Temperature-Dependent Radiation Induced Conductivity of Diverse Highly Disordered Insulating Materials

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Temperature-Dependent Radiation Induced Conductivity of Diverse Highly Disordered Insulating Materials

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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.
What Is Radiation Induced Conductivity (RIC)?

Uniform Trap Density

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

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

Exponential Trap Density

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

\[ k(T) \rightarrow k_{RIC1} \left[ 2 \left( \frac{m_e k_B T}{2 \pi \hbar^2} \right)^{3/2} \left( \frac{m^* m^*}{m_e m_e} \right)^{3/4} \right] \]

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

### RIC Depends on Power Deposited

<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>neutrons and γ-rays</td>
<td>6.5 × 10⁴ to 3.8 × 10⁶ R/s</td>
<td>13 ms pulses</td>
</tr>
<tr>
<td>5</td>
<td>electrons</td>
<td>30 MeV</td>
<td>5 × 10⁷ to 7 × 10⁹ rad/s</td>
<td>4.5 µs pulses</td>
</tr>
</tbody>
</table>
Dose Rate

DOSE RATE is the deposited power per unit mass is:

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

which is proportional to incident electron absorption:

- Incident areal power density, \((J_b \cdot E_b)/q_e\)
- Energy-dependent correction for unabsorbed quasielastic backscattered electrons, \([1-\eta(E_b)]\)
- For biased samples, or when excess charge is stored in the trap states, a surface voltage \(V_s\) results and \(E_b\) is replaced everywhere by the landing energy, \([E_b - q_e \cdot V_s]\)
- Absorbing mass, \(m_{\text{absorb}} = \rho_m \cdot (\text{Beam Area} \cdot \text{Penetration Depth})\)
- Only a fraction of the incident power, \([L / R(E_b)]\), when range exceeds sample thickness
RIC Is Time Dependant

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

\[
\begin{align*}
B_{on}(t, \lambda(D,T)) &= 1 - e^{-\left(t-t_{on}\right) \cdot \lambda(D,T)} \\
B_{off}(t, T, k(T)) &= \frac{1}{1 + k(T) \cdot t_{off}}
\end{align*}
\]
RIC Is Depth Dependant

\[ \dot{D}(J_b, E_b) = \frac{E_b J_b \left[ \frac{1}{\eta(E_b)} - \eta(E_b) \right]}{q_e \rho_m} \times \left\{ \begin{array}{ll} \frac{1}{L} & ; R(E_b) < L \\ \frac{1}{R(E_b)} & ; R(E_b) > L \end{array} \right. \]
RIC Dependence on Temperature

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

$$\sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)}$$
RIC Dependence on Temperature

T dependence of RIC coefficients $k$ (Left) and $\Delta$ (Right) with $k_o = 1.5 \cdot 10^{-16}$ (Ω-cm-Rad/s)$^{-1}$, $k_1 = 7.0 \cdot 10^{-29}$ (Ω-cm-Rad/s)$^{-1}$ and $T_c = 230$ K.

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

Kapton™ (polyimide)
RIC Dependence on Temperature

Luminescent intensity, $I_γ$, scales with incident current density $J_b$, beam energy $E_b$, temperature $T$, and photon wavelength $\lambda$ as:

$$I_γ(J_b, E_b, T, \lambda) \propto \dot{D}(J_b, E_b) \left[ \frac{1}{\dot{D} + \dot{D}_{sat}} \left( \frac{\varepsilon_{ST}}{k_B T} \right) \right] \{ A_f(\lambda)[1 + \mathbb{R}_m(\lambda)] \}$$

which is proportional to:

- Number of electrons in ST, thermalized from CB electrons
  - Trapping rates proportional to number of electrons excited in to CB which is proportional to dose rate
  - Retention rates leads to saturation at high charge, related to dose and $T$-dependant $\dot{D}_{sat}$ from RIC [5]
- Number of available DT states, dependant on space charge and $T$
- Emitted photon absorption
  - Proportional to $A_f$, the optical absorption coefficient of the coating
  - Enhanced by a factor $[1 + \mathbb{R}_m(\lambda)]$, to account for reflection from the metallic layer
Peak amplitudes of four peaks as a function of sample temperature, with baseline subtracted and normalized to maximum amplitudes. This verified the T-dependent behavior observed in the SLR images.
Closed-System Helium Refrigerator Sample Stage Mounting

- High Energy Electron Gun
- Faraday Cup Z Translation Stage
- USU Closed Cycle He Cryostat
Sample Square Holder Assembly Diagram

100 keV Electron Beam
RIC Measurements

RIC current vs 295 K<T<38 K at constant Dose Rate
RIC current vs Dose Rate at 40 K
RIC Results

Low T RIC from data
\[ k_p = 2 \times 10^{-15} \text{ mho/cm-rad-sec} \]
\[ \Delta = 1 \]

room T RIC from Culler paper
\[ k_p = 1.7 \times 10^{-16} \text{ mho/cm-rad-sec} \]
\[ \Delta = 0.967 \]
Ending with a Bang!!!
RIC in Thin Film Disordered SiO$_2$ is:

I. Proportional (nearly) to Dose Rate
II. Weakly (and roughly linearly) T-dependant
III. Complementary with cathodoluminescence
IV. RIC has rapid time dependence
V. Suggests a nearly linear density of localized states (shallow traps)
Acknowledgements

Support & Collaborations

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B42 Amberly E. Jensen
Dependence of Electron Beam Induced Luminescence of SiO₂ Optical Coatings on Energy, Flux, Temperature and Thickness

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Comparison of Radiation Induced Conductivities at Low Temperature

B4 7 Greg Wilson
Power and Charge Deposition in Multilayer Dielectrics undergoing Monoenergetic Electron Bombardment

D1 40 Allen Anderson
Electrostatic Discharge Properties of Fused Silica Coatings
Phase VI: AFRL Bell Jar Chamber Lead Shielding
New Sample Square Holder

New sample holder
Slips over existing multiple Sample holder
New Sample Square Holder

New Sample Mount-Au/Kapton Sample
New Sample Square Holder

New Sample Mount Rear Views
New Sample Square Holder Assembly Diagram
RIC Cryostat Equivalent Circuit

JR Dennison
Ryan Hoffmann
Aug 22, 2012
Ver. 2.0

Cryostat RIC Equivalent Circuit--Full Circuit
Absolute Yields

- SEE, BSE, emission spectra, (<20 eV to 30 keV)
- Angle resolved electron emission spectra
- Photoyield (~160 nm to 1200 nm)
- Ion yield (He, Ne, Ar, Kr, Xe; <100 eV to 5 keV)
- Cathodoluminescence (200 nm to 5000 nm)
- No-charge “Intrinsic” Yields
- T (<40 K to >400 K)

- Conductivity (<10^{-22} [ohm-cm]^{-1})
- Surface Charge (<1 V to >15 kV)
- ESD (low T, long duration)
- Radiation Induced Conductivity (RIC)
- Multilayers, contamination, surface modification
- Radiation damage
- Sample Characterization
End with a Bang
Model for Luminescence Intensity in Fused Silica

\[ I_y (J_b, E_b, T, \lambda) \propto \dot{D}(J_b, E_b) \left[ \frac{1}{D + D_{\text{sat}}} \left( \frac{E_{ST}}{k_B T} \right) \right] \{ \mathbb{A}_f(\lambda) [1 + \mathbb{R}_m(\lambda)] \} \]  (1)

where dose rate \( \dot{D} \) (absorbed power per unit mass) is given by

\[ \dot{D}(J_b, E_b) = \frac{E_b J_b [1 - \eta(E_b)]}{q_e \rho_m} \times \{ \begin{array}{l} [1/L] ; \quad R(E_b) < L \\ [1/R(E_b)] ; \quad R(E_b) > L \end{array} \} \]  (2)

Fig. 2. Qualitative two-band model of occupied densities of state (DOS) as a function of temperature during cathodoluminescence. (a) Modified Joblonski diagram for electron-induced phosphorescence. Shown are the extended state valence (VB) and conduction (CB) bands, shallow trap (ST) states at \( E_{ST} \) within \( \sim k_B T \) below the CB edge, and two deep trap (DT) distributions centered at \( E_{DT} = E_{\text{red}} \) and \( E_{DT} = E_{\text{blue}} \). Energy depths are exaggerated for clarity. (b) At \( T = 0 \) K, the deeper DT band is filled, so that there is no blue photon emission if \( E_{\text{blue}} < E_{\text{eff}} \). (c) At low \( T \), electrons in deeper DT band are thermally excited to create a partially filled upper DT band (decreasing the available DOS for red photon emission) and a partially empty lower DT band (increasing the available DOS for blue photon emission). (d) At higher \( T \), enhanced thermal excitations further decrease red photon emission and increase blue photon emission. Radiation induced

Radiation induced

Fig. 3. Range and dose rate of disordered SiO₂ as a function of incident energy using calculation methods and the continuous slow-down approximation described in [5].
Fig. 1. Optical measurements of luminescent thin film disordered SiO$_2$ samples. (a) Three luminescence UV/VIS spectra at decreasing sample temperature. Four peaks are identified: red (~645 nm), green (~500 nm), blue (~455 nm) and UV (~275 nm). (b) Peak amplitudes as a function of sample temperature, with baseline subtracted and normalized to maximum amplitudes. (c) Peak wavelength shift as a function of sample temperature. (d) Total luminescent radiance versus beam current at fixed incident energy fit by (1). (e) Total luminescent radiance versus beam energy at fixed incident flux fit by (1). (f) Total luminescent radiance versus beam energy at fixed 10 nA/cm$^2$ incident flux for epoxy-resin M55J carbon composite (red; linear fit), SiO$_2$ coated mirror (green; fit with (1)), and...
Fused Silica--Cryo ESD Breakdown Sites

FS 4 Post-Breakdown

FS 4 Breakdown Site Close-up

Kapton Sheet Under FS 4

Kapton Pad Over FS 4