Degradation of Thin Solar-Sail Membrane Films under Interplanetary Medium

Maciej Sznajder

DLR Institute of Space Systems
Bremen, Germany
1. Problematic and motivation
2. The Complex Irradiation Facility
   • Linear proton accelerator
3. Formation of molecular hydrogen bubbles - requirements
4. Formation of molecular hydrogen bubbles - experimental results
5. Protection possibilities of metallic surfaces
6. Impact on the thermo-optical properties
7. Conclusions
Problematic and motivation

Which degradation processes take place in the interplanetary space?

How the sail’s membrane can be protected?
The Complex Irradiation Facility

<table>
<thead>
<tr>
<th>Volume</th>
<th>33.5 l (diameter: 400 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiation target area</td>
<td>80 mm in diameter</td>
</tr>
<tr>
<td>Vacuum pressure</td>
<td>Up to $10^{-10}$ mbar in the empty chamber</td>
</tr>
<tr>
<td>Heating</td>
<td>Halogen spotlights (600 W)</td>
</tr>
<tr>
<td>Cooling</td>
<td>Liquid nitrogen (80 K)</td>
</tr>
</tbody>
</table>

### Proton/electron dual beam

| Energy range                  | 1-10 keV; 10-100 keV       |
| Current range                 | 1-100 nA; 0.1-100 µA        |

### Light sources

| Solar simulator               | 250-2500 nm (5000 W m²)   |
| Deuterium UV lamp             | 112-410 nm (1.65 W m²)    |
| Argon VUV source              | 40-410 nm (50 mW m²)      |

Formation of hydrogen molecular bubbles
(growth mechanism)

The presence of H atoms in metal cause strain in its lattice

H implantation changes the energy of the system (lattice energy), the energy may be decreased by the aggregation of the H atoms into H clusters

When the H and H$_2$ content in the metal exceeds the limit of its solubility, H and H$_2$ start to agglomerate to form bubbles.
Formation of hydrogen molecular bubbles
(growth requirements)

Temperature range of the sample*: 288-573 K,

Minimum dose of H ions: \(10^{16}\) H\(^+\) cm\(^{-2}\),

Kinetic energy of H ions: 1-200 keV,

Impurities and defects within the metal lattice.
Blistering in the interplanetary medium
(temperature requirement)

Material: 7.5 [µm] thick Upilex-S® foil covered on both sides with 100 [nm] vacuum deposited Al layer,

\[ T = \left( \frac{A_a}{A_e} \cdot \frac{\alpha_s}{\varepsilon_t} \cdot \frac{H_{Sun}}{\sigma_{SB}} \right)^{1/4} \]

\[ H_{Sun} = \frac{1}{d^2} \cdot SC \]

\[ \alpha_s = 0.093, \quad \varepsilon_t = 0.017 \]
## Experimental results
(test samples)

<table>
<thead>
<tr>
<th>Probe Symbol</th>
<th>T [K]</th>
<th>E [keV]</th>
<th>D [p+ cm⁻²]</th>
<th>tₛ [days]</th>
<th>t_lab [days]</th>
<th>tₛ/t_lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>323</td>
<td>2.5</td>
<td>7.8 × 10¹⁷</td>
<td>4.8</td>
<td>7.9</td>
<td>0.6</td>
</tr>
<tr>
<td>A2</td>
<td>323</td>
<td>2.5</td>
<td>8.2 × 10¹⁷</td>
<td>5.0</td>
<td>5.5</td>
<td>0.9</td>
</tr>
<tr>
<td>A3</td>
<td>323</td>
<td>2.5</td>
<td>1.3 × 10¹⁸</td>
<td>7.9</td>
<td>10.9</td>
<td>0.7</td>
</tr>
<tr>
<td>B1</td>
<td>300</td>
<td>2.5</td>
<td>4.3 × 10¹⁷</td>
<td>3.6</td>
<td>5.1</td>
<td>0.7</td>
</tr>
<tr>
<td>B2</td>
<td>300</td>
<td>6.0</td>
<td>5.9 × 10¹⁷</td>
<td>4.9</td>
<td>1.8</td>
<td>2.7</td>
</tr>
<tr>
<td>C1*</td>
<td>338</td>
<td>10.0</td>
<td>2.65 × 10¹⁸</td>
<td>13.4</td>
<td>1.9</td>
<td>7.0</td>
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<tr>
<td>C2*</td>
<td>358</td>
<td>10.0</td>
<td>2.65 × 10¹⁸</td>
<td>10.7</td>
<td>3.9</td>
<td>2.7</td>
</tr>
<tr>
<td>C3*</td>
<td>383</td>
<td>10.0</td>
<td>2.65 × 10¹⁸</td>
<td>8.2</td>
<td>1.9</td>
<td>4.3</td>
</tr>
<tr>
<td>D1</td>
<td>323</td>
<td>2.5</td>
<td>2.2 × 10¹⁷</td>
<td>1.3</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>D2 (TNT)</td>
<td>323</td>
<td>2.5</td>
<td>2.2 × 10¹⁷</td>
<td>1.3</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>D3 (TiO₂)</td>
<td>323</td>
<td>2.5</td>
<td>2.2 × 10¹⁷</td>
<td>1.3</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>D4 (SiO₂)</td>
<td>323</td>
<td>2.5</td>
<td>2.2 × 10¹⁷</td>
<td>1.3</td>
<td>1.1</td>
<td>1.2</td>
</tr>
</tbody>
</table>

* Irradiation tests performed with foils where Al. thickness was 1000 nm.
Experimental results

Experimental results

B1 (T = 300 K, E = 2.5 keV, $t_s/t_{lab} = 0.7$)

$\delta_{PR} = 34 \ [\text{nm}]$

0.3% of H\(^+\) deposited in Upilex-S

B2 (T = 300 K, E = 6.0 keV, $t_s/t_{lab} = 2.7$)

$\delta_{PR} = 77 \ [\text{nm}]$

33% of H\(^+\) deposited in Upilex-S
Experimental results

C1 (T = 338 K; \( \frac{t_s}{t_{lab}} = 7.0 \))

C2 (T = 358 K; \( \frac{t_s}{t_{lab}} = 2.7 \))

C3 (T = 383 K; \( \frac{t_s}{t_{lab}} = 4.3 \))

Un-irradiated sample

\[ D = 2.65 \times 10^{18} \text{ p}^+ \text{cm}^{-2} \]
Protection possibilities against bubble formation

100 [nm] Al

\[ d_{PR} = 34 \text{ [nm]} \]

100 [nm] TiO\textsubscript{2}

\[ d_{PR} = 32 \text{ [nm]} \]

200 [nm] TNT

\[ d_{PR} = 32 \text{ [nm]} \]

100 [nm] SiO\textsubscript{2}

\[ d_{PR} = 41 \text{ [nm]} \]
Impact on the thermo-optical properties

100 nm VDA
\[ \frac{\alpha}{\varepsilon} = \frac{0.07}{0.027} \approx 2.6 \]

100 nm VDA exposed to p⁺
\[ \frac{\alpha}{\varepsilon} = \frac{0.09}{0.028} \approx 3.2 \]

\[ D = 1.4 \times 10^{17} \text{ p⁺ cm}^{-2} \]
\[ T = 323 \text{ K} \]
\[ t_s \approx 1 \text{ day at 2.46 AU} \]
Conclusions

Bubble formation mechanism in the interplanetary medium:
• Temperature range: 300 to 383 K (1.75 to 2.85 AU)
• $p^+$ energy range: $E_{\text{kin}} \lesssim E(\text{thickness of Al})$
• Bubble agglomeration on micro-scratches of Aluminum
• Acceleration factor: up to 7.0
• TiO$_2$ and SiO$_2$ are suited to shield the Aluminum and therefore prevent the bubble formation