Optimizing the deposition rate and ionized flux fraction by tuning the pulse length in high power impulse magnetron sputtering

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High power impulse magnetron sputtering

- Power supplied in pulses with high peak currents
- High electron density
- High fraction of target species ions in the flux to the substrate

- Improves certain film properties
  - Density
  - Film-adhesion
  - ...

Ar/Ti HiPIMS discharge
Loss in deposition rate

- extended presheath
  - electric field directed towards the target
  - in the ionization region

- principal cause for the loss in deposition rate
  - high probability of target species ionization $\alpha_t$
  - electric field in the ionization region

*Emissive probe measurements of the plasma potential*
Deposition rate and ionized flux fraction

- material pathways model (Christie, 2005)

- ionization probability of target species $\alpha_t$

- probability of target ion back-attraction $\beta_t$

- deposition rate
  
  (sputter-rate normalized)

- ionized flux fraction:

\[
F_{\text{dep}} = 1 - \alpha_t \beta_t
\]

\[
F_{\text{flux}} = \frac{\alpha_t (1 - \beta_t)}{(1 - \alpha_t \beta_t)}
\]

Goal: Increase deposition rate while not compromising the ionized flux fraction

Christie, JVSTA 23 (2), 330, 2005
Rudolph et al., JAP 129, 033303, 2021
Case study I: constant $\beta_t$, variable $\alpha_t$

- $\alpha_t$ scales with the discharge current
- Increased deposition rate is linked to a lower ionized flux fraction

For a constant $\beta_t$, it is impossible to increase the deposition rate without compromising the ionized flux fraction.
Case study II: $\beta_t$ as a single figure of merit for HiPIMS discharges

A low target ion back-attraction $\beta_t$ gives a better combination of $F_{dep}$ and $F_{flux}$.

$\beta_t$ can be used as a *single figure of merit* for a HiPIMS discharge.

Brenning et al., JVSTA 38, 033008, 2020
Making use of the afterglow to lower the ion back-attraction

\[ \beta_t = \beta_{t,\text{pulse}} \quad \beta_t = 0 \]

\[ \beta(t) = \begin{cases} 
\beta_{t,\text{pulse}} & \text{during the pulse} \\
0 & \text{in the afterglow} 
\end{cases} \]

- Increase the relative contribution from the afterglow to the deposition rate

Idea: Shortening the pulse length while keeping the peak discharge current high.

Butler et al., *PSST* 27, 105005, 2018
The ionization region model (IRM)

- time-dependent global discharge model of the ionization region of a HiPIMS discharge
- well-knowns: pressure, gas, target, geometry, collision rate coefficients, diffusion rates
- unknowns:
  - target ion back-attraction during pulse $\beta_{t,\text{pulse}}$
  - electric potential drop over the IR: $V_{\text{IR}}$
- requires experimental input
  - $U(t)$ and $I(t)$
  - ionized flux fraction $F_{\text{flux}}$

IRM provides $\alpha_t$ and $\beta_t$ of an experimental discharge
Modelling the afterglow

\[ \beta_t = \beta_{t,\text{pulse}} \quad \beta_t = 0 \]

- modifications to existing IRM:

\[ \theta_t(t) = \begin{cases} 
\beta_{t,\text{pulse}} & \text{during pulse} \\
0 & \text{in the afterglow} 
\end{cases} \]
Experimental input to the IRM

Original discharge: 100 µs-long pulse (Haji. 2019)
- 4" Ti target
- 300 W average power
- 41 A (and 76 A) peak discharge current

Virtually cutting the pulses short
\[ t_{\text{pulse}} = 100\mu s, 80 \mu s, 60 \mu s, 40 \mu s \]

Discharge evolution follows the experimental one until the pulse is virtually switched off

Discharge current at end of pulse remains (close to) constant

Black: Original discharge with 100 µs-long pulse

Hajihoseini et al., Plasma 15 (2), 2019
Result for a 100 µs-long pulse

- jump in ion flux when pulse is switched off
  - loss of ion back-attraction
  - ion production ceases slowly only

flux of film-forming material (Ti, Ti\(^+\), Ti\(^{2+}\))
out of the IR during one HiPIMS pulse

Rudolph et al., *PSST* 29, OSLT01, 2020
Result for a 100 µs-long pulse

- jump in ion flux when pulse is switched off
  - loss of ion back-attraction
  - ion production ceases slowly only

- Experimental support by Breilmann et al.
  - time-resolved mass spectrometry
  - peak in ion current after end of pulse
  - explained by acceleration mechanism from jump in plasma potential

Shortening the pulses

flux of film-forming material out of the IR for different pulse lengths

- lower flux during the pulse
- constant flux during the afterglow

Growing contribution to the flux out of the IR from the afterglow with shorter pulses.

Rudolph et al., PSST 29, OSLT01, 2020
Gain in deposition rate is possible for constant average power (frequency to be increased)

Shorter pulses give...
- growing contribution from afterglow
- faster decrease in power/pulse compared to deposition rate

Rudolph et al., PSST 29, 05LT01, 2020
Shorter pulses at constant average power

- Increasing the frequency to constant average power

- Increase in deposition rate by 40 to 50 %
  Constant ionized flux fraction

- Side note: limit to decreasing the pulse length given by the time to build-up a high $n_e$ and the typical time for ionization

Rudolph et al., PSST 29, OS1T01, 2020
Internal discharge parameters $\alpha_t$ and $\beta_t$

Shorter pulses

- decrease target ion back-attraction $\beta_t$ from larger contribution of afterglow to the flux out of the IR

- decrease ionization probability $\alpha_t$
  - effect of shorter time for ionization
  - indicates limit for pulse length

Increasing $F_{\text{dep}} = 1 - \alpha_t \beta_t$.

Overall constant $F_{\text{flux}} = \frac{\alpha_t (1 - \beta_t)}{(1 - \alpha_t \beta_t)}$ for the discharge and the pulse lengths investigated
Experimental verification

6” circular magnetron with Ti target pulse length between 15 and 200 µs peak discharge currents between 0.37 and 1.1 A/cm²

Experiments verify the IRM findings.
Conclusion and outlook

- Shortening the pulse lengths while keeping the peak discharge current high ...

- can partially recover the loss in deposition rate between dcMS and HiPIMS
- gives a constant ionized flux fraction for the discharges and the pulse lengths investigated
  (see Rudolph et al, PSST 29, 05LT01, 2020)

- Modelling results are supported by experiments
  (see Shimizu et al, PSST 30, 045006, 2021)
Acknowledgments

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Appendix: HiPIMS optimization scheme

<table>
<thead>
<tr>
<th>PROCESS parameters</th>
<th>DISCHARGE parameters</th>
<th>FLUX parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_D$</td>
<td>$\alpha_t$</td>
<td>$F_{ti,flux}$</td>
</tr>
<tr>
<td>$B_{rt}$</td>
<td>$\beta_t$</td>
<td>$F_{OR,spur}$</td>
</tr>
<tr>
<td>$\rho_{gas}$</td>
<td></td>
<td></td>
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<tr>
<td>$t_{pulse}$</td>
<td></td>
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</tbody>
</table>

- discharge current
- magnetic field strength
- working gas pressure
- pulse length

ionized flux fraction

deposition rate

Brenning et al., JVSTA 38, 033008, 2020
Appendix: EEPF in HiPIMS discharges

IRM comparison to OBELIX*
- IRM assumes bi-Maxwellian EEDF
- Obelix solves the Boltzmann eq.

Comparison shows a good match of the electron energy probability function (EEPF)

* Orsay Boltzmann equation for ELectrons coupled with Ionization and eXcited states kinetics (OBELIX)