Radiation Hardness of Insulating Materials and Semiconductors

Kurt Schwartz

GSI Darmstadt, Material Sciences

31. 08. 2005
Radiation Hardness of Insulating Materials and Semiconductors

Kurt Schwartz
GSI Darmstadt, Material Sciences
31. 08. 2005

The Problem:
What determine the Sensitivity of Solids to Radiation?
  a) The electronic configuration of the atoms
  b) The crystal structure

I.  Damage creation in Dielectrics
    Two classes of insulating materials

II.  Semiconductors Si; SiC

III. Peculiarities of Damage creation under heavy ion irradiation
I. Damage Creation in Dielectrics by the Decay of Electronic Excitations [1, 3, 5, 6, 12]
other fluoride crystals

LiF (cubic)

- $a = 4.028$ Å
- $\rho = 2.635$ g/cm$^3$
- $F^- \ r = 1.33$ Å
- $Li^+ \ r = 0.74$ Å
- $E_g = 14.6$ eV

MgF$_2$ (tetragonal)

- $a = 4.623$ Å
- $c = 7.354$ Å
- $\rho = 3.18$ g/cm$^3$
- $F^- \ r = 1.33$ Å
- $Mg^{2+} \ r = 0.72$ Å
- $E_g = 11$ eV

CaF$_2$ (cubic)

- $a = 5.463$ Å
- $\rho = 3.18$ g/cm$^3$
- $F^- \ r = 1.33$ Å
- $Ca^{2+} \ r = 0.99$ Å
- $E_g = 11.2$ eV

BaF$_2$ (cubic)

- $a = 6.200$ Å
- $\rho = 4.89$ g/cm$^3$
- $F^- \ r = 1.33$ Å
- $Ba^{2+} \ r = 1.34$ Å
- $E_g = 9.1$ eV

A. El-Said (GSI)
Electronic Band Structure of LiF


CB      Li 2s     VB Li$^+$  1s$^2$[He]
VB      F$^-$ 2p$^6$[Ne]
Electronic structure:
Anion Exciton 13.6 eV
Gap $E_g = 14.2$ eV
Plasmons 25 eV
Cation Exciton 63 eV

D. M. Roessler, W. C. Walker,
Appearance of H centers at 8 K Irradiation

H centers are not stable at T > 70 K
Exciton mechanism

The discovering of exciton mechanism in 60ths

Ch.B. Lushchik et al., Sov. Phys. Solid State 6 (1965) 1789

H.N. Hersh, Phys. Rev. 148 (1966) 928


Ch.B. Lushchik et al., Sov. Phys. Uspekhi 20 (1977) 489 (review)
Exciton Processes in Dielectrics

$E(e^0)$ free Exciton Energy

$E(e^0_s)$ elf trapped Exciton Energy

Frenkel Pair F - H

Luminescence $\nu_L$

\[ E(e^0_s) \]

\[ E_{ex} \]

\[ h\nu_a \]

\[ h\nu^0_L \]

\[ h\omega_p \]

\[ E_{e,d} \leq E_{ex} \]
Efficiency of F-center creation in LiF

![Graph showing absorbance vs. wavelength for different incident energies and ion species](image)

<table>
<thead>
<tr>
<th>Incident Energy / F-center</th>
<th>Photons (eV)</th>
<th>Gammas (eV)</th>
<th>Light Ions (C, S, Ni) (eV)</th>
<th>Heavy Ions (Au, Pb, U) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>42</td>
<td>400</td>
<td>500-600</td>
<td>900-1200</td>
</tr>
<tr>
<td></td>
<td>~3Eg</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F-centers / track</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10^5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10^6</td>
</tr>
</tbody>
</table>
FIG. 1. The measured pair-creation energies $\epsilon$ of several semiconductors, versus the fundamental semiconductor band gap $E_g$. A straight line has been fitted to selected points on this plot.
Defect creation in ionic crystals

LiF, NaCl, KCl, MgF₂, CaF₂, BaF₂

lithium fluoride

non-amorphisable !!

\[ \text{F-center} \]
\[ \text{F}_2\text{-center} \]
\[ \text{H-center} \]
\[ \text{V}_K\text{-center} \]

\[ \text{electron centers} \]
\[ \text{Frenkel pair} \]
\[ \text{hole centers} \]

fcc lattice, \( E_g = 14.6 \text{ eV} \)
cleaving along (100) plane
II. Damage Creation in Dielectrics by Elastic Collisions [1, 2, 4, 7, 8, 10, 11]
### Radiation Hardness and Self Trapping

N. Itoh, NIM B 122 (1997) 405 - 409

#### Table 1
Presence and absence of self-trapping of carriers in major materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Electrons</th>
<th>Holes</th>
<th>Excitons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diamond, silicon, germanium</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>III–V compounds</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>II–VI compounds</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Se</td>
<td></td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>As$_2$S, As$_2$Se</td>
<td></td>
<td></td>
<td>yes</td>
</tr>
<tr>
<td>Copper halides</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Thallous halides</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Alkali halides with NaCl structure</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Alkali halides with CsCl structure</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Alkaline earth fluorides</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>PbCl$_2$</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>PbI$_2$</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>MgO</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>ZnO</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>
Defect production in MgO

\[ \Delta E_{tr} = \frac{4 \cdot M_1 \cdot M_2}{(M_1 + M_2)^2} \cdot E_0 \]

\[ E_0^{\text{min}} = \frac{\Delta E_{tr} \cdot (M_1 + M_2)^2}{4 \cdot M_1 \cdot M_2} \sim 430 \text{ keV} \]

\[ r_{O^-} = 1.40 \text{ Å} \quad E_d (O^-) = 59 \text{ eV} \]

\[ r_{Mg^{++}} = 0.74 \text{ Å} \quad E_d (Mg^{++}) = 64 \text{ eV} \]

\[ M_1 = A_1 \text{ or } A_2 \]

\[ O^- \quad A = M_1 = 16 \]

\[ M_2 = 1/1840 \]
Threshold Effect

$\Delta E(\text{LiF}) / \Delta(\text{MgO}) \approx 0.001$
Damage Creation in MgO
F center absorption

$\Delta E(\text{LiF}) / \Delta(\text{MgO}) \sim 0.001$
Table 2
Displacement energies for some non-metals near room temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>( T^d ) (eV)</th>
<th>Material</th>
<th>( T^d ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (graphite)</td>
<td>28–31</td>
<td>SiC</td>
<td>45–90</td>
</tr>
<tr>
<td>C (diamond)</td>
<td>80</td>
<td>MgO</td>
<td>64(Mg) 60(O)</td>
</tr>
<tr>
<td>Si</td>
<td>11–22</td>
<td>Al(_2)O(_3)</td>
<td>18(Al) 76(O)</td>
</tr>
<tr>
<td>Ge</td>
<td>12–30</td>
<td>MgAl(_2)O(_4)</td>
<td>56(O)</td>
</tr>
<tr>
<td>GaAs</td>
<td>9(Ga) 9(As)</td>
<td>ZnO</td>
<td>40(Zn) 57(O)</td>
</tr>
<tr>
<td>ZnS</td>
<td>10(Zn) 15(S)</td>
<td>UO(_2)</td>
<td>40(U) 20(O)</td>
</tr>
<tr>
<td>CdS</td>
<td>7(Cd) 9(S)</td>
<td>BeO</td>
<td>76(O)</td>
</tr>
</tbody>
</table>

Radiation Damage and Stress Effects in Superconductors: Materials for High-Field Applications

C.L. Snead, Jr and Thomas Luhrman*

*Metallurgy and Materials Science Division
Brookhaven National Laboratory
Upton, NY 11973
USA
# Silicon carbide: synthesis and processing

W. Wesch

Friedrich-Schiller-Universität Jena, Institut für Festkörperphysik, Max-Wien-Platz 1, D-07743 Jena, Germany

## Table 2
Comparison of selected semiconductor properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>GaAs</th>
<th>6H-SiC</th>
<th>4H-SiC</th>
<th>3C-SiC</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap [eV]†</td>
<td>1.1</td>
<td>1.42</td>
<td>3.0</td>
<td>3.3</td>
<td>2.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Melting point [°C]</td>
<td>1420</td>
<td>1238</td>
<td></td>
<td></td>
<td></td>
<td>phase change 20</td>
</tr>
<tr>
<td>Thermal conductivity [W cm⁻¹ K⁻¹]</td>
<td>1.5</td>
<td>0.5</td>
<td>4.9</td>
<td>4.9</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>Electron mobility at 10¹⁶ cm⁻³ [cm² V⁻¹ s⁻¹]</td>
<td>1100</td>
<td>6000</td>
<td>370</td>
<td>800</td>
<td>750</td>
<td>(2200)</td>
</tr>
<tr>
<td>Hole mobility at 10¹⁶ cm⁻³ [cm² V⁻¹ s⁻¹]</td>
<td>420</td>
<td>320</td>
<td>90</td>
<td>115</td>
<td>40</td>
<td>(1600)</td>
</tr>
<tr>
<td>Breakdown field at 10¹⁷ cm⁻³ [MV cm⁻¹]</td>
<td>0.6</td>
<td>0.6</td>
<td>3.2</td>
<td>3</td>
<td>4</td>
<td>(10)</td>
</tr>
</tbody>
</table>
III. Peculiarities of Damage Creation in Dielectric Materials under Heavy Ion Irradiation [1, 5, 6]
The diagram illustrates the energy loss processes in a material, showing:

- **Electronic Energy Loss**: ~1 MeV/u
- **Nuclear Energy Loss**: ~1 keV/u

**Energy Loss Processes**:
- **Collision Processes**: Primary Electrons $\rightarrow$ $\delta$-Electrons $\rightarrow$ Lattice Excitations (Excitons, Electrons, and Holes) $\rightarrow$ Defects $\rightarrow$ Luminescence $\rightarrow$ Vibrations

**Time Constants**:
- Primary Electrons: $10^{-17} - 10^{-16}$ s
- $\delta$-Electrons: $10^{-15} - 10^{-14}$ s
- Lattice Excitations: $10^{-13} - 10^{-3}$ s

**Equation**: $\Sigma N_{\text{electr}} = \Sigma N_{\text{holes}}$
Aggregation of single defects

Frenkel pairs

- electron center (F-centers)
  - $F_n$-centers
  - nF-clusters + metal colloids

- hole center (H- or V-centers)
  - $V_n$-centers
  - nX$^0$-clusters + halogen molecules

aggregates $\rightarrow$ stress

- etching
- SAXS
- swelling
- electronic structure
- surface hillocks
- dislocations & hardness
Self Trapping and Threshold Stopping Power for Track Registration

<table>
<thead>
<tr>
<th>System</th>
<th>Threshold stopping power (keV/nm)</th>
<th>Self-trapped exciton?</th>
<th>Reference (stopping power)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous tracks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>2</td>
<td>Yes</td>
<td>Méftah et al. (1993)</td>
</tr>
<tr>
<td>Y₂Fe₅O₁₂</td>
<td>4</td>
<td>Probably yes</td>
<td>Toulemonde et al. (1994)</td>
</tr>
<tr>
<td>Mica</td>
<td>5</td>
<td>Possibly yes</td>
<td>Toulemonde et al. (1994)</td>
</tr>
<tr>
<td>LiNbO₃</td>
<td>7</td>
<td>Probably yes</td>
<td>Meftah et al. (1993)</td>
</tr>
<tr>
<td>LiF</td>
<td>≥10</td>
<td>Yes</td>
<td>Schwartz et al. (1998)</td>
</tr>
<tr>
<td>Fragmentary tracks</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>20</td>
<td></td>
<td>Canut et al. (1995)</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>21</td>
<td></td>
<td>Canut et al. (1995)</td>
</tr>
<tr>
<td>Bi</td>
<td>31</td>
<td></td>
<td>Wang et al. (1996)</td>
</tr>
<tr>
<td>Si</td>
<td>&gt;28</td>
<td></td>
<td>Dunlop et al. (1998)</td>
</tr>
</tbody>
</table>
Lithium Fluoride
* complex damage structure
* since amorphisation is not possible, swelling is probably linked to the formation of defect aggregates
* SAXS radii in LiF are much smaller than any radii measured in amorphisable crystals

Oxides
* swelling can be explained by a transition from the crystalline to the amorphous phase
* the swelling radii and the threshold is about the same as observed by other techniques (TEM and RBS/C)

<table>
<thead>
<tr>
<th></th>
<th>swelling</th>
<th>etching</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiF</td>
<td>4 keV/nm</td>
<td>10 keV/nm</td>
</tr>
<tr>
<td>SiO₂ quartz</td>
<td>2 keV/nm</td>
<td>7 keV/nm</td>
</tr>
</tbody>
</table>

swelling occurs at a lower threshold than track etching
References


