MeV proton irradiation damage on tungsten

Blisters formation

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I Gavish Segev\textsuperscript{1,2}, E Yahel\textsuperscript{3}, I Silverman\textsuperscript{2} and G. Makov\textsuperscript{1}

\textsuperscript{1}Dept. of Materials Engineering, Ben-Gurion University of the Negev, Beer Sheva 84105, Israel
\textsuperscript{2}Soreq NRC, Yavne, Israel
\textsuperscript{3}Dept. of Physics, NRCN, Beer Sheva 84190, Israel
Introduction:
- SARAF Accelerator
- Tungsten target
Research goals
Experimental part
Irradiation results
Discussion
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Single crystal results
*SARAF Phase-I Accelerator

<table>
<thead>
<tr>
<th></th>
<th>MeV</th>
<th>mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons</td>
<td>4</td>
<td>2 CW</td>
</tr>
<tr>
<td>Deuterons</td>
<td>5</td>
<td>1 CW</td>
</tr>
</tbody>
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*Soreq Applied Research Accelerator Facility (SARAF)
Radiation damage from proton irradiation exhibits specific features (H retention):
* Hydride formation
* Embrittlement
* Nucleation and growth of hydrogen blisters

Radiation damage in Tungsten and its alloys:
  Increased interest
  Choice of tungsten as a structural material in nuclear fusion systems (ITER), and advanced accelerators (ESS).
  Exposing it to high flux, low energy proton plasma, high temperature environment and high energy ions.
Introduction - Why W?

Why Tungsten?

* High Z metal---Low sputtering yield
* Excellent Thermal and Mechanical properties
* Does not create hydrides
* High mobility of H and low solubility---rapid diffusion to surface and evaporation

Nevertheless...

Hydrogen blisters have been identified as a key mode of tungsten degradation under proton irradiation.

Example of Blisters Radiation damage in SARAF beam dump (W)
<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Proton current</td>
<td>0.13-6μA</td>
</tr>
<tr>
<td>Beam flux</td>
<td>$3 \times 10^{12} - 1.4 \times 10^{14}$ Protons/cm$^2$s</td>
</tr>
<tr>
<td>Total dose</td>
<td>$1.4-9.5 \times 10^{17}$ protons/cm$^2$</td>
</tr>
</tbody>
</table>

**Experimental**

- In situ back wall temperature measurement
- Polycrystalline W discs
- Beam diameter: 8mm
- MeV protons beam
- In situ current measurement

**Proton Beam Parameters**

- Protons/cm$^2$s: $1.4-9.5 \times 10^{17}$
- Protons/cm$^2$s: $3 \times 10^{12} - 1.4 \times 10^{14}$
*T affects diffusion processes

Therefore MeV Vs. keV is expected to differ in hydrogen retention, radiation damage evolution and blistering conditions.
The main goal of this research is to explore the effect of irradiation by high energy protons (MeV’s) on blister formation in W.

At these high energies we expect deeper penetration of the protons in W, greater energy transfer and thus higher temperatures, all of which should affect the nature, density, and evolution of the radiation induced defects in the material.

In particular, we shall focus on Nucleation and growth of hydrogen blisters, and the material and irradiation parameters controlling them.
Results - Irradiation T & current

A linear relationship is obtained between the measured temperature and current.

Low scatter - consistency between temperature and flux measurements.
Results - blister formation

SEM

Stereoscope
Results- blisters characterization

Each blister was characterized using 3D optical interferometry. Comparison of blisters obtained at samples with the same total dose and different irradiation T.

At high temperatures, smaller blisters are formed.

340K
- Blister diameter: 700 µm
- Height: 14 µm

640K
- Diameters: 150-250 µm
- Heights: 3.5-6.5 µm

Same total dose: $4.4 \times 10^{17}$ protons/cm$^2$

keVs--T increases: Height decreases; Density decreases

MeVs--T increases: Height decreases; Smaller blisters
Results-Polycrystal W

- Blisters formation as a function of irradiation $T$ and total dose. Dashed lines suggest possible boundaries of blisters formation.

- Critical formation dose $3 \times 10^{17}$ p/cm$^2$.
- A maximum $T$ for blisters formation - keV protons in W: 700-800K
- Critical formation dose in keV protons: $10^{18}$-$10^{20}$ p/cm$^2$

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## Results - blister characterization

<table>
<thead>
<tr>
<th>Irradiation parameters</th>
<th>Diameter range</th>
<th>Total dose [ions/cm²]</th>
<th>Height range</th>
<th>density</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2MeV protons</td>
<td>100-700µm</td>
<td>$10^{17}$</td>
<td>2-15µm</td>
<td>1-10 blisters per 1 mm²</td>
</tr>
<tr>
<td>keV protons</td>
<td>Typical diameter 0.1-3µm</td>
<td>$10^{19}$</td>
<td>0.1-0.5µm</td>
<td>~$10^6$ blisters per 1 mm²</td>
</tr>
<tr>
<td></td>
<td>Max. diameter of 80µm</td>
<td>$10^{21}$</td>
<td></td>
<td></td>
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</tbody>
</table>

- Blisters from MeV protons obtained at low critical dose and very large

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We suggest that the lower critical dose for blister formation in MeV is an outcome of the bulk implantation, far from the surface.

* In MeVs:
  * Hydrogen implanted far from the surface- Decreased H reaches the surface.
  * Decreased recombination of other defects with surface, increases the density of possible traps of H.
  * Decreased sputtering- increases the retained H.
Flux increases, ratio of blister height to area increases.

It could be that larger fluxes/temperatures contribute to higher stresses, allowing smaller area of blisters to elevate the cap.
The cap of the blisters is within several microns of the stopping range for 2.2MeV protons.
1. Poly crystalline W samples were irradiated by 2.2 MeV protons, at a novel regime not explored previously.

2. Large, well developed blisters were obtained at sub critical dose \((3 \cdot 10^{17} \text{ p/cm}^2)\)

3. We correlate it to the bulk implantation, far from the surface.

4. We saw an effect of the irradiation flux\(\text{temperature}\) on blisters dimensions.

5. The blister cap was found to be within several microns with stopping range
**Single crystal- High T results**

* W single crystals (110) irradiated by 2.2MeV protons at SARAF

* Critical blisters formation dose increases to \( \sim 4 \times 10^{18} \text{P/cm}^2 \)

<table>
<thead>
<tr>
<th></th>
<th>2.2MeV</th>
<th>1.5keV</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>PC</td>
<td>SC</td>
</tr>
<tr>
<td>Critical dose[P/cm²]</td>
<td>3 \times 10^{17}</td>
<td>(4 \times 10^{18})</td>
</tr>
<tr>
<td>Blisters diameter[µm]</td>
<td>120-700</td>
<td>50-80</td>
</tr>
<tr>
<td>Blisters Height</td>
<td>2-15µm</td>
<td>50-200nm</td>
</tr>
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</table>

Due to higher critical total dose in SC, Temperature controlled experiments are needed to reach the critical dose at reasonable time.

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Single crystal- High T results

High total dose irradiation
Single crystal - High T results

Temperature Vs Total Dose without cooling

- Poly crystal no cooled
- Single crystal (SC) no cooled

Temperature [K]

Total Dose [microA*hour]
Cooled Target Cell
Results from the cooled target experiments are being analyzed these days,
Please stay tuned...
SARAF Team:
Leo Weissman, Amichay Perry, Hodaya Dafna, Tamir Zchut, Yonatan Mishnayot, Tsviki Hirsh, Ido Silverman, Ilan Eliyahu, Shlomi Halfon, Sergey Vaintraub, Asher Shor, Daniel Kijel.

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