Plasma Interactions with Materials and Metamaterials

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MIPSE Seminar
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UCLA Plasma & Space Propulsion

Plasma Technology

Electric Propulsion, Plasma Devices, Cathodes

Plasma-Material Interactions

Plasma Confinement

i-SEE
e-SEE
i-n

Canonical Experiments for Plasma Model Validation

Applied Plasma Science
“Plasma Propulsion”

A.K.A. Electric Propulsion (EP)
**Chemical & Electric Propulsion**

\[ \text{Thrust} = \dot{m}v_{ex} \]

**Chemical Propulsion**
- Propulsion energy in Fuel/Ox chemical energy
- \(v_{ex}\)-limited by the propellant’s energy density

\[ v_{ex} \approx 3 - 4 \text{ km/s} \]
\[ T \approx 1 \text{ N} - 100\text{ N} \]

**Electric Propulsion**
- Propulsion energy from “Power System” (unlimited)
- Thrust-limited by the available electric power

\[ v_{ex} \approx 5 - 100\text{+ km/s} \]
\[ T \approx 0.1 - 100\text{+ mN} \]
Propellant Mass Req’t

Rocket Equation

\[
\frac{m_{\text{propellant}}}{m_{\text{payload}}} \approx \exp \left( \frac{\Delta V}{v_{\text{ex}}} \right) - 1
\]

Effective Exhaust Velocity, \( v_{\text{ex}} \) [km/s]

\( \Delta V \sim 4 \text{ km/s} \)

Chemical system

EP system

\( \therefore v_{\text{ex}} \sim \text{propellant efficiency} \)
Mission Impulse \( = \int Thrust \times dt \)
Electric Propulsion
Research Areas

Plasma Physics
- Charged particle motion/interactions

Thruster/Cathode
- Thruster/Cathode Development
- Thruster Cathode Miniaturization
- Plasma Production & Confinement
- Plasma-Material Interactions

Spacecraft Interactions
- Plasma-Material Interactions
- e-SEE / i-SEE
Electric Propulsion Technologies

Ion Thrusters

Plasma Thrusters & Cathodes

Electrospray Thrusters
Plasma-Material Interaction (PMI)
**Plasma-Material Interaction (PMI)**

**Plasma Presheath**

\[(EEDF, n, T, \phi)\]

**Sheath**

\[(EEDF, n, T, \phi)\]

**Material Surface**

\[(T, Q, \varepsilon, \sigma)\]

**Plasma Effects:**
- Cooling
- Contamination
- Sheath modification

**Material Effects:**
- Heating
- Erosion/damage
- Prop. modification
Plasma-Material Interaction (PMI)

**Plasma Presheath**

(EEDF, $n$, $T$, $\phi$)

**Sheath**

(EEDF, $n$, $T$, $\phi$)

- **Surface (T, Q, $\varepsilon$, $\sigma$)**

**Material (Q, $\varepsilon$, $\sigma$)**

### Material/Surface Modifications

**Material Properties**: Quality factor ($Q$), permittivity ($\varepsilon$), conductivity ($\sigma$)

**Kinetic Mechanisms**: Sputter, deposition/redeposition, deformation, fracture, flaking, evaporation, etc.

<table>
<thead>
<tr>
<th>Species</th>
<th>~Power (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i^+ (~2-50$ eV)</td>
<td>0.3</td>
</tr>
<tr>
<td>$e^- (~2-10$ eV)</td>
<td>0.5</td>
</tr>
<tr>
<td>$hv (~12$ eV, AR-VUV)</td>
<td>0.3</td>
</tr>
</tbody>
</table>
PMI Experimental and Modeling Efforts

Bulk/Presheath Plasma

Plasma Sheath

Material

Large-scale plasmas (Pi) & Microplasmas

i-SEE

e-SEE

Material Analyses

DC-ION

Sheath modeling

Material Modeling

Experiments

Models

Pi = UCLA Plasma-Interactions Facility
PMI = Plasma Material Interactions
PMI Applications

• Electric Propulsion

• Microplasmas
  - AFOSR MURI: “Plasma-Based Reconfigurable Photonic Crystals and Metamaterials”
    • Stanford, Penn State, Texas, Tufts, UCLA, UW

• Other
  - TWTs, Gyrotrons, High Power Microwave (HPM)
  - Fusion devices
PMI Diagnostics & Modeling

- **Diagnostics**
  - **Diagnostic**
    - Langmuir probes
    - Faraday probe
    - Emissive probes
    - $E\times B$ probe
    - Retarding Potential Analyzer (RPA)
  - **Measurement**
    - $n_e, T_e$
    - 1-D ion energy/flux
    - plasma $\phi$
    - species mix
    - ion energies
  - **Intrusive**
    - Quartz Crystal Microbalance (QCM)
    - Emission Spectroscopy (OES)
    - Laser Ti:Sapphire (+ doubler)
    - Micro-ion gauges
    - Residual Gas Analyzer (RGA)
    - Long Distance Microscopy (LDM)
    - High Speed Videography
  - **Non-intrusive**
    - Ex-situ: SEM, EDS, XRD, profilometry, precision scale

- **Modeling**
  - **Plasma Confinement**
    - Multi-species
    - Multi-physics
    - 2D/3D
  - **Ion Extraction and species interactions**
    - i-n
    - MEX
    - CEX
  - **Plasma-Material Interactions**
    - e-SEE, i-SEE, i-n
    - Sputtering
  - **Device Performance and Lifetime**
UCLA-Pi Facility: Examine the behavior of materials for a wide range of plasma conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma density</td>
<td>( \sim 10^{15} ) to ( 10^{18} ) m(^{-3})</td>
</tr>
<tr>
<td>Electron temperature</td>
<td>1 to 10 eV</td>
</tr>
<tr>
<td>Ion energy</td>
<td>10 to 400 eV</td>
</tr>
<tr>
<td>Ion flux to target*</td>
<td>( 10^{21} ) to ( 10^{23} ) m(^{-2})s(^{-1})</td>
</tr>
<tr>
<td>Target area</td>
<td>( \approx 5 ) cm(^2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Langmuir probes</td>
<td>( n_e, T_e )</td>
</tr>
<tr>
<td>Faraday probe</td>
<td>1-D ion energy/flux</td>
</tr>
<tr>
<td>Emissive probes</td>
<td>plasma ( \phi )</td>
</tr>
<tr>
<td>( E \times B ) probe</td>
<td>species mix</td>
</tr>
<tr>
<td>Retarding Potential Analyzer (RPA)</td>
<td>ion energies</td>
</tr>
<tr>
<td>Quartz Crystal Microbalance (QCM)</td>
<td>differential/angular sputter</td>
</tr>
<tr>
<td>Emission Spectroscopy (OES)</td>
<td>relative species properties</td>
</tr>
<tr>
<td>Laser Ti:Sapphire (+ doubler)</td>
<td>species properties/motion</td>
</tr>
<tr>
<td>Micro-ion gauges</td>
<td>neutral density</td>
</tr>
<tr>
<td>Residual Gas Analyzer (RGA)</td>
<td>partial gas densities</td>
</tr>
<tr>
<td>Long Distance Microscopy (LDM)</td>
<td>surface morphology/imaging</td>
</tr>
<tr>
<td>Ex-situ: SEM, EDS, XRD, profilometry, precision scale</td>
<td>surface imaging, composition, mass loss</td>
</tr>
</tbody>
</table>

AFOSR DURIP, FA2386-13-1-3018
Matlock, Goebel, Conversano, Wirz, PSST (2014)
Movie: Pi Facility in operation. Target at far right, source at far left.
Many Eyes…

Spectrometer Results for Xe on W

The need for non-intrusive diagnostics

**Movie 1**: shows electrostatic probe disturbing the plasma in the Pi Facility very near the target surface

**Movie 2**: shows “green glow” of sputtered atoms excited near the target surface

YouTube Link: https://www.youtube.com/watch?v=RxRyxiMQt5M

YouTube Link: https://www.youtube.com/watch?v=6k_X5q5lUWQ
OES: Xe on W

Increased ion energy causes “green glow” from W sputterants

Li G., Wirz R., Physics of Plasmas, in prep (2016)

PMI FOR MICRO-ARCHITECTURED SURFACES

Dr. Chris Dodson
Cesar Huerta
Gary Li
Ani Thuppul
Angelica Ottaviano
Radial fluence variation

Increasing fluence

Note: Radial flux gradient enables analysis of multiple sites across the surface that experience different levels of fluence over during plasma exposure. Thus providing greater insight into material lifetime and erosion mechanisms.

Sputtering Yield Analysis: QCM

- QCM diagnostic provides the first-ever in-situ measurements of sputtering yield for a microarchitected surface
- Shows reduction in sputtering yield for more highly featured surfaces

\[
\frac{dy(\alpha)}{d\Omega} = \left( \frac{R(\alpha) A_x N_A}{m} \right) \frac{J_1}{e} \left( \frac{A_x}{r_{QCM}^2} \right)
\]

sputtered atoms incident on QCM \quad ions incident on target \quad solid angle subtended by QCM

\[
Y = \int_0^{2\pi} \int_0^{\pi/2} \frac{dy(\alpha)}{d\Omega} \sin(\alpha) \ d\alpha \ d\phi
\]

Modeling PMI for Featured Surfaces

- Technique
  - Monte Carlo VF sputtering erosion model

- Results
  - Reduction in net erosion with featured surfaces due to sputter-deposition
  - Increased erosion with surface pitch

Long-Distance Microscopy (LDM)

- **Objective:** In-situ observation of material response to plasma

- **Capabilities:**
  - Enables in-situ high-resolution imaging of surface structures
  - Focus variation profilometry (FVP) enables height maps and image reconstruction (see next slide). Used to track surface morphology changes in-situ
  - 2.8 µm lateral resolution, 33 µm depth of field @ 650 nm
  - < 2.8 µm height resolution

- **Challenges to Long-Distance Microscopy**
  - Stabilization: vibrations, thermal drifts
  - Lighting
  - Image processing difficult for highly-structured surfaces
In-Situ Observation of Plasma-Foam Interaction

- First-ever *in-situ* observation of plasma interaction with a textured surface
- 17-hour plasma exposure (300 V ions)

**Composite 3D video of images from LDM Focus Variation Profilometry**

**3D Video after stabilization, normalization, and filtering**

**Depth Map 3D Video**

PLASMA-MATERIAL INTERACTIONS...

SECONDARY ELECTRON EMISSION (SEE)
PMI - Effects of SEE

- Reduced sheath potential in plasma devices\(^1\) (plasma thrusters,\(^2\)-\(^4\) plasma processing,\(^5\)-\(^6\) fusion\(^7\)-\(^10\))
  \[ \phi_{\text{sheath}} = T_e \ln \left( \frac{1 - \delta}{\sqrt{2\pi m_e/m_i}} \right) \]
  \(\phi_{\text{sheath}} \sim 3T_e\)
  \(\phi_{\text{sheath}} \sim T_e\)
  \(\rightarrow\) Increased plasma heat flux to the wall
  \(\rightarrow\) Increased power losses
- \(e^-\) multipacting & cloud formation in accelerators\(^11\)-\(^12\)
  \(\rightarrow\) beam instabilities & overheating

e-SEE, for tungsten “fuzz”

PMI: e-SEE modeling (results)

Multi-dimensional Monte Carlo model developed to predict e-SEE for featured surface geometries

Copper carpet

Vertical Fibers

Substrate

Tungsten fuzz

Horizontal Fibers

Substrate

Data: Curren, et al. (1990)

**Objective:** Characterize ion-induced SEE (i-SEE) for relevant plasma environments.

**Approach:** Use canonical “test-cell” experiment to assess i-SEE in controlled environment

- HV (10^-8 Torr) facility with mass analyzed ion beam (0.5-2 keV)
- Materials under investigation
  - Graphite (calibration)
  - C velvet
  - SS-316
- Preliminary results, \( \gamma_{1.5\text{keV} \text{Xe}^+ \text{on SS-316}} \approx 0.3 \)
- Collaboration with Dr. Lee Johnson, JPL

**Previous/related efforts:** Characterized ion-atom collision for validation of plasma models\(^1\-^5\)

Related output:
i-SEE, for carbon “velvet”

L_{fiber} = 2.6\text{mm}, D_{fiber} = 6.8\text{\mu m}

Dennison et al. (2003) 8th Spacecraft Charging Technology Conference
Plasma Metamaterial Interactions

Nolan Uchizono

Stephen Samples
Surface Plasmon Polaritons (SPPs)

EM waves in dielectric
“Polariton”

Metal-dielectric interface

Charge motion in metal
“Surface Plasmon”

“Plasma-based reconfigurable photonic crystals and metamaterials” AFOSR MURI 2015
Stanford, UCLA, U. Texas, Tufts, Penn State, U. Washington
Plasma-Functionalized Metamaterials

- **Objective:** Plasma-functionalization of metamaterial microwave circuit transmission lines

- **Microstrip Waveguides:** used commonly by microwave electronics for EM wave transmission\(^1\)

- **Plasma-Functionalization:** Plasmas can be used to modify the strong field region between the upper strip and ground plane

- **Approach:** Use slow-wave metamaterial microstrips where signal is carried by “spoof” surface plasmon polaritons above the surface.

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Spoof surface plasmon polaritons (SSPPs)

- Corrugated structures support “spoof” surface plasmon (SP) EM waves propagating at dielectric–metamaterial interfaces

- Equivalent circuit element representation
  - Models the unit cell with lumped parameters

- Plasma-functionalization: plasma at the interface expected to alter the dispersion
  - Lumped parameters can approximate plasma effects

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Plasma Modification of Spoof Plasmons

Transmission Gain ($S_{21}$)

Surface plasmon resonance

Plasma Modification of Spoof Plasmons

Experiment

Model (HFSS)
UCLA “Open Plasma” Experiment

Functionalized Microstrip Concept Product

Microstrip with Tungsten Filament Cathode

Microstrip with Small Hollow Cathode
Plasma-Surface Plasmon Polaritons

**Plasma frequency**

\[ \omega_p = \sqrt{\frac{n_e e^2}{m \varepsilon_0}} \]

**Plasma “Drude” permittivity**

\[ \varepsilon_p(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\omega\gamma} \]

**SP resonance**

\[ \omega_{sp} = \frac{\omega_p}{\sqrt{1 + \varepsilon_d}} \]
Tunable microstrip response

Frequency-tunable microstrip via SSP/Plasma-SPP interaction

\[ n_e = 2.29 \times 10^{17} \text{ m}^{-3} \]

\[ n_e = 1.11 \times 10^{17} \text{ m}^{-3} \]

\[ n_e = 6.49 \times 10^{16} \text{ m}^{-3} \]

\[ n_e = 5.30 \times 10^{16} \text{ m}^{-3} \]

\( \nabla n_e \), average \( n_e = 1.11 \times 10^{17} \)

\( \nabla n_e \) produces range of excitation frequencies

Frequency \( k_x [\text{m}^{-1}] \)

\[ k_{x,\text{plasma}} = \frac{\omega}{c} \frac{\varepsilon_p \varepsilon_d}{\sqrt{\varepsilon_p + \varepsilon_d}} \]

\[ k_{x,\text{microstrip}} = \frac{1}{d} \cos^{-1} \frac{1 - S_{11}S_{22} + S_{21}S_{12}}{S_{21}} \]
Plasma-Metamaterial “Reciprocal-Coupling”? 

Magnetized “open plasma” over split microstrip

4 mm gap

split microstrip

“bulb plasma”

“Source” Microstrip surface waves

Surface Plasma Polaritons (in plasma)

“Receiver” Microstrip surface waves

Metamaterial 1

Spoof-SPP coupling to Plasma-SPP’s

Plasma-SPP propagation in gap

Metamaterial 2

Plasma-SPP coupling to Spoof-SPP’s
Plasma-Metamaterial “Reciprocal-Coupling”? Yes!

- "Source" Microstrip surface waves
- Surface Plasma Polaritons (in plasma)
- "Receiver" Microstrip surface waves

Metamaterial 1
Spoof-SPP coupling to Plasma-SPP’s
Plasma-SPP propagation in gap
Plasma-SPP coupling to Spoof-SPP’s

Graphs showing:
- Microstrip reflection loss ($S_{11}$)
- Transmission gain ($S_{21}$)

Results:
- 20dB reduction in loss
- 15dB increase in transmission

Uchizono, Wirz, “Reciprocal coupling of surface plasmon polaritons using overdense plasma,” in prep PoP
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Canonical Experiments for Plasma Model Validation

Applied Plasma Science
Funding & Collaborations

Funding

DOD
NASA
AFRL
AFOSR
U.S. Department of Energy
NSF

Collaborations

JAXA
ICPP
Institute of Geophysics and Planetary Physics
University of California, Los Angeles
The Aerospace Corporation
Michigan
Technische Universität Dresden
Stanford
Penn State
Carlos III de Madrid
MIT
Princeton University
THANK YOU!

QUESTIONS?

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