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Unstable plasma characteristics in mirror field electron cyclotron resonance microwave ion source

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Abstract. Electron cyclotron plasma reactor are prone to instabilities in specific input power [3–7] region (150–450 watts). In this region power absorption by gas molecules in the cavity is very poor and enhanced input power gets reflected substantially without increasing ion density. There are abrupt changes in plasma characteristics when input power was decreased from maximum to minimum, it was observed that reflected power changed from $< 2\%$ to $\sim 50\%$. Minimum two jumps in reflected power were noticed in this specific power region and these appear to be highly sensitive to three stub tuner position in the waveguide for this particular input power zone. Unstable plasma region of this source is found to be dependent upon the magnetic field strength. Some changes in reflected power are also noticed with pressure, flow and bias and they are random in nature.

Keywords. Electron cyclotron resonance; plasma instability; magnetic field.

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1. Introduction

Electron cyclotron resonance (ECR) plasma technology has become very important for fabrication of very large scale integrated circuits (VLSI) in etching and deposition [1,2]. A main advantage of ECR plasma is the independent control of substrate biasing and pressure which in conventional reactive ion etching (RIE, based on 13.56 MHz) are dependent on each other which prohibit etching at low pressure and low biasing. It has been found that these discharges are prone to instabilities [3–7] and lead to abrupt transition in plasma characteristics and therefore, a change in processing capability of machine. It is, therefore, very essential to identify region of instability for a particular machine before the machine is used in industrial environment.

There are only a few studies of stability and mode jumps in the literature. Carl *et al* [3] investigated a transition from low density mode to high density mode in case when TE_{11} mode was propagating in the cavity. The discussion was confined to input power range of 0–200 watts and the authors attributed this transition to a change in the propagation of left hand polarized (LHP) wave. Shufflbotham and Thomson [4] observed several distinct mode of ECR plasmas. Gorbatkin [5] observed abrupt changes in plasma characteristics in mirror field were TM_{01} mode was excited in the cavity. Aydil *et al* [6] has made more exhaustive study regarding multiple steady states in electron cyclotron resonance plasma reaction.

In this study we have tried to recognize these instabilities near processing area in our machine covering power range 50–1000 watts. The effect of the gas pressure, magnetic field strength, gas flow and DC bias on these instabilities are established.

2. Experimental

A schematic diagram of the developed ECR system is shown in figure 1. The ECR plasma chamber is built from a stainless steel cylinder with a diameter 300 mm and length 325 mm. The vacuum system includes a varian mechanical pump, model SD-300 and a varian cryo pump model Cryostack-8 capacity 1500 l/s. The pressure of the gas is measured with two gauges; an ionization gauge for measuring pressure of the range of 10^{-3} Torr and below, and a capacitance diaphragm gauge from vacuum general model CMH-01 for the pressure range of 10^{-4} to 1 Torr. Gas flow was controlled by an Alphagaz mass flow controller. The microwave power was generated by a continuously variable microwave power supply from M/s ASTeX, USA (50–1000 W at a frequency of 2.45 GHz). Microwaves in the TM01 mode were launched in the source region through a quartz window (circular of diameter 145 mm and thickness 10 mm). A three-stub tuner was used to tune the reflected power to the minimum value.

A set of two solenoid coils surround the cavity, where the plasma is produced. Each coil is powered by a separate D.C. supply (Electronic Measurements Inc., USA). The entrance coil is powered by 120 A, 20 V. The independent powered coils provide a static magnetic field of the order of 1.25 kGauss by the entrance coil and 0.87 kGauss by the exit coil.

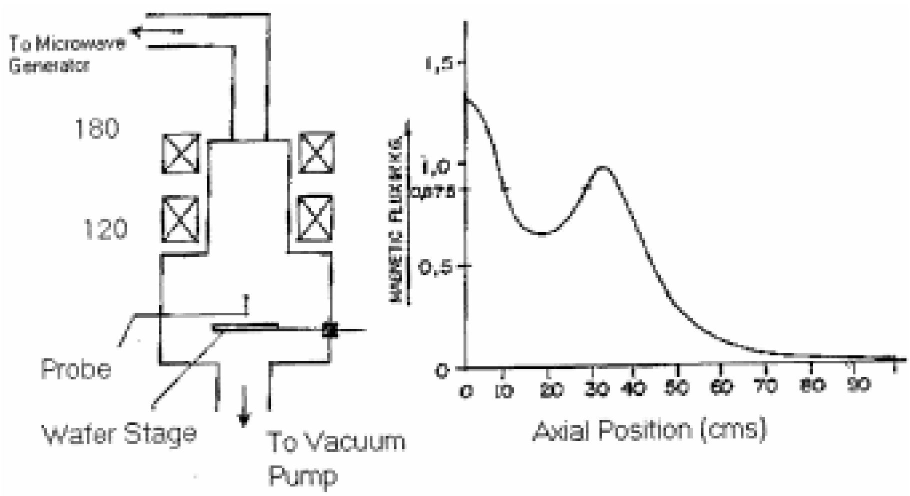

Figure 1. Schematic layout of the ECR system along with distribution of the magnetic field in the system.

The two together create the resonance condition for efficient microwave absorption in the source. A mirror-like configuration of the magnetic field has been formed within the cavity and this configuration is between $Z = 0$ and 33 cms. The ECR zone is found around $Z \sim 10.18$ and 27.9 cms (figure 1). The maximum absorption of the microwave field may be around the first ECR zone [8].

The Langmuir probes were made from tungsten wire (diameter, 0.03 cm) that protruded 0.7 cm from the quartz sleeve. This was mounted on the linear motion feed, so that measurements be taken up along one axis. This linear movement was converted into vertical movement with a simple mechanical arrangement to measure the observation along the Z axis. A bias voltage, in all the subsequent current from the plasma was measured using a digital multi meter. The plasma ion density was estimated from $1 - V$ measurements.

All measurements were made at a distance of 9 cm from the orifice in the process chamber. Magnetic field strength at this distance in the process chamber due to entrance/exit magnets is of the order of 150 Gauss (figure 1). The Larmour radius of electron due to this field is of the order of 0.6–0.8 cm for all gases which is much greater than the probe radius (for a probe position almost parallel to the magnetic field) which favours the assumption of a Maxwellian distribution and also the non-effectiveness of a magnetic field on plasma measurements [9].

3. Results and discussion

The analysis for the instability is based on the calculation of the plasma density from the ion saturation current portion of characteristic curve and corresponding microwave reflected power. The ion current drawn by the probe is given as [10]

$$I_i = \frac{A\mathrm{e}^{2/3} N_i \, 3T_e}{2(\pi)^{1/2} m_i}(1 - \phi/T_e), \tag{1}$$

where $\phi = V_p - V_s$, V_p is the probe potential, V_s is the plasma potential, N_i the ion density, m_i is the ion mass, A is the surface area of probe and T_e the electron temperature in electron volts. The calculated plasma ion density is given by

$$(N_i)^2 = \frac{4\pi m_i}{3A^2 e^3}(\delta I^2/\delta V_p). \tag{2}$$

The ECR microwave plasma of argon (Ar) was studied with variation of microwave power, magnetic field of coils, pressure, flow and at different biasing of the Langmuir probe. The calculated plasma density using the above two equations in all the cases is found to be of the order of $\approx 10^{11}$–10^{12} ions/cm^3.

Experiment was performed at pressure 0.4 mTorr, flow 10 standard cubic centimeter (sccm) and bias -30 volts. It was observed that Pi (input power) versus Pr (reflected power) characteristics are not identical when the power was changed from maximum to minimum and vice versa. In the former case i.e. from maximum to minimum, the reflected power goes to maximum around 50% of input at input power around 450 watts (figure 2) and this value varies from 30 to 45% from observation to observation in the instability range. While in the latter case (i.e. minimum to maximum), around 150 watts of input power (P_i), 20–50% of enhanced input power gets reflected (figure 2) and is not absorbed by gas molecules. Between 150–500 watts of the input power the reflected power jumps between minimum and maximum reflected power (30% to 50% of the input power) but never attains the level of 1% to 2% which is noticed otherwise [3–7,10]. The probe ion current remains almost constant when power is increased linearly from minimum to maximum in the unstable region and it increases as it crosses the unstable region. It is also observed that ion current changes to electron current when there are abrupt changes in the reflected power.

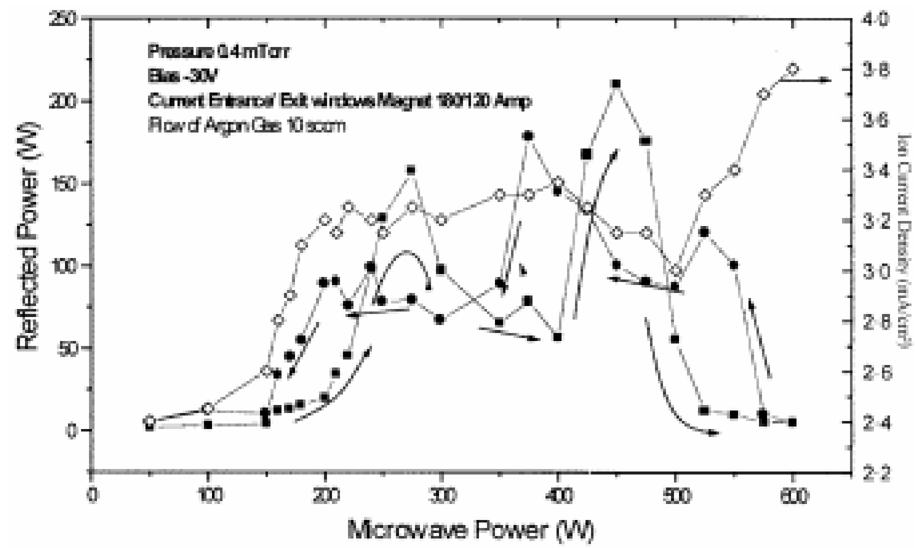

Figure 2. Plot of microwave input power versus reflected power and ion current density at pressure 0.4 mTorr, bias −30 volts of argon flow of 10 sccm at the current of window/exit magnets 180/120 amp respectively. Variation is from minimum to maximum and vice versa also.

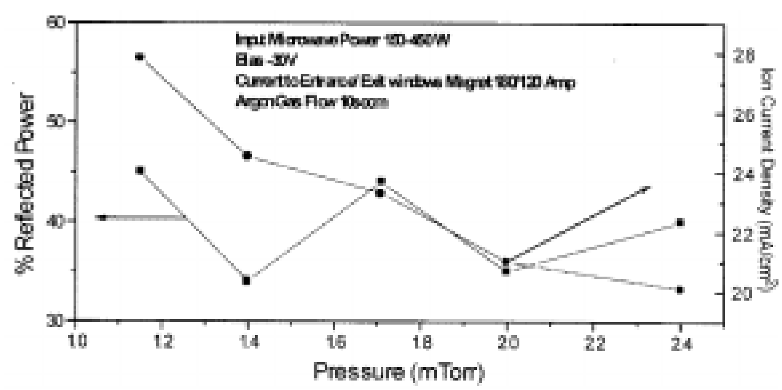

Figure 3. Plot of pressure versus reflected power and ion current density in the microwave power input range of 150–450 W, bias −30 volts of argon flow of 10 sccm at the current of window/exit magnets 180/120 amp respectively.

Experiment was repeated under different pressure, flow rates, magnetic field and bias. It is observed that for different pressures and flow rates, the characteristics of the Pi vs Pr curve remain the same except the small change in the reflected power as compared to figure 2 value is observed.

The observations of pressure and flow are taken where the input microwave power ranges from 150 to 450 W. This is the instability prone region. It is observed that the reflected power is almost 35–45% of input microwave power in the range of pressure from 1.1 to 2.5 mTorr as shown in figure 3 and in the flow range of 10 sccm to 20 sccm argon (Ar) gas as in figure 5. The percentage of reflected power variation with the bias is shown in figure 4 which indicates that the maximum change is at 400 W whereas at low values of input

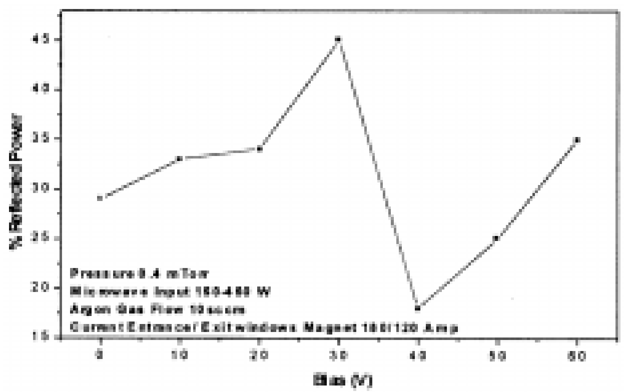

Figure 4. Plot of bias versus reflected power in the microwave power input range of 150–450 W of argon flow of 10 sccm at the current of window/exit magnets 180/120 amp respectively, at presure 0.4 mTorr.

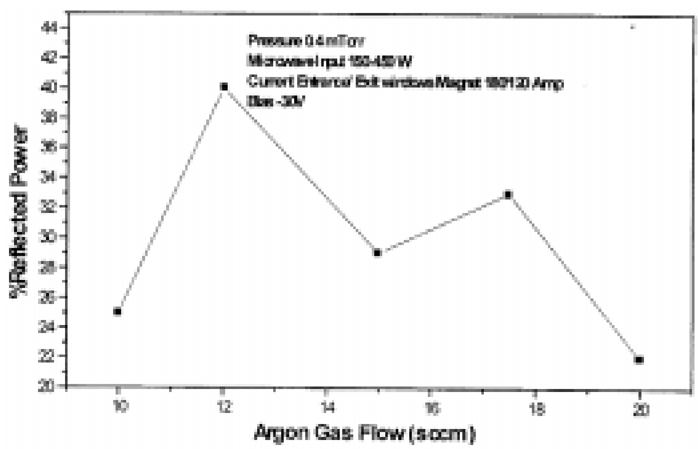

Figure 5. Plot of argon gas flow rate versus reflected power in the microwave power input range of 150–450 W with probe bias −30 volts at the current of window/exit magnets 180/120 amp respectively, at pressure 0.4 mTorr.

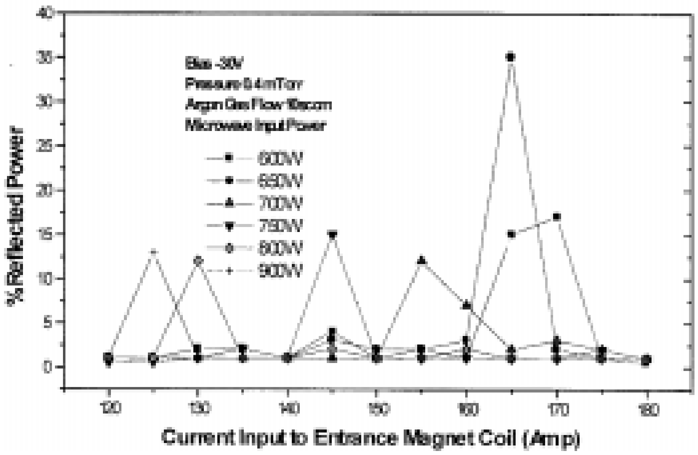

Figure 6. Plot of input current to the entrance coil versus reflected power in the microwave power input range of 150–450 W, bias −30 V of argon flow of 10 sccm at presure 0.4 mTorr.

power the reflectance is low (≈ 18–25%). This instability region also varies with the gas variation which we will be reporting later. It has been observed that such transitions cannot be repeated and are totally random in their characteristics [3–7].

Figure 6 indicates the variation of reflected microwave power (percentage of reflected power) with different magnetic fields [7] at different input microwave power. In the unstable input microwave power region, the per cent changes in the reflected power is not significant. However, there were some changes in per cent reflected power versus magnetic field strength of the window magnet at higher input power range i.e. 600 W to 900 W as shown in figure 6. It shows the retainability of reflected power peak at different power ranges. On higher values of input power, reflected power peak shifts towards the lower value of the input current to the entrance coil. It may be due to the shifts of the magnetic field mirror configuration in the cavity. In this case the strength of the magnetic field in all three conditions is still enough to generate ECR condition. Therefore there is no underdense situation in the cavity at location near ECR zone. The shifting may eventually affect the absorption. We are also working out the temporal effect of plasma instability and will be presenting their finer details in the near future.

4. Conclusion

ECR based system has specific input power region where the plasma conditions are not stable. Processing of the wafer in this region may not lead to repeatable performance in etching and it is therefore desirable for processes to identify such instability regions for optimum use of the system for devise fabrication.

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