RF magnetron discharge model based on power balance

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Abstract. Previously developed theoretical approach to model asymmetrical capacitively coupled RF discharge is applied in the case of RF magnetron discharge. The method is based on deriving theoretical dependence of the FR power dissipated in the discharge on the DC selfbias voltage. These are easily measurable quantities and this experimental data is fitted with the theoretical model. Latter is based on rather broad assumptions and is applicable in large variety of cases. Experiments with Ar and O2 at low pressure are conducted. The data obtained fits perfectly with the model. The dependence of the total ion current, bombarding the target on the discharge conditions (applied power) is derived. The results show that independently on the similarity in the initial data, a substantial difference in the plasma sustaining power in both cases can be distinguished. This fact can be attributed to the presence of a number of vibrational rotational levels in O2 molecules, absent in Ar. The additional power needed to sustain O2 plasma goes for excitation of the vibrational rotational levels.

1. Introduction
Recently a macroscopic model for energy balance in asymmetric capacitively coupled discharge has been developed [1–4]. It is based on treating the discharge as two distinct zones: quasineutral plasma bulk and sheath region. The same RF current flows trough both zones and (because of the higher impedance) is determined by the sheath region U/I characteristics. The range of RF frequency greater than the ion plasma frequency and much less than the electron plasma frequency is treated, because of its widespread in the practice. In this region the ion movement is determined by the averaged in time electric field and the electron current to the walls follows the static U/I characteristics. Because of the strong nonlinearity of the electron current a static selfbias voltage occurs between the plasma and the walls and this voltage equals the maximum of the a.c. electric potential across the sheaths between the plasma and the walls. When the electrodes of the capacitively coupled discharge are asymmetrical and d.c. insulated, the selfbias voltages between the plasma and both electrodes are different and their difference is measured as a d.c. voltage between them. If the asymmetry is substantial, the d.c. voltage between the electrodes approximately equals the selfbias voltage between the plasma and the smaller electrode – usually the active electrode in the technological applications.

As it has been shown in [1–3] on the base of the sheath thickness analysis simple algebraic dependences between this d.c. voltage and the averaged ion current density (or its equivalent – the total ion current to the active electrode) can be derived for various modes of ion motion. Both: the power dispersed in the plasma bulk and the power input in the sheath are connected with this ion current density (total ion current), so an algebraic low showing the dependence of total RF power fed to the discharge (sum of the power dispersed in the plasma bulk and the power input in the sheath) can be written. In this algebraic low all of the discharge features and parameters are compressed into a set of coefficients. By comparing experimental data for the dependence of the selfbias voltage on the
input RF power these coefficients can be determined and the discharge integral parameters
dependence on the input power can be derived.

The magnetron RF discharge is a strongly asymmetric discharge in sense of the
abovementioned model. The ion motion is affected by the magnetic field insufficiently, so that we may
use the developed sheath models. The electron drift is strongly affected by the magnetic field. Some
electrons are trapped in the region close to the active electrode, the ionization processes are
concentrated here and the whole plasma bulk is redistributed. Nevertheless the main dependences
remain valid. The power dispersed in the plasma bulk is proportional to the squared electric field
multiplied by the plasma density and integrated over the quasineutral plasma volume. Only the form-
factor of the plasma resistance is different from the case without magnetic field, but the overall
dependencies retain the same algebraic form.

2. Model
The motion of the ions in the sheath is not substantially modified by the magnetic fields typical for the
magnetron discharges. Thus we can use the previously obtained results for the relation between the
plasma and sheath power on the selfbias voltage. In [1] the following relationship between the plasma
power and the selfbias is derived, taking into account only the capacitive current through the sheath
and the ohmic heating in the plasma bulk:

\[ P_{\text{plasma}} = A U^{1/2} \quad \text{for the free fall motion mode of the ions,} \]

\[ P_{\text{plasma}} = B U^{3/5} \quad \text{for the strong field drift mode of the ion motion,} \]

where \( A, B \) are coefficients, depending on the ion mass and total collision cross-section, and \( U \) is the
selfbias voltage. It is shown also that the plasma inhomogeneity at the boundaries does not change the
nature of relations (1).

In [2] additional mechanisms of power deposition into the plasma bulk are taken into
account. The first is the active electron current through the sheath. Its mean value is much less than
this of the capacitive current, but the ohmic power of some current flowing through the plasma bulk is
proportional to its mean square (or effective) value. The electron conductance current in these
conditions (frequency much less than the electron plasma frequency) consists of short high amplitude
pulses and its mean square is not negligible, though its square value is. This gives rise to the power
input in the plasma, and changes (1) to:

\[ P_{\text{plasma}} = \frac{B}{(1 - D \sqrt{U})^\delta} U^{1/(1 + \alpha)}, \quad \delta = \frac{2 + \alpha}{1 + \alpha}. \]

Here \( \alpha \) is the power in the ion drift flow, \( v_i = a E^\alpha \) is the ion drift velocity, \( E \) is time-
averaged electric field. The coefficient \( a \) can vary from 0.5 when the cross-section of ion – neutral
atom is constant [5], to 1 when it is inversely proportional to \( v_i \). In available experimental data neither
of these extreme cases is observed. The cross-section decreases with ion velocity but not so steep as
inversely proportional. A value of \( \alpha = 0.75 \) seems to be a good approximation.

In [1–3] it is shown that the sheath power \( P_{\text{sheath}} \) has a similar dependence on the selfbias
voltage \( U \) as \( P_{\text{plasma}} \) with different coefficient and multiplied by \( U \). Thus the dependence of the total
power \( P_{\text{total}} \) on the selfbias voltage takes the form:
\[ P_{\text{total}} = \frac{B}{(1-D\sqrt{U})^\delta} U^{1/(1+\alpha)} + \frac{C}{(1-D\sqrt{U})^\delta} U^{(2+\alpha)/(1+\alpha)} \]  

(2)

The coefficients \( B \), \( C \) and \( D \) have to be determined from the experimental data by using a least square regression procedure. The first term is the power sustaining the plasma; the second represents the sheath power. On the other hand the sheath power equals \( IU \), where \( I \) is the total ion current to the active electrode. Hence we can determine the ion current:

\[ I = \frac{C}{(1-D\sqrt{U})^\delta} U^{\delta/(1+\alpha)}. \]  

(3)

3. Experimental

Two inch 13.56 MHz RF powered magnetron was used in a standard configuration. The vacuum chamber was approximately 30 cm in diameter and height, so the discharge was strongly asymmetrical. The operating gases were Ar at pressures 6 and 27 mTorr (3.6 Pa) and \( \text{O}_2 \) at 5 mTorr (0.67 Pa), and for comparison the same vacuum configuration Ar at 14 mTorr (1.9 Pa) without magnetic field – the magnetic field was shortened with a ferromagnetic clamp. In figure 1 the fitted experimental data for the case of \( \text{Ar} – 6 \text{ mTorr (0.8 Pa)} \) are plotted. The curves for the plasma and sheath power are plotted separately. In figure 2 the same data and calculated by (3) ion current are plotted versus the applied RF power. Similar measurements are conducted in discharges in oxygen 5 mTorr, argon at 27 mTorr and pure asymmetrical capacitively coupled RF discharge in Ar at 14 mTorr (the magnetic field is shortened by an iron clamp). Their plots look similar to the plots in figures 1 and 2, and are not shown separately. The mean squared deviances of the measured data from the fitting curves are less than 1% in all of the cases under consideration. The shape of the curves in the investigated cases is the same. The difference between them is quantitative.

4. Discussion of the results

The main quantity characterizing the discharge is \( U_0 = B/C \) (\( B \) and \( C \) being the coefficients obtained by fitting the experimental data with formula (2)). It has a dimension of voltage as shown in [1]. The quantity \( eU_0 \) is proportional (with a formfactor that is greater than unity and depends on the plasma density distribution across the electrodes) to \( E \) – the total energy, used to produce single electron – ion pair, i.e. the ionization energy and sum of all inelastic collisions that the electron suffers until acquiring ionization energy. The values of \( U_0 \) for different experimental situations are:

- 60.9 V for the case \( \text{Ar} \) 6 mTorr,
- 381 V for the case \( \text{O}_2 \) 5 mTorr,
- 37.4 V for the case \( \text{Ar} \) 27 mTorr and
- 29.1 V for the case \( \text{Ar} \) 14 mTorr with clamped magnetic field.

For discharge in oxygen \( U_0 \) is substantially higher than for argon. This is due to the fact that the molecular and electronegative oxygen has larger number of possible inelastic interactions with plasma electrons. This is similar to the discrepancy between SF\(_6\) and nitrogen, observed in [1–3] correspondingly.
The variation of $U_0$ with pressure is reverse to the case of purely RF discharge (without magnetic field support) reported in [1–4]. This can be explained by the existence of zones with high plasma density in the magnetron discharge. In these zones the degree of excitation is much higher than in the case of non-supported by a magnetic field RF discharge. In the high excitation zones a possibility of additional inelastic collisions occurs – step-wise excitation – with high cross-section,
because high percent of the electrons has sufficient energy for them. The degree of excitation grows with decreasing the pressure and this leads to an inversed dependence of $U_0$ on the pressure. By the same reason $U_0$ is lower for the discharge without magnetic support. But nevertheless on the higher power spend on the plasma production the ion current is 0.49 A versus 0.21 A for the non-magnetron discharge (both for 150 W input power), due to the lower sheath power.

5. Conclusions
It is shown that the numerical model developed for the asymmetric capacitively coupled RF discharge can be applied for a RF magnetron discharge. The model gives simultaneously the main parameters describing the ion bombardment: the ion current and the maximum ion energy (selfbias voltage) as a function of the applied RF power. It is shown also that 50 mm magnetron supplied with 150 W RF power can produce substantial degree of excitation. This fact should be taken into account in some discharge applications where is preferable to put more power into excitation of the media – gaseous laser for example.

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