ICMATE
Institute of Condensed Matter Chemistry and Technologies for Energy

HiPIMS: the advantages of a high ionization plasma PVD technology

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Dream Team

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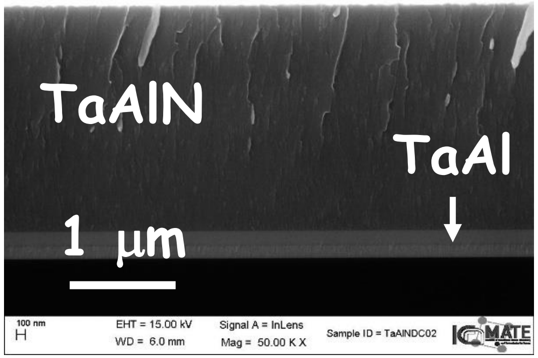
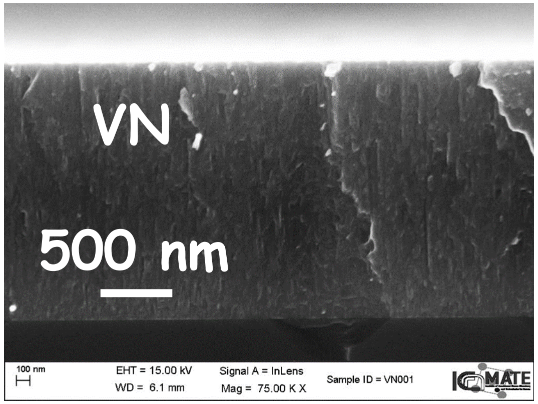
Why coatings?

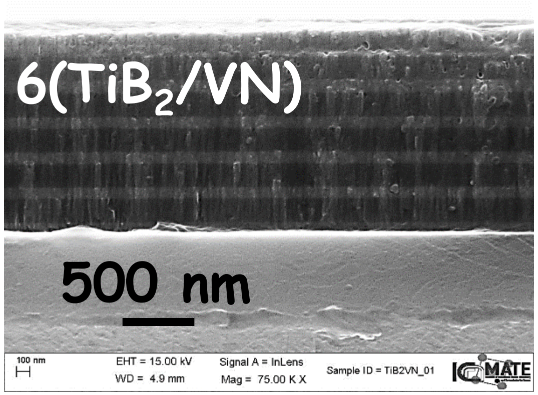
There are ever increasing demands on
- ✓ **performance**,
- ✓ product **quality**, and
- ✓ development of **new materials**.



The ability to coat objects with a film allows
- ✓ combining the properties of the underlying material and the coating,
- ✓ increasing cost efficiency.

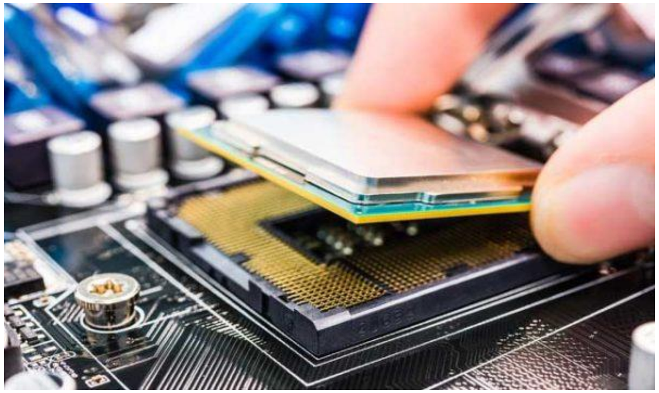


- ✓ Existing products improvement
- ✓ New materials and properties



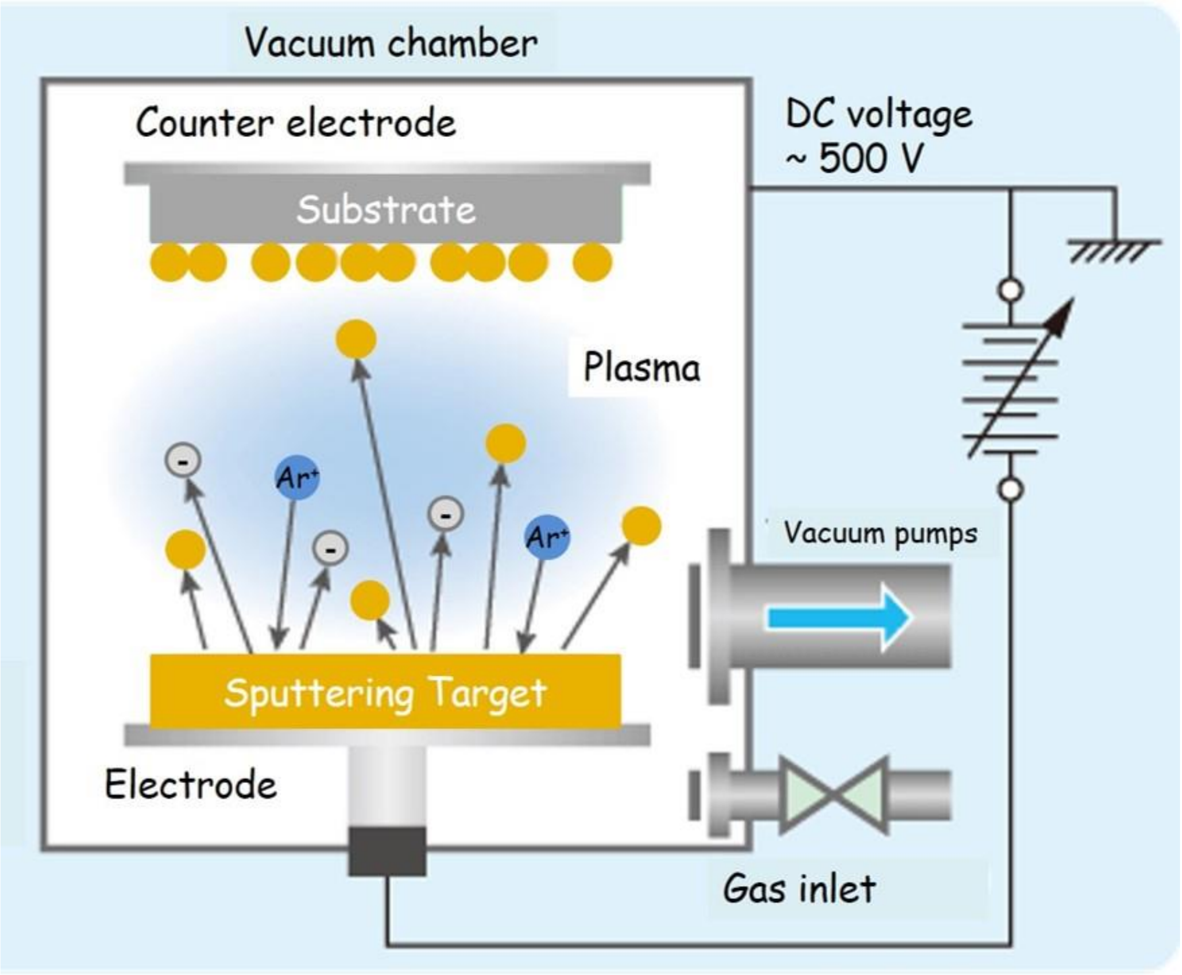
Why sputtering?

- ✓ Wide range of possible sputtered materials including compounds an alloys
- ✓ High deposition rates
- ✓ High purity films (vacuum, low pressure)
- ✓ Good coating/substrate adhesion
- ✓ Good step coverage and uniformity
- ✓ Allow various parameter control
- ✓ Scalability
- ✓ …..



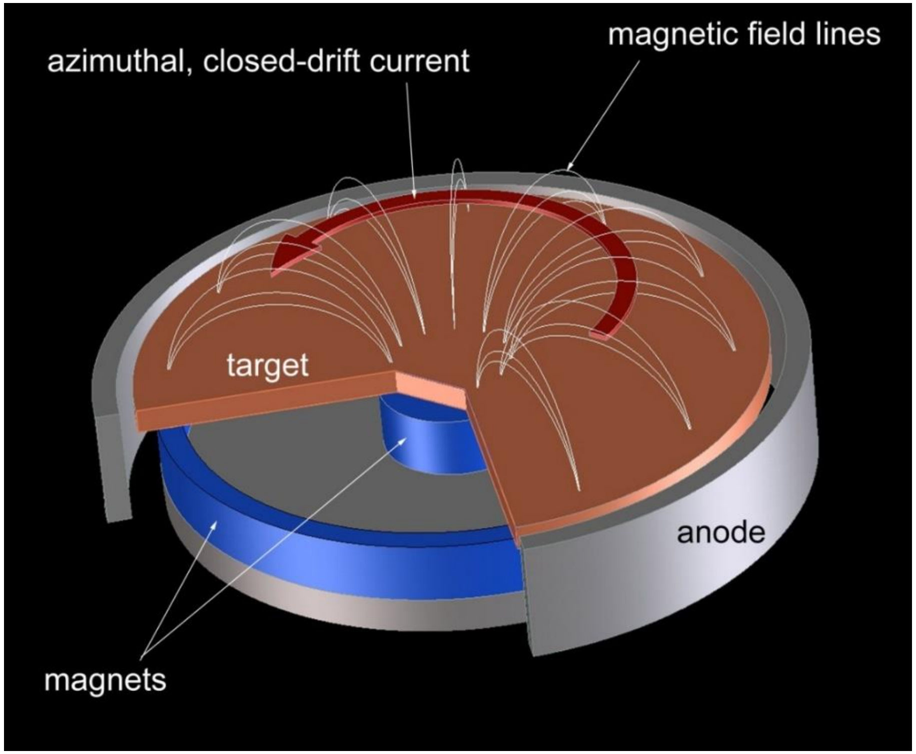
Thin film deposition by Sputtering

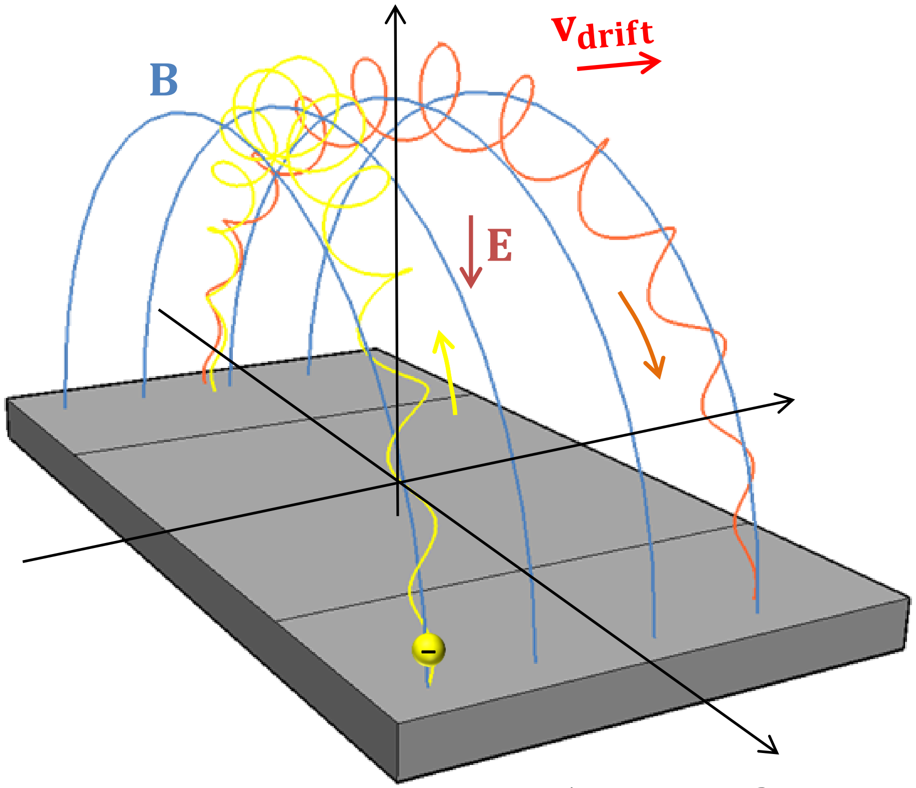
- ✓ Sputtering = ejection of **atoms** due to bombardment of the target by ions.
- ✓ The source of ions is a plasma discharge.
- ✓ Secondary electrons are also emitted.



Magnetron Sputtering

A sputtering device with an effective electrons trapping!





by Matjaz Panjan

A. Anders, Surf. Coat. Technol. 205 (2011) S1.
A. Anders, Journal of Applied Physics 121 (2017) 171101.

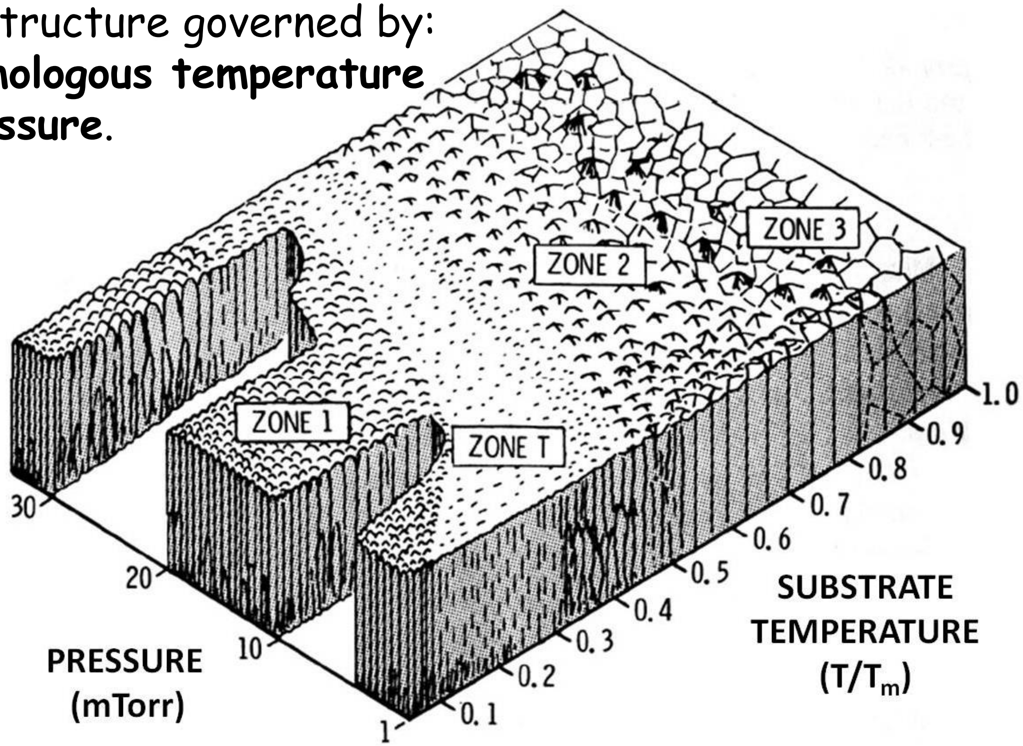
Structure Zone Diagram

In MS techniques, variation of the deposition parameters allows for control of the **energy/momentum** transferred to the film-forming species enabling the manipulation of the **film properties**.

Thornton's SZD

microstructure governed by:

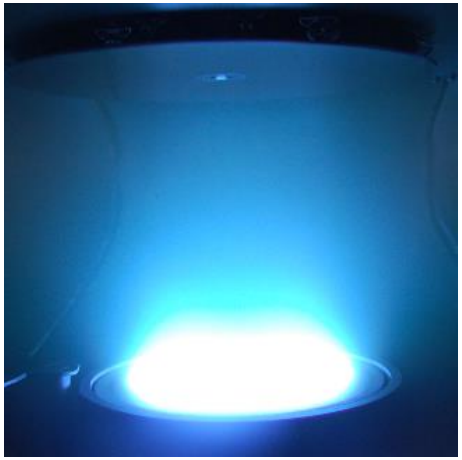
- ✓ **homologous temperature**
- ✓ **pressure**.



- ✓ **Zone 1** = porous structure consisting of tapered crystallites separated by voids;
- ✓ **Zone T** = transition structure consisting of densely packed fibrous grains;
- ✓ **Zone 2** = columnar grains;
- ✓ **Zone 3** = recrystallized grain structure.

Thornton, J. Vac. Sci. Technol. **11** (1974) 666

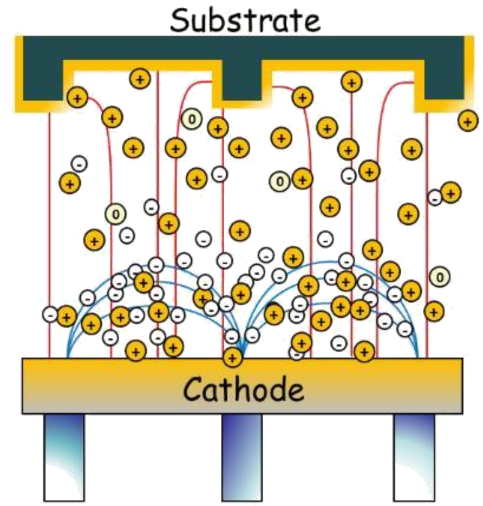
HiPIMS



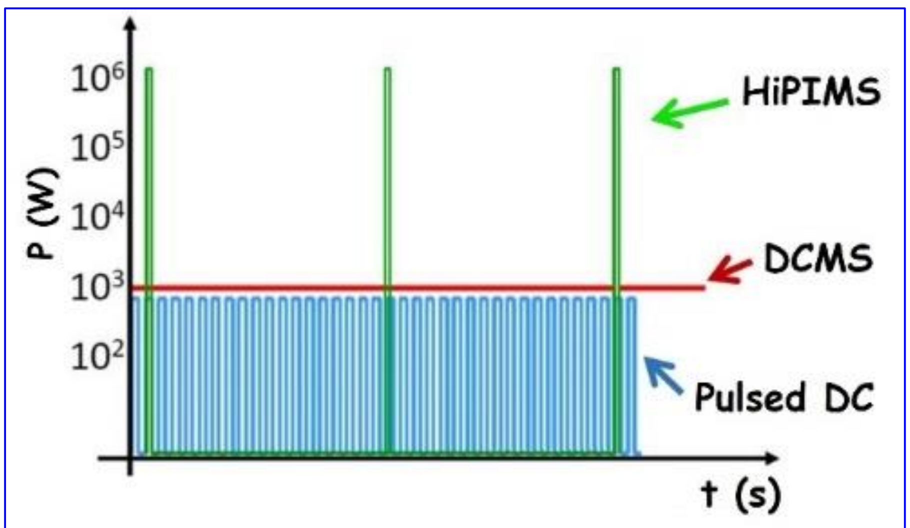
Applying HIGH POWER PULSES to a magnetron cathode

↓

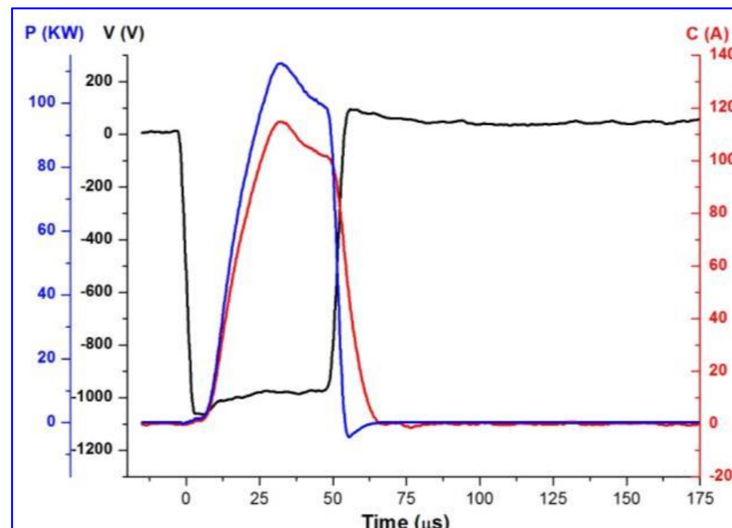
Many SPUTTERED target material ATOMS are IONIZED



< 10% duty cycle (on/off time ratio)

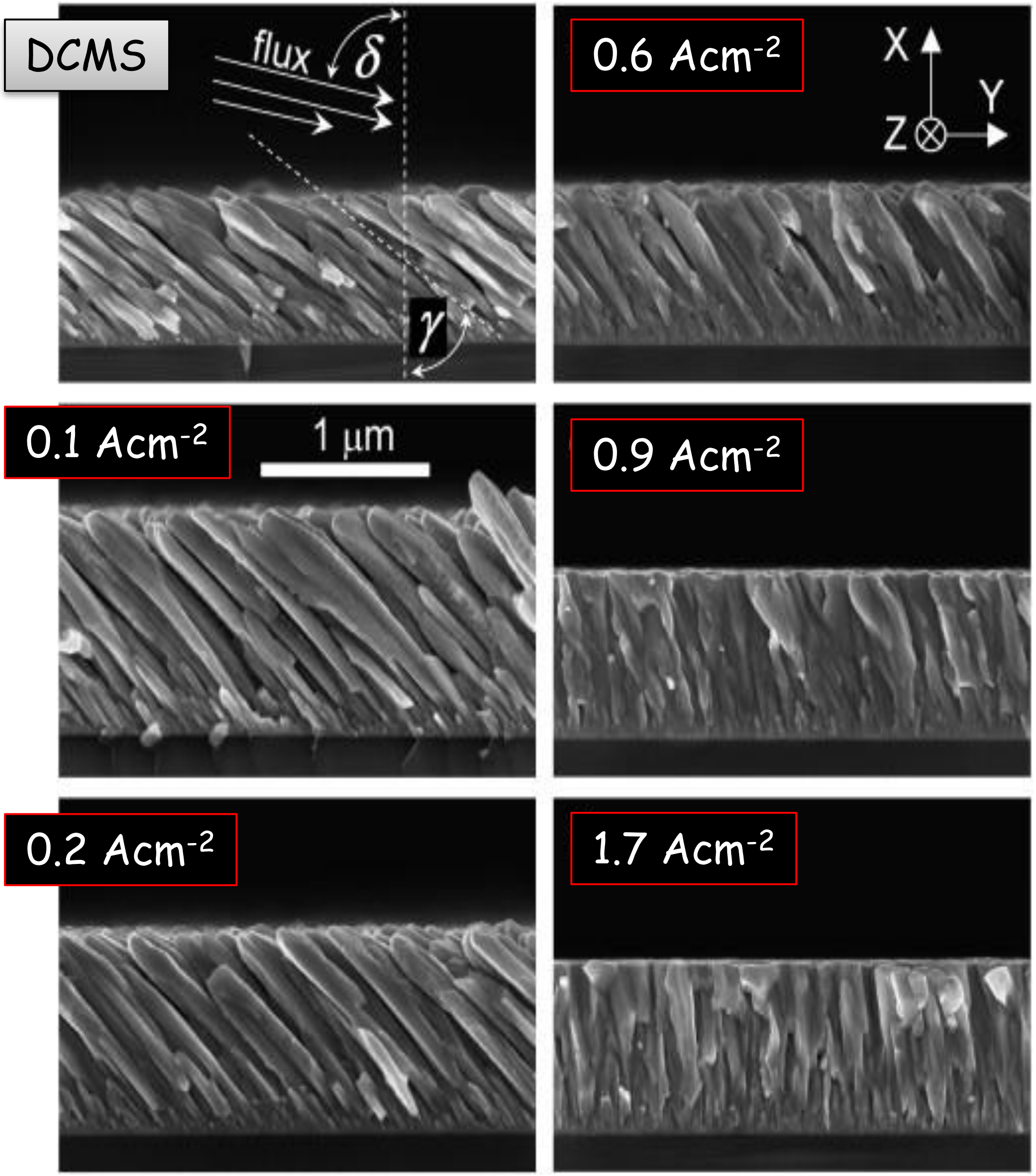


Typical Voltage/Current/Power signals



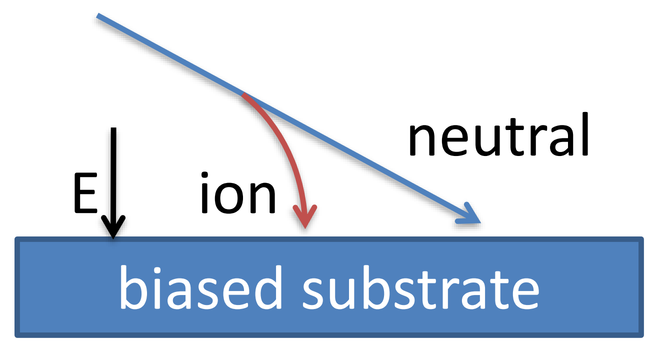
- ✓ V. Kouznetsov, K. Maca´k, J. M. Schneider, U. Helmersson, and I. Petrov, Surf. Coat. Technol. 122 (1999) 290.
- ✓ A. Anders, Surface and Coatings Technology 205 (2011) S1-S9.

Complex-shaped substrates



CrN Glancing Angle Deposition

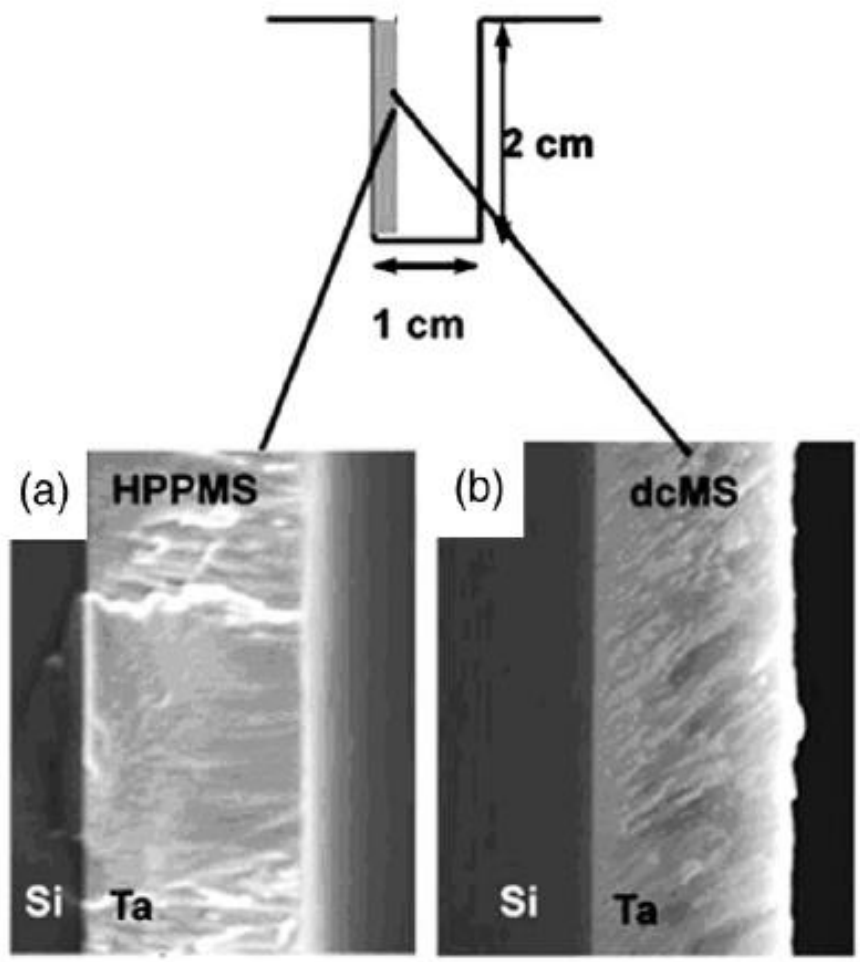
Inclination of columns is reduced at high target current densities due to high ion-to-neutral ratio



G. Greczynski, *et al.*, Thin Solid Films **519** (2011) 6354.

Complex-shaped substrates

Cross-sectional SEM images of **Ta** films grown by **(a) HiPIMS** and **(b) DCMS** on a Si substrate clamped on the side of a trench.

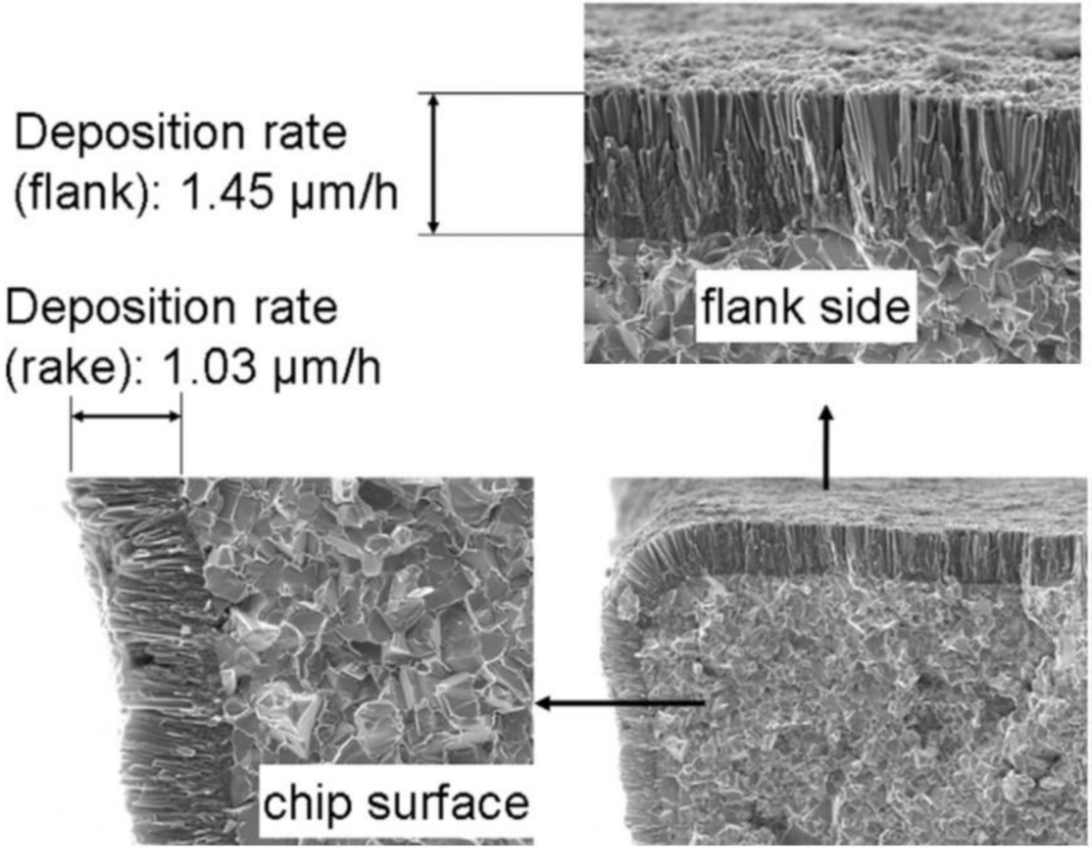


- ✓ HiPIMS films → dense with columns growing perpendicular to the Ta/Si interface.
- ✓ DCMS films → porous microstructure with columns inclined toward the flux direction (atomic shadowing).

J. Alami et al., Journal of Vacuum Science and Technology A, 23 (2005) 278.

Complex-shaped substrates

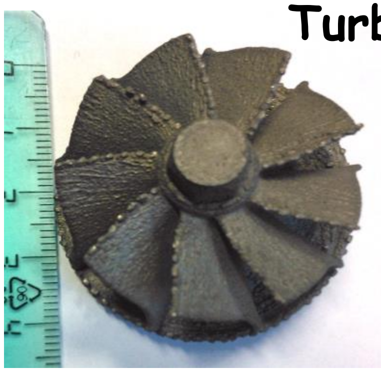
Cross sectional SEM images of TiAlN coating deposited on the flank and the rake side of a cutting insert.

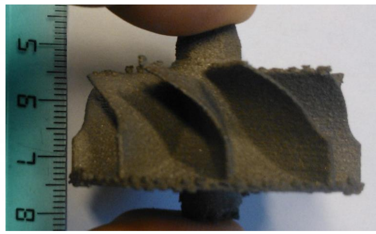


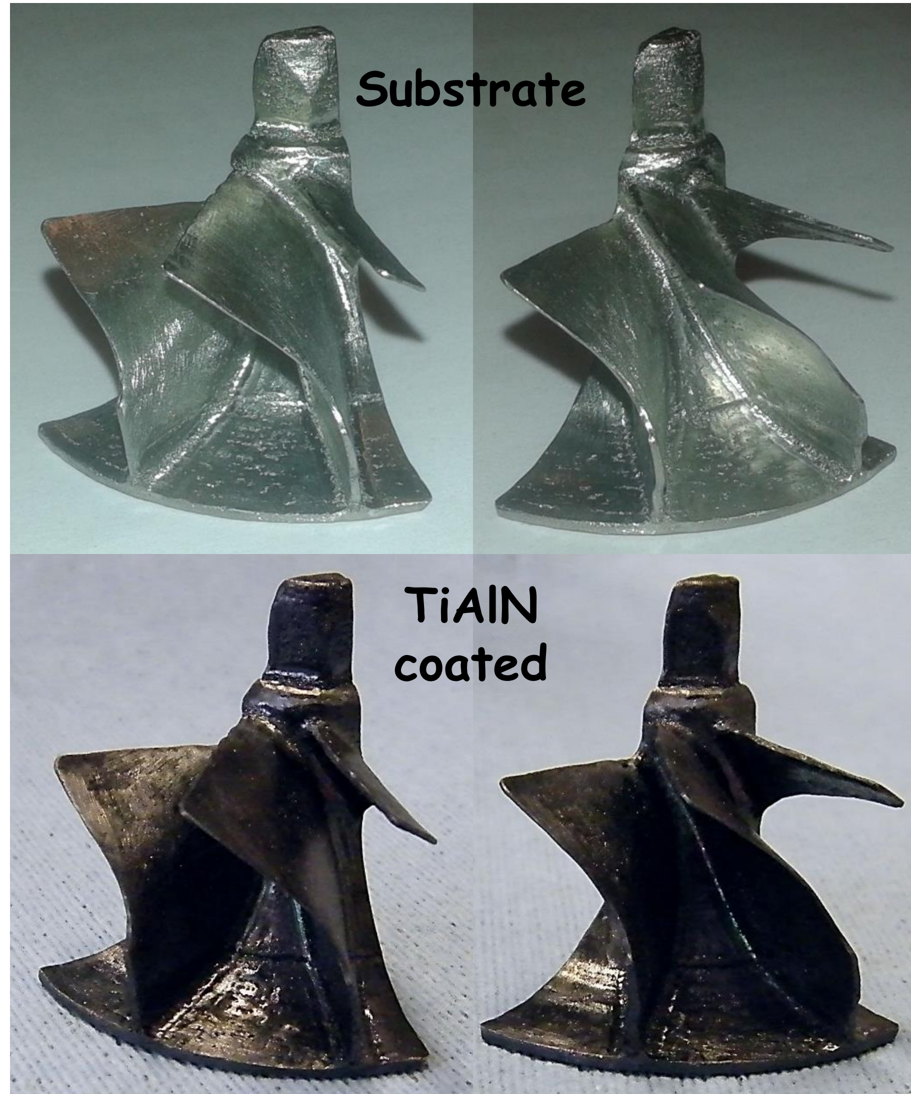
K. Bobzin, N. Bagcivan, P. Immich, S. Bolz, J. Alami, R. Cremer,
J. Mater. Process. Technol. 209 (2008) 165

Complex-shaped substrates

Turbocharger rotor

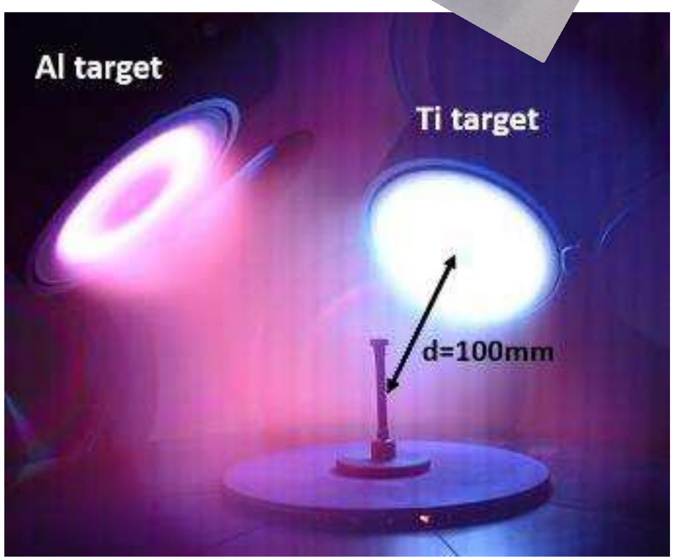


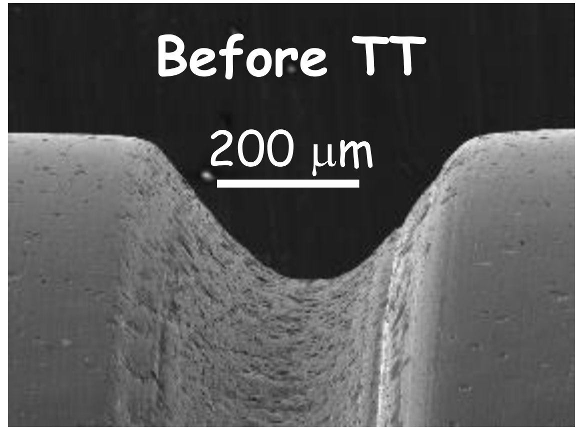


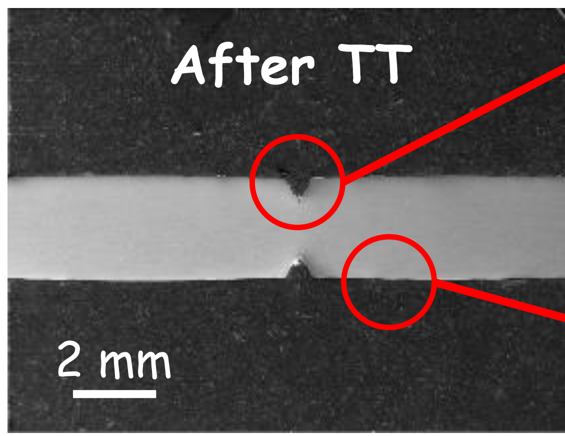


Complex-shaped substrates

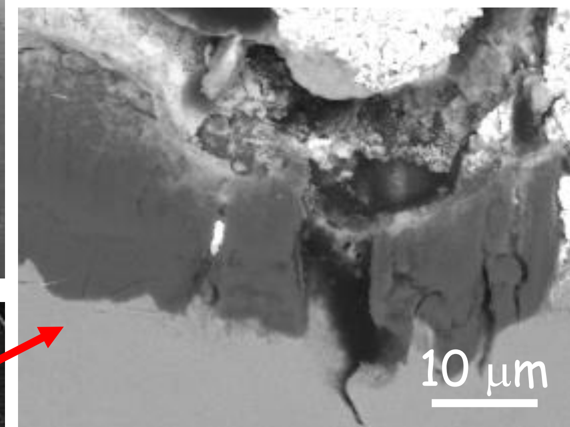
T91 Tensile specimens

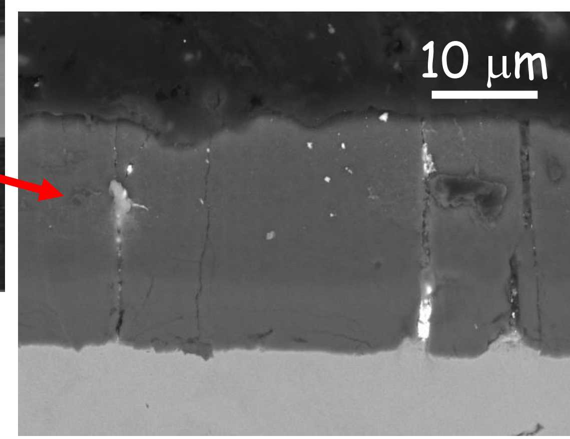






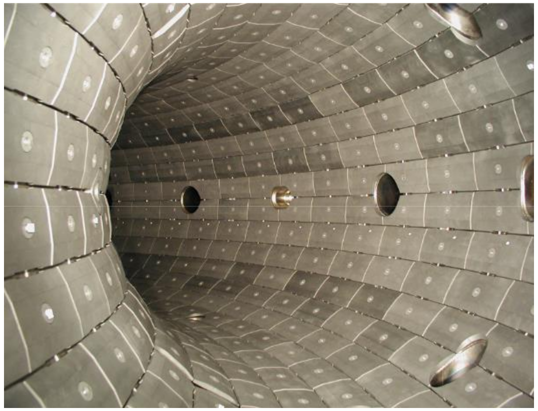
Tensile tests in PbBi, at 550°C (CALLISTO)





MatISSE project: This work was supported by the European Commission under the 7th Framework Programme through the Key Action: Support to the development of joint research actions between national programmes on advanced nuclear materials. **Grant agreement n°: 604862** (FP7 Fission 2013) and under the EERA Joint Programme Nuclear Materials (JPNM) activities

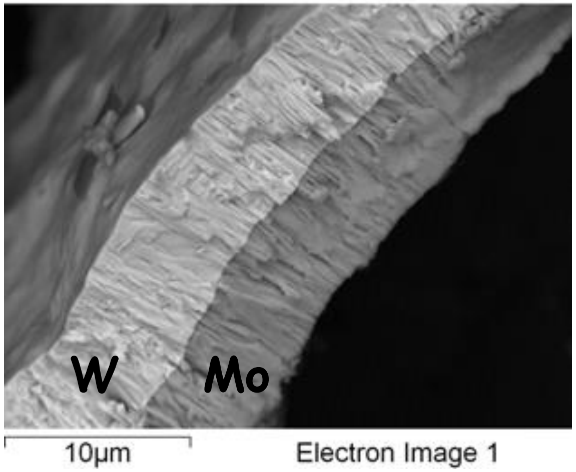
Phase composition tailoring

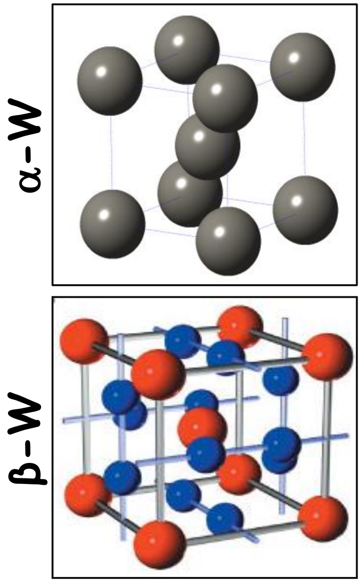


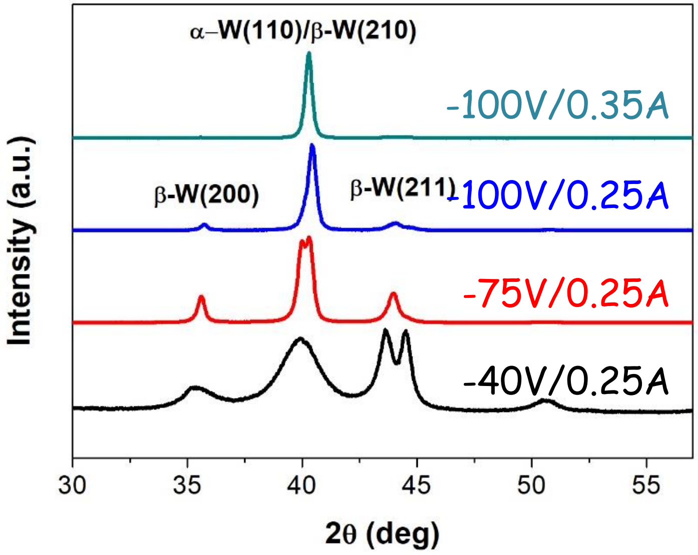
RFX-mod vessel

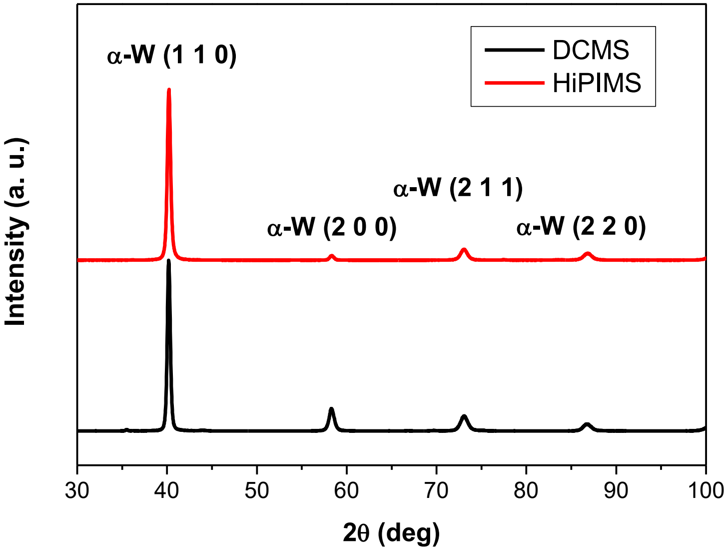
Uncoated

W/Mo coated

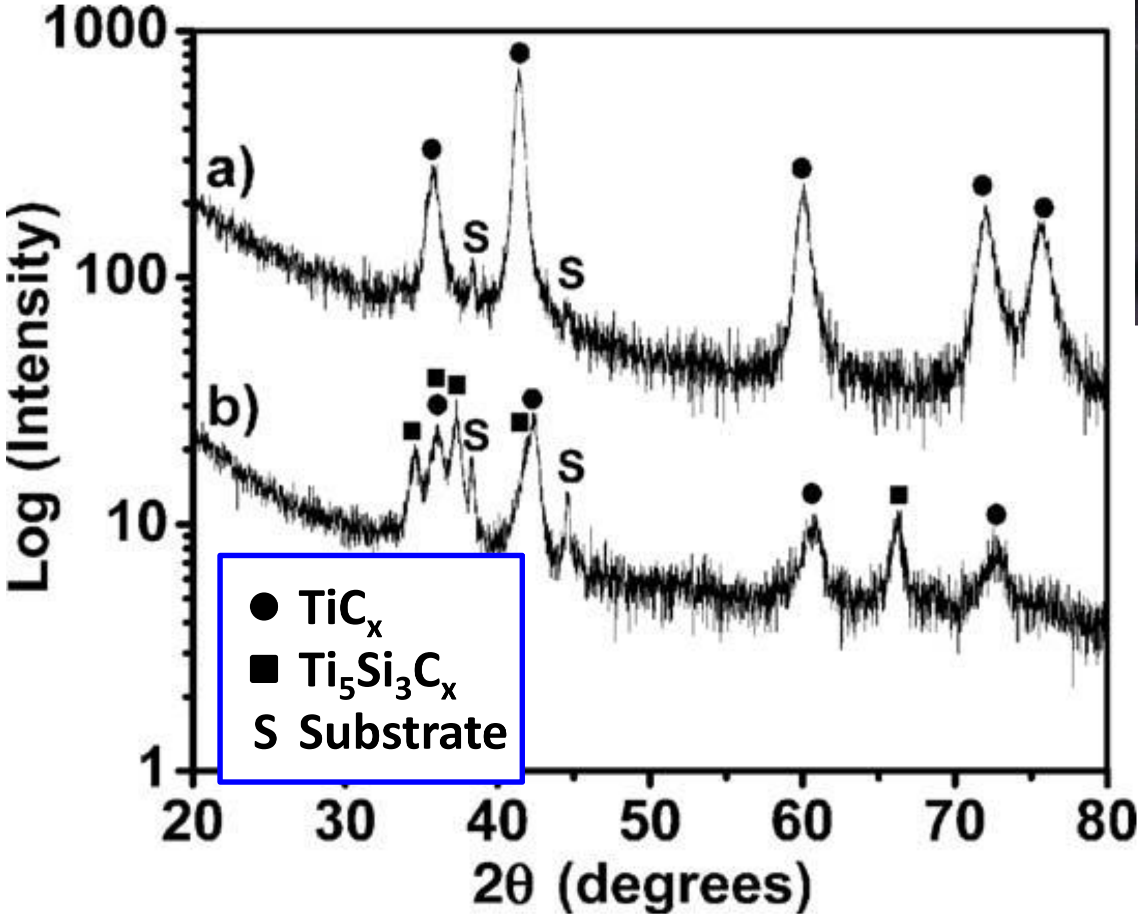


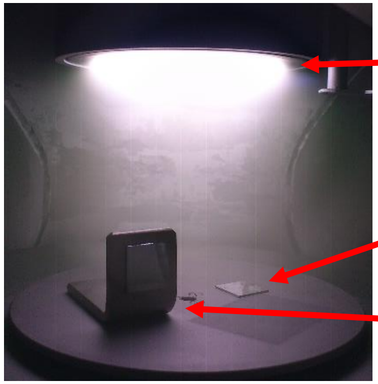






Phase composition tailoring





- Light elements like C are favored at the expense of heavier elements (Ti and Si) along the target normal!

- Substrates placed at an angle of 90° with respect to the target experience a < flux of C because of the < ionization degree of C compared to Ti and Si

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

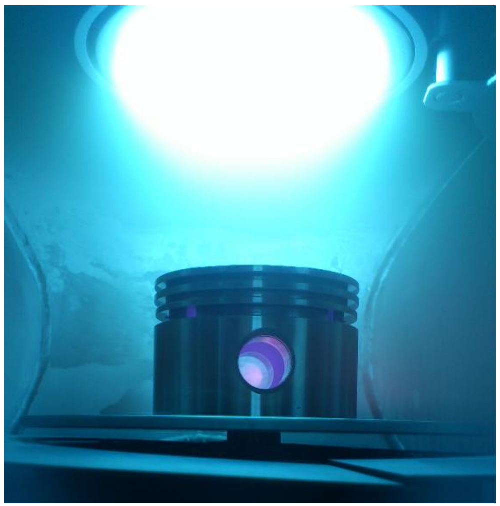
Phase composition tailoring

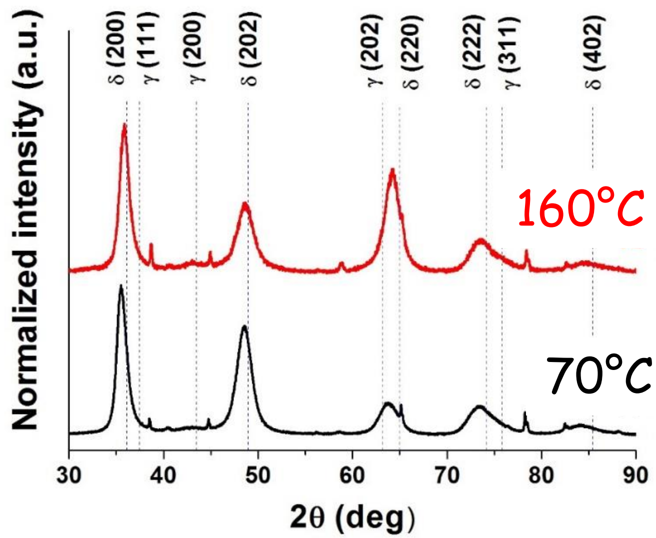
γ-Mo_2N → fcc phase (Fm3m)

δ-MoN → hexagonal phase ($P6_3mc$)

δ-MoN exhibits a low compressibility,

> H and E, < COF and > wear resistance.





At T<<300°C Mo-N with a high % of δ phase

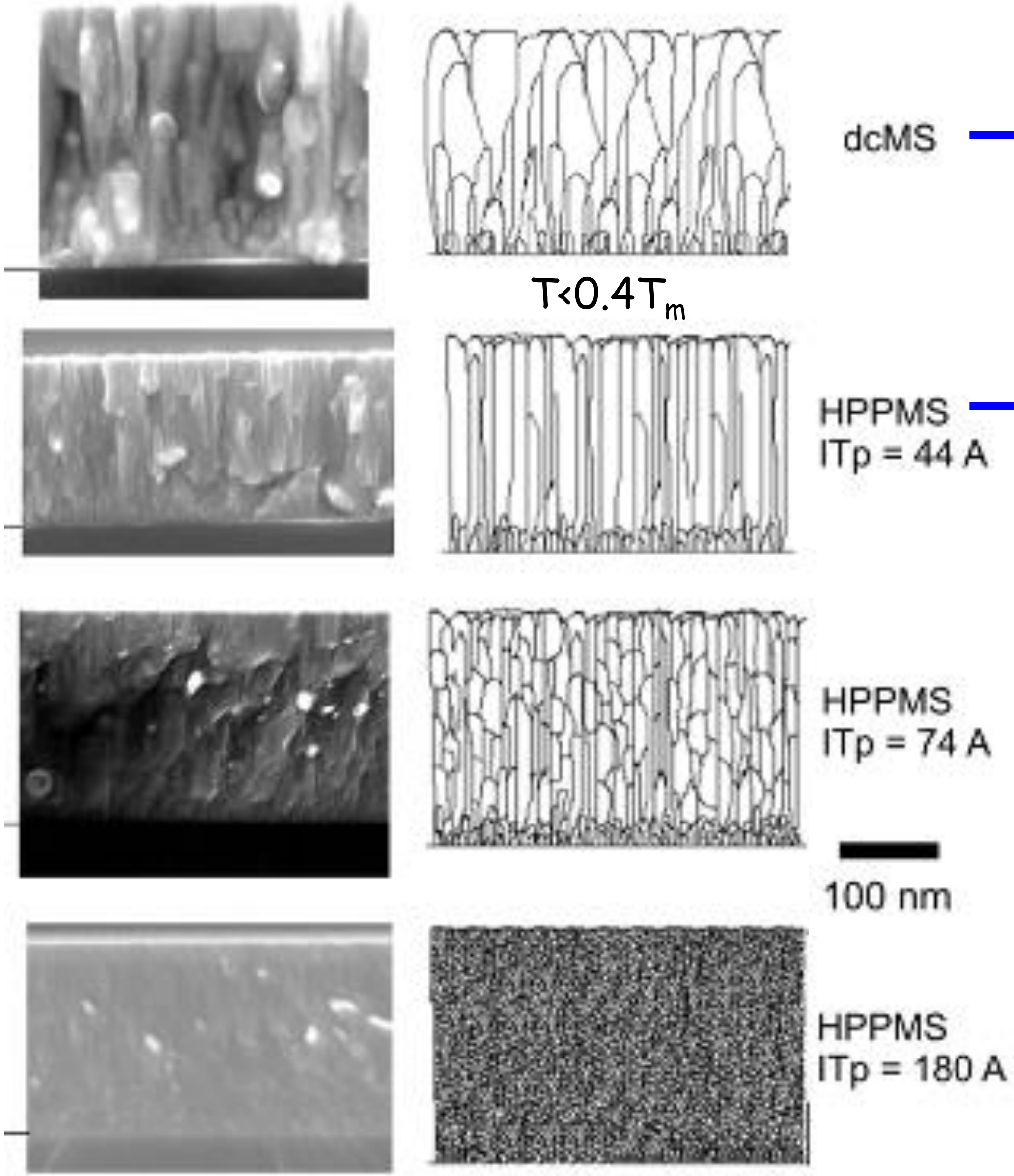
Sample	Phase	a (Å)	c (Å)	Concentration ($\%_{wt}$)	$(C_\gamma/C_\delta)_{\%wt}$
T1	γ-Mo_2N	4.2196	-	23.8	0.31
	δ-MoN	5.8372		76.2	
T2	γ-Mo_2N	4.1751	-	26.8	0.37
	δ-MoN	5.8103	5.621	73.2	
Reference Bulk	γ-Mo_2N	4.1616			
	δ-MoN	5.7395	5.6176		

Rietveld method:

- a, c → cell parameters;
- $(C_\gamma/C_\delta)_{\%wt}$ → wt. concentration ratio between γ and δ phases.

V. Zin, E. Miorin, F. Montagner, M. Fabrizio, S. M. Deambrosis, Tribology International 119 (2018) 372–380.

Control of film microstructure



Columnar microstructure and intercolumnar porosity.

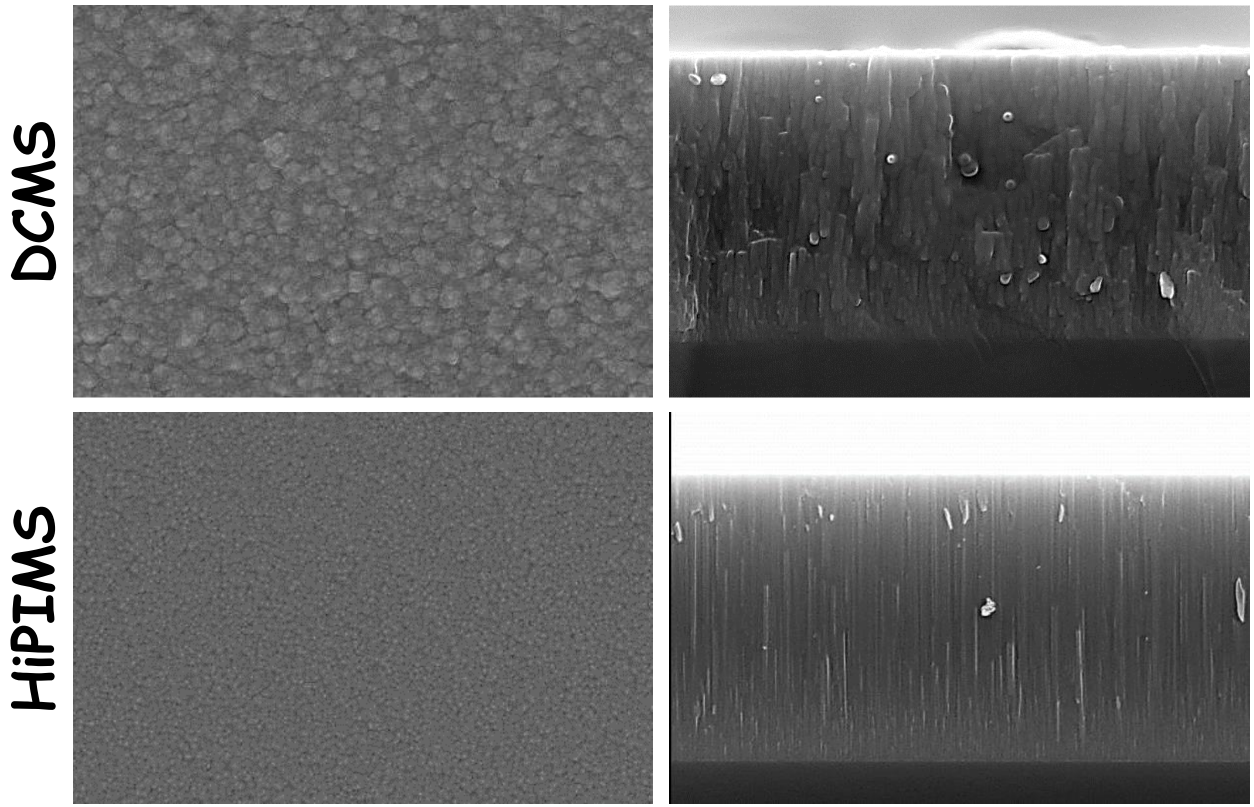
Unique morphologies!

Higher H, lower COF and improved wear and oxidation/corrosion resistance!!!

Cross-sectional SEM images of CrN/Si → > peak target current = from dense polycrystalline to a nanocrystalline featureless.

Control of film microstructure

TiB_2 SEM Analysis: morphology and microstrucure

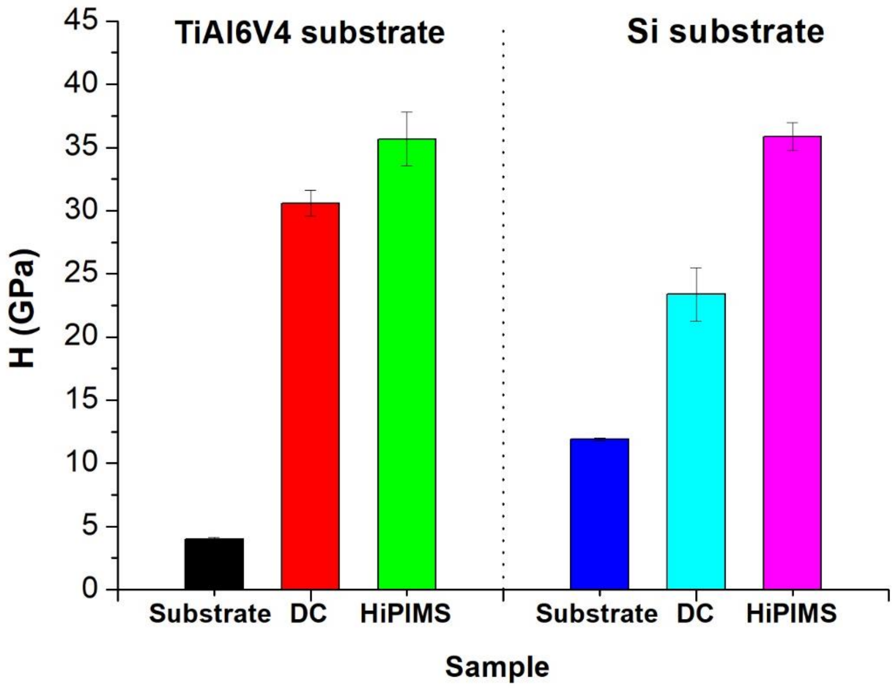


Substrate = Si
Ar p = $5x10^{-3}$ mbar
P = 600 W
Sub. bias = -50 V
T = 300 °C

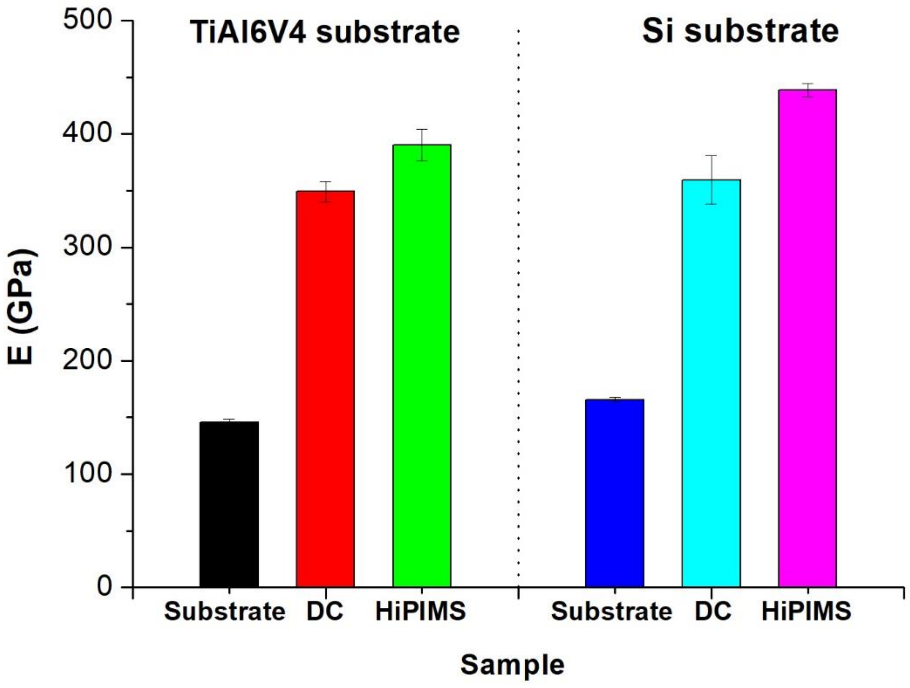
Control of film microstructure

TiB_2 Mechanical Properties: H and E

Hardness

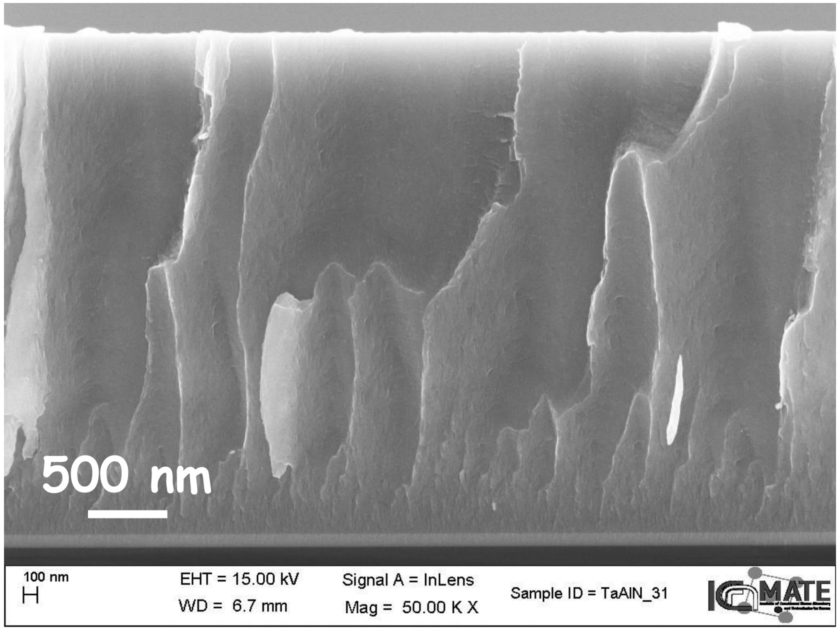


Elastic Modulus

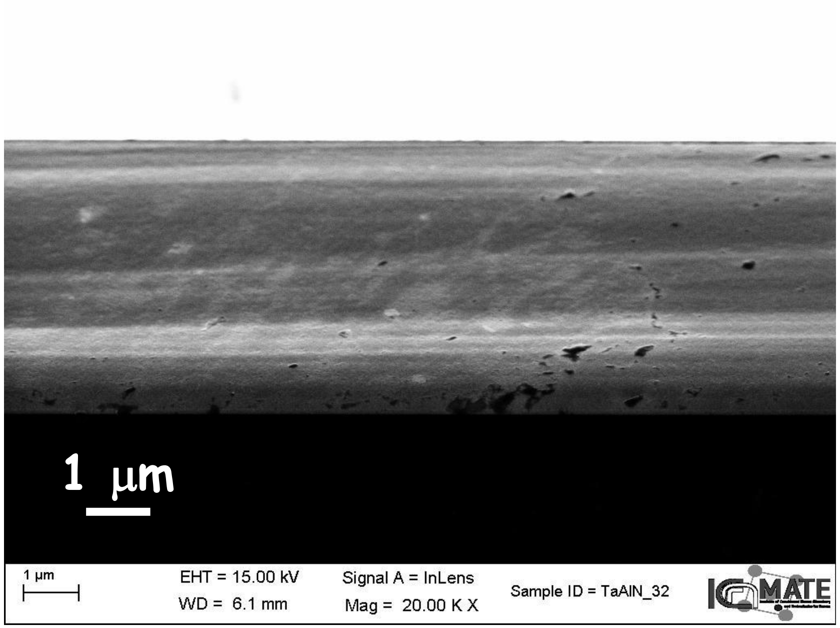


Control of film microstructure

TaAlN 50%



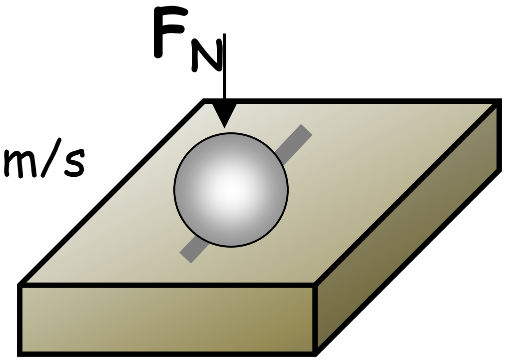
TaAlN 5%



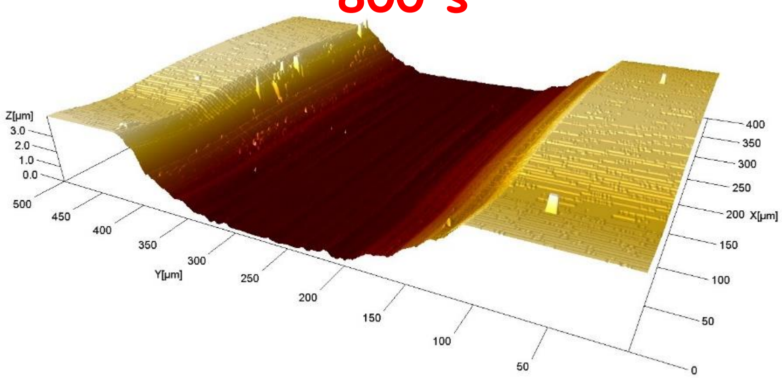
Control of film microstructure

Ball-on-flat wear test

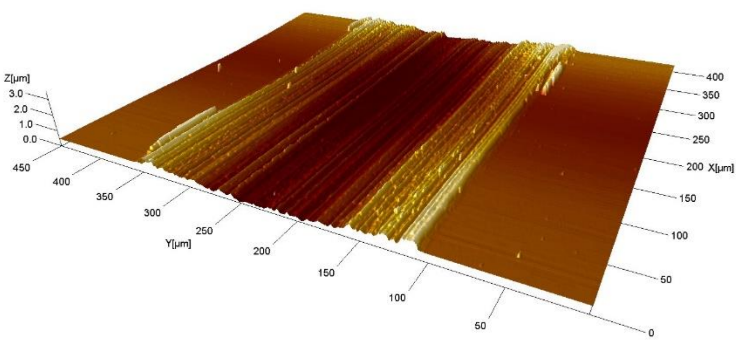
- 5 mm Al_2O_3 ball (H=16.7, E=365 GPa)
- Sliding speed: 10 mm/s
- Normal load: 3 N
- Track l: 3mm



TaAlN 50%
800 s



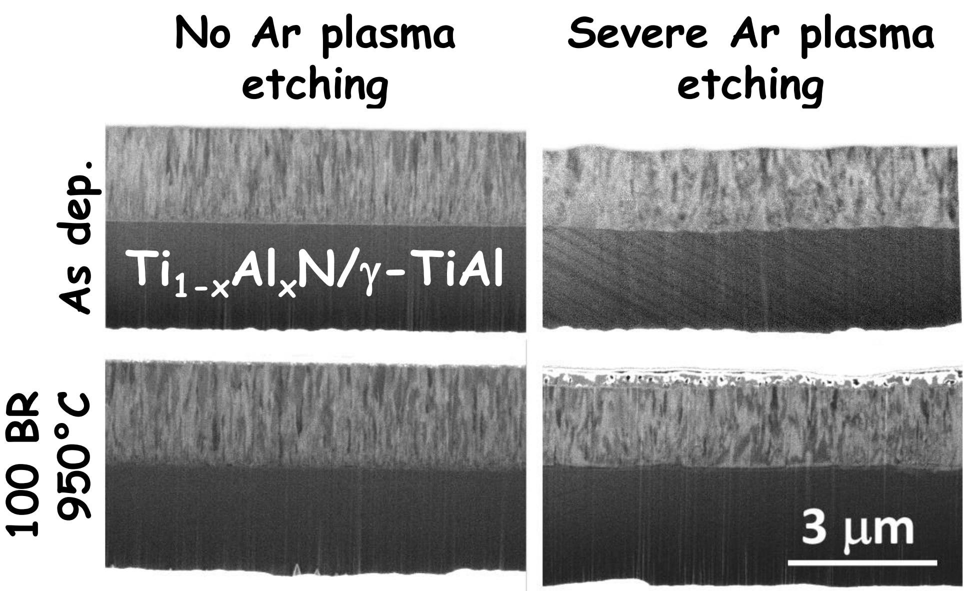
TaAlN 5%
3600 s



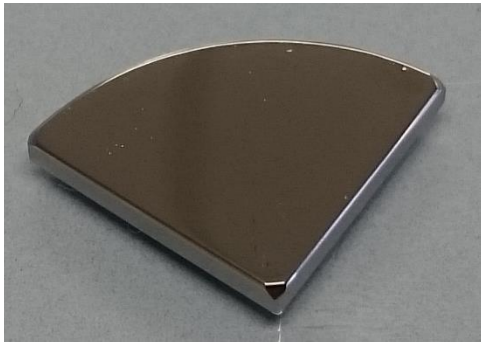
Interface engineering

Highly ionized fluxes + substrate bias =
ion energies 100s ÷ 1000s eV

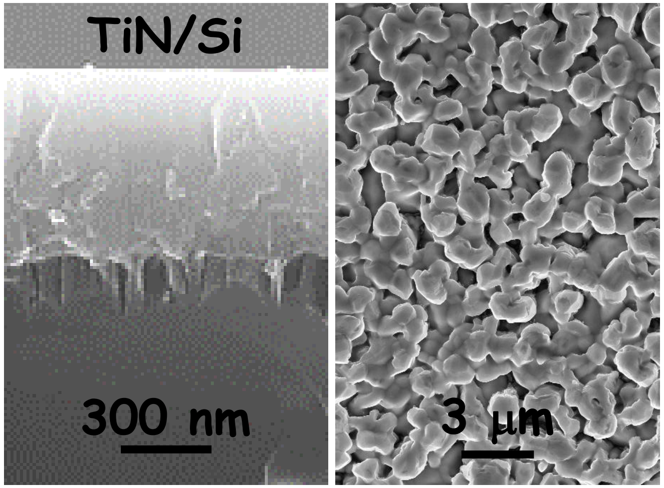
Film-substrate interface engineering to
- ✓ affect the growing mode
- ✓ enhance adhesion



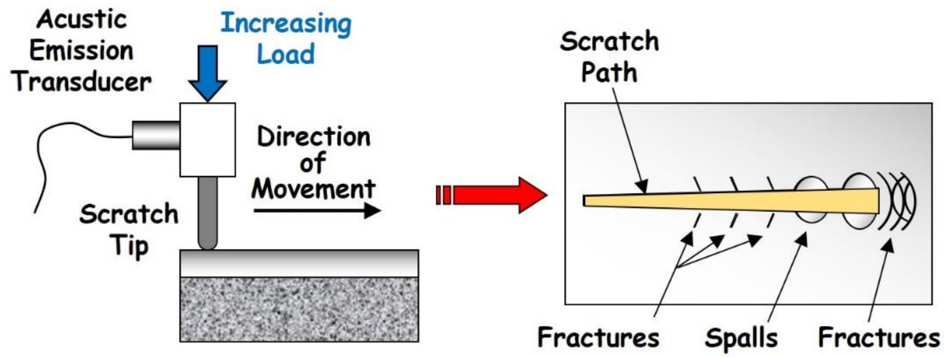
S.M. Deambrosis, et al. Surface and Coatings Technology, 354 (2018) 56-65.



Power (W)	500
Voltage (V)	900
Frequency (Hz)	500
Pulse t (µsec)	25
Bias V (V)	1000
Initial T (°C)	RT
Final T (°C)	200

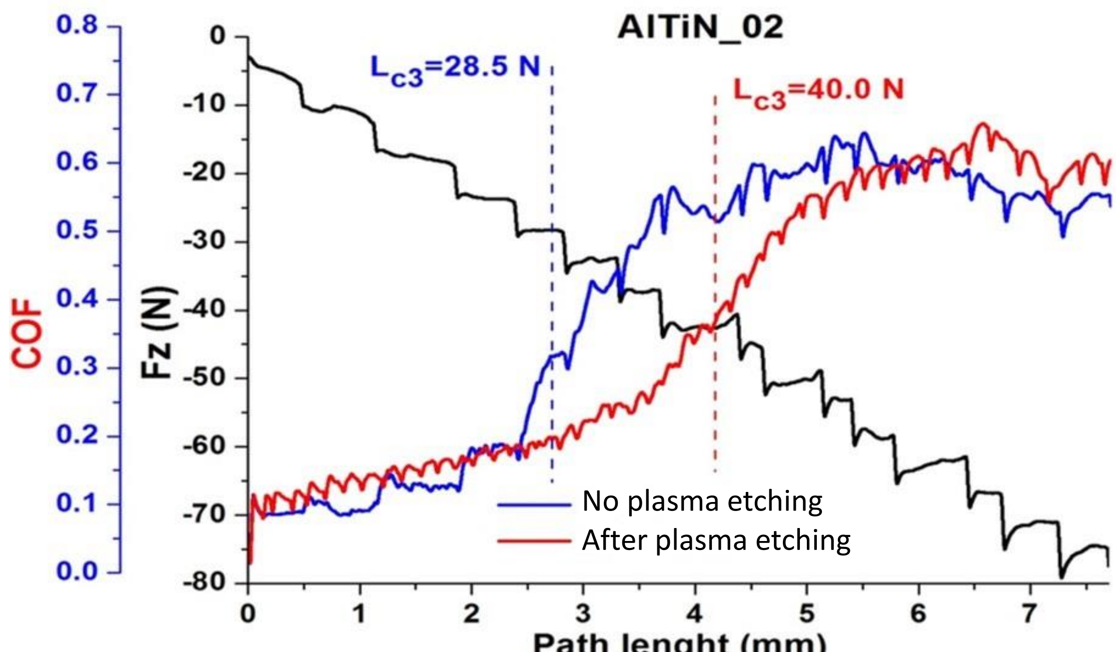


Interface engineering



ISO 1071-3:2005 European standard

100 N/min 10 mm/min
10 N/min 10 mm/min

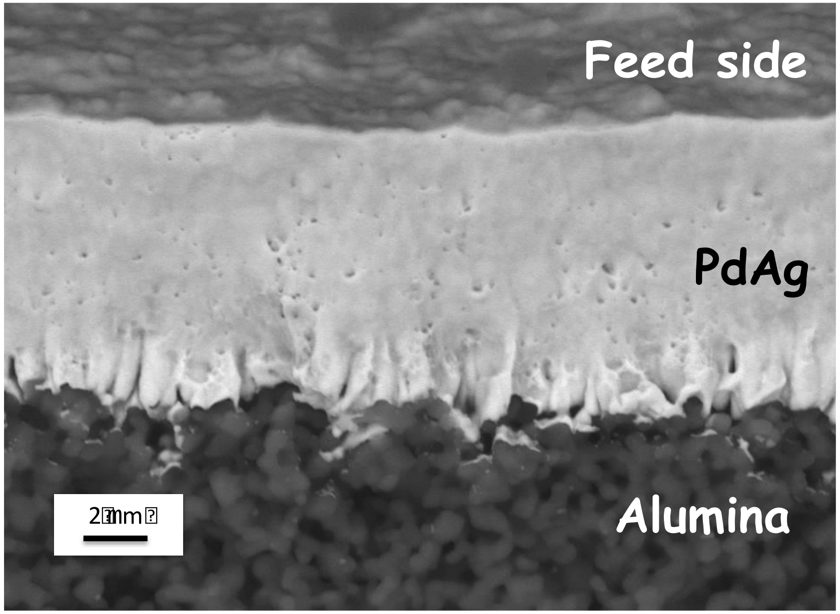


No plasma etching

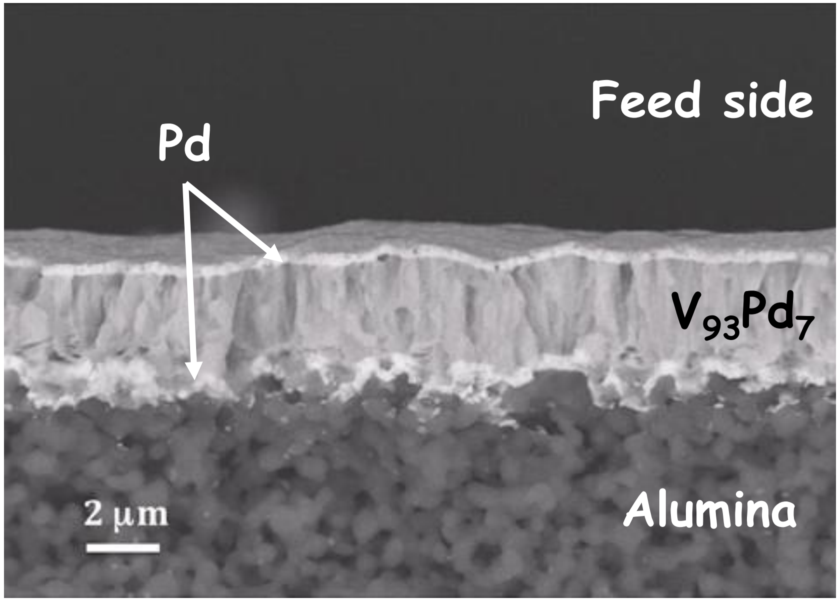
After plasma etching

Insulating substrates

Metallic membranes for hydrogen separation



SEM BS electron image of **$PdAg/Al_2O_3$** membrane (8.7 μm).

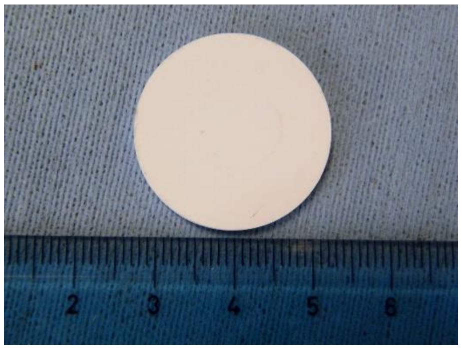


SEM BS electron image of a **$Pd/V_{93}Pd_7/Pd/Al_2O_3$** membrane (4.2 μm).

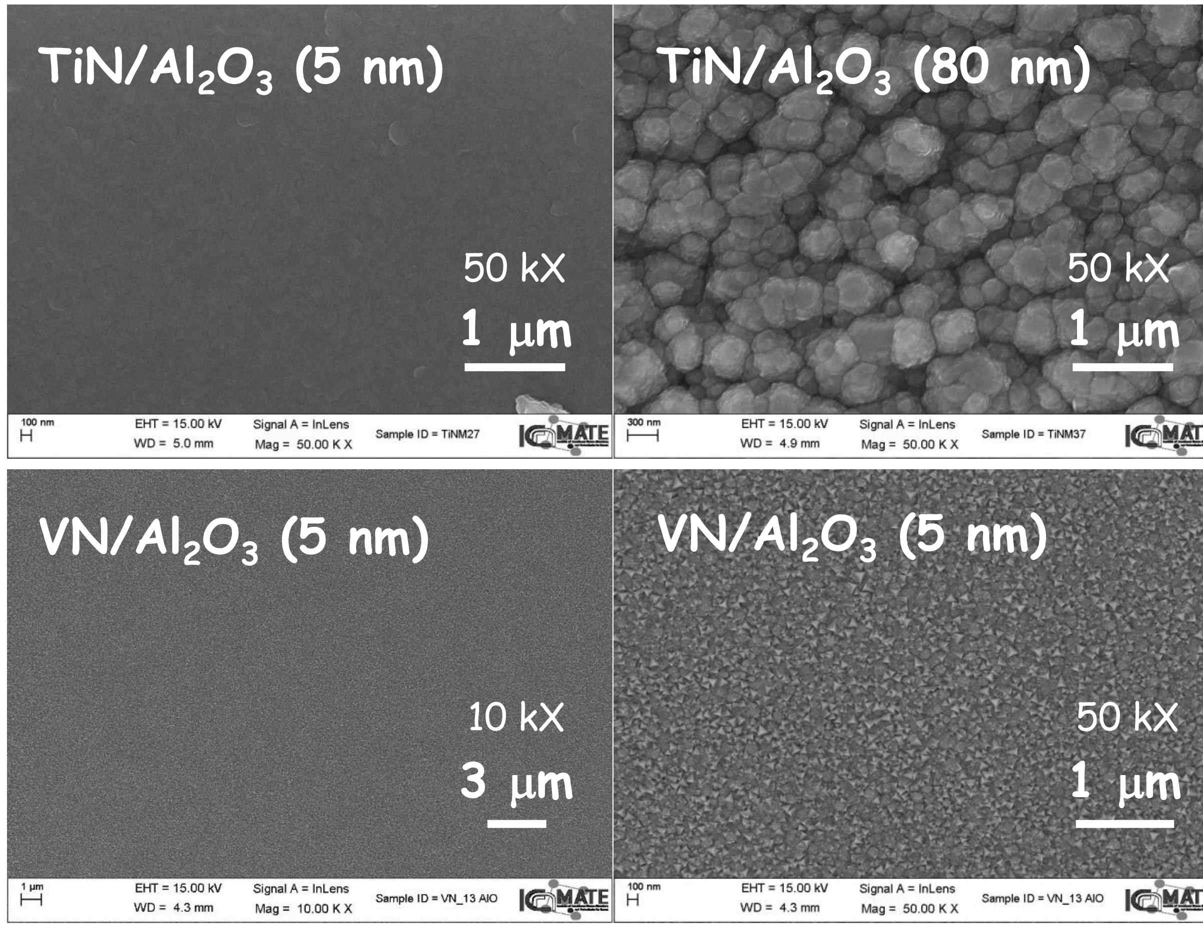
- S. Fasolin, S. Barison, S. Boldrini, A. Ferrario, M. Romano, F. Montagner, E. Miorin, M. Fabrizio, L. Armelao, International Journal of Hydrogen Energy 43 (2018) 3235 – 3243; doi.org/10.1016/j.ijhydene.2017.12.148.
- S. Barison, S. Fasolin, S. Boldrini, A. Ferrario, M. Romano, F. Montagner, S.M. Deambrosis, M. Fabrizio, L. Armelao, International Journal of Hydrogen Energy 43 (2018) 7982 – 7989; doi.org/10.1016/j.ijhydene.2018.03.065.

Insulating substrates

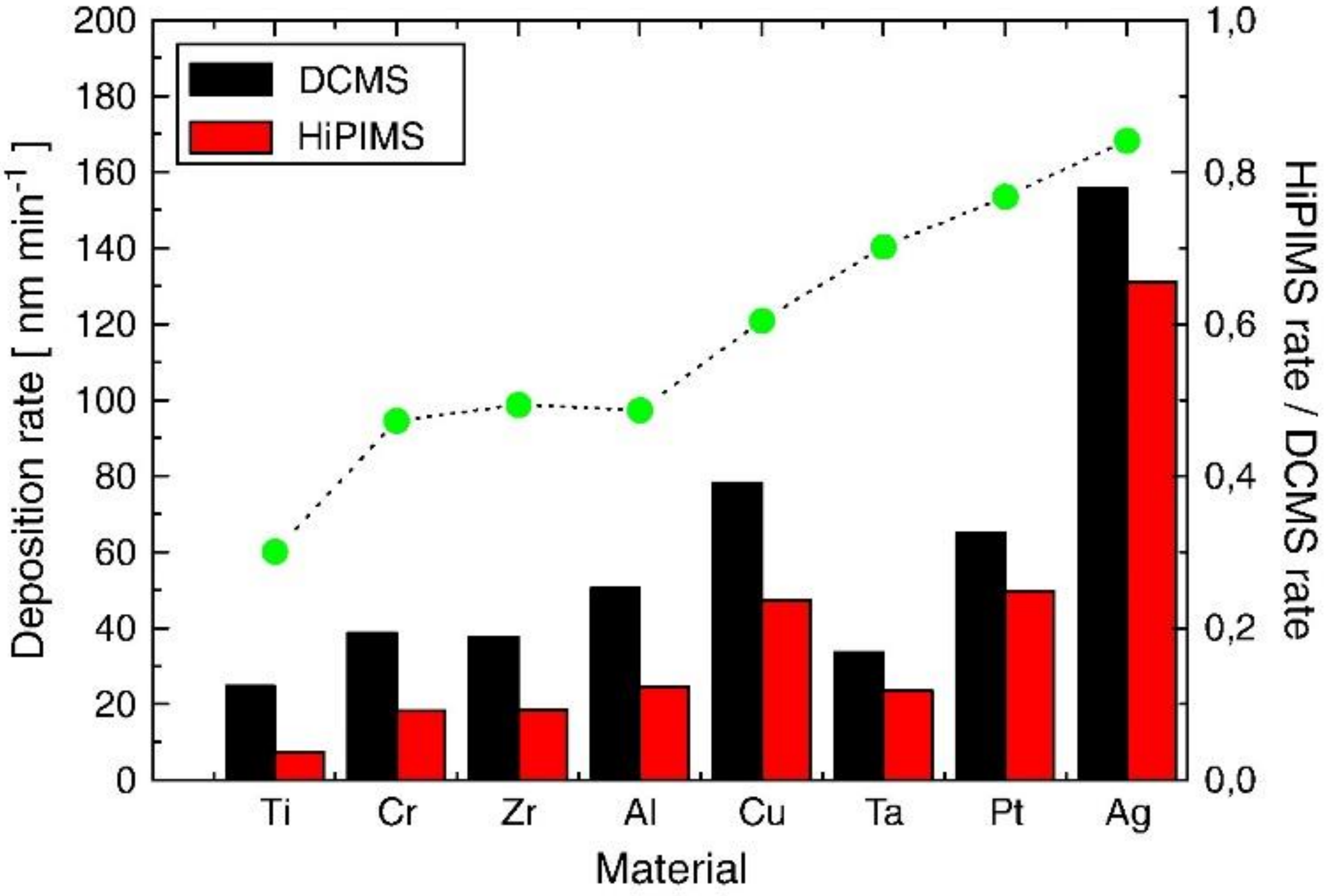
Nitride membranes for hydrogen separation



α-Al_2O_3 discs
Φ = 15mm, 25mm
Thickness = 2mm
Porosity1 = 80nm
Porosity2 = 3-5nm
(lapped on one side + γ-Al_2O_3 film).



HiPIMS deposition rate

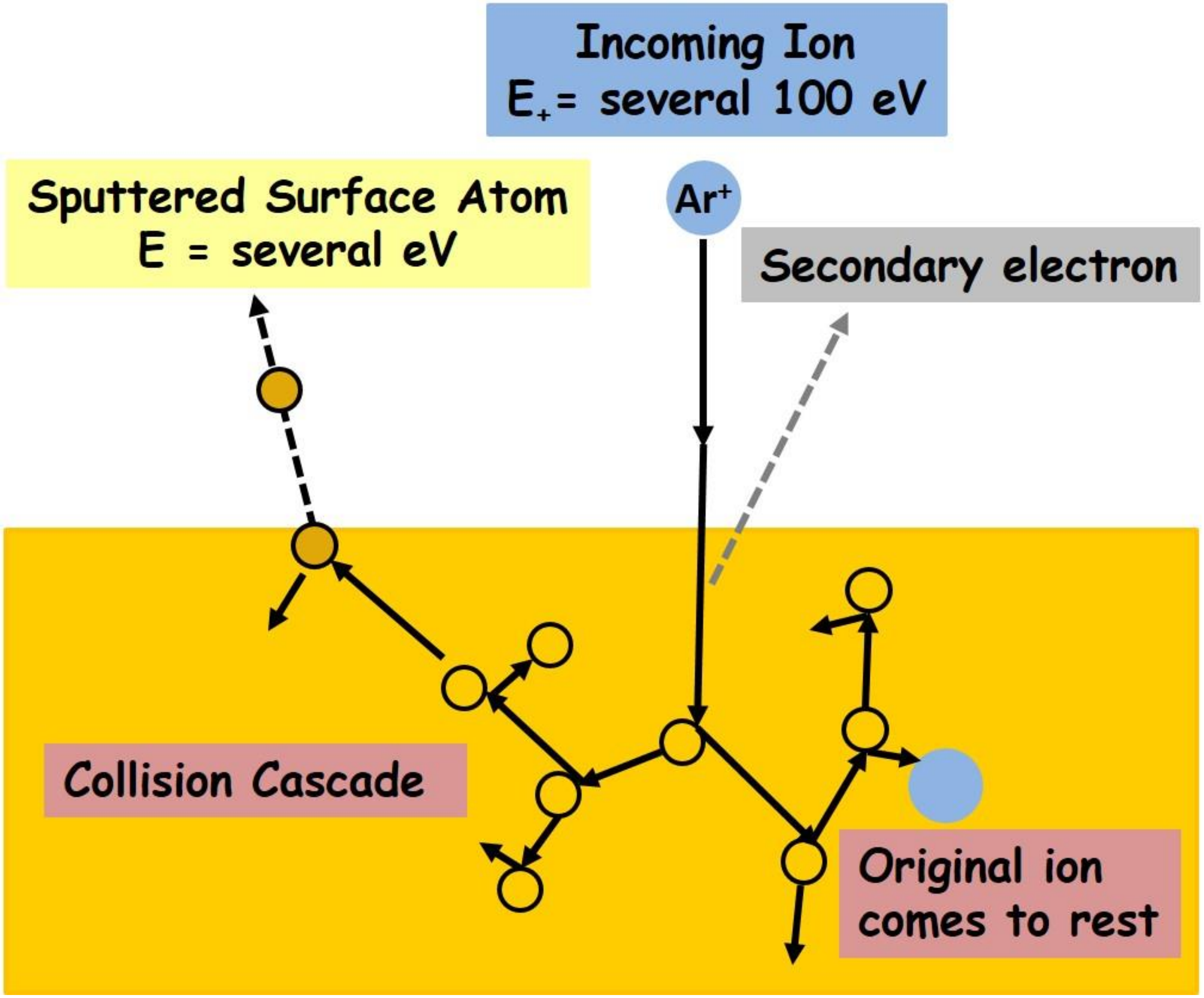


M. Samuelsson, D. Lundin, J. Jensen, M. A. Raadu, J. T. Gudmundsson, and U. Helmersson, Surface and Coatings Technology, 202 (2010) 591.

https://hipims.cemecon.de/en/

Grazie per l'attenzione!

Schematic of the Sputtering process



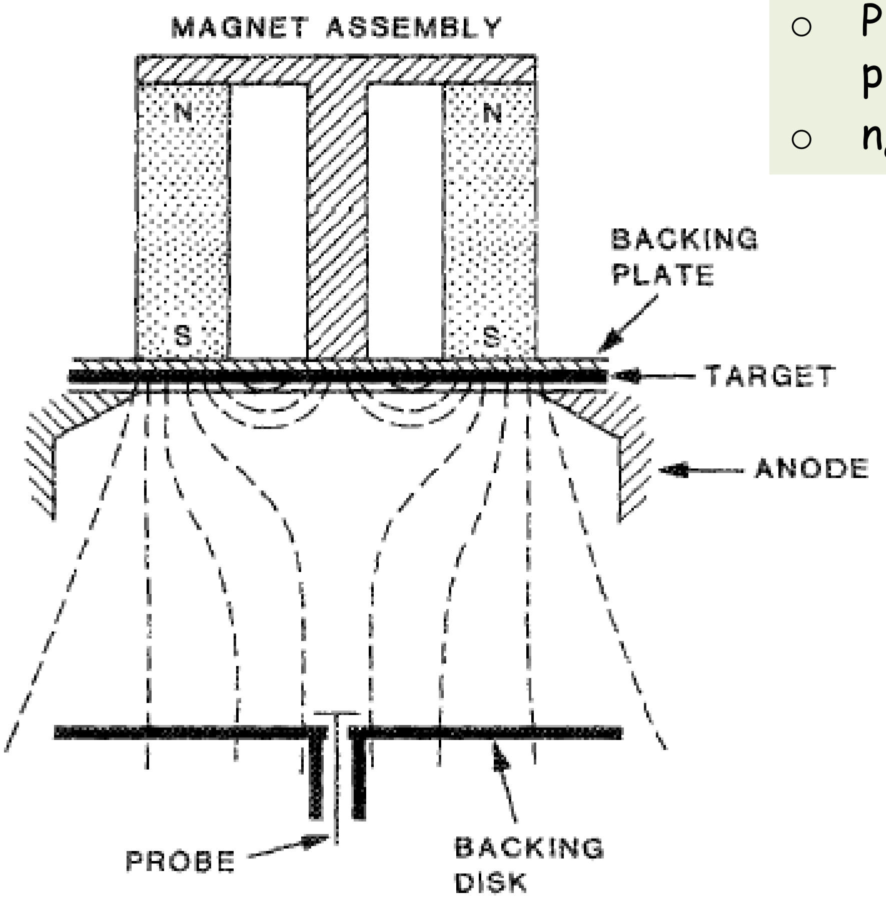
- ✓ Sputtering is the ejection of atoms due to bombardment of a solid surface (the target) by energetic particles (often ions).
- ✓ The source of ions for the sputtering process is achieved by a plasma discharge.
- ✓ Secondary electrons are also emitted from the target surface as a result of the ion bombardment.

✓ A. Anders, Journal of Applied Physics 121 (2017) 171101.
✓ J. F. Ziegler, J. P. Biersack, and U. Littmark, The Stopping and Range of Ions in Solids (Pergamon Press, New York, 1985).
✓ J. F. Ziegler and J. Biersack, see http://srim.org/ see "Monte Carlo code SRIM2013, 2013.

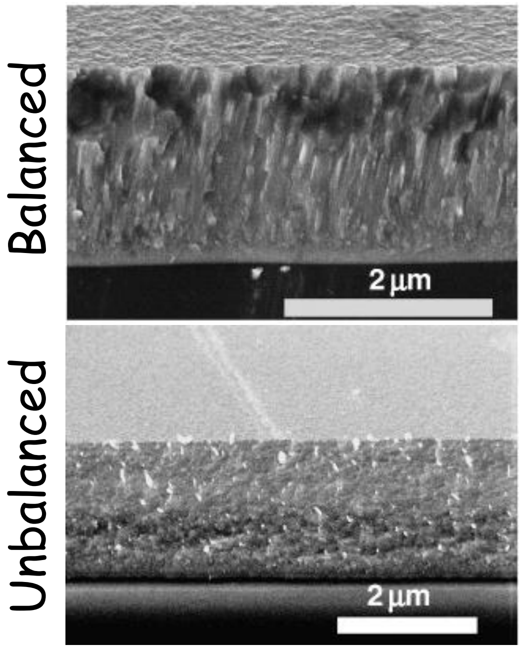
Unbalanced magnetrons

A first step to using the plasma of the magnetron to assist film growth

- Plasma escapes from target region, providing assistance to film growth.
- $n_e \sim 10^{12}$ cm^{-3}, up to a distance of 10 cm.



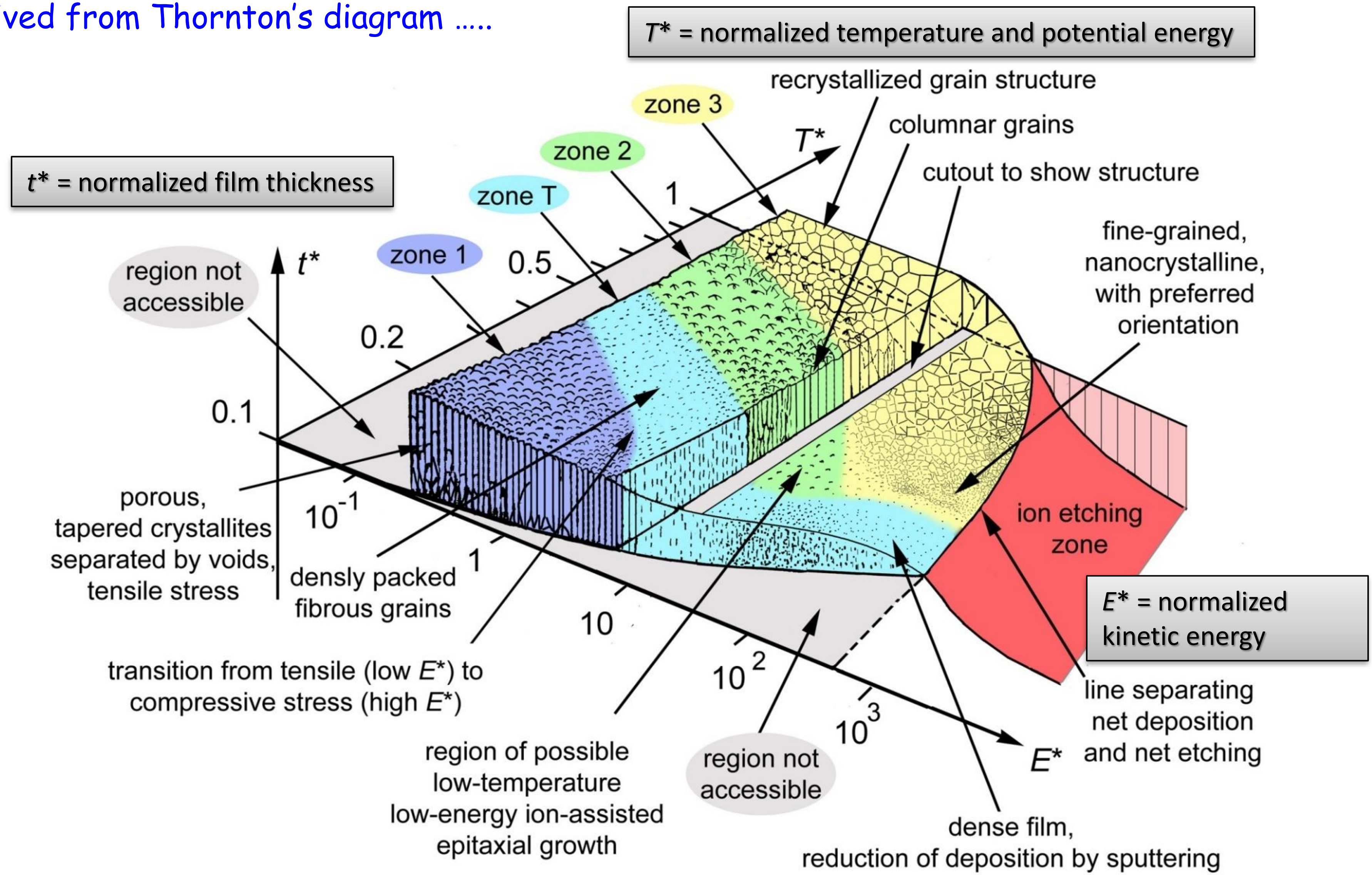
NbN



B. Window and N. Savvides, J. Vac. Sci. Technol. A 4, 196 (1986).
J.J. Olaya, et al.,Thin Solid Films 516, Issue 23 (2008) 8319-8326.

A Generalized Structure Zone Diagram including the Effects of Plasma Assistance to Film Growth

derived from Thornton's diagram …..

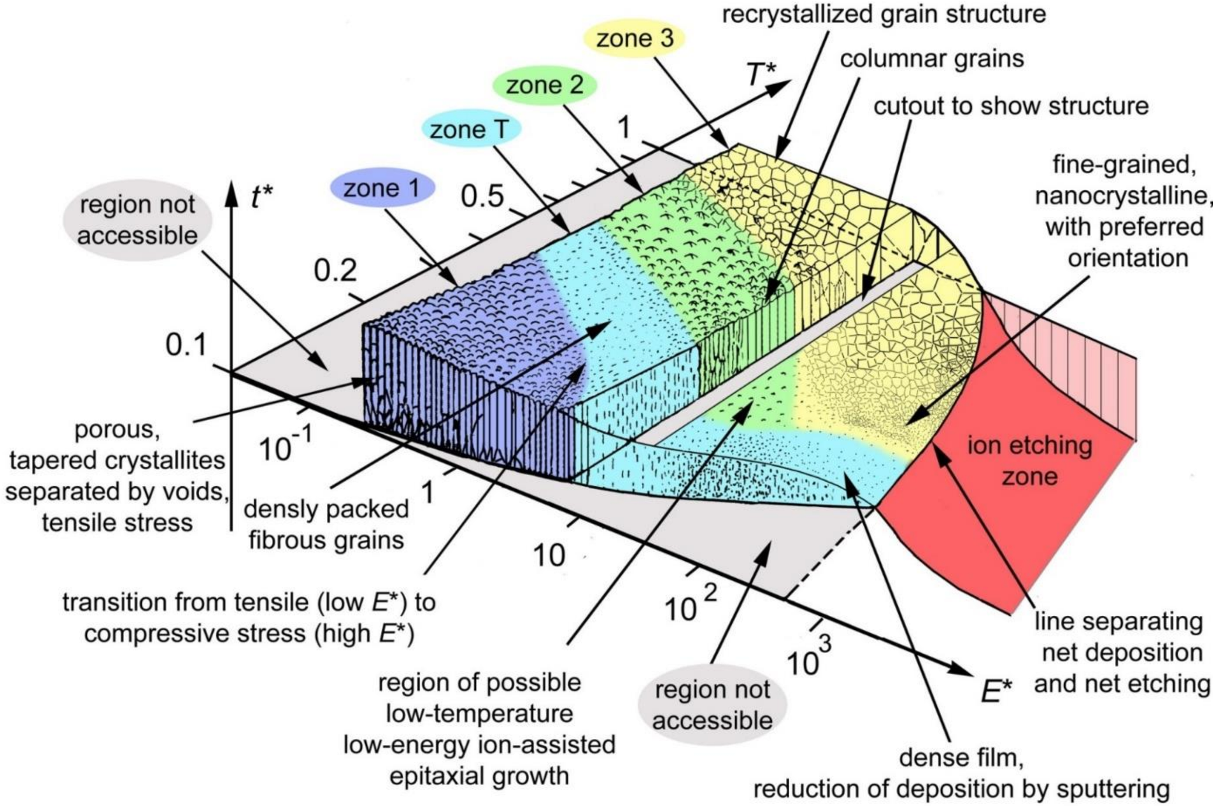


A. Anders, Thin Solid Films **518** (2010) 4087

HiPIMS Advantages

High pulsed ion fluxes are available at the substrate and affect the film growing and properties.

derived from Thornton's diagram …..



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

- **Deposition on Complex-Shaped substrates**
- **Phase composition tailoring by HiPIMS**
- **Control of film microstructure**
- **Interface engineering**

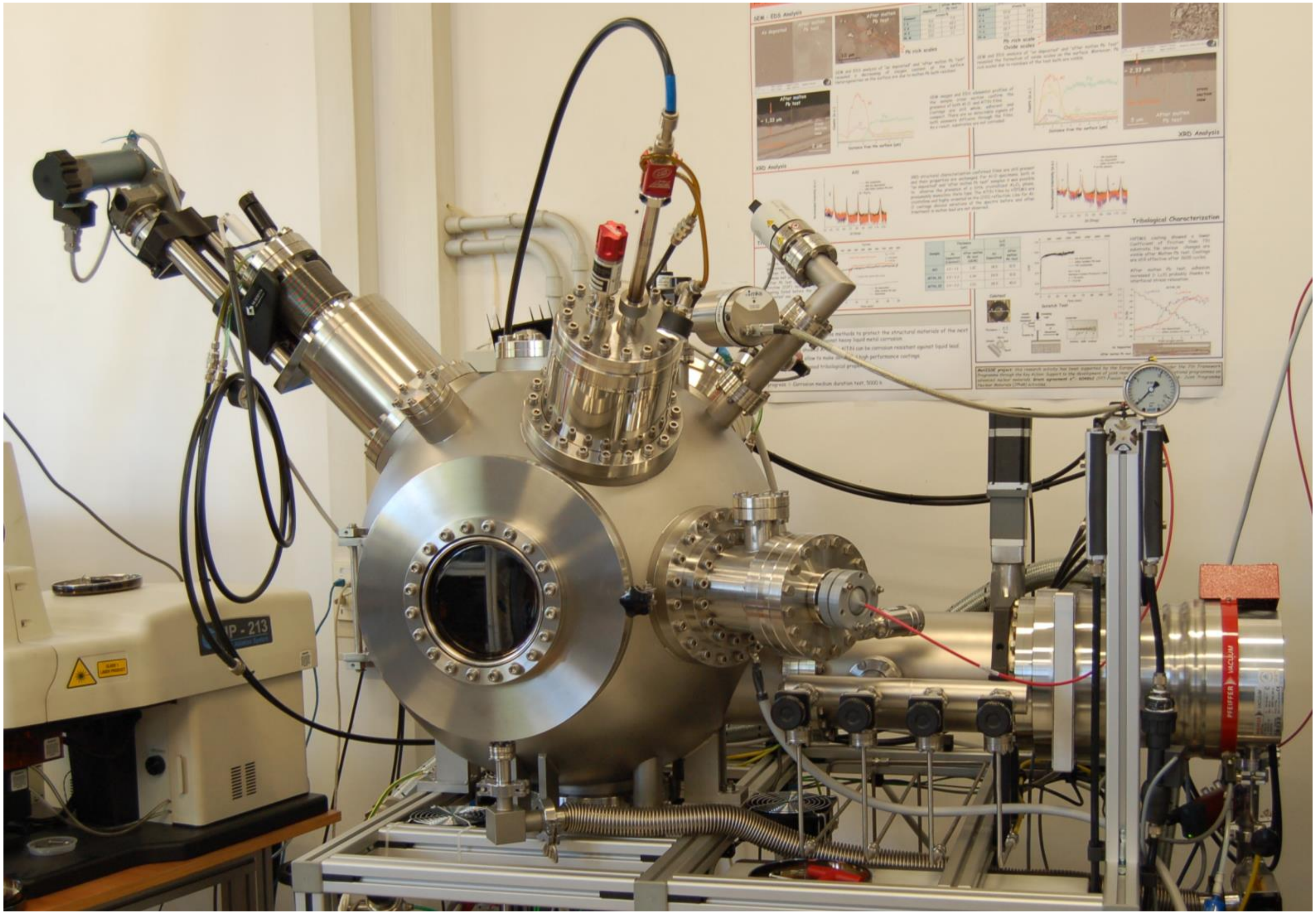
CNR-ICMATE PVD lab

Coating Deposition Lab.

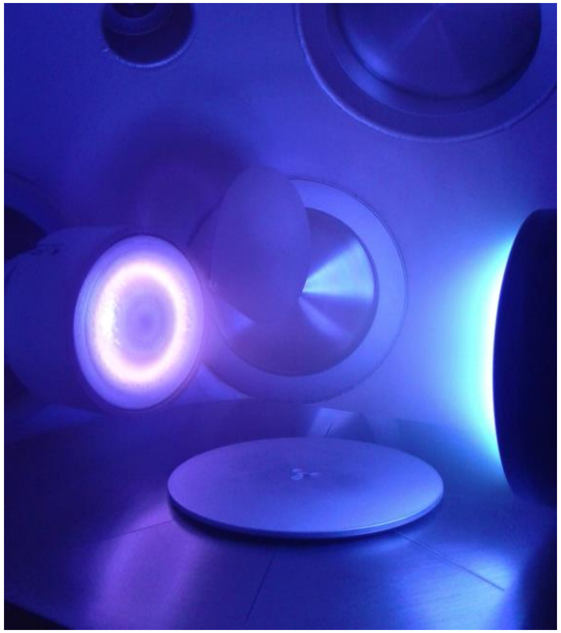
In our laboratories the equipments for the PVD deposition (Physical Vapor Deposition) by Magnetron Sputtering of thin films consists of three completely independent systems:

1. **Confocal chamber**, for the deposition of multi-component films via co-sputtering.
2. **Multi-layer chamber**, for the deposition of multilayer films.
3. **HiPIMS** (High Impulse Magnetron Sputtering) chamber.

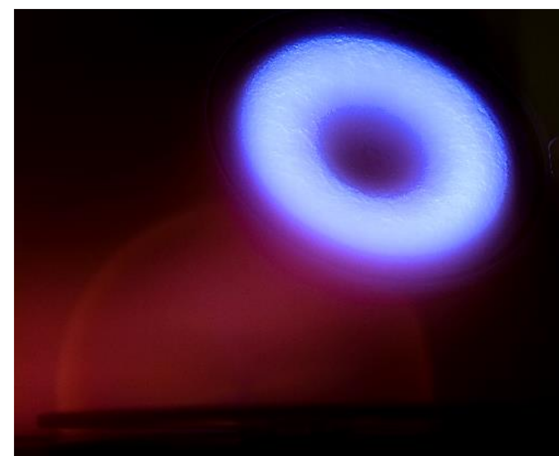
HiPIMS Chamber



HiPIMS Chamber



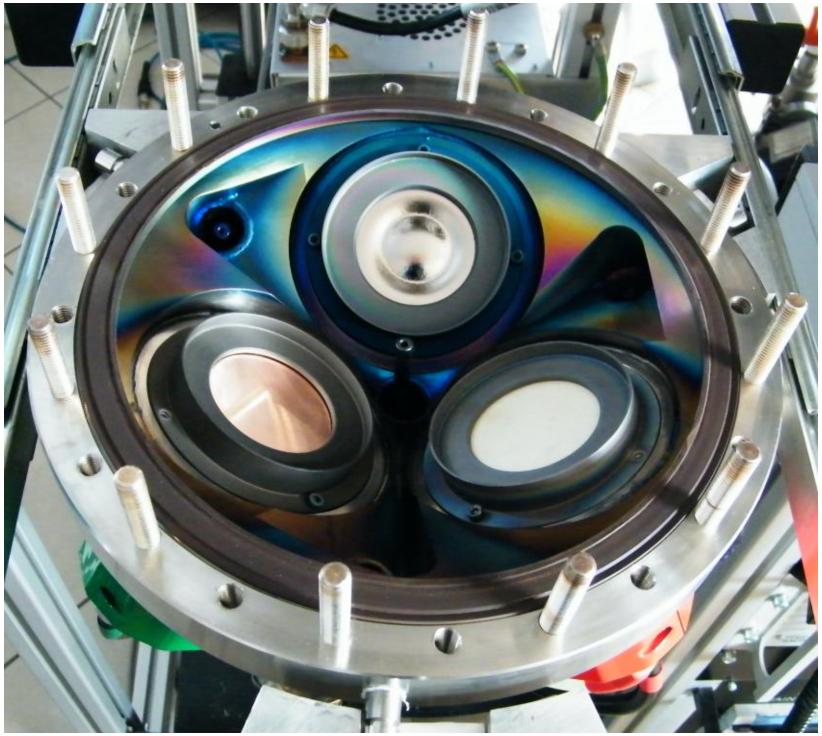
- Multi-magnetron equipment
- Substrate rotation and vertical positioning
- Working up to 500°C,
- Bias voltage up to 1.2 kV for substrate etching
- I-V Probes
- Optical Spectroscopy
- Microbalance with quartz crystals
- Process control interface



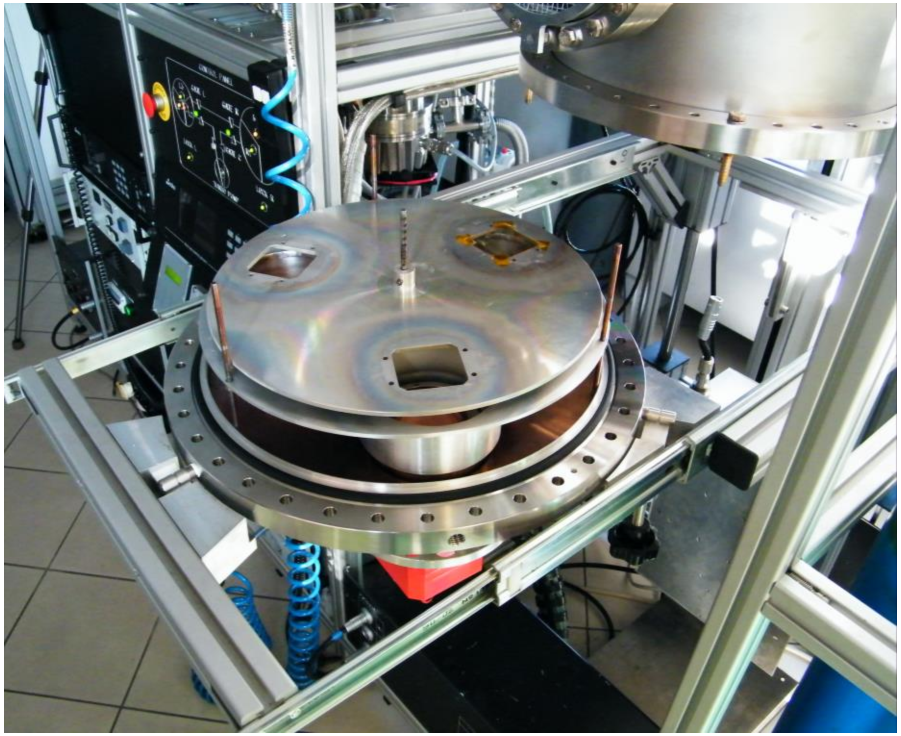
Confocal and Multilayer Chambers

Confocal and Multilayer Chambers: Cathode layout

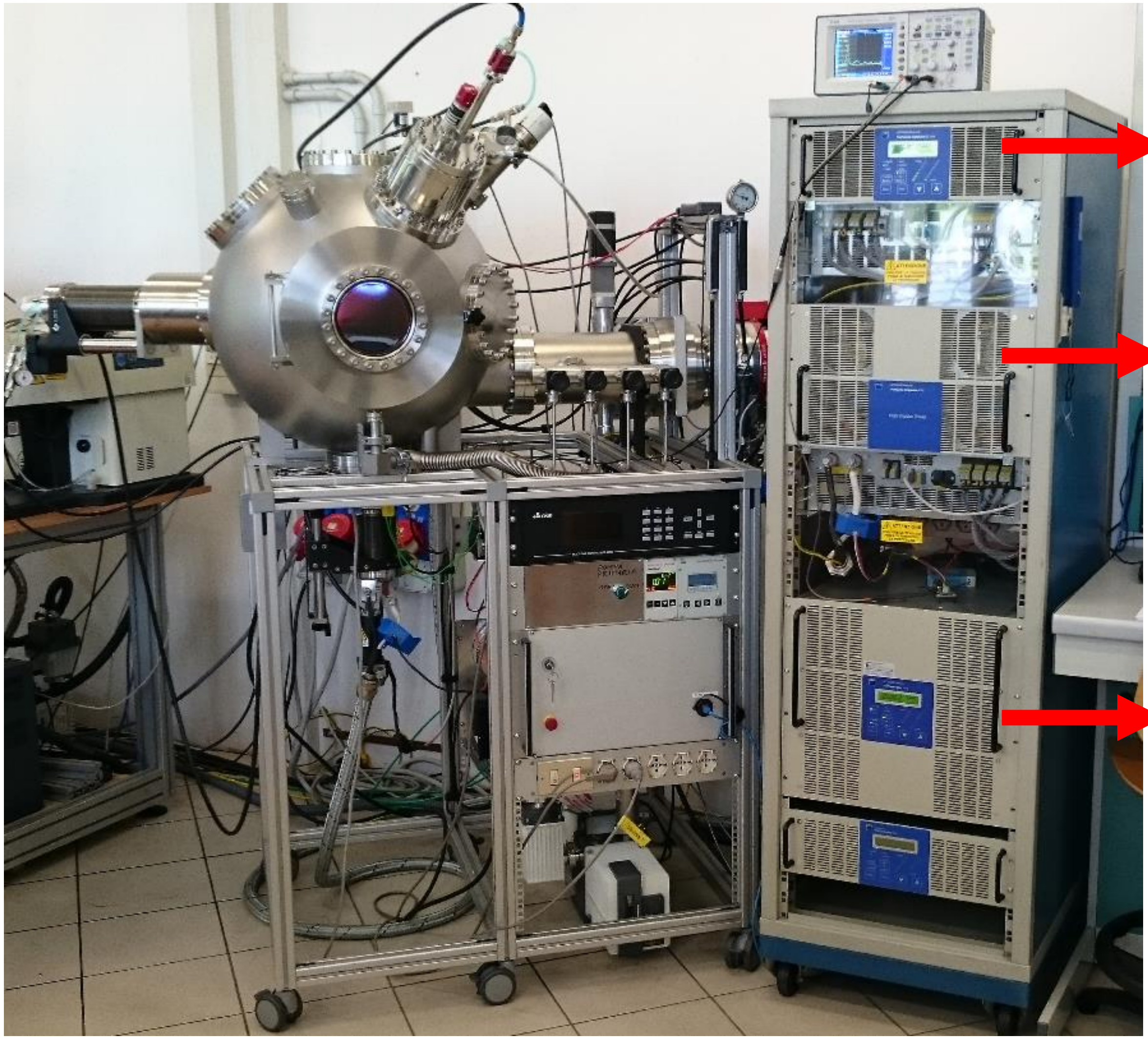
Confocal Chamber



Multilayer Chamber



HiPIMS Chamber Power Supply



DC unit

HiPIMS Pulse unit

Features

i. Active arc suppression
ii. Adjustable pulse duration and frequency
iii. Real-time monitoring and control

Bias unit

Features

i. Two operation modes: a high V mode for substrate etching and a low V mode for biased film depositions
ii. Fast arc management

2nd HiPIMS Power Supply

1 kW HiPIMS Unit

DC driving unit

6 kW HiPIMS Unit

DC driving unit

Features

i. Controlled in master-slave configuration
→ they can be synchronized

ii. Stable operation in the transition mode

iii. Wide process window of reactive gas flow with maintained stoichiometric composition

iv. Active arc suppression: reaction time < 2 μs

v. Pulse frequency: 1 - 10000 Hz

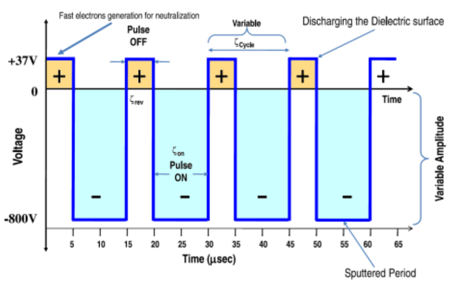
vi. Pulse Duration: 2.5 μs to 1000 μs

vii. Real-time monitoring and control

Other PVD Power Supply: DC, Pulsed DC, RF

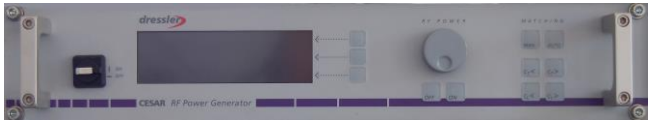
DC

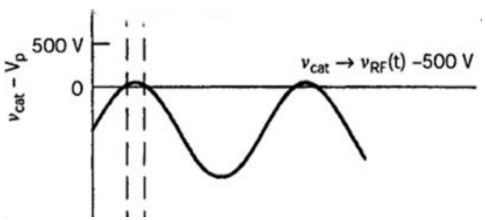
Pulsed DC



Especially designed to used to prevent the formation of arcs. Reactive sputtering processes of difficult materials.

RF





It is possible to sputter insulating target because no current could flow through the insulator

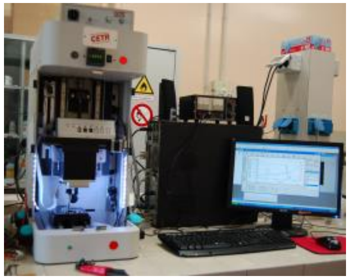
Characterization facilities

- Morphological
- Chemical
- Structural
- Mechanical
- Tribological
- Thickness

SEM / EDS

XRD

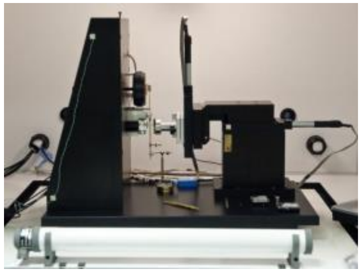
UMT - Tester



Mechanical Profiler

Calotest

Nanoindenter



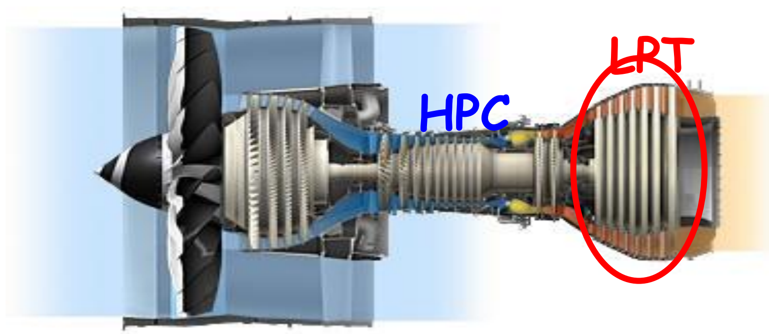
Optical microscope

Applications of the HiPIMS technique

- ✓ Hard coatings
- ✓ Adhesion enhancement
- ✓ Corrosion protection layers
- ✓ Optimized Tribological performance
- ✓ Optical coatings
- ✓ Electrical coatings
- ✓ ………………………………………….

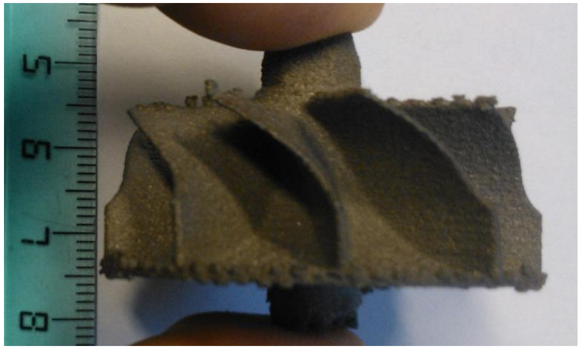
HiPIMS at CNR-ICMATE lab

HiPIMS TiAlN coatings: film/substrate interface design effect on high temperature cyclic oxidation behavior



General Electric GEnx Jet Engine:

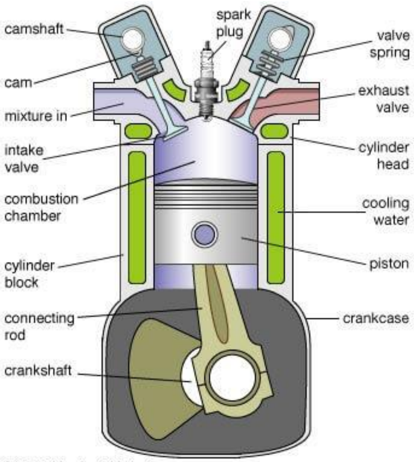
γ-TiAl for Low Pressure Turbine blades and High Pressure Compressor blades to increase the thrust-to-weight ratio.



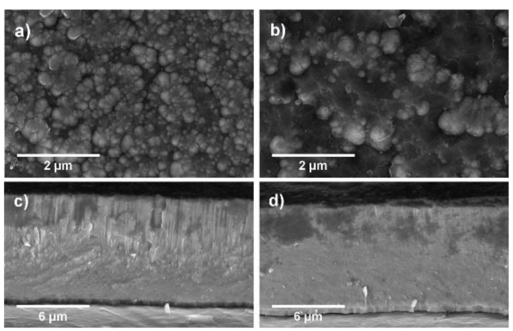
- S.M. Deambrosis, F. Montagner, V. Zin, M. Fabrizio, C. Badini, E. Padovano, M. Sebastiani, E. Bemporad, K. Brunelli, E. Miorin, "Ti1–xAlxN coatings by Reactive High Power Impulse Magnetron Sputtering: film/substrate interface effect on residual stress and high temperature oxidation", Surface and Coatings Technology, 354 (2018) 56-65; https://doi.org/10.1016/j.surfcoat.2018.09.004.
- C. Badini, S.M. Deambrosis, E. Padovano, M. Fabrizio, O. Ostrovskaya, E. Miorin, G. D'Amico, F. Montagner, S. Biamino, V. Zin, "Thermal Shock and Oxidation Behavior of HiPIMS TiAlN Coatings Grown on Ti-48Al-2Cr-2Nb Intermetallic Alloy", Materials 9 (12) (2016) 961; doi: 10.3390/ma9120961.
- C. Badini, S.M. Deambrosis, O. Ostrovskaya, V. Zin, E. Padovano, E. Miorin, M. Castellino, and S. Biamino. 2017. "Cyclic Oxidation in Burner Rig of TiAlN Coating Deposited on Ti-48Al-2Cr-2Nb by Reactive HiPIMS", Ceramics International, 43, 7 (2017) 5417-5426; https://doi.org/10.1016/j.ceramint.2017.01.031.

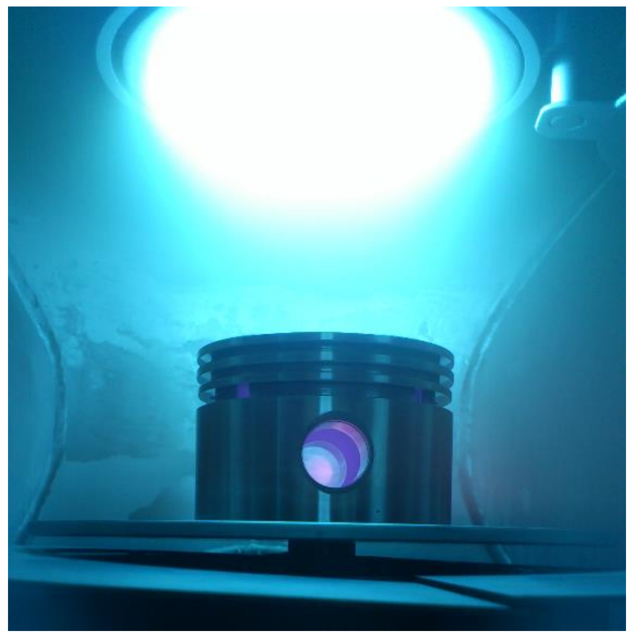
HiPIMS at CNR-ICMATE lab

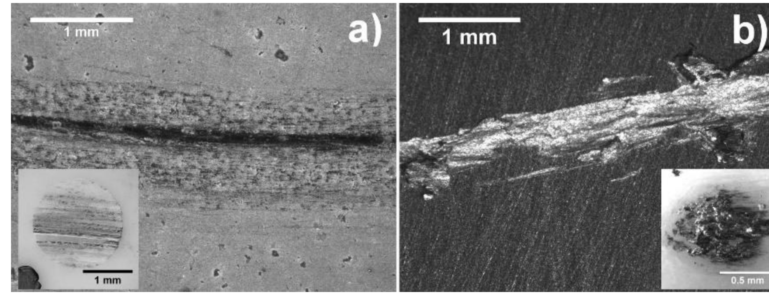
Mechanical and tribological properties of Mo-N coatings deposited via HiPIMS on temperature sensitive substrates

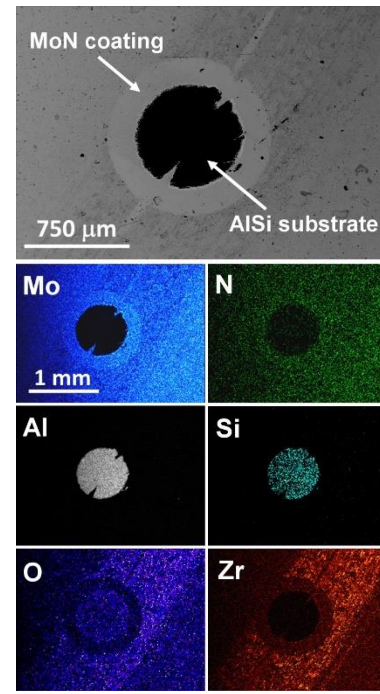


© 2006 Merriam-Webster, Inc.





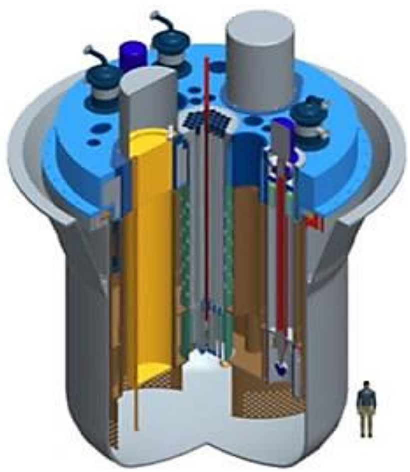


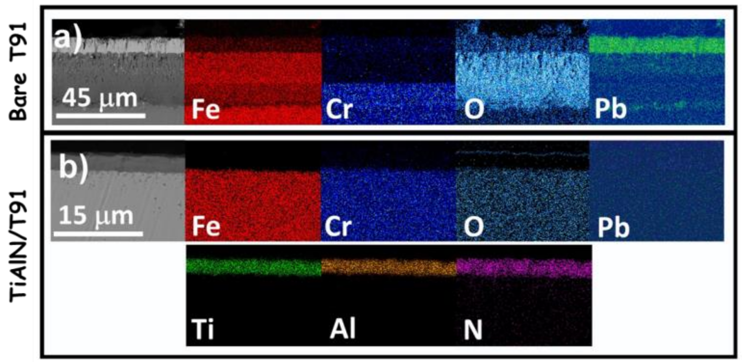


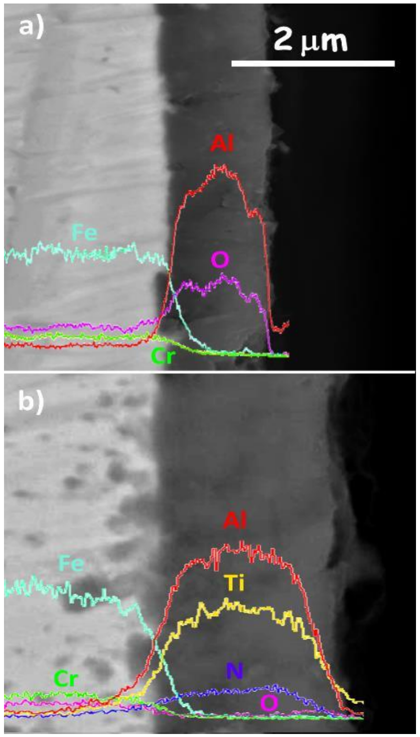
V. Zin, E. Miorin, F. Montagner, M. Fabrizio, S. M. Deambrosis, "Mechanical properties and tribological behaviour of Mo-N coatings deposited via high power impulse magnetron sputtering on temperature sensitive substrates", Tribology International 119 (2018) 372–380; https://doi.org/10.1016/j.triboint.2017.11.007.

HiPIMS at CNR-ICMATE lab

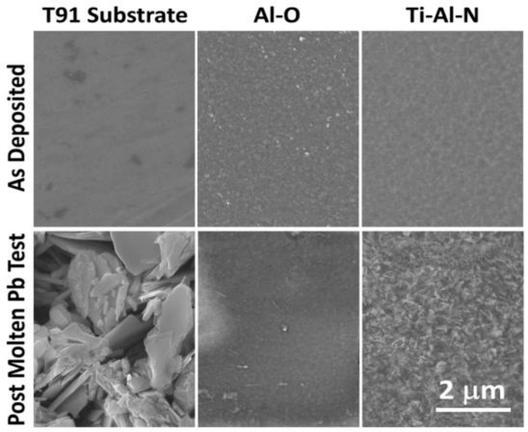
Corrosion barriers in nuclear plants: Aluminum-based PVD protective coatings







Uncoated T91 | AlO_x Sample | TiAlN Sample

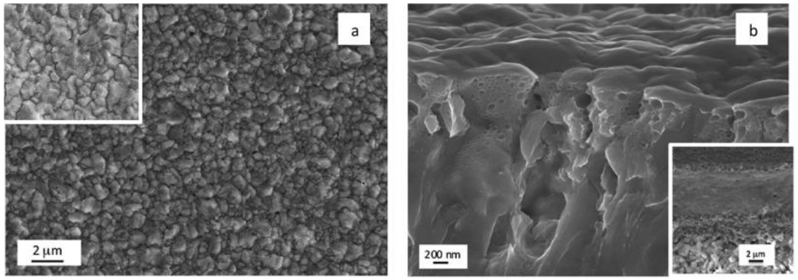


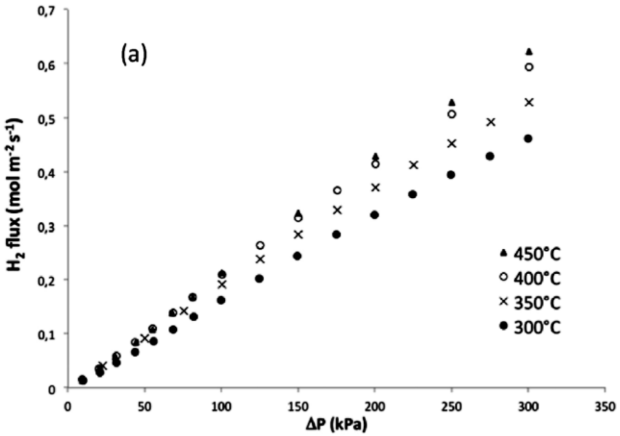
E. Miorin, F. Montagner, V. Zin, D. Giuranno, E. Ricci, M. Pedroni, V. Spampinato, E. Vassallo, S.M. Deambrosis, "Aluminum rich PVD coatings to prevent T91 steel corrosion in stagnant liquid lead: promising results" SUBMITTED to Surface and Coatings Technology.

HiPIMS at CNR-ICMATE lab

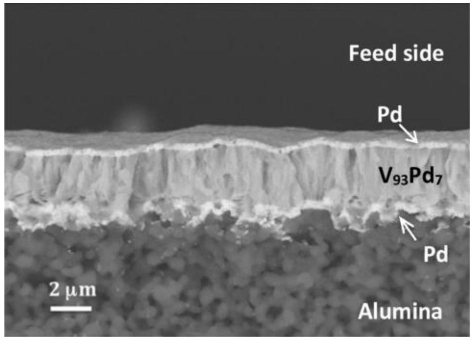
Metallic and ceramic membranes prepared by HiPIMS for hydrogen separation

PdAg membranes

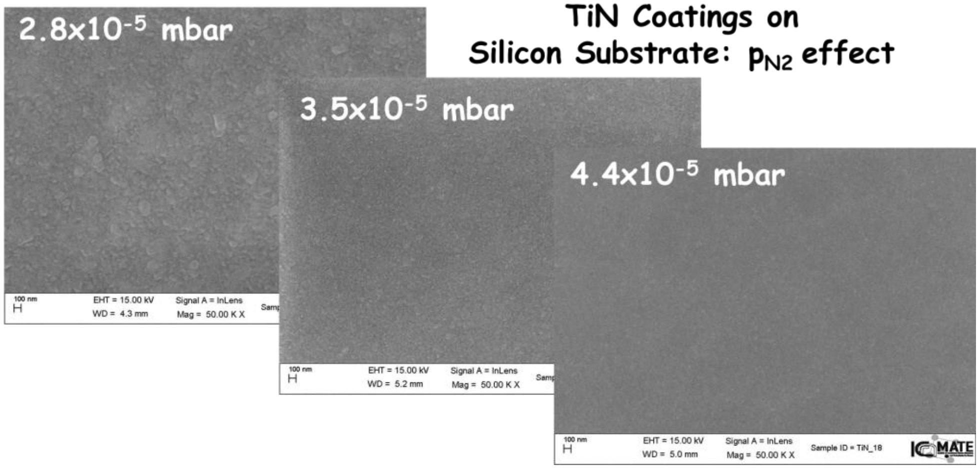




Pd/V-Pd/Pd membranes



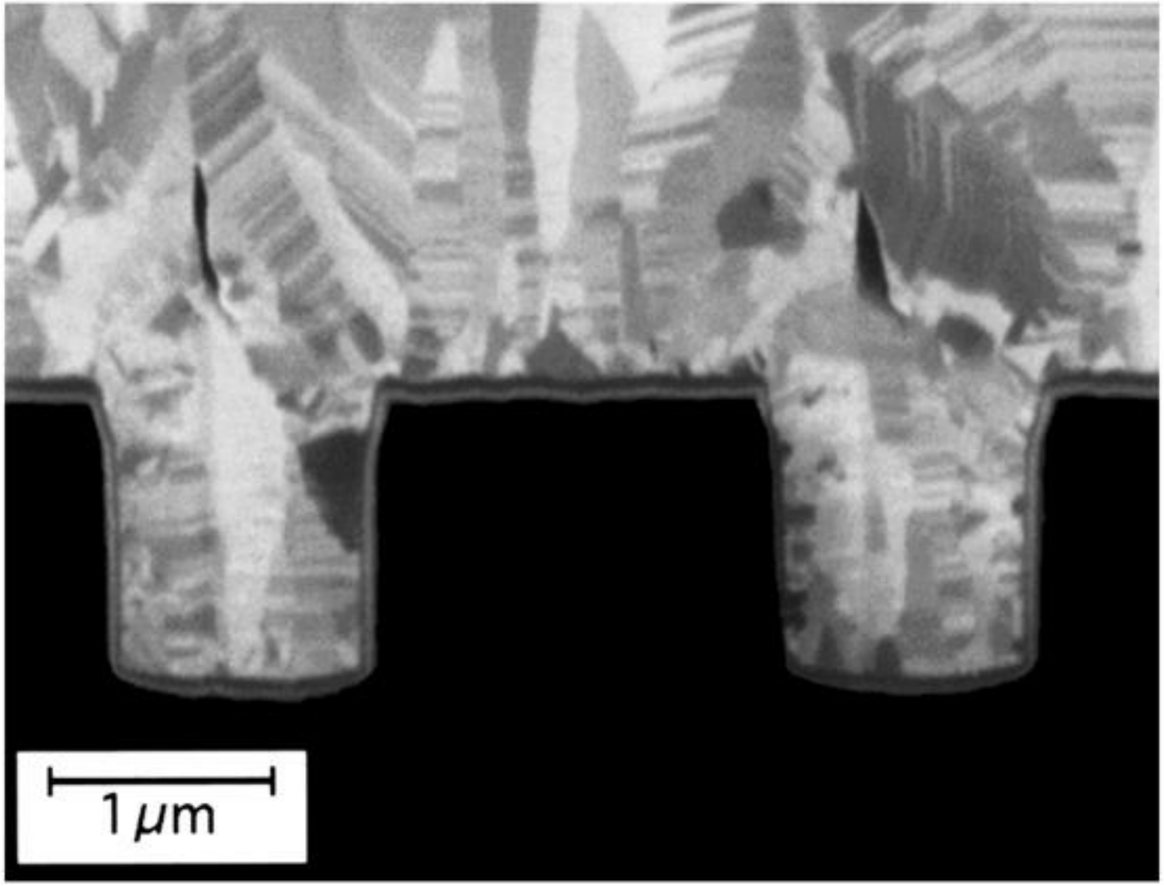
TiN Coatings on Silicon Substrate: p_{N2} effect



- S. Fasolin, S. Barison, S. Boldrini, A. Ferrario, M. Romano, F. Montagner, E. Miorin, M. Fabrizio, L. Armelao, International Journal of Hydrogen Energy 43 (2018) 3235 – 3243; doi.org/10.1016/j.ijhydene.2017.12.148.
- S. Barison, S. Fasolin, S. Boldrini, A. Ferrario, M. Romano, F. Montagner, S.M. Deambrosis, M. Fabrizio, L. Armelao, International Journal of Hydrogen Energy 43 (2018) 7982 – 7989; doi.org/10.1016/j.ijhydene.2018.03.065.

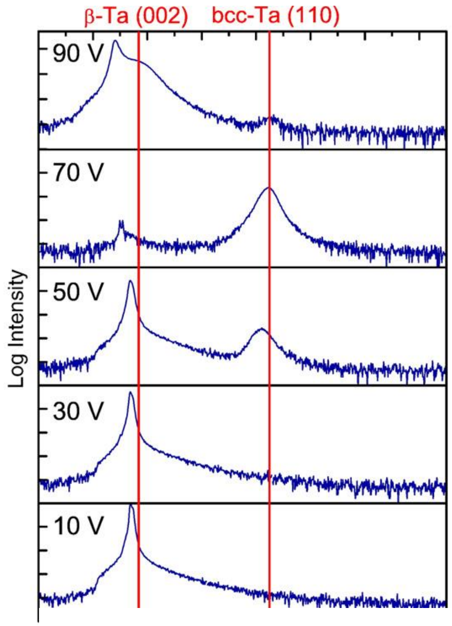
Deposition on complex-shaped substrates

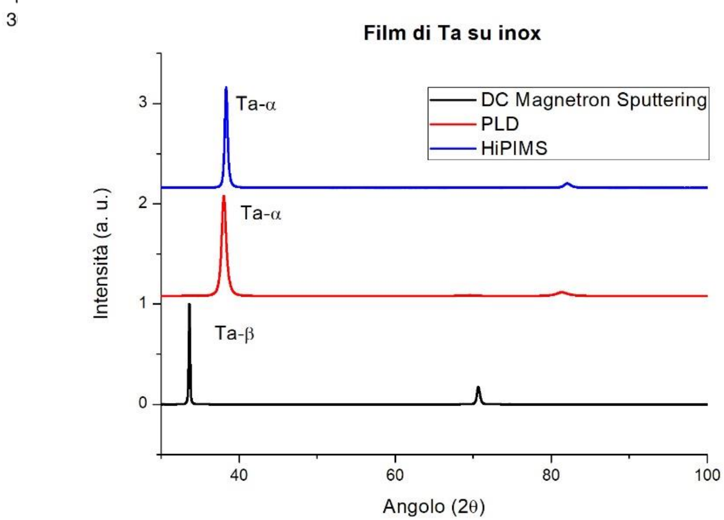
Cross-section SEM image of two via holes with an aspect ratio 1:2 homogeneously filled by Cu using HiPIMS.



V. Kouznetsov, K. Macak, J.M. Schneider, U. Helmersson, I. Petrov, Surf. Coat. Technol. 122 (1999) 290

Phase composition tailoring by HiPIMS



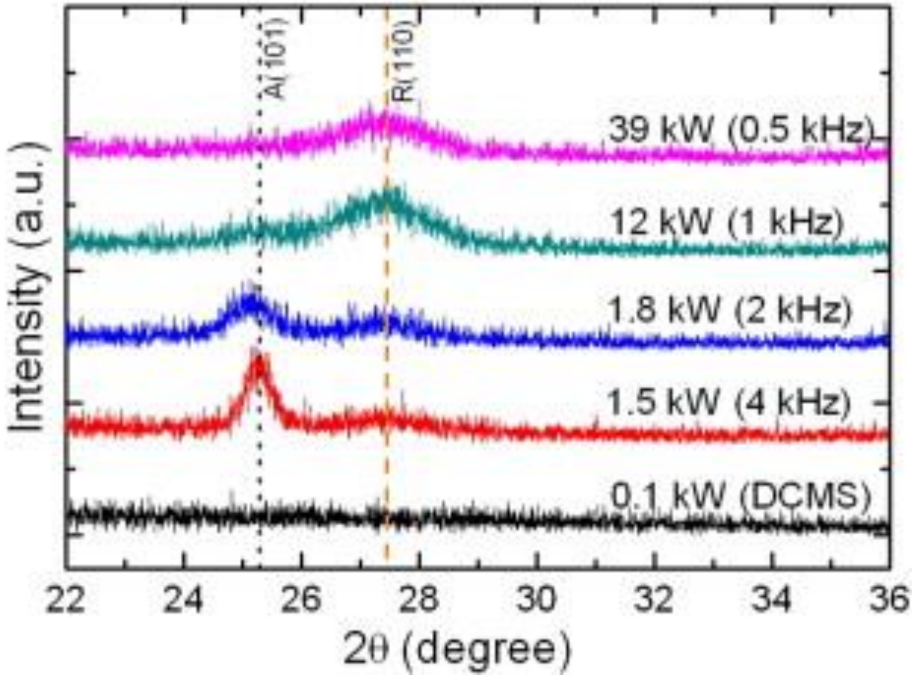


XRD patterns of Ta films deposited by HiPIMS on Si substrates, biased at negative potentials up to 90 V.
The bcc α-Ta phase is obtained at 70 V.

HiPIMS process ion-bombardment influences the internal stresses of the growing films and allows depositing α-Ta at room T!

J. Alami et al., Thin Solid Films, 515 (2007) 3434.

Phase composition tailoring by HiPIMS



XRD patterns of TiO_2 films grown on Si substrates by HiPIMS at various values of peak target power.

✓ The rutile phase can be achieved even at room T!

✓ > peak target power = > number of ions available during deposition → formation of the rutile at the expense of the anatase phase!

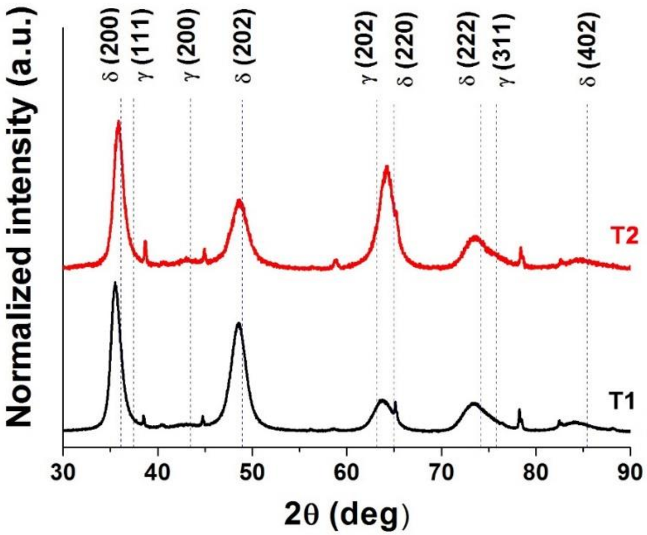
M. Aiempanakit et al., Surface and Coatings Technology, 205 (2011) 4828.

Phase composition tailoring by HiPIMS

γ-Mo_2N → face-centered cubic (space group Fm3m)

δ-MoN → hexagonal phase (space group $P6_3mc$)

δ-MoN phase exhibits a low compressibility, > H and E, < COF and > wear resistance.



- **Even at T<<300°C, HiPIMS technology allows obtaining Mo-N with a >% of δ phase.**
- **Even at T<<300°C, it was possible to deposit suitable coatings for tribological purposes.**

Sample	Phase	a (Å)	c (Å)	Concentration ($\%_{wt}$)	$(C_\gamma/C_\delta)_{\%wt}$
T1	γ-Mo_2N	4.2196	-	23.8	0.31
	δ-MoN	5.8372		76.2	
T2	γ-Mo_2N	4.1751	-	26.8	0.37
	δ-MoN	5.8103	5.621	73.2	
Reference Bulk	γ-Mo_2N	4.1616			
	δ-MoN	5.7395	5.6176		

Rietveld method:

- a, c → cell parameters;
- $(C_\gamma/C_\delta)_{\%wt}$ → wt. concentration ratio between γ and δ phases.

Phase composition tailoring by HiPIMS

Measured H values were comparable, or even superior, to literature hardness data

Technique	T (°C)	δ-MoN	γ-Mo_2N	H (GPa)	Thickness (μm)
HiPIMS	**<160**	yes	yes	**22-28**	8
arc-PVD	**300**	yes	yes	**20**	2
arc-PVD	**450-500**	yes	yes	**32-38**	1.5-2.3
arc-PVD	**>400**	yes	yes	**47**	1.1-3.5
RF-MS	**300**	no	yes	**23**	1.5
RF-MS	**230**	yes	yes	**20-23**	1-2
pulsed DC-MS	**350**	no	yes	**24.5**	2

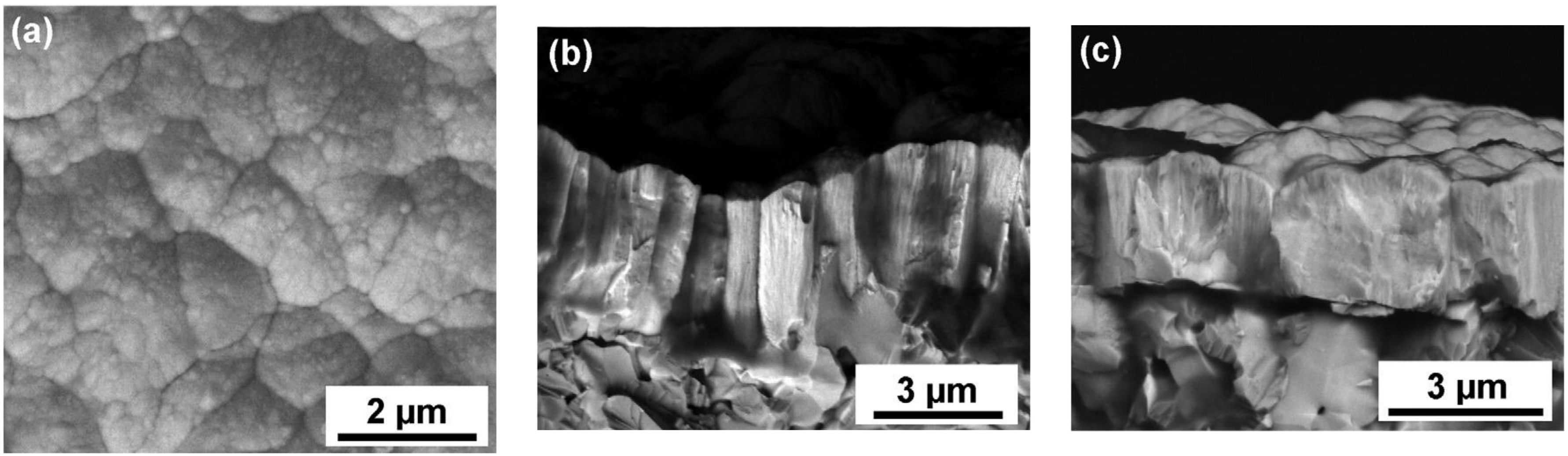
T1 samples showed improved:

- ✓ elasticity index
  $H/E_{T1}=0.094\pm0.008$
  $H/E_{T2}=0.07\pm0.01$
- ✓ resistance to plastic deformation
  $H^3/E^2_{T1}=0.25\pm0.095$ GPa
  $H^3/E^2_{T2}=0.09\pm0.05$ GPa

Better tribological performance!!!

Control of film microstructure

Yttria-Stabilized Zirconia (YSZ) thin films are reactively sputter-deposited by high power impulse magnetron sputtering (HiPIMS) in an industrial setup on porous NiO/YSZ fuel cell anodes.

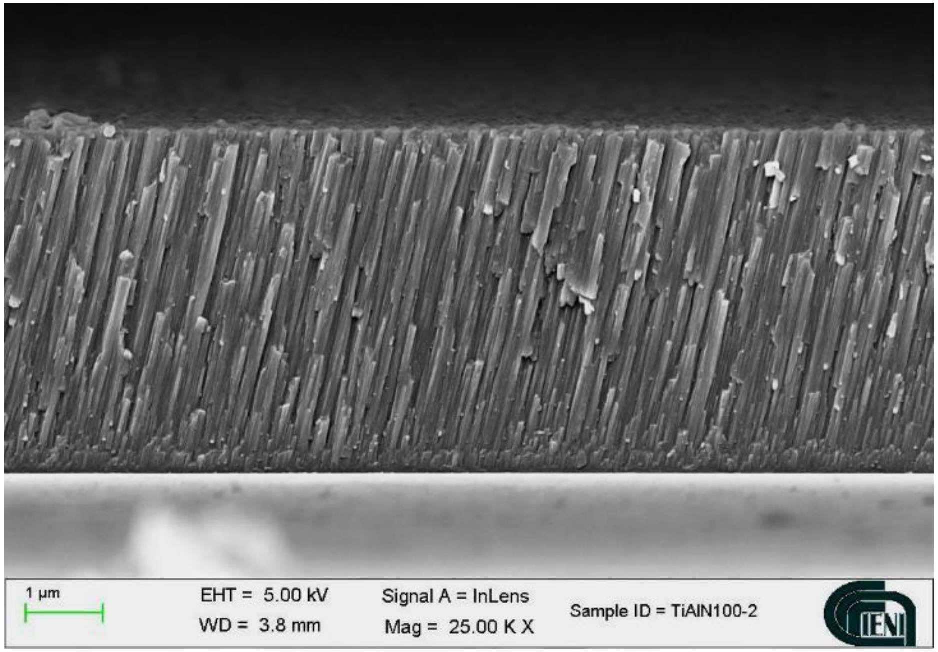


SEM micrographs of films deposited at bias voltages −180 V (a, c) and −120 V (b). The peak power density was 0.6 $kWcm^{-2}$ and the deposition pressure ~750 mPa.

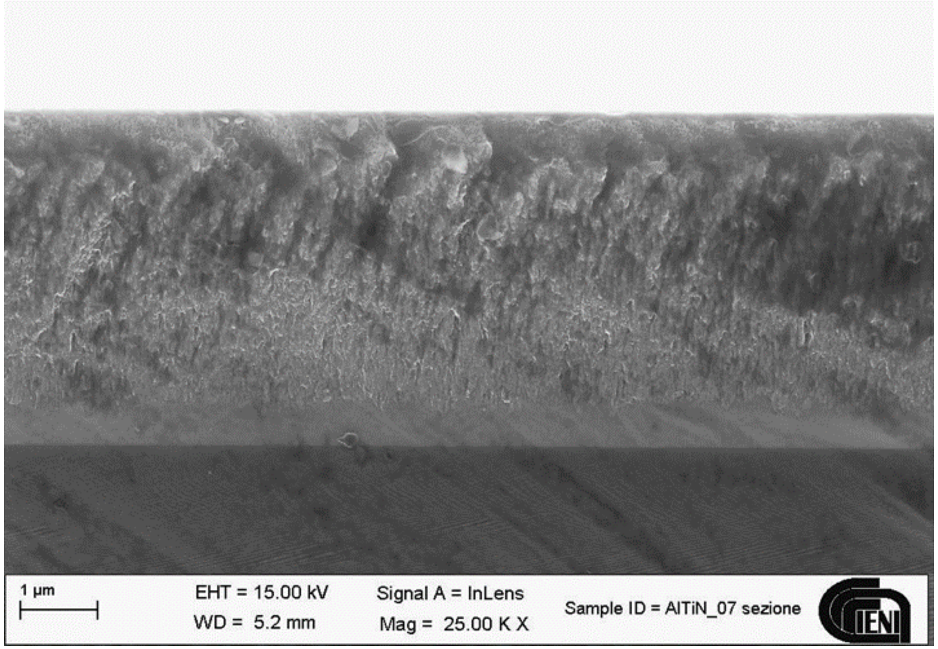
S. Sønderby et al. / Surface & Coatings Technology 281 (2015) 150–156

Control of film microstructure

AlTiN via DCMS

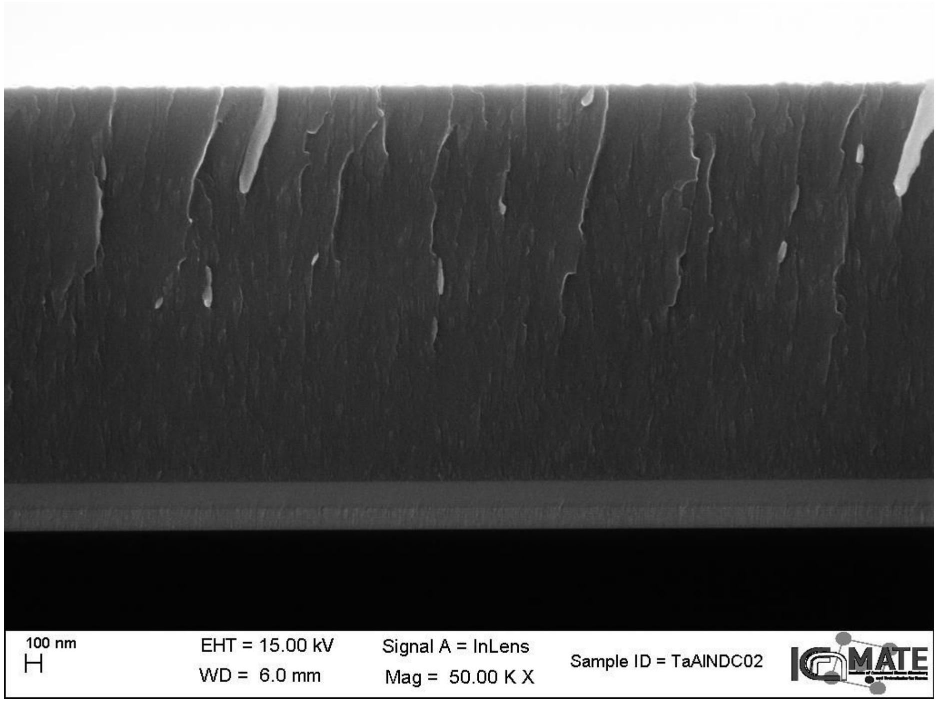


AlTiN via HiPIMS

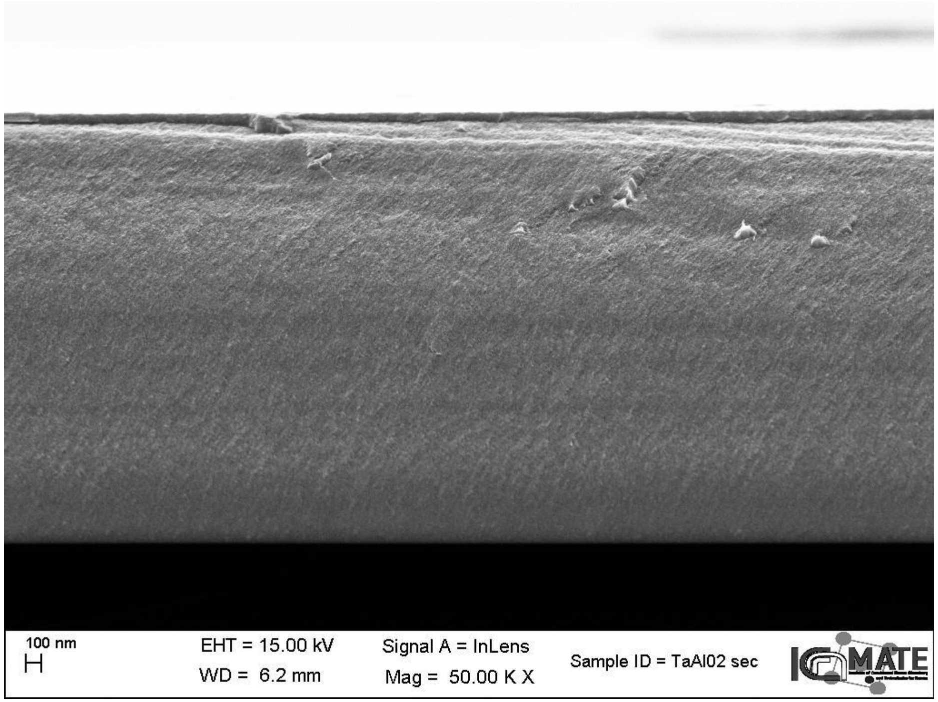


Control of film microstructure

TaAlN via DC-MS

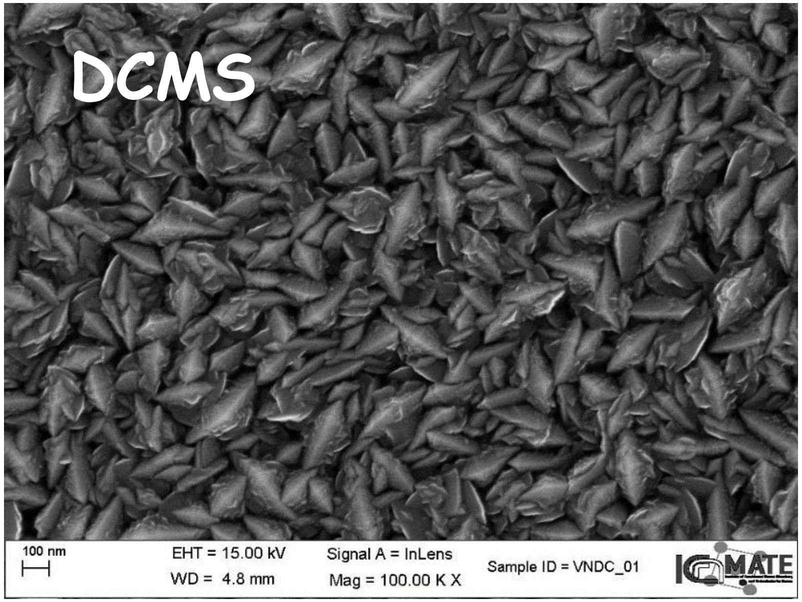


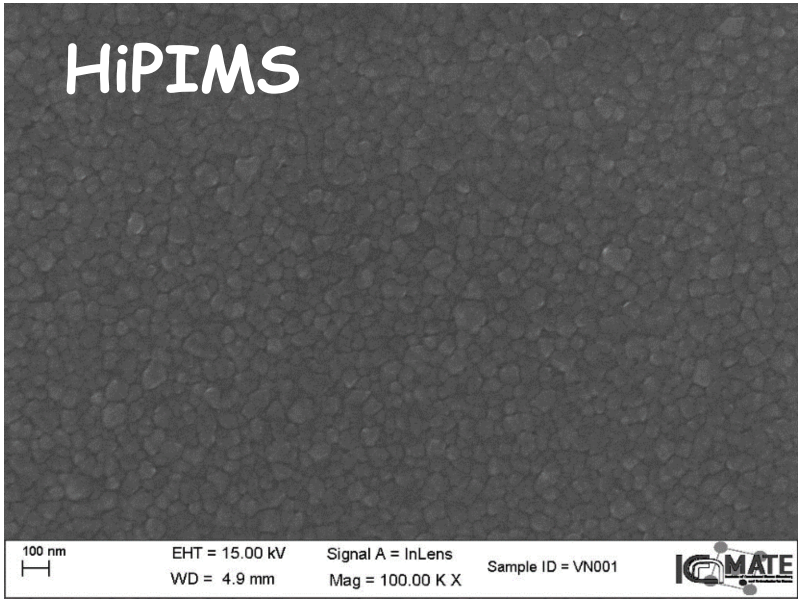
TaAlN via HiPIMS



HiPIMS at CNR-ICMATE lab

VN

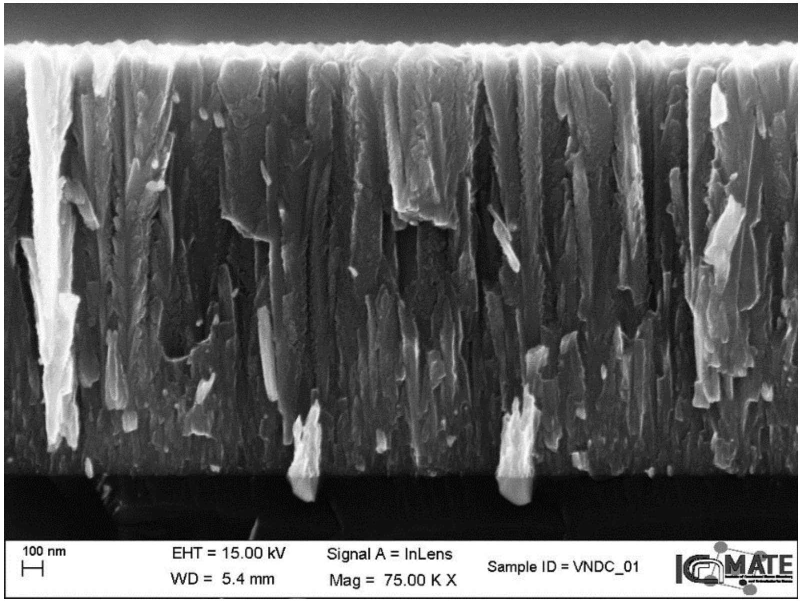




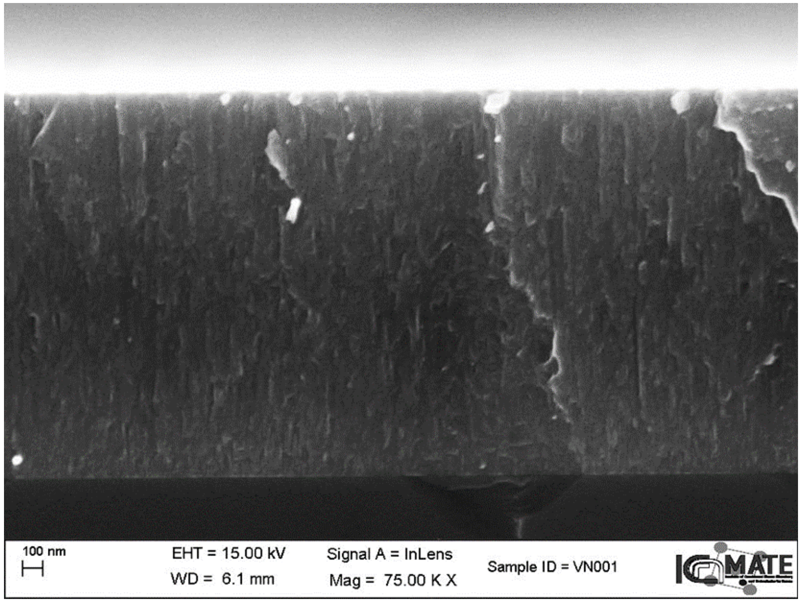
HiPIMS at CNR-ICMATE lab

SEM analysis: Microstructure

DCMS



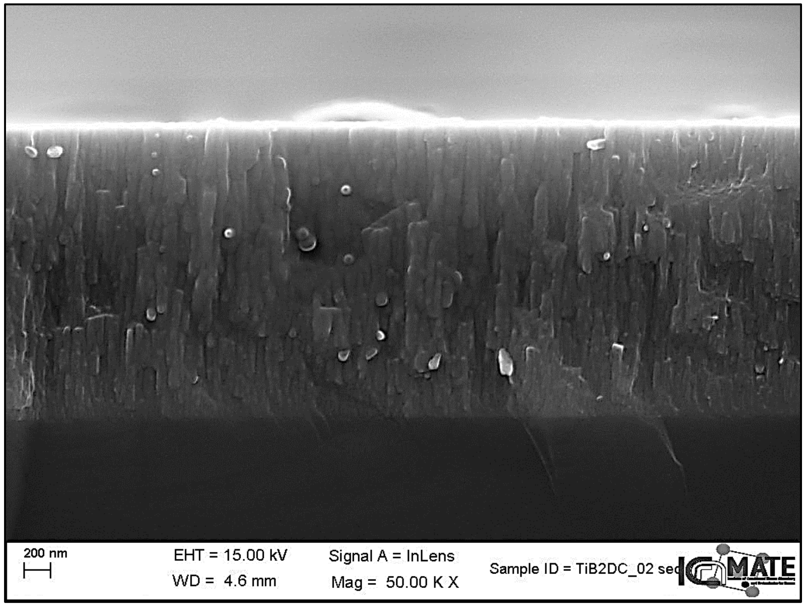
HiPIMS



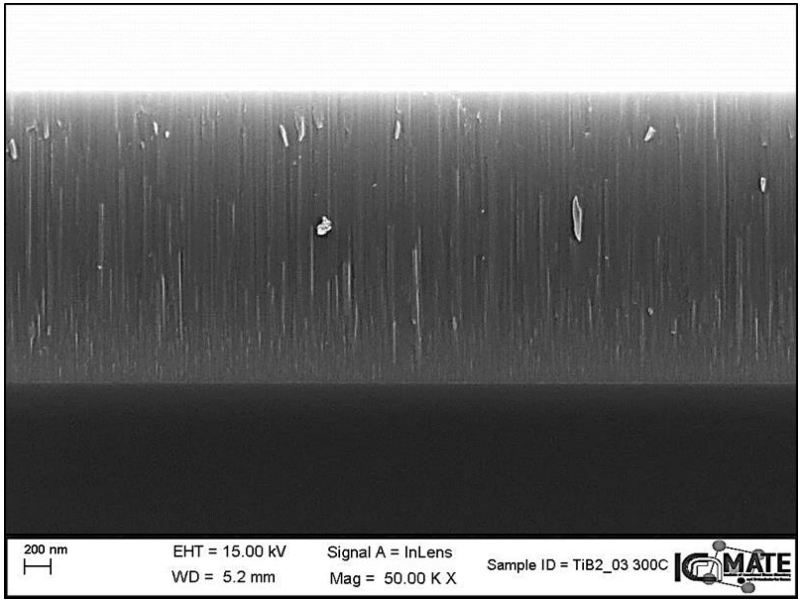
HiPIMS at CNR-ICMATE lab

TiB_2 SEM Analysis: Microstructure

DCMS

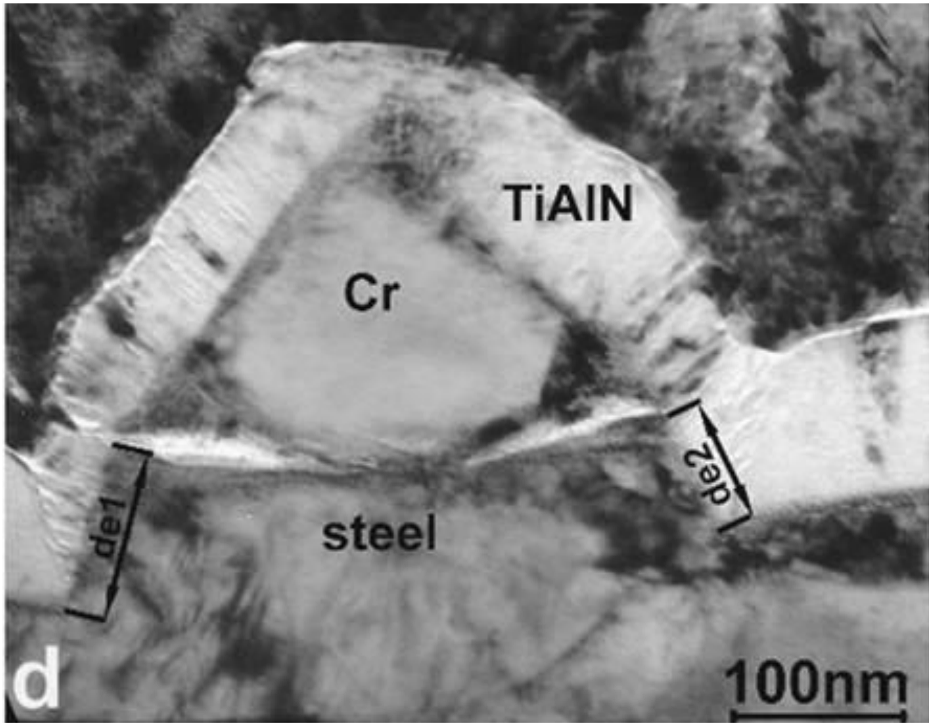


HiPIMS

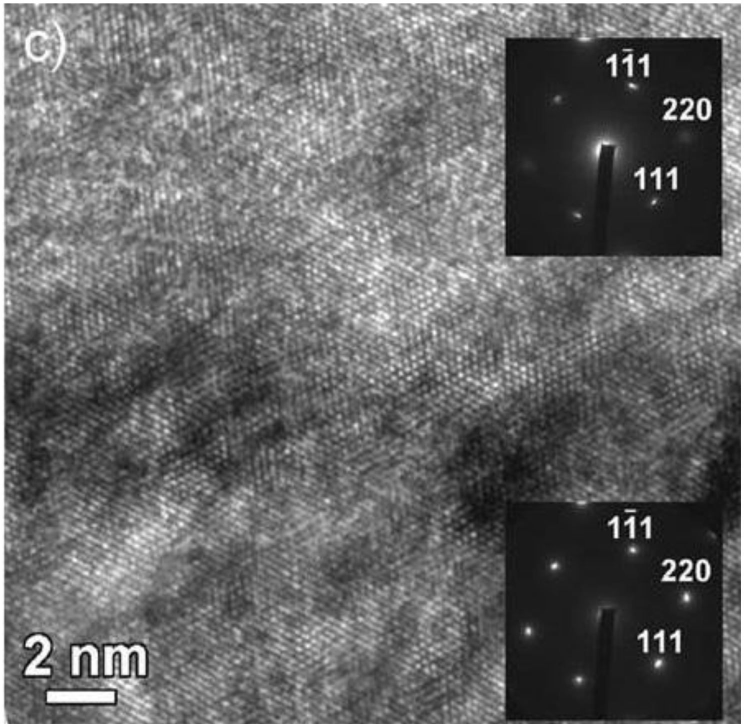


Interface engineering

HiPIMS Metal Etching Pre-treatment



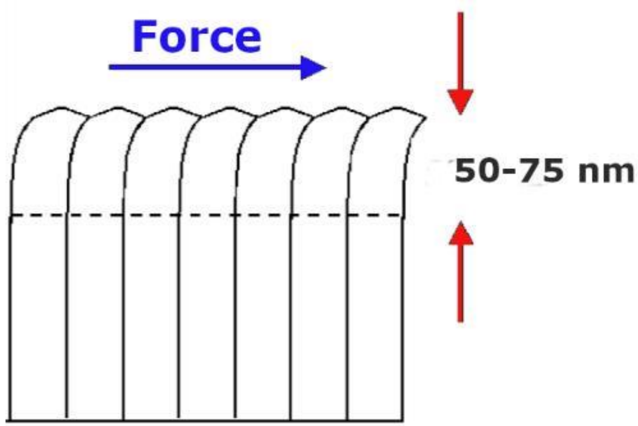
Presence of an unwanted droplet **in arc Cr etching** [C. Schonjahn, L. A. Donohue, D. B. Lewis, W.-D. Munz, R. D. Twesten, and I. Petrov, J. Vac. Sci. Technol. A 18, 4 (2000)].

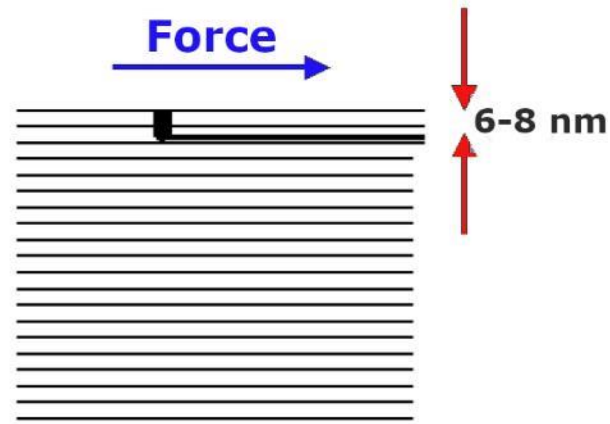


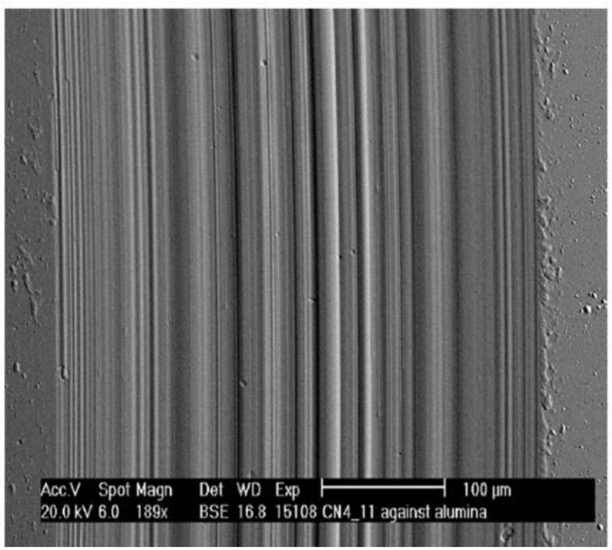
CrAlN layer grown on the γ-TiAl substrate after **HiPIMS Cr pretreatment**. Uniform diffraction contrast is shown [A. P. Ehiasarian, J. G. Wen and I. Petrov. Journal of Applied Physics 101, 054301(2007)].

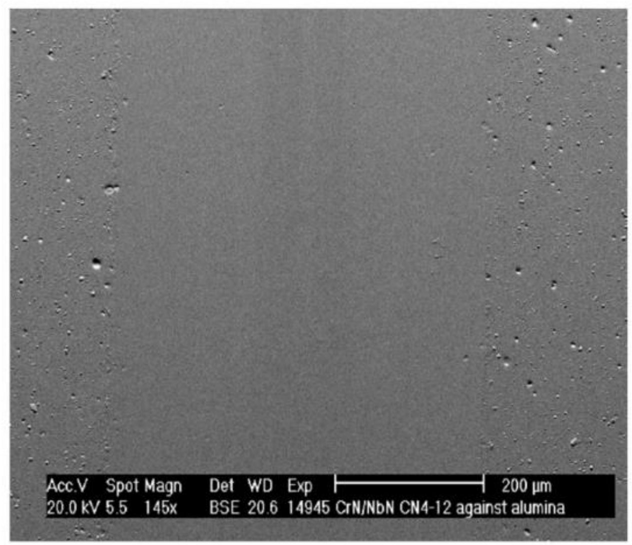
HiPIMS at CNR-ICMATE lab

Wear mechanism of single and multilayer coatings



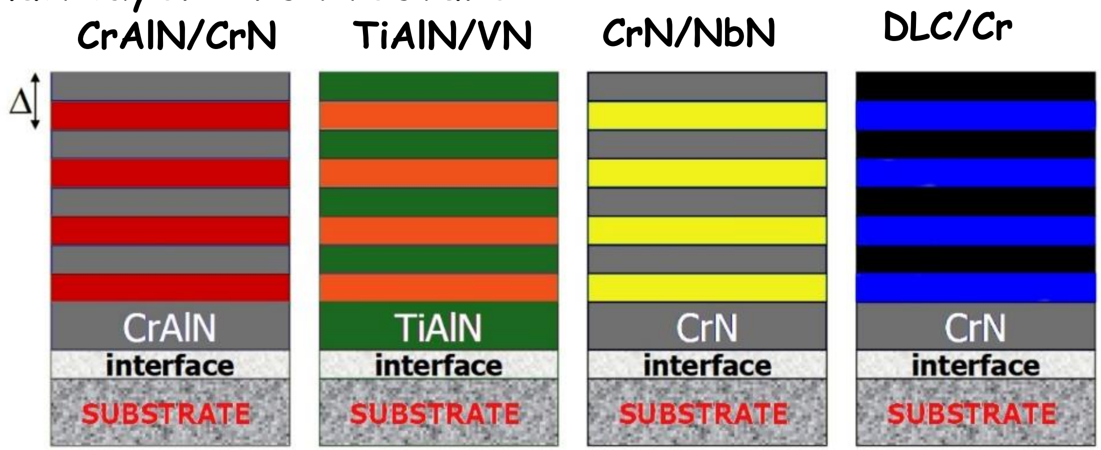




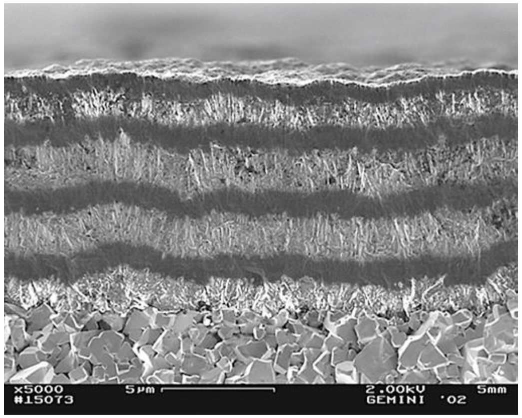


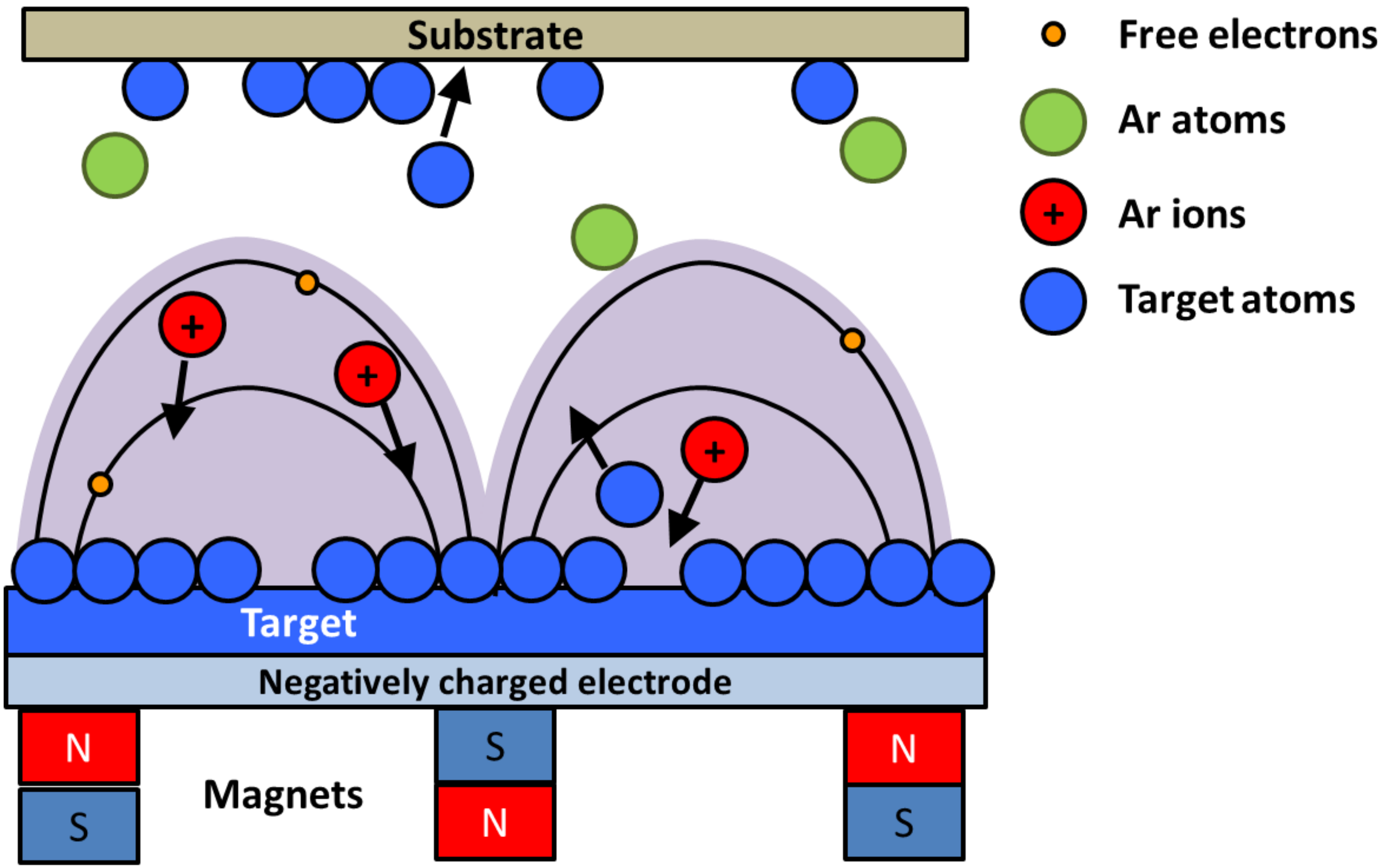
HiPIMS at CNR-ICMATE lab

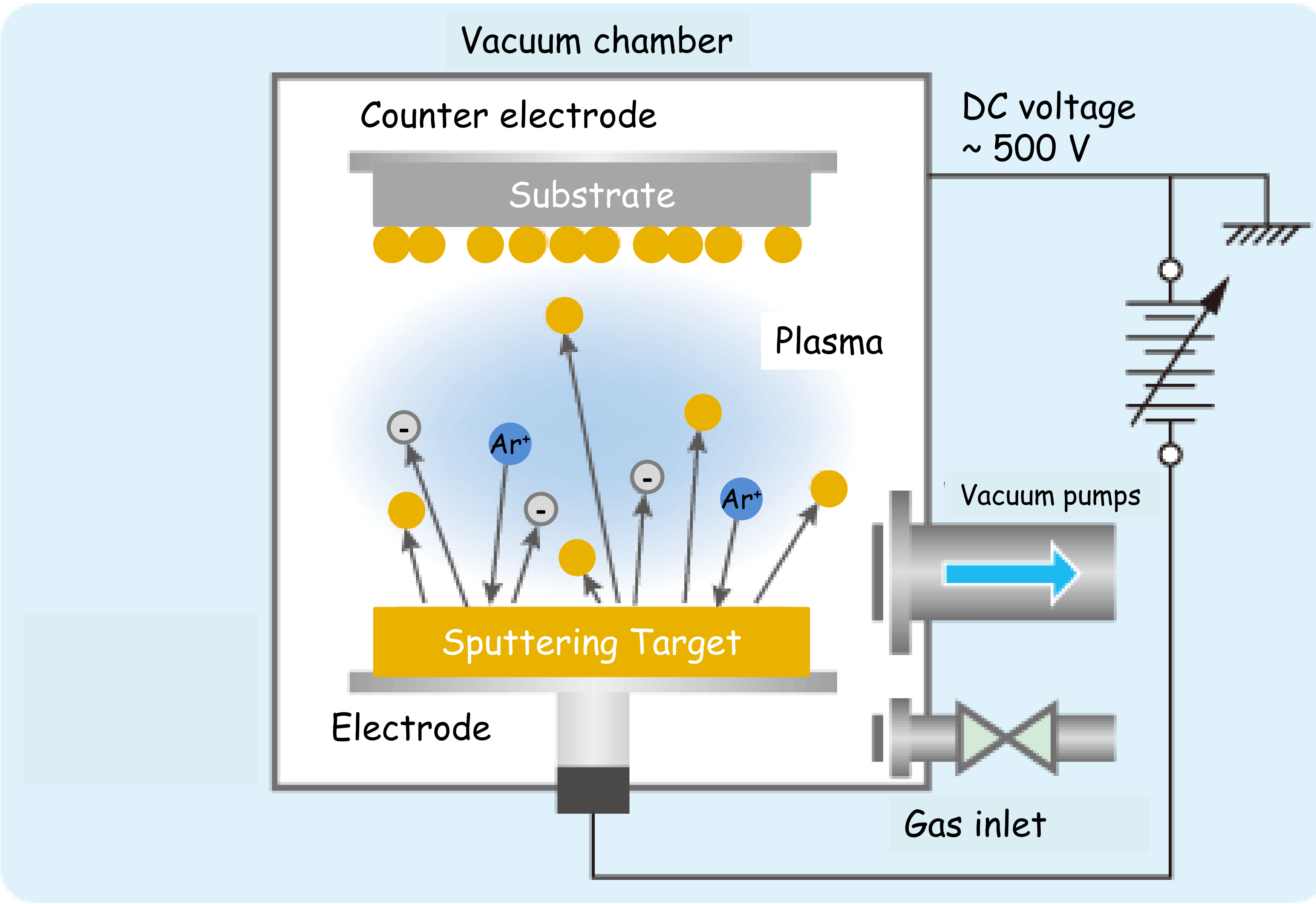
Multilayer Architecture



CrAlN/CrN	TiAlN/VN	CrN/NbN	DLC/Cr
D = 4.0 nm High temperature oxidation resistant Dry machining, automotive and aero engines.	D = 3.2 nm High hardness low friction Al and Ti cutting	D = 3.4 nm Corrosion and Wear resistant	D = 2 nm Low friction - tribological




Substrate
Free electrons
Ar atoms
Ar ions
Target atoms
Target
Negatively charged electrode
N
S
Magnets
S
N
N
S



Vacuum chamber
Counter electrode
Substrate
DC voltage
~ 500 V
Plasma
-
Ar+
Vacuum pumps
Sputtering Target
Electrode
Gas inlet