Effects of Temperature and Radiation Dose on Radiation Induced Conductivity

JR Dennison
Utah State University

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Effects of Temperature and Radiation Dose on Radiation Induced Conductivity

J.R. Dennison

Materials Physics Group
Physics Department, Utah State University
A Rose by any other name would smell as sweet...

In search of the Holy Grail of the Videcon...

Rose found zero x-ray radiography...

Rose-Fowler-Vaserberg theory

RoSETTA STONE
What Is Radiation Induced Conductivity (RIC)?

Uniform Trap Density

\[ \Delta(T) \to 1 \]

\[ k(T) \to k_{RICo} \]

\[ \sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)} \]

Exponential Trap Density

\[ \Delta(T) \to \frac{T_c}{T + T_c} \]

\[ k(T) \to k_{RIC1} \left[ \frac{2\left( \frac{m_e k_B T}{2\pi \hbar^2} \right)^{3/2} \left( \frac{m_e m_h}{m_e m_e} \right)^{3/4}}{T + T_c} \right]^{T \over T + T_c} \]

\[ \sigma_{RIC}(D) = k_{RIC} \cdot D \]

Dose Dependant RIC

\[ \sigma_{RIC}(D) = k_{RIC} \cdot D \]
Radiation Dose Dependence of Conductivity

Radiation-induced conductivity (RIC) is proportional to dosage to the Δ power:

\[ \sigma_{RIC}(D) = k \cdot \left( \frac{D}{\Delta} \right)^\Delta \]

To first order, this does not depend on T or on the incident radiation species, just energy flux.

- The RIC versus radiation dose rate for polyethylene terephthalate (Mylar) [Campbell].
- The exponential fit over 10 orders of magnitude for five different studies implies that RIC is largely independent of the beam energy and type of radiation used.
- Only the amount of energy being deposited determines the magnitude of RIC.

<table>
<thead>
<tr>
<th>Curve Segment</th>
<th>Type of Radiation</th>
<th>Energy</th>
<th>Dose Rate</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>X-rays</td>
<td>250 keV</td>
<td>0.13 rad/s</td>
<td>steady state</td>
</tr>
<tr>
<td>2</td>
<td>X-rays</td>
<td>15 to 30 keV</td>
<td>1 to 400 rad/s</td>
<td>steady state</td>
</tr>
<tr>
<td>3</td>
<td>γ-rays</td>
<td>1.17 and 1.33 MeV</td>
<td>200 to 3500 rad/s</td>
<td>steady state</td>
</tr>
<tr>
<td>4</td>
<td>pulse reactor</td>
<td>mixed</td>
<td>6.5 × 10^4 to 3.8 × 10^6 R/s</td>
<td>13 ms pulses</td>
</tr>
<tr>
<td>5</td>
<td>neutrons and γ-rays</td>
<td>30 MeV</td>
<td>5 × 10^7 to 7 × 10^9 rad/s</td>
<td>4.5 μs pulses</td>
</tr>
</tbody>
</table>
RIC Dependence on Temperature

Family of curves of $\rho_{RIC}$ vs dose rate at various temperatures. Fits are simple power law fits.

$$\sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Lambda(T)}$$

Kapton™ (polyimide)
RIC Dependence on Temperature

\[ \sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)} \]

T dependence of RIC coefficients \( k \) (Above) and \( \Delta \) (Right) with \( k_0 = 1.5 \cdot 10^{-16} \) (\( \Omega \)-cm-Rad/s\(^{-1} \)), \( k_1 = 7.0 \cdot 10^{-29} \) (\( \Omega \)-cm-Rad/s\(^{-1} \)) and \( T_c = 230 \) K.
RIC Is Time Dependant

Initial RIC

\[ B_{on}(t, \lambda(D, T)) = 1 - e^{-(t-t_{on}) \cdot \lambda(D, T)} \]

Dose Dependent Equilibrium RIC

\[ \sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)} \]

Persistent RIC

\[ B_{off}(t, T, k(T)) = \frac{1}{1 + k(T) \cdot \frac{t-t_{off}}{T}} \]
Instrumentation

Idaho Accelerator Center RIC Chamber
Radiation Induced Conductivity Measurements

RIC chamber uses a combination of charge injected by a biased surface electrode with simultaneous energy injection by a pulsed penetrating electrons.
Instrumentation

USU Cryostat RIC Chamber
AFRL RIC Cryostat Chamber

- High Energy Electron Gun
- USU Closed Cycle He Cryostat
- Faraday Cup Z Translation Stage
AFRL RIC Closed-Cycle He Refrigerator Sample Stage Design

Cryo Sample Stage Assembly
Cut-Away Views

Expander Module

Cryo Shroud Stage (~80 K)

Low T Stage (~30 K)

Sample block

Cryo shroud

Sample shutter

Shutter gear assembly
AFRL RIC Closed-Cycle He Refrigerator Sample Stage Design

Multiple Sample Holder
Electrodes
Adapter
Samples
Front Plate

Light spring loaded rods
PEEK screws

Front Side View
Complementary Responses to Radiation

Modified Joblonski diagram

- VB electrons excited into CB by the high energy incident electron radiation.
- They relax into shallow trap (ST) states, then thermalize into lower available long-lived ST.
- Three paths are possible:
  
  (i) relaxation to deep traps (DT), with concomitant photon emission;
  (ii) radiation induced conductivity (RIC), with thermal re-excitation into the CB; or
  (iii) non-radiative transitions or $e^-h^+$ recombination into VB holes.
RIC Cryostat Measurements

RIC current vs 295 K<T<38 K at constant Dose Rate

RIC current vs Dose Rate at 40 K

Fused silica
Room T RIC Cryostat System Results

Fitted parameters:

\[ k_p = (2.0 \pm 0.3) \times 10^{-15} \text{(ohm-cm-rad/sec)}^{-1} \]

\[ \Delta = 1.01 \pm 0.03 \]

Saturation for high dose rate

Fused silica
USU Materials Physics Group Capabilities

**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.
# Dark Current and Radiation Induced Conductivities

## Slab (parallel plate capacitor) Model

### Charge Absorption

**Bethe Approximation:**

Charge absorbed at single (energy dependant) Range, $R$

**Surface Potential**

- **No Dissipation:**
  
  \[ V_s(t) = \frac{J_B R}{2\varepsilon_o \varepsilon_r} t \]

- **Dissipation:**
  \[ V_s(t) = \frac{J_B R}{2\varepsilon_o \varepsilon_r} \left[ \frac{1}{t} + \frac{2}{\tau_{DC}} + \frac{2}{\tau_{RIC}} \right] \]

**Decay Time:**

\[ \tau_{DC} = \varepsilon_o \varepsilon_r / \sigma_{DC} \]

### Energy Absorption

**Continuous Slow Down Approximation:**

Energy absorbed uniformly up to Range, $R$

**Absorbed Dose Rate (J/kg-s):**

\[ \dot{D} = J_B E_B / q_e \rho_m R \]

**RIC:**

\[ \sigma_{RIC}(\dot{D}) = k_{RIC} \cdot \dot{D} \]

**Decay Time:**

\[ \tau_{RIC} = \varepsilon_o \varepsilon_r / \sigma_{RIC} \]
USU Resistivity Calculator Engineering Tool

This Mathcad worksheet calculates the resistivity of JWST spacecraft materials as a function of electric field (E), temperature (T), and adsorbed dose rate (D) based on parametrized, analytic functions used to model an extensive data set taken by the Utah State University Materials Physics Group.

**Select Material from pull down box:**
- Low Density Polyethylene (LDPE)
- Kapton-HN
- Kapton S
- Kapton FN (610)
- PFA (Teflon)
- PEP (Teflon)
- ETFE (Teflon)
- ePTFE (expanded ETFE or GOREtex)
- ETFE (Teflon)

Enter T, E and D to evaluate resistivity at:
- $E_{av} = 10^6 \text{ V/m}$
- $T_{av} = 330 \text{ K}$
- $D_{av} = 0.03 \text{ Rad/sec}$

Enter sample thickness: $d_{av}$ = 25 μm

**List Materials Related Properties Used in Resistivity Calculations**

<table>
<thead>
<tr>
<th>Material name</th>
<th>$\varepsilon_r$</th>
<th>$\rho_{deh}$</th>
<th>$E_{av}$</th>
<th>$E_{av}E_{av}$</th>
<th>$\varepsilon_{av}$</th>
<th>$\rho_{av}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kapton-HN</td>
<td>3.400</td>
<td>1.42 g/cm$^3$</td>
<td>$2.700 \times 10^2$ V/m$^2$</td>
<td>6730 V</td>
<td>0.37%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 1. Mathcad engineering tool user input interface.
Conductivity in Highly Disordered Insulating Materials

\[ \sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t) \]
Conductivity in HDIM--Polarization

\[
\sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t)
\]

\[
\sigma_{Pol}^0 e^{-t/\tau_{Pol}}
\]

Polarization

(a) Electronic
(b) Distortional
(c) Orientational
(d) Interfacial
Conductivity in HDIM—Drift and Hopping Conduction

\[ \sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t) \]

\[ \sigma_{Diff}^{-1} \]

\[ \sigma_{hop}(E,T) = \left[ \frac{2 \cdot n(T) \cdot \nu \cdot a \cdot e}{E} \right] \exp \left[ \frac{-\Delta H}{k_B \cdot T} \right] \sinh \left[ \frac{\varepsilon \cdot E \cdot a}{2 \cdot k_B \cdot T} \right] \]

\[ \ln \sigma \]

(i) Boltzmann

(ii) Transition

(iii) Mott

(iv) \( T^{-1/4} \)
Temperature Dependence of Hopping Conductivity

At high temperatures, the conductivity is proportional to a Boltzmann factor, with trap depth $\Delta H$:

$$\sigma(T) \propto \exp\left[-\frac{\Delta H}{k_B \cdot T}\right] \quad \text{or} \quad \rho(T) \propto \exp\left[\frac{\Delta H}{k_B \cdot T}\right]$$

At low temperatures, the variable-range hopping conductivity is proportional to a Mott factor:

$$\sigma(T) \propto \exp\left[-\frac{1}{k_B \cdot T^{1/4}}\right] \quad \text{or} \quad \rho(T) \propto \exp\left[\frac{1}{k_B \cdot T^{1/4}}\right]$$
Conductivity in HDIM—E-Field Dependence of Hopping Conductivity

At low field, the conductivity is independent of E-field:

$$\rho_{hop}(T) \xrightarrow{\text{low } E} \left[ \frac{n(T) \cdot v \cdot a^2 \cdot e^2}{k_B \cdot T} \right]^{-1} \exp \left[ \frac{\Delta H}{k_B \cdot T} \right]$$

At high field, the potential wells distort. Poole-Frenkle theory predicts:

$$\rho(E;T) = \rho_o(T) \exp \left[ -\frac{\beta}{k_B \cdot T} \right]$$
Diffusive and Dispersive Transport

\[ \sigma(t) = \sigma_{DC} + \sigma_{Polarization}(t) + \sigma_{Diffusion}(t) + \sigma_{Dispersion}(t) + \sigma_{Transit}(t) + \sigma_{RIC}(t) \]

\[ \sigma_{Disp} t^{-(1-\alpha)} + \sigma_{Transit} t^{-(1+\alpha)} \]

\[ I(t) \sim \begin{cases} t^{-(1-\alpha)}, & t < t_T \\ t^{-(1+\alpha)}, & t > t_T \end{cases} \]

- Photoconductivity experiment on semiconductors by Pfister and Sherr
- Amorphous Selenium
- Dispersive transport causes unique shape in log-log graph
- Hopping and trapping mechanisms responsible for dispersive transport
- Dispersive transport results from wide range of hopping times, e.g. from range of \( \Delta H \) and \( a \)
- ‘Universality’ a result of dispersive transport
- Note transit times in ms
Normal vs. Dispersive Transport

I/t Curves

Pulse Propagation

Theory

RIC and Defect Density of States
A Materials Physics Approach to the Problem

Measurements with many methods...

Interrelated through a...

Complete set of dynamic transport equations

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

\[
\frac{\partial}{\partial x} F(z,t) = q_e n_{tot} / \varepsilon_0 \varepsilon_r 
\]

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

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

\[
\frac{d n_e(z,\varepsilon,t)}{d t} = \alpha_{er} n_e(z,\varepsilon) [N_e(z,\varepsilon) - n_e(z,\varepsilon,t)] - \alpha_{te} n_e \exp \left[ - \frac{\varepsilon}{\kappa T} \right] n_e(z,\varepsilon,t) 
\]

...written in terms of spatial and energy distribution of electron trap states

Disordered Localized States

Extended States

Mobility Edge

Polarization \( \sigma_{pd}(T,F,t) \)

Surface Voltage Probe \( \sigma_{SVP}(D_{dov},T,F,t) \)

Frequency Domain \( \sigma_{AC}(\omega(t),T,F) \)

Dark Conductivity \( \sigma_{CV}(D_{dov},T,F,t) \)

Radiation Induced Conductivity \( \sigma_{REC}(D_{dov},T,F,t) \)

Electrostatic Breakdown \( F_{ESD}(V,T,t) \)

Unification \( A^* \)

Mobility Edge

Extended States
A Focus on Defect Densities

What is required is knowledge of:

- Defect (trap) spatial distribution (density)
- Defect energy distribution (DOS)
- Types of charge carriers (e.g., e⁻ or h⁺)
- Occupation of defect states by charge carriers
- Transition frequencies (lifetimes)
- Complete set of dynamic transport equations

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

\[ \frac{\partial}{\partial z} F(z, t) = q_e n_{tot}/\epsilon_0 \epsilon_r \]

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

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

\[ \frac{dn_t(z, \varepsilon, t)}{dt} = \alpha_{et} n_e(z, t)[N_t(z, \varepsilon) - n_t(z, \varepsilon, t)] - \alpha_{te} N_e \exp \left[ -\frac{\varepsilon}{kT} \right] n_t(z, \varepsilon, t) \]
Disorder introduces localized states in the gap

A quantum mechanical model of the spatial and energy distribution of the electron states

Tunneling Between Traps—and Mott Anderson Transitions

Anderson transition between extended Bloch states and localized states caused by variations in well depth affects tunneling between states.

Mott transition between extended Bloch states and localized states caused by variations in well spacing which affects tunneling between states.


Synergistic Models of Electron Emission and Transport Measurements of Disordered SiO$_2$

Look at measurements of fused quartz (a-SiO$_2$) from a synergistic microscopic, defect state perspective

used as coverglass, optical elements, and insulator
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 Energy (eV)</th>
<th>Peak Wavelength (nm)</th>
<th>FWHM (nm)</th>
<th>Defect</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red</td>
<td>1.93±0.01</td>
<td>663±3</td>
<td>42</td>
<td>NBOHC</td>
<td>[16,20,23]</td>
</tr>
<tr>
<td>Green</td>
<td>2.48±0.03</td>
<td>506±7</td>
<td>68</td>
<td>ODC</td>
<td>[17,23]</td>
</tr>
<tr>
<td>Blue</td>
<td>2.76±0.03</td>
<td>450±5</td>
<td>11</td>
<td>Surface</td>
<td>[18-20,23]</td>
</tr>
<tr>
<td>UV</td>
<td>4.97</td>
<td>275</td>
<td>50</td>
<td>ODC</td>
<td>[17-20,23]</td>
</tr>
</tbody>
</table>

Optical Band Gap—Disordered SiO₂

Optical Transmission Data:
• Direct band gap ~8.9 eV
• Additional steps in transmission in 1-4 eV range

$E_{\text{gap}} = 8.9$ eV
Conductivity vs Temperature

\[ \sigma_{\text{hop}}(E,T) = \left[ \frac{2 \cdot n(T) \cdot v \cdot a \cdot e}{E} \right] \exp \left[ \frac{-\Delta H}{k_B \cdot T} \right] \sinh \left[ \frac{\varepsilon \cdot E \cdot a}{2 \cdot k_B \cdot T} \right] \]

Yields:
Defect energy, \( E_d \)
and
Trap density, \( N_T \)

\( E_{\text{gap}} = 8.9 \text{ eV} \)

\( E_d = 1.08 \text{ eV} \)
\[
\sigma(t) = \sigma_{DC} \left[ 1 + \frac{\sigma_{AC}(\nu)}{\sigma_{DC}} + \frac{\sigma_{pol}^0}{\sigma_{DC}} e^{\frac{t}{\tau_{pol}}} + \frac{\sigma_{diffusion}^0}{\sigma_{DC}} t^{-1} + \frac{\sigma_{dispersive}^0}{\sigma_{DC}} t^{(1-\alpha)} + \frac{\sigma_{transit}^0}{\sigma_{DC}} t^{(1+\alpha)} + \frac{\sigma_{RIC}^0}{\sigma_{DC}} \left(1 - e^{-\frac{t_{RIC}}{t_{on}}} \right) \left(1 + \frac{t - t_{off}}{\tau_{RIC}^2} \right)^{-1} \right]
\]

- **Dark current or drift conduction**—Defect density, \( N_{T} \), and \( E_{r} \approx 1.08 \text{ eV} \)
- **Diffusion-like and dispersive conductivity**—Energy width of trap distribution, \( \alpha \)
- **Radiation induced conductivity**—Shallow trap density and \( \varepsilon_{ST} \)
- **Polarization**—Rearrangement of bound charge, \( \varepsilon_{r} \varepsilon_{o} \) and \( \tau_{pol} \)
- **AC conduction**—Dielectric response, \( \varepsilon_{r} (\nu) \varepsilon_{o} \)
Surface Voltage Charging and Discharging

- Uses pulsed non-penetrating electron beam injection with no bias electrode injection.
- Fits to exclude AC, polarization, transit and RIC conduction.
- Yields $N_p E_d$, $\alpha$, $\varepsilon_{ST}$

$$\sigma(t) = \sigma_o \left\{ 1 + \left[ \frac{\sigma_{\text{diffusion}}}{\sigma_o} \right] t^{-1} + \left[ \frac{\sigma_{\text{dispersive}}}{\sigma_o} \right] t^{-(1-\alpha)} \right\}$$

Charging

$$V_s(t) = \frac{q_{m\max}}{\varepsilon_o \varepsilon_r} \left[ \frac{1}{1 - \gamma(E_b)} \right] \left[ R(E_b) \frac{D \left( 1 - R(E_b) \frac{1}{2 D} \right)}{1 - \gamma(E_b)} \right] \left[ 1 - e^{-\left( \frac{1}{\gamma(E_b)} \right) \left[ 1 + \left( \frac{1}{\gamma(E_b)} \right) \right] \frac{\sigma_{\text{diffusion}}}{\sigma_o} + \left( \frac{1}{\gamma(E_b)} \right) \frac{\sigma_{\text{dispersive}}}{\sigma_o} \left( t^{-1} \right) \left( t^{-1} \right) \right]^{11}$$

Discharge

$$V(t) = V_o e^{-\tau \sigma(t)/\varepsilon_o \varepsilon_r} \approx V_o \left[ 1 - \left( \frac{\sigma_o t}{\varepsilon_o \varepsilon_r} \right) \left\{ 1 + \left[ \frac{\sigma_{\text{diffusion}}}{\sigma_o} \right] t^{-1} + \left[ \frac{\sigma_{\text{dispersive}}}{\sigma_o} \right] t^{-(1-\alpha)} \right\} \right]$$
**F_{ESD} Breakdown: Dual (Shallow and Deep) Defect Model**

**Yields:**
- Ratio of Defect energy to Trap density, \( \Delta G_{\text{def}} / N_T \)
- Separate these with T dependence
- \( \Delta G_{\text{def}} = 0.97 \, \text{eV} \)
- \( N_T = 1 \cdot 10^{17} \, \text{cm}^{-3} \)

**Breakdown field measurements:**
\[
N_{\text{def}} \Delta G_{\text{def}} = \frac{\varepsilon_0 \varepsilon_r}{2} \cdot (F_{\text{ESD}})^2
\]

Endurance time measurements:
\[
t_{\text{en}}(F, T) = \left( \frac{h}{2k_B T} \right) \exp \left[ \frac{\Delta G_{\text{def}}(F, T)}{k_B T} \right] \text{csch} \left[ \frac{F^2 \varepsilon_0 \varepsilon_r}{2k_B T N_{\text{def}}(F, T)} \right]
\]

- \( F_{\text{ESD}} = 20 \pm 2 \, \text{MV/m at RT} \)
- \( F_{\text{ESD}} = 27 \pm 2 \, \text{MV/m at 157 K} \)
- \( F_{\text{ESD}} = 19.0 \pm 0.6 \, \text{MV/m at RT and 142 K (irradiated)} \)

“Complete” Breakdown ~2-4X this field

Based on first breakdown
RIC T-Dependence

Shallow Trap DOS Profile
Exponential DOS Below $E_c$

Effective Fermi Level
$E_F^{\text{eff}} = 24 \text{ meV}$

\[ \Delta(T) \rightarrow 1 \]
\[ \Delta(T) \rightarrow \frac{T_c}{T + T_c} \]
\[ k(T) \rightarrow k_{\text{RIC}0} \]
\[ k(T) \rightarrow k_{\text{RIC}} \left[ 2 \left( \frac{m_e k_B T}{2 \pi \hbar^2} \right)^{3/2} \left( \frac{m^*_e m^*_h}{m_e m_h} \right)^{3/4} \right]^{-T/T_c} \]

\[ \sigma_{\text{RIC}} (T, D) = k_{\text{RIC}} (T) \cdot D^{\Delta(T)} \]
Complementary Responses to Radiation: RIC and CL

Modified Joblonski band diagram

- VB electrons excited into CB by the high energy incident electron radiation.
- They relax into shallow trap (ST) states, then thermalize into lower available long-lived ST.
- Four paths are possible:
  (i) Remain in (short lived) shallow traps
  (ii) Non-radiative transitions or $e^-\cdot h^+$ recombination into VB holes;
  (iii) Radiation induced conductivity (RIC), with thermal re-excitation into the CB or;
  (iv) Relaxation to deep traps (DT), with concomitant photon emission.
Photon Emission Spectra
Peak Wavelength

Multiple peaks in spectra correspond to multiple DOS distributions

Peak positions $\leftrightarrow$ Center of DOS
Peak amplitude $\leftrightarrow N_T$
Peak width $\leftrightarrow$ DOS width
Cathodoluminescence—Defect Origins for DOS’s

Based on peak positions for similar disordered SiO₂ samples at room temperature.

Sahl identified 1.98 eV peak as from nonbridging oxygen hole center.

Trukhin identified 2.48 eV and 4.51 eV peaks as from an oxygen deficient center.
Electron Emission Studies and DOS

Electron Yield Curves

Electron Emission Spectra

Surface Voltage Decay Curves
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.

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</tr>
<tr>
<td><strong>Blue</strong></td>
<td>2.76±0.03</td>
<td>450±5</td>
<td>11</td>
<td>Surface</td>
<td>[18-20,23]</td>
</tr>
<tr>
<td><strong>UV</strong></td>
<td>4.97</td>
<td>275</td>
<td>50</td>
<td>ODC</td>
<td>[17-20,23]</td>
</tr>
</tbody>
</table>
USU Materials Physics Group

(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, Alex Souvall, Greg Wilson, Allen Andersen, JR Dennison, Windy Olsen

(Not pictured) Brian Wood, Vladimir Zavyalov, Jodie Gillespie, Jonh Mojica Decena, Katie Gamaunt, Davis Muhwezi, Tyler Kippen

USU MPG Webpage

http://digitalcommons.usu.edu/mp/
J. R. Dennison received the B.S. degree in physics from Appalachian State University, Boone, NC, in 1980, and the M.S. and Ph.D. degrees in physics from Virginia Tech, Blacksburg, in 1983 and 1985, respectively. He was a Research Associate with the University of Missouri—Columbia before moving to Utah State University (USU), Logan, in 1988. He is currently a Professor of physics at USU, where he leads the Materials Physics Group. He has worked in the area of electron scattering for his entire career and has focused on the electron emission and conductivity of materials related to spacecraft charging for the last two decades.
USU Space Survivability Test Chamber

Radiation Sources:
- A High Energy Electron Gun
- B Low Energy Electron Gun
- C UV/Vis/NIR Solar Simulator
- D He/Ne Laser Discharge Lamps
- E Air Mass Zero Filter Set
- F Flux Mask
- G Sr⁹⁰ Radiation Source

Analysis Components:
- F UV/Vis/NIR Reflectivity Spectrometers
- G IR Emissivity Probe
- H Integrating Sphere
- I Photocell UV/Vis/NIR Flux Monitor
- J Cathode Cup Electron Flux Monitor
- K Platinum Resistance Temperature Probe

Sample Carousel:
- L Samples
- M Rotating Sample Carousel
- N Reflectivity/Emittance Collin, Standards
- O Resistance Heaters
- P Cryogen Reservoir

Chamber Components:
- Q Cryogen Vacuum Feedthrough
- R Electrical Vacuum Feedthrough
- S Sample-rotation Vacuum Feedthrough
- T Probe Translational Vacuum Feedthrough
- U Sapphire UV/Vis Viewport
- V Myö UV Viewport
- W Turbomolecular/Vacuum Pump
- X Ion Vacuum Pump
- Y Ion/Convertron Pressure Gauges
- Z Residual Gas Analyzer

Chamber Components:
- α CubeSat
- β CubeSat Test Fixture
- γ Radiation Shielding
- δ COTS Electronics
- ε Rad Hard Breadboard
- η COTS Test Fixture
- θ Electron Gun

Instrumentation (Not Shown):
- Data Acquisition System
- Temperature Controller
- Electron Gun Controller
- UV/Vis/NIR Solar Simulator Controller
- FUV Kr Resonance Lamp Controller
- Spectrometers and Reflectivity Source

Utah NASA Space Grant Consortium Faculty Research Infrastructure Award Program, “Space Survivability Test Facility for CubeSats, Components and Spacecraft Materials,” JR Dennison, (April 2016 to April 2017.)
Simulated Space Environment Fluxes

**Electron Radiation**
A high energy (~10-80 keV) and three lower energy (~10 eV to 5 keV) electron guns provide high electron fluxes.

**Ionizing Radiation**
A 100 mCi encapsulated Sr$^{90}$ β-radiation source (~200 keV to >2.5 MeV) mimics high energy (~500 keV to 2.5 MeV) geostationary electron flux [2].

**Infrared/Visible/Ultraviolet Flux**
A commercial Class AAA solar simulator provides NIR/Vis/UVA/UVB electromagnetic radiation (from 200 nm to 1700 nm) at up to 4 times sun equivalent intensity.

**Far Ultraviolet Flux**
Kr resonance lamps provide FUV radiation flux (ranging from 10 to 200 nm) at 4X sun equivalent intensity. Kr bulbs have ~3 month lifetimes for long duration studies.

**Temperature Control**
Temperature range from 60 K [4] to 450 K is maintained to ±2 K [3]. This is achieved through cartridge heaters, and chilled fluid pumped through a cold plate.

**Controlled Atmosphere and Vacuum**
Ultrahigh vacuum chamber allows for pressures <10$^{-7}$ Pa to simulate LEO.

**Video Discharge Monitoring**
Using custom developed software, live video capture and processing of electrostatic discharge events allows for visual identification of discharge location and frequency.

**Flexible Sample Mounting**
A rotating graphite carousel, ensures uniform irradiation and allows for custom mounting of samples. Or a flange mounted fixture allows for electrostatic discharge testing. Radiation source to sample distance is adjustable.

**Biological Testing**
Biological samples, which are vacuum incompatible, can use a custom designed chamber with controlled atmosphere and temperature.