Plasma diagnostics and simulations

Frequency analysis of electrical measurements in low pressure capacitively coupled plasma

Tasks

1. Realize the measurements of plasma potential waveform by means of a cylindrical probe in a low-pressure capacitively coupled discharge ignited in mixtures of N_2 and O_2.
2. Study the oscillations of plasma potential or current that spontaneously develop in capacitively coupled plasma and analyze how their frequency depends on electron concentration.

Introduction

The properties of capacitively coupled discharges are to a large extent caused by sheaths, areas with high spatial electric charge, which spontaneously develop at boundaries between plasma and any solid surface. Since electric field expels electrons form the sheath area, concentration of positive ions exceeds the concentration of electrons in sheaths and sheaths are positively charged, see fig. 1. Because capacitive discharges are driven by voltage with high-frequency, both the electric field in sheaths and the sheath width strongly vary in time. The electric current flowing through a sheath at a planar electrode can be expressed as a sum of displacement, electron and ion current:

$$I = e\, S_e\, n_i(s)\, \frac{\mathrm{d}s}{\mathrm{d}t} - \frac{e n_0 S_e}{4}\sqrt{\frac{8kT_e}{\pi m}}\, \mathrm{e}^{-eU/(kT_e)} + e n_0 S_e \sqrt{\frac{kT_e}{m_i}} \tag{1}$$

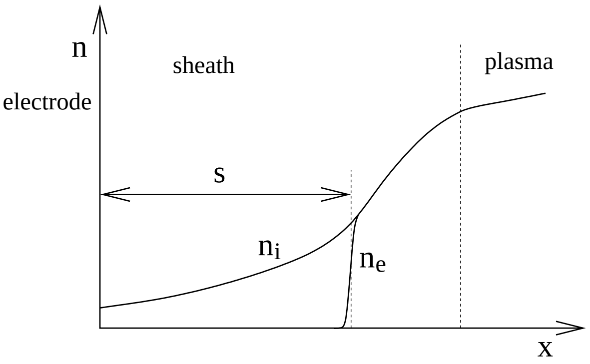
$$U = \frac{e}{\varepsilon_0} \int\limits_0^s \left[\int\limits_0^\xi n_i(x)\, \mathrm{d}x \right] \mathrm{d}\xi, \tag{2}$$

where I denotes the electric current, S_e the electrode area, n_i the concentration of positive ions, s the actual sheath width, n_0 the electron concentration in the bulk plasma, T_e the electron temperature, m and m_i the electron and ion mass, respectively. U is the sheath voltage and ε_0 is the vacuum permitivity. The nonlinear nature of sheaths that is shown in equations (1) and (2) manifests itself in generation of oscillations of plasma voltage and current with frequency that differs from frequency supplied to the discharge from the RF generator. These new electric signals tend to oscillate with the eigenfrequency of the discharge, which is described in the following paragraph.

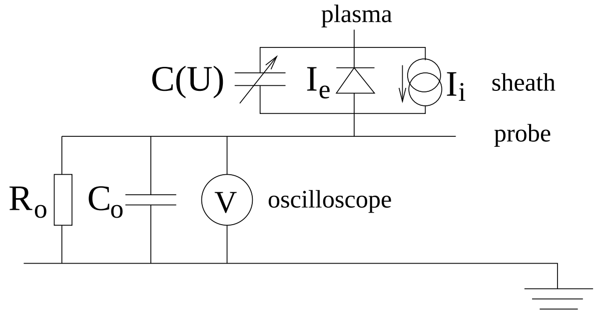
The bulk-plasma conductivity

$$\sigma = \frac{n_0 e^2}{m(\nu + \mathrm{i}\omega)} + \mathrm{i}\omega\varepsilon_0 \tag{3}$$

(where ν is the electron-neutral collisional frequency for the momentum transfer and ω is the angular frequency of the driving voltage) has an inductive character. On the other hand, sheaths with their low concentration of mobile electrons have capacitive character. The serial connection



Obrázek 1: *Concentration of positive ions (n_i) and electrons (n_e) in a sheath.*



Obrázek 2: *Electric schema of the probe with no RF compensation.*

of inductive bulk plasma and capacitive sheaths needs to have a resonance, which is called the series resonance or plasma-sheath resonance. Its angular frequency can be estimated by

$$\omega_{sr} = \omega_{pe} \sqrt{\frac{s_{tot}}{l}}, \tag{4}$$

where $\omega_{pe} = e\sqrt{n/m\varepsilon_0}$ is the plasma frequency of electrons, l is the distance between electrodes and s_{tot} is the total with of both sheaths at the powered and grounded electrodes. ω_{sr} is the eigenfrequency of capacitively coupled discharge. Thus, we can expect that waveforms of potential and current of capacitively coupled discharges will contain oscillations with frequency close to the frequency ω_{sr}. Since these eigenoscillations will be damped by collisions between electrons and neutrals, it can be expected that their amplitude will be high at low pressure [1, 2].

Probe measurements of plasma potential waveforms

The problematic of probe measurements of plasma potential waveforms is described in detail in [3]. The measurement is complicated by the fact that a small sheath develops around the probe and this sheath separates plasma from the probe. Consequently, the sheath voltage needs to be added to the measured probe voltage in order to find the searched plasma potential

$$U_{pl} = U_{probe} + U_{sh}. \tag{5}$$

U_{pl} denotes plasma potential, U_{probe} the measured probe voltage and U_{sh} the voltage on the sheath around the probe. The calculation of the sheath voltage waveform is based on the knowledge of the probe current waveform, which can be measured: From the probe current (I_p) the temporal derivative of electric field intensity at the probe surface can be acquired when the electron and ion current components are subtracted from the total probe current in order to obtain the displacement current

$$I_d = \varepsilon_0 S \frac{\mathrm{d}E}{\mathrm{d}t} = I_p - I_i - \frac{e n_0 S}{4} \sqrt{\frac{8kT_e}{\pi m}}\, \mathrm{e}^{eU_{sh}/kT_e}, \tag{6}$$

where S denotes the probe surface area. Since the applied frequency is significantly higher than the ion plasma frequency, the ion current (I_i) is expected to be constant during the whole RF period. In order to calculate the sheath voltage U_{sh} from the waveform of the electric field intensity, which can be obtained by eq. (6), it is necessary to develop a theoretical model of the sheath. When such a model is made and solved, both the sheath and plasma potential waveforms can be obtained at the requirement that we know the value of the ion current (I_i) and the initial value of the electric field intensity. Fortunately, these two unknown initial conditions can be determined from the following two requirements: the obtained waveform of the plasma potential is periodical and its mean value is equal to the real value that can be measured by means of RF-compensated Langmuir probe. The outlined calculation of plasma potential waveform can be realized by means of the matlab function "plasma_potential.m", which can be downloaded from the study materials of the course.

Experimental

The measurement will be carried out in a spherical stainless-steel reactor with two round electrodes, each of them with diameter 8 cm. The upper electrode is powered with RF voltage (frequency 13.56 MHz), the bottom electrode is grounded. Capacitively coupled discharge will be ignited in nitrogen, oxygen and their mixtures in the pressure range $1 - 100$ Pa.

Electron concentration, temperature and distribution function together with the mean (DC) value of plasma potential can be measured with RF compensated Langmuir probe. This probe blocks the RF signals and, therefore, can not be used for measurements of RF components of plasma potential.

RF components of plasma potential can be measured with a simple probe made from a wire that is directly connected to a high-impedance probe of an oscilloscope. The probe length and diameter are 20.9 mm and 0.27 mm, respectively. The electric schema of the probe, sheath around the probe (which can transmit displacement, electron and ion current) and the probe connection to the oscilloscope (the input impedance of the oscilloscope is described by $10^8\,\Omega$ and 3 pF) is shown in the fig. 2. The probe current can be calculated from measured probe voltage by means of the known input impedance of the oscilloscope.

References

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[3] P. Dvořák, M. Tkáčik, J Bém: *Plasma Sources Sci. Technol.* **26** (2017), 055022.