Nanostructured tungsten as a first wall material for future nuclear fusion reactors

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Outlook

- Introduction and state of the art
- Making nanostructured W → Growth system
- Sample characterization and Results
  - Microstructure and morphology
  - Mechanical properties
  - Thermal stability
- Conclusions

World energy demand continues rapid growth → some proposed solutions

- **Renewable energies**
  - Advantages: They are clean energy
  - Disadvantages: Difficult to produce large quantities of electricity

- **Fusion**
- **Why fusion? What is expected?**
  - **Future fusion Nuclear Power Plants (NPPs) are expected to provide mankind a sustainable energy source and to contribute to the energy required satisfy the growing demand of energy and to limit global warming**
    - Fusion offers important advantages:
      - No carbon emissions therefore, no air pollution
      - Unlimited fuel
      - Intrinsically safe

Introduction and state of the art

- BUT, the severe radiation conditions expected in fusion reactors require the development of new materials able to withstand the harsh environment (thermal loads and radiation) taken place in the reactor chamber.

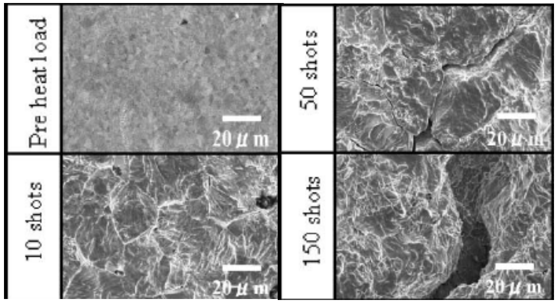
- First wall materials that will be exposed to that adversely atmosphere are called **plasma facing materials (PFM)**.

Introduction and state of the art

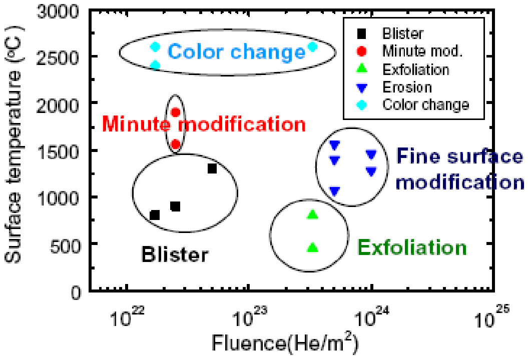
- Requisites of these PFM’s:
  - Excellent structural stability to keep their protection role
  - High thermal shock resistance
  - High thermal conductivity
  - High melting point
  - Low physical and chemical sputtering
  - Because of safety reasons low tritium retention is also a must
- Nowadays, W has been proposed to be one of the best candidates for PFM for both laser (IC) and magnetic (MC) confinement fusion approaches because of:
  - its low physical and chemical sputtering yields
  - high thermal conductivity (174 W/Km)
  - high melting point (3410 °C).
- Although some limitations have been identified for pure conventional (massive) W to fulfill specifications

W limitations

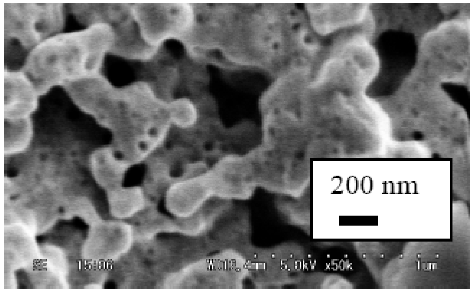
1. W brittleness at T ≤ 400ºC, bellow the DBTT, (due to the high activation energy of screw dislocation glide) limits the application of pure W to the temperature window in between DBTT and recrystallization (~1300ºC). T. J. Renk, et al. Fusion Engineering and Design 65 (2003) 399.
2. Surface modification at T< 3400 ºC (below the melting point).



Cyclic e-beam heat loads experiments (H=50 MW/m², t=30 s) T_s=~1300 ºC. S.Tamura *et al.* JNM **307–311** (2002) 735.



Schematic diagram of the relation of surface modifications to fluence and peak temperature after He irradiation. K. Tokunaga *et al.* JNM **329** (2004) 757.



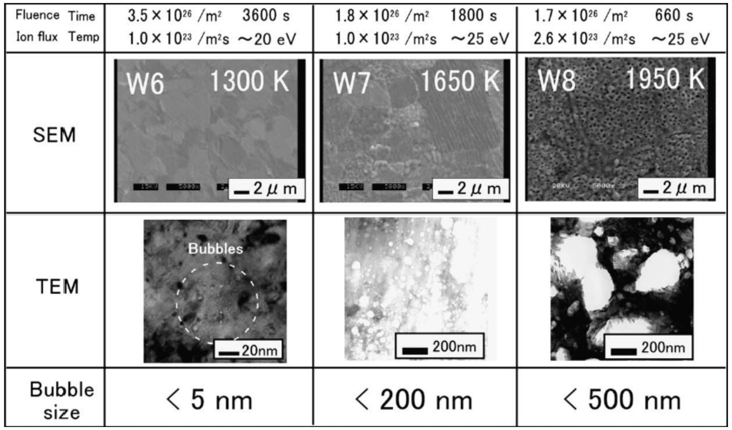
He irradiation (E_{He}=50 keV) T_s=~1700 ºC W. Sakaguchi, *et al.* Proceedings of ITC **18** (2008).

Surface modification by particle (He and H) and electron beam heating is completely different

W limitations

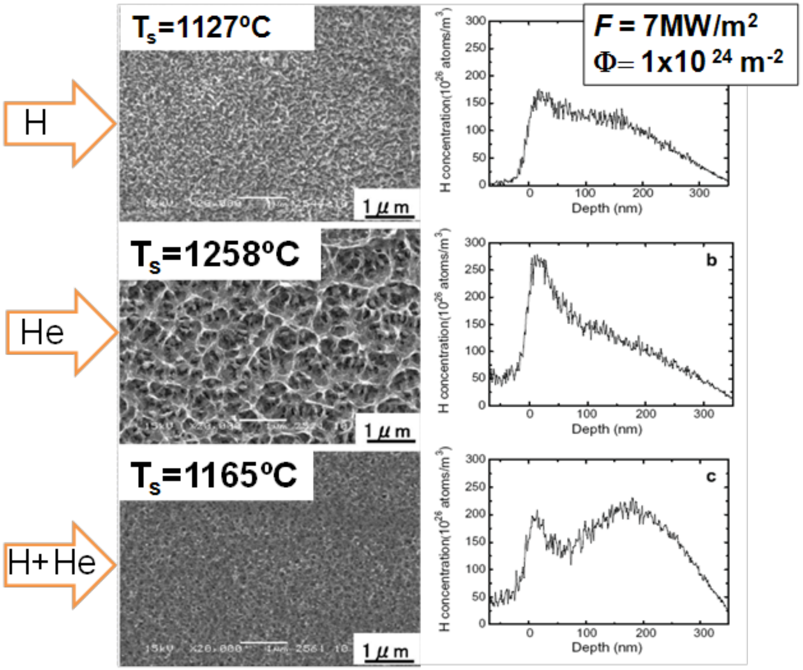
3. Light species retention ⇨ blistering and material ejection

Single beam (D. Nishijima et al. JNM 329 (2004) 1029)



Fluence Time Ion flux Temp	3.5×10^{26} /m² 3600 s 1.0×10^{23} /m²s ~20 eV	1.8×10^{26} /m² 1800 s 1.0×10^{23} /m²s ~25 eV	1.7×10^{26} /m² 660 s 2.6×10^{23} /m²s ~25 eV
SEM	W6 1300 K 2 μm	W7 1650 K 2 μm	W8 1950 K 2 μm
TEM	Bubbles 20nm	200nm	200nm
Bubble size	< 5 nm	< 200 nm	< 500 nm

Mutliple beams →synergetic effects (K. Tokunaga et al. JNM 390–391 (2009) 916.)



Bubbles and holes are formed after He beam irradiation

The formation of bubbles mainly depends on:

- Sample microstructure
- Irradiation conditions (flux, fluence, temperature and particle beam)

SYNERGETIC EFFECTS ARE RELEVANT

Surface modification due to the mixture and single beam irradiation is different .

- Holes with a diameter of a few 100 nm are observed for He - irradiated samples.
- Smooth surface for samples irradiated with double beam.

Introduction and state of the art

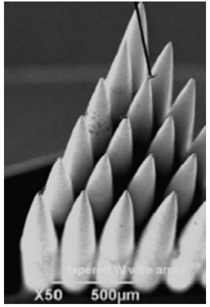
Some strategies as the potential of nanostructured W as a PFM are being investigated to overcome standard W limitations:

- **3D engineered materials**

- Reduce the thermal loads arriving to the PFM by increasing the surface area while keeping the thermal conductivity high.
- Favor light species release??

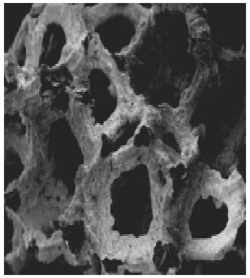
W needles

[T. J. Renk, et al. Fus. Sci.and Tech. 61 (2012)]



W foams

[D. L. Youchison et al. Fus. Eng. and Des. 82 (2007) 1854]



- **Nanostructured materials** due to their high density of grain boundaries

- Delay the pressurized bubble formation→ light species get pinned at grain boundaries
- Self-healing behavior→ Frenkel pair annihilation

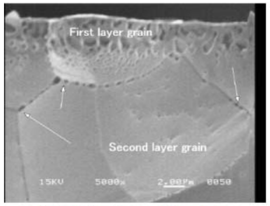


Fig.3 Bubble formation at grain boundary.

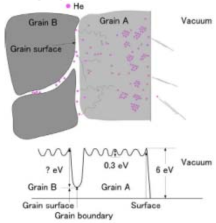


Fig.4 Energy level of He atom at grain interior and grain boundary.

Visit the poster presented by R. Gonzalez-Arrabal *et al.*:

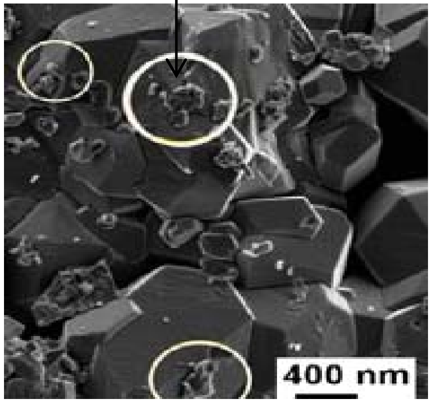
H accumulation in nanostructured W as compare to massive W

Poster session B: **P78**

Introduction and state of the art

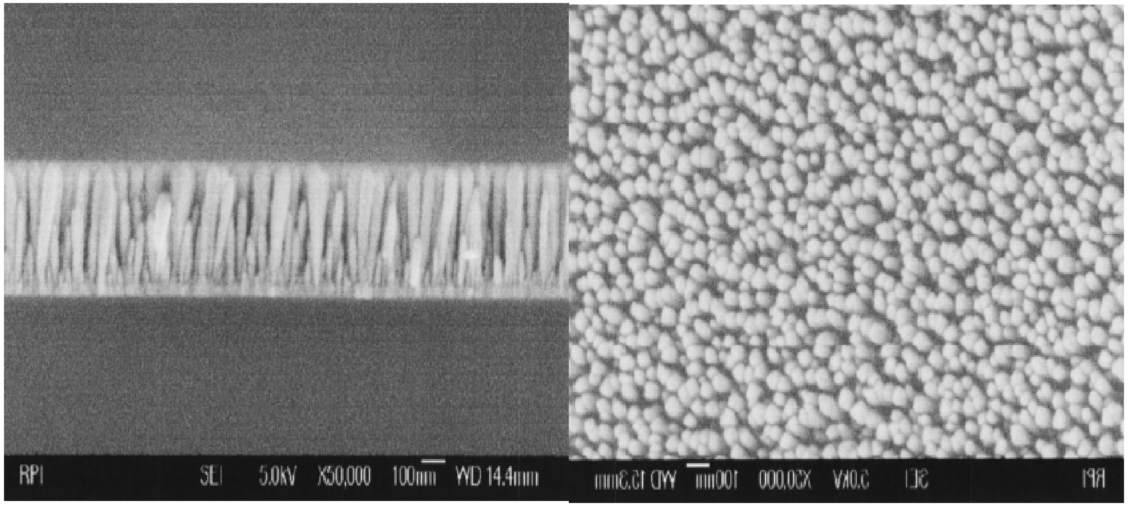
- **Nanostructured materials: two approaches**

ODS_W based materials



La_2O_3 [M. A. Yar *et al*. JNM **408** (2011) 129]

Nanostructured columnar materials



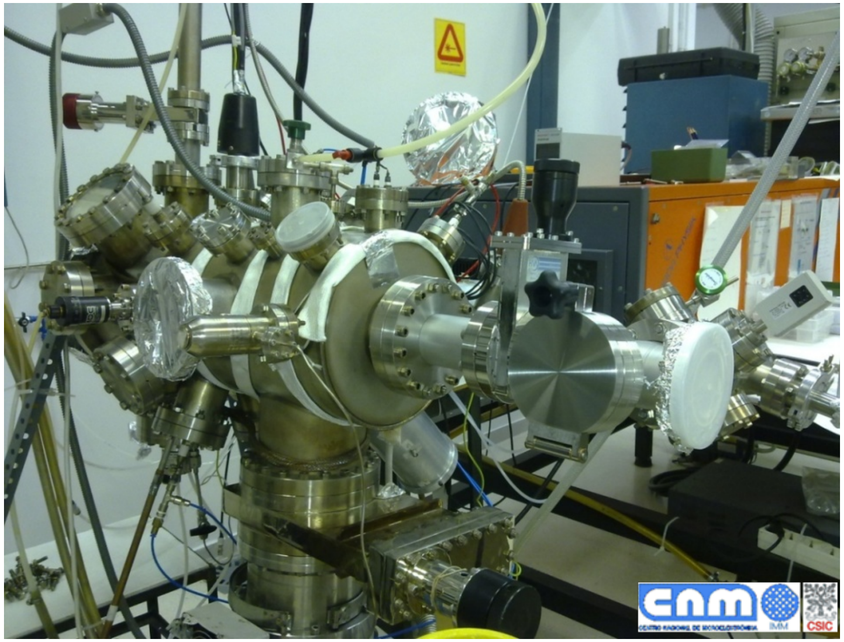
Cross sectional and top view images of tungsten nanocolumns grown by oblique angle deposition

[T. Karabacak et al. J. Appl. Phys 94 (2003) 7723]

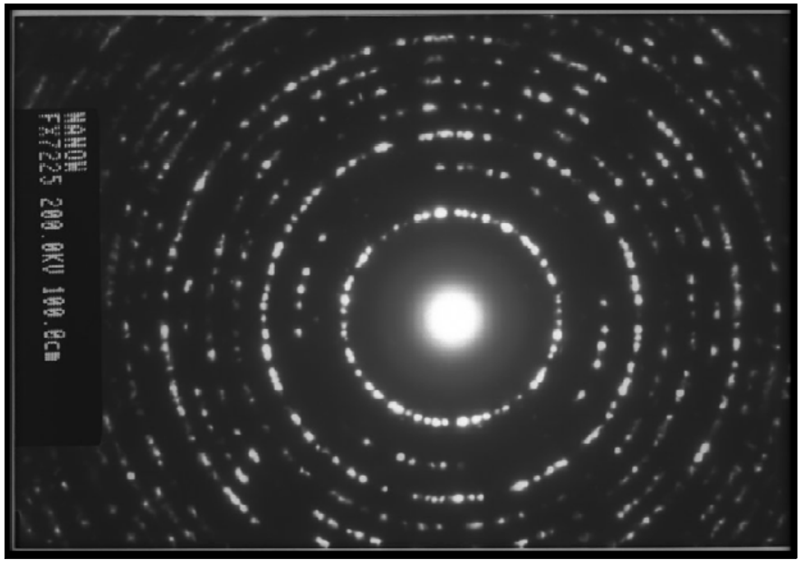
Growth system

DC-Magnetron sputtering

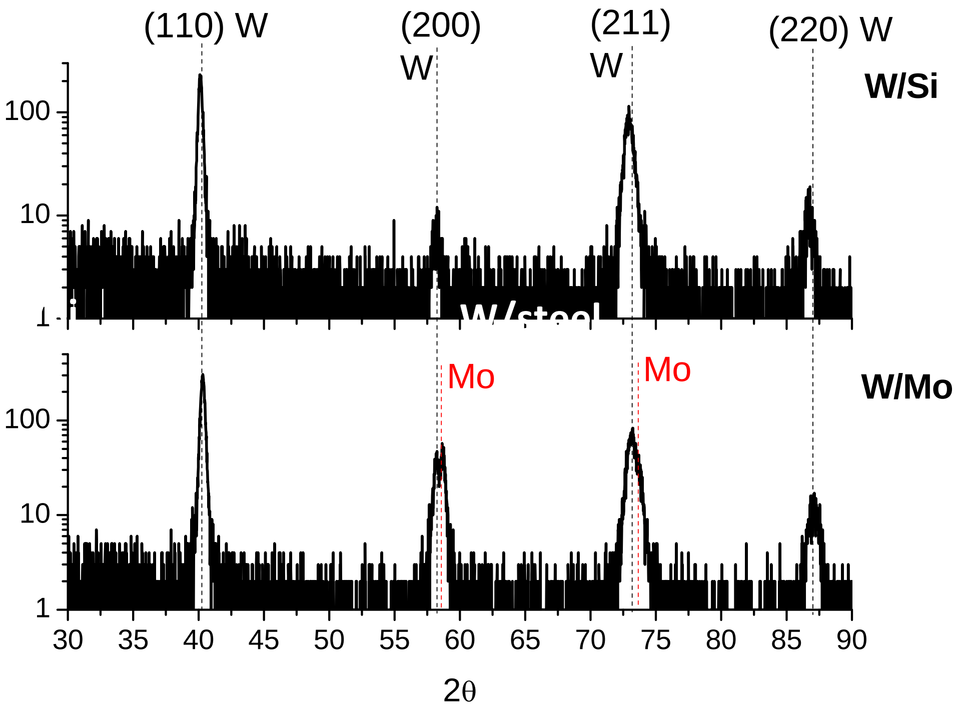
- HV setup, P_{base} ~ 10^{-8} mbar
- Growth parameters:
  - Plasma: Ar/W
  - $P_{working}$ ~ 10^{-3} mbar
  - V_{dc}: 320 V, I_{dc}: 0.15 A
  - Growth rate ~ 3-4 Å/s
- Substrates:
  - **Si, Mo, steel**



Morphology and microstructure

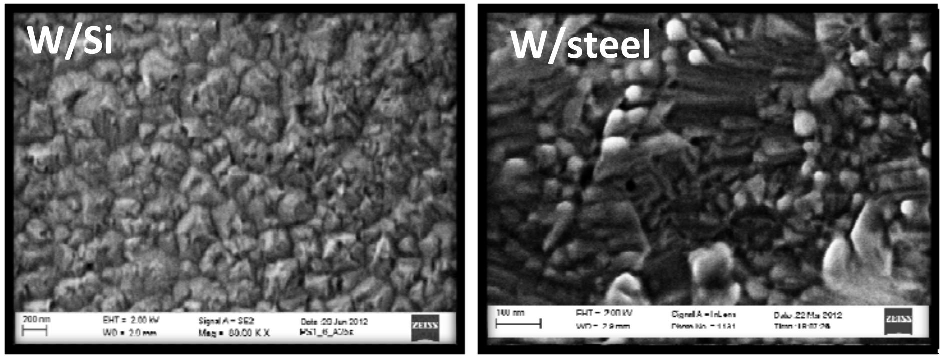


TEM diffraction pattern of a W thin film (~ 30 nm)

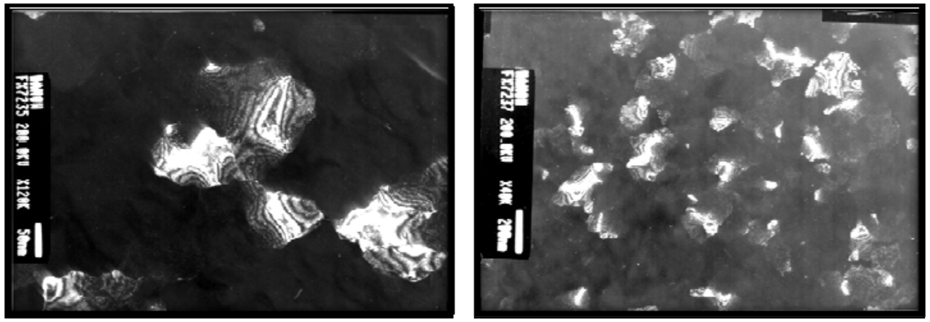


XRD patterns of nW deposited on *Si (100)* and *Mo* → polycrystalline samples with (110) preferential orientation.

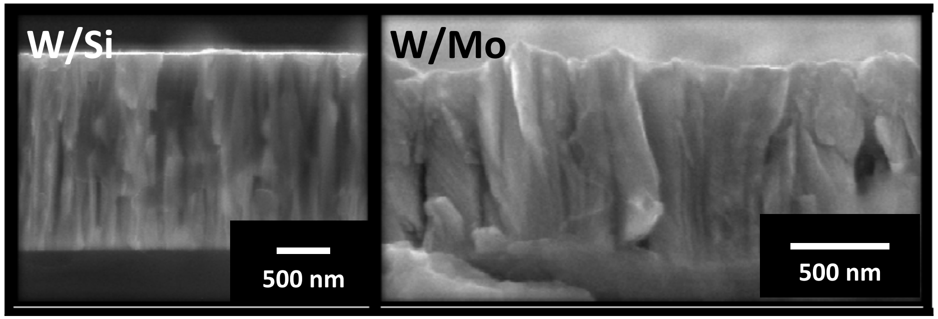
Morphology and microstructure



SEM images of a nW thin deposited on different substrates



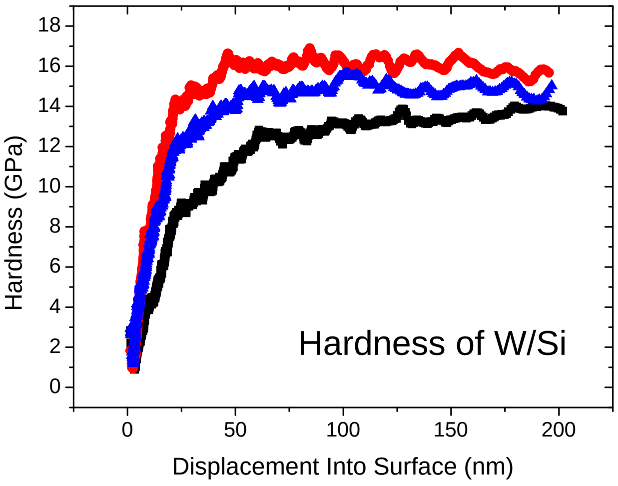
TEM dark field images of a W thin film

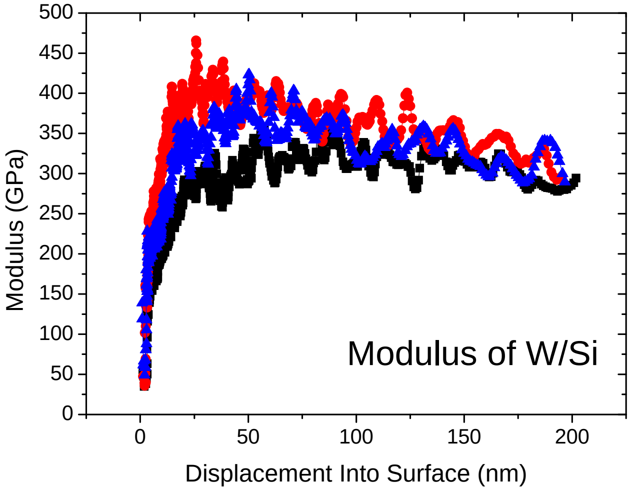


SEM cross section images show a columnar growth

- **The average grain size (column diameter) from SEM and TEM has *Φ* ~ 50- 150 nm.**
- **nW were satisfactorily grown on different substrates keeping the microstructure and morphology.**

Mechanical properties





H.L. Sun et al. J. Mater. Sci. Technol., 2010, 26(1), 87-92.

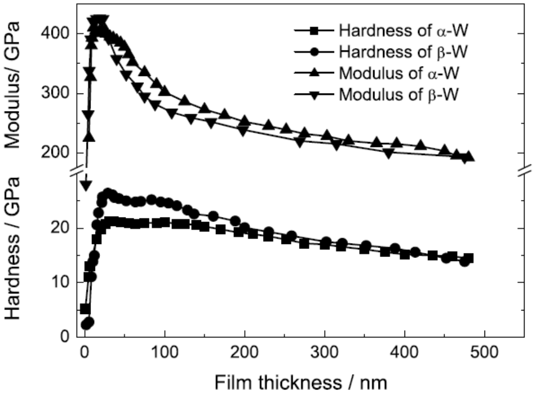
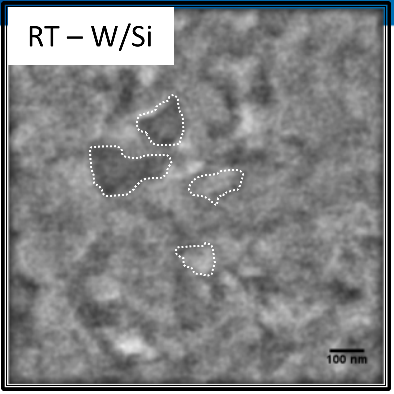


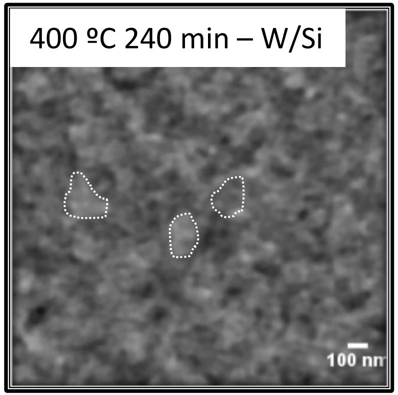
Fig. 6 Hardness and modulus of the deposited and annealed 460 nm W films as a function of indentation depth

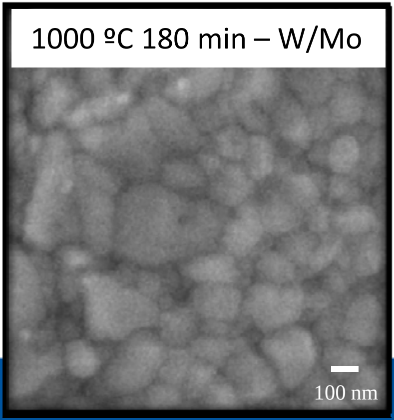
Sample	H (Gpa)	M (GPa)
W/steel	**15±0.5**	**345±3**
W/Si	**14±0.6**	**289±12**
W bulk	2.6	411

A significant enhancement in the hardness is observed from nanoindentation for nW samples deposited on Si and steel compared with bulk W meanwhile the Young’s modulus is slightly lower.

Thermal stability

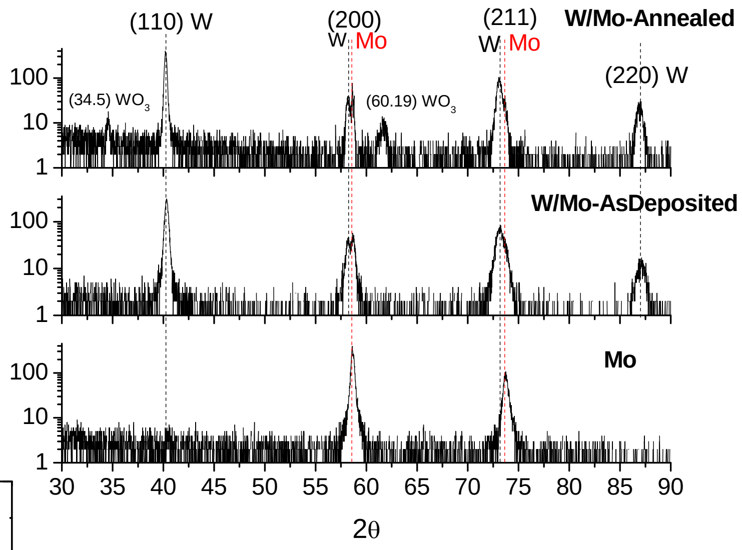

RT – W/Si

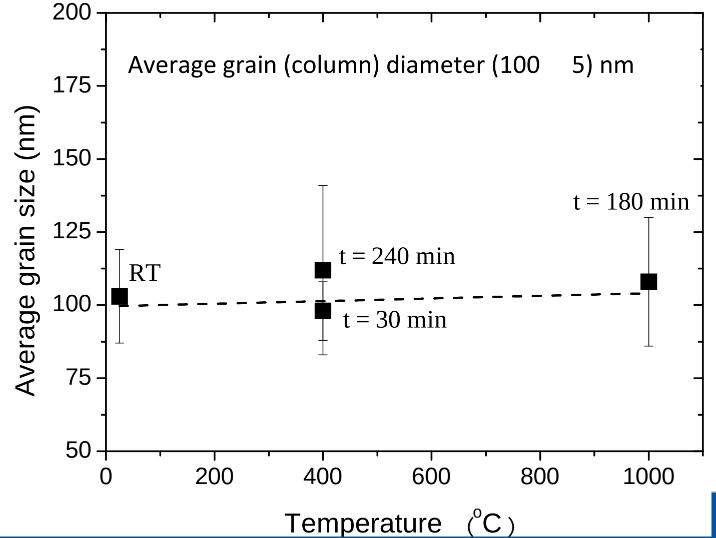

400 ºC 240 min – W/Si


1000 ºC 180 min – W/Mo

The thermal stability study were done for samples deposited on Si and Mo, at different temperatures and times under Ar controlled atmosphere (P~ 10^{-5} mbar)

Sample	T (ºC)	t (min)
nW/Si	400	30
nW/Si	400	240
nW/Mo	1000	180





No significant changes in the microstructure neither grain size evolution is appreciated in the studied temperature range (up to 1000 ºC).

Conclusions

- NanoW thin films with a columnar structure were deposited by DC-magnetron sputtering.
- NanoW coatings were satisfactorily grown on different substrates (Si, Mo, steel) keeping the microstructure and morphology.
- The average grain size (column diameter) from SEM and TEM images is $\Phi \sim$ 50- 150 nm
- No significant changes in the microstructure neither grain size evolution is appreciated in the studied temperature range (up to 1000 ºC).
- A significant enhancement in the hardness is observed from nanoindentation for nW samples deposited on Si and steel compared with bulk W meanwhile the Young's modulus is slightly lower.

Thank you

for your attention