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

J.R. Dennison, Gregory Wilson and Jodie Gillespie

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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 $e^-\cdot h^+$ recombination into VB holes.
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

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

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

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### 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>mixed</td>
<td>6.5 × 10⁴ to 3.8 × 10⁶ 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 × 10⁷ to 7 × 10⁹ rad/s</td>
<td>4.5 μs pulses</td>
</tr>
</tbody>
</table>
DOSE RATE is the deposited power per unit mass is:

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

which is proportional to incident electron absorption:

- Incident areal power density, \((J_b \cdot E_b)/q_e\)
- Energy-dependant correction for unabsorbed quasieelastic 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 Dependent

\[ \rho_{RIC} \]

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

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

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

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

Kapton™ (polyimide)

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 $k_0 = 1.5 \cdot 10^{-16} \text{ (}\Omega\text{-cm-Rad/s)}^{-1}$, $k_1 = 7.0 \cdot 10^{-29} \text{ (}\Omega\text{-cm-Rad/s)}^{-1}$ and $T_c = 230 \text{ K}$.

Kapton™ (polyimide)

$$\sigma_{RIC}(T, D) = k_{RIC}(T) \cdot D^{\Delta(T)}$$
Luminescent intensity, $I_\gamma$, scales with incident current density $J_b$, beam energy $E_b$, temperature $T$, and photon wavelength $\lambda$ as

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

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

A

A

A
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!!!
Conclusions

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 dependance
V. Suggests a nearly linear density of localized states (shallow traps)
Support & Collaborations

Air Force Research Lab

NASA/JWST (GSFC)

National Research Council

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

B4 4 JR Dennison
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
Phase VI: AFRL Bell Jar Chamber Cut Away Diagram

- Faraday Cup Z Translation Stage
- High Energy Electron Gun
- USU Closed Cycle He Cryostat
- Gate Valve to Pumping System
- Faraday Cup Assembly
- AFRL Bell Jar Chamber
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-Broken Silica Sample
New Sample Square Holder

New Sample Mount Rear Views
RIC Cryostat Equivalent Circuit

JR Dennison
Ryan Hoffmann
Aug 22, 2012
Ver. 2.0
USU/AFRL RIC Cryostat System Block Diagram

Legend:
- Standard A/C Power
- Coaxial Cable
- Computer System
- Vacuum System
- Electronics System
- Cooling System
- Standard Ground
- He Cooling Line

RIC Control PC
- CD Drive
- Hard Drive
- GPIB Card

Temp. Control PC
- USB Drive
- Hard Drive
- RS-232

Kellaby 0455
"Source 3"
Kellaby 2410
"Source 2"
0 – 1100 VDC
Kellaby 2410
"Source 1"
0 – 1100 VDC

GPIB

Breakout Patch Panel

3
23
9

GRAM Interface

25 Pin D Connector

CuFC
"Sample 5A"
F1
"Sample Ground"
R1
"Sample 2A"
E-gun

Cryo Pump

Vacuum Chamber Wall

Standard AVC Power
110 VAC 60 Hz

JR Dannison
Kent Hartley
Ver. 1.0 10/01/12
Ver. 1.1 10/02/12
Ver. 1.2 10/11/12
USU Experimental Capabilities

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

\begin{align}
I_y (J_b, E_b, T, \lambda) & \propto \dot{D}(J_b, E_b) \left[ \frac{1}{D + D_{\text{sat}}} \left( \frac{\varepsilon_{ST}}{k_B T} \right) \right] \{ A_f (\lambda) [1 + \mathbb{R}_m (\lambda)] \} \quad (1) \\
\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} \quad (2)
\end{align}

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

\begin{align*}
\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}
\end{align*}

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 \( \varepsilon_{ST} \) within \( ~k_B T \) below the CB edge, and two deep trap (DT) distributions centered at \( E_{DT} = E_{red} \) and \( E_{DT} = E_{blue} \). 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 \( E_{blue} < E_{eff} \). (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

Fig. 3. Range and dose rate of disordered SiO\(_2\) as a function of incident energy using calculation methods and the continuous slow-down approximation described in [5].
Measured Cathodoluminescence Intensity in Fused Silica

Fig. 1. Optical measurements of luminescent thin film disordered SiO₂ 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/cm² incident flux for epoxy-resin M55J carbon composite (red; linear fit), SiO₂ 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
Run 10 Rear Electrode Current Analysis