# Characteristics of a Magnetized Inductively Coupled Plasma in the Presence of a Double Layer

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**Abstract:** The properties of an inductively coupled plasma in uniform magnetic field, at moderate pressures, were measured in the presence of a current-free double layer. The axial profiles of plasma parameters (plasma potential, cold and hot electron temperature, plasma density, and the oscillation level of the time-averaged plasma potential) allowed a better characterization of such a plasma.

**Key words:** Inductively coupled plasma, electric double layer, electrical probes

## 1. Introduction

Inductively coupled plasma (ICP) reactors represent today one of the main tools for semiconductor fabrication. This explains the high interest in elucidating the complex physical phenomena and processes taking place in this type of devices. Recently, the influence of current-free double layers (DL's) on the properties of ICP's has been reported, as well as the phenomenology underlying their emergence [1].

The aim of this paper is to report on new experimental results obtained in a magnetized ICP in the presence of a DL at moderate pressures (*i.e.* about 1 mTorr) with the help of electrical probes. Besides the plasma properties measured with help of the probes, the present results allowed to establish the degree of quiescence of such an RF plasma.

## 2. Experimental device

The experiments were performed on the Saga University inductively coupled plasma device, illustrated in Fig. 1, using Ar as working gas. A three turn helicoidal antenna A produces the plasma in a Pyrex tube T, the open end of which closes a stainless steel cylindrical vessel, which is the main chamber of the device. To increase the plasma density and reduce the wall bombardment the whole system was placed in a uniform and axial magnetic field $\boldsymbol{B} = B\,\hat{z}$, where $\hat{z}$ is the unit vector of the axial direction of the device. The measured value of the magnetic induction was $B = 215 \pm 5$ G.

The plasma properties were axially measured with an RF compensated, movable Langmuir probe (marked P in Fig. 1), facing the plasma source (T in Fig. 1) at 2.0 mTorr. For measuring the axial profile of the time-averaged plasma potential, its oscillation level, as well as the time series of the current collected by the probe at plasma potential, an emissive probe was used instead of the cold one. The plasma potential measurements with the emissive probe were carried out employing the inflexion point method [2], at 0.3 mTorr to have better emission at smaller heating currents. The RF input power was 200 W, with less than 0.5% reflection, at the working frequency of 13.56 MHz.

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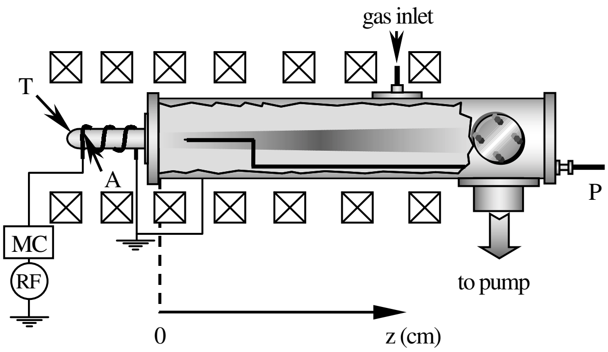

**Fig. 1.** Experimental set-up. A-helical antenna; T-glass tube; C-collector; P-plane Langmuir probe (or emissive probe); RF - radio-frequency power supply; MC - matching circuit.

## 3. Experimental results

The axial profiles of the plasma potential displayed in Fig.2 show the presence of a DL inside the source chamber T of the device. The negative layer of the DL is located at the axial position where the plasma potential $V_s$ has a local minimum (*i.e.* the bottom of the potential dip) and the positive layer at the downstream rim of the dip. Because the axial profiles of the plasma potential in Figs. 2 (a) and (b) are taken at different pressures, the negative side of the DL is formed different axial positions. Another characteristic that can be deduced from Fig. 2 is that the plasma electrons produced upstream are accelerated towards the main chamber of the experimental device by an axial electric field, which decreases when the gas pressure increases. Moreover, if in the source chamber the plasma potential is negative, going downstream its value becomes positive. The explanation of this behavior is based on the fact that the source chamber is electrically floating, while the main chamber of the device is grounded. So, after the plasma breakdown, the inner wall of the source chamber is charged negatively with respect to the ground due to electron bombardment.

The analysis of the static $I$ - $V$ characteristics of the cold probe revealed that this Ar plasma has two electron populations. The spatial profile of the hot electrons population (*i.e.* primary electrons accelerated in the skin depth) is shown in Fig. 3 (a). Even if their temperature is decreasing more than three times when going downstream, the profile displays a pronounced maximum at the negative side of the DL (*i.e.* where the probability of electron-neutral inelastic collision is maximum in the given conditions). Removing from the $I$ - $V$ characteristics the contribution of the hot electron population, it becomes possible to find the real temperature of the plasma (*i.e.* cold) electrons. Fig. 3 (b) shows that the kinetic temperature of the cold electron population decreases slowly when going downstream.

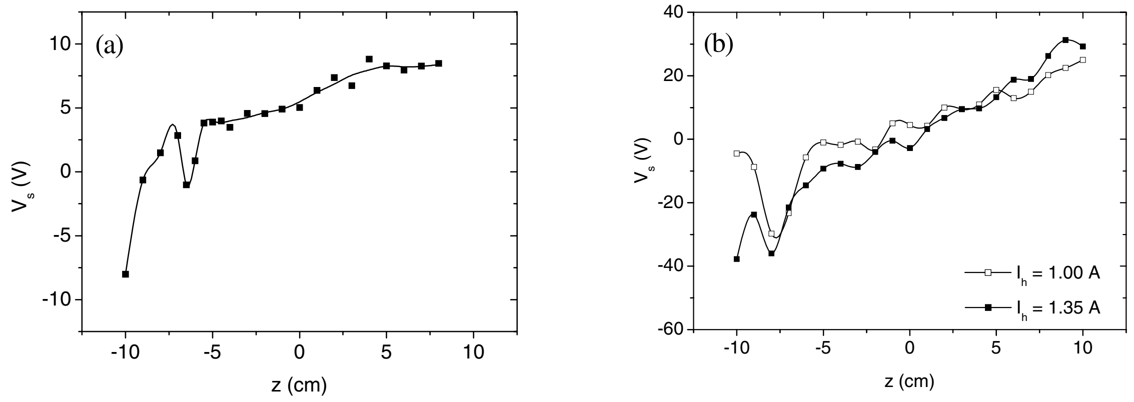

**Fig. 2.** Axial profile of the plasma potential: (a) measured with the cold probe at 2.0 mTorr, and (b) measured with the hot probe at 0.3 mTorr, for two probe heating currents.

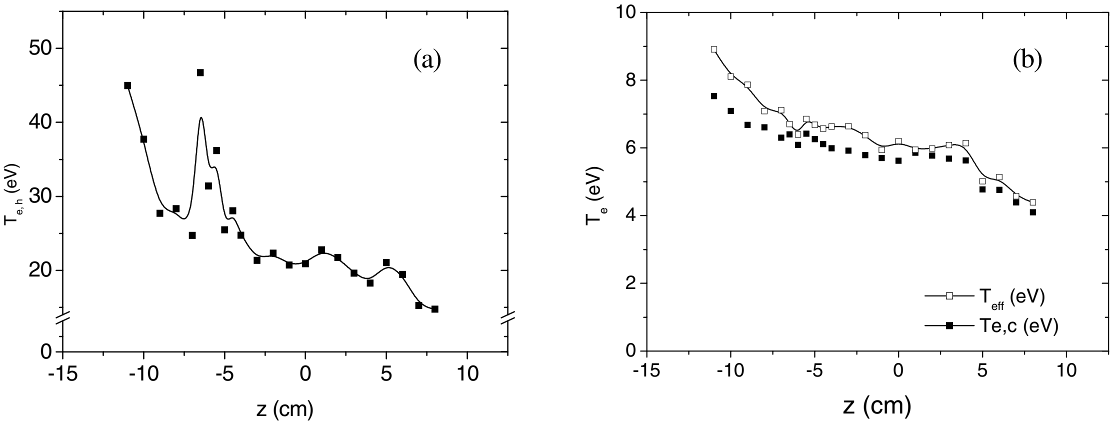

**Fig. 3.** Axial profile of the kinetic temperature for: (a) hot electron population; (b) cold electron population. In (b) the effective electron temperature is also represented.

Because plasma is magnetized, its density can only be found from the ion saturation current, which is not affected by the presence of the moderate magnetic field. Because the plasma has two-electron populations, for using the Bohm current, an effective electron temperature must be calculated. It can be seen from Fig. 3(b) that the effective electron temperature has the same profile as the cold electron temperature, though having slightly higher values. Under these conditions, the ion concentration has the profile displayed in Fig. 4. It increases when going downstream, as previously found [1], and has a small bump in the place where the positive side of the DL is located. The increasing tendency of the ion concentration downstream shows that even there the ion production rate is higher than the diffusion term, so that the name of "diffusion chamber" for the main chamber of the device is inappropriate.

## 4. Oscillation level measurement of the plasma potential

Using the heated emissive probe and polarized at the local time-averaged plasma potential, as found above, its oscillation level along the symmetry axis of the system, upstream and downstream, was also measured. Defining this level as the ratio of the plasma potential oscillation amplitude to its time-averaged value, its axial dependence looks as in Fig. 5 (a), for both probe heating currents. Excepting the region between the DL and the exit towards the main chamber (*i.e.* $z = 0$), where the time-averaged plasma potential changes its sign, the oscillation level of the plasma potential is below 5 everywhere in the probing domain. Going downstream the oscillation level decreases towards zero (at $z = +10$ cm its value is 0.7), which means that departing from the

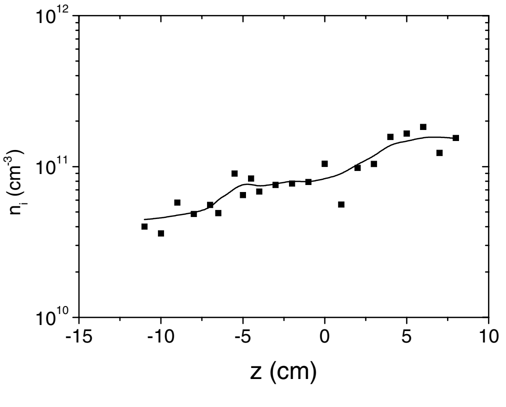

**Fig. 4.** Axial profile of the ion concentration.

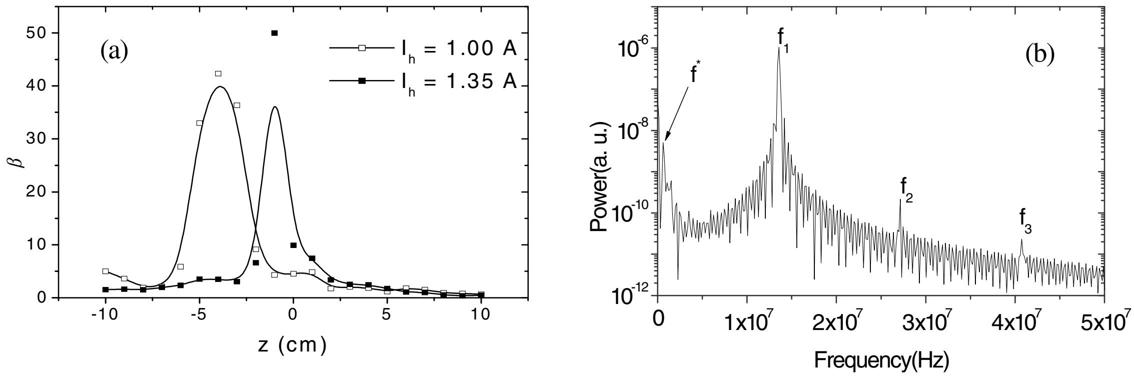

**Fig. 5.** (a) Axial dependence of the oscillation level of the plasma potential for both probe heating currents. (b) Power spectrum of the plasma oscillation signal, recorded in z = – 4 cm, for $I_h$ = 1.00 A.

source chamber the plasma becomes more quiescent. However, inside the source chamber, close to its centre, the oscillation level increases to almost 5 for 1.00 A heating current. This proves that inside the source chamber the plasma is more turbulent than downstream. This behavior is in good concordance with the results of previous experiments on the same set-up [2], which showed that the electron kinetic temperature evaluation, from a cold probe characteristic, is less reliable upstream than downstream. In the place where the DL is formed the oscillation level is small, due to the fact that the time-averaged plasma potential reaches a high absolute value in the same location.

Analyzing the recorded signals corresponding to the time-averaged plasma potential, it was observed that downstream, the power spectrum of the signal in the frequency interval [0; 1.25] GHz, displays peaks only for the driving RF frequency $f_1$ = 13.56 MHz and its superior harmonics $f_2$, $f_3$, etc. Upstream, besides these frequencies, all the power spectra contain another peak, as can be seen from Fig. 5(b), the frequency of which is $f^*$ = 0.61 MHz. For more clarity, in Fig. 5(b) the frequency range was set [0; 50] MHz. This frequency, smaller than the ion plasma frequency about 5 times, corresponds to a new dynamic phenomenon taking place inside the source chamber. However, for its identification further experimental work is needed.

## 5. Conclusions

The above experimental results prove that the presence of a current-free electric double layer in the plasma column modifies its parameters: the plasma potential, the hot electron temperature, as well as the ion concentration display non-monotonous spatial variations, with local extremes in the place where the double layer is located. Moreover, at the negative side of the double layer the concentration of hot electrons strongly decreases, due to inelastic collisions with neutrals, fact emphasized by their negligible contribution to the effective temperature there, although the temperature of the hot electrons reaches a local maximum in the same place. The emissive probe measurements clearly show, once more, that downstream the plasma is more quiescent than upstream.

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