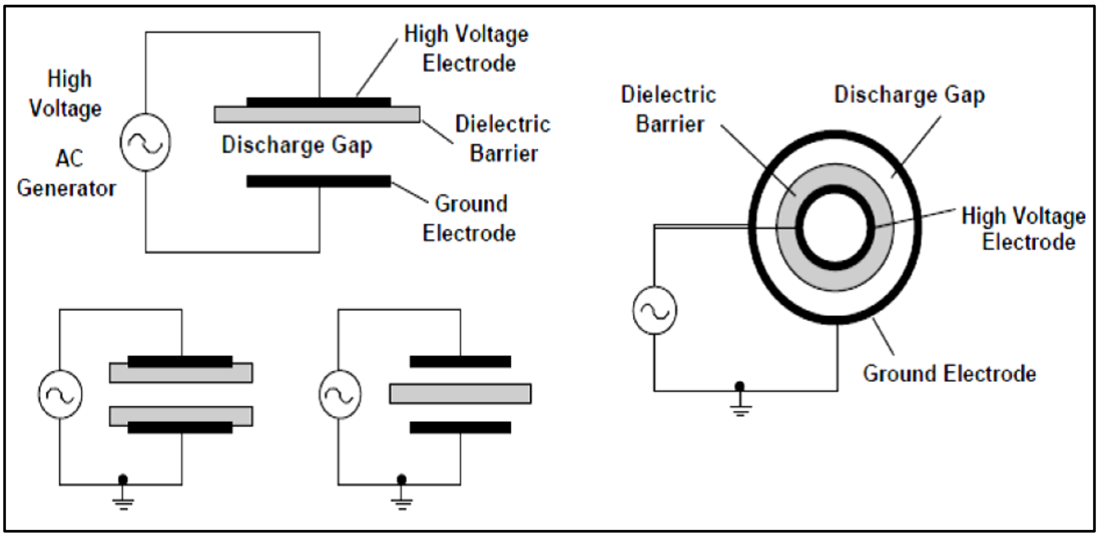

Figure 1: The electrode configurations of DBD Plasma[8].

3. Experimental Work

In this research, the DBD Plasma system was designed to generate plasma atmospheric pressure. This design consists of two electrodes made of Copper and Aluminum, respectively. The radius of each electrode is (25mm) surrounded by Teflon with thickness (29 mm) for the. The electrodes are fixed on a holder at one end, moving up and down to control the distance between the electrodes, and each of them is connected to alternating voltage power.

A dielectric material of thickness (2 mm) was used, and the dielectric constant was (3.7 – 10) [8]. The dielectric material is placed between the two electrodes to form a discharge process. Figure 2 showed the locally designed DBD Plasma system.

Figure 2: The locally designed DBD Plasma system.

The power supply for the alternating voltage and the locally designed produces high voltage up to (20 kV) and a frequency of up to (35 kHz) and current in mA. The electrodes are surrounded by a dielectric material of Teflon with constant isolation (2.1) at room temperature and frequency (1 kHz).

4. Results and Discussion

In this research, two types of electrodes (copper electrode and aluminum electrode) were applied using high voltages (12, 14, 16, 18 and 20) kV,with a frequency constant (22.507 kHz) and distance between the electrodes (d = 3 mm). Glass dielectric between the electrodes with thickness (2 mm) was used. Plasma parameters were calculated by measurement of plasma spectrum analysis using optical emission spectroscopy (OES) and using the Boltzmann plot method.

5. Plasma Parameters using OES

Optical Emission Spectroscopy (OES) is one of the modern method used to measure basic plasma properties such as electron temperature (T_e), electron density (n_e), Debye length (λ_D), Debye number (N_d), and plasma frequency (f_P). Plasma is produced at atmospheric pressure, therefore, nitrogen is the main gas in the ionization process, so nitrogen gas (N_2) is the main factor in the discharge of the generated plasma. Using OES and Boltzmann Plot method to calculate the characteristics of DBD Plasma. In this research two electrodes made of the Copper and Aluminum materials were used. The spectrum lines are getting by using dielectric material and electrodes made from Copper and Aluminum. The spectrum lines comparison with (NIST) standards are illustrated in Table (1).

Table 1: Spectrum Emission Data of Nitrogen Lines

Ion	λ (nm) (NIST)	λ (nm) (exp.)	$A_j.g_j$ S^{-1}	E_i (eV)	E_j (eV)	Lower Level Conf., Term, j	Upper Level Conf., Term, j
NV	315.976	315.8	3.09×10^8	84.0993	88.0220	$1S^2 5P$ $2P^o$ 1/2	$1S^2 6S$ ^2S 1/2
NIII	336.736	336.81	8.89×10^8	35.6714	39.3523	$2S^2P(^3P^o)3S$ $4P^O$ 5/2	$2S^2P(^3P^o)3P$ P^4 5/2
NII	359.359	357.5	7.26×10^7	20.9401	24.3893	$2S^2 2P^3 P$ ^3S 1	$2S^2 2P^4 S$ $^3P^O$ 2
NIII	379.297	380	7.21×10^7	38.4168	41.6847	$2S^2P(^3P^o)3P$ 4D 7/2	$2S^2P(^3P^o)3d$ $^4P^O$ 5/2
NIII	393.450	293.21	3.74×10^8	38.3277	41.4780	$2S^2P(^3P^o)3P$ 2P 1/2	$2S^2P(^3P^o)3d$ $2D^O$ 3/2

Plasma parameters for N_2 spectrum lines with a different voltage applied(12 - 20 kV) and different electrodes by using OES and Boltzmann Plot were calculated, in order to obtain the best parameters for the generated DBD plasma, which can be calculated in this research.

5.1 CopperElectrodes

The spectral analysis of the plasma produced by the spectroscopy device was studied. Spectrum lines of plasma for the Copper electrodes indicate in Figure3.

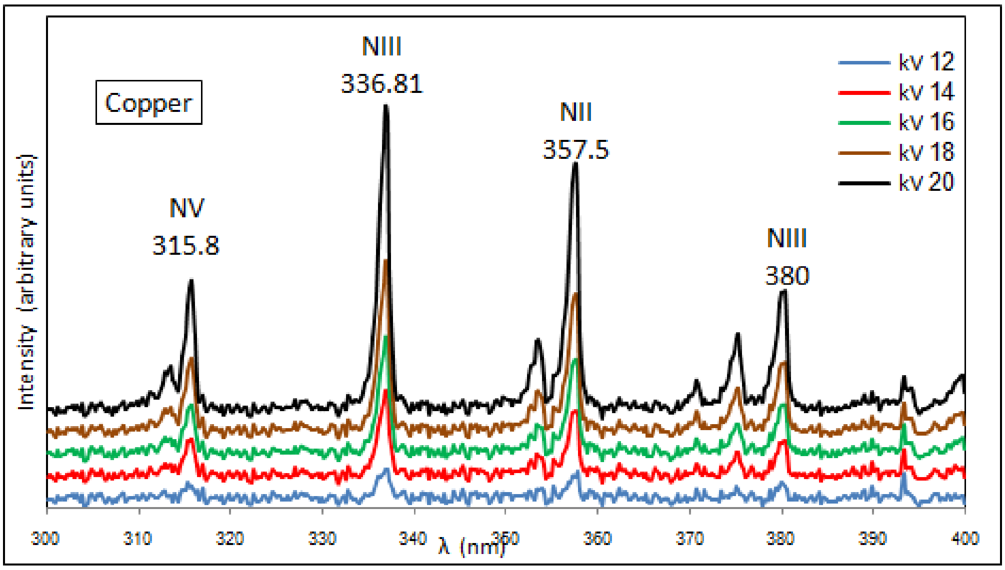

Figure 3: The distribution of the intensities of the spectrum lines with a different high voltage applied using the Copper electrode.

Figure (3) shows that the appearance of several peaks of intensities when using a different applied voltage (12-20 kV), depending on the wavelength which limited (300-400 nm). This intensities which belong to the nitrogen spectrum correspond to the data (NIST). One can observe that the high different voltage applied has a greater intensity of the same wavelength (336.81 nm), and the spectrum of nitrogen behaves the same behavior with a different applied voltage as illustrated in Figure (4).

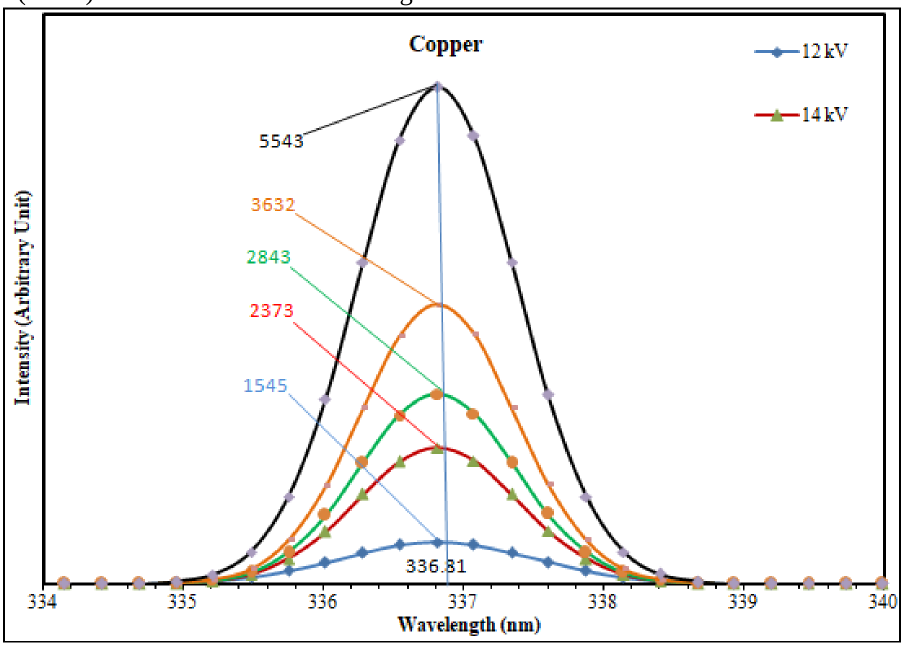

Figure (4): Variation of the highest peak intensities with wavelength for different values of the voltages applied

In Figure (4), one could note that increasing peak intensity with increasing the applied voltage this means that increasing N_2 species emission in DBD plasma. At a small value of a voltage applied there is decreasing in the intensity which may due to the saturation of plasma ionization. For top peak intensity and by plotting $\ln\left(\frac{I_{ji}\lambda_{ji}}{g_j A_{ji}}\right)$ verses E_j, the electron temperature of plasma were calculated. The temperature of the electron was calculated from:

$$\ln\left(\frac{I_{ji}\lambda_{ji}}{g_j A_{ji}}\right) = -\frac{E_j}{k_B T_e} + C \qquad \ldots\ldots\ldots\ldots(1)$$

where, I_{ji} : intensity of the emitted light from (j) to (i) levels, λ_{ji} : wave length, g_j : statistical weight of the upper level, A_{ji} : the Einstein transition probability of spontaneous emission, E_j/k_B : the normalized energy of the upper electronic level, C can be calculated by the relation:

$$C = \ln\left(hcN_j/4\pi Q(T)\right) \qquad \ldots\ldots\ldots\ldots\ldots(2)$$

Q(T) : the partition function.

$$Slope = -\frac{1}{k_B T_e} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

hence $k_B = 8.617 \times 10^{-5}\ eVK^{-1}$

The slope of the linear fitting of the resulting curve indicates in Figure (5) using equation (1). Also, electron density can be calculated by using the equation (2).

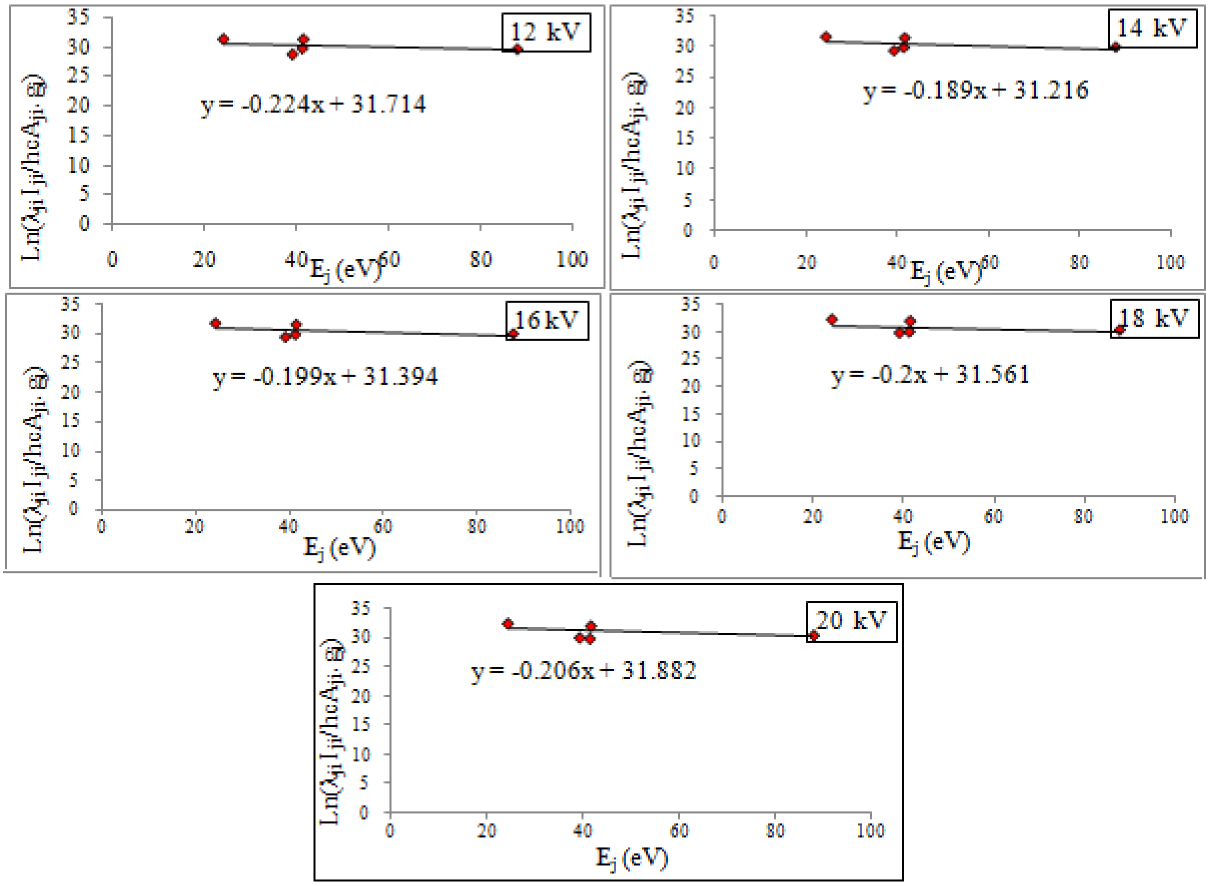

Figure (5): The Boltzmann Plot for a different values of the applied voltage

In Figure (5), T_e of the generated plasma can be calculated using the Boltzmann Plot method, through which all the parameters of the plasma can be calculated. The effect of the voltage applied on DBD Plasma parameters by using the Copper electrode can be illustrated in Table (2).

Table 2: Plasma parameters by using the Copper electrode.

V (kV)	T_e (eV)	$n_e\times10^{17}$ (cm^{-3})	f_p (Hz) $\times10^{12}$	$\lambda_D\times10^{-5}$ (cm)	$N_d\times10^3$
12	4.464	12.30	9.959	1.416	14.613
14	5.291	10.20	9.069	1.685	20.455
16	5.025	9.90	8.935	1.667	19.217
18	5.000	9.75	8.867	1.676	19.219
20	4.854	10.05	9.002	1.626	18.109

Figure (6) shows that (n_e) and (T_e) with different applied voltage, one can be noted that the increase in applied voltage leads to decreasing in n_e.

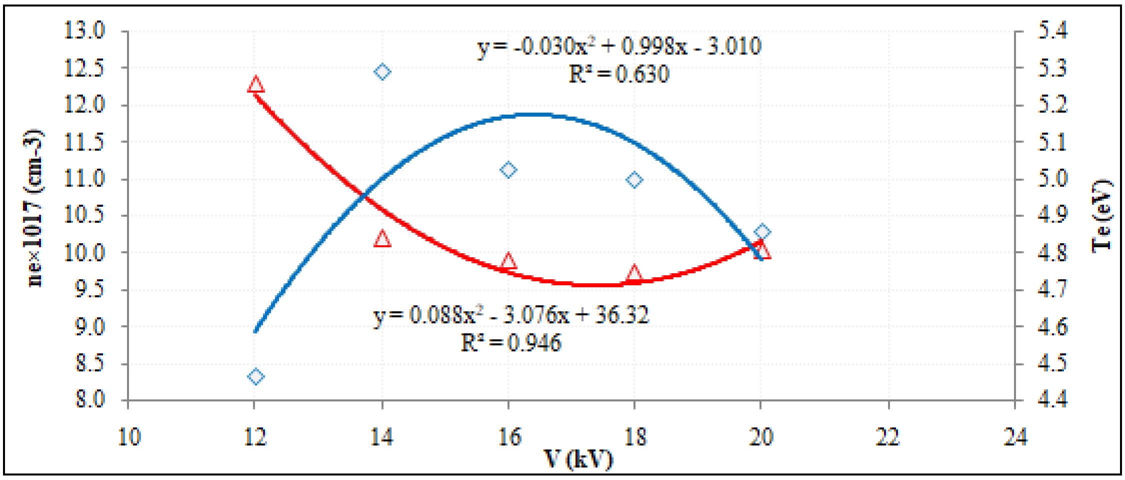

Figure 6: Electron density and temperature variation with increasing applied voltage

From Figure (6), the increase of applied voltage leads to increasing of an ionized atom this means increasing of the free electron, this means increasing of T_e. For high voltage applied, there is a decreasing in the T_e due to the saturation of gas ionization. This behavior due to the excitement of electrons and atoms. So, it causes increase the collisions between the electrons and the gas atoms. The energy transferred from the electrons to the particles of the gas increases causing an increase in the temperature of the gas by lowering the T_e. The increasing of the voltage applied causes increasing in ionized of the gas atom this leads to increasing of n_e.

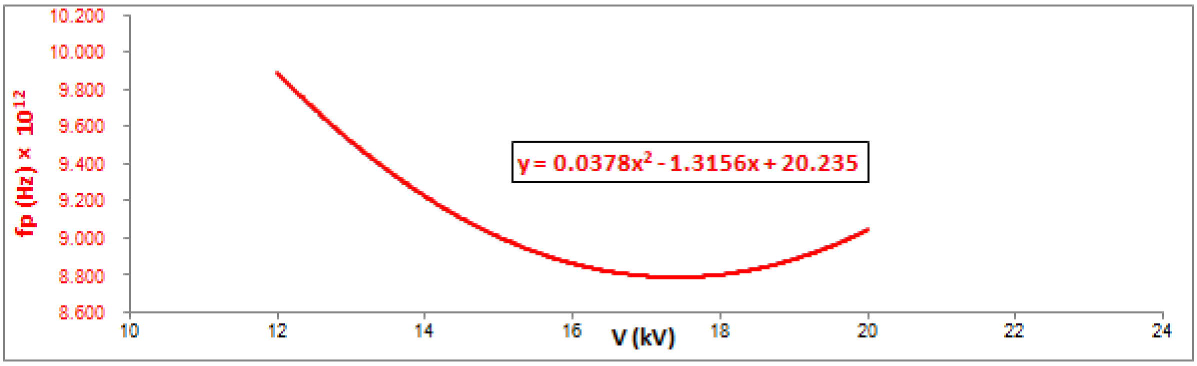

Figure (7): Variation of Plasma frequency with applied voltage.

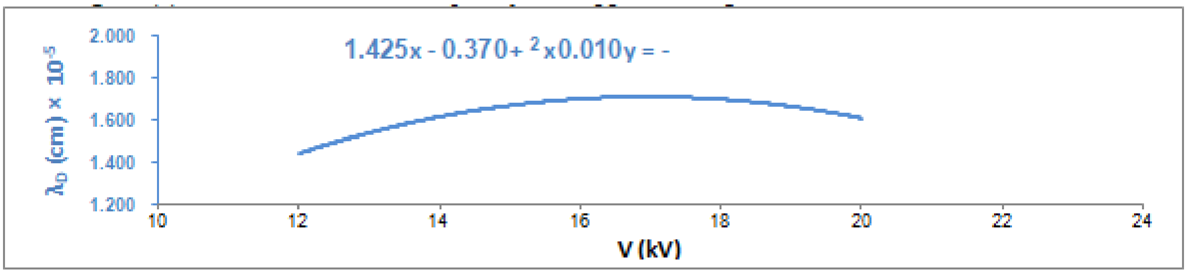

Figure (8): Variation of Debye length with applied voltage

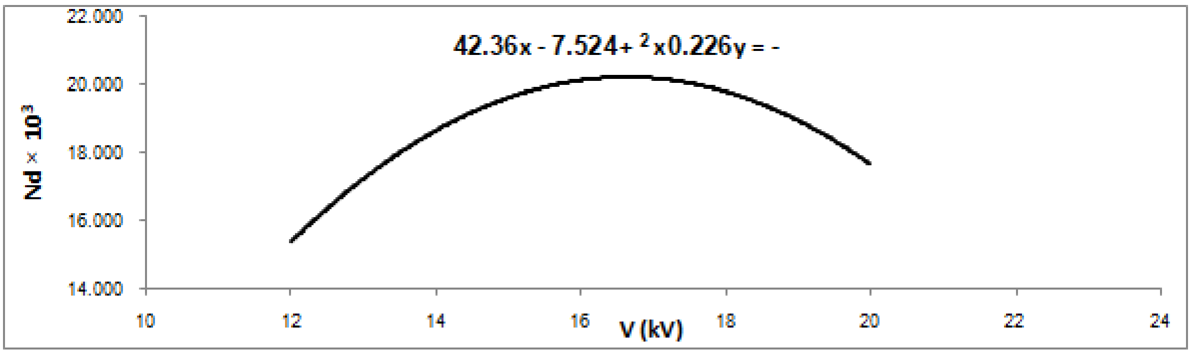

Figure (9): Variation of Debye Number with applied voltage

Figure (7), illustrates that, the plasma frequency (f_p) with applied voltage has the same behavior (n_e). it is decreasing by increase applied voltage then increases at a high applied voltage as a result of increasing in electron density because ionization stopping in the gas. Then begin increase at the highest voltage because of the gas molecules possessed higher energy, which in turn, ionizing the atoms of gas that need high energy to occur ionization.

Debye length (λ_D) variation with applied voltage illustrated in Figure (8). It is clear that increasing of Debye length with an increase in the voltage applied as a result to increase electron temperature. When the voltage applied is increased, the length of the Debye is reduced depending on the electron temperature. Figure (9) shows that the Variation of Debye number (N_d) with the voltages applied. One can note that the number of particles in the sphere of Debye increase by increasing applied voltage. The number of Debye decreases with increasing the voltage applied because the increase in the last allows the particles to leaves the Debye sphere.

5.2 Plasma Parameters using Aluminum Electrode

In this research, the electrode of Aluminum with a diameter (5 cm) and surrounding with the Teflon dielectric material with thickness (2 cm) for the down electrode and (2.5 cm) for the top electrode was used. OES was used to a distribution of the intensities of the nitrogen spectrum produced by the DBD Plasma system with a different high voltage applied can be shown in Figure (10). One can notes that, Figure (10) has the same behaviour illustrated in Figure (3) but the difference in the intensities only. When comparing the highest peak intensities of the same wavelength (336.81 nm) notes that, by using the aluminium electrode, the intensities are less than the intensities produced when using the Copper electrode. As illustrated in Figure (11). Where the highest intensity when using the Copper electrode and the Aluminum electrode.

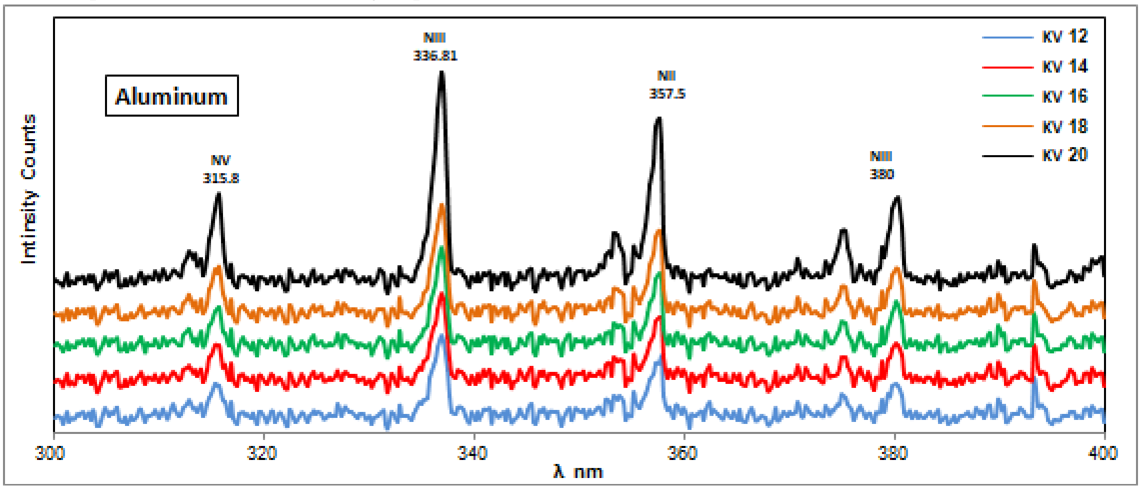

Figure (10): The distribution of the intensities of the spectrum lines with a different high voltage applied using the Aluminum electrode

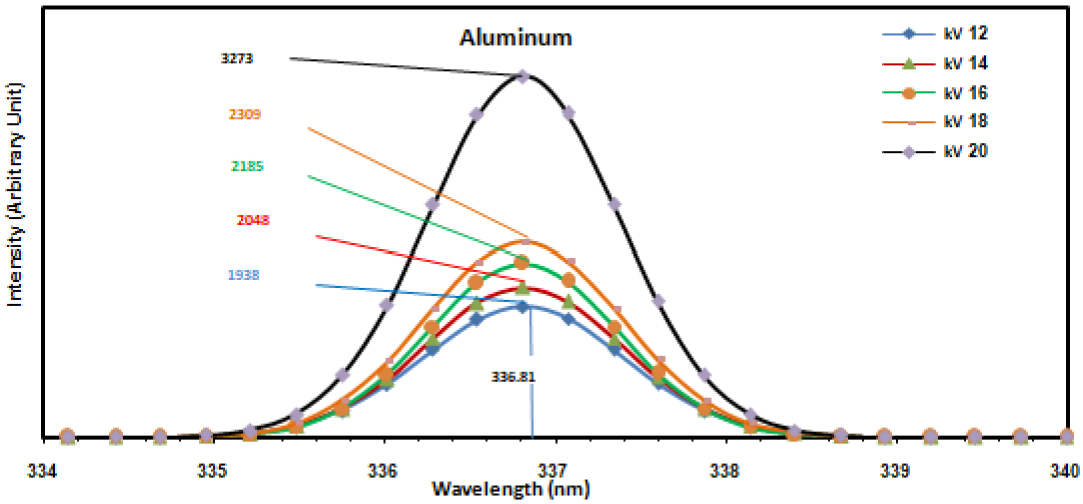

Figure (11): Variation of the highest peak intensities with wavelength for different values of the voltages applied

For highest peak intensities, and by plotting $\ln\left(\frac{I_{ji}\lambda_{ji}}{g_j A_{ji}}\right)$ verses E_j, the electron temperature of DBD plasma were calculated.

The Boltzmann Plot for calculating the electron temperature was used, as shown in Figure (12).

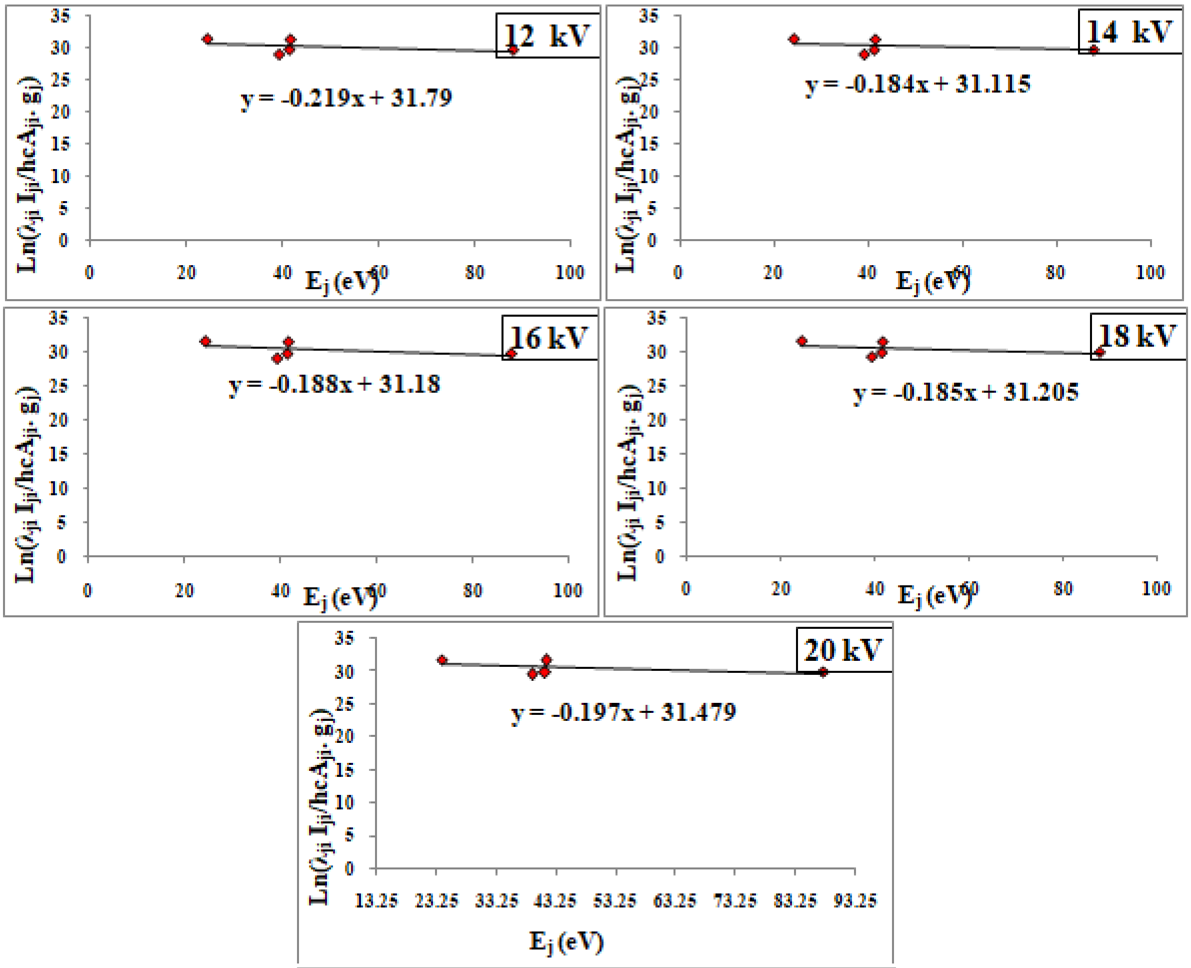

Figure 12: The Boltzmann Plot for a different values of the applied voltage

The effect of the voltage applied on DBD Plasma parameters by using the Aluminum electrode can be illustrated in Table (3).

Table 3: Plasma parameters by using the Aluminum electrode.

V (kV)	T_e (eV)	$n_e \times 10^{17}$ (cm^{-3})	f_p (Hz) $\times 10^{12}$	$\lambda_D \times 10^{-5}$(cm)	$N_d \times 10^3$
12	4.566	10.50	9.202	1.549	16.360
14	5.435	10.28	9.103	1.702	21.216
16	5.319	9.90	8.935	1.715	20.928
18	5.405	10.28	9.103	1.697	21.044
20	5.076	9.98	8.969	1.669	19.437

By the increase of applied voltage, the electron temperature was increased. This leads to an increase of ionized atoms and of the free electron. While the electron density decreases slightly when the applied voltage increases as in Figure (13).

For high voltage applied, there is a decreasing in the T_e due to the saturation of gas ionization. This behavior due to the excitement of electrons and atoms. In the other hand, the increasing of the voltage applied causes increasing in ionized of the gas atom. The plasma frequency (f_p) with applied voltage is decreasing by increase applied voltage then increases at a high applied voltage as a result of increases in n_e because ionization stopping in the gas as shown in Figure (14). Then begin increase at the highest voltage because of the gas molecules possessed higher energy, which in turn, ionizing the atoms of gas that need high energy to occur ionization. Figure (15) illustrates that Debye length (λ_D) variation with applied voltage, this clear that increasing of Debye length with an increase in the voltage applied as a result to increase electron temperature. When the voltage applied is increased, λ_D is reduced depending on the electron temperature. While Figure (16) shows that the Variation of Debye number (N_d) with the voltages applied. One can note that the number of particles in the sphere of Debye increase by increasing applied voltage. The number of Debye decreases with increasing the voltage applied because the increase in the last allows the particles to leave the Debye sphere.

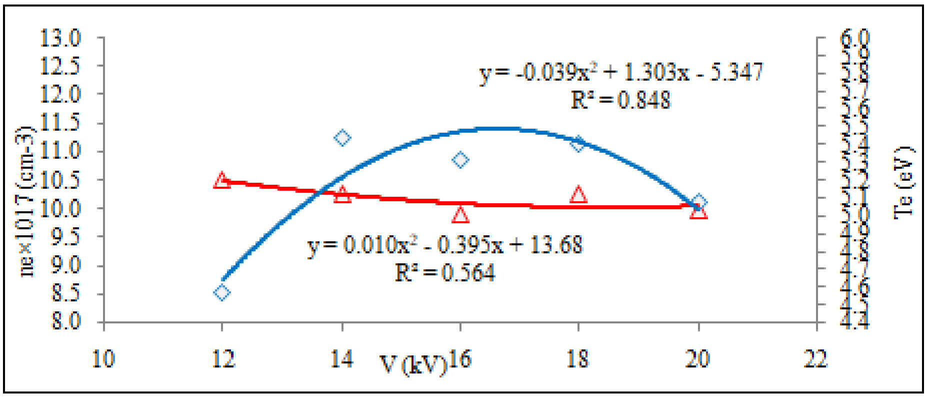

Figure 13: Temperature and density of electron with increasing appliedvoltage

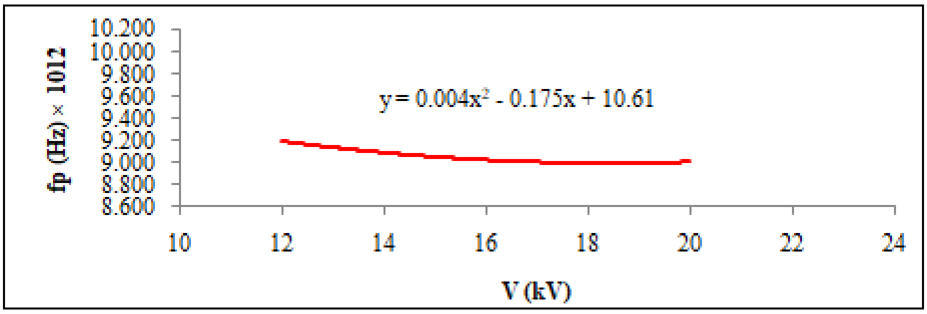

Figure 14: Variation of Plasma frequency with applied voltage

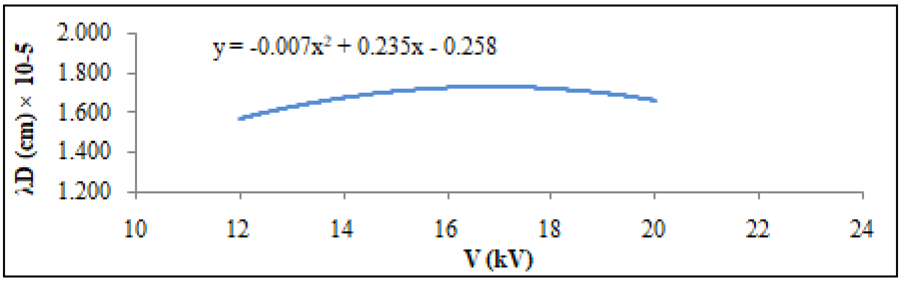

Figure 15: Variation of Debye length with applied voltage.

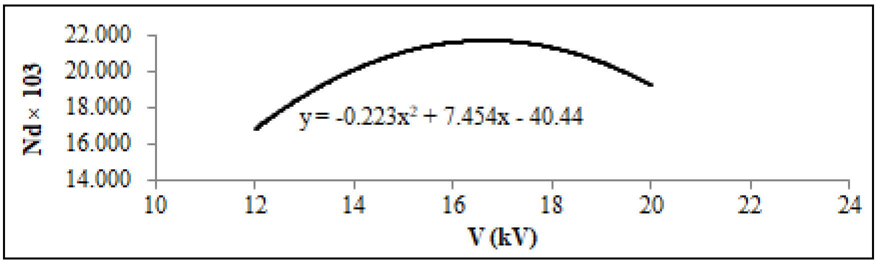

Figure (16): Variation of Debye Number with applied voltage

Plasma has recently made great progress in industrial and medical applications due to Plasma unbalanced nature with the different temperatures of ions and electrons. DBD Plasma uses to control environmental pollution, produce ozone to sterilize drinking water and treated the surface polymer to improve wettability and adhesion. So the most important methods used to modify the surface of polymers are non-thermal atmospheric plasma.

6. Conclusion

The results obtained by using two electrodes Copper and Aluminum by DBD Plasma system at (16 kV) voltage and Spectrum lines measuring by Optical Emission Spectroscopy (OES) were analyzed to calculate the plasma properties using the Boltzmann plot method, can be summarized in:

- The produced plasma is Nitrogen plasma.
- The intensity in the plasma spectrum forCopper electrode is higher than thatforAluminum electrode for the same wavelength (λ = 336.81 nm)
- The electron temperature for plasma found to be (4.46 eV) and (4.18 eV) for Copper and Aluminum respectively.
- There is no change in electron density of plasma found for both electrodes Copper and Aluminum.
- Copper electrode is better than Aluminum to produced non thermal DBD plasma.

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