Chapter 3

Discharge Characteristics of the ICP System

3.1 Overview

Around the mid to late 1980s, inductively coupled plasma system started to be used in plasma processing. The solenoid type inductively coupled plasma system was first used and later planar coil system was introduced[52]. Planar coil inductively coupled plasma system has attracted much interest since it can produce a large area of uniform plasma which is suitable for ultra-large-scale integrated circuit fabrication process.

In an inductively coupled plasma, two distinct modes of plasma condition exist. At low power, the discharge is said to be in E mode operation, it is also called the first stage of discharge[53]. At higher power, the discharge is said to be operated in H mode. The transition between these modes exhibits hysteresis[54,55].

A basic understanding of the mechanisms of RF discharge is required for process control and to obtain the optimum choice of the most important plasma parameters. In order to study the characteristics of the RF ICPs, a series of experiments have been carried out and the results are presented in this chapter.
In the planar coil configuration, cylindrical coordinate system is used with the origin at the center of the coil and positive $\hat{z}$ is pointing away from the coil on the plasma side while $\hat{r}$ is the radial coordinate. When the induction coil as shown in Figure 3.1 is powered by an RF source, the RF current will pass through the coil thus generating the electromagnetic field.

![Cylindrical Coordinate System Diagram](image)

**Figure 3.1:** The cylindrical coordinate of the planar spiral coil configuration

At low input RF power, the discharge in an ICP is characterized by a faint light emission from the plasma and a low electron number density. At this stage the radial electrostatic field ($E_r$) is larger than the azimuthal inductive field ($E_\phi$) produced by magnetic induction and it is responsible for maintaining the plasma. This is called the E mode discharge.
When the input RF power reaches a certain critical value, there will be a sudden increase in the plasma’s luminosity and the electron density, signaling the onset of the inductive RF discharge known as H mode discharge. The H mode discharge is maintained primarily by the azimuthal inductive \((E_\theta)\) and the radial electrostatic field \((E_r)\) plays only a small role.

It should be emphasized that, in either working regime, the two components coexist and it is the relative contribution which changes drastically during the E to H mode transition.

### 3.2 Experimental observation of E to H mode transition

The reactor chamber is cleaned thoroughly before the experiment. The reactor chamber is evacuated to the base pressure \((\approx 10^{-4} \text{ mbar})\) by the turbomolecular pump. Argon or hydrogen gas is introduced into the chamber to a pressure of 1 mbar through the MKS mass-flo controller.

The chamber is discharge cleaned by hydrogen discharge for 10 minutes. After that, the chamber is pumped down to the base pressure again and the same procedure is repeated for 3 times to minimize the contaminants in the reactive chamber. Then, the pressure is adjusted to the desired value. Finally, the RF generator, fans and diagnostic instruments are switched on. The RF generator is first set to a low power level and the tunable capacitor of the matching network is adjusted to minimize the reflected power.
The forward RF power is then increased until the desired mode of plasma is generated. The coil current is measured by the Pearson probe and the coil voltage is measured by the capacitive voltage probe.

The observation of E to H mode transition is carried out with argon gas for the preliminary study by following the procedure described above. The relationships of coil current and coil voltage versus RF power are similar. Both of the plots (Figures 3.2 and 3.3) demonstrate a sudden change during E to H mode transition and manifest hysteresis-like behaviour.

From Figure 3.2, when the RF power is increased, the coil current also increases [from point (1) to point (2)] due to the increase of the RF forward power and hence more current passes through the induction coil. The discharge is operated in the E mode. At the critical point (2), the transition from E mode to H mode occurs. The coil current drops abruptly from point (2) to point (3). This is due to an increase in the plasma resistance which dominates over the decrease in the effective inductance of the induction coil during the transition. The discharge is operated in H mode from point (3) to point (4). On reducing the RF power from point (4), the H to E mode transition is observed to occur at point (5) instead of point (3). Such hysteresis behaviour of the planar coil ICP has been studied by El-Fayoumi[55]. Figures 3.4 and 3.5 show the E mode and H mode argon discharges generated by the ICPs.
This experiment is repeated with hydrogen gas. The coil current and coil voltage versus RF power in hydrogen discharge are obtained and shown in Figures 3.6 and 3.7 respectively. It can be seen that the E to H mode transition of hydrogen discharge cannot be obtained within the RF power of 550W available in the present system. The discharge is characterized by faint light emission. The discharge is mainly sustained by electrostatic field referred to as E-mode discharge.
Figure 3.2: Coil current versus RF power of argon discharge at 0.7 mbar

Figure 3.3: Coil voltage versus RF power of argon discharge at 0.7 mbar
Figure 3.4: Argon E mode discharge

Figure 3.5: Argon H mode discharge
Figure 3.6: The coil current versus RF power of hydrogen discharge

Figure 3.7: The coil voltage versus RF power of hydrogen discharge
The RF power required to produce E to H mode transition in the various types of plasma described above can be reduced by changing the configuration of the system to a smaller volume so that a denser plasma can be obtained as evidence from the significant increase of the luminosity emitted from the plasma. This can be done by placing a glass funnel on the quartz plate located on the upper side of the planar induction coil as shown in Figure 3.8. The base diameter of the glass funnel is 7 cm and the height is 6 cm while the gradient of the wall is 60°. There is an opening with diameter of about 0.7 cm at the upper part of the funnel.

![Diagram of glass funnel and chamber](image-url)

**Figure 3.8:** The position of the glass funnel inside the chamber
With the same operation condition described earlier except now the glass funnel is placed inside the chamber, the E to H mode transition of argon discharge is obtained at 70W RF power as shown in Figures 3.9 and 3.10. It is clear that the H mode discharge can be obtained with lower power by using a glass funnel to restrict the plasma into a smaller volume. The study is also carried out on hydrogen gas and H mode hydrogen discharge can be obtained with RF power below 550W. The hysteresis behaviour of E to H mode transition is clearly shown in Figures 3.13 and 3.14. In this case the transition RF power in the increasing power direction occurs at about 510W, when a sudden increase in plasma luminosity is observed. Simultaneously, an abrupt decrease of coil current and coil voltage are observed as shown in Figures 3.13 and 3.14. All these observations indicate the onset of H mode discharge as shown in Figure 3.16.
Figure 3.9: The coil current versus RF power for argon discharge with glass funnel at 0.7 mbar

Figure 3.10: The coil voltage versus RF power for argon discharges with glass funnel at 0.7 mbar
Figure 3.11: Argon E mode discharge with glass funnel

Figure 3.12: Argon H mode discharge with glass funnel
Figure 3.13: The coil current versus RF power for hydrogen discharge with glass funnel at 0.06 mbar

Figure 3.14: The coil voltage versus RF power for hydrogen discharge with glass funnel at 0.06 mbar
Figure 3.15: Hydrogen E mode discharge with glass funnel

Figure 3.16: Hydrogen H mode discharge with glass funnel
The observation on the effect of introducing a glass funnel into the chamber can be explained as follows: When the plasma is generated inside the chamber without the glass funnel, the plasma will expand to a bigger volume as shown in Figure 3.17. Hence, higher RF power is needed to sustain the plasma as well as to achieve the E to H mode transition.

![Diagram showing plasma expansion](image)

**Figure 3.17**: The plasma expand to bigger volume

While for the second case, the glass funnel placed on the quartz plate is able to trap the plasma into a smaller volume. The discharge is being restricted to the gas inside the funnel as shown in Figure 3.18, resulting in a more efficient heating of the plasma. Hence, H mode discharge can be achieved with a lower power than the case without the glass funnel.
Figure 3.18: The concentration of plasma with glass funnel

One of the distinct indications of the transition from E mode to H mode is the abrupt change in the luminosity of the discharge. In this project, Argon discharge is used to study the change in the intensity of light emission. The argon (Ar⁺) spectral line at 763.5nm is recorded while the RF power is increased to 200W. In Figure 3.19, the plot shows that when the input RF power reaches a threshold value, there is significant increase in the line intensity. This indicates the sharp increase in the density of Ar⁺. The electron number density will also increase. The coupling efficiency of the plasma, i.e. the
ability to absorb RF power, of the ICP discharge increases significantly when it changes from E mode to H mode [54]. The jump in electron density occurring during the transition has also been observed by others [55].

Figure 3.19: The intensity of Argon discharge spectral line at 763.5nm versus RF forward power
3.3 Effect of operating pressure on E to H mode transition

Argon and hydrogen gases are used to investigate the influence of pressure on E to H mode transition of ICP discharges. Figures 3.20 and 3.21 show the RF power for obtaining E to H mode transition and vice versa for argon and hydrogen discharges at different pressures. The RF power required for E to H mode transition is shown by the upper curve whereas the RF power required for the H to E mode transition is shown by the lower curve.

From Figure 3.20, it is shown that higher RF power is needed to obtain E to H mode transition for argon discharge at lower pressure. This is because at lower pressure, there is less particle and electron to initiate the discharge. However, when the pressure is gradually increased, the power required for E to H mode transition decreases until a minimum power of 50W at 0.7 mbar. For the range of pressure between 0.5 mbar to 1.3 mbar, the RF power required for E to H mode transition remains below 100W. Similar investigation has also been carried out for hydrogen discharge at pressure range from 0.02 to 0.11 mbar as shown in Figure 3.21. The observation shows that the E to H mode transition for hydrogen discharge can only be obtained at relatively high power within the pressure range of 0.04 to 0.1 mbar.

There can be several reasons governing the difference between argon discharge and hydrogen discharge. In a discharge volume, an electron travelling through a gas may take part in several processes: elastic scattering, excitation, ionization, recombination,
attachment and other processes. The most important type of collision is electron impact ionization.

\[
e + Ar \rightarrow Ar^+ + 2e
\]

\[
e + H \rightarrow H^+ + 2e
\]

The first ionization potential of hydrogen is 13.6eV while for argon is 15.8eV. However, for hydrogen discharge, dissociation process must occur first to break apart the hydrogen molecule into two hydrogen atoms. This dissociation process is mainly created by electron impact with energy of 8.8eV [56].

\[
e + H_2 \rightarrow 2H + e
\]

Besides, the probability of ionization by electron impact also depends on the density of excited atoms and hence on their lifetime. The lifetimes of these excited states for most species are very short (few milliseconds). However in the case of inert gases, an excited state that has a long lifetime may be populated. Argon has metastable states with lifetime of 55.9s and 44.9s for metastable states of \(4^3\)\(P_2\) and \(4^3\)\(P_0\). For hydrogen, only the state \(2^2\)\(S_{1/2}\) is metastable with a lifetime of 0.12 s[56]. Lonsbury has pointed out that two metastable argon atoms, each of energy 11.55eV, have sufficient energy that their collision can result in the ionization (threshold 15.76eV).

\[
Ar^* + Ar^* \rightarrow Ar^* + Ar + e
\]
Besides, metastable atom can also be ionized by electron impact,

\[ e + Ar^* \rightarrow Ar^+ + e + e \]

The major difference between the ionization of a metastable and of a ground state is that the threshold for the latter of 15.76 eV, while that of the former is 4.21eV for metastable state of energy 11.55eV [57]. These phenomena may explain why argon discharge needs lower power to achieve H mode than hydrogen discharge.

Figure 3.20: RF power required for E to H mode transition of argon gas
Figure 3.21: RF power required for E to H mode transition of hydrogen gas

3.4 Discharge of hydrogen and methane admixture

The plasma enhanced chemical vapour deposition of diamondlike carbon film requires abundance of hydrogen gas mixed with a small portion of methane gas, in order to eliminate the formation of amorphous carbon compound in the thin film. The studies on the effect of varying percentage of methane (0%, 1% and 5%) on the discharge have been carried out and the results are shown in Figures 3.22, 3.23 and 3.24.

Figures 3.22 and 3.23 show the changes of coil current versus RF power which is one of the indication of the E to H mode transition. The pressure of these experiments are set at $6 \times 10^{-2}$ mbar. For a pure hydrogen discharge, E to H mode transition is observed to occur at RF power of about 500W as shown in Figure 3.22. Under similar
condition, 1% methane mixed with hydrogen requires a higher RF power of 540W to achieve H mode discharge. While for 5% of methane mixed with hydrogen, no H mode discharge is observed for up to 550W. The E and H mode of this discharge may occur at power higher than 550W.

For pure hydrogen discharge at $6 \times 10^{-2}$ mbar, RF power of 520W is sufficient for it to achieve H mode. However, when 1% of methane is added, higher power is needed. This phenomenon may be due to more RF power is needed to decompose the methane molecules. Many molecular species can be formed from the decomposed methane molecules such as $\text{CH}^+$, $\text{CH}_3^+$, $\text{C}_2\text{H}_5^+$, $\text{C}_2\text{H}_2$, $\text{CH}_3$, $\text{C}_2\text{H}_2^+$ and $\text{C}_3\text{H}_5^+$. Such species are very reactive and hence higher RF power may be needed to maintain the equilibrium. This can be clearly shown when higher percentage of gas methane is presented in the hydrogen plasma as shown in Figure 3.24.
Figure 3.22: The coil current versus RF power for pure hydrogen discharge

Figure 3.23: The coil current versus RF power for mixture of hydrogen with 1% methane discharge
Figure 3.24: The coil current versus RF power for mixture of hydrogen with 5% methane discharge
3.5 The study of induction heating effect of silicon substrate in hydrogen and methane discharge

The CVD of DLC film requires the sample to be heated to temperatures of about 500°C to 1000°C. In this project, the sample is heated by the induction heating, induced by the electromagnetic field that is generated via the induction coil. The magnetic field is produced when the RF current at a frequency of 13.56MHz is applied to the induction coil. The magnetic field intersects the sample which is placed near to it generating a circulating current in the sample as shown in Figure 3.25. The circulating current induced inside the sample is called eddy current, since it flows in circular path through the cross section of the sample. This eddy current produces a heating effect, equal to $I^2R$ where $I$ is the amount of eddy current and $R$ is the resistance of the sample. The magnitude of this power loss to heat depends on the type of the sample used.

The advantage of induction heating is that the heat is generated directly inside the sample. This enables less hazardous and more pleasant working environment than conventional methods. Furthermore, this heating method requires small space compared to using a heater inside the chamber.

Figure 3.26 shows the change of substrate temperature versus RF power. The graph is nonlinear since the silicon sample is a semiconductor material. The resistance of the semiconductor decreases with increase of temperature. After the RF power of 400W, the sample is observed to be heated faster until about 900 °C at the maximum RF power
of 550W. As can be seen from Figure 3.27, the silicon sample is heated to red hot at this temperature.

Figure 3.25: The induction heating process

Figure 3.26: Substrate's temperature versus RF power
Figures 3.28 and 3.29 show the changes of coil current and coil voltage with the increase and decrease of RF power. Both graphs show a hysteresis behaviour in which the current or voltage abruptly drops and rises at different RF powers. It can be seen that the induction heating sets in at RF power of 400W, in agreement with the graph of substrate temperature versus RF power shown in Figure 3.26. The induction heating, however, switches off at a much lower RF power at about 150W.

In the presence of induction heating of the silicon sample, no H mode discharge is obtained. This is because induction current is in this case induced to flow in the silicon sample instead of through the plasma.
From Figures 3.26, 3.28 and 3.29, it is observed that initially the sample is heated by the plasma heating and the temperature increases gradually. At RF power of about 400W, Figure 3.26 shows an abrupt change in temperature. Meanwhile, the decrease of coil current and coil voltage signaling the onset of the eddy current in the sample. At this stage, the sample is heated by the induction heating effect and the temperature rises sharply.
Figure 3.28: The coil current versus RF power for induction heating of silicon substrate

Figure 3.29: The coil voltage versus RF power for induction heating of silicon substrate