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Electron Yield of Challenging Materials: Low Density Polyethylene and Carbon-composite Nanodielectrics

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NASA-JPL (Europa Lander)
AFRL
Box Elder Innovations
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Sienna Technologies

(Back row Left to Right) Ben Russon, Heather Zollinger, Zack Gibson, Matthew Robertson, Jordan Lee, David King

(Front row Left to Right) Justin Christensen, Alexandra Hughlett Nelson, Alex Souvall, Greg Wilson, Allen Andersen, JR Dennison, Windy Olsen

(Not pictured) Brian Wood, Vladimir Zavyalov, Jodie Gillespie, Jonh Mojica Decena, Tyler Kippen, Lisa Phillipps, Phil Lundgreen, Tanner Linton
Interactions with this harsh space environment can modify materials and cause unforeseen and detrimental effects to spacecraft. Therefore, we:

• simulate the space environments,
• characterize their effects on materials properties,
• use these results to predict and mitigate space environment effects,
• work to understand the materials physics involved at the atomic scale to
• extend our work to more diverse problems and materials.

Bottom line for the **USU Materials Physics Group**:

![Diagram of space missions](image)
To paraphrase Douglas Adams,

“Space is [harsh]. Really [harsh]. You just won’t believe how vastly, hugely, mind-bogglingly [harsh] it is.

I mean, you may think it's a long way down the road to the chemist, but that's just peanuts to space.”

D. Adams--*Hitchhiker’s Guide to the Galaxy*

Where Materials Testing Fits into the Solution

Charge Accumulation
• Electron yields
• Ion yields
• Photoyields
• Luminescence

Charge Transport
• Conductivity
• Radiation Induced Conductivity
• Permittivity
• Electrostatic breakdown
• Penetration range

ABSOLUTE values as functions of materials species, flux, fluence, energy, and temperature.

Complex dynamic interplay between space environment, satellite motion, and materials properties
Facilities & Capabilities

Sample Characterization & Preparation
- Bulk composition (AA, IPC).
- Surface contamination (AES, AES mapping ESD).
- Surface morphology (SEM, optical microscopy).

Conduction Related Properties:
- Bulk & surface conductivity.
- High resistivity testing.
- Capacitance, dielectric constant, charge decay monitoring, and electrostatic discharge.

Electron Induced Emission:
- Total, secondary and backscattered yield vs. incident energy and angle.
- Energy-, angle-resolved emission spectra.
- Cathodoluminescence

Ion Induced Emission:
- Total electron and ion yield versus incident energy and angle.

Photon Induced Emission:
- Total electron yield vs photon energy.
- Energy-angle resolved photoelectron yield cross-sections.

Electron Induced Arcing:
- Four ultrahigh vacuum chambers for electron emission tests equipped with electron, ion, and photon sources, detectors, and surface analysis capabilities.
- Two high vacuum chambers for resistivity tests.
- High vacuum chamber for electrostatic breakdown tests.
- Ultrahigh vacuum chamber for pulsed electro acoustic measurements of internal charge distributions.
Myriad of Applications

Spacecraft Charging

HVDC Transmission

Electron Microscopy

Nanodielectrics

Particle Accelerators

High Voltage Switching & Devices

Dielectric Layers

Plasma Devices

Klystron, Multipactors

Photomultipliers

Dielectric Layers

Microelectronics

Supercapacitors
A Materials Physics Approach to the Problem

Measurements with many methods...

Interrelated through a...

Complete set of dynamic transport equations

\[ J = q_e n_e(z,t) \mu_e F(z,t) + q_e D \frac{dn_{tot}(z,t)}{dz} \]

\[ \frac{\partial}{\partial z} F(z,t) = \frac{q_e n_{tot}}{e_0 e_r} \]

\[ \frac{\partial n_{tot}(z,t)}{\partial t} - \mu_e \frac{\partial}{\partial z}[n_e(z,t)F(z,t)] - q_e D \frac{\partial^2 n_e(z,t)}{\partial z^2} = N_{ex} - \alpha_{er} n_e(z,t)n_{tot}(z,t) + \alpha_{et} n_e(t)[N_e(z) - n_e(z,t)] \]

\[ \frac{dn_e(z,t)}{dt} = N_{ex} - \alpha_{er} n_e(z,t)n_h(z,t) \]

\[ \frac{dn_h(z,t)}{dt} = \alpha_{et} n_e(z,t)[N_e(z,\epsilon) - n_e(z,\epsilon, t)] - \alpha_{te} N_e \exp\left[\frac{\epsilon}{eT}\right] n_t(z,\epsilon, t) \]

...written in terms of spatial and energy distribution of electron trap states
Putting the Pieces Together

Focus on DOS:

• **Synthesis of results** from different studies and techniques

• **Development of overarching theoretical models** allow extension of measurements made over limited ranges of environmental parameters to make predictions for broader ranges encountered in space.

<table>
<thead>
<tr>
<th>Band</th>
<th>Peak</th>
<th>FWHM</th>
<th>Defect</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>1.93±0.01 eV</td>
<td>663±3 nm</td>
<td>42 nm</td>
<td>NBOHC [16,20,23]</td>
</tr>
<tr>
<td>Green</td>
<td>2.48±0.03</td>
<td>506±7</td>
<td>68</td>
<td>ODC [17,23]</td>
</tr>
<tr>
<td>Blue</td>
<td>2.76±0.03</td>
<td>450±5</td>
<td>11</td>
<td>Surface [18-20,23]</td>
</tr>
<tr>
<td>UV</td>
<td>4.97</td>
<td>275</td>
<td>50</td>
<td>ODC [17-20,23]</td>
</tr>
</tbody>
</table>
Electron Yield Tests

EET Chamber
Animated Video of Chamber
Measuring Pulsed / DC Yields

- Pressures from $10^{-7}$ Torr – $10^{-9}$ Torr
- Temperature range of 40 – 400 K
- Electron energies from 20 eV – 30,000 eV
- The hemispherical grid retarding field analyzer (HGRFA) measures the electron yield of different materials.

Conductors
No difference between Pulsed and DC measurements

Insulators
Embedded charge
Difference between Pulsed and DC measurements
Flooding (UV LED & Flood Gun)
Pulsed Backscattered and Secondary Yield Measurements

Charges

\[ Q_{\text{incident}} = Q_{\text{sample}} + Q_{\text{collector}} + Q_{\text{grid}} + Q_{\text{stage}} \]

\[ Q_{\text{emitted}} = Q_{\text{collector}} + Q_{\text{grid}} + Q_{\text{stage}} \]

Currents

\[ (\text{TEY}) \quad \sigma = \frac{Q_{\text{emit}}}{Q_{\text{incident}}} = \frac{\int [I_{\text{collector}} + I_{\text{grid}} + I_{\text{stage}}] \, dt}{\int [I_{\text{sample}} + I_{\text{collector}} + I_{\text{grid}} + I_{\text{stage}}] \, dt} \]

\[ (\text{BSEY}) \quad \eta = \frac{Q_{\text{emit}}}{Q_{\text{incident}}} = \frac{c \int I_{\text{collector}} \, dt}{\int [I_{\text{sample}} + I_{\text{collector}} + I_{\text{grid}} + I_{\text{stage}}] \, dt} \]

\[ (\text{SEY}) \quad \delta = \sigma - \eta \]
Tungsten Pulsed Yield

\[ \delta_{\text{max}}, E_{\text{max}} \]

Electron Yield

Electron Energy [keV]

Energy Levels: \( E_1 \) and \( E_2 \)
• High material resilience
• High chemical resistance
  • Acids
  • Bases
• Range of uses
  • Industrial packaging
  • Laboratory bottles
  • Insulator for electrical equipment on satellites
LDPE (Graph)
Next step for LDPE
Modeling Composite Materials
Possible Problem Areas for Electroluminescent Glow

- C/Epoxy Composite + black Kapton Struts
- Black Kapton frill
- Black Kapton SM mount
- C/Epoxy Composite ISIM structure
- C/Epoxy Composite + black Kapton AOS Enclosure
- Black Kapton bib
Multilayer/Nanocomposite Effects???

C-fiber composite with thin ~1-10 µm resin surface layer

Black Kapton™ (C-loaded PI)

**Length Scale**
- Nanoscale structure of materials
- Electron penetration depth
- SE escape depth
Round Robin Comparison of HOPG Graphite Data

• HOPG data have been compared with data taken by other laboratories in a Round Robin test and show that Agreement between data from different labs is good above ~30-50 eV.
• Values agree within ~10% above 200 eV and ~20 % down to ~30 eV.
• USU data may be noisy due to low yield or to negative charging. Yield values <30 eV may be higher than actual values due to stage bias.

PEEK Sample Comparison

\[ \delta_{\text{max}}, E_{\text{max}} \]

- **Total Electron Yield**
- **Incident electron energy [eV]**
Range of Materials versus Incident Energy

Beam Energy (eV)

Range (nm)

0.7 nm to 1000 nm
Gold with Carbon Contamination

\[ \delta_{\text{max}}, E_{\text{max}} \]

\[ E_1, E_2 \]

\[ \text{TEY} \]

\[ \text{Energy [eV]} \]

March 2016

August 2016

December 2016
Electron Yield of M55J

\[ \delta_{\text{max}}, E_{\text{max}} \]

Electron Yield

Incident Electron Energy [eV]

TEY
BSEY
SEY
Fit SEY
Fit BSEY
Fit TEY
The sample glows when charged with the electron beam.
Vertical layers

e\textsuperscript{−}

![Diagram of vertical layers with an electron (e\textsuperscript{−}) falling through them.]

![Graph showing the secondary yield (\(\delta(E)\)) as a function of energy (\(E\text{[eV]}\)). The graph includes curves for Bulk Kapton, Bulk HOPG, and the fraction of each.]
Horizontal layers

![Diagram of horizontal layers with electron (e^-) trajectories]

![Graph showing secondary yield δ(E) vs. energy [eV] with different layers and materials: Bulk Kapton, Bulk HOPG, Multilayer, and Kapton Film]