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Electron Temperature Measurement of Argon Capacitive Coupling Plasma by Optical-Emission Spectroscopy

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Abstract

The study of electron interaction with the electric field in low temperature plasmas is a current area of research with various practical applications. Specifically, in the context of low pressure (< 1 mtorr), electrons can travel distances comparable to the size of the reactor without experiencing collisions. The primary objective of this work is to investigate the basic physics of electron behaviors in an argon discharge at low pressure regime. The main aim of the current study is the investigation the electron temperature (T_e). Optical emission spectroscopy was used as diagnostic tool to find the electron temperature based on line ratio method. The link between the fundamental plasma parameter (T_e) and its spatial dynamics is analyzed. The study also looks into how the T_e is affected by the input plasma radio frequency power throughout the electrode distance.

Keywords: Electron Temperature (T_e), Capacitively Coupled Plasma, RF Discharge.

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Introduction

The capacitively coupled plasma (CCP) technique uses a high frequency AC voltage to produce a homogeneous and controllable plasma. Its efficiency and flexibility are demonstrated by the wi range of scientific and commercial applications to which it can be applied. As plasma technology advances, capacitively coupled plasma systems are expected to be important in stimulating grow and innovation across multiple fields. [1]. Owing to its affordability, simplicity of usage, and ability to produce uniform plasma over large regions, this kind of plasma generation is frequently use There are several advantages to capacitive coupling in plasma applications. In the microelectronic and semiconductor industries, it is helpful for procedures like thin layer deposition, surface cleaning and etching since it first makes it possible to generate a very homogeneous and controllable plasma discharge. Because of the plasma's homogeneity, its density, temperature, and chemistry can carefully controlled, producing results that are reliable and reproducible. Moreover, systems using capacitive coupling plasmas can operate at low pressures, usually between a few milli-torr and a few hundred milli-torr. This low-pressure operation reduces the possibility of unintentional interaction with air pollutants through efficient plasma creation. Its compatibility with vacuum systems at relatively low operating pressure makes it suitable for integration into existing vacuum-bas operations. Capacitively connected plasma finds applications in many different industries, include chemical vapor deposition aided by plasma, surface modification, and biomaterials processing. It preferred for usage in both industry and research because of its versatility, ease of use, and ability create [2,3]. For example, in the semiconductor sector, optimal radio frequency etching processes control is needed for the production of Nano scale size architectures for integrated circuits, which requires the formation of high-quality high-aspect-ratio trenches [4]. For the purpose of forming high caliber layers on a substrate, radio frequency sputtering and plasma-enhanced chemical vapor deposition (PECVD) are becoming more and more important. Among other purposes, these process are required to create passivation layers within a trench in order to prevent sidewall etching [5, 6] order to perform atomic layer etching (ALE) and atomic layer deposition (ALD), it is essential effectively control the different types of particles' energy distribution. Apart from the plasma volume surfaces on which the process takes place also require management. To improve these processes bas on information, a detailed knowledge of the spatiotemporal behavior of various species with capacitively coupled radio frequency (CCRF) plasmas is necessary. Various atmospheric pressure micro-plasmas, such as micro-atmospheric pressure plasma jets and some forms of dielectric barrier discharges, can be operated at radio frequencies by capacitive coupling. [7,8]. In all of these systems, knowledge-based distribution function management based on fundamental insights of the spatiotemporal particle dynamics is required to better applications like sterilization and cancer treatment. It is usually necessary to optimize the production of process-relevant radical densities for this. However, plasmas used in the aforementioned applications typically have strongly non-equilibrium neutral and charged constituent velocity and energy distributions which are called plasma properties [9,10]. The plasma radiation spectrum can be examined to determine these plasma properties. As a non-intrusive diagnostic method, optical emission spectroscopy (OES) has been used to determine the electron temperature and describe the chemical composition [11,12]. A significant amount of chemically reactive species can be produced as a result of electron impact processes in gas phase activities in low-temperature plasma processes where the electron impact reaction is predominantly.

Low-pressure capacitively coupled plasma CCPs have received a great deal of research attention and are used widely in technology today for ion sources, illumination, and the processing of materials. Due to the significance of the argon gas in many low-temperature plasma applications, it was selected as the test gas in the current study. In addition to that, the argon gas has a simple gas-phase chemistry. The vast body of literature that already exists on describing argon plasmas, and the accessibility of data on electron impact cross sections. When employing the optical emission spectroscopy (OES) approach to determine the electron temperature (T_e) and electron density (n_e), the commonly used method is the line-ratio methodology. To begin, a population model is constructed to consider the main processes responsible for creating and depleting a specific pair of excited levels that emit light. For these levels and other pertinent species, this model also provides a set of rate balance equations. By utilizing this model, one can determine the density ratio between these two levels. The density ratio relies on both the operational factors (such as pressure and plasma dimensions) and plasma parameters (such as electron temperature and electron density). Using the operational parameters that are known, one can extract the plasma parameters by comparing the expected density ratio with the measured emission intensity ratio. These line-ratio methods are frequently used for a variety of low-temperature plasmas with pressures ranging from very low to very high.

Experimental Setup and Discharge System

A typical setup of capacitively coupling plasma system is shown in Figure 1. The system consists of two circular-surfaced flat electrodes that are placed parallel to one another inside of a vacuum chamber. Pure Argon gas is introduced at a specific location on the chamber surface, and the gas flows through the gap between the electrodes before being removed by a vacuum pump. Throughout the measurements, the Argon gas pressure is maintained at a constant value of 3 mtorr. The distance between the circular electrodes, one being the power electrode and the other being grounded, is 10 cm, with each electrode having a diameter of 5 cm.

The first electrode remains connected to the ground while the second electrode is coupled to an RF generator using a blocking capacitor and a matching unit. The RF power is coupled into the plasma discharge using the matching network unit to ensure impedance matching between the plasma and the RF generator. In this setup, a typical RF frequency of 13.56 MHz is used, with RF powers ranging from 15 W to 65 W. To drive the plasma, a sinusoidal RF voltage with an amplitude of 200 V is applied to the driven electrode. The blocking capacitor plays a crucial role in the RF circuit by preventing the flow of DC current and compensating for any self-bias voltage that may occur due to discharge asymmetry in the plasma.

The area between the electrodes is the most crucial component of such a CCP discharge. The center of the discharge produces a quasi-neutral plasma bulk. In this area, the majority of gas phase chemistry takes place (ion, radical, and other molecule production). Two positively charged layers, known as plasma sheaths, appear in front of the electrodes. Positively charged particles (ions) are accelerated toward the nearby electrode in these regions by an electric field whereas negatively charged particles (mostly electrons and occasionally negative ions) are maintained in the bulk by the field.

To investigate the plasma parameters along the distance between the electrodes using OES, an electronically monitoring of the excited species was achieved using a laboratory made optical spectrometer. The spectra in the range of 0.6 μm to 1μm was recorded immediately after the plasma ignition.

Results and Discussion

When a certain amount of power is applied to gas under low-pressure a light emission can be observed as a result of de-excitation processes. Figure (1) depicts the spectral patterns that result from an ongoing discharge of argon gas in the vacuum cell. These patterns can be used to locate the argon spectral lines, which can then be calculated by comparing them to the global spectra. The (Ar) gas exhibits a number of molecular peaks in the region of wavelengths from 600 to 1000 nm. The interaction of the electron with the electric field results in an increase in electron energy, which causes the peak intensity to rise proportionately to the applied voltage. The electron configuration of argon's ground state is $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6$, often known as $3p^6$. For these configuration of electron, the total angular momentum J = 0. Figure 1 shows how transitions between the excited states primarily control plasma emissions. The first excited configuration, represented by the notation $3p^5$ 4s in Paschen's notation, has four levels: $1s^2$, $1s^3$, $1s^4$, and $1s^5$, with corresponding values of J of 1, 0, 1, and 2, respectively. The excitation and radiation processes essentially depend on the value of J, even if the Paschen notation enables the identification of certain levels within a setup. The only radiative decay paths allowed by dipole transitions for the 2px levels are transitions to the 1s level [13]. Figure 1 displays the wavelengths associated with each of these lines, which span a range of 696.4 to 811 nm.

In the present work, broadband fiber optics were employed to direct optical emissions along the plasma volume into the spectrograph's entrance slits. Although emission spectra in the 650–900 nm range were acquired, the study provided here only uses the $2p_x\ 1s_y$ emissions in the 650–820 nm range.

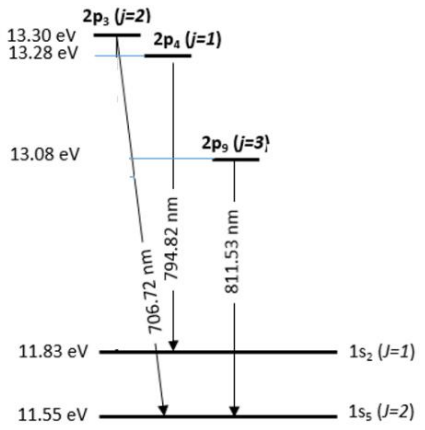


Figure 1: The Ar species' Partial Energy Diagrams Utilized in the Line-ratio Methods

To explain argon plasma emissions, a modified zero-dimensional corona model is used. The ground state and the persistent $1s_y$ levels are the main sources of excitation for the $2p_x$ levels, according to this hypothesis. On the other hand, excitation loss only occurs through radiative decays for excited 2p levels. Additionally, the model takes into account radiation reabsorption and radiation trapping, which function as modified mechanisms for filling the $2p_x$ levels. In the context of our application, we use this model to look at emissions coming from the plasma volume's center. The model is considered zero-dimensional as it does not explicitly consider spatial variations in the number densities. Nevertheless, by incorporating radiation-trapping effects that are influenced by the spatial distribution, the model can be extended to explain emissions originating from any specific volume element within the plasma. In low-temperature argon plasmas, the primary mechanism for atom excitation is the collisions between the grounded state atmos and appropriately energetic electrons. The excited species produce a variety of emission lines that correspond to their (known) transitions between various electronic states in a certain wavelength range. According to Suzuki and Nobata [14], the intensity of such radiation can be determined by,

$$I_1 \alpha h v_1 A_1 n_1 \; \alpha \, h v_1 A_1 n_{Ar} n_e \, \sigma(E) \qquad (1)$$

where I_1 is the initial transition's radiation intensity and v_1 is the transition's rate (frequency). The likelihood of changing from the excited state to a lower state, A_1, is 1. While the electron and argon concentrations are n_e and n_{Ar}, respectively, and the excitation cross section is (E), the density of excited Ar atoms excited to state 1 is n_1. By assuming that the electrons in plasma have a Maxwell-Boltzmann energy distribution, one can get the mean electron temperature kT_e from equation (2) by comparing the relative emission of two emission lines, I_1 and I_2.

$$\ln\left(\frac{I_1}{I_2}\frac{C_2 v_2 A_2 (E_2 + 2kT_e)}{C_1 v_1 A_2 (E_1 + 2kT_e)}\right) = (E_2 - E_1)/kT_e \qquad (2)$$

where C_i is constant relating the corresponding excitation cross sections, I_i is the intensity of emission line and the subscript i represents the specific transition. The value of kT_e can be computed from the emission spectra under the assumption that C_2/C_1 is equal to 1 [15]. The base of chosen emission lines is selecting the lines in the same range of wavelength to prevent overlapping with the emission lines from other plasma species. This is due to the challenges of sensitivity and adsorption.

Plasma species are promoted to higher energy levels by interactions with electrons during radio frequency (RF) discharges. They then emit photons with particular energies and wavelengths to return to lower energy states. If the concentration of metastable states in the discharge is kept to a minimum, it is possible to establish a precise link between the intensities of emission lines and the population densities of the associated excited states. However, several groups of electrons are involved in the electron impact excitation process, each associated with different energy thresholds, if the excitation energies necessary for electrons to transition vary. Any fluctuation in the emission intensity-ratio implies a change in the emission intensity since the EEDF varies along with the vibrational and electron temperatures. When there are numerous metastable phases, the analysis gets more challenging. Figure 2 displays the spectra at various locations along the electrode distance. It is clear that the most common emission lines are those at 696.4, 706.7, 738.4, 747.1, 772.3, 794.8, and 811.4 nm. The electronic transition characteristics of these lines are summarized in Table 1.

Table 1: Argon Electronic Transition Characteristics [16]

Transmission line number (arbitrary)	λ (nm)	Tranission probability 10^{-6} (s)	Upper energy level (eV)	Lower energy level (eV)	Tranission
1	696.4	*6.4*	*13.32*	*11.55*	$2P_2 \rightarrow 1S_5$
2	706.7	*3.9*	*13.30*	*11.55*	$2P_3 \rightarrow 1S_5$
3	738.4	*1.8*	*13.30*	*11.62*	$2P_2 \rightarrow 1S_4$
4	772.3	*11.6*	*13.15*	*11.55*	$2P_2 \rightarrow 1S_3$
5	811.8	*33.1*	*13.08*	*11.55*	$2P_9 \rightarrow 1S_5$

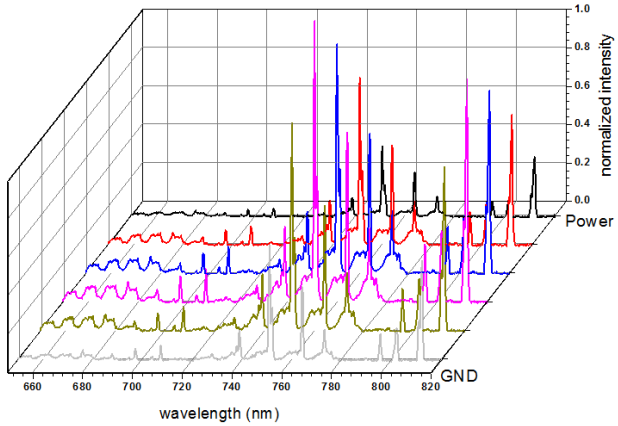


Figure 2: Emission Spectra of RF Ar-discharge along the Distance between the Electrodes at Power of 45 W Gas Pressure of 3 Mtorr

Figure 3 shows the results of electron temperature T_e measurements along the distance between the electrodes at the discharge power of 45 W obtained by the line-ratio method. It can be seen that the electron almost constant (~2.2 eV) along the distance between the electrodes with a noticeable increases to 3 eV close to the powered electrode. This can be ascribed to the relative high electron energy at the anode sheath region. The electron temperature is comparable to what was measured by Langmuir probe technique achieved by others for the similar type of plasma system [17].

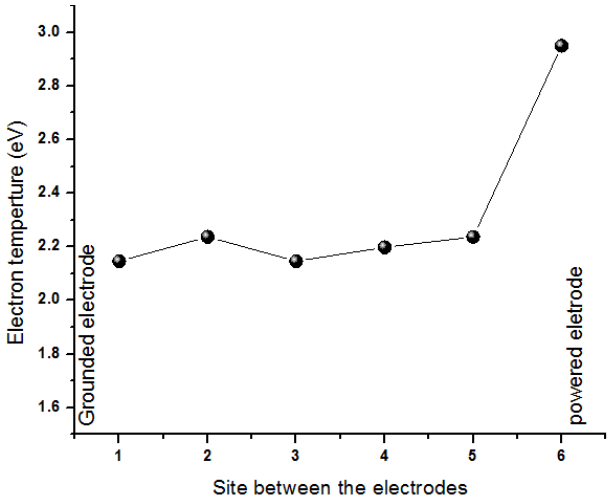


Figure 3: Electron Temperature T_e Measurements along the Distance between the Electrodes

Figure 4 illustrates the positive correlation between RF power and electron temperature. This relationship arises from the increased energy transferred to the electrons during collisional processes, which they subsequently transmit to the plasma species at higher RF field values and input power. The population states, which are the excited state that produce light rises as a result of collisional processes, increasing the intensity of the emitted lines. Multi-stage excitation or de-excitation rarely occurs in this situation. The relationship between the population density of the upper states which involved in the optical emission process and the electron temperature is direct.

Through interactions known as inelastic collisions, electrons with high energies exceeding the excitation thresholds actively participate in exciting or ionizing species within the plasma. The link between electron energy and density is described by the excitation rate coefficient. As a result, as the RF power is increased, more ion-electron pairs and excited plasma species are created as a result of collisions between plasma particles and high-energy electrons in an inelastic collision process. The dissipation of electron energy during these collisions leads to a significant cooling effect on the electrons and reduces the high-energy portion of the electron energy distribution function (EEDF). Nevertheless, despite the cooling effect on electrons, higher RF power levels result in an increase in both electron temperature and electron density. This is caused by the ongoing RF power absorption, which makes up for the electrons' energy loss. As a result, higher levels of electron density and temperature are maintained overall.

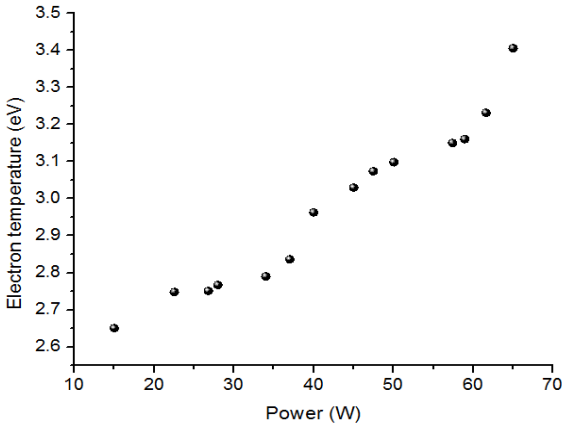


Figure 4: Variation of Electron Temperature T_e with RF Power

Conclusion

In the present study, RF argon plasma is created at a constant frequency of 13.6 MHz, and its properties are examined using OES (optical emission spectroscopy) technique. The emission intensity of specific spectral lines was examined to determine the electron temperature (T_e) along the electrode distance while keeping other relevant parameters constant, with radio frequency power ranging from 15 to 65 W. The experimental results revealed that the electron temperature remained relatively constant along the electrode distance, except for a noticeable increase near the powered electrode due to the formation of the anode sheath. The findings indicated that T_e increases as the radio frequency power increases. This is due to the electronic excitation becomes more prevalent, which is more sensitive to high-energy electrons than vibrational excitation. As the RF power increases, the number of low-energy electrons that cause vibrational excitations decreases due to changes in the electron energy distribution function (EEDF) towards higher energies. Consequently, the vibrational temperature decreases relative to the electron temperature.

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