Study of Neon-Argon Plasma for metastable states and electron temperature measurement

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شروع اللہ رحمن اور رحیم، اور ہم سب کے درمیان سب سے زیادہ خود مختار کے نام کے ساتھ .

Beginning with the name of ALLAH, The Most Beneficent and The Merciful.

CERTIFICATE

This is to certify that the Dissertation entitled "**Study of neon-argon plasma for metastable states and electron temperature measurement"** by Shehbaz Hassan submitted to Quaid-i-Azam University, Islamabad for the degree of Master of Philosophy (M.Phil.) in Physics is a record of Bonafide research carried out by him in industrial plasma physics Laboratory, under my supervision. I believe that this Dissertation fulfills the part of requirement for the award of Master of Philosophy. The result embodied in the Dissertation has not been submitted for the award of any other degree.

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DEDICATED TO

My Hero my Father, Supportive Mother, Loving Sisters, Wife and specially my cute baby girl.

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All praises to Almighty **ALLAH,** the most Merciful and kind who enabled me to complete my research work successfully. I also offer my humblest thanks to His last prophet **Muhammad** (Peace Be upon Him) who is a source of guidance, inspiration and knowledge for the humanity.

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Shehbaz Hassan

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Abstract

The behavior of neon-argon intensity of the selected emission spectral lines is measured using Optical Emission Spectroscopy (OES). The intensity of spectral lines of neon is 640.2 nm which shows a decreasing trend when the fraction of argon is added. The intensity of spectral line of argon is 811.2nm shows increasing trend when the concentration of neon is added in argon. The second step of this research work is to investigate the effect of Argon fraction variation on Neon discharges. The experiment was performed for the different pressures 2 Pa, 6 Pa, 12 Pa while RF power is varied from 5 watt to 100 watt with an increment of 5 watt. The argon concentration within the neon discharges for each power and pressure varies from 0 to 100 % with an increment of 20 %. It is observed that measured electron temperature (T_e) and excitation temperature (T_{exc}) shows a decreasing trend with an increase in RF power and argon concentration due to the ionization cross-section atoms of ionization potential.

Chapter 1

INTRODUCTION

1.1 Definition of Plasma

A liquid often forms when a solid is heated to a point where the thermal motion of the atoms causes the crystal lattice structure to disintegrate. A gas is formed when a liquid is heated to the point where atoms evaporate from the surface more quickly than they condense. A Plasma forms when a gas is heated to a point where atoms collide and lose their electrons as a result, becoming the so-called "fourth state of matter"[1].

In 1929 Irving Langmuir and Lewi Tonks both are American scientists described glowing ionized gas produced by the electrical discharges in a tube. [2].

The definition of plasma is "A disorganized mixture of neutral particles, ions, and electrons with a high level of microscopic activity" [3]. Plasma simply defines "Quasi-neutral gas of charge and neutral particles which shows collective behavior" [4].Quasi-neutrality and collective behavior is the properties of plasma .These two properties must be necessary for the existence of plasma. Collective behavior means that plasma species would move depending on local concentrations and on the state of plasma in remote regions [4]. The collective behavior also refers to columbic interaction between neighboring particles due to the electric field form. Plasma is charged particles as these charged particles generate electric field. Electric currents are produced due to motion of charged and produced magnetic field.

Word of quasi neutrality comes from Latin which means "resembling" [4]. In plasma Quasi neutral means that plasma is overall neutral. It means that negative charge density corresponds to positive charge density.

$$n \cong n_e \cong n_i \tag{1.1}$$

Where n_i and n_e represent an ion and electron density respectively, and n is a Plasma density [1].

1.2 Existence of Plasma in Nature

It is said 99% of the universe in plasma state, on which only 1% is on the earth. There is a certain amount of plasma in the sun, stars, space, and planets in the universe [1].

1.2.1 The Sun and its Atmosphere

The sun is composed of 92% hydrogen, 7.9% helium, and 1% other gases, that is why the sun is called ball of gases. The sun is closer to the earth than all other planets. Ionizing radiation from the sun goes deep into the earth's atmosphere. The solar atmosphere is split into three parts. The photosphere is the lowest layer and has the color of the sun atmosphere, in this region most energy is emited. This is the layer of the sun from where the light comes toward the earth. Another layer which is red in color is called chromosphere. It appears red when the hydrogen is ridiculously hot, and it lies between the photosphere and corona [2]. Corona is the outermost layer of sun atmosphere, it is also known as the solar corona. Corona is the hottest part of the sun in which the gases present are ionized.

1.2.2 The Solar Wind

The solar wind is a stream of charged particles released from the upper atmosphere of the sun, called corona. This plasma mostly consists of electron, proton and alpha particles with kinetic energy 0.5 to 10 keV. The composition of the solar wind plasma includes a mixture of material found in the solar plasma: trace amounts of heavy ions and atomic nuclei of elements such as carbon, Nitrogen, oxygen, silicon and iron. Superimposed with the solar-wind plasma is the interplanetary magnetic field. The solar wind varies density, temperature and speed over time and over solar latitude and longitude. Its particles can escape the sun gravity because of their high temperature of the corona, which in turn in a result of the coronal magnetic field [5].

1.3 Types of Plasma

There are two types of plasma one is hot plasma and other is called cold plasma.

1.3.1 Local Thermodynamic Equilibrium (LTE)

In LTE (hot temperature) discharges chemical process and conversion are succeeds by particles collision, despite this, there is no correlation between radiative interactions. And the mechanism of collision particle in thermal plasma is micro-reversible which means that every forward process whose excitation /de-excitation and kinetic energy are equal. Laboratory plasma that has high density and low temperature are often described by LTE model. For LTE must be satisfied condition for plasma [6].

$$n_e\,(cm^{-3}) \geq 1.6\times 10^{12} T_e^{1/2} \Delta E^3 \qquad (1.2)$$

T_e denotes electron temperature, n_e known as electron density and ΔE is the energy difference. Electron temperature and energy difference in eV between radiative states. The electron temperature and gas temperature are the same in LTE plasma.

1.3.2 ΔΔΔ Non-Local Thermodynamic Equilibrium (Non-LTE)

Non -LTE a vital temperature variance exists between the other large particle like neutrals, ions etc. The temperatures of light particles are greater than heavy particles because the ions and neutrals are closely at room temperature, but the lighter particles are approximately 10,000k. The rate of collision of de-excitation by electron is less than the rate of collision excitation induced by electron, but radiative power of de-excitation is eminent. The electron thermal velocity is greater than ions in non -LTE plasma [7].

1.4 Fundamental processes in Plasma

There are following fundamental processes of plasma ionization, excitation and electron loss.

1.4.1 Ionization Process

Ionization is a process in which electrically neutral atoms are converted to charged atoms. Therefore, ionization is a necessary mechanism in plasma, what changes due to the reaction. It can be divided into direct impact of electrons, stepwise, beam of high energy electrons, photoionization, ionization of surface atoms, and penning ionization.

In direct impact ionization, when high energy electrons directly interact with the electron of outermost shell of atoms/molecules and ionize it. This process takes place when an electron having energy greater than the ionized neutral particles. For a diatomic molecule, these reactions take place [8].

$$e + PQ \rightarrow PQ^{+} + e + e \quad (1.3)$$

$$e + PQ \rightarrow P + Q^{+} + e + e \quad (1.4)$$

$$e + PQ \rightarrow P + Q^{*} + e + e \quad (1.5)$$

In equation (1.3) the electron interacts with PQ molecules than the molecules emit an electron and the ionized molecule PQ^{+} and electron. In equation (1.4) further this process is followed. In equation (1.5) Q^{*} is an excited atom.

In stepwise ionization, ionization potential is much greater than an electron average energy. The ionization potential of the ground atom is a few times larger than the metastable atom. Excited ionization occurs when an excited atom interacts with electrons of low energy. This is known as the stepwise ionization [9].

In plasma generation need the beam of high energy electron, apart from electric field discharge .The energy transmits from 50 KeV to 2MeV of high energy electrons [10]. It shows that to generate plasma at exceptionally large volume and high energy beam of electron are required. High energy electron beam is needed when a large volume of plasma is produce.

Photoionization is another process when high energy photon hit with target particles like atoms and molecules, as a resultant electron and ion are produced.

$$hv + P \rightarrow P^{+} + e \qquad (1.6)$$

This reaction clearly shows that when photon is heated then the molecules break into the ions [9].

When the surface of atoms is heated, the electron ejected from the surface atom. This process is called ionization of surface

The most important in ionization process is penning ionization. It is a fundamental atomic collision process where ions are produced in chemical reactions involving excited atoms. The ionization energy required for neutral particles is less than the energy of excited atoms [11].

$$P^{*} + Q \rightarrow P + Q^{+} + e \quad \text{(penning ionization of atoms)} \qquad (1.7)$$

$$P^{*} + Q_2 \rightarrow Q_2^{+} + P + e \quad \text{(penning ionization of molecules)} \qquad (1.8)$$

$$P^{*} + Q \rightarrow PQ^{+} + e \quad \text{(Associative ionization)} \qquad (1.9)$$

$$P^{*} + Q_2 \rightarrow P + Q + Q^{+} + e \quad \text{(Dissociative ionization)} \qquad (1.10)$$

$$P^{*} + Q_2 \rightarrow P + Q^{+} + Q^{-} \quad \text{(Positive and negative ionization)} \qquad (1.11)$$

1.4.2 Excitation process

In excitation, electrons jump from lower energy to higher energy. The excitation process will continue until de-excitation occurs [12].

A metastable state is an excited state in which an excited electron is unusually stable and from which the electron spontaneously falls lower state only a long time, in which the atom can reside

for 10^{-3} sec much longer than 10^{-8} sec. In excitation process, these are the mechanisms that take place like Electron impact, charge transfer, penning excitation, and ion-electron recombination [13].

An electron with high energy when colliding with neutral particles transfers energy to the atom and ionize them, known as electron impact ionization. The following reaction takes place

$$e + P_l \rightarrow P_h^* + e \qquad \text{(l and h are lower and higher energy states)} \tag{1.12}$$

During the reaction charge will be transferred. One molecule or atom gives the electron, and it accepts the electron. Therefore, this process is called charge transfer excitation process. [13]

$$P^+ + Q \rightarrow P + Q^{+*} + \Delta E \tag{1.13}$$

Where, P and Q are donor and accepter species.

The interaction of atoms / molecules and metastable states leads to the process of penning excitation. In this excitation process the excitation potential must be less than metastable energy.

$$P^* + Q \rightarrow P + Q^{+*} + e \tag{1.14}$$

Where P*, Q is metastable and neutral target atom.

In the process of Ion-Electron recombination, excitation of particles can also occur. There are following categorized in the radiative process [13].

$$P + e \rightarrow P^* + hv \tag{1.15}$$

$$P^+ + e + e \rightarrow P^* + e \tag{1.16}$$

1.4.3 Electron – Loss Mechanism

Loss of electron occurs in Electron-Loss mechanism. There are several additional process exist.

For molecular ions, dissociative recombination process is fast in molecular ions, the following reaction takes place [14].

$$e + AB^+ \rightarrow (AB)^* \rightarrow A + B^* \tag{1.17}$$

During interaction with atomic ions, an electron is lost in three body recombination [15].

$$e + e + A+ \rightarrow A^* + e \tag{1.18}$$

Another mechanism an electron is loss is called radiative electron –ion recombination [16].

$$e + A+ \rightarrow A^* \rightarrow A + hv \quad (1.19)$$

In the electron–ion process there is another process namely electron attachment process, which appears in the name of something attached to it. And a result of ions is formed when electron is attached with the neutral [17].

$$e + e + AB \rightarrow (AB^-)^* \rightarrow A + B^- \quad (1.20)$$

1.5 Generation of Low temperature discharges.

Plasma is generated when external power is applied to a gas at low pressure. It is also known as LTP. Several methods for generating plasma like Direct current, RF (Radio Frequency) and microwave (MW) discharges .Commonly, plasma can be generated through a renowned technique by passing current across the confined gas and therefore also known as gas discharges. DC and RF plasma are commonly used for material processing.

1.5.1 Direct current Discharges

This type of plasma is normally generated when enough DC potential is applied to a gas at low pressure through electrode placed parallel to each other in a closed container as shown in figure (1.1). The vacuum pump controls the pressure inside the tube. When the gas pressure is reduced, more energy is required to collide with the particles. In any gas, a small amount of free electron present every time owing to background radiations. When the DC voltage is applied to a gas, these electrons are accelerated and absorbed energy. During collision with ambient gas particles (atoms /molecules), the electrons loss their energy. When the voltage is not applied the excitation and ionization process are not observed because particles do not collide with them. When the voltage is applied, gases particles are accelerated and collide with each other, both process are occur in the glass tube. In the excitation process the atom /electron jumps from lower orbit to the higher orbit. When excited atoms /electrons spontaneously transition to the lower they emit electromagnetic radiation. Neon lights, plasma, screening television, fluorescent lamps and surface treatment are the applications of the DC discharges.

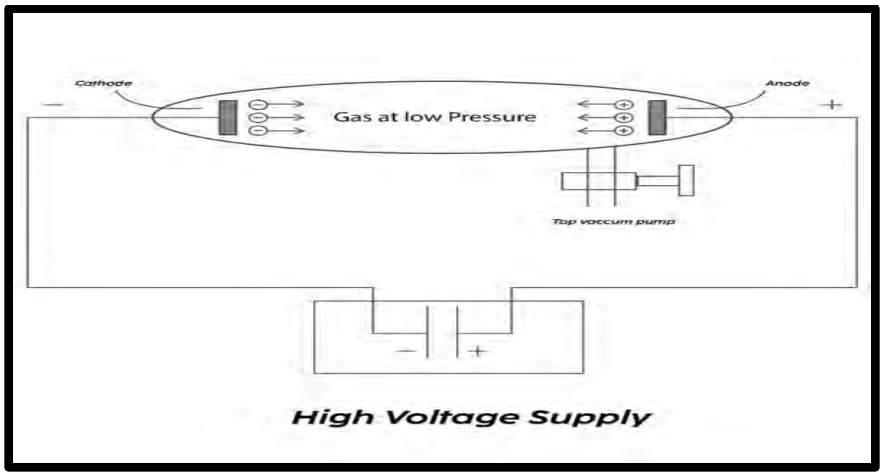

Figure 1.1 A sketch of DC discharge system

1.5.2 Radio Frequency (RF) discharges

As technology advances, Radio Frequency was introduced as an alternative to DC discharge, but radio frequency is more important than the DC discharges. One of the most important uses is etching and deposition of thin solid layer on the substrate placed [18]. The frequency range of RF is (1-100 MHz) for the operating RF discharges. The frequency range (13.56 MHz) is used for commercial and research purposes under the regulation of International telecommunication Authority (ITA). In RF discharges, there are two dominant conditions for operating the system. ($\omega_{pi} \gg \omega_{rf} \gg \omega_{pe}$) means that frequency of an electron must be greater than the ions and radio frequency.

$$\omega_{Pe} = \sqrt{\frac{n_e e^2}{m_e \varepsilon_o}} \tag{1.21}$$

$$\omega_{pi} = \sqrt{\frac{n_e e^2}{M_i \varepsilon_o}} \tag{1.22}$$

The high frequency regime is ($\omega_{pi} \ll \omega_{rf} \ll \omega_{pe}$). In this regime the frequency of plasma ions is less than radio and electron frequency. Indicative coupled plasma (ICP) and capacitive coupled plasma (CCP) are categorized by the RF discharges.

1.5.2.1 Capacitive Coupled Plasma (CCP)

This type of discharge is also known as E-discharge, or discharge caused by an electric field [19]. It consists of two parallel electrodes placed inside a plasma chamber. The surface of one or

both electrodes may be insulated and remain in direct contact with plasma. CCP discharge electrodes can be symmetrical or asymmetrical in shape or size. The formation of sheath in front of electrodes in steady discharge is the underlying significance of using asymmetrical electrodes. This results in self-bias in CCP discharges [18]. The shape and size of a plasma chamber vary depending on the application.

In CCP configuration, one electrode is grounded while the other is powered via a matching network required between the source of RF power and the powered electrode. This is since in RF discharges, an oscillating input power causes a variation in the discharge's impedance. As a result, the only purpose of matching network is to maximize power transfer from the RF source while minimizing signal reflection from the load. This is accomplished by matching/transforming the input impedance of the load (plasma reactor and discharge) and the (fixed) output impedance of the power source. Fig (1.2) depicts a basic sketch of a CCP discharge.

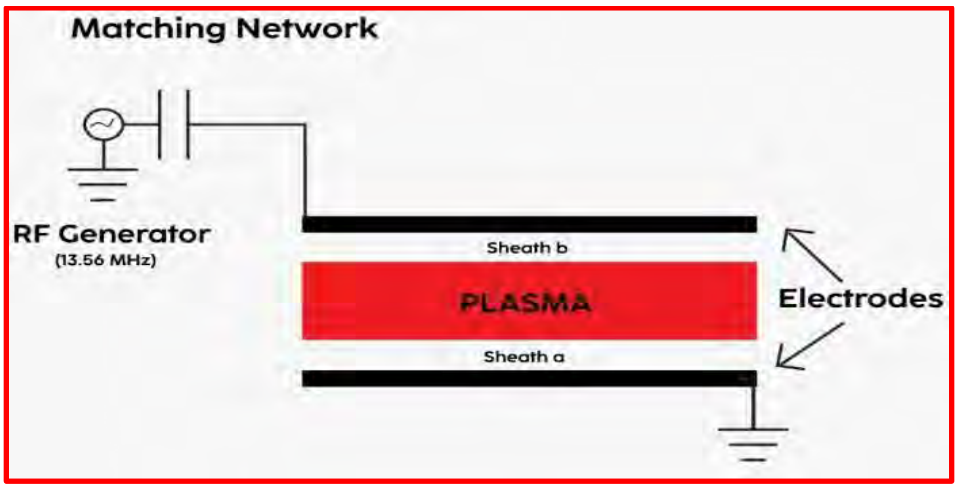

Figure1. 2 Sketch of CCP Discharge arrangement.

The presence of cosmic radiation generates free electrons and ions in the discharge chamber. However, because of their high mobility, the flux of randomly moving electrons is much higher than that of ions. The externally applied RF field simply accelerates these electrons, providing them with energy to produce more ions and electrons while interacting with the neutrals in the gas. As a result, the neutral gas breaks down as the number of charged species increases. However, because electrons are lighter than ions, they respond much faster to the RF field in the high frequency regime, gaining a lot of energy from the applied field and raising their

temperature T. Ions, on other hand, remain unaffected and mostly at room temperature. Because of the difference in electron and ion temperatures, most RF discharges are non-LTE in nature. The fast-moving electrons rush towards the electrodes and the chamber walls. It causes the formation of a positive space charge sheath region between the plasma and an electrode, breaking the quasi-neutrality in the vicinity of the electrode. The electric field within the sheath, on the other hand, repels electrons and accelerates ions towards the electrode, balancing the electron and ion fluxes.

Positive ions accelerated by the electric field in sheath gain energy in this region and strike the electrode with a large amount of energy. The ion bombardment generates more electrons from the electrode surface, which are known as secondary electrons. While moving towards the plasma bulk, secondary electrons collide with neutrals inelastic causing ionization and excitation. As a result, not only electron density increases but so plasma temperature.

The RF CCP plasmas can be simply modeled using an 'equivalent circuit' describing the plasma characteristics. Here power dissipation in the bulk plasma via electron collisions can be represented by a resistance. Moreover, the displacement current in the sheath region that exists due to space charges is represented by a capacitor. The diode considers the conduction current flowing in one direction. An inductor can represent electron inertia which becomes important at low pressures.

1.5.2.2 Inductive Coupled Plasma (ICP)

While CCPs have advantages, and also have many disadvantages. As the technology evolved in CCPs, unnecessary impurities within the chamber enter it via the electrodes. The main disadvantage of CCPs is when the applied voltage causes the size of sheath to decrease and changes in density of the plasma. When the applied power increases, the pressure to increase as the results impurities within the chamber also increase totally change the chemistry of plasma. This problem was solved by introducing external inductor (Antenna) in ICP, which works on Faraday's law of induction. Time varying magnetic field is generated when current (from RF generator) is passing through the coil. The magnetic field directed induced the time varying electric field.

$$\nabla \times E(r,t) = -\frac{\partial B(r,t)}{\partial t} \tag{1.24}$$

B(t) represents a magnetic field and E is an electric field.

In Laboratory cylindrical and planer coil are used to plasma generation as shown in figures 1.3 (a) and 1.3 (b). These are known as ICP reactors. In cylindrical the RF coil is encircled in chamber, like in planner coil configuration the RF coil is placed stovetop on the planner chamber. The electromagnetic field is coupled with plasma (dielectric window) in both types of reactors which separate the antenna from the plasma. Other characteristics of ICP discharge compared to CCPs discharge in which has low electron temperature, lower pressure, and high electron density (10^{11} to 10^{13} cm^{-3}). As before connected in CCP, RF generator with coupled to through a matching machine same procedure adapt in the ICP just replace of antenna electrodes. The antenna coil drives at the electrical resonance condition having frequency 13.56 MHz and impendence of 50ohm using the matching network. As a result the inductor coils having high current flow due to the matching network. In the plasma region a strong magnetic flux is generated due to higher power of RF. Due to the electrical resonance condition in the Antenna ends, the high potential appears. In CCPs voltage is coupled same as in ICP RF potential are coupled and dominant at lower power. These modes are known as E-mode and H – mode. These modes are observed by power coupling mechanism in ICP [19].

E-mode is also known as capacitive mode with the similarities CCP. ICP discharges at low RF power (E-mode) are called dark mode. A weak light emission and low plasma density is characterized by this mode. A small number of current flows through the coil and high potential drops between the power ends and the grounded ends at low RF power, the resultant electrostatic field are produced. In CCP discharges, the sheath shows similar behavior because due to the electrostatic field the number electron density is lower. The heating mechanism resembles CCP Discharges [20].

The induced field is responsible for plasma generation as RF power increases the electron density and increases the value of power to a certain point where the electrostatic field overcomes the induced electric field. This is H-mode or known as inductive mode. The important parameters for these modes are low plasma potential, low temperature high density (10^{11}cm) and strong glow. In this mode power coupling efficiency is determined by Antenna current and discharges due to transformer action in plasma.

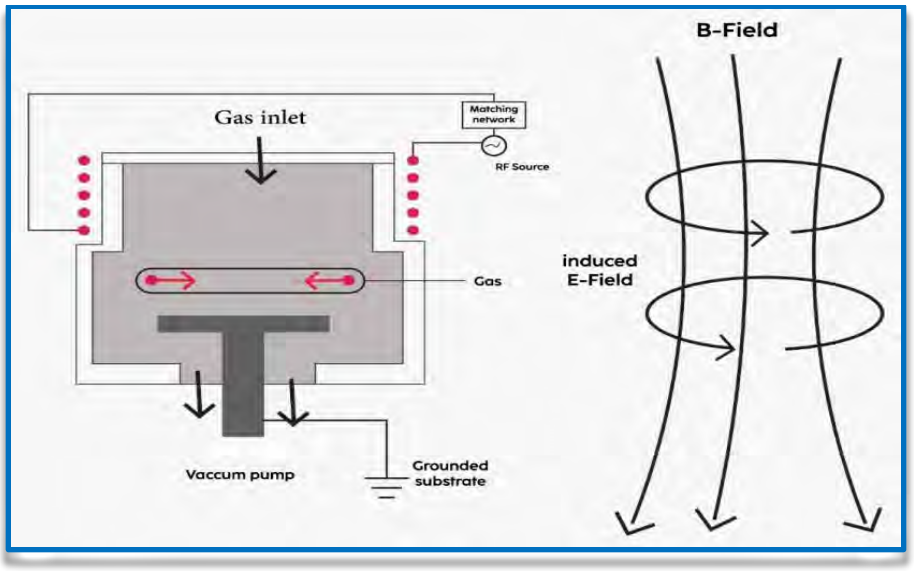

Figure1. 3(a) Cylindrical ICP configuration and Direction of magnetic and Induced Electric field.

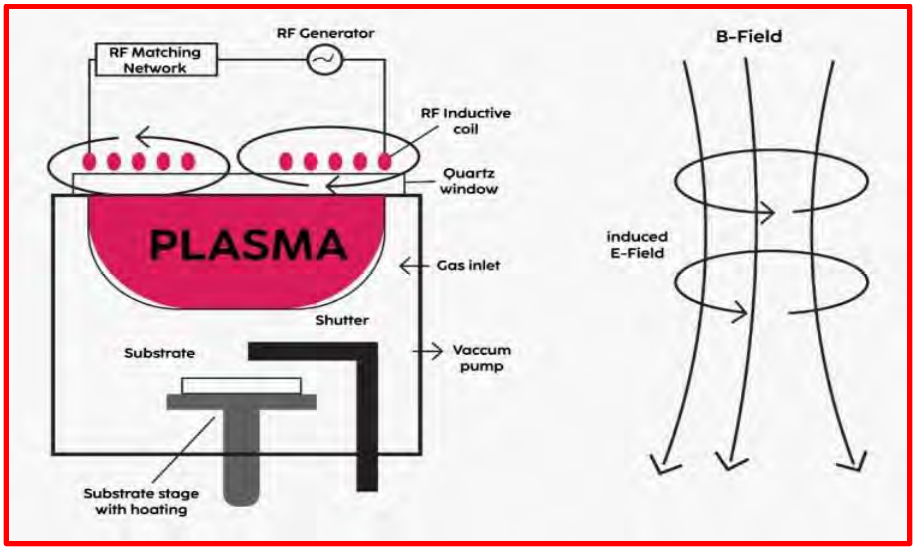

Figure1. 3 (b) Planer ICP Configuration and direction of magnetic and Induced Electric field.

In H-mode charges are heated by two methods, one is stochastic heating and other is ohmic heating [21]. These two modes, E and H mode have significant importance in ICP due to these having distinguished characteristics in discharges and important parameters of these modes are particle density, plasma potential, current and plasma luminosity.

1.6 Application of low temperature plasma

Science and technology have always strived to provide comfort and convenience for life.

These are the following applications of low temperature plasma.

Nitriding of iron metal and stainless steel is a modern technique of Low temperature Plasma, and it is being worked on intensively, to be clear it causes an increase on the lifetime of the material and protect against rusting [22].

Plasma etching process is used to change the physical and chemical properties of any material [23]. Today is digital era, and it is used for fabrication of digital integrated circuits. When semiconductor materials are used in Hydrogen Plasma etching if it is subjected to the etching process, it has been scanning that this process has proved to be helpful in removing some parts of the local oxides.

Plasma Electrolytic oxidation (PEO) also known as Micro-Arc- oxidation (MAO) is a technique in which light metals and their alloys are coated with ceramic coating that improves the properties of the material .This technique increases the hardness of steel by two to four times.

The application of Low Temperature Plasma is also helpful in cleaning and sterilizing the surface of any material, called process sterilization [24].

The cathode Ray Tube (CRT) is another application of low temperature plasma [25]. In recent years, another technology is used Plasma Display Penal (PDP) and Plasma Addressed Liquid Crystal (PALC), this is also known as a modern technique, it reduces the side effects low weight, and flat slim TV monitor also in the computer.

There are wide range of applications of low temperature plasma, including light, textile, material processing. In the light industry fluorescent lamps are the biggest examples of low temperature plasma, due to it having light emitting properties. In textile industries dry technique is used of the material.

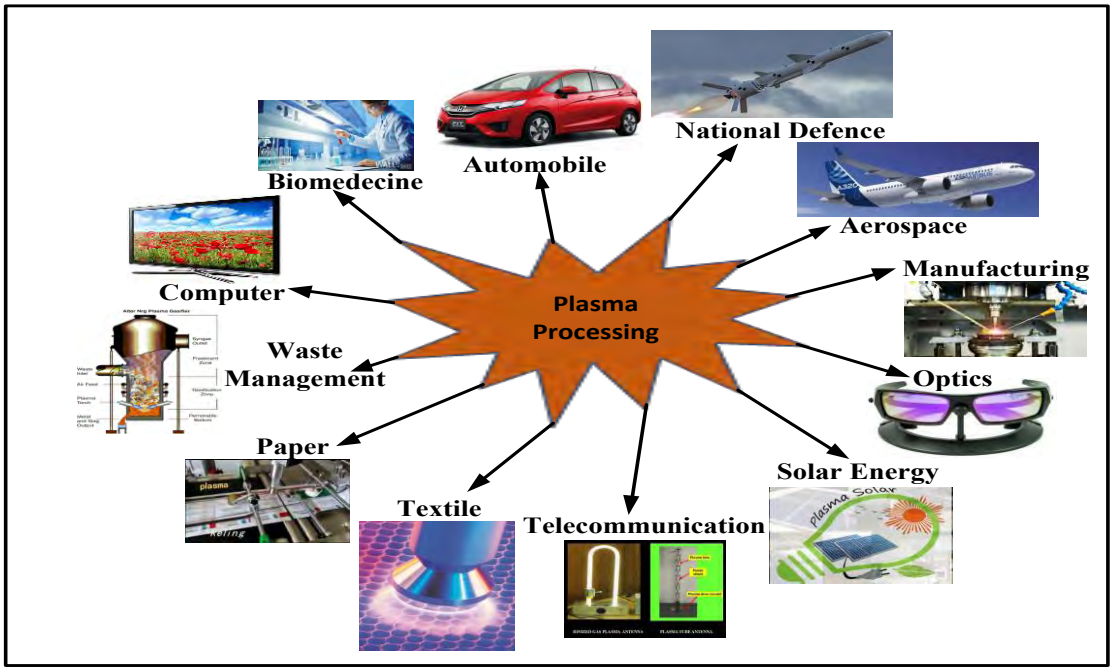

Figure1.4 Industrial application of the low temperature

1.7 Layout of Dissertation

In this dissertation chapter 1 includes introduction to plasma and their types, what are the methods to generate plasma in a laboratory and also discussed the applications of low temperature plasma. Chapter 2 describes the fundamental concepts related to spectroscopy and the evaluation of excitation and electron temperature by using optical emission spectroscopy. In chapter 3, experimental arrangements used for generation of discharges and diagnostic technique employed for evaluation of various plasma parameter like electron and excitation temperature are discussed. Chapter 4 describes the experimental results and discussion about the correlation study of spectroscopic temperature (excitation and electron temperature) for Ne-Ar mixture plasma.

Chapter 2

OPTICAL EMISSION SPECTROSCOPY

2.1 Spectroscopy

The word spectroscopy is taken from Latin language. The term 'Spectron' which means "ghost or spirit" similar spectrum is also word of Latin which means "appearance.' Spectrum represents the absorption and emission of electromagnetic radiation.[26].

OES technique which measures the absorption and emission of light with interaction of matter, and calculated the wavelengths, precise measurement of color (visible light)using optical emission spectroscopy. The behavior of the internal structure and properties of the matter can easily be described through spectroscopy. Spectrometer is an instrument, for example to find the mass to charge ratio of the element and isotopes of the element which is measured by mass spectrometer.

Plasma consists of neutrals (atoms and molecules), ions and electrons [4]. During reactions radiation emission from the excitation and recombination process is obtained. So, it is difficult to analyze the radiation which comes from plasma. Therefore, use of imaging procedure is applied through optical, and this procedure is known as OES (Optical Emission Spectroscopy). OES plays a vital role in diagnostics used in the plasma structure. Light has three-regions ultraviolet, visible, and infrared.

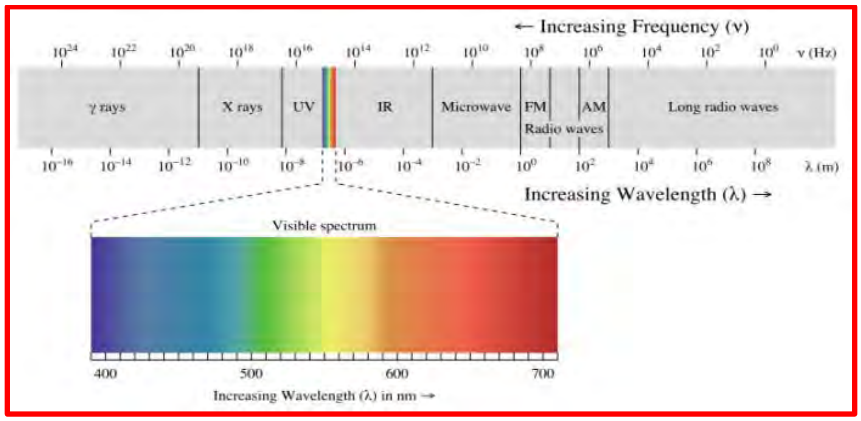

Figure2. 1 An ordinary spectrum of electromagnetic radiation.

One of the simple types of electromagnetic radiation spectrum starts from the short wavelength called gamma radiation [27]. X-rays lies between gamma radiation and ultraviolet radiation.

Moving from left to right the frequency is increasing for example radio waves as shown in figure(2.1).

2.1.1 **Absorption Spectroscopy**

When a light beam having some wavelength is incident upon a metal surface, the intensity of certain wavelength within the incident radiation is decreased and energy of these wavelength is absorbed by particles. This phenomenon is called absorption spectroscopy. Absorption efficiency will be greater if light is more absorbed.

The "Lambert-Beer's Law" states that the absorption of radiation is expressed through an empirical formula and is given by a relation,

$$I(\lambda) = I_o\ (\lambda) \times e^{-n\sigma(\lambda)L} \qquad (2.1)$$

Where

$I_0\ (\lambda)$ Intensity of the incident radiations

$I\ (\lambda)$ transmit intensity.

σ denote as cross section.

n is the density of absorbing medium [28].

As shown in the figure 2.2, when the incident light interacts with the material sample, the atoms absorb the energy in the ground state then jumps to the excited state due to the absorption of energy.

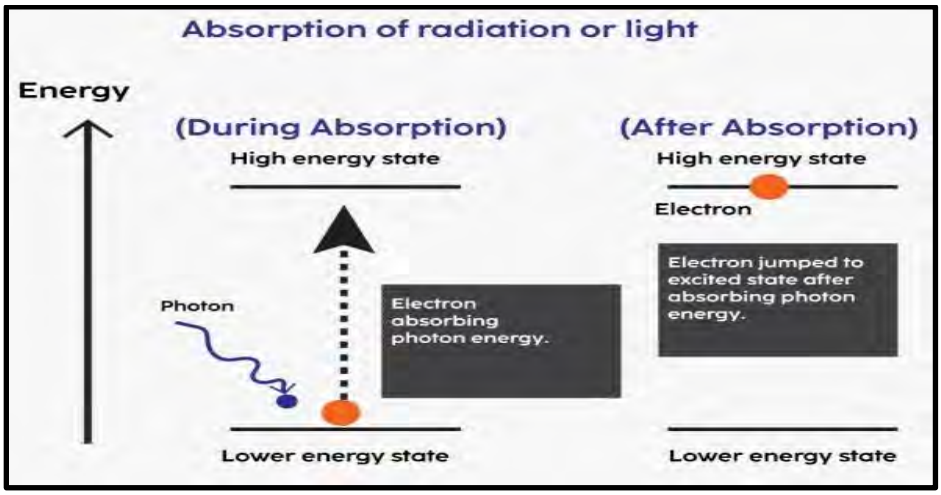

Figure2. 2 Radiation absorbed by the atom in lower states and jump to higher state

2.1.2 **Emission Spectroscopy**

Emission spectroscopy is known as the second type of Spectroscopy. In this type of spectroscopy radiation is emitted in the form of photon when electrons having energy states jumps to a lower energy state due to de-excitation process. Lifetime in high energy state is short, and radiation is emitted in the range of ultraviolet and visible regions during de-excitation process. It is a technique which measures the wavelength of the photon. Spectral analysis examines the different wavelengths of photons. The human eye can be visualized as the visible spectrum which has a range 390 nm to 750 nm wavelengths. From the given figure spectrum has described the different wavelengths.

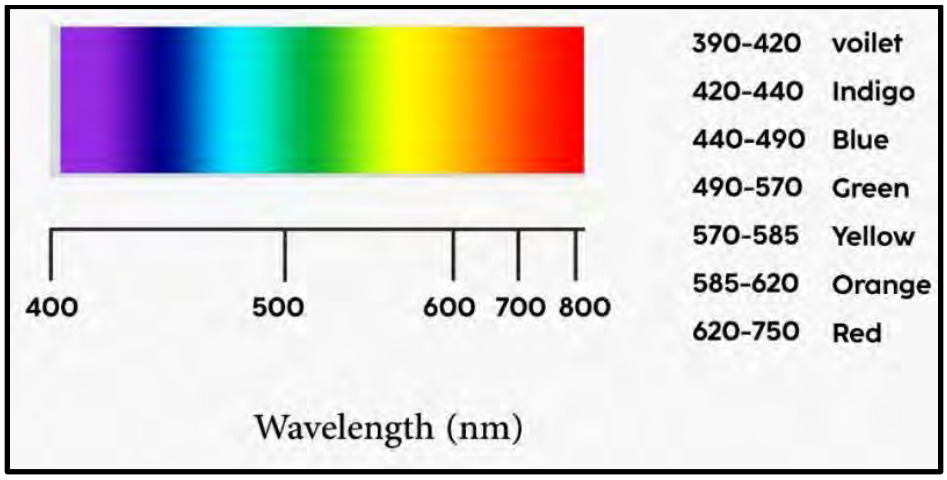

Figure2. 3 Spectrum of light in visible range.

When an electron in an atom transit from a higher energy state "E_j" to a lower energy state "E_i", the emitted radiation carries energy with the corresponding frequency of photon, which can be measured by using the following relation,

$$E_j - E_i = h\nu_{ij} \tag{2.2}$$

$$E_j - E_i = \frac{hc}{\lambda_{ij}} \tag{2.3}$$

$$\lambda_{ij} = \frac{hc}{E_j - E_i} \tag{2.4}$$

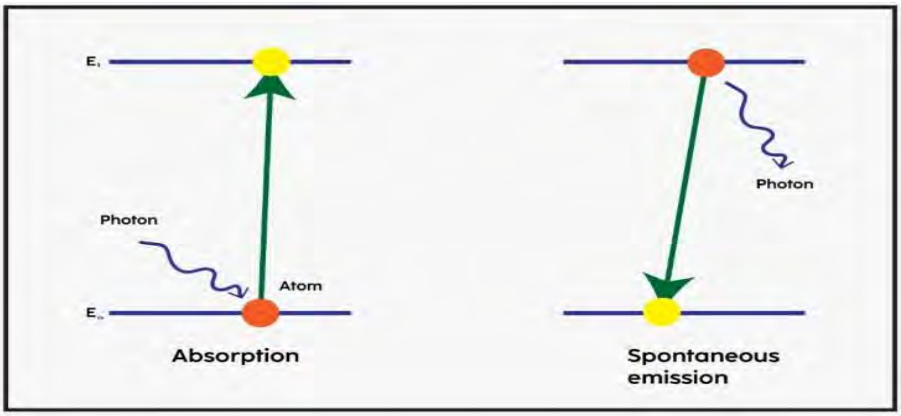

Figure2. 4 Spontaneous emissions of radiation

2.1.3 **Stimulated Emission of Spectroscopy**

Albert Einstein Theoretically explained stimulated emission in the Sense of old quantum mechanics. In this mechanism emissions are known as photons. These emissions are also produced in classical models without quantum mechanics.

An atom that may be one or two energy States which one is called ground State and other higher states is known as excited states having energy E_1 and E_2 respectively. In excited states atoms loss, their energy and decay from higher to lower states this process is also known as spontaneous emission [29]. In excited states atom is disordered due to electric field, it emits another photon which have the same frequency by dropping the atom to the lower states. This process is called stimulated emission.

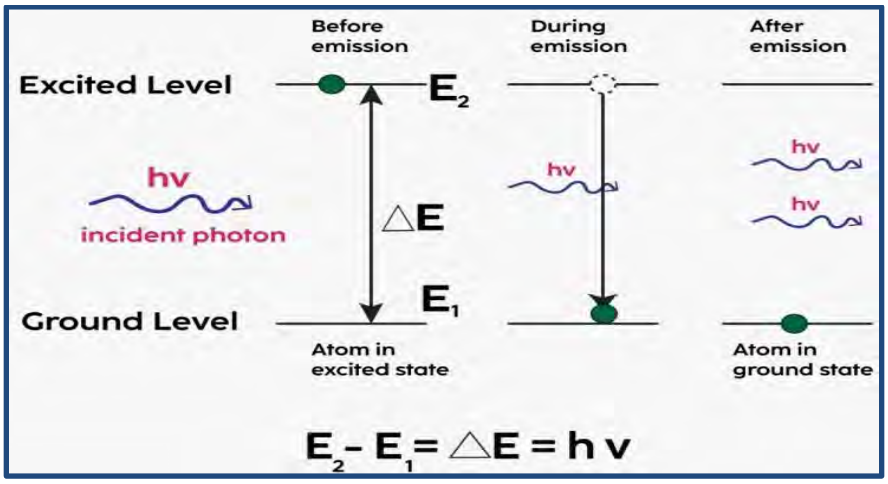

Figure2. 5 Sketch diagram of Stimulated emission of radiation.

Where, E_1 and E_2 are the lower and higher energy states respectively. ΔE is the difference between energy states and V_o is the frequency of photons.

2.1.1 Calculation of Plasma Parameter through Optical Emission Spectroscopy

As science and technology is progressing, different techniques are developing. In plasma physics use of OES has increased. In which plasma characterization is done. It provides information about energy distribution and other plasma parameters.

In OES, spark is generated when electrical energy is applied in between metal sample and an electrode. Discharge plasma is generated due to excited atoms and ions, emissions are formed. These emissions are spectral lines and study through a spectrometer which describes the behavior lines. Concentration of the element describes the intensity of the emission. Let calculate the plasma parameter through OES by applying different methods like Boltzmann.

2.1.2 Excitation Temperature

In plasma the most important parameter is electron temperature but during reaction measuring and control is so difficult. Therefore, it is also known as a fundamental parameter. Excitation temperature and electron temperature are equal in low temperature plasma [30]. In such words physical there is no meaning of excitation temperature.

Excitation temperature is measured through Boltzmann plot method. Radiation is emitted during different process like de-excitation process of molecule. This radiation is supposed to be caused by the Boltzmann distribution.

In de-excitation process the Intensity of radiation. [31]

$$I_{mn} = h\nu_{mn} N_m A_{mn} K_{mn} \quad (2.4)$$

Where, N_m represents the population density of excited state m. A_{mn} is transition probability form 'm to n' level. K_{mn} is the calibration factor, which describes the experimental and actual values. The value of calibration factor is $(4\pi)^{-1}$.

Put this value in equation (2.4)

$$I_{mn} = h\nu_{mn} N_m A_{mn}(4\pi^{-1}) . \quad (2.5)$$

Population levels of excited states in LTE plasma, The Boltzmann distribution function.

$$\frac{N_m}{N_o} = \frac{g_m e^{-\frac{E_m}{KT(exc)}}}{U(T_{exc})} \quad (2.6)$$

g_m is the statistical weight.

K is Boltzmann temperature and $U(T_{exc})$ known as partition function.

$$N_m = N_o \frac{g_m e^{-\frac{E_m}{KT(exc)}}}{U(T_{exc})} \quad (2.7)$$

Put the value of N_o in equation (2.5)

$$I_{mn} = h\nu_{mn} A_{mn} 4\pi^{-1} \frac{g_m}{U(T_{exc})} \exp(-\frac{E_m}{KT_{exc}}) \quad (2.8)$$

$$I_{mn} = \frac{hc}{4\pi\lambda_{mn}} A_{mn} N_o \frac{g_m}{U(T_{exc})} \exp(-\frac{E_m}{KT_{exc}}) \quad (2.9)$$

$$\frac{I_{mn}\lambda_{mn}}{A_{mn}g_m} = \frac{hc}{4\pi U(T_{exc})} N_o \exp(-\frac{E_m}{KT_{exc}}) \quad (2.10)$$

$$\ln(\frac{I_{mn}\lambda_{mn}}{A_{mn}g_m}) = \ln(\frac{hc}{4\pi U(T_{(exc)})} N_o) - \frac{E_m}{kT_{(exc)}} \quad (2.11)$$

$$\ln(\frac{I_{mn}\lambda_{mn}}{A_{mn}g_m}) = -\frac{E_m}{kT_{exc}} + C \quad (2.12)$$

The discharge gas A_{mn}, g_m, and E_m can be obtained from the National Institute of Standards and Technology (NIST) website [32]. The values of ln ($I_{mn}\lambda_{mn}$ / A_{mn} g_m) are plotted against energy E_m, and T_{ext} can be estimated from the inverse of the slope of this plot. Each data point corresponds to a single emission line of a specific wavelength.

2.1.3 Electron Temperature

Excitation and electron temperature are equivalent in LTE plasma. The impact of control parameters on plasma kinetics in non-LTE discharge, however, can be examined with excitation temperature. Using the modified-BP technique, the electron temperature in these plasmas can be predicted.

The excited states population densities due to electron collisional excitation processes in non-LTE plasma are counterbalanced by spontaneous radiative emission in the corona balance regime. In other words, the populating mechanism is electron impact collisional processes from

ground states, while the depopulating mechanism is spontaneous radiative emission from excited states [33].

$$N_e\ N_1\ R_{1m} = N_m \Sigma A_{mn} \tag{2.13}$$

Where N_e, N_1 and R_{1m} represent electron, ground state, and excited level densities, respectively, and R_{1m} is the rate coefficient of electron impact excitation and the ΣA_{mn} sums for each excited energy level, as well as the number of radiative transitions from higher energy level m to lower energy level n. According to the relationships, the excited level density can be written as fellow.

$$\varepsilon_{mn} = \frac{hCo}{4\pi\lambda mn} A_{mn} N_m \tag{2.14}$$

$$\varepsilon_{mn} = \frac{hCo}{4\pi\lambda mn} \tag{2.15}$$

If we assume that the free electrons in the plasma have a Maxwellian distribution, an equation for R 1m can be written as [33];

$$R_{1m} = 8.69 \times 10^{-8} \times \alpha_{1m} \times Z_{eef}^{-3} \frac{U_\alpha^{\frac{3}{2}}}{U_{1m}} \times \psi_\alpha(U_{1m}, \beta_{1m}) \mathrm{cm^3 s^{-1}} \tag{2.16}$$

In the above equation, a constant $\alpha_{1m} 1Z_{eef}$ presents effective atomic number (for atomic species,($Z_{eff} \approx 1$), f_{1h} stands for absorption oscillator strength, and

$$U_{1m} = \frac{(E_1 - E_m)}{KT_e} \tag{2.17}$$

In Equation, (2.16), the function a (U_{1m}, β_{1m}) can be expressed as

$$\psi_\alpha(U_{1m},\ \beta_{1m}) = \frac{e^{-U_{1m}}}{1+U_{1m}} \times \left[\frac{1}{1+U_{1m}} + \ln\left(1.25 \times \left(1 + \frac{1}{U_{1m}}\right)\right)\right] ;\ \beta_{1m} \approx 1 \tag{2.18}$$

The rate coefficients of electron impact excitation in terms of electron temperature can be expressed in a more suitable form after simplification as:

$$R_{1m} = b_{1m} \exp\left(-\frac{E_1}{kT_e}\right) \mathrm{cm^3}\, s^{-1} \tag{2.19}$$

We can estimate the value of by using the nonlinear curve fitting of Equation.

After calculating and simplifying Equations. The modified-BP method for calculating electron temperature [34].

$$\ln\left(\frac{(\varepsilon_{mn}\lambda_{mn}\Sigma_{m>n}A_{mn})}{hfA_{mn}b_{1m}}\right) = -\frac{E_{1m}}{KT_e} + C \quad (2.20)$$

$$\ln\left(\frac{I_{mn}\Sigma_{m>n}A_{mn}}{hfA_{mn}b_{1m}}\right) = -\frac{E_{1m}}{KT_e} + C' \quad (2.21)$$

The spectroscopic data of the constant A_{mn} and E_{1m} can be obtained from the NIST database. The values of $\ln\left(\frac{I_{mn}\Sigma_{m>n}A_{mn}}{hfA_{mn}b_{1m}}\right)$ are plotted versus E m and the inverse of the slope of the linear equation can be used to calculate the electron temperature (T_{OES}) of these data point.

Chapter 3

EXPERIMENTAL SETUP

3.1 Plasma Generation System

Figure 3.1 represents the diagnostic tools and experimental setup that is use for plasma generation. T. Meziani et. Al. was the first scientist who described the MaPE-ICP system as shown in Figure 3.2 [34]. The reactor has a cylindrical configuration with a planner coil embedded in a ferrite core material placed above the reactor. In comparison to conventional ICP, the concentration of magnetic field in the MaPE-ICP system increases fourfold with modification of the patented ferrite core material. Second, the primary benefit of using a rigid and hard magnetic core material is that it acts as a vacuum seal, allowing for easier system scaling. In this case, the mechanical function of the dielectric window has been reduced and it now serves as an insulating barrier between the coil and the plasma. Its thickness can be reduced and increasing the mutual inductance between the coil and the plasma.

3.1.1 Plasma Reactor

The discharge chamber is made of stainless steel and has a cylindrical geometry. It is 25 cm in height and 34 cm in diameter. There are several ports for gas injection, probe insertion, and pressure monitoring gauges. A viewing window made of quartz glass is also available to observe the discharge and record the spectrum using a spectrometer from within the chamber.

3.1.2 Radio Frequency Generator

A power supply (model PGF-RF Generator-1600 W) was used via matching network unit to generate plasma in the MaPE-ICP reactor (PFM-3000 A). The frequency and characteristic impedance of the RF generator are fixed at 13.56 MHz and 50 ohms, respectively. The applied power can be adjusted with 1W increment up to maximum power of 1600 W. The discharge power is the difference between forward and reflected power.

Figure3. 1 Photograph of experimental setup used in this research work.

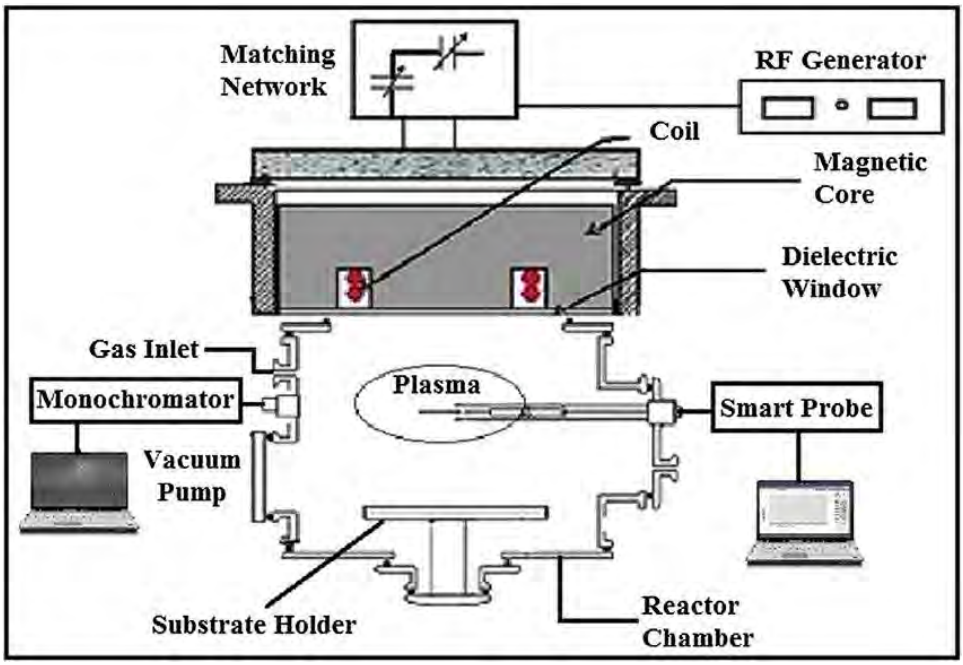

Figure3. 2 A sketch of the MaPE-ICP system and diagnostic tools.

3.1.3 Matching Network Unit

Another important aspect of this arrangement is matching network. Because of enormous difference in impedance between plasma and RF generator, external power is not effectively transferred to the plasma. As a result, power will be reflected in the power supply. The main

function of matching network is to minimize input power reflection by adjusting the impedance of the plasma and RF generator so that maximum power is transmitted to the plasma. In the current study, an L-type impedance matching network with control and tuning units was used. The tuning unit is made up of a variable capacitor and an inductor. The matchbox operates in various modes; however, the current experiment is carried out in automatic mode. In this mode, it adjusts itself to achieve the best value for no RF power reflection.

3.1.4 Cooling system

A chilled water (~15 °C) arrangement is used to prevent overheating of the chamber, RF generator, matching network, and vacuum pump. Pure, decalcified water is used for chilling. The chilled water is circulated throughout the arrangement using a motor pump.

3.1.5 Pressure Controlling and Monitoring System

The reactor pressure was reduced to a base pressure of about 10^{-3} Pa using a turbo molecular pump aided by a rotary pump. Pirani and Penning gauges were used to monitor the reactor's internal pressure. Hasting mass flow meters were used to measure the flow rate of the working gases.

3.2 Plasma Diagnostic

Plasma diagnostics is a collection of methods, instruments and experimental techniques used to measure plasma parameters. The diagnostic techniques (RF compensated OES) used in the current study for calculating and estimating various plasma parameters are discussed in detail here.

3.2.1 Optical Emission Spectroscopy System

To obtain local information about the discharge, an optical imaging procedure is required in which the spectrum of emitted radiation recorded, and various plasma parameters are extracted through further analysis of this spectrum. The radiation emitted during optical transition of various species in the spectral range of 100 nm to 900 nm can be recorded in this process. The spectrum of molecular discharges is also affected by changes in their rotational or vibrational energies levels, and they are typically found in the infrared and microwave regions [35].

We can investigate the following by using OES.

1: Laboratory Plasma at low temperatures ranging from low density (currently used for plasma processing) to high density arcs and plasma torches at atmospheric pressure.

2: High temperature pulse low-density plasmas with long lifetimes in magnetically confined fusion devices such as Tokamaks and Stellarators.

3: Short-lived Inertially confined pellets with densities up to 100 times solid-state density.

4: In the semiconductor industry, analysis of the deposited layer on the surface of the substrate and examination of hard coating deposition on the instrument.

5: To determine the composition of various materials in the form of gases, liquids, and solids.

6: To investigate naturally occurring plasma in astronomical objects such as the sun, stars, and interstellar matter. The composition of these plasmas can be better understood using OES.

In general, the spectrum of the nearby regime in plasma is not possible because the radiation emitted is not emitted from a single point "S," but from the entire Volume. In general, the measured spectrum is integrated along a line of sight, which can be identified by an aperture "P" or detection system "D" with a small opening angle, as shown in Figure 3.3.

Because the electronic levels have well defined energies and electrons during transition must absorb or emit energy equal to the difference between the states, spectroscopy of plasma using atomic gases, or their combination is simple and comparatively easy. As a result, the emission spectrum recorded due to atom electronic transitions has sharp and monoenergetic peaks.

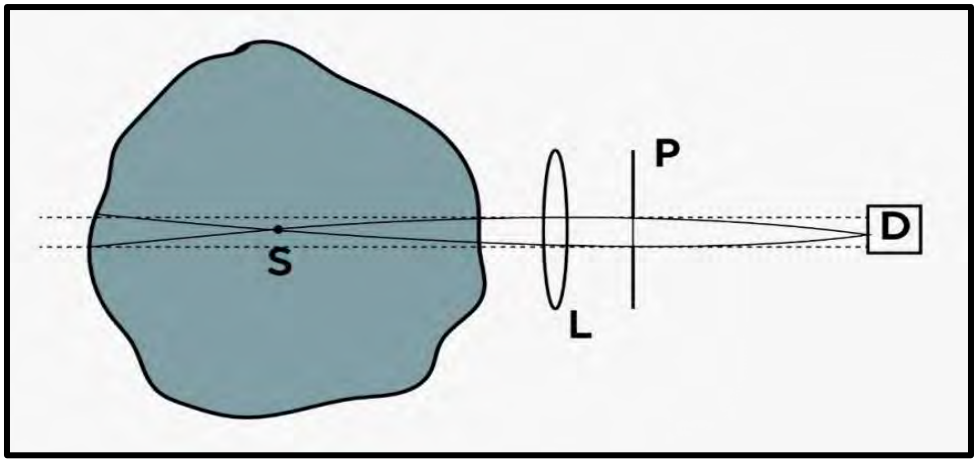

Figure3. 3 Schematic diagram of Optical Emissions Spectroscopy from a discharge

Molecular spectra, on the other hand, are made up of vibrational and rotational energy bands, as well as a greater number of electronic transitions. Because of the closely spaced rotational and vibrational energy levels, emission line broadening caused by collisions and radiating molecular motion causes the emission spectrum to superimpose. As a result, rather than sharp and well-defined peaks, the molecular spectrum appears as bands.

As shown in Figure 3.4, the sharp peak band head identifies the molecular band, whereas the red and blue shading replicates that the upper level of energy is less or more forcefully bounded than the lower level of energy. These shadings or band heads are not constantly visible. However, the emission energy band expands during collision at high pressure in LPP.

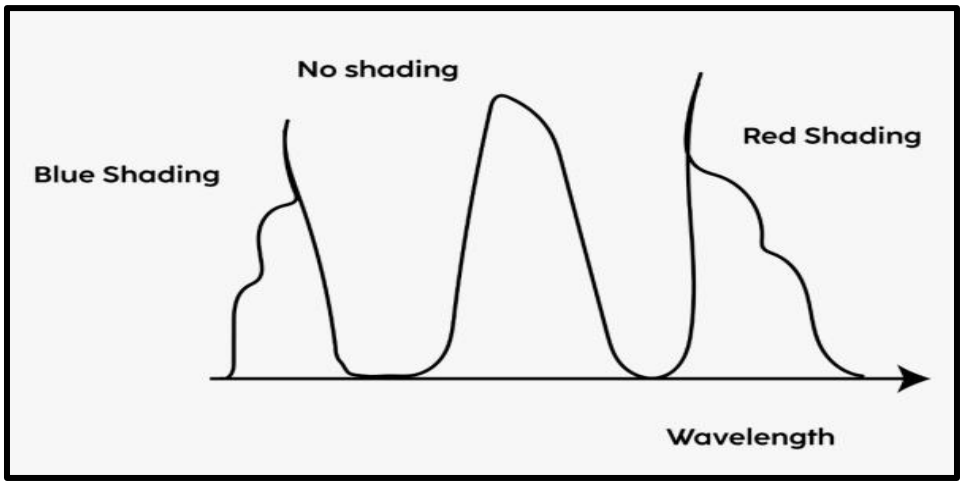

Figure3. 4 Molecular Spectra of a diagram with and without shading.

The OES system is made up of several components, which are detailed below.

Optical window

The radiation emitted by the plasma is routed through an optical window made of quartz glass, which reduces radiation loss. Cleaning the optical window is necessary because in reactive plasma, a layer is deposited on the inner side, increasing transmission losses. It modifies the spectral emission due to selective absorption and reduces the emission intensity. The severity of the problem can be reduced by physically or chemically cleaning the glass with feed gas. Furthermore, the deposition of the coating layer can be reduced by heating the window glass.

Spectrometer

A spectrometer is a device used to measure light properties over a wide range of wavelengths. It is commonly used in spectroscopic analysis of radiation to separate and measure different spectral components of physical phenomena. Most spectrometers have a flat response to emitted photons of various wavelengths. As a result, the emitted radiation from the discharge must be separated into different wavelengths before entering the detector.

The spectrum of Ne-Ar mixture discharges was recorded using an Optics spectrometer HR4000 in this study. Figure 3.5 depicts the names of various components of this spectrometer.

Figure3. 5 Schematic diagram of the Oceon Spectrometer HR4000.

Following is a brief discussion of various aspects of the Ocean Spectrometer HR4000.

SMA Connector

SMA (Sub-miniature Version A) Connectors are 50 1 RF Coaxial connectors that operate at up to 18 GHz. These connectors have a screw-type coupling mechanism that minimizes reflections and attenuation by ensuring uniform contact. The optical fiber is linked to the spectrometer via an SMA connector. Radiation from the plasma enters the optical bench via optical fiber and an SMA connector.

Entrance and Exist Slit

The slits in a spectrometer are designed in such a way that they describe the geometry of the radiation passing through them. The slit also controls the size and position of the light beam. When radiation enters the slit, it allows only a small fraction of the light in and makes the arriving radiation parallel. The size of the slits is variable and can be adjusted as needed.

Filter

A filter transmits radiation in a specific wavelength range. Colored glass filters are the most common in ultraviolet, visible, and infrared spectral ranges. The ray passes through the filter before reaching the optical bench. The filter can be used for spectral emission analyses of recognized wavelengths. Some lines' superposition with other nearby spectral lines can be ignored. The resolution of a high-quality filter is 1 nm to 2 nm.

Collimating Mirror

The primary function of this mirror is to direct the enter light toward the grating. Mirrors have their surfaces polished with metal film such as aluminum, silver, or gold. The mirror is protected with a clear protective coating to prevent tarnishing.

Diffraction Grating

Rowland's invention of the ruling machine allows for the construction of Grating. Grating is widely used in optical spectroscopic analysis. Various gratings with groove density ranging from 600 to 4200 grooves/mm are available. The resolution of the spectrometers is determined by the grating's groove density [36].

Focusing Mirror

When a ray of light strikes a grating, it disintegrates into multiple wavelengths and is directed toward a focusing mirror. This light is redirected from the focusing mirror to the L2 detector collection lens (L2-DCL (L2 detector collection lens)) or Charged Coupled Device (CCD) detector.

L_2 Detector Collection Lens

The primary function of the L2 detector lens is to focus incident light from a focusing mirror onto the shorter CCD Detector. The L2-DCL should be used with large diameter slits or in low light applications. It also improves efficiency by reducing the effects of stray light.

Charged Coupled Device Detector

CCDs (Charged Coupled Device), as shown in Fig., are a recent integrated circuit invention. The absorbed photon in the light sensitive detection area in CCDs excites electrons to the conduction band. When a high voltage is applied, these excited electrons pass through the detection area and accumulate in the adjacent capacitor. Charge will be stored until more electrons enter the

capacitor and the capacitor is discharged for display. The advantages of CCDs include a small detector dimension, an extremely high signal-to-noise ratio, and high sensitivity. A typical CCD detector dimension is only about 10 to 20 m; thus, a CCD with a 10241024 array of pixels will have a dimension of about 2 x 2 cm^2. The more sensitive CCDs now approach a quantum efficiency of about 0.8, which means 0.8 charges per photon striking the CCD. However, because of the greater number of pixels, the information display period is frequently longer, and the time resolution is typically several kilohertz (K Hz).In ocean spectrometers, CCDs collect radiation incidents on the L2 detector lens from the focusing mirror and convert the optical signal into a digital signal. CCD detectors are made up of pixels, each of which relates to the wavelength of light that strikes it, resulting in a digital signal. The digital signal is then transmitted by the spectrometer to the OOIBase32 application.

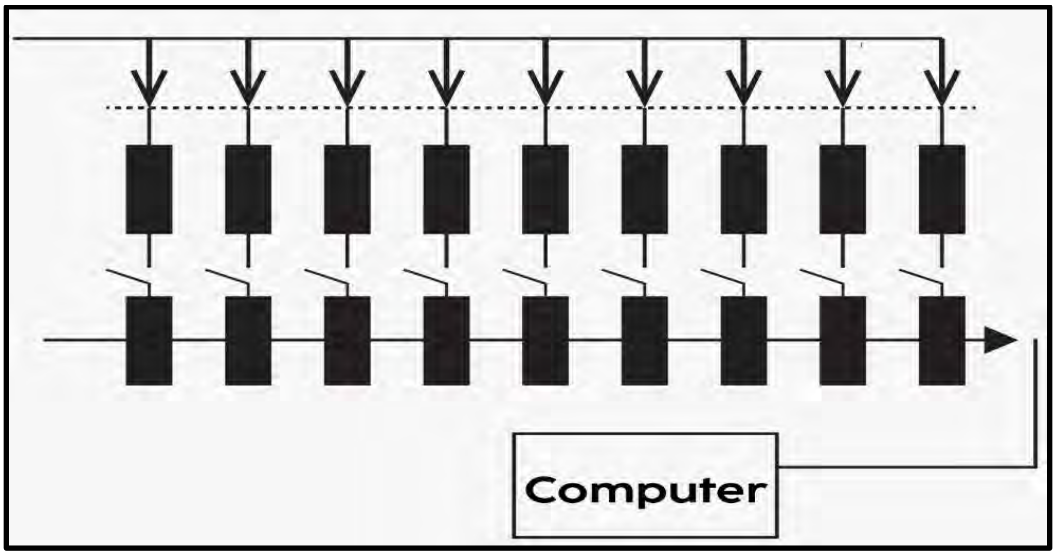

Figure3. 6 Sketch of charge coupled detector.

Chapter 4

RESULTS AND DISCUSSION

4.1 Evaluation of Metastable states of Neon-Argon

The experiment was performed in a different pressure (2 Pa, 6 Pa and 12 Pa) and RF power was varied from 5 watt to 100 watt with increment of 5 watt. The flow rate of Ne and Argon gas to the discharge chamber was kept constant at 30 sccm. However, Argon fraction varied from 0 % to 100 % with increment of 20% within the Ne discharge.

Neon has two metastable states having electronic configuration $2p^6\ ^1S_0$. The spectral lines of metastable states of neon atoms are 640.4nm and 703.4 nm respectively. These states are $1S_5$ to $2P_9$ and $1S_5$ to $2P_{10}$.

(a)

Figure 4.1 (a) Neon intensity behavior with Argon Concentration at 50 watt and wavelength 640.4 nm.

(b)

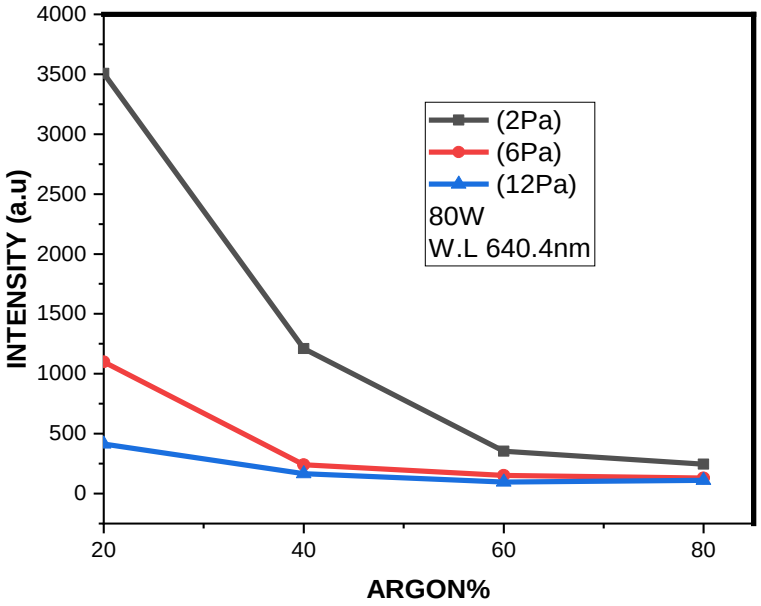

Figure 4.1 (b) Neon intensity behavior with Argon Concentration at 80 watt and wavelength 640.4 nm.

(c)

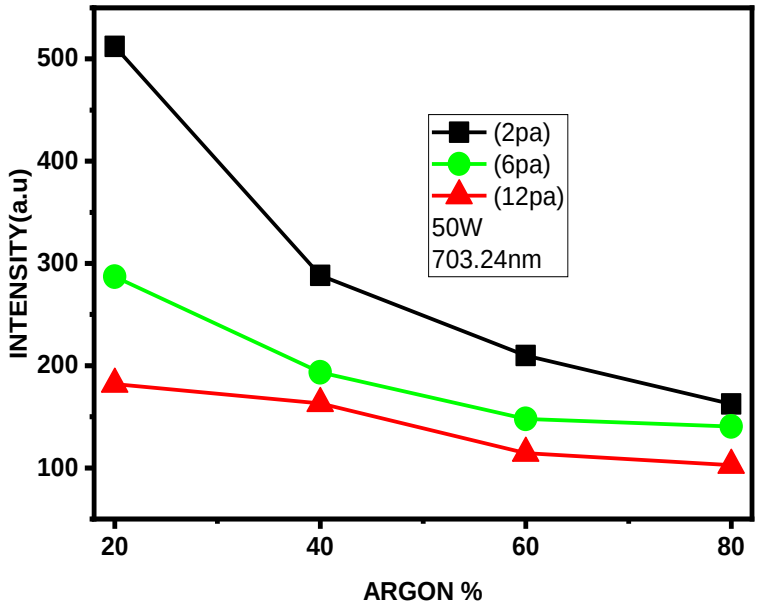

Figure 4.1 (c) Neon intensity behavior with Argon Concentration at 50 watt and wavelength 703.24 nm.

(d)

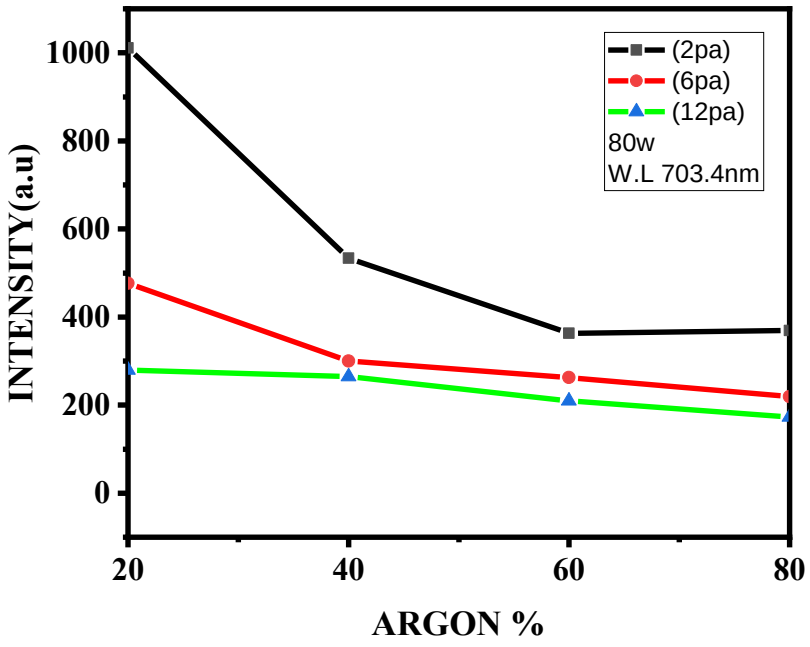

Figure 4.1 (d) Neon intensity behavior with Argon Concentration at 80 watt and wavelength 703.24 nm.

Figure 4.1 (a, b, c and d) shows a decreasing trend of intensity of Neon when addition the concentration of the Argon in the Ne. Addition of argon to neon atoms increases the frequency of collision between argon atom and neon atoms. These collision results in energy transfer, where the energy of excited neon atoms is transferred to argon. As a consequence, the population of excited neon atoms is decreases. The decrease in the population of excited neon atoms leads to a reduction in the intensity of neon's emission lines [37].

In Argon metastable state also measured by the Selection rule and having electronic configuration of $3p^6\ ^1S_0$. Metastable state of argon having spectral lines is 811.2 nm.

(a)

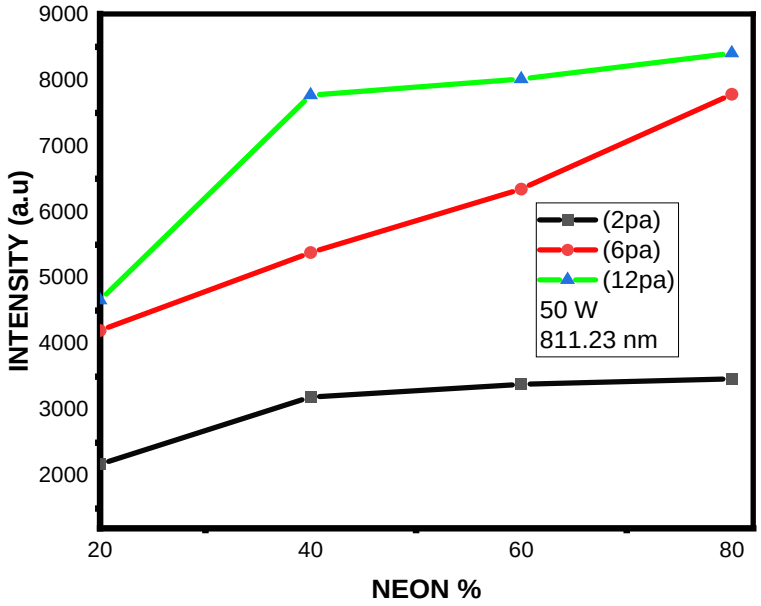

Figure 4.2 (a) Argon intensity behavior with Neon Concentration at 50 watt and wavelength 811.23 nm.

(b)

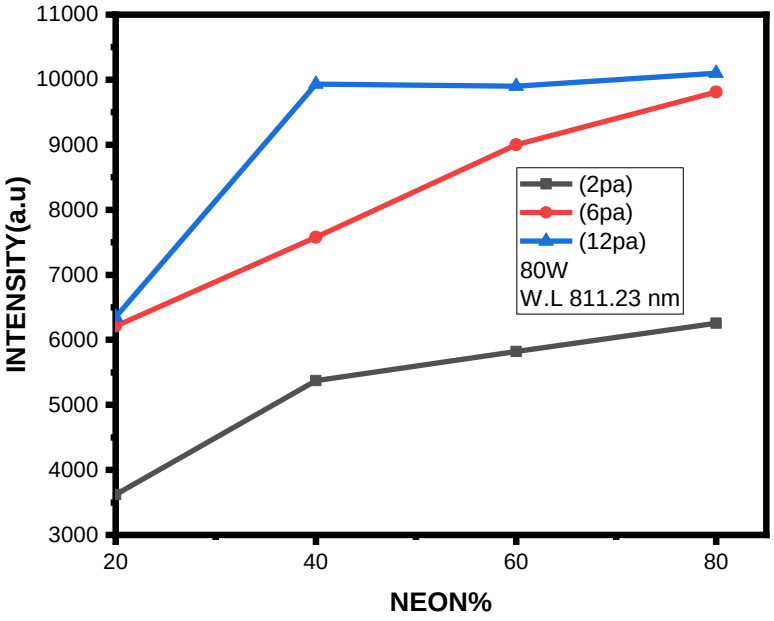

Figure 4.2 (b) Argon intensity behavior with Neon Concentration at 80 watt and wavelength 811.23 nm.

In figure 4.2 (a and b) described the trends of intensity of Argon are increased. In this case addition of neon atoms in argon . Argon intensity shows an increasing trend because Increasing concentration of neon leads to a higher frequency of collisions between neon and argon atoms.

The increased collisions result in a greater frequency of energy transfer between the two gases. As a consequence, more argon atoms become excited due to the transferred energy. The excited argon atoms subsequently emit more photons during de-excitation. The increased photon emission from the excited argon atoms leads to higher argon intensity in the emission spectrum.

4.2 Evaluation of Electron and Excitation Temperature by OES

λ_{mn}(nm)	E_m(ev)	g_m	A_{mn} 10^7 s^{-1}	$\Sigma_{m>n}A_{mn}$
352.05	20.36886	1	0.93	1.86
359.35	20.29728	5	0.099	0.099
363.37	20.25918	1	0.11	0.48
585.25	18.96596	1	6.82	6.91
607.43	18.71138	1	6.03	6.06
609.62	18.70407	5	1.81	5.27
614.31	18.63679	5	2.82	4.98
626.64	18.69336	3	2.49	5.08
640.22	18.55511	7	5.14	5.14
650.65	18.57584	5	3.00	4.90
667.83	18.70407	5	2.33	5.27
703.24	18.38162	3	2.53	3.71

Table 4.1 Ne-I selected lines for determination of excitation and electron temperature by BPM and MBPS respectively.

These emission lines used for plotting of Boltzmann plot and modified Boltzmann which are given in table 4.1

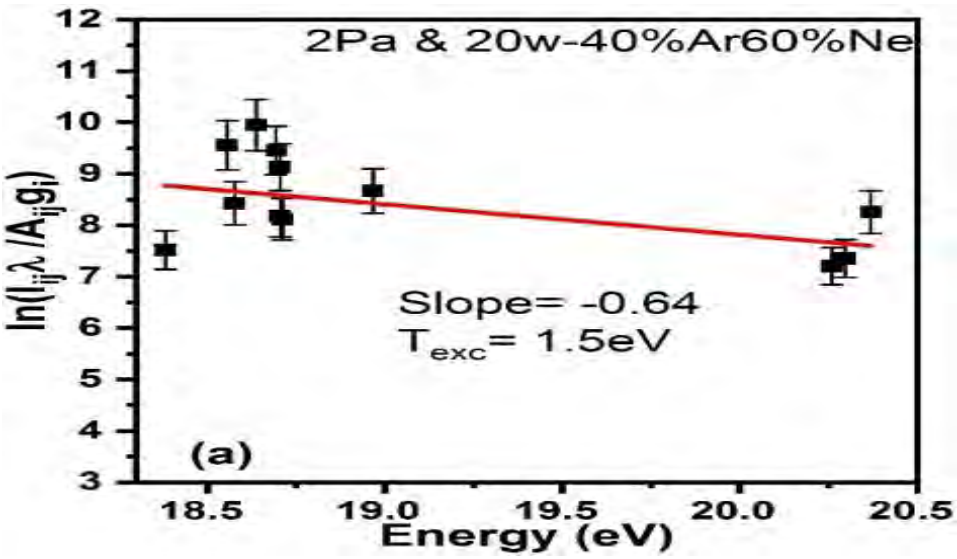

Figure 4.3 (a) Boltzmann plot of calculation of excitation temperature.

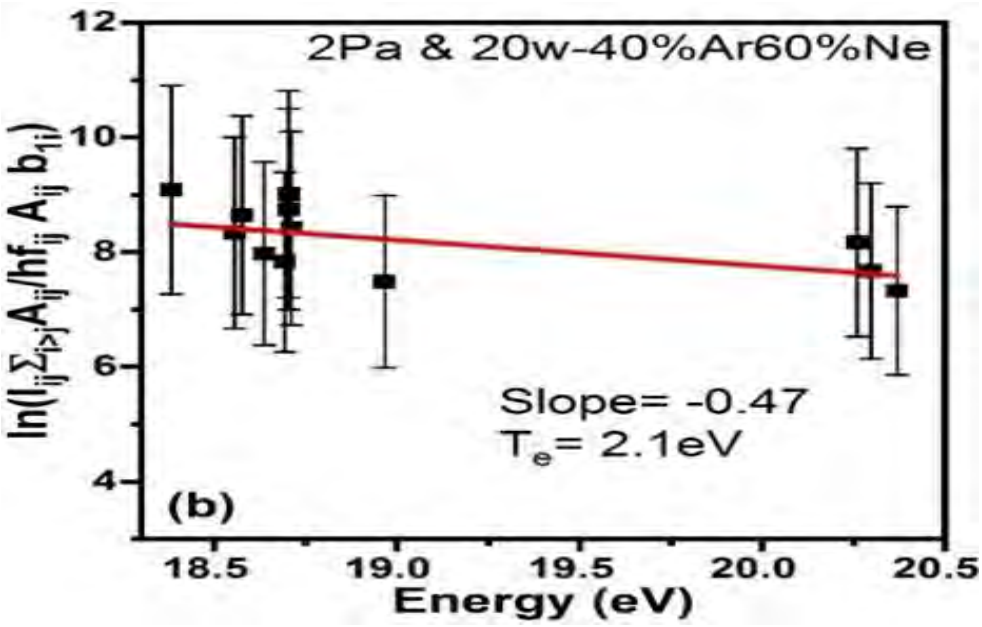

Figure 4.3 (b) Modified Boltzmann plot for calculation of electron temperature.

The excitation temperature from optical emission spectroscopy (OES) recorded spectrum is estimated by Boltzmann plot through a relation. Excitation temperature is determined with the help of this formula.

$$\ln\left(\frac{I_{mn}\,\lambda_{mn}}{A_{mn}g_m}\right) = -\frac{E_m}{kT_{exc}} + C \qquad (4.1)$$

A_{mn} is a transition probability from m to n level.g_m is the statistical weight.E_m is the energy level. I_{mn} is intensity of radiation during de-excitation of an excited species from higher level "m" to lower level "n" and and $\boldsymbol{\lambda}_{mn}$ is wavelength of lower and higher level .

The discharge gas $A_{mn,}$ g_m, and E_m can be obtained from the National Institute of Standards and Technology (NIST) website. The values of ln (I_{mn} λ_{mn} /A_{mn} g $_m$) are plotted against energy Em, and Text can be estimated from the inverse of the slope of this plot. Each data point corresponds to a single emission line of a specific wavelength.

The following factors are the main sources of error when calculating excitation temperature with

1: Incorrect A_{mn} values.

2: Inaccuracy in recorded intensities.

3: choosing emission lines with a low energy difference.

However, using a logarithmic relation reduces the error in the argument. For example, a 20% error is reduced to 5%.

The modified BP (Boltzmann plot) method for calculating electron temperature is by using the following relation.

$$\ln\left(\frac{I_{mn}\Sigma_{m>n}A_{mn}}{A_{mn}b_{1m}}\right)=-\frac{E_{1m}}{KT_e}+C' \qquad (4.2)$$

The spectroscopic data of the constant A_{mn} and E_{1m} can be obtained from the NIST database. The values of ln $\left(\frac{I_{mn}\Sigma_{m>n}A_{mn}}{A_{mn}b_{1m}}\right)$ are plotted versus E m and the inverse of the slope of the linear equation can be used to calculate the electron temperature (T_{OES}) of these data points.

The main source of error is when we calculate the electron temperature by modified Boltzmann plot.

1: A_{mn} values are incorrect.

2: Inaccuracy in recorded intensities.

3: Choosing emission lines with a low energy difference.

4: R_{1m} coefficient for Inaccuracy in excitation rate numerical fitting obtaining b_{1m} value.

4.2.1 Variation of Electron and Excitation temperature with RF power

The experiment was performed at different pressures (2 Pa, 6 Pa and 12pa) and Rf power was applied from 5 watts to 100 watts with an increment of 5 watts.

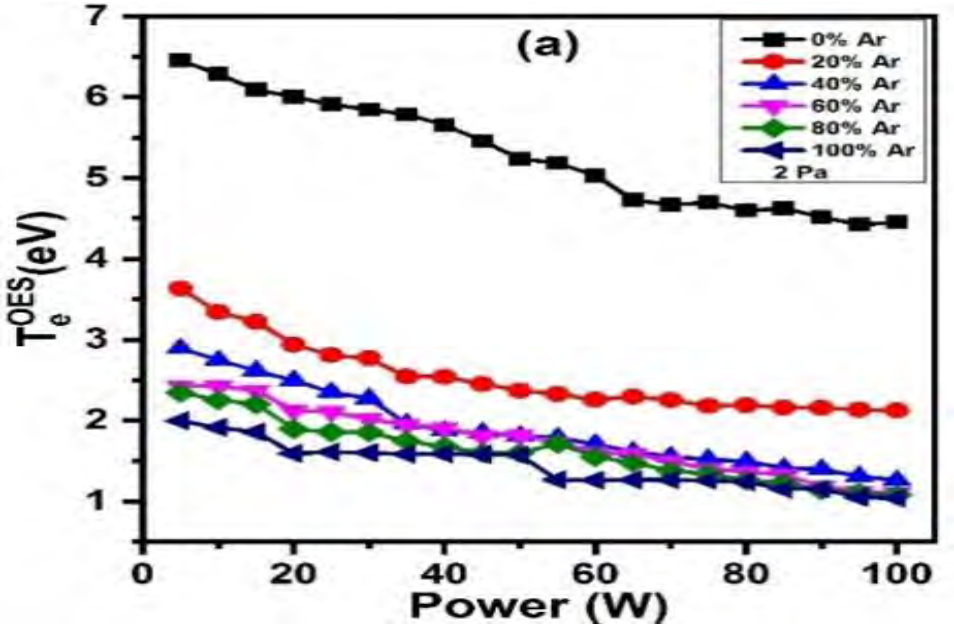

Figure 4.4 (a) Variation of Electron temperature by OES with RF power with different Ar percentages at 2 Pa.

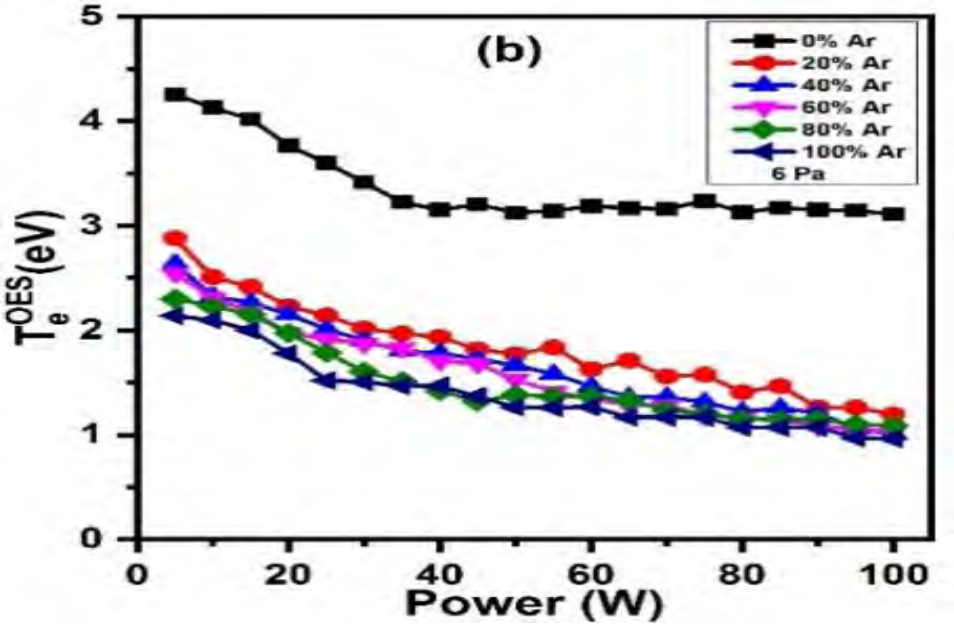

Figure 4.4 (b) Variation of Electron temperature by OES with RF power with different Ar percentages at 6 Pa.

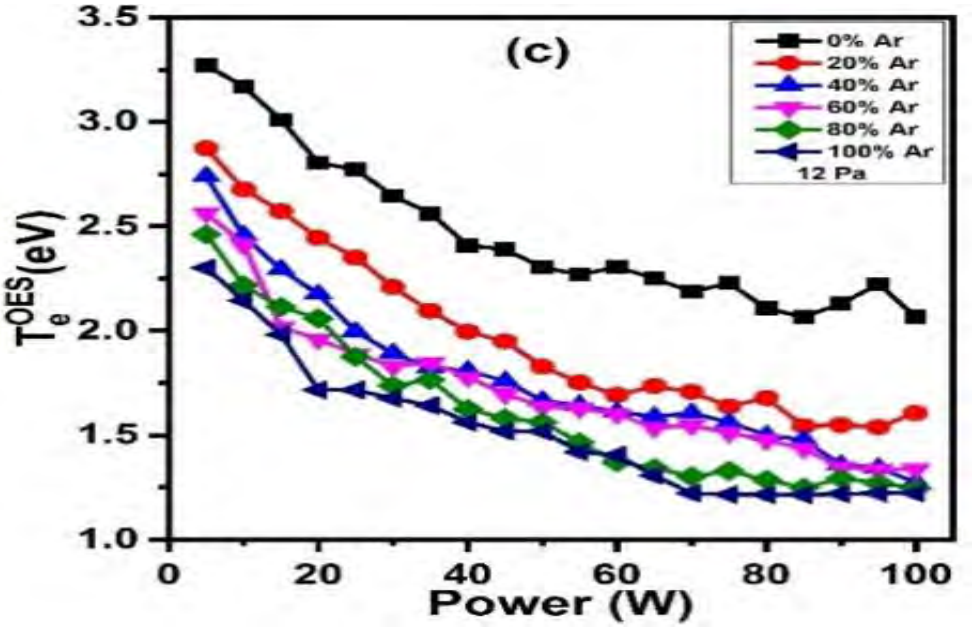

Figure 4.4 (c) Variation of Electron temperature by OES with RF power with different Ar percentages at 12 Pa.

Figures 4.4 - 4.5(a, b ,c) shows the behavior of the excitation and electron temperatures by the OES with different RF power at constant pressure and varying Ar content in the mixture. The spectroscopic temperature is shown to decrease as RF power increases. It can be explained by the fact that high-energy electrons lose energy during inelastic collisions with neutral atoms, which causes the rate of ionization to rise and, in turn, lowers the electron temperature. It might alternatively be explained as an increase in input RF power that is intended to intensify ionization processes and, as a result, an increase electron concentration in the discharge [38]. As a result of an increase in electron collision frequency, the temperature of the electron and excitation is decreasing. The suddenly temperature decreases are seen in Figures 4.4-4.5 (a) at 2 Pa and 65 watt (E-H mode transition), and when the Ar concentration increases, the RF power is reduced. Because of the improved RF power coupling provided by the ferrite core in the MaPE-ICP, the abrupt rise in electron density during the E-H mode transition can be used to explain the temperature reduction.

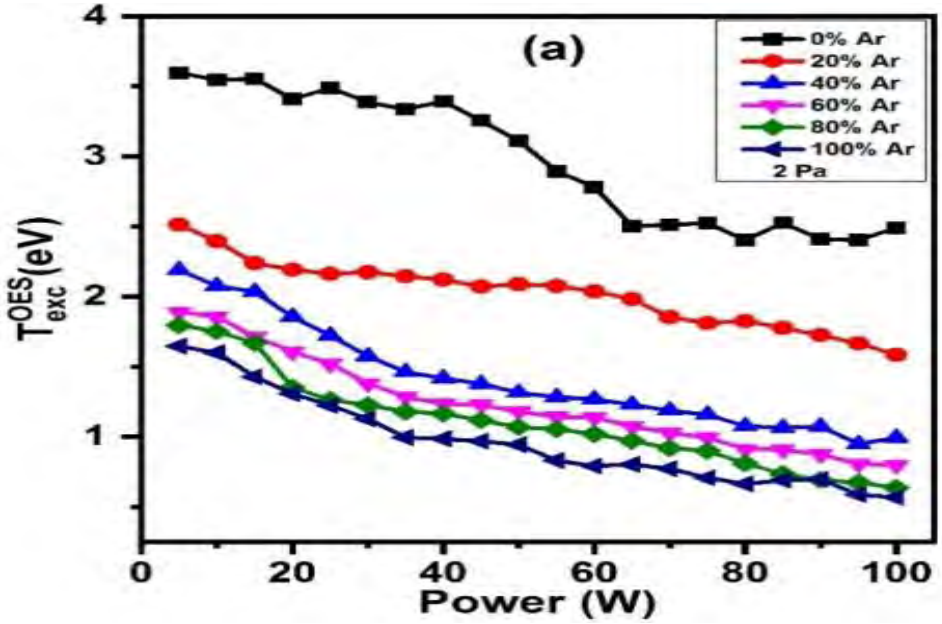

Figure 4.5 (a) Variation of Electron Excitation temperature with power at different Ar percentages at 2 Pa.

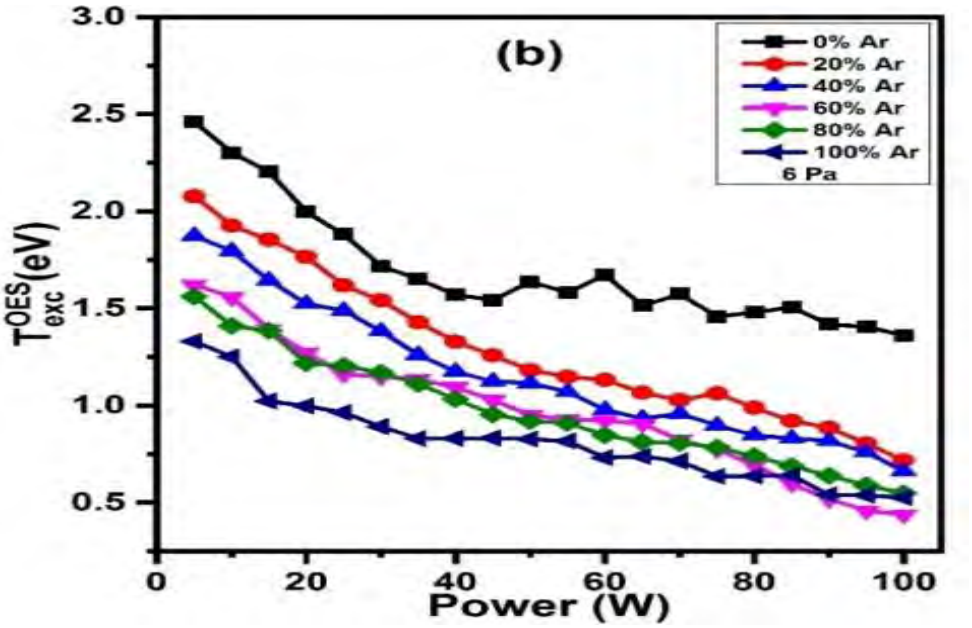

Figure 4.5 (b) Variation of Electron Excitation temperature with power at different Ar percentages at 6 Pa.

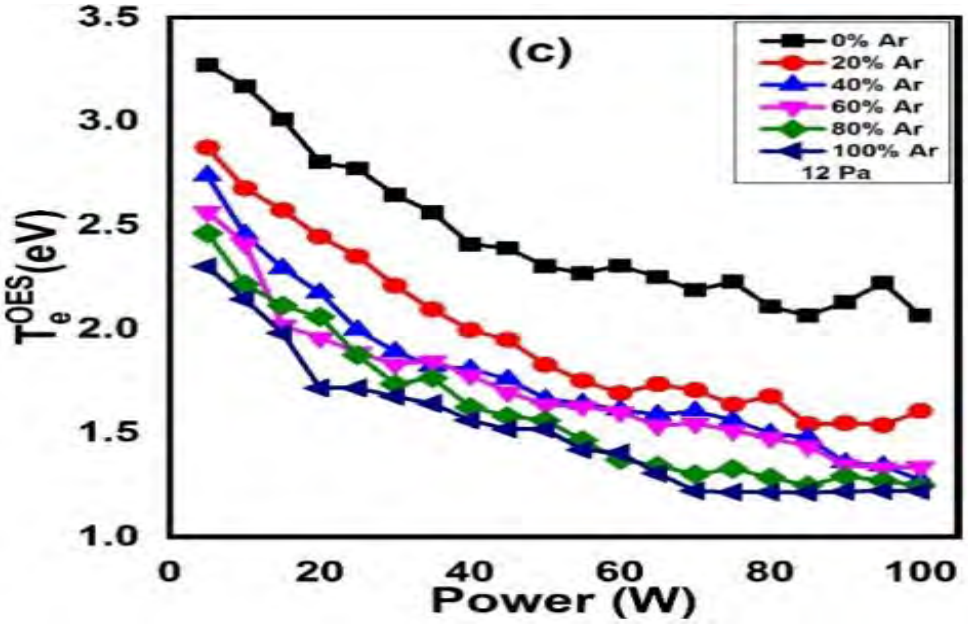

Figure 4.5 (c) Variation of Electron Excitation temperature with power at different Ar percentages at 12 Pa.

4.2.2 Variation of Electron and Excitation Temperature with Argon Concentration

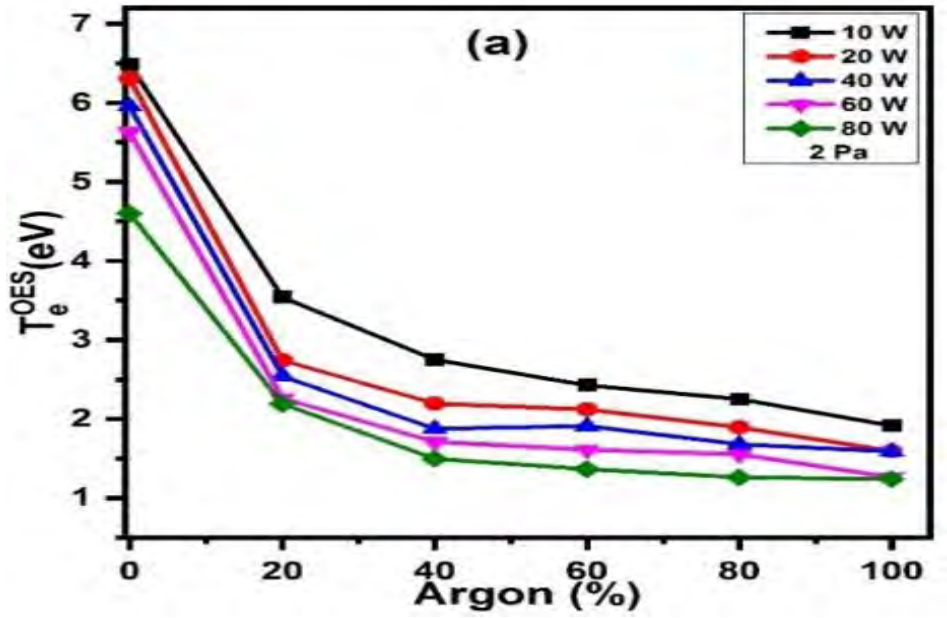

Figure 4.6 (a) Variation of Electron temperature by OES with Ar concentrations with RF Power at 2 Pa.

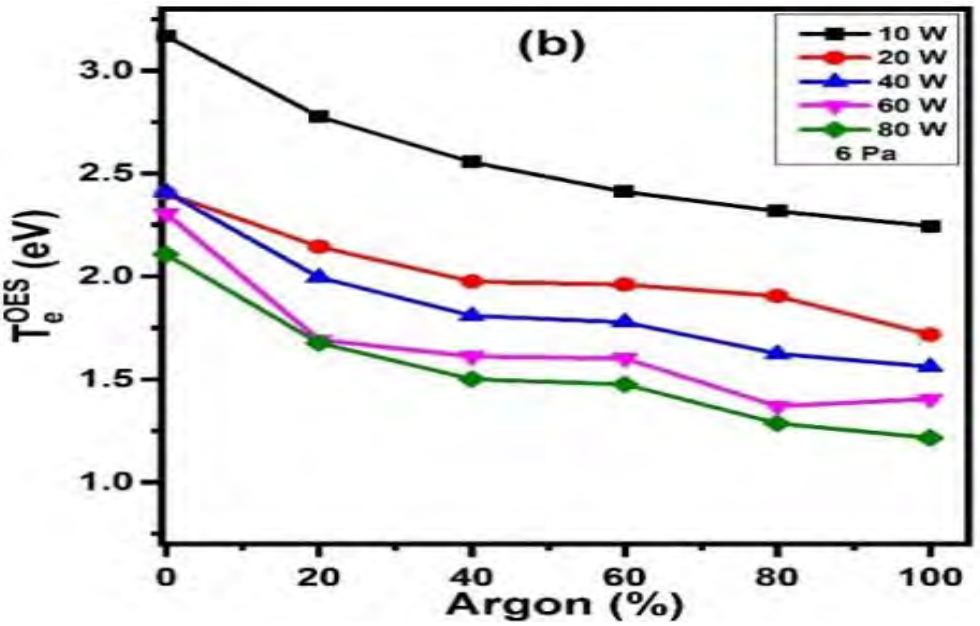

Figure 4.6 (b) Variation of Electron temperature by OES with Ar concentrations with RF Power at 6 Pa.

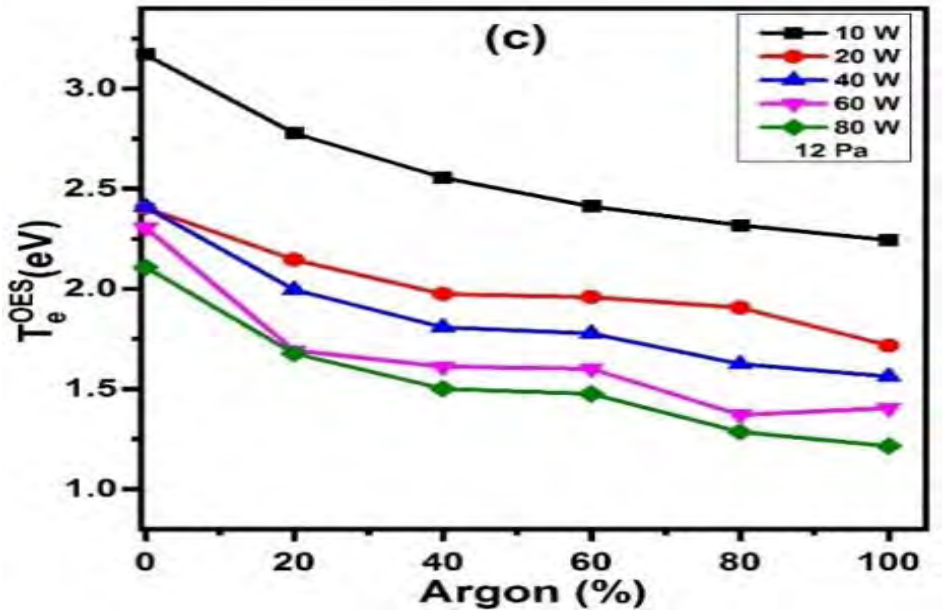

Figure 4.6 (c) Variation of Electron temperature by OES with Ar concentrations with RF Power at 12 Pa.

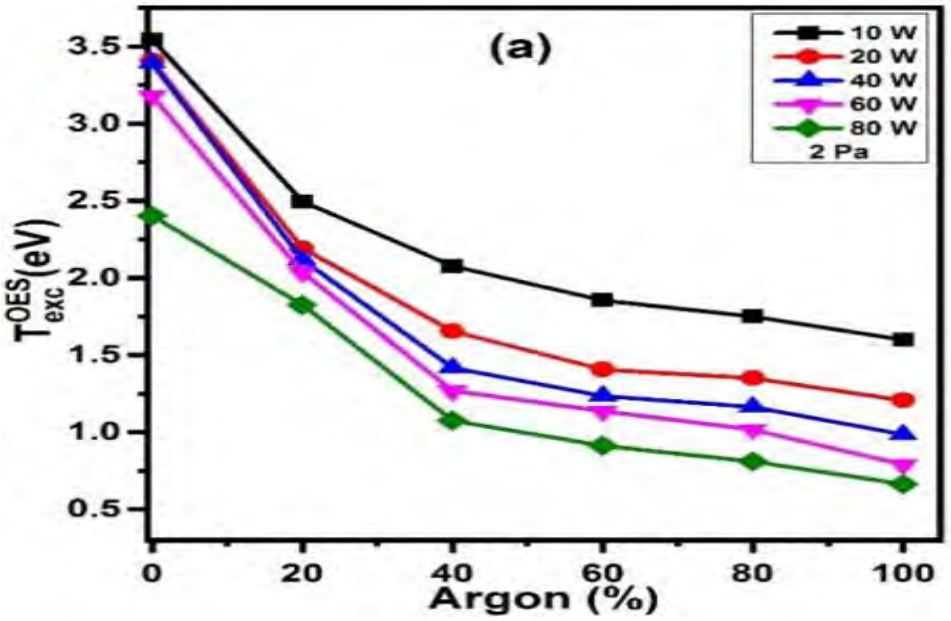

Figure 4.7 (a) Variation of Electron Excitation temperature with Ar concentrations at different RF power and Pressure 2 Pa.

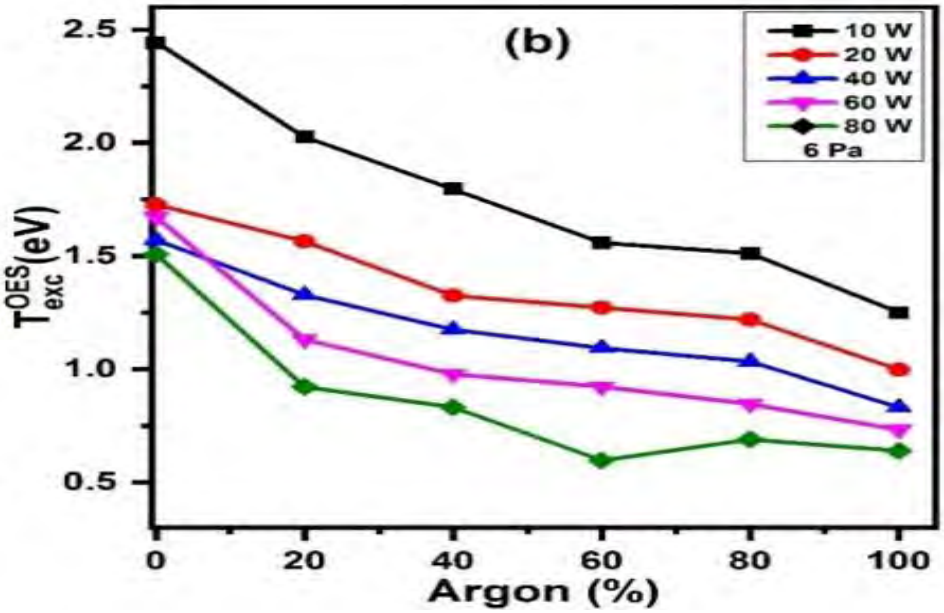

Figure 4.7 (b) Variation of Electron Excitation temperature with Ar concentrations at different RF power and Pressure 6 Pa.

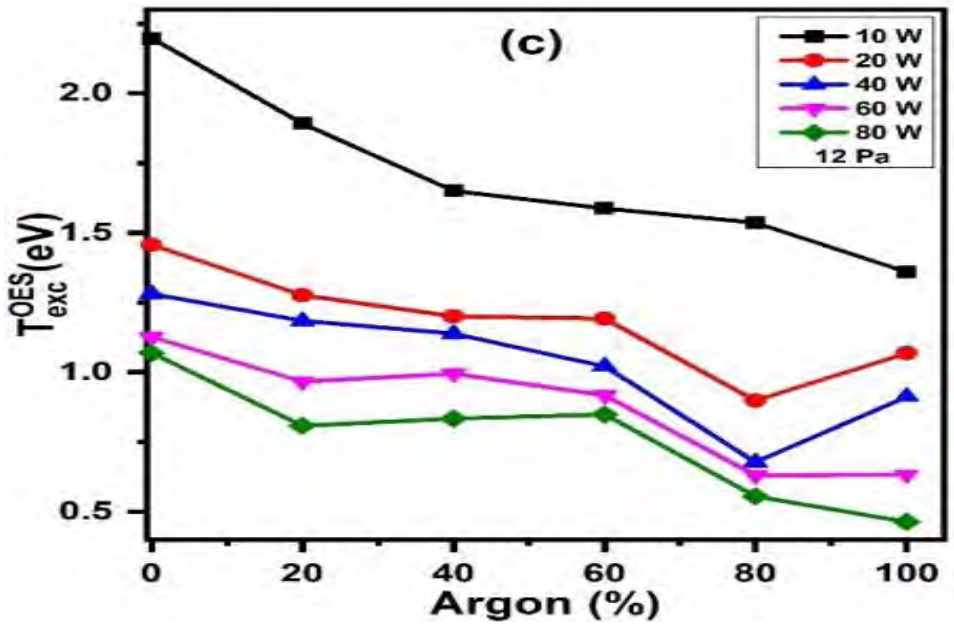

Figure 4.7 (c) Variation of Electron Excitation temperature with Ar concentrations at different RF power and Pressure 12 Pa.

Figures 4.6(a, b and c) and 4.7(a, b and c) shows the variation in excitation temperature and electron temperature relative to the amount of argon in the discharge for various RF powers under constant pressure. The spectroscopic temperatures show a characteristic that decreases with Argon concentration. Ionization cross-section of atoms and ionization potential can be used to explain it. In comparison to Argon, the neon atom has a larger ionization potential, and its ionization cross-section area is smaller. As a result, Argon atoms are ionized more successfully than Ne atoms. Due to repeated inelastic collisions between electrons and plasma species of the constituent gases, the temperature of the electrons decreases in this situation. [38]

4.3 Conclusion

In the first step of this experiment, the behavior of neon-argon intensity of the selected emission spectral lines is measured from Optical Emission Spectroscopy (OES) recorded spectrum. The relationship between intensity of spectral lines of neon is 640.2 nm which shows a decreasing trend when the fraction of argon is added and increasing trend show of argon spectral lines is 811.2 nm when the addition of neon concentration in argon.

The second step of this research work is to investigate the effect of Argon fraction variation on Neon discharges. The experiment was performed for the different pressure 2,6,12 pa and RF

power is varied to 5 to 100 watt with an increment of 5 watt. The argon concentration within the neon discharges for each power and pressure varies from 0 to 100 % with an increment of 20 %.It is observed that measured electron temperature and excitation temperature shows a decreasing trend with an increase in RF power and argon concentrations due to the ionization cross-section atoms of ionization potential. Neon atoms have a higher ionization potential in comparison to argon atoms as well as ionization cross–section of neon is smaller.

4.4 Suggestion for Future Work

1 The effect of the mixing with argon on the rotational temperature must be studied because, in plasma processing, rotational temperature plays the important role of plasma thermometer.

2 To investigate the contribution of capacitive and inductive coupling in each mode, a theoretical model should be developed for ICP and Ma PE –ICP which considers these coupling mechanisms.

3 The study of non –LTE He-O_2 and Ar-O_2 mixture plasma with an admixture of nitrogen can be beneficial in Ma-PE –ICP source because reactive nitrogen /oxygen and mono–nitro oxide radicals can be treated with heat-sensitive materials.

4 The role of other rare gases, for instance, e;g helium should be studied in plasma processing material because mixing of neon with reactive gases produces high energy electrons.

References

[1] "Large Optics Manufacturing Study (LOMS)," Fin Bittencourt J.A. fundamentals of plasma physics (oxford, 1986).

[2] D. Macauley, “Elemental Philosophy, Earth, air, water and fire as fundamental ideas” Suny Press 2010,

[3] Robert J. Goldstone and Paul H. Rutherford “Introduction to plasma physics” Plasma Physics laboratory Princeton University 1995 IOP Published ltd.

[4] F. F. Chen, "Introduction to plasma physics and controlled fusion", Springer, 1984.

[5] Illingworth, V. Facts on file Dictionary of Astronomy (Facts on File, Inc .New York, 1997).

[6] M. Calzada et.al, ‘Experimental investigation and characterization of the departure from local thermodynamic equilibrium along a surface –wave –sustained discharge at atmospheric pressure. Journal of applied physics, 80 (1996).

[7] H. Griem ‘’Principles of plasma Spectroscopy,’’ Cambridge University Press, 1997.

[8] H. Rauscher ET. al. "Plasma technology for hyper functional surfaces: food, biomedical and textile applications", John Wiley & Sons, 2010.

[9] A. Freidman, "Plasma medicine", John Wiley & Sons, 2012. 2017

[10] Y. P. Raizer, "Radio-frequency capacitive discharges", CRC Press,

[11] K. S. Harsha, "Principles of vapor deposition of thin films", Elsevier, 2005.

[12] D. M. Mattox, "Handbook of physical vapor deposition (PVD) processing”,. William Andrew,2010

[13] G. C. Y. Chan, "Fundamental mechanisms and diagnostic tools for interference effects in inductively coupled plasma-atomic emission spectrometry", Indiana University, 2007

[14] I. Shimamura, ET. al. "Electron-molecule collisions", Springer Science & Business Media, 2013.

[15] B. M. Smirnov, "Reference data on atomic physics and atomic processes", Springer Science & Business Media, 2008

[16] A. Fridman, "Plasma chemistry", Cambridge university press, 2008.

[17] M. A. Lieberman et. al. "Principles of plasma discharges and materials processing", John Wiley & Sons, 2005

[18] Grill, A., Cold plasma in materials fabrication. Vol. 151. 1994: IEEE Press, New York.

[19] V. Godyak, Steady-state low –pressure RF discharges, Sov. J. Plasma Physics. 2(1976).

[20] K. Mackinon, on the origin of the electrodeless discharge', The London, Edinburgh, and Dublin Philosophical Magazine and Journal for science, 8 (1992) 605-606.

[21] I. El-Fayoumi, I. Jones and M. Turner, Hysteresis in the E-to H-mode transition in a planar coil, inductively coupled RF argon discharge, J. Phys. D: Appl. Phys. 31 (1998) 3082.

[22] M. Turner and M. Lieberman, Hysteresis and the E-to-H transition in radiofrequency inductive discharges, Plasma Sources Sci. Technol. 8 (1999) 313.

[23] F. F. Chen, ET .al 'lecture notes on principles of plasma processing', springer science and business media, 2012.

[24] https://en.wikipedia.org/wiki/Plasma -etching

[25] https://tuttnauer.com/blog/low-temperature-hydrogen-peroxide-plasm

[26] "The Fundamentals of Spectroscopy," D. W. Ball, SPIE-The International Society of Optical 'Engineering, 2001.

[27] https://commons.wikimedia.org/wiki/File:EM spectrum's, in.

[28] D. Pavia et al., "Introduction to Spectroscopy," Brooks-Cole, Berkeley, CA, 2003. (2009).

[29] G. C. Y. Chan, "Fundamental Mechanisms and Diagnostic Tools for Interference Effects in Inductively Coupled Plasma-atomic Emission Spectroscopy," Indian University, 2007.

[30] "Parametric study on excitation temperature and electron temperature in low pressure plasmas," H. Park et al., Current Applied Physics, 10(2010) 1456-1460.

[31] P. Chapelle et al., "Plasma diagnostic by emission spectroscopy during vacuum arc remelting," Plasma Sources Science and Technology, 11(2002)301.25] P. Chapelle et al., "Plasma diagnostic by emission spectroscopy during vacuum arc remelting.

[32] http://WWW.nist.gov/.

[33] Spectroscopic measurements of electron temperature in low pressure radiofrequency Ar/H2/C2H2 and Ar/H/cCH4 plasmas used for the synthesis of nanocarbon structures, F. Gordillo-Vázquez et al., Plasma Sources Science and Technology, 15(2005) 42.

[34] T. Meziani and colleagues, "Design of a magnetic pole enhanced inductively coupled plasma source," Plasma Sources Science and Tec al Report Cranfield University, P. Shore et al (2003).

[35] "Inductively coupled plasma spectrometry and its applications,"

[36] N.K. Piracha et al.' Laser excited population redistribution in the $2p^3$ 3p Multiplet in neon. optical communication 2011.

[37] Z.I. Khattak, et al, "Correlation between Langmuir Probe and Spectroscopic Temperature in inductively coupled Neon-Argon Mixture Plasma, Plasma physics Report ,46(2020)800-814.

[38] S. Orazbayev, et.al. "A calculation of the electron temperature of complex plasma of nobel gases mixture in CCRF discharge", Contribution to plasma physics, 55(2015) 428-433.