RF PLASMA MONITORING USING SELF EXCITED ELECTRON RESONANCE SPRECTROSCOPY

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ABSTRACT

The non-linearity of the sheath at the powered electrode and oscillations in the plasma are analysed for the RF discharge. For asymmetrical discharges and sinusiodal discharge the current can be shown to consist of a saw tooth shaped part and a superposed damped oscillation. This model result in a new method for plasma monitoring and allows to estimate density and collision rate of the electrons. It is called self excited electron resonance spectroscopy (SEERS) and can be used for various plasma processes.

INTRODUCTION

In asymmetrical RF discharges non-linear phenomena are known for many years. In modelling RF discharges non-linear phenomena usually are treated as inconvenient effects, e.g. concerning the application of linear models. It will be shown without a kinetic approach that non-linear mechanisms play a dominant role for the power dissipation within the discharge and can be used for RF plasma monitoring and process control [1].

The simple model of a step wise electron density distribution within the sheath is used to investigate the occurrence of harmonics in the RF discharge. Because of the inertia of the bulk electrons these harmonics excite oscillations in the discharge at the geometric resonance frequency located below the plasma resonance frequency.

The most complete investigations were carried out for symmetrical RF discharges. Because of the symmetry of the discharge only odd harmonics appear and the non-linearity of the whole system is only weakly pronounced [2]. On the other hand the use of RF discharges for plasma-enhanced dry processing is dominated by asymmetrical discharges, e.g. reactive ion etching (RIE), plasma etching (PE) or plasma enhanced chemical vapor deposition (PECVD). Contrary to the symmetrical case the treatment of asymmetrical discharges is more diffcult and the non-linarity of the sheath of the RF electrode leads to occurence of harmonics which may influence the maintainance of the RF plasma [3].

PHYSICAL ASSUMPTIONS

For RF frequencies well above the ion plasma frequency, $\omega \gg \omega_i$, the ions cannot respond to the fast variations of the electric field. The ion and electron plasma frequency is defined by

$$\omega_{e,i} = \left(\frac{n_0 e^2}{m_{e,i} \epsilon_0} \right)^{1/2} \quad . \tag{1}$$

Therefore the ion density depends only on the time averaged electric field and is not a function in time. Usually the plasma density is sufficiently high so that the Debye length

$$\lambda_D = \left(\frac{\epsilon_0 k T_e}{n_0 e} \right)^{1/2} \ll L, R \tag{2}$$

and, respectively, for moderate sheath voltages, also the sheath width are significantly less than electrode gap L and radius R. n_0 denotes the ion density at the sheath edge $\xi = 0$ which is located at the point of maximum sheath extension.

THE RF SHEATH

For the one-dimensional analysis of the RF sheath we introduce the dimensionless quantities

$$\zeta_e = \frac{n_e}{n_0}, \quad \zeta_i = \frac{n_i}{n_0}, \quad \eta = \frac{V_0 - V}{kT_e/e}, \quad \xi = \frac{z - z_0}{\lambda_D}, \quad \varphi = \omega_{rf} \tag{3}$$

normalizing the electron and ion densities $n_{e,i}$ with the plasma density at sheath edge n_0, the potential V with the (thermal) electron energy kT_e, the space coordinate z with the Debye length λ_D. The plama density n_0 and the electron temperature T_e are supposed to be constant. φ denotes the normalized time. Since the ions can respond only to the time averaged electric field, the Bohm criterion has to be satisfied at $\xi = 0$.

The instantaneous potential within the sheath can be calculated from the Poisson equation

$$\frac{d^2 \eta}{d\xi^2} = \zeta = \zeta_i - \zeta_e \tag{4}$$

and the additional boundary condition $\eta(\xi_w) = \eta_s(t)$ that the potential drop of the sheath is known. The approximation of the Boltzmann factor for the electron density by a step-wise profile was applied considering the RF response of a Langmuir probe [4] and for the numerical modeling of RF discharges [5,6]. We introduce the normalized sheath δ width between the wall and the step of the electron density, where the ion density is ζ_{+1}. If the displacement current j_d is expressed in units of the electron saturation current j_{es}

$$\Gamma_d = \frac{j_d}{j_{es}(2\pi)^{1/2}}, \quad (2\pi)^{1/2} j_{es} = e n_0 \lambda_D \omega_e = e n_0 \left(\frac{k T_e}{m_e} \right)^{1/2} \tag{5}$$

the (normalized) displacement current Γ_d results in

$$\Gamma_d = \zeta_{.1} \Omega \delta' ; \quad \Omega = \omega_{rf} / \omega_e , \tag{6}$$

where $'$ denotes the temporal derivation $d/d\varphi$. Integrating the Poisson equation yields [7]

$$\frac{d\eta_s}{d\delta} = \zeta_{.1}\,\delta \tag{7}$$

and combining the above equations provides

$$\Gamma_d = \frac{\Omega}{\delta}\eta_s' \tag{8}$$

a fundamental relation without any direct dependence on the density distributions $\zeta_{e,+}$. In Ref [7] this relation is found to be not bounded on the step-wise electron density if a generalized definition of the time dependend sheath boundary is used.

SELF EXCITED ELECTRON RESONANCE

For $(\omega_e/\omega)^2 \gg 1+(\nu/\omega)^2$ the complex conductivity of the plasma body can be written as $ne^2/m_e(i\omega+\nu)$ [8,9]. In order to obtain the effective length of l of the plasma body the radial and axial current has to be taken into account. Because of the small electrode gap $L \ll R$ in the chamber the effective length of the plasma can approximated by (s.. sheath width)

$$l \approx \left(\frac{1}{L-s} + \frac{2}{R}\right)^{-1}, \tag{9}$$

a slightly corrected electrode gap. We introduce the normalized coefficients

$$\tilde{n} \approx \left[\frac{1}{V}\int_V \frac{dr}{n(r)}\right]^{-1}, \quad \Lambda = \frac{n_0}{\tilde{n}}\frac{l}{\lambda_D}\frac{\omega_{rf}}{\omega_e}, \quad \rho = \frac{n_0}{\tilde{n}}\frac{l}{\lambda_D}\frac{\nu}{\omega_e}, \tag{10}$$

where ν the electron collision rate. The potential drop of the plasma can now be written as

$$\eta_p = \Lambda\Gamma' + \rho\Gamma. \tag{11}$$

Neglecting the thin sheath at the grounded electrode the total discharge voltage can be expressed as $\eta_{rf} = \eta_s + \eta_p$ and we obtain for the whole RF discharge the following set of two coupled first order, non-linear differential equations for sheath voltage and discharge current ($\Omega = \omega_{rf}/\omega_e$)

$$\begin{aligned} \eta_s' &= \frac{\delta(\eta_s)}{\Omega}\Gamma \\ \Gamma' &= \Lambda^{-1}[\eta_{rf} - \eta_s - \rho\Gamma] \end{aligned} \tag{12}$$

The convection current, ion and electron current in the sheath, is neglected ($\Gamma = \Gamma_d$). In order to calculate the discharge current a sinusiodal voltage at the RF electrode

$$\eta_{rf}(\varphi) = \hat{\eta}\sin\varphi + \eta_B \ , \qquad (13)$$

is assumed, η_B is the (self) bias voltage. This assumption was verified in Ref [7]. As first order approximation the ion density in the sheath is, supposed to be homogeneous ($\zeta_+ = 1$). Integrating Eq. (7) we obtain the dependence of the sheath width on the sheath voltage

$$\delta = (2\,\eta_s)^{1/2} \ . \qquad (14)$$

The differential equations were solved by a fourth-order Runge-Kutta method. The discharge current for two typical sets of parameters are shown in Fig. 1. The current can be shown to consist of a saw tooth shaped part and a superposed damped oscillation. Close to the geometric resonance frequency [9,10]

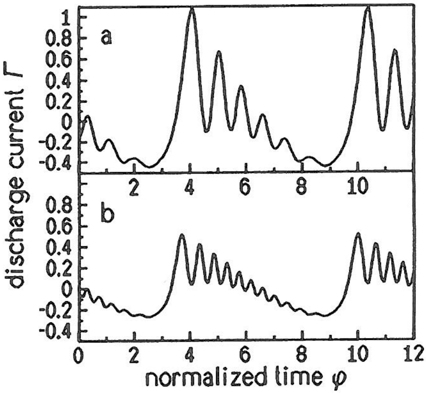

Fig. 1. Discharge current using Eq. (12) for $\hat{\eta} = 100$, $\eta_B = 105$,
a) $\Omega = 0.05$, $\rho = 8$, $\Lambda = 6$;
b) $\Omega = 0.03$, $\rho = 4$, $\Lambda = 3$.

$$\omega_r \approx \omega_e \left(\frac{\lambda_D \bar{\delta}}{l} \right)^{1/2} \qquad (15)$$

a pronounced maximum occurs in the Fourier spectrum. $\bar{\delta}$ denotes the averaged sheath width. Taking into account the electron mobility the damping of the oscillations is proportional to the collision frequency and the pressure respectively.

EXPERIMENTAL RESULTS

In order to measure the true discharge current a special, additional electrode was inserted into the chamber allowing measurements with a bandwith of about 500 MHz using a digital sampling oscilloscope. The current was measured in a plasma etcher Plasma Therm 790 with Al electrodes (⌀ 280 mm) and an electrode spacing of l = 52 mm. The discharge was driven by a 13.56 MHz generator. The measurement circuit consists of a

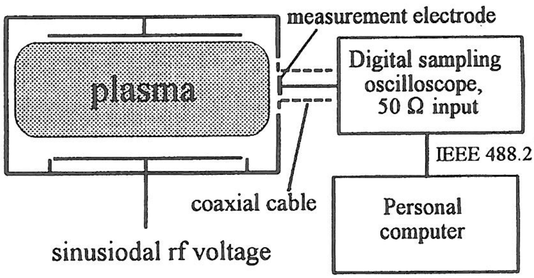

Fig. 2. Experimental setup for the measurement of the discharge current.

small electrode (Al, ⌀ 4 mm) positioned in a flange. Thus a small part of the discharge current flows into the additional electrode and causes an RF voltage at the input of a digital sampling oscilloscope Tektronix TDS 520A. Compared with the capacitance of the thin sheath, located between plasma and additional electrode, the impedance of the electrode is much lower with respect to ground. Finally it should be noted that this method excludes the influence of feedthrough and stray capacitances of the RF electrode [7].

The measured discharge current, strictly speaking a part of the current, is shown in Fig.3 and found to be in qualitative agreement to the numerical results shown in Fig. 2. The Eqs. (1) and (15) can be used to determine the mean electron density in the plasma from the maximum in the Fourier spectrum at ω_r

$$\tilde{n} = \omega_r^2 \frac{l\, m_e \epsilon_0}{\bar{s}\, e^2} \quad , \qquad (16)$$

the time averaged sheath width $\bar{s}$ is approximated by an optical measurement, here about 1 cm. The above equation yields for an Ar discharge $\tilde{n} = 1.4\cdot10^9\ cm^{-3}$ ($\omega_r/2\pi \approx 147$ MHz) and a CF_4 discharge $\tilde{n} = 1.6\cdot10^9\ cm^{-3}$ ($\omega_r/2\pi \approx 158$ MHz). The electron collision rate ν can be estimated from the damping constant to be of the order of $10^8\ s^{-1}$.

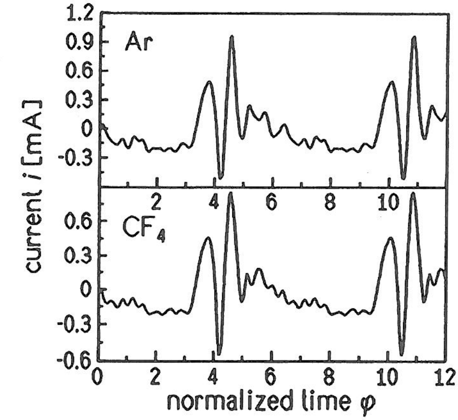

Fig. 3. Current of the measurement electrode
Ar: U_B = *450* V, 1.5 Pa, 180 W
CF_4: U_B = *600* V, 1.5 Pa, 310 W

The Fourier transformation of Eq. (12) in conjunction with Eq. (14) was used to develop a numerical, non-iterative algorithm in order to determine the plasma parameter and the current pitch ratio of true discharge and measured current. Thus the paramter can be calculated in situ and without the rough estimations given above.

The knowledge of the density and collision rate of the electron allows to evaluate the resistance of the plasma body. Now the power dissipated in the plasma body can be evaluated in conjunction with the harmonics of the true discharge current using Parseval's theorem.

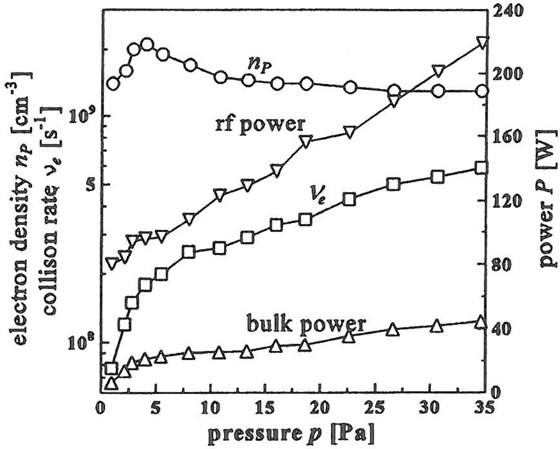

Fig. 4. Plasma parameters vs. pressure
13.56 MHz; U_B = 300 V; 10 sccm O_2

The Figs. 4 and 5 show the

dependence of the electron density, collision rate and the power dissipated in the plasma body (bulk) on bias voltage and pressure in plasma etcher Alcatel GIR 300 (electrode gap 70 mm, graphite electrode ⌀ 155 mm).

The maximum in the (average) electron density results from a radial contraction of the plasma at higher pressure. The collision rate varies linear with the pressure expeted for $p > 5$ Pa, as expected.

In Fig. 5 we find, contrary to the RF power, a approximately linear relation of the bulk power on the bias voltage. The dependence of the RF power appears to satisfy Ohm's law and indicates that the main part of the RF power will be dissipated outside the discharge.

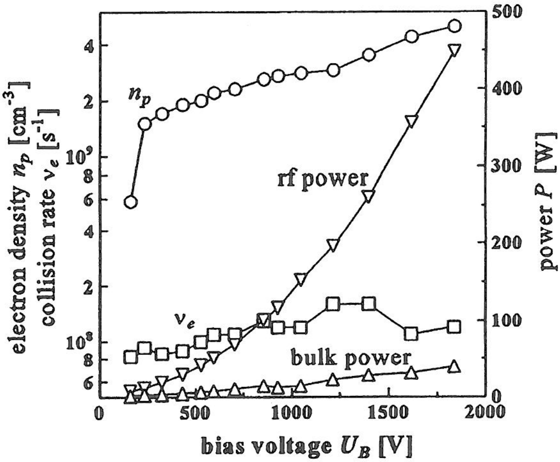

Fig. 5. Plasma parameters vs. bias voltage 13.56 MHz; p = 5 Pa; 10 sccm Ar

Conclusions

The presented model results in a new method for plasma monitoring - called self excited electron resonance spectroscopy (SEERS). A further improvement of model and experiment will enable SEERS to determine in situ electron density and electron collision rate in the plasma body.

Since SEERS is the manifestation of an RF resonance effect, it is not affected by insulating layers within the chamber. This passive method can be used for various plasma processes, as plasma etching and plasma enhanced chemical vapour deposition, to improve development, verification, and quality assurance of plasma processing.

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