CHAPTER II

THEORETICAL BACKGROUND

In this chapter, the definition of plasma parameters and the probe characteristics are introduced. The process of the probe data analysis is then described in detail, including the limitation of the technique. Finally, the brief description of a few type of plasma discharges are exhibited in this chapter as well.

2.1 Plasma Parameters

Plasma is the fourth state of matters after the solid, liquid and gas. When gas is given with an external energy, the outer shell electron could be taken away from the gas atom creating free electron and positive ion [12]. At this state, the gas becomes electrical conductive due to charge particles (ion-electron pairs). Afterward, the electron with excited energy will recombine with an ion and then emit photons, where one can see luminousness. The ion-electron particles are continuously generated by ionization (excitation) and depleted by recombination (relaxation); therefore, the balance of both processes requires the external source to sustain a steady state of electron and ion populations. This is the mechanism in the plasma formation.

2.1.1 Plasma Density

Because of the ionization mechanism, clusters of the positive ions and negative electrons are formed in a sea of neutral gas (as shown in figure 2.1). The densities of these clusters are the same on average, but much less when compared with the neutral density, so they are well known as the "plasma density." Typically the electron and ion densities is related by

$$n_e \approx n_i = n_p \tag{2.1}$$

where n_e, n_i and n_p are electron, ion and plasma densities, respectively. This relation shows the electrical neutrality for the plasma (quasi-neutrality), since sum of the net Coulomb interaction become zero. The plasma, however, is more electrically conductive than gas does, because there are electron and ion particles conducting the electricity.

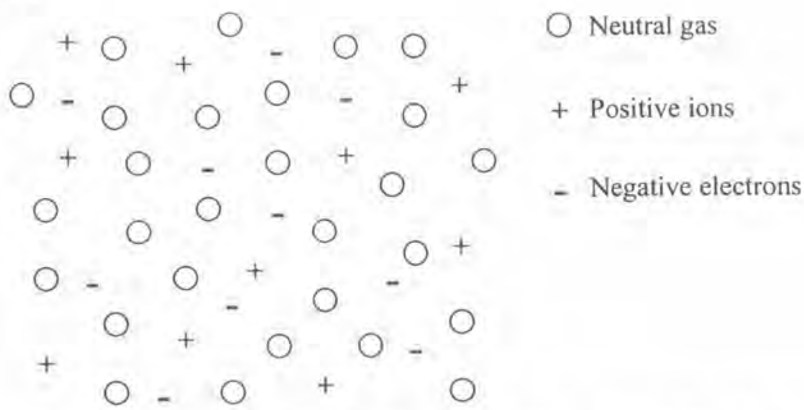


Figure 2.1: A simple plasma consisting of positive ions, negative electrons and neutral gas.

2.1.2 Ion and Electron Temperatures

In general, gas molecules would absorb energy from the environment, which is stored in the form of kinetic energy. For the overall kinetic energy of the gas, the mean kinetic energy ($\overline{E}$) is used to describe the relation between the mean square velocity ($\overline{c^2}$) and the absolute temperature (T) [13,14].

$$\overline{E} = \frac{1}{2}m\overline{c^2} = \frac{3}{2}kT \tag{2.2}$$

where m is the mass of the gas molecule, and k is Boltzmann's constant. From the equation, the higher the gas temperature is, the faster the gas particles motion get. However another useful parameter is

$$\overline{c} = \sqrt{\frac{8kT}{\pi m}} \tag{2.3}$$

where $\bar{c}$ is the mean velocity quite. The concept of kinetic energy in gas molecules is based on Maxwel-Boltzmann distribution, which is usually used to describe the statistical distribution of random velocity.

In plasma, which is a collection of charged and neutral particles, this concept can apply to positive ions and negative electrons, according to the temperature of charged particles—ion temperature (T_i) and electron temperature (T_e). This is because of the energy transfer in collision. The energy transfer between the lighter electrons and the heavier molecules or positive ions rarely takes place, except for electron-electron collisions; as a result, the energy is only deposited in the electron, i.e. $kT_e >> kT_i \approx kT$.

$$\bar{c}_i = \sqrt{\frac{8kT_i}{\pi m_i}} \tag{2.4}$$

$$\bar{c}_e = \sqrt{\frac{8kT_e}{\pi m_e}} \tag{2.5}$$

where the "i" and "e"subscripts represent the positive ion and the negative electron, respectively. Since m_e is very much smaller than m_i and T_e is higher than T_i, one will expect the electron in equation (2.5) to move very fast when compared with the ions in equation (2.4) and neutral gas molecules. Also, whereas the energy of electrons is enormous, the ion can have a mean kinetic energy not higher than the energy of the gas molecule because of the low mean speed and low temperature.

2.1.3 Plasma Potential

Consider if a small plate is inserted into plasma, charge fluxes (electrons and ions) or current densities will flow into it. For the electrons and ions, the current densities represent in the equation (2.6) and (2.7), respectively.

$$j_e = \frac{en_e\bar{c}_e}{4} \tag{2.6}$$

$$j_i = \frac{en_i\bar{c}_i}{4} \tag{2.7}$$

In the beginning, electrons will accumulate in the plate, since $\bar{c}_e$ is much higher than $\bar{c}_i$; in other word, j_e is very large. So the object will be negatively charged by the electron current and build a negative potential up with respect to the plasma. In this case, the plasma will be perturbed with the negatively-charged plate by repelling electrons and attracting ions, and an electric field will appear around negative object. Then the electron flux decreases because of the repulsion, in the meantime the cloud of ions will surround the negative object to shield the electric field, leaving no electric field outside the cloud. Generally, the plasma is in an equipotential, except around the perturbation; therefore, this equipotential is termed as the "plasma potential" or "space potential."

2.1.4 Sheath Formation

When an isolated plate appears in the plasma, it will be suddenly charged with the negative potential, this causes electrons to be forced away from the object, except a few electrons with high energetic energy can overcome such repulsion. Consequently, the cloud of ions (namely space charge) forms a barrier so called "sheath" around the plate to attenuate that potential. Figure 2.2 shows the space charge surrounding in front of the plate. In the context of glow discharge plasma, the luminosity in the sheath is lower than the glow region, hence it is known as a dark space. The reason is that the glow intensity of plasma results from the relaxation of electrons, when the electron density in the sheath decreases; therefore, the luminosity of the sheath is dimmer.

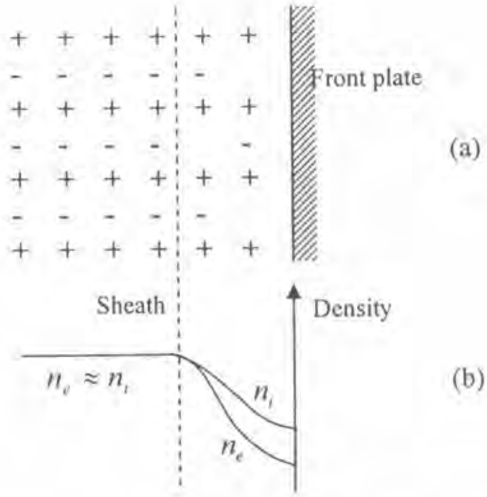


Figure 2.2: (a) a space charge forms up from the plate and results in the sheath formation, and (b) density profiles in the sheath.

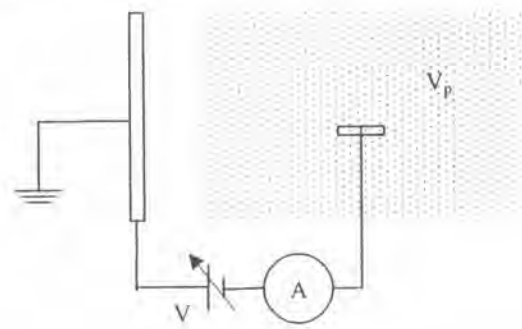
A meaningful value, used to estimate how far the sheath is formed to attenuate the potential perturbation, is termed as Debye length having the length dimension. If the equipotetial in the plasma is disturbed, the thickness of the sheath will shield the perturbation over distances of the order of the Debye length. In the glow discharge plasma; for example, the electron density is in the order of 10^{10} cm^{-3} and we choose kT_e approximately 2 eV; therefore, the Debye length is about 105 micrometers [13]. This means that the thickness of the sheath to shield the perturbation in order not to disturb the plasma is around one hundred micrometers; however, this value depends upon both the plasma density ($n_e \approx n_i$) and the electron temperature as

$$\lambda_D = \sqrt{\frac{kT_e \varepsilon_0}{n_e e^2}} \qquad (2.8)$$

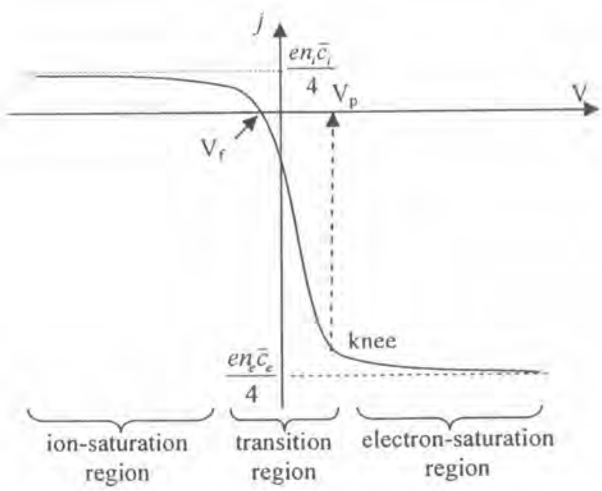
where λ_D and ε_0 are the Debye length and the permittivity of vacuum, respectively.

2.2 Probe Characteristics

As mentioned previously, when an electrically isolated plate is inserted into plasma, a sheath will be built up to shield the voltage derivation. The potential outside the shielding is of the plasma potential. Now, we will consider an external power source supplies to a probe by varying from negative to positive voltage with respect to the plasma potential. The characteristic of probe current density versus probe voltage is depicted in figure 2.3(b). By biasing with negative voltage, the ions will be accelerated and collected by the probe; subsequently, the probe current density becomes positive saturation. This saturation current strongly depends on the random flux in the plasma discharge, i.e. $n_i \bar{c}_i / 4$, because of no electron flux reaching the probe. This region is then defined as the ion-current saturation region. When the probe is biased toward the positive voltage, the current density gradually decreases until it becomes zero because of the equality of both ion and electron fluxes. At this state, the potential is termed as the "floating potential" (V_f), which is occasionally used to separate the ion-saturation region out from the next region, knows as the "transition region" or "retarding-field region" [1,10].



(a)



(b)

Figure 2.3: Showing (a) schematic for probe measurement with respect to the plasma potential and (b) Current density-voltage curve of the probe [13].

In the transition region, the probe current density abruptly changes because of the combination of current inflow of both electron and ion densities. In other word, the total current density to the probe is due to j_i plus j_e, when the probe voltage is less than the plasma potential, that is

$$j = \frac{en_i\bar{c}_i}{4} - \frac{en_e\bar{c}_e}{4}\exp\left(\frac{-e(V_p - V)}{kT_e}\right) \tag{2.9}$$

In contrast, the net current in the ion-saturation region is only of j_i; therefore, the exponential change of the probe current density in the transition results from j_e for $V < V_p$.

$$j_e = \frac{en_e\bar{c}_e}{4}\exp\left(\frac{-e(V_p - V)}{kT_e}\right) \tag{2.10}$$

This expression is derived on the assumption that the electrons have a Maxwellian energy distribution. A similar argument for $V > V_p$ is written by

$$j = \frac{en_i\bar{c}_i}{4}\exp\left(\frac{-e(V - V_p)}{kT_i}\right) - \frac{en_e\bar{c}_e}{4} \tag{2.11}$$

On account of $T_i << T_e$, the exponential term will rapidly go to zero, when V exceeds V_p, leaving only the second term, the electron-saturation current density. This region is called the "electron-saturation region" which lies behind V_p at the knee of the curve.

2.2.1 Probe Diagnostic

In practical plasma experiment, an electrical probe is widely used to study properties of plasma. Such properties include the plasma potential which is an equi-potential in the plasma, the electron temperature that represents the electron motion in the kinetic energy form, and the electron or plasma density that means a number of electrons, equal to ions, occurring from the ionization. By directly inserting the electrical probe tip into the plasma, the plasma will be locally perturbed. The other end of the probe is supplied by a power source with respect to ground, as seen in figure 2.4.

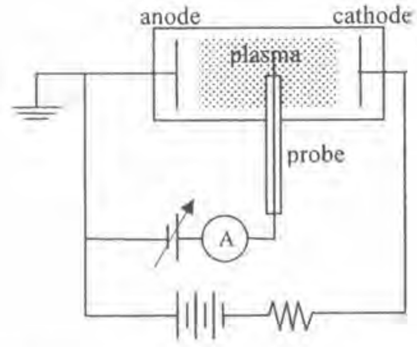


Figure 2.4: A simple circuit of probe measurement.

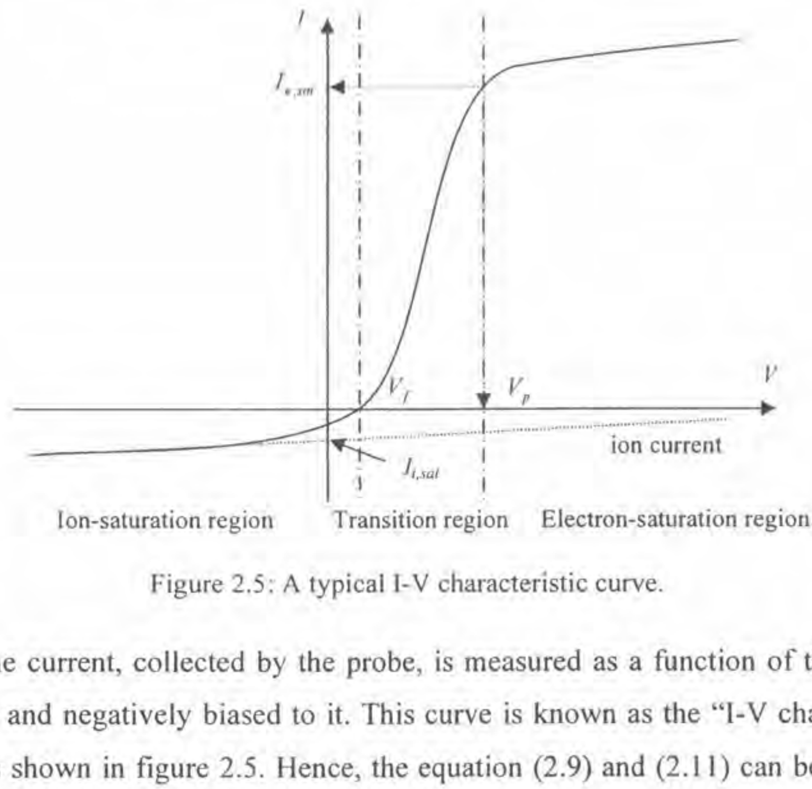


Figure 2.5: A typical I-V characteristic curve.

The current, collected by the probe, is measured as a function of the voltage positively and negatively biased to it. This curve is known as the "I-V characteristic curve", as shown in figure 2.5. Hence, the equation (2.9) and (2.11) can be rewritten by

$$I = \frac{en_i\bar{c}_i A}{4} - \frac{en_e\bar{c}_e A}{4}\exp\left(\frac{-e(V_p - V)}{kT_e}\right) \tag{2.12}$$

for $V < V_p$, and

$$I = \frac{en_i\bar{c}_i A}{4}\exp\left(\frac{-e(V - V_p)}{kT_i}\right) - \frac{en_e\bar{c}_e A}{4} \tag{2.13}$$

for $V > V_p$, respectively [15], where A is the area of the probe tip exposed to the plasma. From the equation (2.10), the electron current (I_e) can be written as

$$I_e = \frac{en_e\bar{c}_e A}{4}\exp\left(\frac{-e(V_p - V)}{kT_e}\right). \tag{2.14}$$

By taking the natural log of this equation, we will get

$$\ln I_e = c - \frac{e(V_p - V)}{kT_e} \tag{2.15}$$

where c is a constant, i.e. $\ln(en_e\bar{c}_e A/4)$. The tendency of the $\ln I_e$, depending on V, will be probably linear, hence the inverse slope ($\Delta V/\Delta \ln I_e$) of this expectation can yield the electron temperature.

$$\frac{kT_e}{e} = \frac{\Delta V}{\Delta \ln I_e} \tag{2.16}$$

In the interpretation of the probe characteristic, I-V curve can be divided into three major regions, as seen in figure 2.5. The first is the ion-saturation region where the current gradually decreases, as the probe voltage negatively increases. This region is named as aforementioned because it is saturated by the ion current (I_i). The next region is defined as from the floating potential to the plasma potential, namely the transition region. One can see the rapid increase in the current, whereas the voltage only slightly changes. Since the probe not only gains the ion current, but also draws in the electron current (I_e). Besides, the latter is based on the electron having Maxwellian distribution with single temperature. And the last part where the probe voltage exceeds the plasma potential is the electron-saturation region, which is saturated by the electron. From the division of the I-V characteristic curve, plasma parameters could be figured out from each region.

The first parameter that can be found from the curve directly is the plasma potential. At the knee between the transition and electron-saturation regions, the voltage on the x axis is that of the plasma potential. An easy way to define this potential is to fit two straight lines in the two regions, transition and electron-saturation. The intercept of these lines will give not only the plasma potential, but also the electron-saturation current ($I_{e,sat}$), which can be used to calculate the electron density later. In addition, the other potential, floating potential, can be directly defined from the curve, when the probe current approach to zero.

For the electron temperature and density analysis from the I-V characteristic curve, one should comply with the following steps. First of all, the ion current must be subtracted from the I-V curve. Since this curve comes from the combination of the ion and electron currents collected by the probe, so only the electron current has to be taken into account. To subtract the ion current, one ought to fit a straight line in the ion-saturation region and then extrapolate this line to all over V . The second step, after the I-V curve subtracting out the ion current, is to re-plotting the I-V curve in the semi-log scale. According to the expectation in the equation (2.15), the natural log of the electron current versus the probe voltage curve would show the linear line in the transition region (from the floating to plasma potentials). The inverse of the slope would give the value of the electron temperature, expressed in the equation (2.16). Finally, the electron density can be calculated from the equation (2.17) into which the electron temperature and the electron-saturation current are substituted.

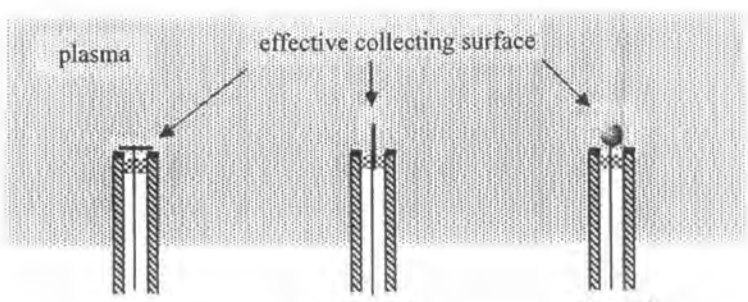
$$n_e = \frac{I_{e,sat}}{eA}\sqrt{\frac{2\pi m_e}{kT_e}} \tag{2.17}$$

Another way to calculate the plasma density is to figure out the ion density (n_i). The expression of the density is written in equation (2.18) by substituting the electron temperature, the ion-saturation current ($I_{i,sat}$), and the ion mass (M_i) into it [16]. For the ion mass, it depends on the gas species that contain in the chamber.

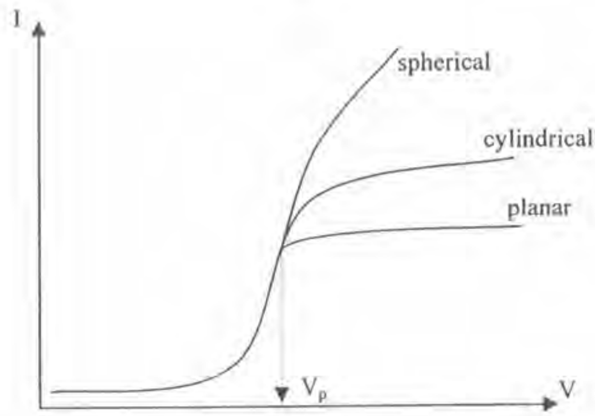
$$n_i = \frac{I_{i,sat}}{eA}\sqrt{\frac{2\pi M_i}{kT_e}} \tag{2.18}$$

2.2.2 Complexity of Probe Technique

There are some concerns when the probe technique is used to analyze plasma parameters. One of them arises from shapes of probes, such as planar, cylindrical and spherical, which exposed to the plasma. The reason is that not the geometric surface areas that draw current into the probes, but rather the effective current-collecting areas of the probes that occur from the interface between the plasma and the sheath, as shown in figure 2.6(a). The effective areas would change as a function of the probe voltage, and the sheath of the spherical probe seems to be the larger of the two probes. So, these effects attempt to draw more electron current into them, and cause an effect on the I-V characteristic curves, illustrated in figure 2.6(b). The planar probe takes less effect when the probe voltage approaching the plasma potential, whereas the plasma potential of the spherical probe is difficult to define. Unfortunately, the construction of the planar probe is difficult. Therefore, the cylindrical probe seems to be the compromise solution which is easily constructed and clearly determination of the plasma potential. And the solution of the probe-collected current could be handled by choosing as very small probe as possible.



(a)



(b)

Figure 2.6: Effects of the probe types, such as planar, cylindrical, and spherical, on (a) the effective current-collecting area of probes and (b) I-V characteristic curves.

Additional charge generation, secondary electrons, is another problem. These electrons can come from many ways, most of which result from the impact of particles on to surfaces, including electrodes and reactor chamber [17]. Such impact could give rise to heating effects which may result in the additional electrons. Even in the sheath itself, electron impact ionization could take place. In the dc discharge, electrons at the cathode would be accelerated into the plasma not only to cause ionization but also to enhance additional current flow [18]. These charge generation can cause the problem in the probe measurement by enhancement of probe current.

2.3 Plasma Discharges

There are a few types of discharge systems to ionize gas into plasma phase. Direct-current, alternative-current, and radio frequency plasma discharges are generally used in plasma laboratory.

2.3.1 Direct Current (DC) Plasma Discharge

A DC glow discharge is one of the plasma-generating systems in laboratory. It is one of the simplest and less complex plasma discharges. This system consists of two electrodes, anode and cathode, which separately lie in a vacuum vessel which fills with gas. By supplying a high enough voltage to the electrodes, the gas that is between two electrodes will breakdown, and the plasma is then generated. The voltage breakdown depends on the gas species, gas pressure and the separation distance of the electrodes. For example, at 0.18 torr in pressure and 2.5 cm of the discrepancy between the electrodes, the voltage breakdowns of air and argon gas are approximately 360 V and 400 V, respectively [15]. In addition, the geometry of the system also has an effect on the breakdown. The simplicity of the DC discharge system is shown in figure 2.4.

2.3.2 Alternative Current (AC) Plasma Discharge

Similar to the dc system, electrodes of an AC discharge are supplied by the alternative current with low frequency, typically conventional mains frequency 50 Hz. The electrodes act as capacitive plate like the capacitive coupled plasma in RF discharge, which is discussed in the next section. The AC source is another discharge type of which the schematic system is shown in figure 2.7.

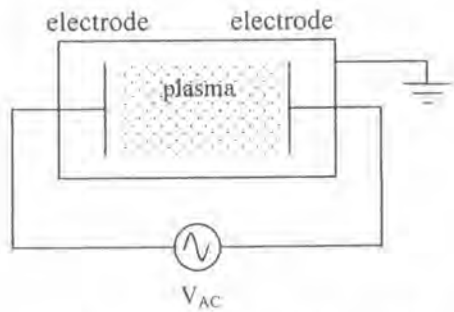


Figure 2.7: A schematic system of an AC discharge.

2.3.3 Radio Frequency (RF) Plasma Discharge

An RF plasma system is another plasma discharge by using a power source at the radio frequency, typically 13.56 MHz, to generate plasma under the low pressure condition. The system can be divided into two categories, capacitive coupled plasma (CCP) and inductive coupled plasma (ICP). For the first one, CCP, two parallel plates, located in the vacuum chamber with a gas, are supplied by the power source with the RF, as depicted in figure 2.8(a). The power would transfer energy to the gas and ionized to the plasma phase. The ICP is another system which uses a coil flowed with current so as to induce the secondary current in the chamber, illustrated in figure 2.8(b). The secondary current causes the gas in the chamber into turn to plasma.

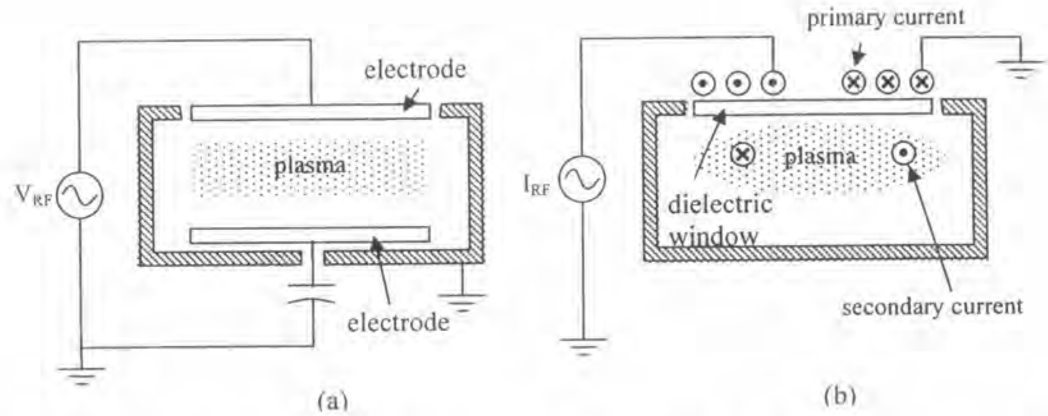


Figure 2.8: Schematic diagrams of (a) capacitively coupled plasma and (b) inductively coupled plasma.