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Plasma Diagnostics of Argon-Oxygen Gases Mixture using Different Applied Power in a DC Sputtering System

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ABSTRACT

Sputtering is the process of depositing thin films on the surface of a material using plasma. Plasma is created by adding extremely high energy to a surrounding gas, which turns into plasma. The plasma is directed towards the material on which you want to deposit the films, and the plasma particles interact with the material to form a thin film of the desired material. Oxygen plasma has many important applications in industry. When adding a small percentage of it, it can change the properties of the plasma significantly. In this research, the spectrum of the plasma generated from the application of different energies (175,200,250,300) watts of direct current was studied on a mixture of argon and oxygen gases in a ratio of (9: 1). The spectrum emitted from the plasma was measured Within the wavelength range (400-800) nm, the plasma parameters (Te, ne, λD, ND) were diagnosed by examining the spectrum corresponding to the applied power using optical emission spectroscopy (OES). The results showed an increase in the electron temperature and electron density with the increase in the applied power. Where the highest and lowest values for the electron temperature and density were respectively (1.645-1.305) eV, (26.03-25.36) x $10^{17}/cm^3$.

KEYWORDS: DC sputtering; Glow discharge; OES; Plasma diagnostic.

الخلاصـة

الترذيذ هو عملية ترسيب الأغشية الرقيقة على سطح مادة ما باستخدام البلازما. يتم إنشاء البلازما بإضافة طاقة عالية للغاية إلى غاز محيط، والذي يتحول إلى بلازما. يتم توجيه البلازما نحو المادة التي تريد ترسيب الأغشية عليها، وتتفاعل جزيئات البلازما مع المادة لتشكيل طبقة رقيقة من المواد المرغوب فيها. لبلازما الأوكسجين العديد من التطبيقات المهمة في الصناعة. عند إضافة نسبة صغيرة منه يمكن أن يغير خصائص البلازما بشكل كبير. تم في هذا البحث دراسة طيف البلازما المتولدة من تطبيق طاقات مختلفة (١٧٥,٢٠٠,٢٥٠,٣٠٠) واط بالتيار المستمر على خليط من غازي الاركون و الاوكسجين بنسبة (١:٩) تم قياس الطيف المنبعث من البلازما ضمن نطاق الطول الموجي (٤٠٠-٨٠٠) نانومتر تم تشخيص معلمات البلازما (T_e ، n_e ، λ_D ، N_D) عن طريق فحص الطيف المقابل للقدرة المطبقة باستخدام التحليل الطيفي للانبعاثات الضوئية (OES) أظهرت النتائج زيادة في درجة حرارة الالكترون وكثافة الالكترون بزيادة القدرة المطبقة حيث كانت اعلى وادنى قيمة لدرجة حرارة الإلكترون وكثافته على التوالي (١,٦٤٥-١,٣٠٥) الكترون فولت , (٢٦,٠٣-٢٥,٣٦) × ١٠^{17}/ سم^3.

INTRODUCTION

Direct current (DC) sputtering is a thin film deposition technique that uses ionized gas molecules to steam (sputter) molecules off the target material into plasma. DC sputtering is considered the favorite technique for electrically conductive target materials because of its low cost and high level of control [1]. The reason for the applications of Argon plasma discharges in various technological fields, there is an increasing interest in studying and characterizing Argon plasma sources [2]. Many applications of plasma physics are expected from the characterization of Argon-Oxygen plasma. This temperature range is neither close to the classical low-temperature plasmas generated in atmospheric pressure gases by for instance glow or dielectric barrier discharges (DBD) gripped by electron impacts fragmentation, ionization, and excitation [3]. Many techniques have been utilized in the diagnosis of plasma parameters [4], which we include in the following Table 1 [5][6].

Table 1. Plasma diagnostic techniques.

Technical type	Plasmas parameters
Langmuir probe	λ_D, ω_{pe}, N_D, T_e, n_e
Interferometry	=
Mass spectroscopy,	=
Thompson dispersion method	=
Optical emission spectroscopy (OES)	=

The experimental determination of the main characteristics of the considered plasma is based on new optical emission spectroscopy OES characterization tools. This technique depends on the analysis of the light emanating from spectral from the excited state to the ground state, characterized by speed and ease of implementation without contact with the plasma which may be affected by the plasma itself [7][8].

A number of researchers used the optical emission spectroscopy (OES) method to describe the argon glow discharge plasma [9][10]. The goal of multiple methods of plasma diagnosis is to better understand and control plasma.

Plasma diagnostic techniques focus on elucidating the relationship between control variables and plasma parameters [11].

Plasma Parameters

The properties of the plasma can be determined by the plasma parameters [12].

Electron Plasma Oscillation (Ω_{pe})

Plasma oscillation is the frequency produced by the collision of charged particles with neutral atoms, which causes charged particles to oscillate at a specific frequency that depends on the hydrodynamic and electromagnetic forces present. This frequency is given by:

$$\omega_p = \left(\frac{n_e e^2}{\epsilon_o m}\right)^{\frac{1}{2}} \quad (1)$$

where ne= electron density, e=elementary charge, m=electron mass ϵ_o= permittivity of free space. This frequency is often given to electrons because the frequency of positive ions is low compared to the frequency of electrons because their mass is large compared to the mass of electrons [13].

Debye Length (λ_D)

One of the important characteristics of plasma is charge neutrality. This means the negative and positive charges are balanced. If we assume that the charge density is zero everywhere inside the plasma, then there should be no electrostatic field. However, the potential is not zero inside the plasma, although it is uniform. Thus, the charged particles inside the plasma will redistribute themselves, shielding the effect of a small sphere called (Debye sphere). The Debye length is the distance over which a charge separate. It can be expressed as [14][15]:

$$\lambda_D = \left(\frac{\epsilon_o k T_e}{n e^2}\right)^{\frac{1}{2}} \quad (2)$$

where ε_0: is the permittivity of free space, k :is Boltzmann's constant, e :is the charge of the electron, n : represents the respective species, and T_e: electron temperature.

The Typical Number of Particles (N_D)

The number of particles (N_D) present in a Debye cloud can be found by assuming that this cloud has a spherical shape [16]:

$$N_D = n\frac{4}{3}\pi\lambda_D^3 \quad (3)$$

Where n=plasma density.

Electron Temperature (T_e)

The Boltzmann diagram method involves calculating the proportionate intensities of different emission lines, and the electron temperature associated with the linear fitting slope can be estimated using the following equation [17,18]:

$$ln\left(\frac{I_{ji}\,\lambda_{ji}}{A_{ji}\,g_j}\right) = \left(-\frac{E_j}{k_B T_e}\right) + C$$
$$slope = -\frac{1}{k_B T_e} \quad (4)$$

Where C is a constant, λ_{ji} is the wavelength of the emitted light, and A_{ji} is the transition probability.

Electron Density (n_e)

One of the key characteristics of spectral line broadening that provides the electron density with the known electron temperature of plasma is stark broadening [19][20]. The following relationship is used to calculate the electron density using Stark broadening:

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$$n_e = exp\, exp\,(44.2476 + 1.20\, ln\Delta\lambda - 0.6\, ln\, T_e) \quad (5)$$

Where T_e is the electron temperature and n_e is the electron number density in cm^{-3} [21][22].

Materials and Methods

DC reactive sputtering was used to create the plasma. The system includes an evacuated chamber, a titanium target as the cathode, and a disk made of the alloyTi6Al4 (one of the titanium's alloys. It is composed of 90% titanium, 6% aluminum and 4% vanadium).as the anode. An electric field is created for the gas discharge by the cathode that is facing the anode. The target (titanium) diameter is 5 cm, and the distance among the two electrodes is 4 cm. Argon gas and oxygen are combined in the same tube to produce this discharge ($Ar:O_2$, 9:1). The working pressure was equal to 4 x 10^{-2} mbar and applied sputtering power has been varied in the range (175, 200, 250, and 300) Watt.

Optical Emission Spectroscopy (OES) is a method used for optical diagnostics of reactive sputtering-generated plasma. The radiation released from the plasma is collected using a spectrometer with a spectral resolution (FWHM) of (>2.5 nm) and an optical system that includes a spectrophotometer and optical fiber that is coupled to collecting lenses (K-MAC Spectra Academic- Korea Material and Analysis group). as a shown in Figure 1.

Results and Discussion

The variation in the power, and plasma characteristics of a glow discharge in the (Ar/O_2) gas mixture was the subject of this paper. The Spectrum of plasma as a function of the applied sputtering power, the SCDP contains intensities of plasma spectrum, electron temperature, and electron density. Spectroscopic data are shown in Table 2. According to the (National Institute of Standards and Technology Atomic Spectra Database) (NIST) [23].

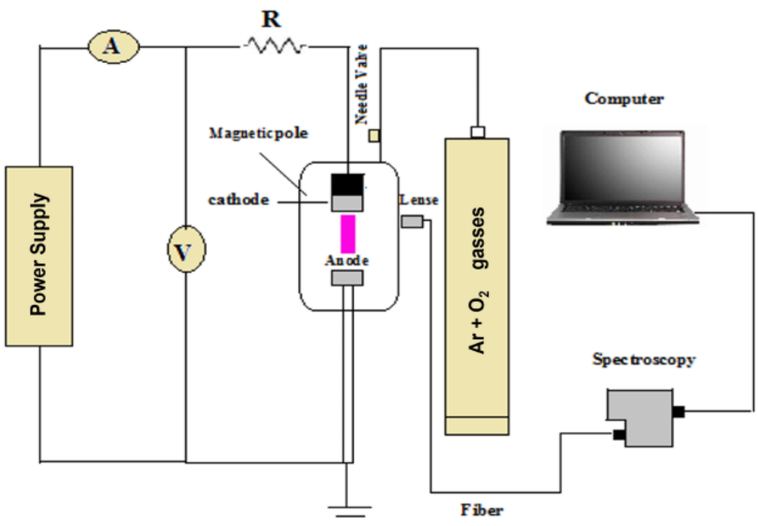

Figure 1. System for Plasma Diagnostics and DC Sputtering Experiment.

Table 2. Ar line spectroscopic data utilized in the Boltzmann plot method

Species	Wavelength (nm)	A_k x10^6(s^{-1})	E_k (ev)	g_k
AII	417	4.80E+06	19.6103	4
AII	424.8	2.00E+05	18.734	6
AI	694.68	3.08E+06	13.172	1
AI	747.786	2.20E+04	13.2826	3
AII	807.524	1.40E+05	14.8388	5
AI	837.551	2.40E+05	14.7805	7

Spectrum of a typical Argon discharge plasma obtained under previous operational circumstances (The working pressure was equal to 4×10^{-2} mbar and applied sputtering power has been varied in the range (175, 200, 250, 300 Watt) is shown in Figure 2. It is evident that the intensity of spectral lines of: ArI and ArII increases when the sputtering power is increased. The electron-neutral impact excitation rate will rise as the power is increased since this increases the ionization level and electron energy. By striking other particles, the electron excites them and transmits energy to them. Atoms and ions emit spectral lines by de-excitation.

Electron temperature T_e was calculated by using Equation (4) for different applied sputtering powers. Figure 3 shows Boltzmann plot method for several spectral lines that illustrates the relationship between different sputtering powers (P) and the electron temperature T_e (eV). It demonstrates an increase in electron temperature T_e as sputtering power is increased. This fact can be clearly justified by Table 3. In this table, the variation of the electron temperature with applied sputtering power under constant pressure. It is evident that the electron temperature rises, which is explained by an increase of electron-argon atom collisions. which is because the electric field increases, and the acceleration and momentum of the electrons increases, with increased applied sputtering power. The increasing of T_e leads to increases in the values of the Debye length and the number of electrons.

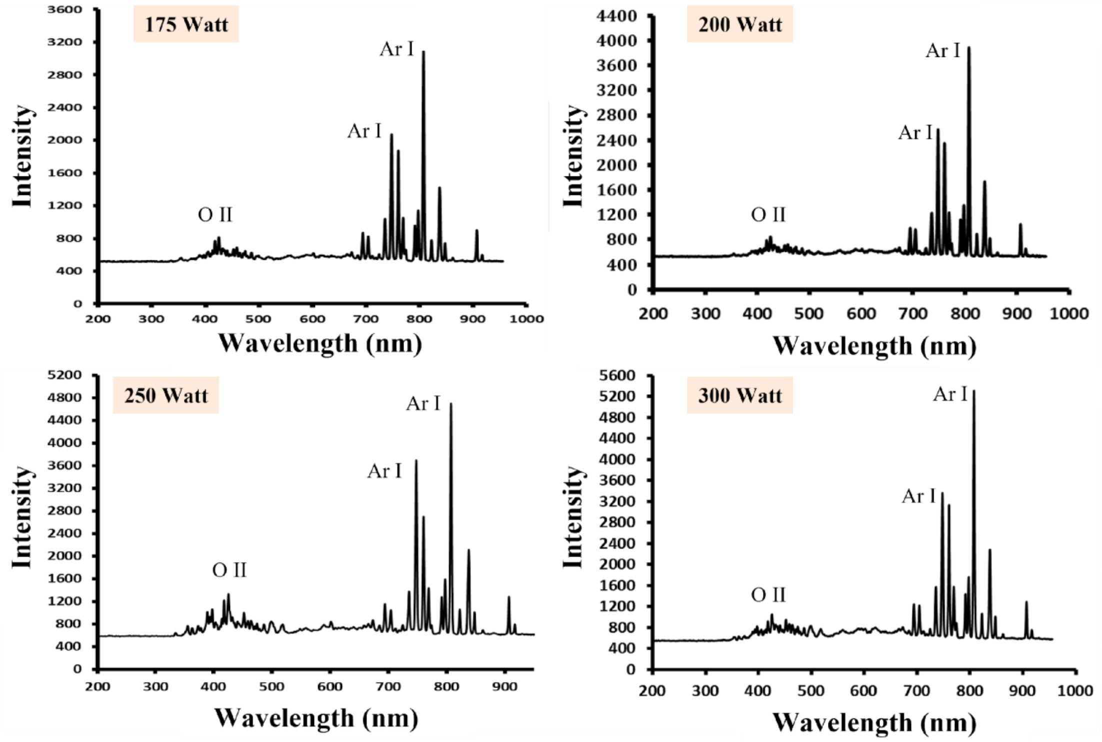

Figure 2. The spectra intensity of Argon plasma with different sputtering power.

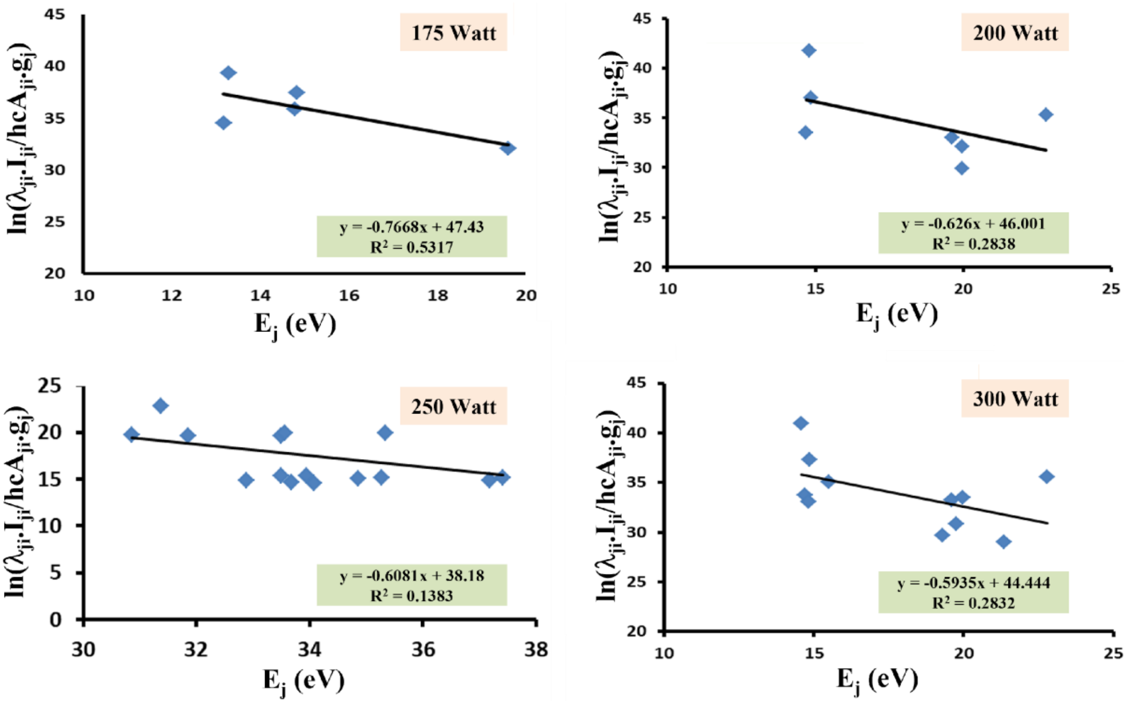

Figure 3. The electron temperature for different values of Sputtering power.

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Table 3. The plasma parameters for different sputtering power.

P (watt)	T_e (eV)	$n_e \times 10^{17}$ (cm^3)	$f_p \times 10^{12}$ (Hz)	$\lambda_D \times 10^{-5}$ (cm)	$N_d \times 10^3$
175	1.304	25.36	14.300	0.533	1.607
200	1.597	25.70	14.397	0.583	2.138
250	1.645	26.03	14.487	0.588	2.219
300	1.685	26.31	14.566	0.592	2.289

Equation 5 used to count the plasma electron density (n_e) using stark broadening. Figure 4 demonstrates that the electron (n_e) density rises with an increment of applied power. This observation has the following explanation:
The increase of sputtering power leads to excess; the cathode emits more electrons, and the energy of those electrons also rises. The electron exerts its energy by interacting with other particles and exciting them, which results in the production of new free electrons and positive ions, hence the incrementing in the ionization processes leads to the excess density of electrons. In addition, the electron density increases with increasing applied power. This is consistent with earlier studies [24-26].

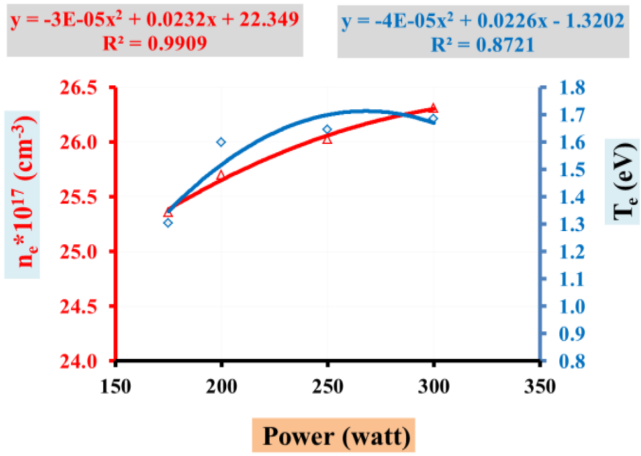

Figure 4. Variation of electron temperature and electron density with applied power.

CONCLUSIONS

In this study, an (Ar/O2) plasma was generated with a ratio of 9:1. The manipulation of the DC power supply system within the range of 175 to 300 Watts resulted in heightened intensity of the plasma spectrum. Specifically, the intensity value of the primary spectral line at 807.524 nm exhibited an escalation from 3100 counts at a DC power supply of 175 Watts to 5000 counts at 300 Watts. Concurrently, an elevation in plasma temperature was observed with the augmentation of the DC power supply. Furthermore, a marginal increase in Debay's length was noted as the DC power supply for the system was increased.
The gradual augmentation of the DC power supply system, ranging from 175 to 300 Watts, induced an elevation in the densities of both electrons and ions. This increment signifies a potential amplification in the sputtering process of the target material.

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