Micro-Architectured Materials for Electric Propulsion and Pulsed Power

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Brian Williams (Ultramet)

Collaborators
Alp Sehirlioglu (Case Western)
Richard Wirz (UCLA)

AFOSR Program on Materials and Processes Far From Equilibrium
Objectives and Project Structure.

Severe, Non-equilibrium Material Environment for Electric Propulsion & Pulsed Power.

Material Damage & Failure Mechanisms.

Manufacturing of refractory metal architectures.


Modeling of Particle-Surface Interaction.

Surface Instabilities.
Project Objectives

- Enable the development of plasma-resilient, micro-architected materials for the severe, far-from-equilibrium plasma and ion environments in electric propulsion and pulsed power systems.

- Utilize multiscale modeling & experimental verification to understand the mechanisms that limit plasma performance and material lifetime.

- The focus will be on refractory metals in various architectures (e.g. W, Re, Mo) and on candidate fiber reinforced ceramics (e.g. BN).

- The aim is to develop the basic science of materials in the extreme energetic plasma environment, and during electron & ion pulsed power operation.
**Approach and Methodology**

**Approach:**
1. Evaluation of surface performance and behavior
   - Measurement of erosion yields (sputtering & exfoliation)
   - Measurements of ion and electron induced secondary electron emission
   - Measurement of performance-limiting surface properties (emissivity, reflectivity, HV standoff, etc.)
3. Evaluation of surface stability and modification in representative environment(s)
   - High sputter-rate plasmas
   - Plasmas with re-deposition
   - High heat flux
   - Other environments (co-deposition, etc.)

**Method:**
1. Exposure to plasma bombardment from plasma sources
2. Exposure to high heat fluxes from arc-jets & e-guns
Propulsion & Aerospace (Wirz - UCLA).
Plasma science and technology (Goebel – JPL/ UCLA, Raitses, Kaganovich - PPPL).
Material characterization (Sehirlioglu - CW).
Materials engineering and high heat flux testing (Sharafat - UCLA).
Refractory and ceramic material processing and fabrication (Williams - ULTRAMET).
Multiscale modeling (Ghoniem - UCLA).
## Environments for Hall Thrusters

<table>
<thead>
<tr>
<th>Device</th>
<th>Particle Flux (#/m²/s)</th>
<th>Particle Energy (eV)</th>
<th>Heat Flux (MW/m²)</th>
<th>Pulse Duration (s)</th>
<th>Ion/Photon Type</th>
<th>Material</th>
<th>Life Fluence (TJ/m²)</th>
<th>Lifetime (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall thrusters</td>
<td>1x10²¹</td>
<td>50 – 300</td>
<td>0.05</td>
<td>CW</td>
<td>xenon</td>
<td>Boron nitride</td>
<td>3</td>
<td>1 - 2</td>
</tr>
<tr>
<td></td>
<td>5x10²²</td>
<td>30 - 100</td>
<td>0.8</td>
<td>CW</td>
<td>electron</td>
<td></td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

- **Anode gas feed**
- **Cathode gas feed**
- **Hollow cathode**
- **Boron nitride rings erode**
- **Thruster center line**
Surface Damage of BN/Borosil

**U.S. Hall Thruster**

- BPT-4000, 5,800 hrs

**Russian Hall Thruster**

- SPT-100, 6,900 hrs

**French Hall Thruster**

- BPT-4000, 10,400 hrs
- PPS-1350, 10,530 hrs

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**Environments for Ion Thrusters**

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<th>Material</th>
<th>Life Fluence (TJ/m²)</th>
<th>Lifetime (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion thruster</td>
<td>- screen grid</td>
<td>3x10²⁰</td>
<td>25-50</td>
<td>0.0025</td>
<td>CW</td>
<td>Xenon</td>
<td>Moly</td>
<td>0.4</td>
<td>3 - 5</td>
</tr>
<tr>
<td></td>
<td>- accel grid</td>
<td>6x10¹⁸</td>
<td>250-500</td>
<td>0.0005</td>
<td>CW</td>
<td>Moly</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- cathode</td>
<td>6x10²¹</td>
<td>25-50</td>
<td>0.05</td>
<td>CW</td>
<td>Mo/W</td>
<td>7.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*grid erosion is major issue
Environment for MPD Thrusters

<table>
<thead>
<tr>
<th>Device</th>
<th>Particle Flux (#/m²/s)</th>
<th>Particle Energy (eV)</th>
<th>Heat Flux (MW/m²)</th>
<th>Pulse Duration (s)</th>
<th>Ion/Photon Type</th>
<th>Material</th>
<th>Life Fluence (TJ/m²)</th>
<th>Lifetime (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MPD thrusters</td>
<td>10^{24}</td>
<td>50 – 100</td>
<td>8</td>
<td>10⁻³ - CW</td>
<td>Li, electron</td>
<td>Copper, W</td>
<td>0.5</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>2x10^{23}</td>
<td></td>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
<td>0.1</td>
<td>0.1 -2</td>
</tr>
</tbody>
</table>

*cathode issues primarily focused on ion erosion and high heat flux
**anode issues are high heat flux and high energies (causing erosion)*
Blisters and Fuzz @ 50 eV

Blisters on a powder met W, 550K, H plasma, 90 eV, fluence $3.4 \times 10^{26}$ H/m$^2$

He hole/bubble formation on a powder met W, 2200K, He plasma, 15 eV He, $8.3 \times 10^{22}$ m$^2$/s, (a) 1000 s, (b) 10000 s.

Ohno, Kajita, Nashijima, Takamura, (Nagoya U.)
Surface modification of W and W-coated graphite due to low energy and high fluence plasma and laser pulse irradiation,

NAGDIS-II: pure He plasma
1250 K, 36,000 s, $3.5 \times 10^{27}$ He+/m$^2$, $E_i = 11$ eV
Ohno et al., Nagoya U.
Transmission electron microscope (TEM) by Kyushu University

PISCES-B: He plasma
1200 K, 4290 s, $2 \times 10^{26}$ He+/m$^2$, $E_i = 25$ eV
Baldwin et. al, Center for Energy Research, UCSD,

1-6 TJ/m$^2$ @ 10-100 eV

0.1 TJ/m$^2$ @ 10-100 eV
## Environments for TWTs/Gyrotrons

<table>
<thead>
<tr>
<th>Device</th>
<th>Particle Flux (#/m²/s)</th>
<th>Particle Energy (eV)</th>
<th>Heat Flux (MW/m²)</th>
<th>Pulse Duration (s)</th>
<th>Ion/Photon Type</th>
<th>Material</th>
<th>Life Fluence (TJ/m²)</th>
<th>Lifetime (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gyrotrons (collector)</td>
<td>2x10²¹</td>
<td>≈100kV</td>
<td>16</td>
<td>10⁻³- CW</td>
<td>Electron</td>
<td>Copper</td>
<td>2.5</td>
<td>1-5</td>
</tr>
<tr>
<td>Traveling Wave Tubes (collector)</td>
<td>1x10²⁰</td>
<td>1 – 10 kV</td>
<td>0.16</td>
<td>10⁻³- CW</td>
<td>Electron</td>
<td>Copper, moly, graphite</td>
<td>0.15</td>
<td>25</td>
</tr>
</tbody>
</table>

*high electron heat flux in collector*
Environments for HPM Sources

<table>
<thead>
<tr>
<th>Device</th>
<th>Particle Flux (#/m²²/s)</th>
<th>Particle Energy (eV)</th>
<th>Heat Flux (MJ/m²)</th>
<th>Pulse Duration (s)</th>
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<th>Material</th>
<th>Life Fluence (TJ/m²)</th>
<th>Lifetime (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPM sources</td>
<td>1x10²²</td>
<td>0.1-1MV</td>
<td>1600</td>
<td>10⁻⁷-10⁻⁵</td>
<td>Electron</td>
<td>Copper, moly, W</td>
<td>0.05 (1 Hz)</td>
<td>5 (100 Hz)?</td>
</tr>
</tbody>
</table>

*high electron heat flux in resonant structure and in the e-beam collector
Pulsed Power Material Damage Characteristics

Heat Flux: ~7 MW/m²

Gyrotron Damage
Coolant Leak  Columnar Grain Growth¹


¹Courtesy Communications & Power Industries http://www.cpii.com/
Heat Flux on Materials in EP & PP Applications

**LIFETIME ENERGY-FLUENCE BY ELECTRONS & IONS**

- FET
- HALL
- TWT
- HPM*
- GYROTRON
- MPD-Anode
- ION-Cathode
- ION-Accel Grid
- ION-Screen Grid

*Energy Fluence (TJ/m²)*

- *Pulse Duration: 10⁻⁷ - 10⁻⁵ s*

**HEAT FLUX DUE TO IONS/ELECTRONS**

- FET
- HALL
- TWT
- HPM*
- GYROTRON
- MPD
- ION-Cathode
- ION-Accel Grid
- ION-Screen Grid

*Heat Flux (MW/m²)*

- *Pulse Duration: 10⁻⁷ - 10⁻³ s*

1SRIM Calculations: [http://www.srim.org/SRIM/SRIMLEG.html](http://www.srim.org/SRIM/SRIMLEG.html)

Research Tasks


>> Task (3): In-situ testing and modeling of plasma-material interactions.

>> Task (4): Measurements and modeling of secondary electron emission in architecture material surfaces.

>> Task (5): Erosion and thermo-mechanical experiments on architecture materials.

>> Task (6): Characterization of materials microstructure and properties.
Micro-Architectured Surfaces (Meta-Materials)

**Refractory Metal Networks**
- Isotropic
- Anisotropic

**Textured Refractory Surfaces**
- Micro-spears
- Micro-Nodules
- Micro-Velvets & Micro-brushes
Performance-Enhancement Potential of Micro-Architectured Surfaces

- Electron & ion energies are distributed into 3-D architectured structures of great surface area promoting better heat distribution.

- Net sputtering erosion due is minimized because of geometric trapping of re-deposited atoms.

- Implanted ion residence time in the material is reduced due to fine surface features, thereby facilitating rapid and preventing formation of bubbles and blisters.

- Thermal stress is reduced because fine surface features are capable of a greater level of distortion.

- The high thermal and dimensional stability of CVD refractory armor prevents fragmentation and dust formation.
Textured Coatings: Ultramet applies high-emittance dendritic rhenium coatings in a production environment to tungsten cathodes used in special-purpose, high-wattage discharge lamps for semiconductor microlithography. These components operate at an impressive 2700°C for 100,000 hours.

Ultramet also applies thin dendritic rhenium coatings to the outer surface of radiation-cooled iridium-lined rhenium combustion chambers used in satellite propulsion systems with over 75 units now in space.
A minimum of eight material and process variations will be selected from the following potential variables:

1. Matrix material: BN, Si$_3$N$_4$, AlN, TiO$_2$, Al$_2$O$_3$;
2. Matrix infiltration process: CVI and MI;
3. Fiber material: alumina, alumina-silica, silicon carbide, carbon;
4. Surface layer: variable thickness CVD coatings to reduce fiber conductivity contribution.
MATERIALS TESTING PLANS

Materials testing is divided into three categories:
- High heat flux environments
- Plasma sputtering environments
- Low-energy electron bombardment environments (secondary electron yields)

1) **High Heat-flux Testing**
   - Addresses requirements found in vacuum tubes (gyrotrons) & HPM sources
   - Use a modified arc-jet to provide high power, low energy bombardment of material samples at UCLA
   - High power e-beam facilities (at SNLA) will be used later in the program for evaluation of final-engineered materials

2) **Plasma/Sputtering Testing:**
   - Biased samples inserted into the plasma from an rf plasma source at UCLA will be used to measure the sputtering yield of the engineered materials
   - The PISCES Plasma-Surface Interactions facility at UCSD can be used as a backup for sputtering measurements

3) **Secondary Electron Yield Testing:**
   - The facility at PPPL will be used to characterize the secondary electron yield of insulator materials intended for Hall thrusters and other emerging thruster applications
Electron emission from the wall can increase the plasma heat flux to the wall many times.

- Without SEE, sheath of space charge near the wall reflects most electrons back to the plasma, thus effectively insulating wall from the plasma (Right Figure).

- SEE reduces the wall potential and allows large electron flux to the wall (Left Figure).

\[ \phi_w \approx 6T_e \]

\[ \phi_w \approx T_e \]

Wall - Sheath - Plasma

Wall – Sheath - Plasma

\( \Gamma_i \)

\( \Gamma_e \)

\( \Gamma_{\text{see}} \)

Y. Raitses et al., Phys. Plasmas 2005

Y. Raitses et al., IEEE TPS 2011
For many plasma applications, electron heat flux to the wall needs to be calculated kinetically. Large quantitative disagreement between experiments and fluid theories for predictions of the electron temperature in Hall thrusters.

Kinetic simulations predict electron velocity distribution function to be non-Maxwellian (anisotropic, depleted, with beams of SEE electrons) leading to a reduced heat flux compared to fluid theory predictions, but enhanced cross-field transport.

New non-stationary regimes of plasma-wall interactions are discovered by particle-in-cell simulations.

Classic theory of Hobbs and Wesson cannot be applied to Hall thruster plasma conditions.
Task 6: Characterization of Materials Microstructure – Sehirlioglu (Funded Separately)

- Temperature dependence of properties.

- Microstructure characterization for: (1) structure-property relationships, (2) preferential erosion sites, (3) erosion rate differences as a function of grain orientation.

- Surface characterization: roughness, chemistry, and ion interaction depth

- Introduction of chemicals as sintering aids to modify the overall chemistry and control several key properties:
  - 1. Create phonon scattering to decrease thermal conductivity
  - 2. Increase bonding strength
  - 3. Modify electrical properties and the band gap structure.
Task 2: Modeling Plasma and Ion Effects on Materials - Ghoniem

Task 2.1: Modeling Thermomechanics of Micro-architectured Surfaces: Multi-physics modeling of energy & particle deposition in CW & pulsed power, FEM modeling of coupled heat conduction, elastoplasticity, and surface fracture.

Fractional Implantation Profile of Xenon in Tungsten & BN

Hall Thruster Flux = $1 \times 10^{17}$ cm$^{-2}$ s$^{-1}$

Atoms/cm$^2 = 1.6 \times 10^{15}$
Vacancy Production in Surface Layers Leads to Surface Instabilities

\[ \nabla \cdot \mathbf{U} = -z m \Delta \xi, \]

\[ \frac{\partial^2 \xi}{\partial t^2} + \frac{c^2 h}{12} \Delta^2 \xi - \frac{c^2}{2} \sigma_{ij} \frac{\partial^2 \xi}{\partial t \partial x_i} - \frac{\theta_v}{\rho h} (C_+ - C_-) = 0, \]

\[ \partial_t C = D_\perp \frac{\partial^2 C}{\partial z^2} + D_{\parallel} \Delta C - \frac{C}{\tau} + \nabla \frac{\theta_v D_{\parallel} C}{kT} \nabla (\nabla \cdot \mathbf{U}) \]

\[ + \nabla_z \frac{\theta_v D_{\parallel} C}{kT} \nabla_z (\nabla \cdot \mathbf{U}) + g \exp[-\frac{E_f}{kT}] (1 + \theta_v \nabla \cdot \mathbf{U}) \]


FIG. 14.20. Groove patterns seen under a biaxial stress state in which one side is under tension and the other is under compression [713].

FIG. 14.21. Phase diagram for roughening (crack) pattern selection in biaxially
Plasma Sheath Modeling

Deep Sheath

\[ \lambda_d = \sqrt{\frac{\varepsilon_0 k T_e}{n_0 e^2}} \approx 740 \sqrt{T_{eV}/n_0} \]

Shallow Sheath

Graph showing Debye Length (\(\mu m\)) vs. Plasma Density (1/cm\(^3\)) for a 10 eV Plasma.