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


Instituto Nuclear de Fusión, ETSI Industriales, UPM, Madrid
Instituto de Energía Solar (IES), UPM
Instituto de Microelectrónica de Matrid IMM-CSIS
Grupo de Espectroscopia de Aniquilación de Positrones. Defectos y Microestructuras, UCM, Madrid
Dpto. Materiales, ETI Caminos UPM, Madrid

nuria.gordillo@upm.es
Institute of Nuclear Fusion
Outlook

• Introduction and state of the art
• Making nanostructured W \( \rightarrow \) 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 to 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
• 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).
• 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
1. W brittleness at $T \leq 400^\circ$C, 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 ($\sim 1300^\circ$C). T. J. Renk, et al. Fusion Engineering and Design 65 (2003) 399.

2. Surface modification at $T < 3400^\circ$C (below the melting point).

Cyclic e-beam heat loads experiments ($H=50$ MW/m$^2$, $t=30$ s) $T_s=\sim 1300^\circ$C. S.Tamura et al. JNM 307–311 (2002) 735.


He irradiation ($E_{He}=50$ keV) $T_s=\sim 1700^\circ$C W. Sakaguchi, et al. Proceedings of ITC 18 (2008).

Surface modification by particle (He and H) and electron beam heating is completely different.
### 3. Light species retention $\Rightarrow$ blistering and material ejection


<table>
<thead>
<tr>
<th>Flux</th>
<th>Time</th>
<th>Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.5 \times 10^{10}$</td>
<td>3600 s</td>
<td>1300 K</td>
</tr>
<tr>
<td>$1.8 \times 10^{10}$</td>
<td>1800 s</td>
<td>1650 K</td>
</tr>
<tr>
<td>$1.7 \times 10^{10}$</td>
<td>600 s</td>
<td>1950 K</td>
</tr>
</tbody>
</table>

**SEM**
- W6: 1300 K
- W7: 1650 K
- W8: 1950 K

**TEM**
- Bubbles

<table>
<thead>
<tr>
<th>Bubble size</th>
<th>SEM</th>
<th>TEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 5$ nm</td>
<td>![SEM Image]</td>
<td>![TEM Image]</td>
</tr>
<tr>
<td>$&lt; 200$ nm</td>
<td>![SEM Image]</td>
<td>![TEM Image]</td>
</tr>
<tr>
<td>$&lt; 500$ nm</td>
<td>![SEM Image]</td>
<td>![TEM Image]</td>
</tr>
</tbody>
</table>

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)

**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.

**Mutliple beams $\Rightarrow$ synergetic effects (K. Tokunaga et al. JNM 390–391 (2009) 916.)**

- $T_s=1127^\circ C$
- $T_s=1258^\circ C$
- $T_s=1165^\circ C$

**SYNERGETIC EFFECTS ARE RELEVANT**
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??

- **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

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$_2$O$_3$ [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

DC-Magnetron sputtering

- HV setup, $P_{\text{base}} \sim 10^{-8}$ mbar
- Growth parameters:
  - Plasma: Ar/W
  - $P_{\text{working}} \sim 10^{-3}$ mbar
  - $V_{\text{dc}}$: 320 V, $I_{\text{dc}}$: 0.15 A
  - Growth rate $\sim 3$-4 Å/s
- Substrates:
  - Si, Mo, steel
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.
The average grain size (column diameter) from SEM and TEM has $\Phi \sim 50$-150 nm.

nW were satisfactorily grown on different substrates keeping the microstructure and morphology.
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.
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)

<table>
<thead>
<tr>
<th>Sample</th>
<th>T (ºC)</th>
<th>t (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nW/Si</td>
<td>400</td>
<td>30</td>
</tr>
<tr>
<td>nW/Si</td>
<td>400</td>
<td>240</td>
</tr>
<tr>
<td>nW/Mo</td>
<td>1000</td>
<td>180</td>
</tr>
</tbody>
</table>

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 °C).

• 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