On the relation between deposition rate and ionized flux fraction in high power impulse magnetron sputtering

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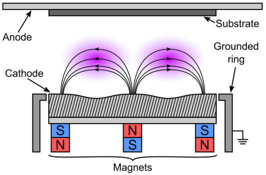
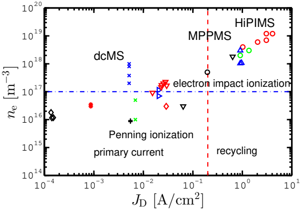
73$^{\text{rd}}$ Gaseous Electronics Conference, Virtual Conference, October 6, 2020

Introduction – Magnetron sputtering

- Magnetron sputtering has been a highly sucessfull technique that is essential in a number of industrial applications
- In a dcMS the power density (plasma density) is limited by the thermal load on the target
- High ionization of sputtered material requires very high density plasma
- In a HiPIMS discharge a high power pulse is supplied for a short period
  - low frequency
  - low duty cycle
  - low average power

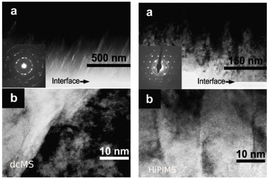


Gudmundsson and Lundin (2020) in High Power Impulse Magnetron Sputtering Discharge, Elsevier, 2020

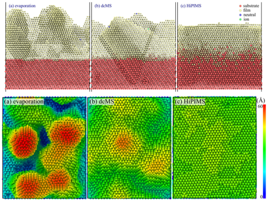


From Gudmundsson (2020) PSST **29** in press

Introduction – Fraction of ionization



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

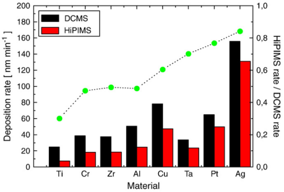


Kateb et al. (2019) JVSTA **37** 031306

- In HiPIMS deposition, the high fraction of ionization of the sputtered species has been shown to lead to
  - the growth of smooth and dense films
  - enable control over their phase composition and microstructure
  - enhance mechanical and optical properties
  - improving film adhesion
  - enabling deposition of uniform films on complex-shaped substrates

Introduction – Deposition rate

- There is a drawback
- The deposition rate is lower for HiPIMS when compared to dcMS operated at the same average power
- The HiPIMS deposition rates are typically in the range of 30 – 85% of the dcMS rates depending on target material
- Many of the ions of the target material are attracted back to the target surface by the cathode potential



From Samuelsson et al. (2010) SCT **202** 591

Introduction – Fraction of ionization

- Quantification and control of the fraction of ionization of the sputtered species are crucial in magnetron sputtering
- We distinguish between three approaches to describe the degree (or fraction) of ionization
  - the ionized flux fraction

$$F_{\mathrm{flux}} = \frac{\Gamma_{\mathrm{i}}}{\Gamma_{\mathrm{i}} + \Gamma_{\mathrm{n}}}$$

  - the ionized density fraction

$$F_{\mathrm{density}} = \frac{n_{\mathrm{i}}}{n_{\mathrm{i}} + n_{\mathrm{n}}}$$

  - the fraction α_{t} of the sputtered metal atoms that become ionized in the plasma (probability of ionization)

Butler et al. (2018) PSST **27** 105005

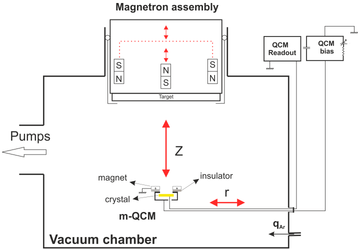
Influence of magnetic field

Influence of magnetic field – Deposition rate

- The Ti deposition rate and the ionized flux fraction are measured using a gridless ion meter (m-QCM)

Kubart et al. (2014) *SCT* **238** 152

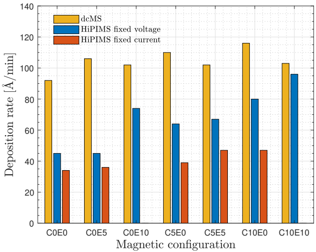
- The ion meter is mounted on a probe holder which can be moved around within the chamber
- The Ar pressure was set to 1 Pa
- In all cases the pulse width was 100 μs at an average power of 300 W



From Hajihoseini et al. (2019) *Plasma* **2** 201

Influence of magnetic field – Deposition rate

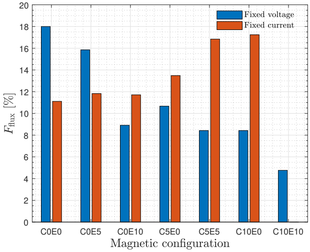
- The Ti deposition rate recorded at substrate position using a gridless ion meter (m-QCM)
  - **dcMS**
    $+10\%$ with decreasing $|\mathbf{B}|$
    (but no obvious trend)
  - **HiPIMS fixed voltage**
    $+110\%$ with decreasing $|\mathbf{B}|$
  - **HiPIMS fixed peak current**
    $+40\%$ with decreasing $|\mathbf{B}|$
- In HiPIMS operation the deposition rate increases with decreasing $|\mathbf{B}|$, ordered from high $|\mathbf{B}|$ at the left to low $|\mathbf{B}|$ on the right



From Hajihoseini et al. (2019) *Plasma* **2** 201

Influence of magnetic field – Ionized flux fraction

- Ionized flux fraction recorded
  - dcMS
    Always around 0 %
    (Kubart et al., 2014)
  - **HiPIMS fixed voltage**
    -75% with decreasing $|\mathbf{B}|$
  - **HiPIMS fixed peak current**
    $+50\%$ with decreasing $|\mathbf{B}|$
- The ionized flux fraction decreases with decreasing $|\mathbf{B}|$ when the HiPIMS discharge is operated in fixed voltage mode but increases in fixed peak current mode
- Opposing trends



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Internal parameters and optimization

Influence of magnetic field – α_t and β_t

- We can relate the measured quantities deposition rate $F_{\mathrm{DR,sput}}$ and the ionized flux fraction $F_{\mathrm{ti,flux}}$

$$F_{\mathrm{DR,sput}} = \frac{\Gamma_{\mathrm{DR}}}{\Gamma_0} = (1 - \alpha_\mathrm{t}\beta_\mathrm{t})$$

$$F_{\mathrm{ti,flux}} = \frac{\Gamma_{\mathrm{DR,ions}}}{\Gamma_{\mathrm{DR,sput}}} = \frac{\Gamma_0 \alpha_\mathrm{t}(1 - \beta_\mathrm{t})}{\Gamma_0(1 - \alpha_\mathrm{t}\beta_\mathrm{t})} = \frac{\alpha_\mathrm{t}(1 - \beta_\mathrm{t})}{(1 - \alpha_\mathrm{t}\beta_\mathrm{t})}$$

to the internal parameters back attraction probability β_t

$$\beta_\mathrm{t} = \frac{1 - F_{\mathrm{DR,sput}}}{1 - F_{\mathrm{DR,sput}}(1 - F_{\mathrm{ti,flux}})}$$

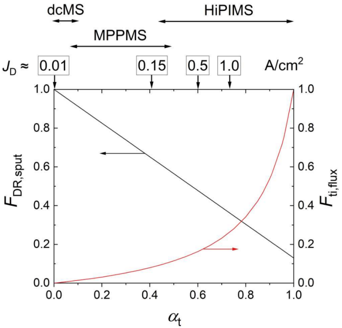
and ionization probability α_t

$$\alpha_\mathrm{t} = 1 - F_{\mathrm{DR,sput}}(1 - F_{\mathrm{ti,flux}})$$

Hajihoseini et al. (2019) *Plasma* **2** 201

Influence of magnetic field – Optimization

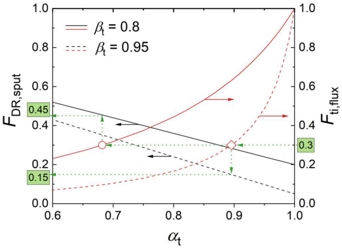
- There are two measures of how good a HiPIMS discharge is: the fraction $F_{\mathrm{DR,sput}}$ of all the sputtered material that reaches the diffusion region (DR) and the fraction $F_{\mathrm{ti,flux}}$ of ionized species in that flux
- There is a trade off between the goals of higher $F_{\mathrm{DR,sput}}$ and higher $F_{\mathrm{ti,flux}}$
- The figure shows $F_{\mathrm{DR,sput}}$ and $F_{\mathrm{ti,flux}}$ as functions of α_{t} at assumed fixed value of $\beta_{\mathrm{t}} = 0.87$



From Brenning et al. (2020) *JVSTA* **38** 033008

Influence of magnetic field – Optimization

- For a particular application an ionized flux fraction of 30 % is suitable but $0.8 \le \beta_t \le 0.95$
- Following the green dotted line from the value $F_{\rm ti,flux} = 0.30$ to the red dashed curve gives $\alpha_t = 0.9$ (red square)
- The black dashed line then shows α_t only 15 % of the total sputtered flux enters the diffusion region ($F_{\rm DR,sput} = 0.15$).
- Solid lines show that reducing the back-attraction to $\beta_t = 0.8$ where $\alpha_t = 0.69$ is sufficient to maintain $F_{\rm ti,flux} = 0.30$ (red circle) and $F_{\rm DR,sput} = 0.45$ or a factor of three increase in the deposition rate



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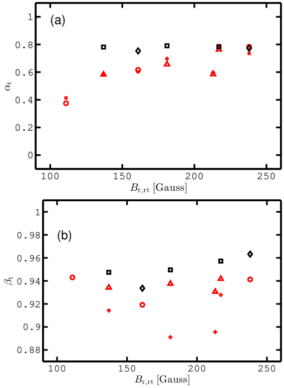
Influence of magnetic field – α_t and β_t

- When operating in the fixed voltage mode (**red**) the ionization probability α_t increases with increased magnetic field strength – which is essentially the discharge current
- When operating in the fixed peak current mode (**black**) the ionization probability α_t is roughly constant independent of the magnetic field strength
- α_t can be varied in the range $0 \leq \alpha_t \leq 1$ by the discharge current amplitude J_D
- β_t is variable within a much smaller achievable range and depends heavily on the magnetic field strength



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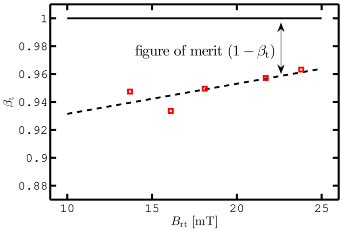
Influence of magnetic field – Optimization

- The figure shows β_t as a function of the magnetic field strength (measured 11 mm above the racetrack center)
- There is a clear trend that β_t is lowered when the magnetic field strength is reduced
- Using the line fit, we find that β_t = 0.96 for the highest magnetic field strength and β_t = 0.93 for the lowest magnetic field strength
- Our proposed figure of merit $(1 - \beta_t)$ changes by a factor of $(1 - 0.93)/(1 - 0.96) = 1.8$



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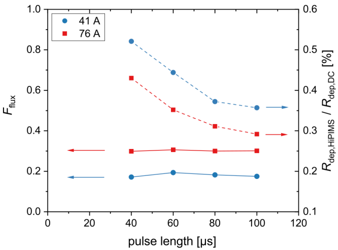
Influence of magnetic field – Pulse length

- For the same average power, shorter pulse lengths give higher deposition rate than with longer pulse lengths
- The same average power can simply be achieved by increasing the frequency
- Shortening the pulses does not affect the ionized flux fraction, which remains essentially constant
    - with shorter pulses, the afterglow contributes increasingly more to the total deposition rate
    - the ionized flux fraction from the afterglow is typically higher compared to that during the pulse due to absent back-attracting electric field

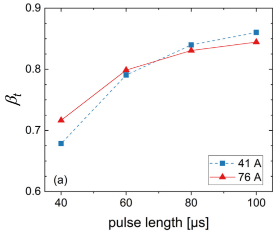


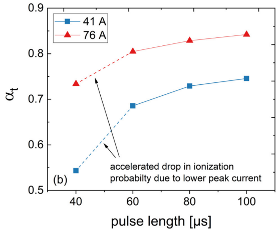
From Rudolph et al. (2020) *PSST* **29** 05LT01

Influence of magnetic field – Pulse length

- By switching-off the cathode potential during the afterglow decreases the effective β_t
- β_t decreases with decreasing pulse length
- The relative contribution of the afterglow ions to the flux toward the DR increases steadily for shorter pulses
- The ionization probability α_t also decreases with a shorter pulse length
- The useful fraction of the sputtered species

$$F_{\mathrm{DR,sput}} = \frac{\Gamma_{\mathrm{DR}}}{\Gamma_0} = (1 - \alpha_t \beta_t)$$





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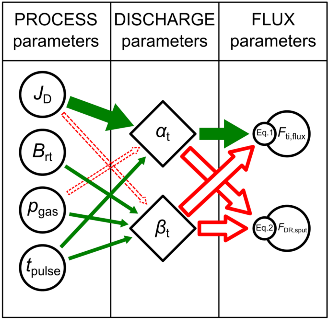
Influence of magnetic field – Pulse length

- HiPIMS can be optimized by selecting
  - pulse power
  - pulse length
  - working gas pressure
  - magnetic field strength
- The HiPIMS compromise – a fully ionized material flux is not required to achieve significant improvement of the thin film properties
- A sufficiently high peak discharge current is required to reach the desired ionized flux fraction
- Further increase would lead to unnecessarily low deposition rates



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Summary

Summary

- For HiPIMS in the fixed voltage mode: A trade-off between the deposition rate (increases by more than a factor of two) and the ionized flux fraction (decreases by a factor 4 to 5) with decreasing $|\mathbf{B}|$
- For HiPIMS in the fixed peak current mode: Decreasing $|\mathbf{B}|$ improves both the deposition rate (by 40%) and the ionized flux fraction (by 50%)
- There is an inescapable conflict between the goals of higher deposition rate and higher fraction of ionized species in the sputtered material flux
- The HiPIMS discharge can be optimized by adjusting the pulse power, pulse length, working gas pressure and the magnetic field strength

Thank you for your attention

The slides can be downloaded at
`http://langmuir.raunvis.hi.is/~tumi/ranns.html`
and the project is funded by

- Icelandic Research Fund Grant Nos. 130029 and 196141

References

Alami, J., P. O. A. Petersson, D. Music, J. T. Gudmundsson, J. Bohlmark, and U. Helmersson (2005). Ion-assisted physical vapor deposition for enhanced film deposition on non-flat surfaces. *Journal of Vacuum Science and Technology A 23*(2), 278–280.

Brenning, N., A. Butler, H. Hajihoseini, M. Rudolph, M. A. Raadu, J. T. Gudmundsson, T. Minea, and D. Lundin (2020). Optimization of HiPIMS discharges: The selection of pulse power, pulse length, gas pressure, and magnetic field strength. *Journal of Vacuum Science and Technology A 38*(3), 033008.

Butler, A., N. Brenning, M. A. Raadu, J. T. Gudmundsson, T. Minea, and D. Lundin (2018). On three different ways to quantify the degree of ionization in sputtering magnetrons. *Plasma Sources Science and Technology 27*(10), 105005.

Gudmundsson, J. T. (2020). Physics and technology of magnetron sputtering discharges. *Plasma Sources Science and Technology 29*, in press.

Gudmundsson, J. T. and D. Lundin (2020). Introduction to magnetron sputtering. In D. Lundin, T. Minea, and J. T. Gudmundsson (Eds.), *High Power Impulse Mangetron Sputtering: Fundamentals, Technologies, Challenges and Applications*, pp. 1–48. Amsterdam, The Netherlands: Elsevier.

Hajihoseini, H., M. Čada, Z. Hubička, S. Ünaldi, M. A. Raadu, N. Brenning, J. T. Gudmundsson, and D. Lundin (2019). The effect of magnetic field strength and geometry on the deposition rate and ionized flux fraction in the HiPIMS discharge. *Plasma 2*(2), 201–221.

Kateb, M., H. Hajihoseini, J. T. Gudmundsson, and S. Ingvarsson (2019). Role of ionization fraction on the surface roughness, density, and interface mixing of the films deposited by thermal evaporation, dc magnetron sputtering, and HiPIMS: An atomistic simulation. *Journal of Vacuum Science and Technology A 37*(3), 031306.

Kubart, T., M. Čada, D. Lundin, and Z. Hubička (2014). Investigation of ionized metal flux fraction in HiPIMS discharges with Ti and Ni targets. *Surface and Coatings Technology 238*, 152–157.

Rudolph, M., N. Brenning, M. A. Raadu, H. Hajihoseini, J. T. Gudmundsson, A. Anders, and D. Lundin (2020). Optimizing the deposition rate and ionized flux fraction by tuning the pulse length in high power impulse magnetron sputtering. *Plasma Sources Science and Technology 29*(5), 05LT01.

Samuelsson, M., D. Lundin, J. Jensen, M. A. Raadu, J. T. Gudmundsson, and U. Helmersson (2010). On the film density using high power impulse magnetron sputtering. *Surface and Coatings Technology 202*(2), 591–596.