WALAILAK JOURNAL
http://wjst.wu.ac.th Engineering and Physical Sciences

Spatial Temperature Profile in a Magnetised Capacitively Coupled Discharge†

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Received: 15 December 2017, Revised: 8 July 2018, Accepted: 15 July 2018

Abstract

A floating emissive probe has been used to obtain the spatial electron temperature (T_e) profile in a 13.56 MHz parallel plate capacitive coupled plasma. The effect of an external transverse magnetic field and pressure on the electron temperature profile has been discussed. In the un-magnetised case, the bulk region of the plasma has a uniform T_e. Upon application of the magnetic field, the T_e profile becomes non-uniform and skewed. With increase in pressure, there is an overall reduction in electron temperature. The regions adjacent to the electrodes witnessed a higher temperature than the bulk for both cases. The emissive probe results have also been compared with particle-in-cell simulation results for the un-magnetised case.

Keywords: Emissive probe, electron temperature, transverse magnetic field, capacitive coupled discharge.

Introduction

Plasma processing has always played a crucial role in the advancement of microelectronic and semiconductor industries [1]. The discharge used in etching, thin film formation and material processing is usually driven by RF power at 13.56 MHz or its harmonics. Capacitive coupled plasma (CCP) also known as reactive ion etcher is the primary choice in plasma processing industries, due to its low cost, ease of maintenance and simpler electrode geometry. Usually, the CCP is formed by applying a high amplitude RF potential between 2 similar or dissimilar sized parallel plate electrodes. The silicon wafer or the sample to be processed is attached to the plate and a strong electric field accelerates the ions to bombard the surface to create the desired effects. Sometimes, a transverse magnetic field is applied to provide better control over the discharge. The introduction of the magnetic field enhances the performance of CCP reactors by increasing the etching rate and plasma density. Such discharges are known as magnetically enhanced reactive ion etchers (MERIE) [2,3]. However certain studies have revealed that the plasma uniformity is compromised with imposition of the magnetic field [4-8]. When the magnetic field is applied, the electron exhibits cyclotron motion, thereby increasing collisions with the background neutrals and ions. Obtaining the spatial distribution of the plasma parameters would be

†Presented at the 10th International Conference on Plasma Science and Applications 2017: October 10th - 11th , 2017

decisive not only for controlling the overall stability of the discharge but also to account for the loss of plasma across the magnetic field.

For obtaining plasma parameters, several diagnostics tools such as microwave, interferometry, laser diagnostics, spectroscopy techniques and electrical probes are available. The emissive probe is one of the electrical probes introduced by Langmuir in 1929, which gives a direct measure of the plasma potential. Accurate measurement of the plasma potential allows the determination of the electric field profile in the discharge, which is responsible for the acceleration of ions, charged particle flow and electron temperature. The emissive probes are useful for wide practical implementation and interpretation owing to the simple electric circuitry and straight forward data analysis.

In this paper a floating emissive probe has been applied along the centre of an argon discharge to obtain a spatially resolved measurement of electron temperature with and without a magnetic field. Particle-in-cell (PIC) simulation has also been performed for the given discharge set-up. The emissive probe results have been compared with the particle-in-cell simulation results for the un-magnetised case.

Experimental set-up and diagnostics

The experimental setup consists of a cylindrical glass vacuum chamber equipped with a turbo-molecular pump and a rotary pump. The discharge electrodes are composed of 2 rectangular plates of dimension 40×10 cm^2 made from S.S.304. The pair of plates is kept parallel maintaining a gap of 8 cm between them. This parallel plate assembly is supported on 2 Teflon discs. The glass chamber is kept between 2 race-track shaped electromagnetic coils such that magnetic field lines are parallel to the plate. This arrangement creates a uniform magnetic field between the parallel plates. The schematic diagram of the experimental setup is shown in **Figure 1**.

A 13.56 MHz RF generator (AG 1213W T&C Power conversion) is used in conjunction with an automatic L type impedance tuner (AIT-600R T&C Power conversion) to couple the RF power to the electrodes via a 1:1 ferrite transformer. The plates are capacitively driven in a push-pull configuration.

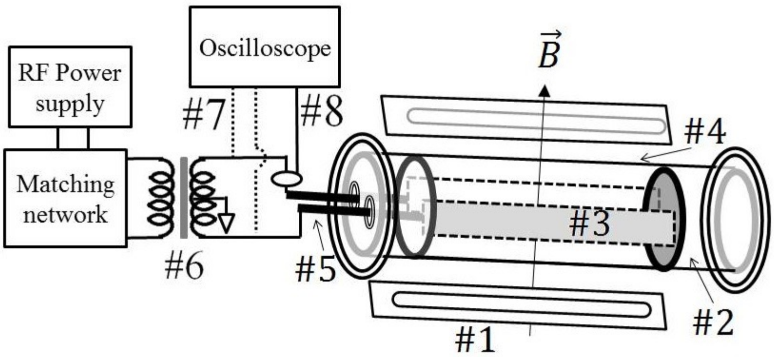

Figure 1 Schematic of experimental setup;1) Electromagnetic coils, 2) Teflon support, 3) SS Parallel plates, 4) Glass chamber, 5) High voltage copper feedthrough, 6) Ferrite transformer, 7) Voltage probes, 8) Current transformer.

For the measurement of electron temperature T_e, a floating emissive probe was constructed (image and schematic in **Figure 2**. The filament of the emissive probe is of thoriated tungsten, 0.2 mm in diameter. The filament is tightly push fitted into a 2 bore alumina tube with copper wires placed inside. The filament is bent into a U-shape, extending 5 mm from the end of the alumina tube. The probe tip is heated using a step down isolation transformer. The secondary of the transformer is connected to the 2 ends of the probe and the potential is measured at the centre tap of the transformer with a high impedance voltage probe connected to a digital storage oscilloscope. The emissive probe works on the principle that, at strong emission, the floating potential of the probe tends towards the plasma potential [9,10]. The reason for this is the following; upon heating the filament, the electrons are emitted from it due to thermionic emission. The emitted electrons neutralises the sheath around the filament, which makes the probe float at the plasma potential. For determining the correct heating current, the floating potential of the probe is observed as a function of increasing filament current. After initially showing an increase as the filament is heated, the potential ultimately saturates with increasing heating current. This potential is considered as the plasma potential.

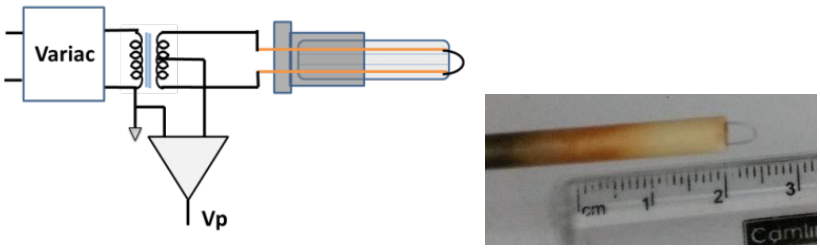

Figure 2 Schematic and image of emissive probe.

Results and discussion

The experiment has been conducted in a both a magnetised and un-magnetised Argon discharge, at a constant RF power of 40 W. The probe is scanned across the separation between plates by passing it through the centre of the discharge via a slit on the top electrode. When the probe is not heated, it measures the floating potential (V_f) and when the probe is at strong emission it gives the plasma potential (V_p). Electron temperature can be estimated by having information of the floating and plasma potential from the relation [1];

$$V_p - V_f = T_e \ln(M_{ion}/2\pi m_e)^{1/2} \quad (1)$$

where M_{ion} is the mass of Argon ion and m_e is electron mass. **Figure 3** represents the response of the floating emissive probe in the capacitive plasma as a function of time.

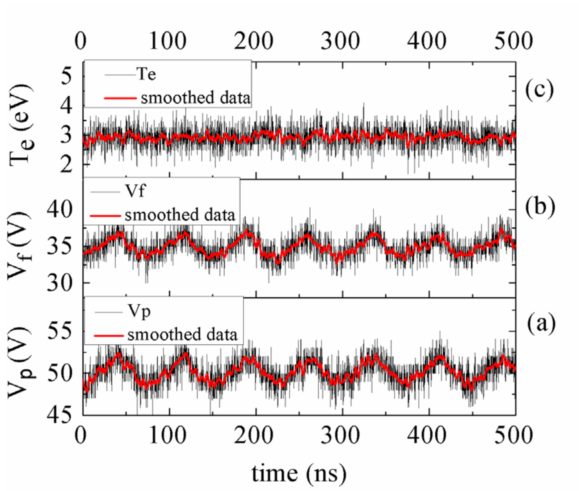

Figure 3 Response of emissive probe at 40 W of RF power at 1.0 Pa pressure in the presence of a magnetic field parallel to the plates.

In **Figure 3**, the graph (a) shows the hot emissive probe characteristic i.e. the plasma potential, the graph (b) represents the cold emissive probe characteristic giving the floating potential. The top most graph (c) gives the electron temperature estimated using Eq. (1) in eV which is almost constant along the RF cycle. The red line represents the smoothed data for each graph.

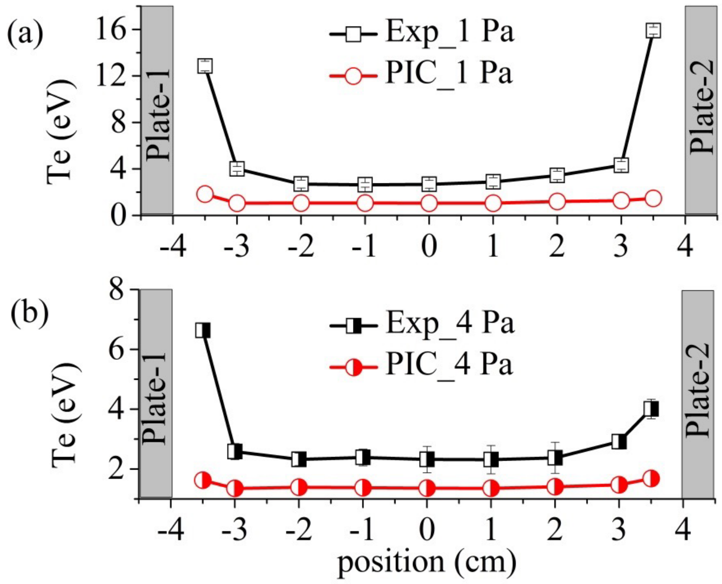

Figure 4 Graph showing electron temperature obtained experimentally with emissive probe (black square) and electron temperature estimated by PIC simulation (red circle) for given conditions; (a) P = 1.0 Pa and B = 0; (b) P = 4.0 Pa and B = 0.

The spatial electron temperature profile for the un-magnetised case is shown in **Figure 4**, for pressure values of 1.0 Pa and 4.0 Pa. The experimentally obtained T_e is plotted on the same scale with the T_e obtained from Particle-In-Cell (PIC) simulations. In both cases T_e remains constant throughout the bulk and shows an increasing trend adjacent to the plates. The experimentally obtained T_e is twice the value obtained using PIC results. However the trends of both experimental and PIC results are in fairly good agreement and serves to validate the usefulness of the emissive probes in RF discharges.

The shape of the T_e profile can be explained as follows. In the absence of the B-field, the discharge is homogenous and hence the bulk has a uniform temperature, as here electron heating due to ohmic collisions is prominent. The high temperature near the plates can be attributed to the fact that stochastic heating is the dominant factor determining electron temperature adjacent to the sheath region. Stochastic heating arises due to the oscillating RF sheaths. The electrons gain net energy from the oscillating electric field, thereby increasing the net temperature. In the literature this feature of CCP has been shown through many numerical approaches [3,11].

The PIC code used here considers the plasma to be uniform. In the presence of magnetic field the plasma becomes non-uniform. This limits the use of the present PIC code in the magnetized case. The detailed description of the PIC code is given in [12].

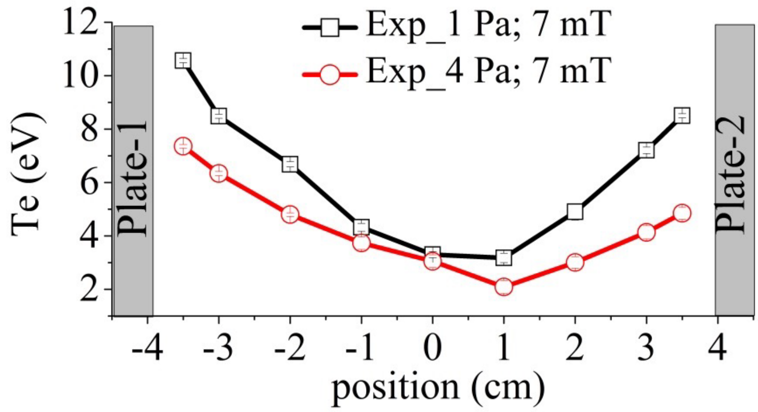

Figure 5 Graph showing electron temperature obtained experimentally with emissive probe for magnetised case at 1.0 Pa (Black Square) and 4.0 Pa (Red Circle).

Figure 5 represents the electron temperature profile when a magnetic field of 7 mT is applied. The T_e profile shows a continuously falling trend from the plates towards the centre. Unlike the un-magnetised case, the bulk does not witness a uniform temperature. The T_e profile seems to be more skewed for 4.0 Pa compared to 1.0 Pa case. This non-uniformity in the T_e profile is in accordance with the inhomogeneity of the discharge introduced by the presence of the B-field. The introduction of the B-field induces drifts in the discharge, which makes the plasm non-uniform.

The effect of pressure for both magnetised and un-magnetised case is the same. Increasing the pressure thermalises the discharge and hence T_e is reduced. The enhanced pressure results in the increase in the probability of electron-neutral collisions.

Conclusion

In conclusion, a 13.56 MHz CCP discharge has been investigated to obtain the spatial dependence of T_e using a floating emissive probe. The experimental results suggest that the stochastic or collision-less heating dominates near the sheath region while ohmic/collisional heating dominates in the bulk. The introduction of a parallel magnetic field created a gradient in T_e along the discharge width. Increasing the pressure has a cooling effect on the electron temperature in both cases.

Acknowledgements

This work has been supported by Department of Science and Technology (DST), Government of India via Projects GITA/DST/ TWN/P-56/ 2014.

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