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Journal Article

N.B.: When citing this work, cite the original article.

Original Publication:

Nils Brenning, J. T. Gudmundsson, D. Lundin, T. Minea, M. A. Raadu and Ulf Helmersson, The role of Ohmic heating in dc magnetron sputtering, Plasma sources science & technology (Print), 2016. 25(6)

<http://dx.doi.org/10.1088/0963-0252/25/6/065024>

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Postprint available at: Linköping University Electronic Press

<http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-133384>

The Role of Ohmic Heating in dc Magnetron Sputtering

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Abstract

Sustaining a plasma in a magnetron discharge requires energization of the plasma electrons. In this work, Ohmic heating of electrons outside the cathode sheath is demonstrated to be typically of the same order as sheath energization, and a simple physical explanation is given. We propose a generalized Thornton equation that includes both sheath energization and Ohmic heating of electrons. The secondary electron emission yield γ_{SE} is identified as the key parameter, which determines the relative importance of the two processes. For a conventional 5 cm diameter planar dc magnetron, Ohmic heating is found to be more important than sheath energization for secondary electron emission yields below around 0.1.

1. Introduction

In most models of sputtering magnetrons the mechanism for energizing the electrons in the discharge is assumed to be sheath energization. In this process, secondary electrons emitted from the cathode surface are accelerated across the sheath into the plasma where they either ionize the atoms of the working gas directly, or transfer energy to the local lower-energy electron population that subsequently ionizes the working gas atoms. Balancing this energy source against the energy lost by electron impact ionization leads to the well known Thornton equation, which in its original form [1, 2] is formulated as a minimum required voltage to sustain the discharge,

$$U_{\min} = \frac{E_{i,\text{eff}}}{\varepsilon_e \beta \gamma_{\text{SE,eff}}}, \quad (1)$$

where $E_{i,\text{eff}}$ is the effective energy cost for the average ion-electron pair created, β is the fraction of the ions that go back to the target, ε_e is the fraction of the secondary electrons that cause ionization before they are lost from the system, and $\gamma_{\text{SE,eff}}$ is the effective secondary electron emission probability per ion bombarding the target. The effective $\gamma_{\text{SE,eff}}$ differs from the secondary electron emission probability γ_{SE} due to ionization in the sheath with a probability m , and recapture of the secondary electron at the target with a probability r . The inclusion of these is described by Depla *et al.* [3]. Above breakdown all the parameters ε_e , β , m , and r can vary with the applied discharge power. Allowing for such variations the Thornton equation is extended [3], from being a breakdown condition to include also dcMS discharges at any voltage $U_D > U_{\min}$,

$$U_D = \frac{E_{i,\text{eff}}}{\varepsilon_e \beta m (1-r) \gamma_{\text{SE}}}. \quad (2)$$

The basic assumption of sheath energization as the main energy source, however, remains in this formulation.

Recently Huo *et al.* [4] presented modeling results in support of an additional electron energization mechanism based on Ohmic heating, *i. e.*, dissipation of locally deposited electric energy $\mathbf{J}_e \cdot \mathbf{E}$ to the electrons carrying the current density $\mathbf{J}_e$ in the plasma volume outside the sheath. Ohmic heating was shown to dominate in a high power impulse magnetron sputtering (HiPIMS) device with an Al target. In that report, the authors used the global (volume averaged) discharge ionization region model (IRM) of Raadu *et al* [5], which was able to fit very well the experimental data from Anders *et al* [6]. An important result was that the fraction of Ohmic heating increased with increased applied power. The reason for this trend was identified as an increase in the degree of self-sputtering with the increased discharge power. At the highest power, Al^+ ions, according to the IRM, carried almost all of the discharge current. Since singly charged metal ions have close to zero γ_{SE} from targets of the same material [3,7], the power input through electron sheath energization here dropped close to zero, leaving a discharge dominated by Ohmic heating.

The result by Huo *et al* [4] indicates a direct link between a low γ_{SE} and a high fraction of Ohmic heating, although demonstrated only in the special case of a high power pulsed

Fig 1. The magnetic field (red dashed lines) and the electric equipotential surfaces (black lines) above the racetrack of a planar sputtering magnetron. The potential U_{IR} across the extended pre-sheath is here shown for our interpretation of the case $\gamma_{se} = 0.1$ in the data set of Depla *et al.* [3]. Please notice that the potential across the sheath varies between the centre of the racetrack and the edge of the racetrack. The block arrows show the directions of electron motion associated with sheath energization (across the sheath) and with Ohmic heating (across $\mathbf{B}$ outside the sheath).

discharge where γ_{SE} was low due to operation in the self-sputtering range. The same effect is here demonstrated also for dc magnetron sputtering (dcMS) far below the self-sputtering range. The paper is organized as follows. In section 2, the differences between sheath ionization and Ohmic heating of electrons is outlined, and a generalized version of the Thornton equation is derived, which includes Ohmic heating. In section 3, this equation is applied to make a revised evaluation of experimental data earlier published by Depla *et al* [3], and section 4 contains a summary and a discussion.

2. Sheath energization and Ohmic heating

In the planar configuration, both dcMS and HiPIMS are simply diode sputtering arrangements with the addition of a magnetic field at the cathode side, across which the electrons have to move in order to carry the discharge current to the anode. Fig 1 shows schematically the magnetic field lines and the electric equipotential surfaces above the racetrack in a sputtering magnetron. A potential U_{sh} falls over the sheath, and the rest of the applied voltage $U_{IR} = (U_D - U_{sh})$ falls across the extended presheath, which will herein be called the ionization region (IR), following the nomenclature of the IRM [5].

Let us start with sheath energization of electrons. Since the magnetic field is usually at an angle to the target surface (the exception being at the centre of the target erosion zone, the race track), most of the electrons created by secondary emission can cross the cathode sheath

even while being bound to the magnetic field lines. In crossing the sheath they gain the energy eU_{SH} . For typical magnetron sputtering parameters the mean free path of electrons is much longer than the thickness of the sheath, and sheath energization results in an monoenergetic beam injected into the plasma which is both spread in energy and shifted to lower energies, mainly through inelastic collisions with the neutral gas. Sheath energization is thus characterized by acceleration that is not hindered by the magnetic field, energization on a time scale much shorter than the collision time, and a hot non-Maxwellian electron population denoted by e^H . Ohmic heating is different in all three respects. It can be defined as the electron energization due to $\mathbf{J}_e \cdot \mathbf{E} > 0$ in the plasma outside the sheath. The equipotentials are here in Fig. 1 drawn parallel with the magnetic field lines, in accordance with both experiments [8] and modelling [9, 10]. Ohmic heating is in this situation associated with the electron motion across magnetic field lines. This is a much slower process than crossing the sheath and is limited by the electrons' cross-B mobility [1]

$$\mu_{e,perp} = \frac{\mu_e}{1 + \omega_{ge}^2 \tau_c^2} \quad (3)$$

where $\mu_e = e\tau_c/m_e$ is the mobility of the electrons in the absence of a magnetic field, $\omega_{ge} = eB/m_e$ is the electron (angular) gyro frequency, and τ_c is the electrons' effective collision time including anomalous transport [11]. Electron energization by Ohmic heating is characterized by cross-B electron transport, and a cold electron population denoted by e^C that, following [4], can be assumed to be close to Maxwellian.

According to probe measurements in both dcMS [8] and in HiPIMS [12, 13], U_{IR} is often about 10% - 20% of the discharge voltage, *i. e.*, $U_{IR}/U_D \sim 0.1 - 0.2$, although some models have predicted even higher values for HiPIMS discharges [4,14]. This fraction will herein be denoted as

$$\delta_{IR} = \frac{U_{IR}}{U_D}. \quad (4)$$

It was pointed out by Huo *et al* [4] that, for any given applied potential, Ohmic heating of electrons is more efficient than sheath energization. The reason is that a larger average fraction of the discharge current, $\langle \frac{I_e}{I_D} \rangle_{IR}$, is carried by electrons in the ionization region than

the corresponding fraction $I_{e,sh}/I_D$ in the sheath. For a numerical example let us take typical values proposed in the literature for a dcMS discharge operating in Ar, see *e.g.* [3] : $\gamma_{SE} = 0.1$, $r = 0.5$, and $m = 1.5$. This gives the electron current in the sheath as $I_{e,sh} = I_D \gamma_{SE} (1 - r) m = 0.075 I_D$. Outside the sheath the electron fraction of the discharge current varies with the distance from the target. At the sheath edge the ion current dominates, and with increasing distance from the cathode the electron fraction increases. On the anode side of the ionization region the electrons carry most of the discharge current. Following Huo *et al* [4] we assume that on average half the current in the ionization region is carried by electrons, giving $\langle \frac{I_e}{I_D} \rangle_{IR} \approx 0.5$. Since $I_{e,sh}/I_D = 0.075$, Ohmic heating of electrons is in this example more efficient than sheath energization by a factor of $0.5/0.075 \approx 7$. This means that Ohmic heating is equally important as sheath energization already when the potential across the ionization region is $1/7$ of the potential across the sheath. This is the case in the middle of the experimentally observed range $\delta_{IR} = 0.1 - 0.2$. With higher δ_{IR} , corresponding to larger potentials U_{IR} , such as reported by Minea *et al* [14] early in the pulse of a HiPIMS discharge, the relative importance of Ohmic heating should be dominating.

One powerful way to derive constraints on a discharge is to formulate a Townsend condition, a necessary condition for the self-reproduction of the discharge. The classical example is Townsend's original derivation of the breakdown voltage of a glow discharge [15]. The general procedure is to identify a closed loop of events, begin with a selected starting event in the loop, and then require that exactly one new event, of the type started with, is reproduced after one passage through the loop. If there is only a single loop involved the starting point can be chosen arbitrarily. For example, the Thornton equation in the form of Eq. (2) can be derived starting with the emission of a secondary electron, starting with the impact of an ion at the target, or starting with an ionization event. When more than one loop is involved, however, the starting point must be selected with more care. In our case, in order to include both sheath ionization and Ohmic heating, we begin with the creation of N_0 electron-ion pairs. This starts two chains of events, one associated with the produced N_0 ions, and the other with the produced N_0 electrons. Let us first follow the ions. They are attracted to the target with a probability β and release secondary electrons with a probability γ_{SE} . These electrons have a recapture probability r and a probability for ionization in the sheath m , and they gain the energy U_{sh} (eV) by acceleration across the sheath. This is the source of the hot electron population e^H . Some of the energy that is put into the e^H population is lost with electrons that

leave the ionization region, with the consequence that only the fraction ε_e^H of this energy is used for ionization. The number of new ions that will be produced is obtained by division of this remaining energy with the effective cost of ionization of the hot electrons¹, $E_{i,\text{eff}}^H$, which closes this first loop. It leads to a number of new ionization events

$$N_1 = N_0 \beta \gamma_{SE} (1 - r) m \varepsilon_e^H U_{sh} / E_{i,\text{eff}}^H . \quad (5)$$

The Thornton equation is recovered for the combination $N_1 = N_0$ and $U_{sh} = U_D$.

Now let us follow the second loop, started by the N_0 electrons within the cold e^C population that were produced in the initial N_0 ionization events. Their energization is due to Ohmic heating by the potential U_{IR} across the ionization region. A complication here is that each individual electron crosses a fraction of U_{IR} that depends on the location of the ionization event, see Fig 1. Those that are created close to the target cross the full U_{IR} , while those that are created further away experience only a smaller fraction. To account for this variation, we follow Huo *et al* [4] and use the average fraction of electron current in the ionization region, $\langle \frac{I_e}{I_D} \rangle_{IR}$. This gives a total energy $N_0 \langle \frac{I_e}{I_D} \rangle_{IR} U_{IR}$ that goes to these electrons, of which a fraction ε_e^C is used for ionization with an effective energy cost of $E_{i,\text{eff}}^C$. The number of new ionization events after this second loop becomes

$$N_2 = N_0 \langle \frac{I_e}{I_D} \rangle_{IR} U_{IR} \varepsilon_e^C / E_{i,\text{eff}}^C . \quad (6)$$

The Ohmic heating can be understood as the gain of the average electron in the N_0 created ion-electron pairs, being moved across a fraction $\langle \frac{I_e}{I_D} \rangle_{IR}$ of the potential U_{IR} .

¹ It is here necessary to separate between the costs of ionization for the two electron populations since they differ significantly for typical dcMS conditions. At electron temperatures (in eV) below around E_i the energy loss per ionizing collision rises as the excitation loss exceeds that of ionization [2]. For a numerical example we can take the average energy of the e^H component to be 300 - 500 eV and a electron temperature of the e^C component to be 3 eV. This gives $E_{i,\text{eff}}^H \approx 22 - 25$ eV and $E_{i,\text{eff}}^C \approx 53.6$ eV [2].

Fig. 2. The inverse of the discharge voltage as function of the ion induced γ_{SE} for 18 different target materials. The measurements were made in a conventional 5 cm diameter dc magnetron sputtering discharge in a 0.4 Pa pure argon atmosphere and a discharge current of 0.4 A. The dotted line is a linear fit. From Depla *et al* [3].

A steady state discharge requires $N_1 + N_2 = N_0$. Combining this condition with the relation $U_{sh} = U_D - U_{IR} = U_D(1 - \delta_{IR})$, using Eq.s (5) and (6), and solving for U_D gives the generalized Thornton equation

$$U_D = \left(\frac{\beta \epsilon_e^H m(1-r) \gamma_{SE}(1-\delta_{IR})}{E_{i,eff}^H} + \frac{\epsilon_e^C (I_D)_{IR} \delta_{IR}}{E_{i,eff}^C} \right)^{-1}. \quad (7)$$

A special case is that of zero potential over the extended pre-sheath, $U_{IR} = 0$, giving $\delta_{IR} = 0$. In this case the usual Thornton equation (2) is recovered.

3. Application of the generalized Thornton equation to experimental data

To experimentally investigate the physics predicted by the Thornton equation, Depla *et al* [3] measured the discharge voltage for a 5 cm diameter magnetron target for Ar as the working gas at pressures of 0.4 and 0.6 Pa, for discharge currents 0.4 A and 0.6 A, and for 18 different

target materials with γ_{SE} in the range from 0.05 to 0.18. They interpreted the data based on the Thornton equation in the form of Eq. (2). Since the data for all targets were taken in the same magnetron, they argued that for each set of data using the same discharge current and pressure, the discharge parameters $E_{i,eff}$, ε_e , β , m , and r should be almost constant, *i.e.*, independent of γ_{SE} of the target material. If Eq. (2) holds, a plot of the inverse discharge voltage $1/U_D$ against γ_{SE} should then give a straight line through the origin. As an example of their results, the combination of pressure $p = 0.4$ Pa and $I_D = 0.4$ A is shown in Fig. 2 and shows that a straight line indeed results, but that it does not pass through the origin. We here propose that this intercept is due to Ohmic heating. To show this, we write the inverse discharge voltage $1/U_D$ from the generalized Thornton equation (7) as

$$\frac{1}{U_D} = \frac{\beta \varepsilon_e^H m (1-r) (1-\delta_{IR})}{E_{i,eff}^H} \gamma_{SE} + \frac{\varepsilon_e^C \langle \frac{I_e}{I_D} \rangle_{IR} \delta_{IR}}{E_{i,eff}^C} . \quad (8)$$

Eq. (8) has the form of a straight line, with $\frac{1}{U_D} = k \gamma_{se} + l$. The slopes k and the intercepts l for the four combinations of pressure and current in Depla *et al* [3] are shown in Table I. They are related to the discharge parameters through

$$k = \frac{\beta \varepsilon_e^H m (1-r) (1-\delta_{IR})}{E_{i,eff}^H}, \quad (9)$$

and

$$l = \frac{\varepsilon_e^C \langle \frac{I_e}{I_D} \rangle_{IR} \delta_{IR}}{E_{i,eff}^C} . \quad (10)$$

From the derivation above it is clear that l is associated with the Ohmic heating process, and therefore most interesting for the present discussion. The rightmost column in Table I shows δ_{IR} evaluated from Eq. (10) with the values of l from Table I, and with the assumed value $\varepsilon_e = 0.8$, with $\langle \frac{I_e}{I_D} \rangle_{IR} \approx 0.5$ as argued by Huo *et al* [4], and with $E_{i,eff}^C \approx 53.6$ eV, which corresponds to $T_{e,cold} \approx 3$ eV, see footnote 1 above. This gives δ_{IR} in the range 0.15 - 0.19, *i.e.*, the ionization region in the studied dcMS discharges carries typically 15 – 19 % of the applied discharge voltage.

I_D	p	slope k	intercept l	$\delta_{IR} = U_{IR}/U_D$
0.4 A	0.4 Pa	0.0117	0.00145	0.19
0.4 A	0.6 Pa	0.0129	0.00120	0.16
0.6 A	0.4 Pa	0.0130	0.00130	0.17
0.6 A	0.6 Pa	0.0140	0.00110	0.15

Table I. Data for four dashed-line fits made in [3], such as shown for the combination of 0.4 A and 0.4 Pa in figure 2. The rightmost column shows estimates of the fraction of the applied potential that falls over the ionization region, based on Eq. (10).

From the analysis above it is possible to derive, with some precision, how important the energy input through Ohmic heating is for the ionization in the discharge. From Eq:s (5), (6), (9), and (10) follows that the fraction i_{Ohmic} / i_{total} of the total ionization that is due to Ohmic heating can be obtained directly from the line fit parameters k and l , and written as a function of only the secondary electron yield γ_{SE} :

$$i_{Ohmic} / i_{total} = \frac{l}{k \gamma_{SE} + l}. \quad (11)$$

This relation is plotted in Fig. 3 for the four dcMS cases in Table I. In addition, Fig. 3 also shows a high power example from the HiPIMS discharge at an argon pressure of 1.8 Pa modelled by Huo *et al* [4], marked by a circle². It is taken at the end of a 400 μ s long pulse, when the discharge was deep into the self-sputtering mode. A large fraction of Al^+ ions here gave an effective γ_{SE} close to zero. Please notice that this HiPIMS case is perfectly consistent with the dcMS cases.

4. Summary and discussion

Experimental data from Depla *et al* [3] of the discharge voltage as function of the secondary electron emission yield γ_{SE} of different target materials is re-evaluated using a generalized Thornton equation. The analysis gives estimates both of the potential difference U_{IR} over the

² The value of γ_{SE} is obtained from Fig. 5(d), case C, and the fraction of ionization due to Ohmic heating from Fig. 6(b), the 1000 V case, both in Huo *et al* [4].

Fig. 3. The relative contributions to the total ionization I_{total} due to Ohmic heating, I_{Ohmic} , and sheath energization, I_{sheath} . The curves show Eq. (11) using k and l from the four combinations of pressure and discharge current in the dc magnetron studied by Depla *et al* [3]. They are plotted in the same top-down order as the labels, and are drawn solid only in the range of γ_{se} where they are supported by the measurements in [3]. A blue circle marks the HiPIMS study by Huo *et al* [4].

ionization region, and of the contribution of Ohmic heating of electrons to the ionization in the discharge. Both these quantities are found to be mainly determined by the secondary electron emission yield γ_{SE} of the target material. The following two trends are found:

- Increasing γ_{SE} from 0.05 to 0.18 decreases the ionization by electrons that get their energy from Ohmic heating from about 2/3 to about 1/3 of the total ionization, the rest being due to sheath energization. This trend is easily understood: a high γ_{SE} gives a higher flux of energetic secondary electrons from the target, and Ohmic heating therefore contributes with the energy to a smaller fraction of the total ionization.
- Increasing the pressure by 50% at constant current decreased the potential U_{IR} by $\sim 10\%$ for both currents studied, 0.4 and 0.6 A. A probable explanation is that the electrons in the magnetron are strongly magnetized ($\omega_{\text{ge}}\tau_{\text{c}} \gg 1$). In this case a

higher electron-neutral collision rate (e-n collisions per second for the average electron) increases the cross-**B** mobility that is given in Eq. (3). A higher gas density therefore gives a higher cross-B conductivity. A lower electric field is therefore required to drive the same discharge current, and consequently a lower potential difference U_{IR} .

We regard the results concerning the fractions of ionization due to Ohmic heating in Eq. (11) and Fig. 3 to be quite realistic since they are directly derived from the slopes k and intercepts l of the line fits to experimental data, with no need for any *ad hoc* assumptions. The direction of the trend in U_{IR} with pressure is probably also correct, while the absolute values of U_{IR} might be more uncertain, being obtained from Eq. (10) with the assumed discharge parameters $E_{\text{i,eff}}^{\text{C}} = 53.6$ eV, $\varepsilon_{\text{e}}^{\text{C}} = 0.8$, and $\langle \frac{I_{\text{e}}}{I_{\text{D}}} \rangle_{\text{IR}} = 0.5$. Other values would change the estimate. However, the U_{IR} values are in line with previously reported potential profiles of the extended pre-sheath [12, 13].

The consequences of including Ohmic heating in the description of sputtering magnetrons are basically two. The first is that it changes the understanding of what determines the discharge voltage. As a particularly striking example let us take gasless self-sputtering operation, which is possible for target materials with a high self-sputtering yield such as Cu or Zn. Andersson and Anders [16] demonstrated gasless self-sputtering operation for long pulses, several ms, in a conventional planar dcMS magnetron with a Cu target that was kick-started via short vacuum-arc plasma pulses. In this case a voltage of 600 V was sufficient to ignite the discharge. It is very difficult to reconcile this low discharge voltage with the original Thornton equation, Eq. (3), for the reason that the effective secondary electron emission yield here must be very low: there are no Ar^+ ions, which leaves metal-ion impact as the only source for secondary electrons. The majority of the copper ions were, however, reported in a follow-up paper [17] to be singly charged, and therefore have close to zero γ_{se} [3]. A large reduction of γ_{se} in the denominator of Eq. (3) should result in a large increase in the breakdown discharge voltage. This is not the case: the real breakdown voltage, 600 V, was only 20 % higher than the burning voltage of the Cu discharge in the study of Depla *et al* [3] which we analyze in the present work. The second consequence of including Ohmic heating is that the electron energy distribution (EEDF) shifts from one where the e^{H} component dominates ionization and excitation, to one where the e^{C} component becomes more important.

This causes a shift in the discharge kinetics from ionization and excitation of argon, with high energy thresholds, to reactions with lower energy thresholds. Two specific cases of interest are ionization of the sputtered material and, in the case of reactive sputtering, dissociation and excitation of the reactive gas. This shift in reaction probability towards reactions with lower energy thresholds also changes the interpretation of line excitation in a discharge, and therefore has consequences for discharge diagnostics based on optical emission spectroscopy (OES).

We want to stress finally that the curves in Fig. 3, which show the relative importance of Ohmic heating, shall be seen as examples, strictly valid only for the magnetron studied by Depla *et al* [3]. The four cases in Table I show that the Ohmic energy fraction, besides γ_{SE} , is a function of the pressure and the discharge current. It probably also increases with higher magnetic field strength, which has been shown experimentally by Bradley *et al* [18] to increase U_{IR} . Other important differences between individual magnetrons that would come into play are the size, the degree of magnetron unbalance, the state of target erosion, the degree of target poisoning, etc. The important findings here are therefore qualitative rather than quantitative: the demonstrated existence of Ohmic heating also in dcMS, a physical explanation that makes it consistent with the proposed Ohmic heating in HiPIMS [4], and the identification of the secondary electron emission yield as the key parameter for the relative importance of Ohmic heating.

Acknowledgements

This work was partially supported by the Icelandic Research Fund Grant No. 130029-053 and the Swedish Government Agency for Innovation Systems (VINNOVA) contract no. 2014-04876.

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