On Electron Heating and Ion Recycling in the High Power Impulse Magnetron Sputtering Discharge

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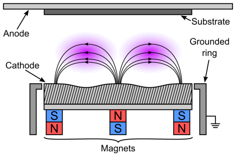
Introduction – Magnetron sputtering

- Magnetron sputtering is a highly sucessfull and widely used technique for thin film deposition

Gudmundsson (2020) PSST **29** 113001

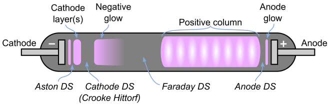


Gudmundsson and Lundin (2020) in High Power Impulse Magnetron Sputtering Discharge, Elsevier, 2020

- Two fundamental topics will be discussed:
  - **Electron power absorption in magnetron sputtering discharges**
  - **Recycling in HiPIMS discharges**

Electron power absorption in magnetron sputtering discharges

Electron power absorption



T. J. Petty, LPGP, Université Paris Sud

Gudmundsson and Hecimovic (2017) PSST **26** 123001

- A dc discharge with a cold cathode is sustained by secondary electron emission from the cathode due to ion bombardment
- The discharge current at the target consists of electron current I_e and ion current I_i or

$$I_D = I_e + I_i = I_i(1 + \gamma_{see})$$

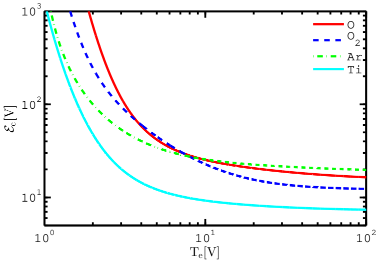
  where γ_{see} is the secondary electron emission coefficient
- Note that $\gamma_{see} \sim 0.05 - 0.2$ for most metals, so at the target ion current dominates

Electron power absorption

- These secondary electrons are accelerated in the cathode dark space
- They must produce sufficient number of ions to release more electrons from the cathode
- The number of electron-ion pairs created by each secondary electron is then

$$\mathcal{N} \approx \frac{V_{\rm D}}{\mathcal{E}_{\rm c}}$$

where $\mathcal{E}_{\rm c}$ is the energy loss per electron-ion pair created



Gudmundsson et al. (2016) PSST **25** 065004

Electron power absorption

- In magnetron sputtering effective secondary electron emission coefficient

$$\gamma_{\mathrm{see,eff}} = m\epsilon_{\mathrm{e}}(1 - r)\gamma_{\mathrm{see}}$$

where r is the recapture probability

- To sustain the discharge the condition

$$\gamma_{\mathrm{see,eff}}\mathcal{N} = 1$$

defines the minimum voltage

$$V_{\mathrm{D,min}} = \frac{\mathcal{E}_{\mathrm{c}}}{\beta\gamma_{\mathrm{see,eff}}}$$

referred to as Thornton equation

Magnetron sputtering: basic physics and application to cylindrical magnetrons

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(Received 22 September 1977; accepted 7 December 1977)

Magnetron sputtering sources can be defined as diode devices in which magnetic fields are used in concert with the cathode surface to form electron traps which are so configured that the **E**×**B** electron-drift currents close on themselves. Coaxial cylindrical magnetron sputtering sources in which post or hollow cathodes are operated in axial magnetic fields have been reported for a number of years. However, their performance is limited by end losses. A remarkable performance is achieved when the end losses are eliminated by proper shaping of the magnetic field or by using suitably placed electron-reflecting surfaces. High currents and sputtering rates can be obtained, nearly independent of voltage, even at low pressures. This characterizes what has been defined as the *magnetron mode* of operation. This paper reviews the basic principles that underly the operation of dc sputtering sources in the magnetron mode with particular emphasis on cylindrical magnetrons. The important attributes of these devices as sputtering sources are also reviewed.

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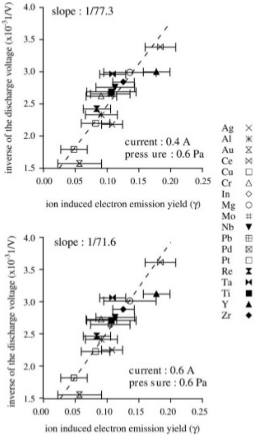
Thornton (1978) JVST **15**(2) 171

Electron power absorption

- We can rewrite the Thornton equation

$$\frac{1}{V_\mathrm{D}} = \frac{\beta m \epsilon_\mathrm{e}(1-r)}{\mathcal{E}_\mathrm{c}}\gamma_\mathrm{see}$$

- A plot of the inverse discharge voltage $1/V_\mathrm{D}$ against γ_see should then give a straight line through the origin
- Depla et al. measured the discharge voltage for 18 different target materials
- It can be seen that a straight line indeed results, but that it does not pass through the origin



From Depla et al. (2009) TSF **517** 2825

Electron power absorption

- We have proposed that the intercept is due to Ohmic heating
- We can now write the inverse discharge voltage $1/V_{\rm D}$ in the form of a generalized Thornton equation

$$\frac{1}{V_{\rm D}} = \underbrace{\frac{\beta \epsilon_{\rm e}^{\rm H} m(1-r)(1-\delta_{\rm IR})}{\mathcal{E}_c^{\rm H}}}_{a} \gamma_{\rm see} + \underbrace{\frac{\epsilon_{\rm e}^{\rm C} \langle I_{\rm e}/I_{\rm D}\rangle_{\rm IR} \delta_{\rm IR}}{\mathcal{E}_c^{\rm C}}}_{b}$$

or

$$\frac{1}{V_{\rm D}} = a\gamma_{\rm see} + b$$

- We associate a with hot electrons $\rm e^H$, sheath acceleration
- We associate b with the Ohmic heating process and cold electrons $\rm e^C$

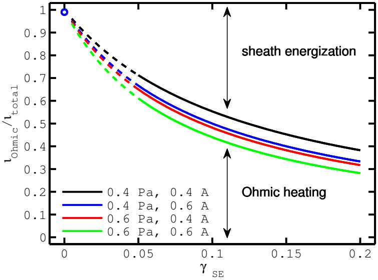
Electron power absorption

- The fraction of the total ionization that is due to Ohmic heating can be obtained directly from the line fit parameters *a* and *b* or as a function of only the secondary electron yield $\gamma_{\rm SE}$

$$\frac{\iota_{\rm Ohmic}}{\iota_{\rm total}} = \frac{b}{a\gamma_{\rm SE} + b}$$

- The fraction of the discharge voltage that falls over the ionization region

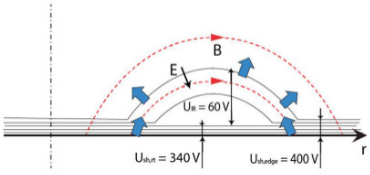
$$\delta_{\rm IR} = \frac{V_{\rm IR}}{V_{\rm D}} = 0.15 - 0.19$$



From Brenning et al. (2016) PSST **25** 065024

Electron power absorption

- The figure shows schematically the magnetic field lines and the electric equipotential surfaces above the racetrack
- A potential V_{SH} falls over the sheath, and the rest of the applied voltage, $V_{\mathrm{IR}} = V_{\mathrm{D}} - V_{\mathrm{SH}}$, falls across the extended pre-sheath, the ionization region (IR), $\delta_{\mathrm{IR}} = V_{\mathrm{IR}}/V_{\mathrm{D}}$
- Ohmic heating, the dissipation of locally deposited electric energy $\mathbf{J}_{\mathrm{e}} \cdot \mathbf{E}$ to the electrons in the plasma volume outside the sheath



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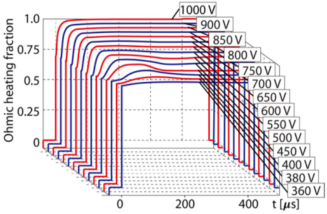
Electron power absorption

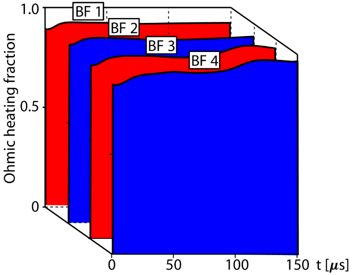
- Applying the ionization region model (IRM) to a HiPIMS discharge
- For the Al target, Ohmic heating is in the range of 87 % (360 V) to 99 % (1000 V)
- The domination of Al^{+}-ions, which have zero secondary electron emission yield, has the consequence that there is negligible sheath energization
- The ionization threshold for twice ionized Al^{2+}, 18.8 eV, is so high that few such ions are produced



From Huo et al. (2017) JPD **50** 354003

Electron power absorption

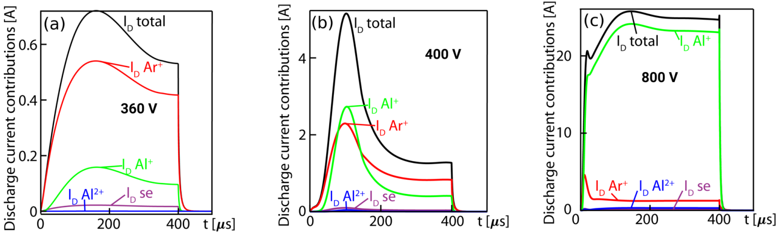
- For a Ti target Ohmic heating is about 92 %
  - Both Ar^{+} and Ti^{2+}-ions contribute to creation of secondary electrons
- For Ti target in Ar/O_2 mixture
  - In the metal mode Ohmic heating is found to be 90 % during the plateau phase of the discharge pulse
  - For the poisoned mode Ohmic heating is 70 % with a decreasing trend, at the end of the pulse



From Huo et al. (2017) JPD **50** 354003

Recycling in HiPIMS discharges

Recycling in HiPIMS discharges



- A **non-reactive** discharge with 50 mm diameter Al target
- Current composition at the target surface

From Huo et al. (2017) JPD **50** 354003

Experimental data from Anders et al. (2007) JAP **102** 113303

Recycling in HiPIMS discharges

- A primary current I_{prim} is defined as ions of the working gas, here Ar^+, that are ionized for the first time and then drawn to the target
- This is the dominating current in dc magnetron sputtering discharges
- This current has a critical upper limit

$$I_{\mathrm{crit}} = S_{\mathrm{RT}} e p_{\mathrm{g}} \sqrt{\frac{1}{2\pi m_{\mathrm{g}} k_{\mathrm{B}} T_{\mathrm{g}}}} = S_{\mathrm{RT}} e n_{\mathrm{g}} \sqrt{\frac{k_{\mathrm{B}} T_{\mathrm{g}}}{2\pi m_{\mathrm{g}}}}$$

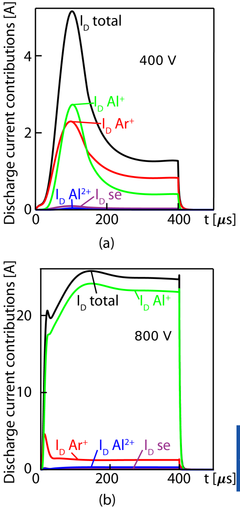
- Discharge currents I_{D} above I_{crit} are only possible if there is some kind of recycling of atoms that leave the target, become subsequently ionized and then are drawn back to the target

Anders et al. (2012) JPD **45** 012003

Huo et al. (2014) PSST **23** 025017

Recycling in HiPIMS discharges

- For the 50 mm diameter Al target the critical current is $I_{\rm crit} \approx 7$ A
- The experiment is operated from far below $I_{\rm crit}$ to high above it, up to 36 A.
- With increasing discharge current $I_{\rm prim}$ gradually becomes a very small fraction of the total discharge current $I_{\rm D}$
- The current becomes mainly carried by singly charged Al^{+}-ions, meaning that **self-sputter recycling** or the current $I_{\rm SS-recycle}$ dominates



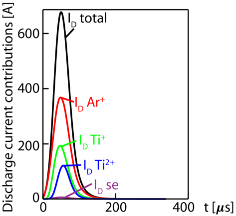
From Huo et al. (2017) JPD **50** 354003

Experimental data from Anders et al. (2007) JAP **102** 113303

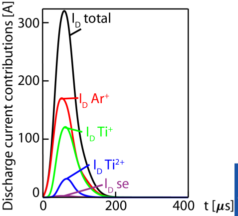
Recycling in HiPIMS discharges

- For discharges with Ti target the peak current is far above the critical current (up to 650 A, while $I_{\text{crit}} \approx 19$ A)
- However, this discharge shows close to a 50/50 combination of **self-sputter recycling** $I_{\text{SS-recycle}}$ and **working gas-recycling** $I_{\text{gas-recycle}}$
- Almost 2/3 of the current to the target is here carried by Ar^+ and Ti^{2+}-ions, which both can emit secondary electrons upon target bombardment, and this gives a significant sheath energization

From Huo et al. (2017) JPD **50** 354003



(a)



(b)

Recycling in HiPIMS discharges

- The total discharge current is

$$I_{\mathrm{D}} = I_{\mathrm{prim}} + I_{\mathrm{gas-recycle}} + I_{\mathrm{SS}}$$

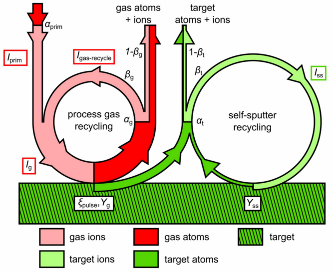
$$= I_{\mathrm{prim}} \left(1 + \frac{\pi_{\mathrm{g}}}{1-\pi_{\mathrm{g}}}\right)\left(1 + \frac{Y_{\mathrm{g}}}{Y_{\mathrm{SS}}}\frac{\pi_{\mathrm{SS}}}{1-\pi_{\mathrm{SS}}}\right)$$

where the working gas-sputtering parameter is

$$\pi_{\mathrm{g}} = \alpha_{\mathrm{g}}\beta_{\mathrm{g}}\xi_{\mathrm{pulse}}$$

and the self-sputter parameter

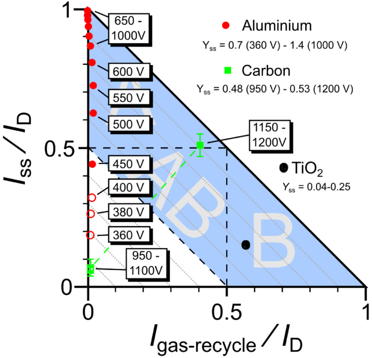
$$\pi_{\mathrm{SS}} = \alpha_{\mathrm{t}}\beta_{\mathrm{t}} Y_{\mathrm{SS}}$$



From Brenning et al. (2017) PSST **26** 125003

Recycling in HiPIMS discharges

- With increased discharge voltage the discharge with Al target moves from the dcMS regime to the HiPIMS discharge regime – **type A**
- A discharge with carbon target jumps from the dcMS regime to the HiPIMS regime – both SS recycling and working gas recycling play a role – intermediate **type AB**
- For reactive sputtering of Ti target in poisoned mode working gas recycling dominates – **type B**



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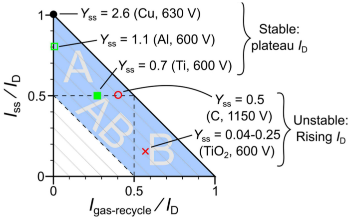
Recycling in HiPIMS discharges

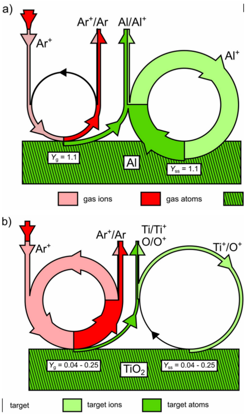
- Recycling map for five different targets with varying self-sputter yield
  - Cu – $Y_{SS} = 2.6$
  - Al – $Y_{SS} = 1.1$
  - Ti – $Y_{SS} = 0.7$
  - C – $Y_{SS} = 0.5$
  - TiO_2 – $Y_{SS} = 0.04 - 0.25$
- For very high self-sputter yields $Y_{SS} > 1$, the discharges above I_{crit} are of **type A** with dominating **SS-recycling**
- For very low self-sputter yields $Y_{SS} < 0.2$, the discharges above I_{crit} are of **type B** with dominating **working gas recycling**



From Brenning et al. (2017) PSST **26** 125003

Recycling in HiPIMS discharges

- Recycling loops
- Discharge with Al target – SS recycling dominates
  - high self sputter yield
- Reactive discharge with TiO_2 target – working gas recycling dominates
  - low self sputter yield



From Brenning et al. (2017) PSST **26** 125003

Summary

Summary

- It has been demonstrated that Ohmic heating of the electrons can play a significant role in both dc magnetron sputtering discharge and in particular HiPIMS
- The fraction of the total electron heating that is attributable to Ohmic heating is over 90 % in the HiPIMS discharge
- We used a ionization region model to explore the plasma composition and the electron heating mechanism in a high power impulse magnetron sputtering (HiPIMS) discharge
  - For high currents the discharge with Al target develops almost pure **self-sputter recycling**, while the discharge with Ti target exhibits close to a 50/50 combination of **self-sputter recycling** and **working gas-recycling**
  - For a poisoned Ti target, the sputter yield is low and working gas-recycling necessary at high currents

Thank you for your attention

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The slides can be downloaded at

http://langmuir.raunvis.hi.is/~tumi/ranns.html

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