On electron heating and ion recycling in high power impulse magnetron sputtering

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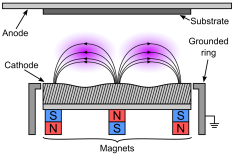
Introduction – Magnetron sputtering

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

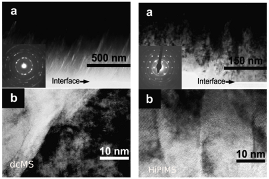
Gudmundsson (2020) PSST **29** 113001



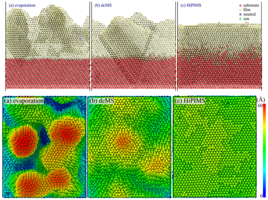
Gudmundsson and Lundin (2020) in High Power Impulse Magnetron Sputtering Discharge, Elsevier, 2020

- If the cathode plate is circular, the magnetic confinement is seen as a torus shaped plasma that hovers in front of the target

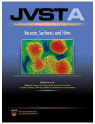
Introduction



Alami et al. (2005) JVSTA **23** 278



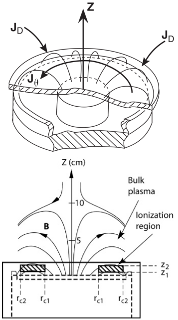
Kateb et al. (2019) JVSTA **37** 031306



- High power impulse magnetron sputtering (HiPIMS) provides higher ionized flux fraction than dc magnetron sputtering (dcMS)
- Due to the higher fraction of ionization of the sputtered species
  - the films are smooth and dense
  - control over phase composition and microstructure is possible
  - enhanced mechanical, electrical and optical properties
  - improved film adhesion

Ionization region model of HiPIMS

- The ionization region model (IRM) is a time-dependent volume averaged plasma chemical model of the ionization region (IR) of the HiPIMS discharge
- It gives the temporal evolution of the densities of ions, neutrals and electrons
- The IR is defined as an annular cylinder with outer radii r_{c2}, inner radii r_{c1} and length $L = z_2 - z_1$, extends from z_1 to z_2 axially away from the target



The definition of the volume covered by the IRM

From Raadu et al. (2011) PSST **20** 065007

Detailed model description is given in

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

Recycling in HiPIMS discharges

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

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

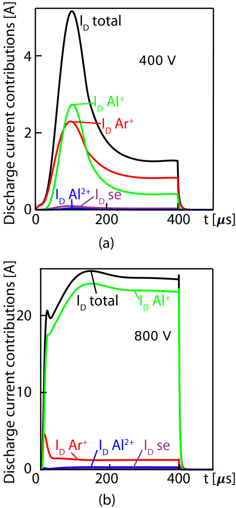
- Discharge currents I_{D} above I_{crit} are only possible if there is some kind of recycling of atoms that leave the target, become subsequently ionized and then are drawn back to the target

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

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

Recycling in HiPIMS discharges

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

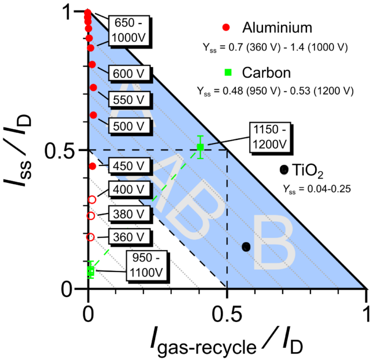


From Huo et al. (2017) JPD **50** 354003

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

Recycling in HiPIMS discharges

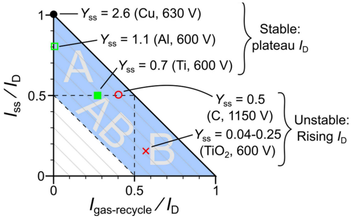
- With increased discharge voltage the discharge with Al target moves from the dcMS regime to the HiPIMS discharge regime – **type A**
- For reactive sputtering of Ti target in poisoned mode working gas recycling dominates – **type B**



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

Recycling in HiPIMS discharges

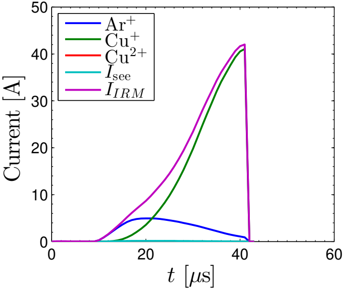
- Recycling map for five different targets with varying self-sputter yield
    - Cu – $Y_{\mathrm{SS}} = 2.6$
    - Al – $Y_{\mathrm{SS}} = 1.1$
    - Ti – $Y_{\mathrm{SS}} = 0.7$
    - C – $Y_{\mathrm{SS}} = 0.5$
    - TiO$_2$ – $Y_{\mathrm{SS}} = 0.04 - 0.25$
- For very high self-sputter yields $Y_{\mathrm{SS}} > 1$, the discharges above I_{crit} are of **type A** with dominating **SS-recycling**
- For very low self-sputter yields $Y_{\mathrm{SS}} < 0.2$, 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 – copper

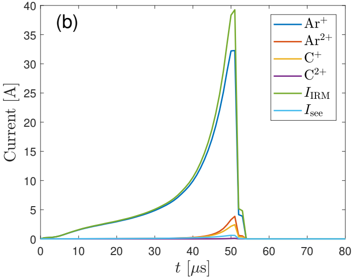
- The temporal evolution of the discharge current composition at a Cu target surface for a peak discharge current density 2 A/cm^2
- A discharge with 2 inch copper target – $I_{\mathrm{crit}} \approx 3.8$ A
- The Cu$^+$ ion is the dominating positively charged species in the discharge
- The ionized flux fraction of copper is roughly 15 %



From Gudmundsson et al. (2021) manuscript in preparation

Recycling in HiPIMS discharges – carbon

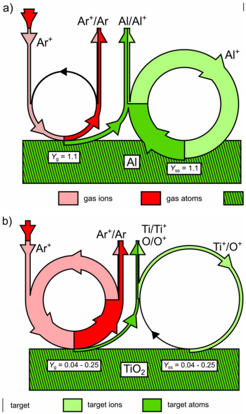
- The temporal evolution of the discharge current composition at a graphite target surface for a peak discharge current density 2 A/cm^2
- A discharge with 2 inch graphite target – $I_{\mathrm{crit}} \approx 7.6$ A
- The Ar$^+$ ion is the dominating positively charged species in the discharge
- Less than 5 % of the total discharge current is carried by C$^+$ ions
- The ionized flux fraction of carbon is roughly 2 %



From Eliasson et al. (2021) manuscript in preparation

Recycling in HiPIMS discharges

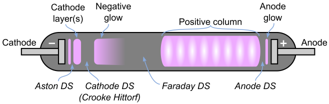
- Recycling loops
- Discharge with Al or Cu target – SS recycling dominates
  - high self sputter yield
- Reactive discharge with graphite or TiO_2 target – working gas recycling dominates
  - low self sputter yield



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

Electron power absorption

Electron power absorption



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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

- In magnetron sputtering effective secondary electron emission coefficient

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

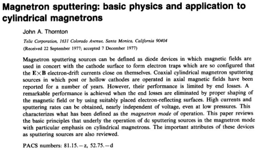
where r is the recapture probability

- To sustain the discharge the condition

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

with $\mathcal{N}$ the number of electron-ion pairs defines the minimum voltage (Thornton equation)

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



Magnetron sputtering: basic physics and application to cylindrical magnetrons

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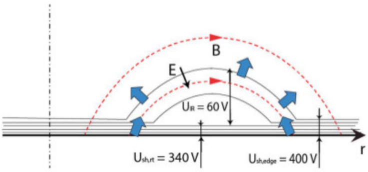
Magnetron sputtering sources can be defined as diode devices in which magnetic fields are used in concert with the cathode surface to form electron traps which are so configured that the **E**×**B** electron-drift currents close on themselves. Coaxial cylindrical magnetron sputtering sources in which 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.

PACS numbers: 81.15.−z, 52.75.−d

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

Electron power absorption

- However, the presence of a transverse magnetic field in magnetron sputtering enables a potential drop to exist outside the cathode sheath
- A potential $V_{\rm SH}$ falls over the sheath, and the rest of the applied voltage, $V_{\rm IR} = V_{\rm D} - V_{\rm SH}$, falls across the extended pre-sheath, the ionization region (IR), $\delta_{\rm IR} = V_{\rm IR}/V_{\rm D}$
- Ohmic heating, the dissipation of locally deposited electric energy $\mathbf{J}_{\rm e} \cdot \mathbf{E}$ to the electrons in the plasma volume outside the sheath



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

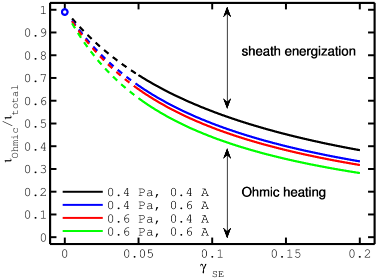
Electron power absorption

- The fraction of the total ionization that is due to Ohmic heating can be obtained directly from the line fit parameters *a* and *b* of the $1/V_{\rm D}$ vs $\gamma_{\rm see}$ curves for dcMS

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

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

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

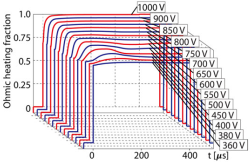


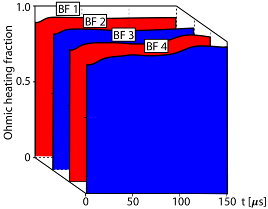
From Brenning et al. (2016) PSST **25** 065024

based on measurements of Depla et al. (2009) TSF **517** 2825

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
- For a Ti target Ohmic heating is about 92 %

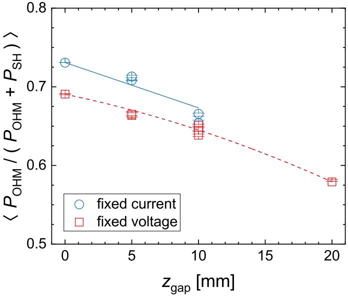




From Huo et al. (2017) JPD **50** 354003

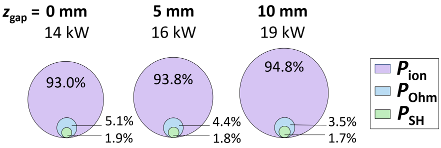
Electron power absorption

- Discharges with Ti target with adjustable confining magnetic field Hajihoseini et al. (2019) Plasma **2** 201
- $P_{\mathrm{Ohm}}/(P_{\mathrm{Ohm}}+P_{\mathrm{SH}})$ versus the magnetic field parameter z_{gap} (magnetic field strength)
- For increasing z_{gap} (lower magnetic field), the fraction $P_{\mathrm{Ohm}}/(P_{\mathrm{Ohm}}+P_{\mathrm{SH}})$ decreases
- $P_{\mathrm{Ohm}}/(P_{\mathrm{Ohm}}+P_{\mathrm{SH}})$ can be regarded as a measure for energy efficiency of a discharge



From Rudolph et al. (2021) JPD submitted for publication

Electron power absorption



From Rudolph et al. (2021) JPD submitted for publication

- The use of the pulse power for different values of $z_{\rm gap}$
  - ion acceleration ($P_{\rm ion}$)
  - Ohmic heating ($P_{\rm Ohm}$)
  - sheath energization ($P_{\rm SH}$).
- Most of the pulse power $\langle P_{\rm pulse}\rangle$ is used to accelerate ions and this power is finally dissipated in the target as heat
- The fraction of the pulse power that is absorbed by the electrons decreases for higher values of $z_{\rm gap}$ and more energy is spent on heating up the target

Summary

Summary

- In HiPIMS discharge operation there is always recycling:
  - For high currents the discharge with Al or Cu 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, or a graphite target the sputter yield is low and **working gas-recycling** necessary at high currents
- 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

Thank you for your attention

- The work is in collaboration with
  - Prof. Daniel Lundin, Linköping University, Sweden
  - Prof. Nils Brenning, KTH Royal Institite of Technology, Stockholm, Sweden
  - Dr. Michael A. Raadu, KTH Royal Institite of Technology, Stockholm, Sweden
  - Dr. Martin Rudolph, Leibniz Institute of Surface Engineering (IOM), Leipzig, Germany
  - Prof. Tiberu Minea, Université Paris-Sud, Orsay, France
  - Dr. Hamidreza Hajihoseini, now at University of Twente, The Netherlands

The slides can be downloaded at

`http://langmuir.raunvis.hi.is/∼tumi/ranns.html`

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