Impedance characteristics of a magnetized 13.56 MHz capacitive discharge

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Capacitive driven discharges are well known due to its vast application in microelectronics industries. The operating RF frequency, ω_{rf}, typically lies between electron and ion plasma frequencies, such that $\omega_{pe} >> \omega_{rf} > \omega_{ion}$. The overall impedance of the discharge remains largely capacitive due to the sheath reactance; while the bulk plasma remains inductive. The plasma condition at which the reactance of the sheath and the bulk plasma mutually cancels out is identified as the electron series resonance (ESR). In this work the existence of ESR in the presence of transverse magnetic field, has been investigated from the impedance characteristics of the discharge, for a planar plate and cylindrical electrode configuration in a linear device. The impedance characteristics have been obtained from phase calibrated external power measurements. It is found that the net reactance in the case of parallel plates changes from inductive to capacitive (positive to negative) crossing zero (ESR) as the plasma density increases with applied RF power levels. However, in the cylindrical configuration, discharge produced in argon remains largely inductive for the unmagnetized case; whereas it changes to capacitive in presence of axial magnetic field. For lighter gas helium, the discharge behaviour remains entirely inductive with/without axial magnetic field. This observation can be attributed to effect of low frequency ($\omega_{rf} \approx \omega_{ion}$) RF sheaths, which results in minimal sheath widths leading to small sheath reactance. The ESR condition for the planar geometry has been qualitatively explained based on cross-field plasma conductivity model.

Capacitive discharges are common in plasma etchings of silicon substrates [1]. A capacitive coupled discharge is created by application of RF potentials across 2 separate electrodes where, usual electrode configuration is a parallel plate system. However, a discharge can also be created in other electrode configurations. As the operating RF frequencies are such that $\omega_{pe} >> \omega_{rf} > \omega_{ion}$, the electrons respond to the instantaneous RF potentials in the plasma; while the ions only respond to the time averaged DC potentials; which are mainly concentrated in the sheaths. This leads to some representative features of the capacitive discharge such as capacitive sheath dominated discharge impedance; low current and high voltage discharge as the sheath impedance limits the current through the discharge. this features not only determines the plasma load impedance but also determines the power coupling to different species (electrons/ions) in plasmas [1]. Thus, plasma load impedance is an indirect means to understand the plasma behaviour and power coupling in a capacitive discharge. In this paper we have obtained the impedance characteristics of the capacitive plasma load for 2 electrode configurations in presence of external magnetic fields.

Equivalent circuit Analogy of a Capacitive discharge

A RF CCP discharge is analogous to a complex dynamic electrical load which can be treated as an R-L-C series load, where the sheath behaves as a capacitor C_{sh} in series with an inductor L_p due to electron inertia and resistor R because of electrons/ions collisions in the plasma and sheaths near the electrodes respectively. In this analogy; we have ignored the displacement current in the bulk plasma and the conduction current in the sheath; which is a practical assumption in the operating frequency range of 13.56 MHz ($\omega_{pe} >> \omega_{rf} > \omega_{ion}$) [2,3]. Capacitor C_{st} represents the stray capacitances; which are always encountered in any practical discharge setup.

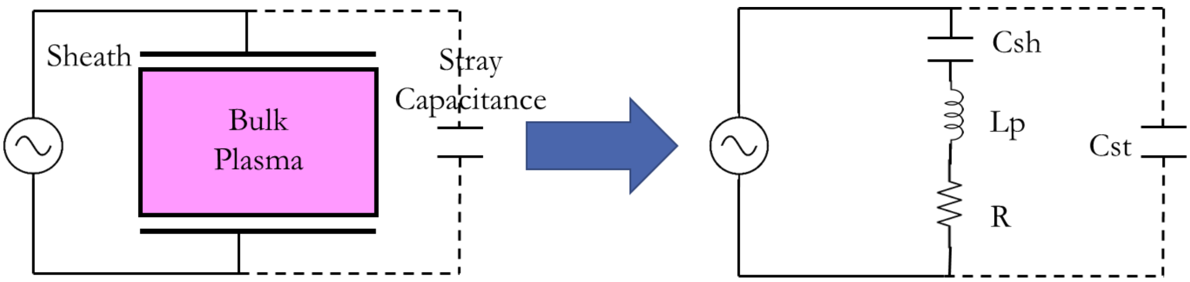

Fig-1: Equivalent Circuit analogy of a CCP discharge

The overall electrical load can be treated as a complex load with impedance R+jX (R-L-C series load) in parallel with a complex capacitive load of -jX_{st} (Reactance of C_{st}). Now, from the electrical measurements of the Voltage (V_{rms}), Current (I_{rms}) and Phase (ϕ) of the discharge circuit and having an estimation of the stray capacitance C_{st} one can solve to obtain the true impedance of the R-L-C series circuit only (value of R+jX; True plasma load impedance); which has been reported in our previous article [4]. Once, the value of R and X are known the phase of the plasma load can be obtained by the using;

$$\phi' = tan^{-1}\left(\frac{X}{R}\right) \tag{1}$$

This actual phase of the plasma can be plotted for various plasma conditions and electrode configurations to characterise the state of plasma.

Experimental setups

Two experimental setups used are (1) Parallel plate discharge setup with transverse B-field and (2) Cylindrical electrode system in a linear chamber in presence of axial B-field.

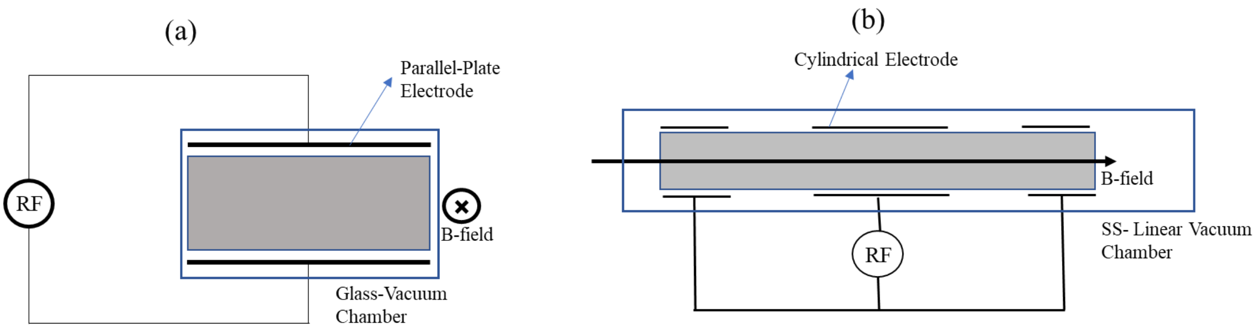

Fig-2: (a) Parallel plate discharge with transverse B-Field and (b) Cylindrical electrode discharge with axial B-field

As shown in Fig-2 (a) Parallel plate setup consists of rectangular electrodes inside a glass vacuum chamber with a provision to generate a transverse magnetic field by a pair of electromagnetic coils placed outside the vacuum chamber; further details of the setup can be found in Ref [4]; while the second setup is a 3-cylindrical electrode system connected as shown in Fig-2 (b) inside a linear Vacuum chamber in presence of axial magnetic field which are generated by external electromagnetic coils.

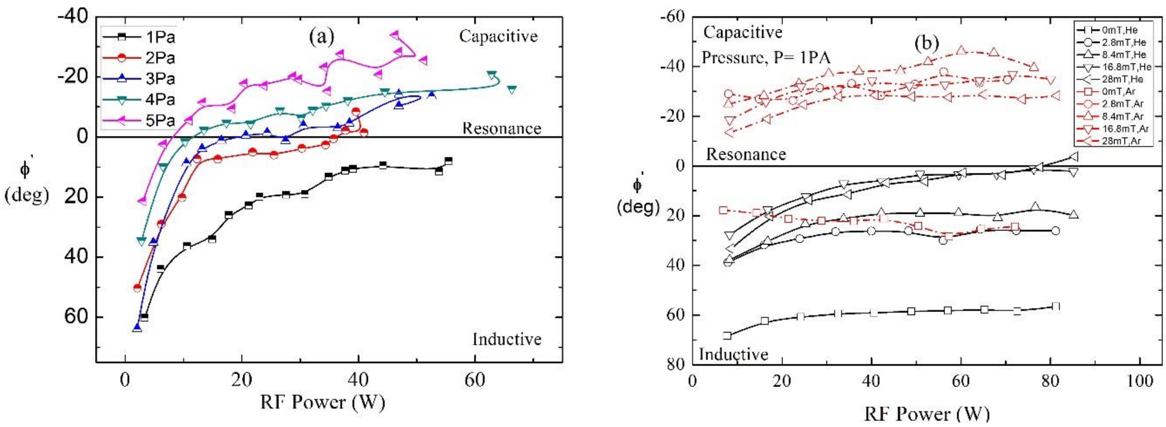

Fig-3: (a) Plasma load Phase for Parallel plate setup for transverse B-Field and (b) Plasma load Phase for Cylindrical electrode discharge with axial B-field

Experimental Results and Discussions

Fig-3 (a) plots the phase (ϕ') obtained by equation (1) with increasing RF power for parallel plate argon discharge in presence of a fixed transverse magnetic field for varying pressures; while Fig-3 (b) plots the phase (ϕ') for the cylindrical setup for Helium and Argon discharge at 1 Pa pressure for different axial magnetic fields. The negative phases in the plot represents a capacitive plasma load; while positive represents an inductive load. Since, plasma load is a R-L-C series load; a condition of series resonance arises when the capacitive (negative) reactance of the plasma sheath balances out the inductive (positive) reactance of the plasma bulk due to electron inertia. This condition of series resonance for the R-L-C series load of plasma can be observed as shown in Fig-3 for phase value of zero degrees. Theoretically, for a conventional CCP discharge the frequency at which this condition is achieved resonance frequency ω_{res} can be given by $\omega_{res} = 1/\sqrt{L_p C_{sh}} = \omega_{pe}\sqrt{s/d}$; [3] where s and d are the sheath width and bulk plasma column and ω_{pe} is the electron plasma frequency. This is usually in 100's of MHz; Godyak et. al observed this resonance for a 135.6 MHz discharge [5]. We previously reported a modified condition of resonance for a parallel plate discharge in presence of transverse B-field $\omega_{res,B} = \omega_{res}\left[\frac{\nu_m^2+\omega^2}{\Omega^2-(\nu_m^2+\omega^2)}\right]^{\frac{1}{2}}$; [4] where ω and ν_m are the RF and collision frequency. This equation in the experimental pressure range of 1-5 Pa (ν_m $range$) reduces the resonance frequency and a resonance is observed at 13.56 MHz. In cylindrical discharge a resonance condition is observed only for a helium at strong B-fields; which is attributed to the low frequency sheaths in case of helium ($\omega_{rf} \approx \omega_{ion}$) which operates with minimal sheath widths (Low sheath reactance). Thus, the overall discharge is predominantly inductive for helium for magnetized/unmagnetized case; while in case of argon the discharge remains capacitive in nature in presence of magnetic field; while it is seen to be inductive for the unmagnetized case. This behaviour is attributed to the elongated plasma column length l and smaller cross-section A; which enhances the bulk plasma inductance $L_p \propto l/A$; [3]; while the enhancement in the density (n) of bulk plasma in presence of magnetic field decreases the plasma inductance $L_p \propto 1/n$. Hence, the phase becomes capacitive in nature in presence of magnetic field.

References:

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