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Tutorial
Magnetron sputtering

Principles and practice

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Sweden

MICRONOVA myfab NorFab DTU Nanolab NNN Nordic Nanolab Network

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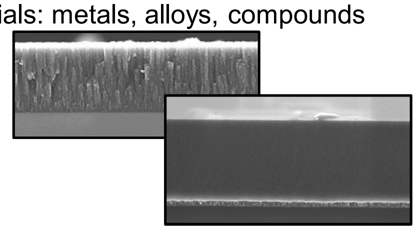
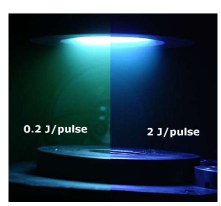
Outline

NNN Nordic Nanolab Network

- Motivation
  - Synthesis of thin film materials: metals, alloys, compounds
  - Control of microstructure



- Magnetron sputtering
  - Physics of sputtering
  - Deposition by sputtering
- New approaches in sputtering
  - Ionized deposition
  - HiPIMS



Review of the field, new possibilities

Magnetron sputtering

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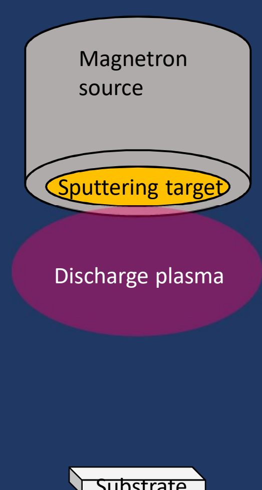
Widely used technique

- Flexible: Wide range of materials including alloys and compounds
- Scalable –from lab to industry
- Dense films with good adhesion
- Decent coverage (compared to evaporation!)
- Low deposition temperature

Sputter source Ø 5 cm

Inline coater, coated size is 3.21x 6 m

Magnetron **sputtering**



Sputtering by ions
- Sputtering yields
- Energy

Magnetron plasma
- Ionization
- Plasma chemistry

Deposition by sputtering
- Thin film growth

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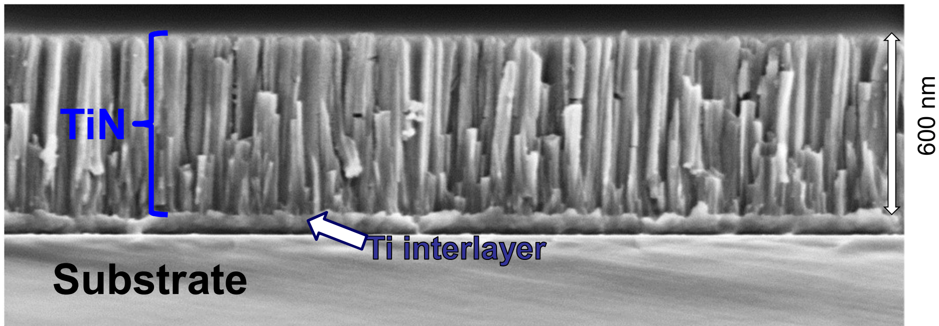
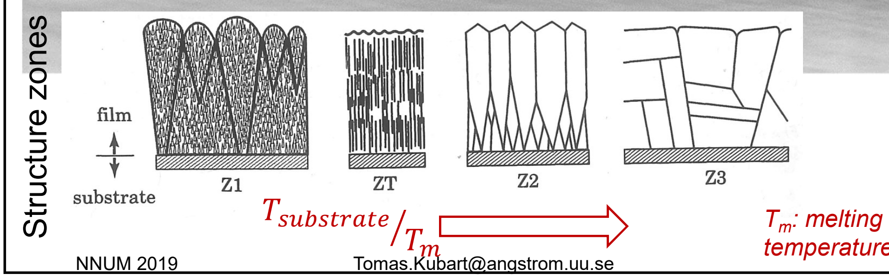
Typical thin film microstructure





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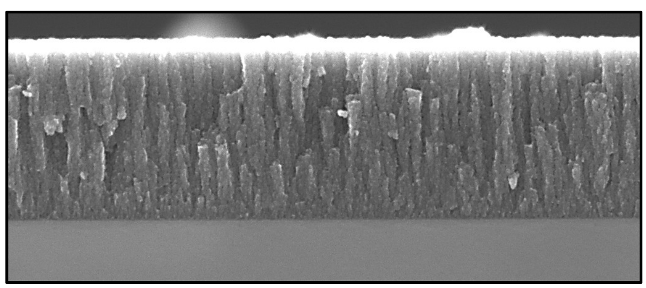
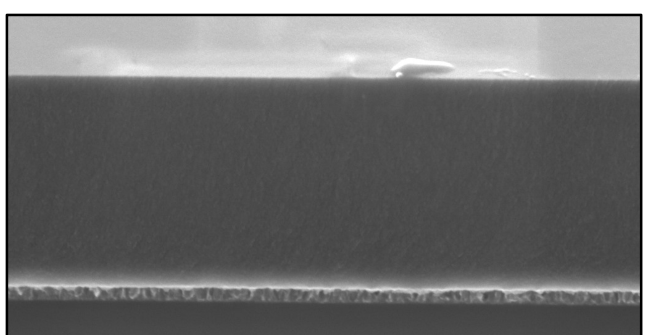
Microstructure control

Low energy deposition



Deposition by energetic particles



Film morphology: Structure Zone Model

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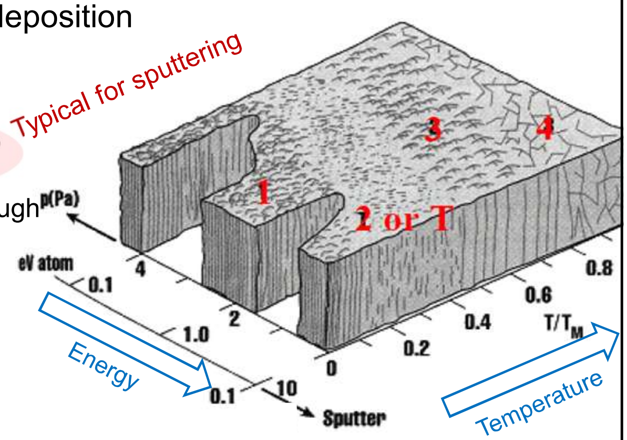
Additional parameter: deposition pressure (**energy**)

- Zone 1 –porous
- Zone T –dense, smooth, small grains
- Zone 3 –large grains, rough surface
- Zone 4 –huge grains



Non-thermal energy input desired!

T_m: melting temperature.

Energy of Sputtered Species

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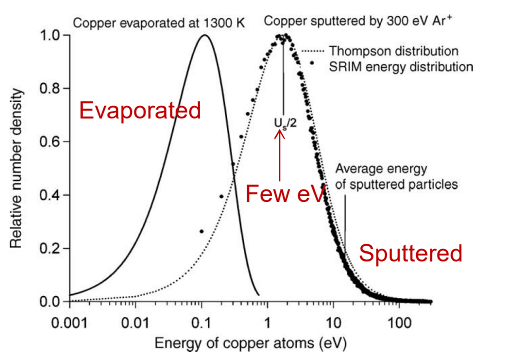
Sputtered vs. evaporated atoms

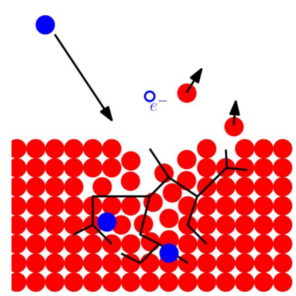
Handbook of Deposition Technologies for Films and Coatings



- Sputtered particles **3-10 eV**
- Improved film properties

Other energetic species

- Ions reflected from the target
- Negative ions (O^-) from the target
- Secondary electrons



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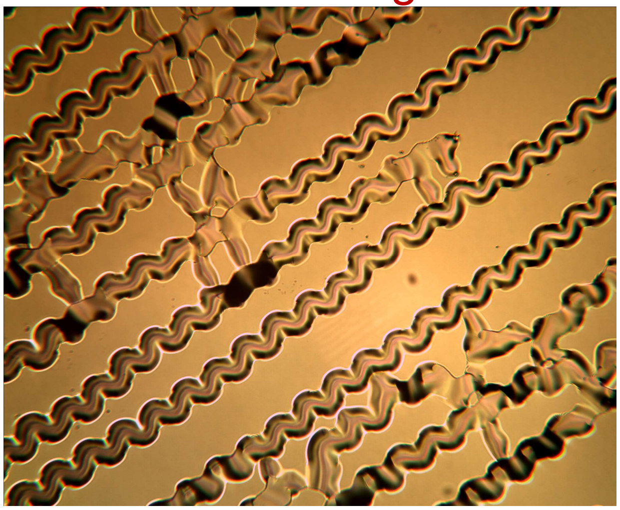
Example: W coating delamination



Delamination due to compressive stress

Stress caused by Ar implantation

Solution: increased deposition pressure

Ideally, energies below sputtering threshold!

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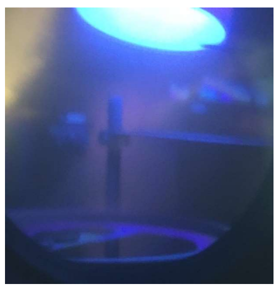
Magnetron Sputtering

- Most materials can be sputtered
- Plasma confined close to the target (no substrate heating)
- Reactive processes especially interesting (plasma activation)



- Sputtering provides atoms with substantial energy (several eV) => improved film growth

Thornton, J.A. Magnetron sputtering - basic physics and application to cylindrical magnetrons. J. Vac. Sci. Technol. 1978, 15, 171-177.

Handbook of Deposition Technologies for Films and Coatings

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Ionized magnetron sputtering

Utilizing ions for deposition

Increasing ionization of sputtered atoms

Examples

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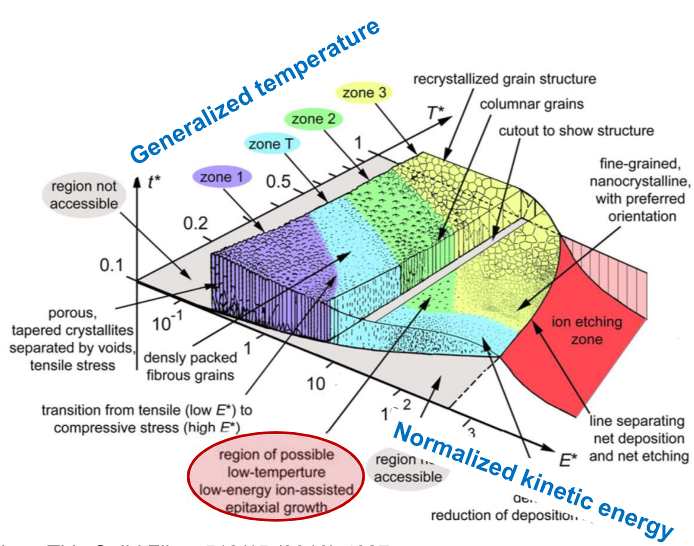
Extended SZM -energetic deposition



A. Anders, Thin Solid Films 518/15 (2010) 4087

Production of Ions in a Plasma

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I) Electron impact ionization

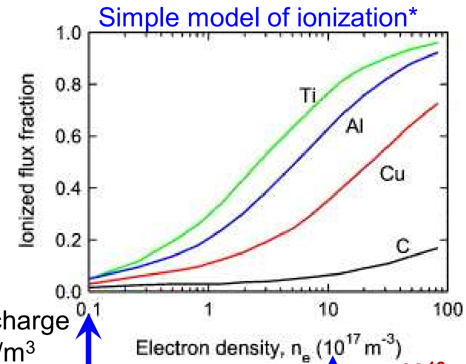
$$e^- + Me \rightarrow Me^+ + 2e^-$$

II) Penning ionization

$$Ar^* + Me \rightarrow Ar + Me^+ + e^-$$

$$Ar + e^- \rightarrow Ar^* + e^-$$

Either way, we need electrons!



Ionization energy [eV]	
Ar	15.76
Ti	6.83
Cu	7.73
Al	5.99

Metals easier to ionize than Ar

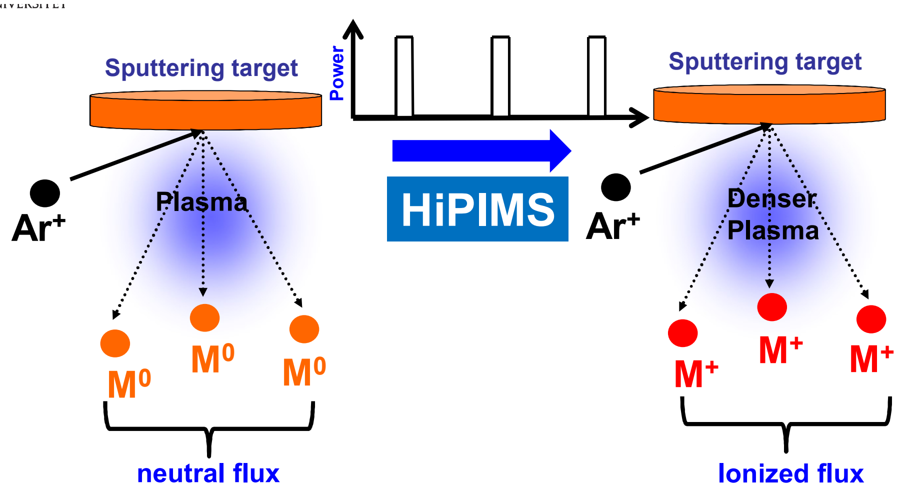
DC discharge ~10^{16} *e*/m^3
Few % of ions at most

~10^{18} *e*/m^3 required!

Low ionization in DC sputtering, higher plasma density required!

Thin Solid Films 513/1-2 (2006) 1.

High Power Impulse Magnetron Sputtering



HiPIMS excellent for metals, high ionization achieved

D. Lundin, K. Sarakinos, Journal of Materials Research 27/5 (2012) 780.

High Power Impulse Magnetron Sputtering HiPIMS

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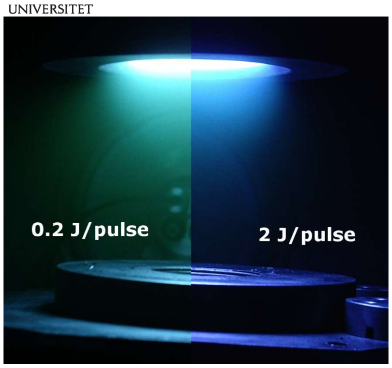

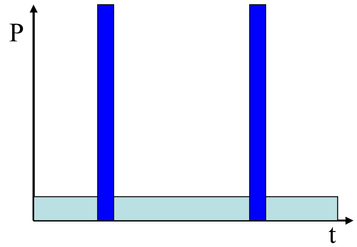

- Large fraction of the sputtered material ionized
- HiPIMS compatible with standard sputtering systems
- Many examples of improved film properties

Typical values

Pulse power	MW
Current	kA
Pulse power density	kW/cm^2
Pulse current density	A/cm^2
Pulse length	50-200 μs
Frequency	50 -1 000 kHz

Discharge current in HiPIMS

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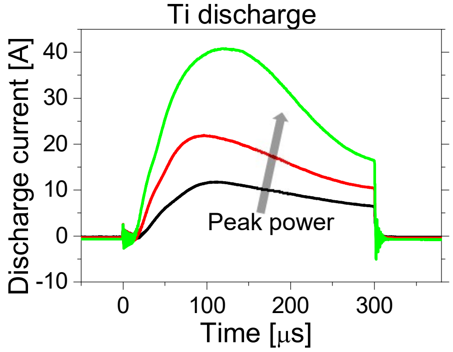
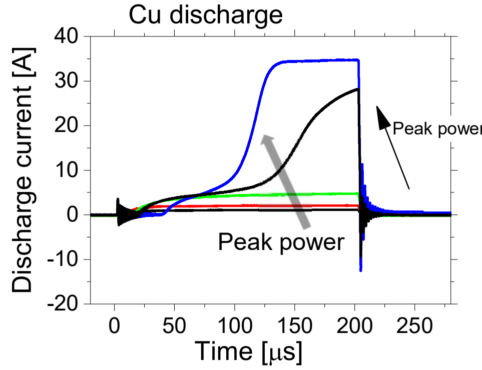


Typical HiPIMS pulse –peak caused by gas rarefaction

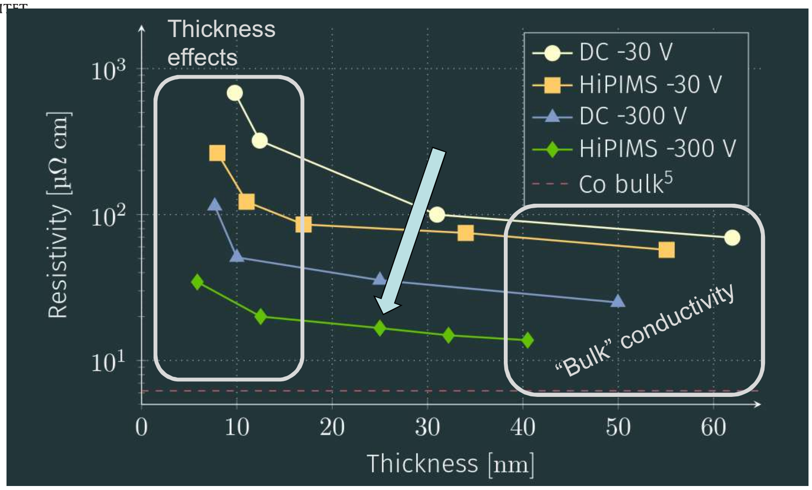


Transition to metal plasma dominated discharge

Discharge current waveforms provide guidance for process development

J Phys D 45/1 (2012) 012003.

Example: Co metallization

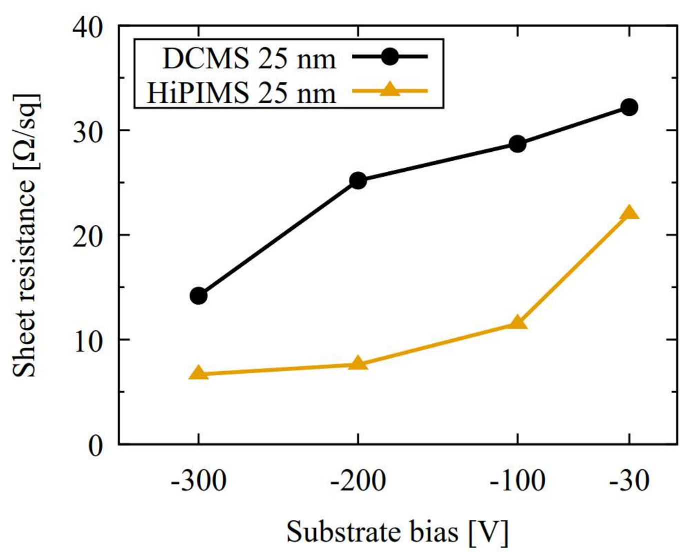


Resistivity reduced, huge improvement at lower thickness!

No Ar incorporation in HiPIMS Co

Appl. Phys. Lett. 112/4 (2018) 043103

Co metallization



Bias of -100 V sufficient in HiPIMS

Appl. Phys. Lett. 112/4 (2018) 043103

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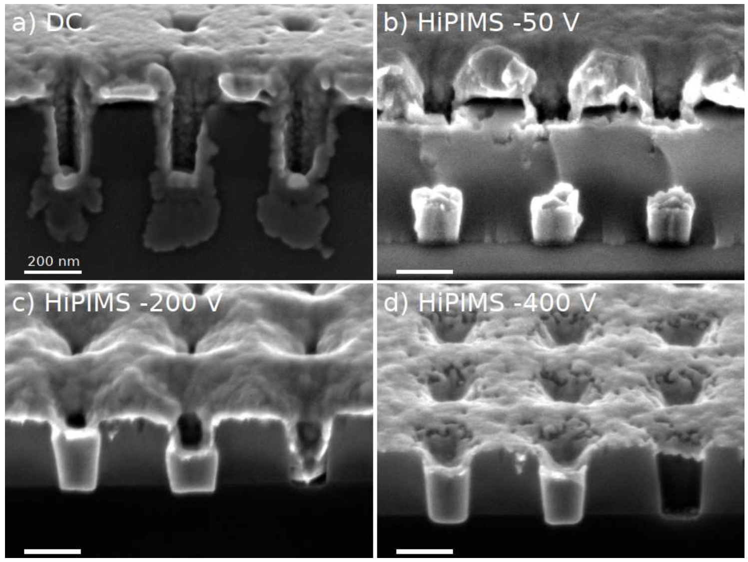
Example: Cu deposition inside holes



Hole filling by metal improved by HiPIMS

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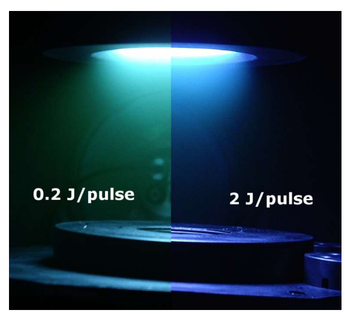
HiPIMS

- New variant of magnetron sputtering
- HiPIMS provides highly ionized flux for deposition
- Compatible with existing systems
- Need for process development



HiPIMS: deposition by ions, potential to improve material performance

Reviews

Thin Solid Films 513/1-2 (2006) 1

Journal of Materials Research 27/5 (2012) 780

Surf. Coat. Technol. 204/11 (2010) 1661

Coming soon: High Power Impulse Magnetron Sputtering, Elsevier

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Reactive sputtering

Reactive HiPIMS

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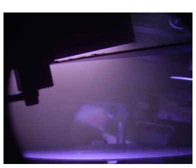
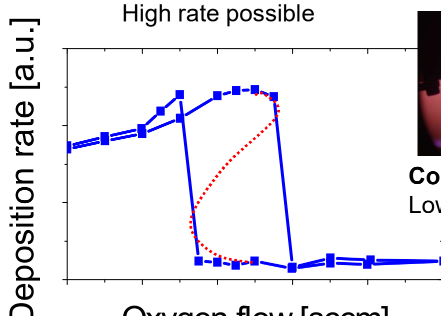
Hysteresis and deposition rate

Complex interaction between sputtered material and reactive gas

Metal mode
High rate, substoichiometric



Transition region
Unstable
High rate possible



Compound mode
Low rate, high p_{O2}

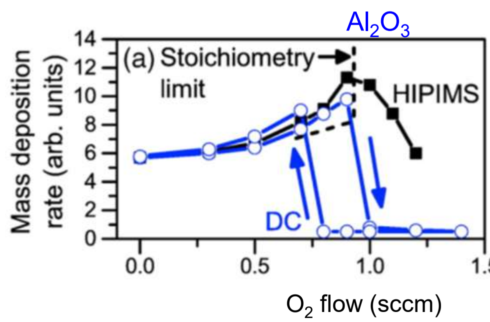
Reactive sputter deposition, Springer, 2008.

Typical hysteresis curve for a metal target

Corresponding hysteresis in voltage, partial pressure

Deposition rate in HiPIMS

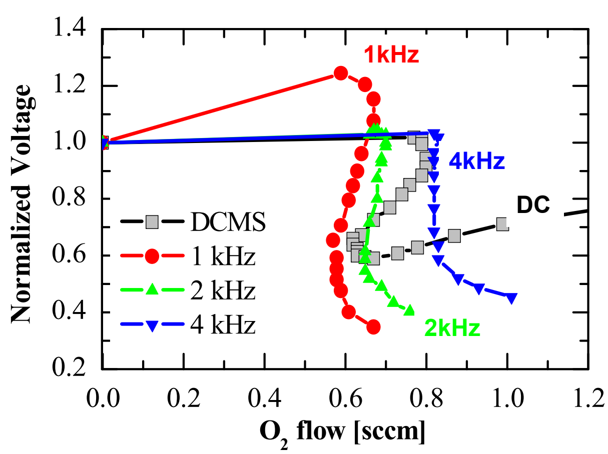
- Deposition rate in HiPIMS lower than in dcMS
- Reports on absence of hysteresis in R-HiPIMS
- High rate reactive HiPIMS?



E. Wallin, U. Helmersson, Hysteresis-free reactive high power impulse magnetron sputtering, Thin Solid Films 516/18 (2008) 6398.

➢ Metal mode conditions stabilized

Reduced hysteresis in HiPIMS



Ce target Ø 50mm
Constant power of 70W

HiPIMS: SPIK 1000A
35µs on-time

Hysteresis minimized at 4kHz.

M. Aiempanakit, et al., Thin Solid Films 519 (2011)

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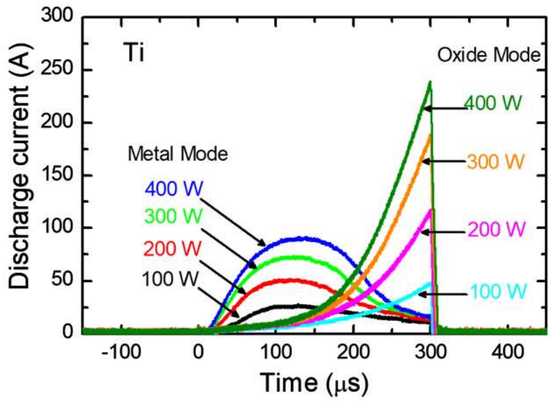
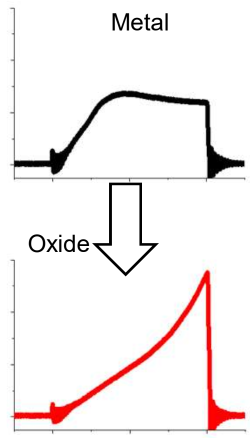
Discharge characteristics





- Discharge current–indication of the operating mode
- Exact physics still unknown

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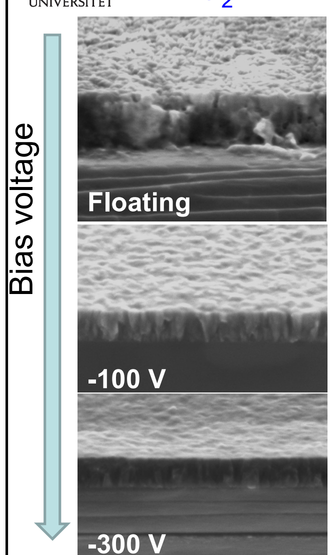
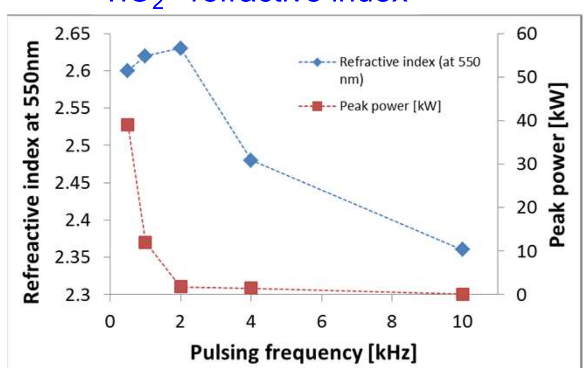
Example: TiO_2

TiO_2



TiO_2 –refractive index



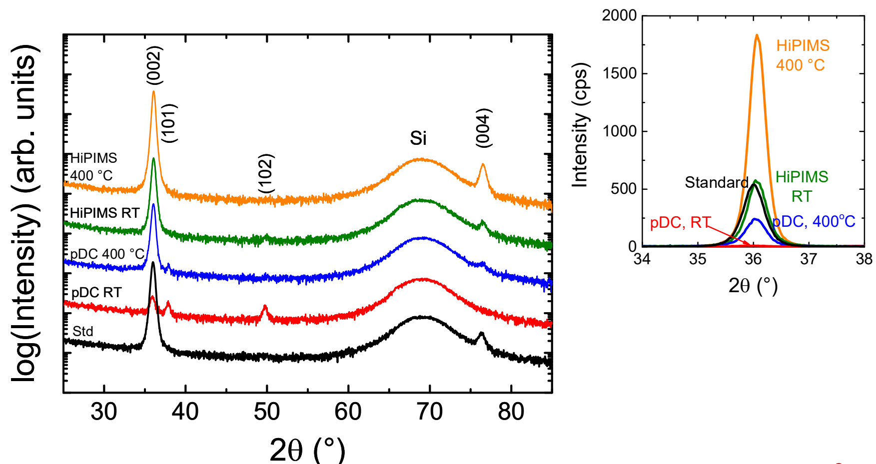
Surf Coat Technol 2011, 205, 4828-4831

- Highest refractive index at 10% duty cycle –low peak power

LowPIMS! –optimization of pulse parameters possible

Example: AlN

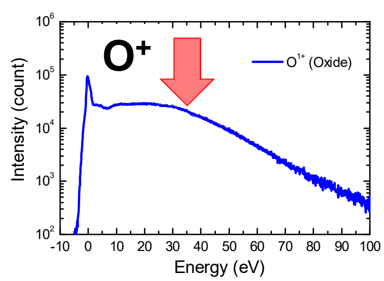
High degree of texture required for piezoelectric AlN

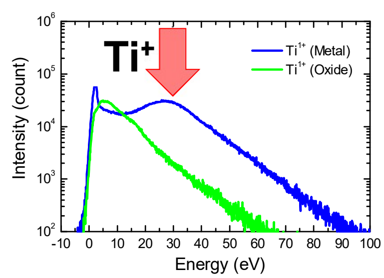


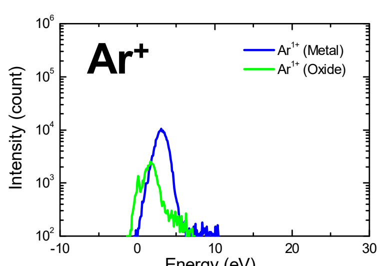
HiPIMS films at RT comparable with the optimized reference process at 400°C

J Vac Sci Technol A. 2015;33(2):021518

Ion energy distribution R-HiPIMS with Ti in Ar+O_2







- **IEDF of O^+ resembles Ti^+!**
- **O^+ originate from the target surface!**

M. Aiempanakit, et al., J App. Phys. 113 (2013) 133302.

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Is HiPIMS always better than DCMS?

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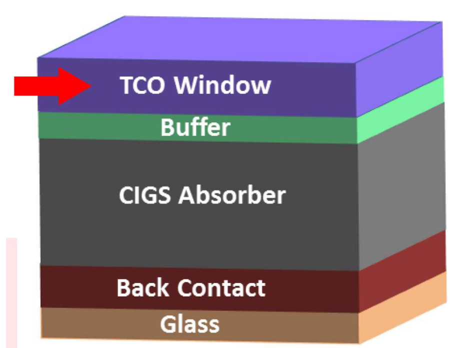
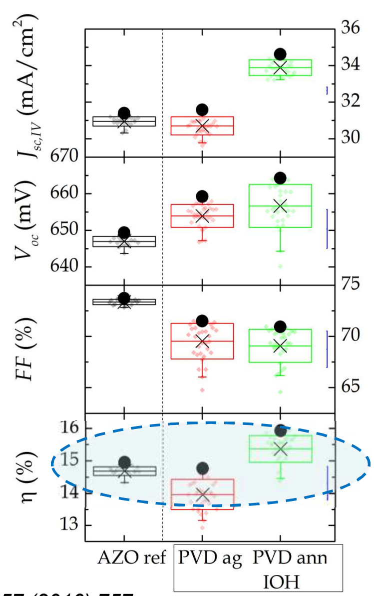
In_2O_3:H –Highly transparent TCO

RF sputtering





IOH –high mobility, low free carrier absorption => Highly transparent

Sol Energ Mat Sol C 157 (2016) 757.

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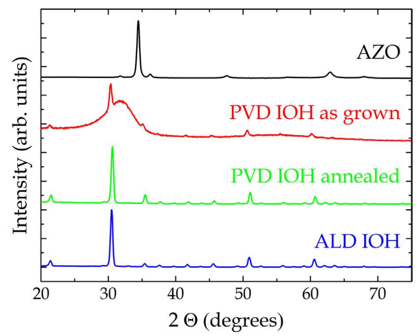
Ionized deposition of TCO?

TCO in general sensitive to energetic bombardment

Especially energetic O/O^-

Issues even in DCMS



Ionized deposition of TCO materials difficult!

Sol Energ Mat Sol C 157 (2016) 757.

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Reactive HiPIMS

+ Opening a new process window –consider low peak power
+ Potential for high deposition rate
+ Performance material specific

- Complex behaviour
- Still in development

Review: Plasma Physics and Controlled Fusion 58/1 (2016) 014002.

VO_2: *Sol Energ Mat Sol C 149 (2016) 137*
AlN: *J. Vac. Sci. Technol. A 33/2 (2015) 021518*
TiO_2: *Surf Coat Technol 205/20 (2011) 4828*

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Conclusions

- Energy is the key in control of growth
- Sputtering: flexible process, new variants available
- Adjust your process to the material/properties