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Amberly Evans
JR Dennison
Utah State University

Greg Wilson
Utah State University

Justin Dekany
Utah State University

Charles W. Bowers
NASA Godard Space Flight Center

Robert H. Meloy
ASRC Federal Holding Co.

See next page for additional authors

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Properties of Cathodoluminescence for Cryogenic Applications of SiO$_2$-based Space Observatory Optics and Coatings

Amberly Evans Jensen*, JR Dennison$^a$, Gregory Wilson$^a$, Justin Dekany$^a$, Charles W. Bowers$^b$, Robert Meloy$^c$, and James B. Heaney$^d$

$^a$Materials Physics Group, Physics Department, Utah State University
$^b$NASA Goddard Space Flight Center, $^c$MEI Technologies, Inc.
$^d$Stinger Ghaffarian Technologies, Inc.
Outline

• Introduction
• Experimentation
• Results
• Considerations for Application
• Conclusions
Introduction

Today’s space-based astronomical observatories:
• more complex and sensitive detectors
• reside in more extreme and remote environments
• larger and require open architectures
• operate at broader temperature ranges
Introduction
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Experimentation
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Results

273 K

193 K

163 K

Distorted, defocused beam

Spectral Radiance [W/cm²-nm-sr]

Temp [K]
Results

Proposed Model: Band Theory

1. incident high energy, charged particle undergoes a series of inelastic collisions exciting valence band electrons into the conduction band.
2. excited electron rapidly decays to localized (shallow trapped) states, with a mean binding energy below the mobility edge.
3. electron in short-lived shallow trap states falls to longer lived deep trap states producing a photon.
Results

Proposed Model

\[ I_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D} + \dot{D}_{sat}} \left\{ \left[ e^{-\left(\varepsilon ST/k_B T\right)} \right] \left[ 1 - e^{-\left(\varepsilon ST/k_B T\right)} \right] \right\} \left\{ \left[ 1 - A_f(\lambda) \right] \left[ 1 + R_m(\lambda) \right] \right\} \]

- \( I_\gamma \): luminescence intensity
- \( J_b \): incident current density
- \( E_b \): incident beam energy
- \( T \): temperature
- \( \lambda \): photon wavelength
- \( D \): dose rate
- \( q_e \): is the electron charge
- \( \rho_m \): is the mass density of the coating
Results

Incident Beam Current

\[
\dot{D}(J_b, E_b) = \frac{E_b J_b [1 - \eta(E_b)]}{q_e \rho_m} \times \begin{cases} 
[1/L] ; & R(E_b) < L \\
[1/R(E_b)] ; & R(E_b) > L 
\end{cases}
\]

Glow Radiance [W cm\(^{-2}\) nm\(^{-1}\) sr\(^{-1}\)]

- **25 keV**
- **5 keV**

Beam Current [nA/cm\(^2\)]

- 0
- 50
- 100
- 150
- 200

- 0
- 20
- 40
- 60
- 80
- 100
Results

Incident Beam Current

Low Currents: intensity is proportional to the incident current through the dose rate.

High Current: saturation can occur when trap states fill, limiting the number of states electrons can decay into, and leading to

\[ I_y \propto \left( \dot{D} + \dot{D}_{\text{sat}} \right)^{-1} \]

\( \dot{D}_{\text{sat}} \) is a material dependant saturation dose rate, found equal to \(~10\) Gy/s for these disordered SiO\(_2\) coatings.
Incident Beam Energy

\[ D(J_b, E_b) = \frac{E_b J_b [1 - \eta(E_b)]}{q_e \rho_m} \times \begin{cases} \frac{1}{L} & ; R(E_b) < L \\ \frac{1}{R(E_b)} & ; R(E_b) > L \end{cases} \]

**Graph:**
- Y-axis: Glow [W/cm² nm⁻² Sr⁻¹]
- X-axis: Energy [keV]
- Lines for different currents: 2 nA, 10 nA, 40 nA, 100 nA
Results

Incident Beam Energy

\[ \dot{D}(J_b, E_b) = \frac{E_b J_b [1 - \eta(E_b)]}{\eta q_e \rho_m} \times \begin{cases} \frac{1}{L} & ; R(E_b) < L \\ \frac{1}{R(E_b)} & ; R(E_b) > L \end{cases} \]

Nonpenetrating Radiation \( \{R(E_{\text{inc}}) < L\} \): all incident power is absorbed in the coating and intensity and dose rate are linearly proportional to the incident power density.

Penetrating Radiation \( \{R(E_{\text{inc}}) > L\} \): the absorbed power is reduced by a factor of \( L/R(E_{\text{inc}}) \).

An energy-dependent correction to the incident flux is included in the dose rate equation to account for quasi-elastic backscattered electrons that do not deposit substantial energy; \( \eta \) is the backscattered electron yield. For the most part, this correction is small and weakly dependant on energy.
Results

Temperature

\[ I_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{Q}(J_b, E_b)}{\dot{D} + \dot{D}_{sat}} \left\{ e^{-\left(\frac{\varepsilon_{ST}}{k_B T}\right)} \left[ 1 - e^{-\left(\frac{\varepsilon_{ST}}{k_B T}\right)} \right] \right\} \left\{ [1 - A_f(\lambda)] [1 + R_m(\lambda)] \right\} \]
Results

Temperature

\[ I_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{I}(J_b, E_b)}{\dot{D} + \dot{D}_{sat}} \left\{ \left[ e^{-\left(\frac{\varepsilon_{ST}}{k_B T}\right)} \right] \left[ 1 - e^{-\left(\frac{\varepsilon_{ST}}{k_B T}\right)} \right] \right\} \left\{ 1 - A_f(\lambda) \right\} \left[ 1 + R_m(\lambda) \right] \]

The thermal dependence of luminescence is proportional to

1. the number of electrons in the conduction band that can fall into the shallow traps \( \propto e^{-\left(\frac{\varepsilon_{ST}}{k_B T}\right)} \)

2. the fraction of electrons that are retained in the shallow traps and not thermally excited into the conduction band \( \propto \left[ 1 - e^{-\left(\frac{\varepsilon_{ST}}{k_B T}\right)} \right] \)

At higher temperatures, the thermal energy exceeds the mean energy depth of the shallow traps below the conduction band and \( I_\gamma \propto \left(\frac{\varepsilon_{STQ}}{k_B T}\right) \)
Results

Photon Wavelength

\[ I_\gamma(J_b, E_b, T, \lambda) \propto \frac{\dot{D}(J_b, E_b)}{\dot{D} + \dot{D}_{sat}} \left\{ e^{-(\varepsilon_{ST}/k_B T)} \left[ 1 - e^{-(\varepsilon_{ST}/k_B T)} \right] \right\} \left\{ [1 - A_f(\lambda)] [1 + R_m(\lambda)] \right\} \]
Here, we account for photon propagation through the coating.

High Optical Absorption Coating: intensity is limited to emission from the near-surface region from which photons can escape and is approximately independent of electron energy.

Low Optical Reflection Metallic Layer: photons reflected from the metallic layer do not substantially increase the luminescence.
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Considerations

Detection of extremely faint signals (distant objects) observed by space-based observatories can be limited by background light levels from:

- astronomical sources within and outside our solar system (zodiacal and galactic background, respectively)
- contributions from the observatory itself (i.e., thermal self emission in the infrared)
- scattered light from the combination of astronomical sources and observatory properties
- cathodoluminescence from electron impact onto coatings or optical components

A maximum stray light condition is often set by the zodiacal sky background. As a reference point, the intensity of the zodiacal background at 1AU near the south ecliptic pole is $8 \cdot 10^{-14}$ W cm$^{-2}$ nm$^{-1}$ sr$^{-1}$ at 500 nm, $3 \cdot 10^{-14}$ W cm$^{-2}$ nm$^{-1}$ sr$^{-1}$ at 1000 nm, and $6 \cdot 10^{-15}$ W cm$^{-2}$ nm$^{-1}$ sr$^{-1}$ at 2000 nm.

To determine the magnitude of cathodoluminescence for a specific space-based observatory situation, to compare with these background sources, requires knowledge of:
Considerations

• The observatory electron environment and specifically the electron flux spectrum

These are typical flux ranges but fluxes for each observatory will depend on the particular environments that are encountered throughout the mission.
Considerations

• The degree of baffling or shielding of electrons onto potentially luminescent optics

An open architecture and minimal shielding, often required for large observatories due to size and mass constraints, permits stray light to enter the optical path of the telescope and also exposes optical elements and surrounding support structures to greater environmental electron fluxes.
Considerations

• The effectiveness of the optical system in transmitting the generated cathodoluminescence from the impacted optics to instrument focal planes.

This depends on the juxtaposition of the luminescent elements and the location of stops along the optical path.
Considerations

- The thickness of the luminescent coating
Considerations

- The temperature of the luminescent coating
Considerations

• The composition of the luminescent coating

To a modest extent, the luminescent spectrum and overall intensity will change with the exact composition and atomic scale structure of the luminescent coating.

See Dennison, JR: *Diverse electron-induced optical emissions from space observatory materials at low temperatures*
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Conclusions

- Disordered, thin film SiO$_2$/SiO$_x$ coatings, commonly used as protective mirror coatings, exhibit cathodoluminescence under electron-beam bombardment.
- This was measured as a function of electron energy, beam current and temperature.
- A simple model was proposed that describes the dependence of this cathodoluminescence on irradiation time, incident flux and energy, sample thickness, and temperature.
- Other factors necessary for the estimation of the magnitude and effect of this potential source of background light for a particular mission include the electron environment and variability, considerations of baffling of the impacted elements, transmission of this luminescent light to instrument focal planes, thickness of the coatings used on particular elements, and the temperatures of the coated elements.
- The information provided in this study, coupled with these specific mission specifications, is sufficient to determine the risks posed to the performance of spaced-based observatories from space plasma environmentally-induced cathodoluminescence.
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