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

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Introduction – Magnetron sputtering

- Magnetron sputtering has been a highly successful 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.
Introduction – Fraction of ionization

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

Alami et al. (2005) JVSTA 23 278

Kateb et al. (2019) JVSTA 37 031306
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
    \[ F_{\text{flux}} = \frac{\Gamma_i}{\Gamma_i + \Gamma_n} \]
  - the ionized density fraction
    \[ F_{\text{density}} = \frac{n_i}{n_i + n_n} \]
  - the fraction \( \alpha_t \) of the sputtered metal atoms that become ionized in the plasma (probability of ionization)
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Influence of magnetic field
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**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 $\mu$s at an average power of 300 W

From Haji hoseini et al. (2019) *Plasma* 2 201
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**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 $|B|$
      - (but no obvious trend)
  - *HiPIMS fixed voltage*
    - +110% with decreasing $|B|$
  - *HiPIMS fixed peak current*
    - +40% with decreasing $|B|$

- In HiPIMS operation the deposition rate increases with decreasing $|B|$, ordered from high $|B|$ at the left to low $|B|$ on the right

From Hajihoseini et al. (2019) *Plasma 2* 201
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**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 $|B|$%
  - **HiPIMS fixed peak current**
    - +50% with decreasing $|B|$%

- The ionized flux fraction decreases with decreasing $|B|$ when the HiPIMS discharge is operated in fixed voltage mode but increases in fixed peak current mode

- Opposing trends

![Graph](From Hajihoseini et al. (2019) Plasma 2 201)
Internal parameters and optimization
On the relation between deposition rate and ionized flux fraction in high power impulse magnetron sputtering

Influence of magnetic field – $\alpha_t$ and $\beta_t$

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

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

$$F_{\text{ti,flux}} = \frac{\Gamma_{\text{DR,ions}}}{\Gamma_{\text{DR,sput}}} = \frac{\Gamma_0 \alpha_t (1 - \beta_t)}{\Gamma_0 (1 - \alpha_t \beta_t)} = \frac{\alpha_t (1 - \beta_t)}{(1 - \alpha_t \beta_t)}$$

to the internal parameters back attraction probability $\beta_t$

$$\beta_t = \frac{1 - F_{\text{DR,sput}}}{1 - F_{\text{DR,sput}} (1 - F_{\text{ti,flux}})}$$

and ionization probability $\alpha_t$

$$\alpha_t = 1 - F_{\text{DR,sput}} (1 - F_{\text{ti,flux}})$$
Influence of magnetic field – Optimization

- There are two measures of how good a HiPIMS discharge is: the fraction $F_{DR,sput}$ of all the sputtered material that reaches the diffusion region (DR) and the fraction $F_{ti,flux}$ of ionized species in that flux.

- There is a trade off between the goals of higher $F_{DR,sput}$ and higher $F_{ti,flux}$.

- The figure shows $F_{DR,sput}$ and $F_{ti,flux}$ as functions of $\alpha_t$ at assumed fixed value of $\beta_t = 0.87$.

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
  \(0.8 \leq \beta_t \leq 0.95\)

- Following the green dotted line from the value \(F_{ti,flux} = 0.30\) to the red dashed curve gives \(\alpha_t = 0.9\) (red square)

- The black dashed line then shows \(\alpha_t\) only 15% of the total sputtered flux enters the diffusion region \(F_{DR,sput} = 0.15\).

- Solid lines show that reducing the back-attraction to \(\beta_t = 0.8\) where \(\alpha_t = 0.69\) is sufficient to maintain \(F_{ti,flux} = 0.30\) (red circle) and \(F_{DR,sput} = 0.45\) or a factor of three increase in the deposition rate

From Brenning et al. (2020) JVSTA 38 033008
On the relation between deposition rate and ionized flux fraction in high power impulse magnetron sputtering

Influence of magnetic field – $\alpha_t$ and $\beta_t$

- When operating in the fixed voltage mode (red) the ionization probability $\alpha_t$ increases with increased magnetic field strength – which is essentially the discharge current.

- When operating in the fixed peak current mode (black) the ionization probability $\alpha_t$ is roughly constant independent of the magnetic field strength.

- $\alpha_t$ can be varied in the range $0 \leq \alpha_t \leq 1$ by the discharge current amplitude $J_D$.

- $\beta_t$ is variable within a much smaller achievable range and depends heavily on the magnetic field strength.

From Hajihoseini et al. (2019) * Plasma, 2019
Influence of magnetic field – Optimization

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

From Brenning et al. (2020) JVSTA 38 033008
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 $\beta_t$
- $\beta_t$ 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 $\alpha_t$ also decreases with a shorter pulse length
- The useful fraction of the sputtered species

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

From Brenning et al. (2020) J.V.ST. A38 033008
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

From Brenning et al. (2020) JVSTA 38 033008
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 $|B|$

- For HiPIMS in the fixed peak current mode: Decreasing $|B|$ 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
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References


