Optimizing Ionization and Deposition Rate in High-Power Impulse Magnetron Sputtering

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Outline

Part 1: Introduction

- HiPIMS
- Ionization and deposition rate
- The HiPIMS compromise

Part 2: Optimizing HiPIMS

- Minimize ion back-attraction
  - Working gas pressure
  - Pulse length
  - Magnetic field strength
- Physical mechanisms and interplay
- Summary

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HiPIMS background

In 1999 a new I-PVD technique based on magnetron sputtering, called high-power impulse magnetron sputtering (HiPIMS) was developed by Kouznetsov *et al*.

HiPIMS uses high-power pulses at low duty cycle to ionize a large fraction of the sputtered material.

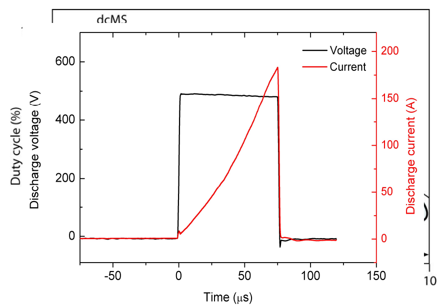
Key specs

Peak power ~ kW/cm^2

Average power ~ W/cm^2

Frequency ~ 10-5000 Hz

Pulse width ~ 10-500 µs



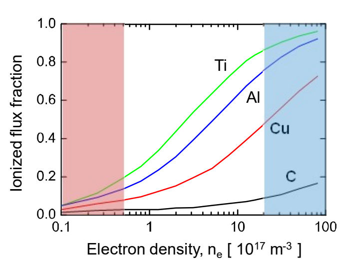
Kouznetsov *et al*., Surf. Coat. Technol. 122, 290 (1999)
Gudmundsson *et al*., J. Vac. Sci. Technol. A 30 030810 (2012)

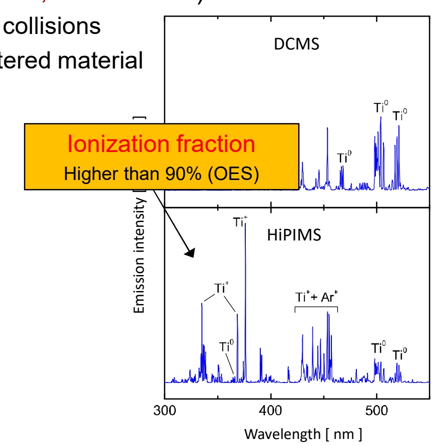
Ionization in HiPIMS

High plasma density (~1×10^{19} m^{-3}) compared to conventional direct current magnetron sputtering (DCMS, ~1×10^{16} m^{-3})

→ Increased probability for ionizing collisions

→ High degree of ionization of sputtered material





Helmersson *et al*., Thin Solid Films 513, **1** (2006)
Hopwood, *Thin Films: Ionized Physical Vapor Deposition*, Academic Press, San Diego (2000)
Bohlmark *et al*., J. Vac. Sci. Technol. A 23, 18 (2005)

Definition of ionization fractions

1. **Ionized flux fraction**

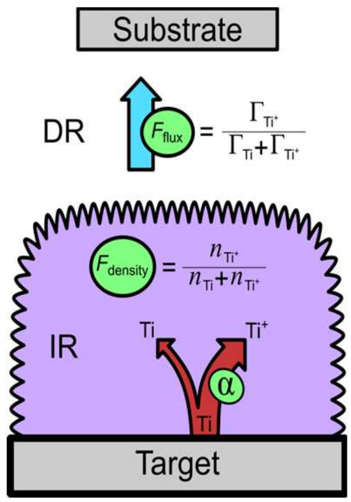
$$F_{flux} = \frac{\int_{pulse} \Gamma_{Ti^+}(t)dt}{\int_{pulse}\left(\Gamma_{Ti^+}(t)+\Gamma_{Ti}(t)\right)d}$$

2. **Ionized density fraction**

$$F_{density} = \frac{\int_{pulse} n_{Ti^+}(t)dt}{\int_{pulse}\left(n_{Ti^+}(t)+n_{Ti}(t)\right)dt}$$

3. **Ionization probability**

$$\alpha = \frac{N_{Ti^+,created}}{N_{Ti,sput}} = \frac{\int_{pulse} \sum R_{iz,Ti}(t)\,dt}{\int_{pulse} \sum R_{sput,Ti}(t)\,dt}$$



Butler *et al.*, Plasma Sources Sci. Technol. 27, 105005 (2018)

Reports on ionization in HiPIMS

Al

- Dekoven et al. (2003): 9.5% (ionized flux fraction)
- Lundin et al. (2015): 78% (ionized flux fraction)
- Huo et al. (2014): 65% - 70% (ionization probability)

Cu

- Meng et al. (2014): 16% - 42% (ionized flux fraction)
- McLain et al. (2018): 7% - 35% (ionized flux fraction)
- Kouznetsov et al. (1999): 70% (ionized flux fraction)
- Kozak et al. (2013): 64% - 75% (ionization probability)

Ti

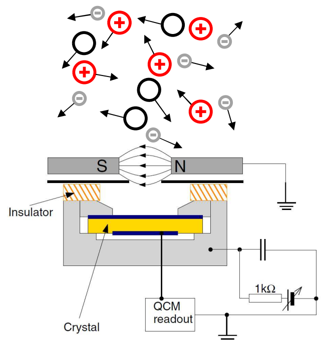
- Bohlmark et al.(2006): > 90% (ionized density fraction)
- Lundin et al. (2015): 20% - 68% (ionized flux fraction)
- Gudmundsson et al. (2016): 92% (ionization probability)

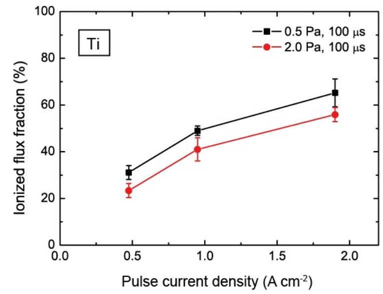
See Butler *et al.*, Plasma Sources Sci. Technol. 27, 105005 (2018) for references

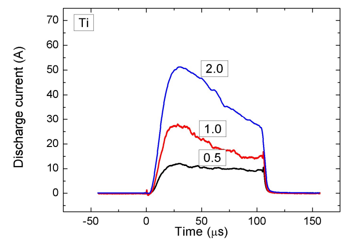
Measure ionized flux fraction

Ionized flux fraction
20 – 68 % with incr. J_D

Gridless ion meter: measure absolute values of the ionized flux fractions of the sputtered material.

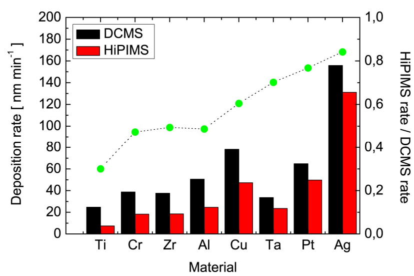




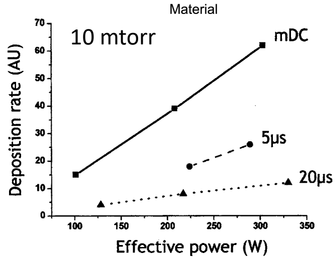


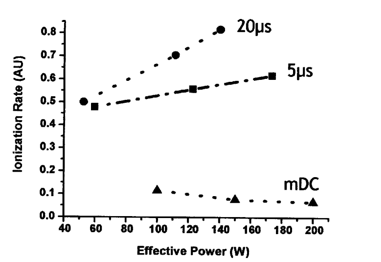
Kubart *et al.*, Surf. Coatings Technol. 238, 152 (2014)
Lundin *et al.*, Plasma Sources Sci. Technol. 24, 035018 (2015)

Deposition rate and ionization rate



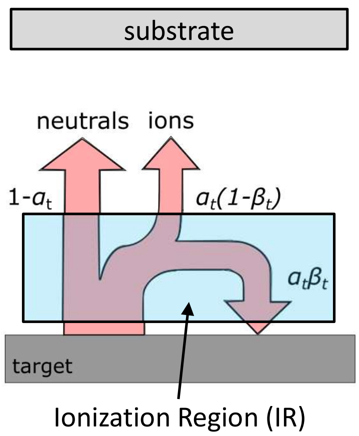
Deposition rate
Lower in HiPIMS compared to dcMS (at least non-reactive processes)





Konstantinidis *et al.*, *J. Appl. Phys.* 99, 013307 (2006)
Samuelsson *et al.*, Surf. Coatings Technol. 205, 591 (2010)

Quantifying F_{dep} and F_{flux}



Material pathways model

- ❑ Ionization probability α_t
- ❑ Back-attraction probability β_t

- ➢ Deposition rate fraction (sputter-rate normalized)

$$F_{dep} = 1 - \alpha_t\beta_t$$

- ➢ Ionized flux fraction

$$F_{flux} = \frac{\alpha_t(1-\beta_t)}{(1-\alpha_t\beta_t)}$$

Goal: Increase F_{dep} while not compromising F_{flux}

Christie, J. Vac. Sci. Technol. A 23, 330 (2005)
Rudolph *et al.*, J. Appl. Phys. 129, 033303 (2021)

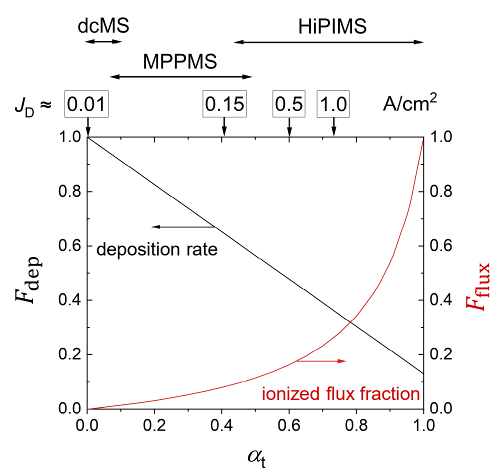
The HiPIMS compromise: α_t varied, β_t const.

Observations

- Ionization (α_t) scales with discharge current density
- Increased ionization is linked to lower deposition rate

$$F_{flux} = \frac{\alpha_t(1-\beta_t)}{(1-\alpha_t\beta_t)}$$

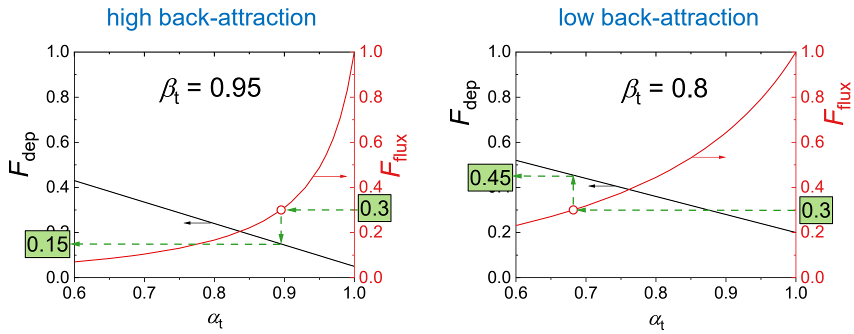
$$F_{dep} = 1 - \alpha_t\beta_t$$



$\beta_t = 0.87$

Brenning *et al.*, J. Vac. Sci. Technol. A 38, 033008 (2020)

Minimize back-attraction probability



A low back-attraction β_t → better combination of F_{dep} and F_{flux}

β_t is a ***single*** *figure of merit* for a HiPIMS discharge

Brenning *et al*., J. Vac. Sci. Technol. A 38, 033008 (2020)

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Minimize ion back-attraction

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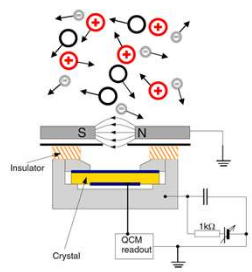
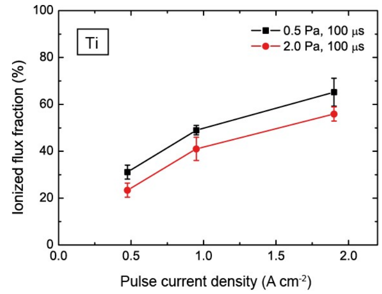
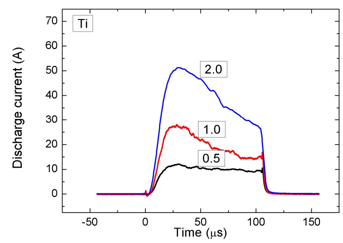
Ionized flux fraction vs working gas pressure

Ionized flux fraction
- 20 – 68 % with increasing J_D
- Increases by 10 – 30 % with decreasing p_{Ar}







Kubart *et al.*, Surf. Coatings Technol. 238, 152 (2014)
Lundin *et al.*, Plasma Sources Sci. Technol. 24, 035018 (2015)

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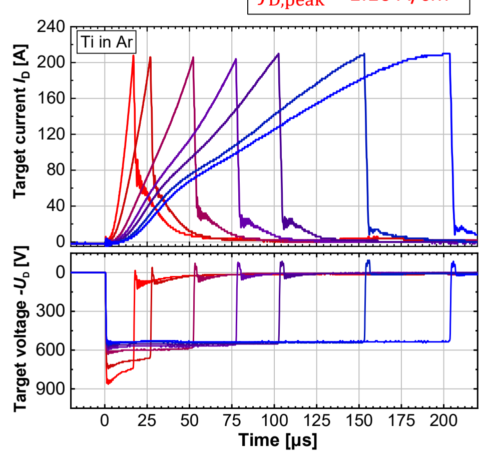
Dep. rate & ionized flux fraction vs pulse length

$J_{D,peak}$ = 1.10 A/cm^2

Experimental details
- 6” Ti target operated at 0.3 Pa Ar
- HiPIMS at 1 kW average power

- Peak current density maintained for different pulse lengths
- Three peak current densities: 1.10, 0.70, and 0.37 A/cm^2



Shimizu *et al.*, Plasma Sources Sci. Technol. 30, 045006 (2021)

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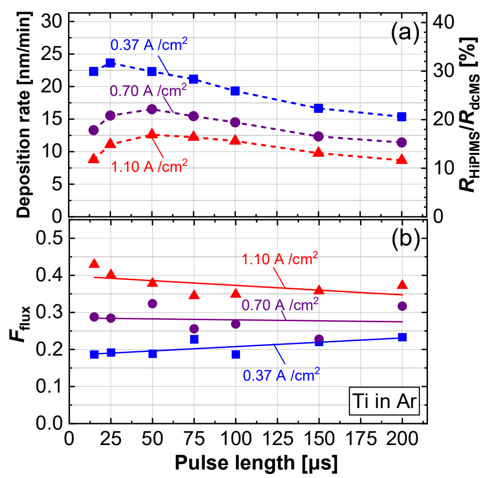
Dep. rate & ionized flux fraction vs pulse length

Dep. rate & ionized flux fraction recorded at substrate position using a gridless ion meter

- Peak current density
  R_{HiPIMS} ↓ & F_{flux} ↑ when $J_{\mathrm{D,peak}}$ ↑
- Deposition rate
  +50% with decreasing pulse length
- Ionized flux fraction
  ~ constant with decreasing pulse length



Shimizu *et al.*, Plasma Sources Sci. Technol. 30, 045006 (2021)

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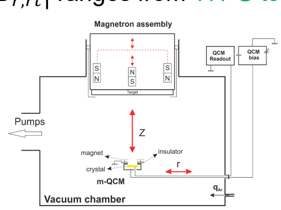
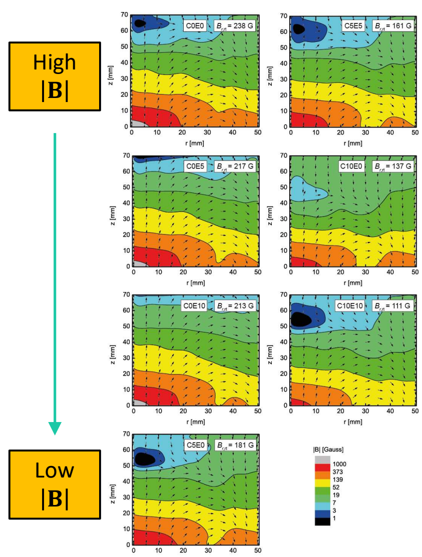
Magnetic field configurations

The magnetic field distribution above the target for seven different magnet configurations.

- Always a magnetic null point found
  → Unbalanced type II
- Magnetic null in the range 43-74 mm
- Recorded $|B_{r,rt}|$ used as a measure of $|\mathbf{B}|$. $|B_{r,rt}|$ ranges from 111 G to 238 G.





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

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Discharge characteristics vs |B|

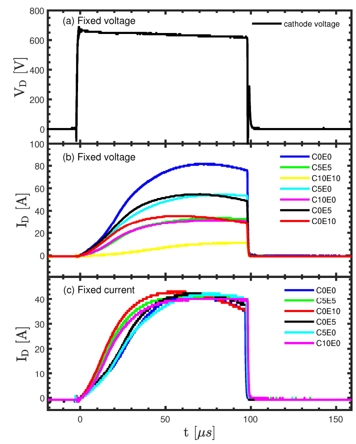
Experimental details
- 4” Ti target operated at 1 Pa Ar pressure
- DCMS and HiPIMS at 300 W average power

HiPIMS

a) Discharge voltage in fixed voltage mode ($I_{D,pk} \approx 12 - 80$ A)

b) Discharge current in fixed voltage mode

c) Discharge current in fixed peak current mode ($I_{D,pk} \approx 40$ A)

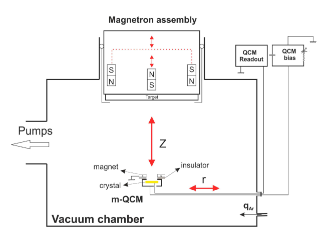


Hajihoseini *et al.*, Plasma 2, 201 (2019)

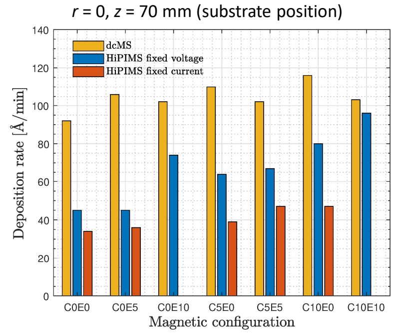
Deposition rate vs |B|

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 $|\mathbf{B}|$



r = 0, *z* = 70 mm (substrate position)



High $|\mathbf{B}|$ → Low $|\mathbf{B}|$

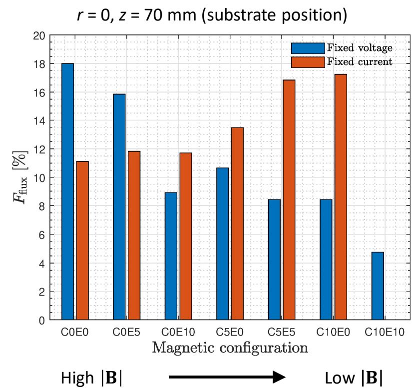
Hajihoseini *et al.*, Plasma 2, 201 (2019)

Ionized flux fraction vs |B|

Ionized flux fraction recorded at substrate position using a gridless ion meter

- DCMS:
  Always around 0% (Kubart *et al.*)
- HiPIMS fixed voltage:
  -75% with decreasing $|\mathbf{B}|$
- HiPIMS fixed peak current:
  +50% with decreasing $|\mathbf{B}|$

Opposing trends in HiPIMS!



Hajihoseini *et al.*, Plasma 2, 201 (2019)
Kubart *et al.*, Surf. Coatings Technol. 238, 152 (2014)

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Physical mechanisms and interplay

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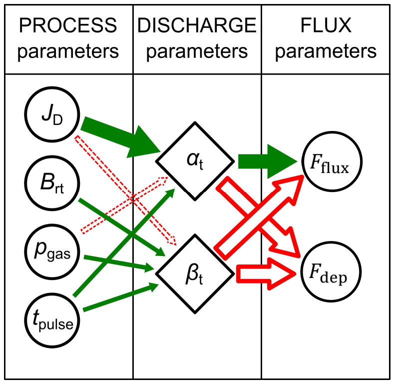
Physical mechanisms and interplay



Influence of α_t & β_t

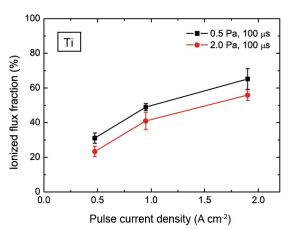
- $\alpha_t \uparrow$: $F_{flux} \uparrow$ & $F_{dep} \downarrow$
- $\beta_t \downarrow$: $F_{flux} \uparrow$ & $F_{dep} \uparrow$

$$F_{flux} = \frac{\alpha_t(1-\beta_t)}{(1-\alpha_t\beta_t)}$$

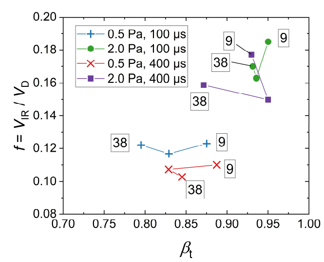
$$F_{dep} = 1 - \alpha_t\beta_t$$

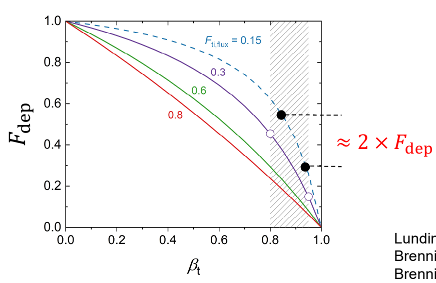
Brenning *et al.*, J. Vac. Sci. Technol. A 38, 033008 (2020)

The effect of pressure on β_t



Modeled by IRM





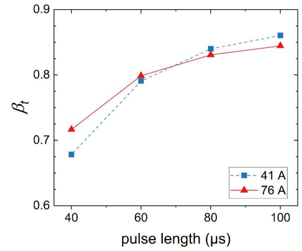
Change of β_t

- *β_t changes 0.93 → 0.84*
- F_{dep} increases by x2
- Physical reason not understood (Ohmic heating?)

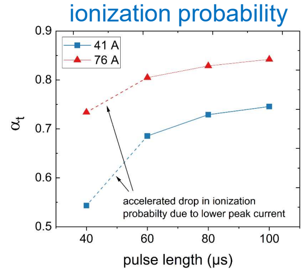
Lundin *et al.*, Plasma Sources Sci. Technol. 24, 035018 (2015)
Brenning *et al.*, J. Vac. Sci. Technol. A 38, 033008 (2020)
Brenning *et al.*, Plasma Sources Sci. Technol. 30, 015015 (2021)

The effect of pulse length on β_t (and α_t)

ion back-attraction



ionization probability



Shorter pulses

- Decrease target ion back-attraction β_t

→ release of afterglow ions

- Decrease ionization probability α_t

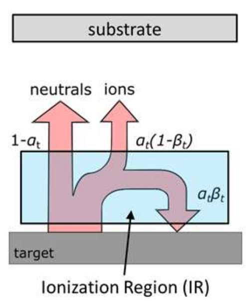
→ more neutrals escape ioniz.

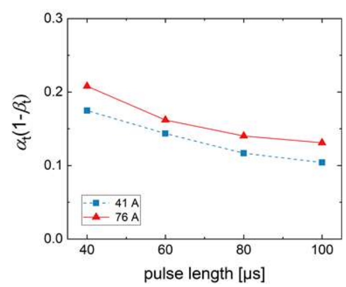
Rudolph *et al.*, Plasma Sources Sci. Technol. 29, 05LT01 (2020)
Brenning *et al.*, J. Vac. Sci. Technol. A 38, 033008 (2020)

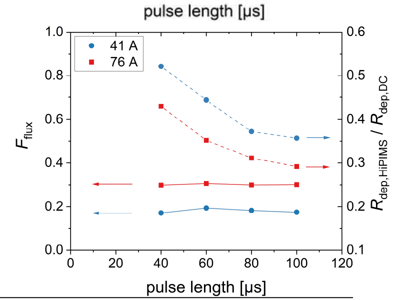
The effect of pulse length cont'd

Combined effect of α_t & β_t

- Total ion flux to substrate: $\Gamma_{\mathrm{DR,ions}} = \alpha(1-\beta)\ \Gamma_0$ increases
- Increased deposition rate by 40-50%
- Constant ionized flux fraction







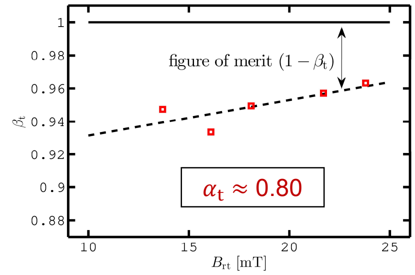
Rudolph *et al.*, Plasma Sources Sci. Technol. 29, 05LT01 (2020)
Brenning *et al.*, Plasma Sources Sci. Technol. 30, 015015 (2021)

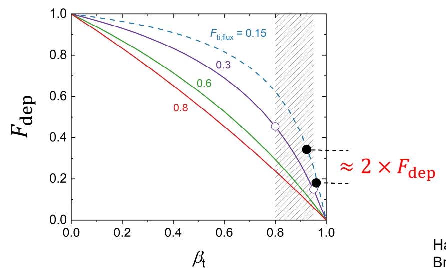
The effect of magnetic field strength on β_t

Change of β_t

- Total ion flux to substrate: $\Gamma_{DR,ions} = \alpha(1-\beta)\,\Gamma_0$
- Linear increase of $(1-\beta)$ +30% with decreasing $|\mathbf{B}|$
- Weaker $|\mathbf{B}|$ → reduced back-attracting E-field

constant peak current





If β ↓ and α maintained, F_{flux} ↑ increased deposition rate possible

Hajihoseini *et al.*, Plasma 2, 201 (2019)
Brenning *et al.*, J. Vac. Sci. Technol. A 38, 033008 (2020)

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Conclusions

The HiPIMS compromise: an inescapable conflict between the two goals of high deposition rate and high ionized flux fraction

α_t ↑ : F_{flux} ↑ & F_{dep} ↓	β_t ↓: F_{flux} ↑ & F_{dep} ↑

Pressure: Decreasing p_{Ar} increases deposition rate and/or the ionized flux fraction (+10-30%)

- Significant decrease of ion back-attraction (β decreases)

Pulse length: Decreasing pulse length increases deposition rate (+50%) and the ionized flux fraction remains constant

- $\Gamma_{DR,ions} = \alpha(1-\beta)\,\Gamma_0$ increases

B-field: Decreasing |**B**| in fixed peak current mode increases the deposition rate (+40%) and the ionized flux fraction (+50%)

- We find that α is roughly constant, whereas β decreases

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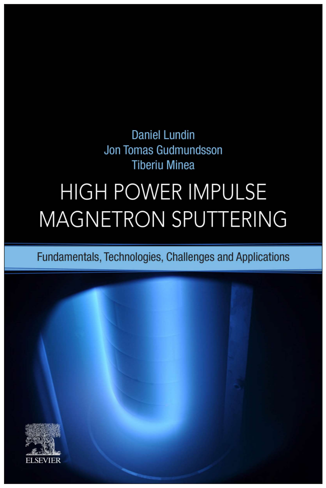
Book on HiPIMS



Key features

- Includes a comprehensive description of the HiPIMS process from the fundamental discharge physics to applications.
- Provides a link, in terms of process understanding, between the process plasma and the thin film communities.
- Shows how the HiPIMS process parameters can be adjusted to control film growth and thereby tune film properties, including hardness, refractive index, and residual stress.

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References: https://publons.com/researcher/1559854/daniel-lundin/
HiPIMS book: https://www.elsevier.com/books/high-power-impulse-magnetron-sputtering/lundin/978-0-12-812454-3