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Characteristics of capacitively coupled helium plasma driven by various frequencies under constant power conditions

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ABSTRACT

The influence of excitation frequency (13.56–96 MHz) on the characteristics of capacitively coupled helium plasma is investigated by means of Langumir probe and CCD camera. Measurements are performed in helium pressure of 10.66 and 33.3 Pascal (Pa) under fixed dissipated power of 10 W. With increasing the driving frequency, the RF/HF voltage and dc-self bias markedly decrease. Meanwhile, the plasma density and electron temperature peak in the frequency range 27–56 MHz, beyond which they decrease as exciting frequency increase. A different feature of the electron energy probability function EEPF is observed with exciting frequency; Maxwellian type EEPF at low frequency of 13.56 MHz evolves into a bi-Maxwellian type with a hump/beamlike in the frequency range 27–56 and eventually comes back to Maxwellian distribution at frequency ≥76 MHz. The observed results are explained in terms of electromagnetic wave effect and capacitive to inductive heating transition induced by exciting frequency.

1. Introduction

Recently, very high frequency (VHF) capacitive coupled glow discharges have attracted a considerable attention due to its great utilizes over the conventional 13.56 MHz discharges. For example, the higher growth rate and better uniformity of hydrogenated amorphous silicon (*a* -Si:H) film deposition [1,2] and a high etch rate and less micro-loading effect in the self-aligned contact hole process [3]. These benefits have motivated researchers to investigate the role of the excitation frequency on the capacitively coupled discharges. In particular, knowledge of the electron energy probability function (EEPF) evolution with the exciting frequency is crucial because radicals and positive ions are created by inelastic collisions between electrons and neutral parent molecules. At constant discharge voltage and gas pressure, the increase of the excitation frequency (13.56–50 MHz) causes a dramatic increase in the discharge power. This change induces major effects in most of the microscopic discharge parameters such as, electron density n_e, electron temperatures T_e and the electron energy probability function (EEPF) [4–6]. Though much understanding of the role of exciting frequency on the discharge characteristics have been achieved through these studies, however, Moisan et al. [7] reported that for reliable dependences of excitation frequency on the discharge parameters in capacitive discharge, one should ensure constant dissipated power into the bulk plasma.

On the other hand, from plasma technology point of view, increasing the exciting frequency to an arbitrary higher value in pursuit of higher electron density was found to affect the uniformity of the produced plasma [8]. Namely, at very high frequency when the corresponding excitation wavelength λ becomes comparable to the electrode radius and the plasma skin depth δ becomes comparable to half of electrode spacing, electromagnetic effects and/or surface waves SW start to have a profound influence on the plasma properties [9,10]. Two of the most significant effects are the standing wave effect, which enhances power deposition at the discharge center, and the plasma skin effect; the latter accounts for an increased inductive heating component at high electron densities in the VHF regime. In addition, the discharge experiences a capacitive-to-inductive (E- to- H) transition at certain exciting frequency and discharge voltage [11,12]. Though, through theoretical and experimental studies, electromagnetic induces phenomenon such as non-uniform capacitive and inductive electric fields were observed [13,14]. However, measurements of electron energy probability function (EEPF) in a discharge conditions whereas the conditions of electromagnetic effects may applicable in a capacitive discharge working under dissipated power conditions have not yet been observed. It is important to understand this influence on the plasma parameters in particular the EEPF, in order to control the discharge parameters and optimize the plasma technique.

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In this paper, by using Langmuir probe and CCD camera, we studied the exciting frequency effects on the discharge power dissipation, EEPF and other plasma parameters, under a constant dissipated power conditions for two helium pressures of 10.66 and 33.3 Pa. Our results showed that, the EEPFs are Maxwellian at low exciting frequency <27 MHz and evolve into a Non-Maxwellian with beam-like electrons in the frequency range 43–56 MHz and eventually come back to Maxwellian distribution as frequency increases higher than 56 MHz. This EEPFs evolution reflects non-monotonic plasma parameters dependences with the exciting frequency.

2. Experimental setup

A schematic drawing of the experimental set-up is shown in Fig. 1(a). The capacitive discharge was driven between two parallel electrodes of 15 cm in diameter with the gap distance $L = 6.6$ cm. The lower electrode was connected to a power supply through a matching box, while the upper electrode as well as the chamber walls was grounded. The back and the sides of each electrode were covered by a thick Teflon layer to confine the discharge. The voltage waveform at the powered electrode was monitored using a calibrated high voltage probe, while the net dissipated power was estimated using subtractive method [15,16]. Measurements were performed at a fixed helium pressures of 10.66 and 33.3 Pa, respectively. The excitation frequency used throughout this work was 13.56, 27, 37, 43, 50, 56, 72 and 96 MHz, which are available in a rf compensated Langmuir probe system. The design of the rf-compensated probe is shown in Fig. 1(b) and more details can be found in [4]. The probe tip P_1 is connected to a series of LC filters with impedance resonances at the fundamental frequency and it is second and third harmonic. In addition, a rf compensation electrode (reference probe) P_2 (0.15-mm-diameter tungsten wire tightly wound 20 times around ceramic tube, starting near the probe tip end) is connected to the probe tip through a 10 nF capacitor to drive the probe tip so that it follows the rf oscillations in plasma potential. The reference probe P_2 incorporated in the design has an advantage of reducing the sheath impedance by coupling to the oscillating plasma potential near the location of the collection probe without appreciable perturbation to the plasma. The short range between the chosen frequencies makes it difficult to hold the whole set of LC filters in one probe. So we choose to use six identical probes; one for frequencies 13.56, 27 and 43 MHz, while other five probes were used at exciting frequencies 37, 50, 56, 72 and 96 MHz, respectively. Special care was taken to ensure that the probe tip position always fixed in the mid of the discharge. The transmitted impedance (including the stray capacitance of the probe) of the filters are measured and presented as function of frequency in Figs. 1(c)–1(h). As one can see, there is dip corresponding to the resonances frequencies of the fundamental and its second and third harmonic for each chosen frequency, except at 50 MHz where the rf signal is compensated at 48 MHz as seen in Fig. 1(e). The Langmuir probe circuit, including analog-to-digital and digital-to-analog converters with 12-bit resolution, was driven by a personal computer. In order to reduce the noise, each data point of the probe characteristic $I(V)$ was averaged 1000 times, and numerical program made it possible to obtain $I'(V)$,$I''(V)$ [17]. Electron energy distribution function (EEDF) data acquisition was made by calculating the second derivative $I''(V)$ at discrete energy increment $\Delta\varepsilon = 0.02$ eV from the probe characteristics.

For EEDF measurements, Druyvesteyn method has been used, in which the measured second derivative $I''(V)$ of the Langmuir probe characteristic is proportional to the electron energy probability function (EEPF), $f_p(\varepsilon)$, and related to the EEDF as

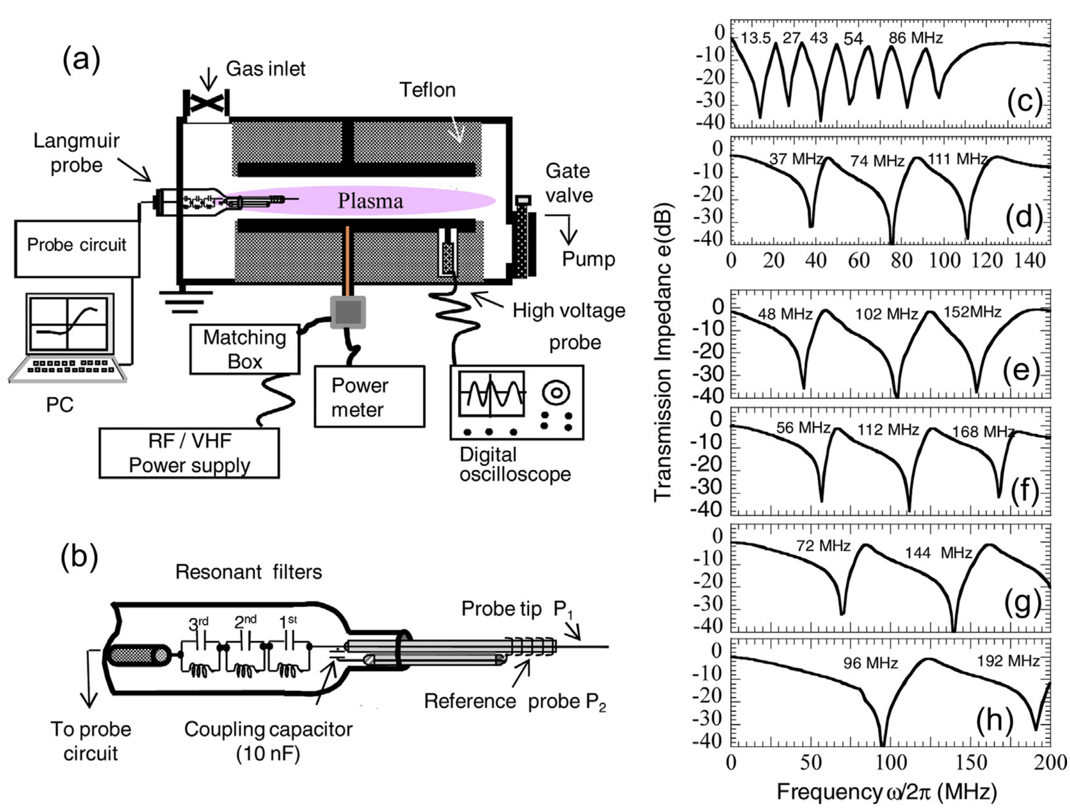

Fig. 1. (a)Schematics of the experimental setup, (b) rf compensated Langmuir probe, and (c–h) LC rf filter transmitted impedance-frequency characteristics for the chosen frequencies.