Ion flux and energy virtual sensor for measuring ion flux and energy distribution at a RF biased electrode in ICP reactor (RIE-mode)

M A Bogdanova¹,², D V Lopaev¹ and S M Zyryanov¹,²

¹ Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics, Leninskie gory, GSP-1, Moscow 119991, Russian Federation
² Lomonosov Moscow State University, Faculty of Physics, Leninskie Gory, Moscow 119991, Russian Federation

E-mail: bogdanova.marya@mail.ru

Abstract. The modern technology of micro- and nanoelectronics involves a great number of steps, such as pattern transfer, where Reactive Ion Etching (RIE) in rf plasma reactors is widely used. To control the etching process, the ion flux and ion energy distribution should be managed precisely. However, the measurements of these parameters during the process in the real-time operation are impossible. This paper is devoted to the construction of a virtual diagnostics of the Ion Energy Distribution (IED) function. This method for the determination of the ion energy spectrum on the surface of rf biased electrode is based on model calculations using in-situ measured discharge parameters. The results of IED virtual diagnostics were compared with data, obtained by Retarded Field Energy Analyzer (RFEA). This was done for Ar- and H₂-plasmas operated under low-pressure rf plasma conditions. The good agreement between the model and the experimental justifies the conclusion that the IED virtual diagnostics can be applied successfully. This enables the in-situ monitoring of the IED at the electrode surface in RIE reactors.

1. Introduction
Pattern creation for the production of microstructures cannot be achieved without Reactive Ion Etching (RIE). This RIE process is carried out by placing samples on the surface of an rf biased electrode, as rule in an asymmetric rf low-pressure discharge. To control the etching process precisely it is essential to follow the ion flux and the ion energy distribution (IED) at the surface of the rf biased electrode. However, both the IED and ion flux cannot be measured directly in an industrial plasma reactor during the etching process. Therefore the development of some virtual plasma diagnostics for IED measurements is of great interest. In other words, such diagnostics is supposed to predict the energy distribution and the flux of the ions bombarding the sample, by using model calculations. The model input is formed by the set of easy measurable discharge parameters; the model output, being the ion flux and energy distribution, will be shown in the real-time on a computer screen. In the simple case of a low-pressure plasma the IED calculations can be based on a straightforward physical model of the ion motion.
in a collisionless rf sheath. Moreover, the modeling should be rather fast to be fulfilled in the real-time operation mode.

2. The model of the ion motion in an RF collisionless sheath

The simplest approach to describe the ion energy spectrum at a rf-biased electrode is based on the model of collisionless rf sheath [1]. Such an approach allows obtaining the IED at a CCP rf biased surface by using simple physical relations. Since the response of the ions to rapid changes of a rf sheath potential is negligible, we may introduce the notion of the mean ion energy \( eV_s \) gained in the sheath, where \( V_s \) is a mean sheath potential. This potential can be calculated, using two measurable external discharge parameters: namely the amplitude of the rf voltage \( V_{rf} \) applied to the electrode and the negative dc self-bias voltage \( V_{dc} \). The latter originates from the difference between the areas of the biased and grounded electrodes, i.e. from the asymmetry of the rf discharge. Thus we get:

\[
V_s = \frac{1}{2}(V_{rf} - V_{dc})
\]  

(1)

In the case of the collisionless rf sheath the ion energy spectrum \( F(E) \) can be calculated by the following way [2]:

\[
F(E) = \frac{2\Gamma_i}{E} \left[ 1 - 4 \left( \frac{E - eV_s}{\Delta E} \right)^2 \right]^{-1/2},
\]  

(3)

where \( \Gamma_i \) is ion flux to the rf biased electrode while the ion energy

\[
E = eV_s \pm \Delta E,
\]  

(2)

dePENDS on the ion energy addition \( \Delta E \) — being caused by the influence of the rf voltage applied to the electrode on the ion motion in the sheath. The magnitude of the energy addition \( \Delta E \) is determined by the ion response to applied rf voltage and is a function of the ratio between the ion pass time through the sheath \( \tau_i \) and the rf period \( \tau_{rf} \):

\[
\Delta E = 2eV_{rf} \left[ 1 + \left( \frac{2\pi \cdot \tau_i}{3 \cdot \tau_{rf}} \right)^2 \right]^{-1/2},
\]  

(4)

\[
\tau_i = 3s \sqrt{\frac{M}{2eV_s}}, \quad \tau_{rf} = \frac{1}{f},
\]  

(5)

Here \( M \) is the ion mass and \( f \) — the frequency of applied rf voltage. The sheath thickness \( s \) can be obtained from the well known Child law, which modified for the case of rf sheath reads [2]:

(6)
\begin{equation}
    s = \left( \frac{0.82 \varepsilon_0}{\bar{J}_i} \right)^{1/2} \left( \frac{2e}{M} \right)^{1/4} \frac{V}{s}^{3/4},
\end{equation}

With \( \varepsilon_0 \) – the dielectric constant and \( \bar{J}_i \) – the mean ion current density on the rf biased electrode.

3. Experimental setup

The described model for the ion energy spectrum was used to develop the IED virtual diagnostics. The experimental set up is shown in fig.1. Experiments in Ar- and H\textsubscript{2}-plasma at pressure < 20 mTorr were carried out in order to verify the proposed approach for plasmas with different ion mass and ion composition. To generate plasma an ICP rf coil was used operated at 13.56 MHz. The frequency of the CCP rf bias, applied to the electrode, could be varied from 1 till 27 MHz. The plasma density \( n_e \) and electron temperature \( T_e \) were measured by an rf-compensated Langmuir probe. An rf-compensated Retarded Field Energy Analyzer (RFEA) was used for ion energy spectrum measurements. In addition the mass-spectrometer was attached to the plasma chamber in order to obtain ion composition (figure 1).

![Experimental setup](image)

**Figure 1.** Experimental setup.

4. Results and discussion

4.1. Ion composition

To perform the calculations of the ion energy spectrum it is necessary to know the ion composition of plasma. In the simple gas, such as pure Ar, it is reasonable to assume that only one sort of ion Ar\textsuperscript{+} is present; while in H\textsubscript{2} the ion composition can be rather complex: H\textsuperscript{+}, H\textsubscript{2}\textsuperscript{+}, H\textsubscript{3}\textsuperscript{+}. To take this into account the ion composition was measured by mass spectrometry. Examples of mass spectra in Ar- and H\textsubscript{2}-plasma are shown in figures 2a and 2b respectively.
As expected, Ar\(^+\) is the main ion in Ar-plasma (ArH\(^+\) density is notably lower), while in H\(_2\)-plasma there are several type of ions– H\(_3^+\), H\(_2^+\) and H\(^+\). Besides there is a small density of water ions H\(_2\)O\(^+\), which is typical for plasma research done is stainless steel chambers.

4.2. Ion energy spectra

In the discussion on experimental data and the IED calculations it is reasonable to consider separately two cases: when the electrode is grounded and when it is rf biased.

4.2.1. Grounded electrode. To characterize the pure ICP plasma, the IED at the grounded electrode was measured. It is well known that at low pressure the Tonks-Langmuir collision-less pre-sheath model \[2\] can be used. The assumption of both collisionless sheath and presheath is then justified and the IED is presented as a monoenergetic peak at energy equal plasma potential. The pre-sheath thickness is determined by the ion mean free path while ions gain the energy equal \(T_e/2\) in the sheath boundary (\(T_e\) is electron temperature). Ion collisions in the presheath region lead to a widening of the peaked IED on the sheath boundary. Therefore it is quite reasonable to assume the presence of a Boltzmann distribution for ions entering the sheath with a temperature equal to \(T_e/2\). Comparison with the experimental results clearly shows that the measured IED is somewhat wider than \(T_e/2\). It is related to capacitive coupling with the ICP antenna that transforms part of the 13.56 MHz voltage to the sheath. The amplitude of the rf voltage at 13.56 MHz was measured by a VI probe and the influence of the capacitive coupling on the ion motion was calculated using the method described in the section 2. Examples of the calculations for Ar- and H\(_2\)-plasma are shown in figures 3a and 3b respectively.

![Figure 2. Ion composition: (a) – Ar-plasma; (b) – H\(_2\)-plasma.](image)

![Figure 3. The IED on the grounded electrode – experimental data and theoretical calculation: (a) – Ar-plasma; (b) – H\(_2\)-plasma.](image)
Since the amplitude of the $V_{rf}$ at 13.56 MHz does not change by applying the rf bias to the electrode so that $V_{13.56MHz} + V_{rf\_bias}$ was really applied to the plasma sheath, we can consider the IED on the grounded electrode as “the apparatus function” for the IED calculations.

4.2.2. RF biased electrode. The experimental IEDs, obtained by the RFEA for several values of the rf bias $V_{rf}$ at 12 MHz are shown in figure 4 for both the Ar- and H$_2$-plasmas. It is clear that the ion response gets more intense with increasing $V_{rf}$ and that the IED becomes wider. Figure 4 also shows that this tendency is observed for both Ar$^+$ ions and for the ions generated in H$_2$-plasma. Moreover, it turns out that the IED-width in H$_2$-plasma is notably wider. This is due to the fact that lighter ions are more sensitive to the rf field.

Figure 4. The experimental IEDs measured by the RFEA for different values of rf bias: (a) – Ar-plasma; (b) – H$_2$-plasma.

Besides, in the H$_2$-plasma, where ion composition is complex, the dependence of the IED shape on the ion mass is also observed: the heavier ions have a smaller response to applied rf field, and are consequently more peaked. So the narrowest small peak on the IED top at the mean ion energy ??eV, corresponds to H$_2$O$^+$ ions, which have the biggest mass. The other two peaks, situated symmetrically relative to H$_2$O$^+$ energy peak, correspond to H$_3^+$, H$_2^+$ and a part also to H$^+$ ions. The calculated IEDs with the ion composition measured by mass spectrometer are shown in figure 5. It is seen, that the model calculations rather well reproduce the experimentally measured IEDs (see figure 4). There is some small difference only at lower energies connected with some rare ion collisions in the sheath.

Figure 5. The model IEDs for different values of rf bias: (a) – Ar-plasma; (b) – H$_2$-plasma.
4.3. Ion flux

For the IED normalization it is necessary to calibrate the RFEA accurately. In principle this can be done by inserting the Langmuir probe data \((n_e \text{ and } T_e)\) into the Bohm relation. But in absence of the probe, i.e. the typical situation for industrial plasma reactors, it should be done by an different method. To normalize the IEDs on the ion flux a special method is developed by using an alternating dc self-bias; in this method the electrode acts as a “flat probe”. When the rf bias is switched off fast enough, the stored charge on the capacitance associated to dc self-bias \(V_{dc}\) will be lost due to ion current to the electrode. The dependence of the current on \(V_{dc}\) (see figure 6) presents the ion part of VAC of the flat probe, i.e. electrode. From this VAC the electron temperature \(T_e\), floating potential \(V_f\) and ion current \(I_{dc}\) (or ion flux) can be extracted.

![Figure 6](image_url)

Figure 6. VAC (ion part) of the electrode that function as a “flat probe” for two power values: (a) – Ar-plasma; (b) – H\(_2\)-plasma.

5. Conclusion

The concept of “virtual diagnostics” is developed for the in-situ measurement of the ion energy distribution (IED) of ions impinging on an rf-biased electrode in a low-pressure RIE reactors. In this way the IED is found from external electric discharge parameters by using model calculations. The proposed approach was verified by experiments in an Ar- plasma and for a complex-composited H\(_2\)-plasma at pressures below 20 mTorr. In the experiments mass-spectrometer, an rf compensated Langmuir probe and an rf compensated RFEA were used to characterize the plasma and to find the IED at rf biased electrode. A simple model of collisionless rf plasma sheath was applied to calculate IEDs from measured discharge parameters and shows a good agreement with IEDs measured by RFEA. This works for both Ar- and H\(_2\)-plasmas. Thus approach of “IED virtual diagnostics” can be successfully applied to the control of the ion flux and energy in the case of a collisionless plasma sheath what is typical for conditions of low-pressure RIE reactors.

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