1997–1998 ACADEMIC TRAINING PROGRAMME

LECTURE SERIES


TITLE: Radiation Damage

TIME: 16, 17, 18 & 19 February, from 11.00 to 12.00hrs

PLACE: Auditorium

ABSTRACT

a) Radiation damage in organic materials

This series of lectures will give an overview of radiation effects on materials and components frequently used in accelerator engineering and experiments. Basic degradation phenomena will be presented for organic materials with comprehensive damage threshold doses for commonly used rubbers, thermoplastics, thermosets and composite materials. Some indications will be given for glass, scintillators and optical fibres.

b) Radiation effects in semiconductor materials and devices

The major part of the time will be devoted to treat radiation effects in semiconductor sensors and the associated electronics, in particular displacement damage, interface and single event phenomena. Evaluation methods and practical aspects will be shown. Strategies will be developed for the survival of the materials under the expected environmental conditions of the LHC machine and detectors.
Radiation and dosimetry
Doses in CERN accelerators
Radiation effects on polymers
Test methods and specification requirements
Cable insulating materials
Rigid plastics and composites
Radiation tests at cryogenic temperatures
Scintillators and optical fibres
Summary tables
Outlook for LHC machine & experiments.
1. RADIATION

ORIGINE

natural
artificial

at CERN: proton accelerators
electron accelerators

TYPE

Electromagnetic: x-rays, gammas

Particles: electrons, positrons, protons, neutrons, pions, etc....

INTERACTION WITH MATTER

Ionization
Displacements
Interstitials
Nuclear reactions

DOSE

\[ 1 \text{ GRAY (Gy)} = \frac{1 \text{ Joule}}{\text{kg}} = 100 \text{ rad} \]
RADIATION EFFECTS ON POLYMERS

MAIN CHAIN RUPTURE

SIDE CHAIN RUPTURE

CROSS LINKING

DEGRADATION

GAS EVOLUTION

REACTION WITH ENVIRONMENT (OXYGEN)
RADIATION EFFECTS ON POLYMERS

IONIZATION
EXCITATION
DISSOCIATION

MAIN CHAIN RUPTURE

SIDE CHAIN RUPTURE

(energetic free radicals)
RADIATION EFFECTS ON POLYMERS

FREE RADICAL REACTIONS

CROSS LINKING

DEGRADATION

GAS EVOLUTION

REACTION WITH ENVIRONMENT (OXYGEN)
ACTIONS OF OXYGEN DURING IRRADIATION OF POLYMERS

- Radical formation

\[ \text{CH}_2 - \text{CH}_2 - \xrightarrow{\text{•••}} \cdot \text{CH} - \text{CH}_2 - + \text{H}^\cdot \]

- Oxidation reaction

\[ \text{CH} - \text{CH}_2 - + \cdot \text{O} - \text{O} \cdot - \rightarrow \cdot \text{CH} - \text{CH}_2 - \]

- Degradation reaction

\[ \text{CH} - \text{CH}_2 - \xrightarrow{} \cdot \text{C=O} + \cdot \text{O} - \text{CH}_2 - \]
# RADIATION INDUCED GAS EVOLUTION

<table>
<thead>
<tr>
<th>POLYMER</th>
<th>G-value*</th>
<th>COMPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyethylene (PE)</td>
<td>2.1</td>
<td>H₂ (95.5%); C₃H₈ (3.4%)</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.03</td>
<td>H₂ (100%)</td>
</tr>
<tr>
<td>Polycrylonitrile</td>
<td>0.4</td>
<td>H₂ (24%); NH₃ (8%)</td>
</tr>
<tr>
<td>Polymethyl methacrylate (PMMA)</td>
<td>1.3</td>
<td>C₂N₂ (67.5%)</td>
</tr>
<tr>
<td>Polyisobutylene</td>
<td>0.87</td>
<td>H₂ (18%); CH₄ (15%); CO (36%); CO₂ (25%); C₃H₈ (5.3%)</td>
</tr>
<tr>
<td>Polyethylene terephthalate (PETP, Mylar)</td>
<td>0.15</td>
<td>H₂ + CH₄ (95.5%)</td>
</tr>
<tr>
<td>Polyamide (Nylon)</td>
<td>1.1</td>
<td>CO₂ + C₃H₈ (4.5%)</td>
</tr>
<tr>
<td>Styrene butadiene rubber (SBR)</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Polyurethane rubber (PUR)</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Polysiloxane</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

*) G-value = number of product molecules formed or reactant molecules consumed per 100 eV of energy absorbed by the polymer. The G-value quoted here is for the production of all gases listed.
RADIATION EFFECTS ON POLYMERS

1. Most radiation sensitive properties are flexural strength and deformation for rigid plastics and elongation at break for flexible plastics.

2. Radiation damage can be related directly to absorbed dose irrespective of the radiation type.

3. Some Polymers eg. Polyolefins are very sensitive to environmental effects such as temperature and oxygen.
DOSE-RATE EFFECT ON POLYETHYLENE

Dose rate [mGy/sec] 5.2 10.2 8.9 60 168 158

No. of points 2 1 7 8 3 4

Normalized elongation $E/E_0$

Short [kJ], High Dose Rate

Long [kJ]

PE

Absorbed dose [Gy] 0 $10^5$ $10^6$ $10^7$
HIGH-LEVEL DOSIMETRY

in existing CERN machines

PS                     since 1966
BOOSTER                since 1975
SPS                     since 1976
LEP                     since 1989

Results published in a yearly TIS Commission Report
DOSIMETRY

TYPES

Calorimetry
Ionization chambers
 nues Formation of colour centres
 nues Formation of radicals
 Chemical reactions in liquids
 nues Gas evolution
 Nuclear activation

DOSIMETERS USED AT CERN

 nues Alanine dosimeter
 nues Radiophotoluminescent dosimeter
 nues Hydrogen pressure dosimeter

DOSES AROUND CERN ACCELERATORS
RADIATION DAMAGE TESTS
IEC STANDARD 544

GUIDE FOR DETERMINING THE EFFECTS OF
IONIZING RADIATION ON INSULATING MATERIALS

PART 1: RADIATION INTERACTIONS

PART 2: PROCEDURES FOR IRRADIATION AND TEST

PART 4: CLASSIFICATION SYSTEM FOR SERVICE IN RADIATION ENVIRONMENTS
1 IRRADIATION CONDITIONS

Short-time exposure at high-dose rates
$3 \times 10^3$ Gy/h to $10^6$ Gy/h

Long-time exposure at dose rates up to
100 Gy/h

2 CRITICAL PROPERTIES

Flexural stress at maximum load for rigid plastics

Percent elongation at break for flexible plastics and elastomers

End point criterion: 50% of initial value

3 RADIATION INDEX

Logarithm (log 10) of the absorbed dose in Grays above which the appropriate critical property value has reached the end point criterion

e.g. for material for which end point is reached at $2 \times 10^4$ Gy, $RI = 4.3$
FLAMMABLE MATERIALS
(non metals)

INSTRUCTION DE SÉCURITÉ
SAFETY INSTRUCTION

CRITERIA AND STANDARD TEST METHODS
FOR THE SELECTION OF
ELECTRIC CABLES, WIRES AND INSULATED PARTS
WITH RESPECT TO FIRE SAFETY
AND RADIATION RESISTANCE

INSTRUCTION DE SÉCURITÉ
SAFETY INSTRUCTION

Publication date: March 1995

The Use of Plastic and
other Non-Metallic Materials at CERN
with respect to Fire Safety
and Radiation Resistance
Specifications and requirements of IS 23 and IS 41

- Halogen- and sulphur-free
- Flame retardant
- Low smoke density
- Low toxicity
- Radiation resistance.

This excludes e.g. PVC, TEFLON, VITON, HYPALON, NEOPRENE

The first version of IS 23 was published in 1984 and all LEP cables are in conformity with IS 23.

Since 10 years the CERN Stores have only cables which conform to IS 23.

Since 01.01.96 the purchase or introduction at CERN of new PVC cables is forbidden and all cable orders are checked by a TIS cable controller. Derogations are rare.

IS 41 (Plastics) is now observed quite generally at CERN, including building construction, furniture and experiments, although its enforcement still requires considerable efforts on the part of TIS.
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

COMPILATION OF RADIATION DAMAGE TEST DATA

PART I. 2nd EDITION:
\[\text{Halogen-free cable-insulating materials}\]

INDEX DES RÉSULTATS D’ESSAIS DE RADIORÉSISTANCE

I\textsuperscript{e} PARTIE, 2\textsuperscript{e} ÉDITION:
Matériaux d’isolation de câbles exempts d’halogène

H. Schönbacher and M. Tavlet

GENEVA 1989
DESCRIPTION OF THE MATERIAL CERN N. 652

MATERIAL : POLYOLEFIN
TYPE : MCR 319 (=O 2983 FR)
SUPPLIER : BP CHEMICALS
REMARKS : USED FOR LEP CONTROL

FIG. -MECHANICAL PROPERTIES VS. ABSORBED DOSE
Determination of Effects of Ionizing Radiation on Insulating Materials, IEC 544

CERN Material No. : 926

Material : EPR
Type : Die 021, crosslinked
Supplier : Kolonmetal Electro
Remarks : Smooth (52)

Test Results:

<table>
<thead>
<tr>
<th>Dose rate (Gy/h)</th>
<th>Tensile Properties</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength (MPa)</td>
<td>Elongation (%)</td>
</tr>
<tr>
<td>0.000</td>
<td>10.3 ± 0.3</td>
<td>565.0 ± 15.5</td>
</tr>
<tr>
<td>0.200</td>
<td>10.5 ± 0.3</td>
<td>468.0 ± 10.4</td>
</tr>
<tr>
<td>0.500</td>
<td>9.5 ± 0.5</td>
<td>330.0 ± 11.2</td>
</tr>
<tr>
<td>1.000</td>
<td>8.6 ± 0.6</td>
<td>220.0 ± 13.7</td>
</tr>
<tr>
<td>3.000</td>
<td>7.0 ± 0.6</td>
<td>65.0 ± 7.6</td>
</tr>
</tbody>
</table>

Radiation Index (2.5x10^4 Gy/h) : 5.8
Radiation Index (100.0 Gy/h) : 5.5

Results of Other Tests:
Oxygen Index (ISO 4589) : 22.0 %
Corrosivity (DIN 57472) : PASS

---

Determination of Effects of Ionizing Radiation on Insulating Materials, IEC 544

CERN Material No. : 929

Material : EPR
Type : G 10
Supplier : Nuova Fuigio Covi
Remarks : Insulation (P)

Test Results:

<table>
<thead>
<tr>
<th>Dose rate (Gy/h)</th>
<th>Tensile Properties</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength (MPa)</td>
<td>Elongation (%)</td>
</tr>
<tr>
<td>0.000</td>
<td>6.1 ± 0.1</td>
<td>404.8 ± 34.5</td>
</tr>
<tr>
<td>0.200</td>
<td>6.3 ± 0.3</td>
<td>244.0 ± 15.0</td>
</tr>
<tr>
<td>0.500</td>
<td>6.9 ± 0.2</td>
<td>160.0 ± 27.3</td>
</tr>
<tr>
<td>1.000</td>
<td>8.9 ± 0.2</td>
<td>42.4 ± 4.6</td>
</tr>
</tbody>
</table>

Radiation Index (3000.0 Gy/h) : 5.6
Radiation Index (100.0 Gy/h) : 5.4

Results of Other Tests:
Oxygen Index (ISO 4589) : 33.0 %
Corrosivity (DIN 57472) : PASS
THERMOSETTING RESIN

BASE MATERIAL: Epoxy-phenol-novolac resin
TYPE: EPN1138/MY745/CY221/HY905
SUPPLIER: Ciba-Geigy
IDENTIFICATION: R297–1976

![Graph](image)

- MATERIAL: EPN 1138+MY 745+ CY 221+HY 905+XB266
- SUPPLIER: CIBA - GEIGY
- REMARKS: ISR-RESIN

<table>
<thead>
<tr>
<th>CURVE PROPERTY</th>
<th>INITIAL VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>ULTIMATE FLEXURAL STRENGTH</td>
</tr>
<tr>
<td>D</td>
<td>DEFLEXION AT BREAK</td>
</tr>
<tr>
<td>M</td>
<td>MODULUS OF ELASTICITY</td>
</tr>
</tbody>
</table>
Material: Epoxy + Carbon Fibres
Type: LY 556 / HY 917 / DY 070
Supplier: Ciba-Geigy
Remark: 8 layers of fibre mat

TIS No.: R 552
UL 94: n.m.
Date: 27/7/94

Radiation test results according to IEC Standard 544 (and ISO 178)

<table>
<thead>
<tr>
<th>Dose rate (kGy/h)</th>
<th>Dose (kGy)</th>
<th>Ultim. strength (MPa)</th>
<th>Deformation $\varepsilon$ (%)</th>
<th>Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>928.6 ± 187.4</td>
<td>1.17 ± 0.23</td>
<td>80.49 ± 2.58</td>
</tr>
<tr>
<td>230</td>
<td>3'000</td>
<td>815.7 ± 99.1</td>
<td>0.97 ± 0.16</td>
<td>81.51 ± 2.10</td>
</tr>
<tr>
<td>230</td>
<td>10'000</td>
<td>857.3 ± 113.6</td>
<td>1.06 ± 0.13</td>
<td>82.23 ± 1.44</td>
</tr>
<tr>
<td>230</td>
<td>62'000</td>
<td>836.7 ± 90.1</td>
<td>1.02 ± 0.12</td>
<td>83.01 ± 1.17</td>
</tr>
</tbody>
</table>

Critical property = flexural strength
Radiation index (RI) > 7.8 at a mean dose rate of 230 kGy/h

Radiation effect on C-C composite R 552

Absorbed dose (kGy)
Material: Polyetherimide + glass fibres  
Type: Ultem 1000  
Supplier: General Electric Plastics  
Remark: 

TIS No: R 504  
UL 94: n.m.  
Date: 14/01/88

Radiation test results according to IEC Standard 544 (and ISO 178)

<table>
<thead>
<tr>
<th>Dose rate (kGy/h)</th>
<th>Dose (kGy)</th>
<th>Ultim. strength (MPa)</th>
<th>Deformation ε (%)</th>
<th>Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>287.97 ± 53.55</td>
<td>2.83 ± 0.08</td>
<td>10.52 ± 1.32</td>
</tr>
<tr>
<td>170</td>
<td>5'000</td>
<td>233.57 ± 28.56</td>
<td>2.86 ± 0.14</td>
<td>9.09 ± 1.40</td>
</tr>
<tr>
<td>70</td>
<td>10'000</td>
<td>234.87 ± 9.37</td>
<td>2.65 ± 0.09</td>
<td>9.47 ± 0.36</td>
</tr>
<tr>
<td>70</td>
<td>50'000</td>
<td>213.59 ± 6.07</td>
<td>2.39 ± 0.10</td>
<td>10.02 ± 0.46</td>
</tr>
<tr>
<td>220</td>
<td>100'000</td>
<td>215.79 ± 3.01</td>
<td>2.15 ± 0.04</td>
<td>10.81 ± 0.13</td>
</tr>
</tbody>
</table>

Critical property = flexural strength
Radiation index (RI) > 8 at a mean dose rate of 220 kGy/h

Radiation effect on insulating resin R 504
Material: Epoxy resin
Type: Vetronite G11
Supplier: Von Roll ISOLA
Remark: grade 64120

TIS No: R 538
UL 94: n.m.
Date: 17/06/94

Radiation test results according to IEC Standard 544 (and ISO 178)

<table>
<thead>
<tr>
<th>Dose rate (kGy/h)</th>
<th>Dose (kGy)</th>
<th>Ultim. strength (MPa)</th>
<th>Deformation ε (%)</th>
<th>Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
<td>557.16 ± 23.07</td>
<td>2.54 ± 0.08</td>
<td>29.78 ± 8.83</td>
</tr>
<tr>
<td>220</td>
<td>5'000</td>
<td>483.50 ± 16.41</td>
<td>2.19 ± 0.15</td>
<td>25.71 ± 0.89</td>
</tr>
<tr>
<td>220</td>
<td>10'000</td>
<td>448.39 ± 23.88</td>
<td>1.96 ± 0.10</td>
<td>26.64 ± 0.58</td>
</tr>
<tr>
<td>220</td>
<td>50'000</td>
<td>294.65 ± 21.58</td>
<td>1.43 ± 0.09</td>
<td>26.10 ± 0.51</td>
</tr>
<tr>
<td>220</td>
<td>100'000</td>
<td>211.03 ± 19.53</td>
<td>1.12 ± 0.12</td>
<td>22.49 ± 1.26</td>
</tr>
</tbody>
</table>

Critical property = flexural strength
Radiation index (RI) = 7.7 at a mean dose rate of (kGy/h): 220

Radiation effect on insulating resin R 538
RADIATION TESTS AT CRYOGENIC TEMPERATURES OF SOME SELECTED ORGANIC MATERIALS

Collaboration with Technical University Vienna

Irradiation at room temperature: ASTRA Reactor Seibersdorf
Doses: 0.2 MGy to 100 MGy

Irradiation in liquid nitrogen: Reactor Ekaterinburg
Doses: 0.18 MGy to 156 MGy

Material Selection: - Films
- Cable insulation
- Epoxy - resins
- Composite materials

Tensile and Flexural tests at ambient temperature and in liquid nitrogen without warming up.
Material: Epoxy resin
Type: MY 745 (100) + HY-906 (90) + DY 073 (1.5)
Supplier: Ciba-Geigy
Remarks: used for the SPS dipoles

Radiation test results according to IEC Standard 544 (and ISO 178)

<table>
<thead>
<tr>
<th>Dose (MGy)</th>
<th>Mechanical test results at RT</th>
<th>Mechanical test results at 77 K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength (MPa)</td>
<td>Deformation (ε (%))</td>
</tr>
<tr>
<td>0</td>
<td>148.1 ± 14.9</td>
<td>8.8 ± 1.3</td>
</tr>
<tr>
<td>5</td>
<td>118.0 ± 10.0</td>
<td>10.0 ± 2.0</td>
</tr>
<tr>
<td>10</td>
<td>98.0 ± 5.9</td>
<td>7.2 ± 1.4</td>
</tr>
<tr>
<td>14</td>
<td>43.0 ± 4.0</td>
<td>3.2 ± 0.6</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>119</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RI =</td>
<td>7.1</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Radiation effect on epoxy resin R 423

Comment:
Material: Composite  
Type: Epoxy + CARBON FIBRE  
Supplier: Ciba-Geigy  
Remarks: LHC magnet cold support  
TIS No: R 550  
UL 94: n.m.  
LOI: n.m.

Radiation test results according to IEC Standard 544 (and ISO 178)

<table>
<thead>
<tr>
<th>Dose (MGy)</th>
<th>Mechanical test results at RT</th>
<th>Mechanical test results at 77 K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength (MPa)</td>
<td>Deformation (ε) (%)</td>
</tr>
<tr>
<td>0</td>
<td>1674 ± 135</td>
<td>1.54 ± 0.05</td>
</tr>
<tr>
<td>10</td>
<td>1681 ± 122</td>
<td>1.65 ± 0.09</td>
</tr>
<tr>
<td>19</td>
<td>1579 ± 75</td>
<td>1.56 ± 0.06</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>156</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RI =</td>
<td>&gt; 7.7</td>
<td>&gt; 7.7</td>
</tr>
</tbody>
</table>

Radiation effect on Composite R 550

![Diagram showing radiation effect on Composite R 550](image)

Comment:
**Material:** Prepreg  
**Type:** Vetonite Epoxy G11  
**Supplier:** von Roll Isola  
**Remarks:** proposed LHC magnets insulation  
**TIS No:** R 538  
**UL 94:** n.m.  
**LOI:**

Radiation test results according to IEC Standard 544 (and ISO 178)  

<table>
<thead>
<tr>
<th>Dose (MGy)</th>
<th>Mechanical test results at RT</th>
<th>Mechanical test results at 77 K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength (MPa)</td>
<td>Deformation (ε %)</td>
</tr>
<tr>
<td>0</td>
<td>557 ± 23</td>
<td>2.5 ± 0.1</td>
</tr>
<tr>
<td>5</td>
<td>484 ± 16</td>
<td>2.2 ± 0.2</td>
</tr>
<tr>
<td>10</td>
<td>448 ± 24</td>
<td>2.0 ± 0.1</td>
</tr>
<tr>
<td>14</td>
<td>295 ± 22</td>
<td>1.4 ± 0.1</td>
</tr>
<tr>
<td>37</td>
<td>211 ± 20</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>7.8</td>
</tr>
<tr>
<td>100</td>
<td></td>
<td>7.2</td>
</tr>
<tr>
<td>RI = 7.6</td>
<td>7.7</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Radiation effect on Prepreg R 538

![Radiation effect graph](image)

**Comment:**
**Material:** Polyimide  
**Type:** Kapton H  
**TIS No.:** M 702 H  
**Supplier:** DuPont de N.  
**Remarks:** 125 micron film  
**UL 94:**  
**LOI:** n.m.

### Radiation test results according to IEC Standard 544

<table>
<thead>
<tr>
<th>Dose (MGy)</th>
<th>Mechanical test results at RT</th>
<th>Mechanical test results at 77 K</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strength (MPa)</td>
<td>Elongation (E (%))</td>
</tr>
<tr>
<td>0</td>
<td>165.0 ± 13.0</td>
<td>23.5 ± 11.0</td>
</tr>
<tr>
<td>1</td>
<td>177.0 ± 5.0</td>
<td>29.5 ± 4.1</td>
</tr>
<tr>
<td>3</td>
<td>171.0 ± 2.0</td>
<td>25.5 ± 4.5</td>
</tr>
<tr>
<td>10</td>
<td>168.0 ± 2.0</td>
<td>21.5 ± 3.4</td>
</tr>
<tr>
<td>35</td>
<td>135.0 ± 6.0</td>
<td>9.0 ± 1.7</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>119</td>
<td>&gt; 7.7</td>
<td>7.3</td>
</tr>
</tbody>
</table>

### Radiation effect on Kapton film M 702

![Radiation effect graph](attachment:image)

**Comment:**
Material: PETP  TIS No: M 701
Type: Mylar
Supplier: CERN stores
Remarks: 300 micron film
UL 94: n.m.
LOI: n.m.

Radiation test results according to IEC Standard 544

<table>
<thead>
<tr>
<th>Dose (MGy)</th>
<th>Mechanical test results at RT</th>
<th>Mechanical test results at 77 K</th>
</tr>
</thead>
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<td>Strength (MPa)</td>
<td>Elongation (%)</td>
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<td>116.7 ± 11.0</td>
<td>62.1 ± 18.0</td>
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<td>0.18</td>
<td>111.5 ± 6.1</td>
<td>57.5 ± 7.4</td>
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<td>106.4 ± 8.1</td>
<td>48.8 ± 13</td>
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<td>92.5 ± 6.5</td>
<td>13.3 ± 11</td>
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<td>RI =</td>
<td>&gt; 6</td>
<td>5.8</td>
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</table>

Radiation effect on Mylar film M 701

Comment:
RADIATION TESTS AT CRYOGENIC TEMPERATURES OF SOME SELECTED ORGANIC MATERIALS

RESULTS

Common rubber and polyolefin cable-insulating materials are not suitable for low-temperature applications. Their elongation at break is reduced to a few percent even without irradiation.

Most of the thermoplastic film materials including Mylar, Peek and Kapton are suitable for the LHC environment. Because of the absence of oxygen in the cryogenic liquid, the radiation degradation may even be less pronounced.

Commonly used materials like Vetronite show the same radiation resistance as at room temperature e.g. between 20 MGy and 50 MGy. Some more recently developed composites based on Kevlar and carbon fibre reinforcements have excellent radiation resistance at the highest doses obtained in the experiment e.g. 156 MGy.
RADIATION TESTS AT CRYOGENIC TEMPERATURES OF SOME SELECTED ORGANIC MATERIALS

RESULTS

No significant influence of the irradiation temperature has been observed in our experiment on the radiation degradation of thermosets and composites. Therefore, good indications for the radiation response of these types of materials for use in a cryogenic environment can be assessed from room-temperature tests after their properties have been measured at low temperature.

Ref. CERN 96-05
REVIEW OF RADIATION DAMAGE
TO SCINTILLATING MATERIALS

PARAMETERS WHICH INFLUENCE
RADIATION EFFECTS:

Base material
Luminophor
Impurities
Environment (air, \( N_2 \))
Dose and dose rate
Sample size
Radiation type
Wavelength
Time between irradiation and measurement
REVIEW OF RADIATION DAMAGE
TO OPTICAL FIBRES

PARAMETERS WHICH INFLUENCE
RADIATION EFFECTS:

Type of fibres
OH content
Dopants
Impurities
Production process
Dose and dose rate
Radiation type
Temperature
Wavelength, light power, light injection
Time between irradiation and measurement

It must be stressed that with such a number of interfacing parameters it is practically impossible to predict the radiation resistance of one fibre or another without proper testing under service conditions.
LHC MACHINE DOSES FOR 10 YEARS NOMINAL INTENSITY
ANNUAL PROTON LOSS RATE = $1.65 \times 10^{11}$ m$^{-1}$

**DIODES**
- at 40cm inter-magnet gap: 1000 Gy ($5 \times 10^{10}$ n/cm$^2$)
- at 1 metre from cryostat along magnet: 10 Gy ($5 \times 10^{11}$ n/cm$^2$)
- at inter-magnet gap: 120 Gy ($6 \times 10^{12}$ n/cm$^2$)

**SC BUS BARS**
- $r = 25$ cm
- 300 Gy

**SUPERCONDUCTING COILS**
- $r = 3$ cm
- $r = 6$ cm
- $7 \times 10^4$ Gy
- $1 \times 10^4$ Gy

**THERMAL SHIELD**
- $r = 40$ cm
- 60 Gy

**VACUUM VESSEL**

**SUPPORT POST**
- idem vac. vessel

**CRYOSTAT**
- $\phi 570$
- He 4.5K 3 bar

**MAGNET**
- $\phi 94$
- 10

**Diagram:**
- Dimensions and labels for various components and distances.
Absorbed doses close to the magnets in Gray per inelastic beam-gas interaction per metre calculated from the data in [Ste92], indicated by the stars (*). Open circles (o) are the results from alongside the magnet taken from Table 1 and crosses (x) are the results from the inter-magnet gap. The lines are fits by eye to the data.
DOSE CLOSE TO THE QUADRUPOLES OF
THE HIGH LUMINOSITY INSERTION
FOR 10 YEARS

At the tunnel walls close to the quadrupoles:

\[ 10^4 \text{ Gy} \]

elsewhere \[ 10^3 \text{ Gy} \]

Between the magnets of the low beta region up to two orders of magnitudes higher

(M. Huhtinen, G.R. Stevenson)
ATLAS

Doses unit neutron fluence

PER YEAR

spectromètre à muons
1 Gy + 10^{11} n.cm^{-2}

calorimètre à hadrons
20 Gy + 10^{12} n.cm^{-2}

calorimètre à hadrons
10 Gy + 10^{12} n.cm^{-2}

calorimètre électromagnétique
600 Gy + 10^{13} n.cm^{-2}

TRT
3 kGy + 10^{13} n.cm^{-2}

e-m. cal.
10^{14} n.cm^{-2}

calorimètre à hadrons
'end-cap'
10 kGy + 5 \times 10^{14} n.cm^{-2}

cal-frontal

faisceau
0 1 2 3 4 5 6 7

30 kGy + 6 \times 10^{13} n.cm^{-2}

2 MGy + 10^{16} n.cm^{-2}
CERN EXPERIENCE
WITH LONG-TERM RADIATION EFFECTS

Extensive experience has been gained at CERN over several decades. This includes accelerated radiation damage tests but also a follow up of THE SAME materials when ageing in the radiation environment during operation of the CERN accelerators.

This allows to check and confirm:

- The effect of time (dose rate)
- The validity of test methods and test parameters (Standardization)
- The effect of radiation type

and allows prediction for existing (PS, SPS, LEP) as well as future installations (LHC).
Classification of rubber materials with respect to their radiation resistance

Polyurethane rubber (PUR)
Ethylene– propylene rubber (EPR/EPDM)
Styrene– butadiene rubber (SBR)
Cross - linked polyolefins (EVA)
Polychloroprene rubber
Acrylonitrile rubber
Acrylic rubber (EAR, EEA)
Silicone rubber (SIR)
Butyl rubber

Dose in gray
10^3  10^4  10^5  10^6  10^7  10^8

Dose in rad
10^5  10^6  10^7  10^8  10^9  10^10

Appreciation of Damage
Radiation index area
Moderate to severe

Elongation
25-75% of in value
< 25% of in value

Utility
Often satisfactory
Not recommended
General classification of rigid thermoplastics with respect to their radiation resistance

Polyimide (PI)
Liquid Crystal Polymer (LCP)
Polyetherimide (PEI)
Polyamideimide (PAI)
Polyphenylsulfide (PPS)
Polyetheretherketone (PEEK)
Polystyrene (PS)
Copolymer PI + siloxane
Polyarylate (PAR)
Polyarylamide (PAA)
Polyethersulfide (PES)
Polysulfone (PSU)
Polyamide 4.6
Polyphenyloxyde (POO)
Acrylonitrile-butadiene-styrene (ABS)
Polyethylene (PE)
Polyethyleneterephthalate (PETP)
Polycarbonate (PC)
Polyamide 6.6 (PA)
Cellulose acetate
Polypropylene (PP)
Polymethylmethacrylate (PMMA)
Polyoxyymethylene (POM)
Polytetrafluoroethylene (PTFE)

mild to moderate damage, utility is often satisfactory

moderate to severe damage, use not recommended

These appreciations can only serve as a general guideline; environmental conditions such as temperature, humidity and dose rate, as well as additives influence the radiation behaviour of materials.

Fibre reinforced composites based on these resins can be at least one order of magnitude better.
General classification of thermoset resins and composites with respect to their radiation resistance

- Epoxy, glass laminate
- Phenolic, glass laminate
- Phenolic, mineral filled
- Aromatic cured epoxy (special formulation)
- Silicone, glass-filled
- Silicone, mineral-filled
- Polyester, glass filled
- Polyurethane (PUR)
- Polyester, mineral filled
- Silicone (unfilled)
- Epoxy (EP)
- Phenolic (unfilled)
- Melamine-formaldehyde (MF)
- Urea-formaldehyde (UF)
- Polyester (unfilled)
- Aniline-formaldehyde (AF)

[Diagram showing radiation resistance levels]

- **mild to moderate damage, utility is often satisfactory**
- **moderate to severe damage, use not recommended**

These appreciations can only serve as a general guideline; environmental conditions such as temperature, humidity and dose rate, as well as additives influence the radiation behaviour of materials.

Fibre reinforced composites based on these resins can be at least one order of magnitude better (see Appendix 3).
### Assessment of radiation damage to organic materials irradiated at various temperatures

<table>
<thead>
<tr>
<th>Irradiations and tests at RT</th>
<th>Materials</th>
<th>Irradiations and tests at 77 K</th>
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<tbody>
<tr>
<td></td>
<td>Polyelefins</td>
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</tr>
<tr>
<td></td>
<td>EP-Rubbers</td>
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</tr>
<tr>
<td></td>
<td>SIO + PEI</td>
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</tr>
<tr>
<td></td>
<td>PETP</td>
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<tr>
<td></td>
<td>Polymide</td>
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<td>PEEK</td>
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<tr>
<td></td>
<td>XB 3192</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vetronite</td>
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</tr>
<tr>
<td></td>
<td>Ep + G.F.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ep+GF+Kevlar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ep + C.F.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Damage level:</th>
<th>material unusable</th>
<th>50% reduction area</th>
<th>no test</th>
<th>undamaged</th>
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<tr>
<td>Dose (Gy)</td>
<td>10^8</td>
<td>10^7</td>
<td>10^6</td>
<td>10^5</td>
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</table>
RADIATION HARDNESS STUDIES

INSULATING AND STRUCTURAL MATERIALS

LARGE EXPERIENCE AVAILABLE AT CERN FROM ACCELERATORS

COMPILATION OF RADIATION DAMAGE TEST DATA

PART 1: Cable Insulating Materials
CERN 79-04

PART 1, 2nd EDITION:
Halogen-free Cable-Insulating Materials
CERN 89-12

PART 2: Thermosetting and Thermoplastic Resins
CERN 79-08
2nd Edition in preparation

PART 3: Materials Used Around High Energy Accelerators
CERN 82-10

Contact at CERN
Marc. Tavled @ cern.ch
RADIATION DAMAGE

b) RADIATION EFFECTS in SEMICONDUCTOR MATERIALS and DEVICES
3 lectures

Erik H.M. HEIJNE
CERN

OVERVIEW
Contents
PART B)

LECTURE 2 TUESDAY
MOSTLY BULK EFFECTS AND DETECTORS

LECTURE 3 WEDNESDAY
SURFACE EFFECTS AND ICs

LECTURE 4 THURSDAY
LHC, WHAT CAN ONE DO?

CERN Academic Training
16-19 February 1998
Lecture 2  Mostly bulk effects and detectors

Introduction
Radiation destroys systems
Telstar I failure
Radiation is used for study and manufacturing
Nuclear interactions cause transmutations of atoms
Neutron activation analysis
Characteristic properties of semiconductors, Si in particular
Silicon crystalline structure
Band diagrams
Doping of Si, Fermi level and carrier concentrations
Semiconductor device structures
Metal-Semiconductor contact (Schottky barrier)
Non-injecting Ohmic contact
MIS / MOS capacitor : 3rd lecture
Carrier concentrations in rectifying p-n junction
Total depletion in a detector
Applications of semiconductors in LHC
Magnet power supplies
Si sensors for tracking
Microelectronic chips

Energy loss
Bethe-Bloch formula and energy deposition measured in Si
Free charge carriers proportional to energy deposition
Carrier concentrations in detectors
Transient effects and single event effects : 4th lecture
Trapping of charge carriers: interface effects : 3rd lecture
Displacements in the crystal: 'Bulk effects'
Potential barriers for atoms
Primary defects by radiation, vacancy-interstitial pair
Threshold energy for displacements
Threshold measurement with electrons
Non-ionizing energy loss NIEL, KERMA and dose definitions
Dependence on particle type, energy and semiconductor
Methods of characterization of defects in the crystal
Thermal identification
Optical absorption
Electrical characterization
Magnetic resonance

Introduction rates
Electron Paramagnetic Resonance EPR
Electron Nuclear DOuble Resonance ENDOR
EPR Spectra
Equipment for EPR and ENDOR
ENDOR spectrometer
Sensitivity
Angular dependence for P-V spectrum
Double vacancy V-V
Partial list of identified defect spectra
Structure of defects from EPR

Charge states of defects
Donor-type and acceptor-type defects
Energy levels in the bandgap
Dependence on the Fermi-level

Principle of electrical methods on diodes
I vs temperature : TSC
C vs temperature : DLTS

Mobility of defects, secondary and tertiary defects
Thermal activation energy of electronic structure of a defect
Defect recovery by thermal annealing

EH  February 20, 1998
Phosphorous - Vacancy
Reverse annealing

Macroscopic manifestations of defects
  Shortening of minority carrier lifetime
  Damage constants
  Increase of generation current
  I-V characteristics of diode
  Carrier removal and trapping
  Change of doping
  C-V characteristics of diode
  Change of total depletion voltage $V_T$

What to do about bulk defects in Si? 4th lecture

Lecture 3  Mostly surface effects and ICs

Influence of bulk defects on bipolar transistor operation
  Reduction of minority carrier lifetime
Low dose rate effects
The Si surface with dangling bonds and oxide
  Oxide traps at the interface
The Metal Oxide Semiconductor (MOS) capacitor
  C - V at low frequency
  C - V at high frequency
  The flat band voltage, accumulation and inversion
Flat band voltage shift due to charging of the oxide
  Oxide charge $Q_{ox}$, interface traps and border traps
  Surface atoms and interface trap density $N_{it}$
Radiation effects in the MOSFET gate oxide
  Generation and transport of carriers in the oxide
  Trapping of the charge near the interface
  Threshold shift due to irradiation
  Determination of the threshold voltage of a transistor
  Sub - threshold current characteristics
Dose rate effects
  Rebound of threshold in long irradiation
  Interface states influence mobility, noise, gain
The field oxide around the transistor
  The bird's beak region
  Field leakage current
  Gated diode allows measurement of interface states
  Charge pumping measurements
  Thermal annealing of oxide charge
  Increased trapping at low temperatures
The role of oxide in a silicon detector
Oxide separations in a detector
  Edge protection
  Surface charge vs bulk charge
  Separation of sensor segments
  AC coupling capacitors
MOS capacitor arrays, the CCD
  Bulk defects in CCD
  $Q_{ox}$ and $N_{it}$ decrease with thickness of oxide
  Tunneling through interface barrier
Effects in sub-micron transistors
  Very thin oxides
  Spacer oxides
  Trench isolation
Hardness comparison of technologies

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Lecture 4  LHC, what can one do

The radiation environment in the LHC experiments
   Ionizing charged particle fluence
   Neutron fluence
   Photon flux and energy spectrum
      Risk of photon pollution
   Geometrical dose distributions
Can one reduce the source term in LHC?
   Studies for lining with polyethylene absorber
Ionization-induced physical or logical destruction
   Upset by cosmic neutrons
   Power MOSFET burnout
   Single Event Phenomena and critical charge
Latch-up
   Gate rupture

ESD phenomena
Ionization density and transient effects in detectors
   Simulation of large energy deposit events
   Critical charge density for upset of a device
Hardening detectors and systems
   Hardening by defect engineering : ROSE
   Gettering
      Denuded zone
      Local ion implantation, e.g. He
Adapt detector and readout design to radiation effects
   Cooling of the system
   Increase of segmentation
   Tolerance for leakage current
Use of other semiconductors
   GaAs (RD7)
   Diamond (RD42)

Comparison of radiation environments in space and at the LHC
Use of Components Off-The-Shelf : COTS
Qualification Procedures
   USA Mil-STD 883C, Test Method TM 1019.4
   Simulation of low dose rate
   ESA/SCC Basic Specification BS 22900
   ASTM Standards E666 E668 E1249 E1250 etc
   Dose equilibrium and dosimetry

Hardening of readout chips
   Radhard technologies
      RD9 and SOI
      RD29 and DMILL (Temic/MHS)
         General characteristics of DMILL
         DMILL uses a SIMOX substrate
         Threshold voltage shifts of n- and p-channel transistors
         Noise spectra after 10 Mrad
         Status of production at Temic/Matra MHS
         Radiation assurance
      Harris, Honeywell, Loral

Use of commercial CMOS
   Experience in the ZEUS calorimeter readout
      Performance in a 1.2 μm radsoft technology
   Radhard design and radhard layout ('Radtol' RD49)
      Thin oxides : small $V_T$ shift
      Enclosed (edgeless) transistors
      Recent results

Conclusions

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Lecture 2  Mostly bulk effects and detectors

Introduction

Energy loss

Displacements in the crystal: 'Bulk effects'

Methods of characterization

of defects in the crystal

Macroscopic manifestations of defects

What to do about bulk defects in Si?  4th lecture
Lecture 2  Mostly bulk effects and detectors

Introduction

Energy loss

Displacements in the crystal: 'Bulk effects'

Methods of characterization

of defects in the crystal

Macroscopic manifestations of defects

What to do about bulk defects in Si?  4th lecture
Radiation destroys systems

Silent satellites
1962 Telstar I
(first case on-orbit)

Processors
Intel 80386 dies at 15 krad

Biological effects
Natural background yr-1
0.2 rem (up to 5 rem)
safety limit 1.5 rem

(100 rem = 1 Sv = 1 Gy x w_R)

1 Gy = 100 rad, w_R is 1 - 20

Lethal dose (50% < 30 days)
250 - 300 rad whole body

Radiation can be useful

Study
Materials analysis
α Rutherford backscattering
Proton Induced X-ray Emission
Neutron activation analysis
sensitivity 10^5 - 10^10 cm^-1

Medical applications
X - rays
Therapy
Sterilization
Manufacturing
Ion implantation
Chips
Surface treatment
Failure of TELSTAR I

Problem:
conductive leakage path induced on the surface
of the base of the MESA-type n-p-n transistors

Irradiation was enhanced
by $e^-$ from 'Starfish' explosion in space

Combination of factors
- ionization of gas in the encapsulation 'can'
- unpassivated surface area

Temporary recovery
by charge desorption under inverted bias

Neutron activation analysis
characteristic $\gamma$-spectra after nuclear excitations

Sensitive method for 'non-destructive'
chemical analysis of some impurities

<table>
<thead>
<tr>
<th>Element</th>
<th>$10^5$</th>
<th>$10^7$</th>
<th>$10^9$</th>
<th>$10^{11}$</th>
<th>$10^{13}$</th>
<th>$10^{15}$</th>
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<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>


can detect concentrations $10^{-10}$ to $10^{-16}$
best sensitivity for Au: $10^5$ atoms cm$^{-2}$

impurity content for virgin Si detector wafers
as determined by Böhm, Kim, Kemmer

thermal neutron fluence $4 \times 10^8$ s $\times 10^{13}$ cm$^{-2}$
Au below 1 ppt, impurities Zn, Br, Fe on surface
also: $^{30}$Si $\rightarrow$ $^{31}$P

EH February 16, 1998
Characteristic Properties of Semiconductors, Si in particular

Single-Crystal
has well-defined band structure: bandgap $E_g$
thermal generation of vacancies + interstitials:
low diffusivity, concentration: $< 10^{11}$ cm$^{-3}$ at 500 °C
review by Zulehner (Wacker Chemiehr) in Semiconductor Silicon, Springer 1989, p127

Extremely pure

typical background of electrical impurities:
$< 10^{-12}$ i.e. $10^{11}$ cm$^{-3}$
very low background of chemical impurities:
C, O in Si usually $10^{15} - 10^{18}$ cm$^{-3}$
metals much lower $< 10^{12}$ cm$^{-3}$

Negative and positive charge carriers
electrons, holes: minority carrier lifetime up to 1 ms
comparable mobility $\mu$ in field: $v = \mu E$

Conductivity can be varied
temperature
impurities
electrical injection
injection by light and radiation

Devices by local variation of carrier densities
Ge Si GaAs SiC InP diamond .....
Doping of Silicon

Intrinsic Si has \( n \cdot p = 2.2 \times 10^{20} \text{ cm}^{-6} \)

equal numbers of electrons and holes \( 1.5 \times 10^{10} \text{ cm}^{-3} \)
corresponding to \( \sim 300 \text{ 000 } \Omega \text{ cm resistivity} \)

Carrier concentrations can be varied over wide range using ion-implantation with dopants.

**n - type conductivity with donors:** P-atoms (As or Sb)
e.g. electrons \( n = 10^{12} \text{ cm}^{-3} \) results in 5000 \( \Omega \text{ cm} \)

**p - type conductivity uses acceptors:** B-atoms (Al, Ga, In)
holes \( p = 10^{12} \text{ cm}^{-3} \) results in 15000 \( \Omega \text{ cm} \)

Ion implantation creates a damaged region with many defects and interstitial atoms.

High-temperature annealing is needed to restore crystal quality and also to activate the doping by allowing them to take substitutional positions in the crystal lattice.

Then all donors or acceptors are ionized at room temperature with a high majority carrier concentration.

In equilibrium the minority carrier concentration is complementary, with \( n \cdot p = 2.2 \times 10^{20} \text{ cm}^{-6} \)

N.B. doping concentration in CMOS is \( \gg 10^{17} \text{ cm}^{-3} \)

so that minority carrier concentration \( \ll 10^{3} \text{ cm}^{-3} \)

---

Crystal structure causes bandgap

Energy band structure arises in crystals but also in amorphous materials due to periodicity. Discrete electron energy states are momentum vectors \( k \) in the reciprocal lattice.

In semiconductors conduction band and valence band are separated by a small energy difference \( E_g \).

<table>
<thead>
<tr>
<th>Ge</th>
<th>Si</th>
<th>GaAs</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Energy band structure for Ge" /></td>
<td><img src="image" alt="Energy band structure for Si" /></td>
<td><img src="image" alt="Energy band structure for GaAs" /></td>
</tr>
</tbody>
</table>

indirect transitions

direct \( \text{Phys.Rev. 141 (1966) 789} \)

Direct bandgap, e.g. in GaAs or indirect bandgap, e.g. Si, if maximum and minimum are not in the same direction in \( k \)-space. Simplified diagrams neglect directional effects.
Semiconductor Device Structures

Contacts

Metal-Semiconductor contact (Schottky barrier)
Ohmic contact, non-injecting

MIS / MOS capacitor

Metal-Semiconductor contact (Schottky barrier)
Ohmic contact, non-injecting

Junctions

p-n junction: ion-implanted, diffused, alloyed
n⁺ - n junction or p⁺ - p junction
  space charge / depletion region

Transistors

ICs

Band diagram and carrier concentrations in p-n junction

forward bias

reverse bias

See, Physics of Semiconductor Devices, after W. Shockley

a) Energy-band diagram with Fermi levels in p and n zones and quasi-Fermi levels $\phi_n$ and $\phi_p$ in the intermediate depletion region

b) Potential diagram with applied bias voltages $V$

c) Carrier distributions; close to the junction there is no equilibrium concentration
The resistivity \( \rho \) can be calculated from the slope of the C-V curve. Total depletion, if space charge to rear.
Energy Loss in Silicon (MeV mm⁻¹) with energy deposition measurements

Ionization

Energy loss of a swift particle is not equal to energy deposit in a thin layer of material, some electrons and photons escape:

- average energy loss in 300 µm Si for m.i.p. 0.36 MeV mm⁻¹
- energy deposit in thin (0.5 mm) Si ~ 0.27 MeV mm⁻¹

In dosimetry: LET (Linear Energy Transfer) MeV/µm

Ionization in Si strictly proportional to energy loss:
- an electron - hole pair is created for 3.64 eV deposit

Small deviations can be found in very dense tracks due to recombination of created pairs

Ionization in Si for \(10^7\) m.i.p. cm⁻² s⁻¹
- is \(7 \times 10^{12}\) e-h pairs cm⁻³
- in 300 µm Si \(2.2 \times 10^{11}\) e-h pairs cm⁻² s⁻¹

Average signal current is then 36 nA cm⁻²

If collection time is 10 ns then steady state density
- \(7 \times 10^4\) e-h pairs cm⁻³ s⁻¹ much lower than doping

Bandgap in Si: 1.12 eV

2.52 eV goes in other types of excitation
Displacements in the Crystal

Energy barriers for movement of atom

diamond

Si

Threshold for Displacements of atoms in lattice

The incident particle with mass \( m \), energy \( E \) transfers energy \( T_m \) in a head-on collision to the Primary Knock-on Atom PKA with mass \( M \). The maximum transferable energy is then:

for neutrons:

\[
T_m = \frac{4 \frac{m}{M} E}{(m + M)^2}
\]

For \( T_m = 20 \text{ eV} \) one needs in Si \( E = 120 \text{ keV} \)

For incident electrons:

\[
T_m = 2E \frac{m}{M} \frac{2 + \frac{E}{mc^2}}{ \left(1 + \frac{m}{M}\right)^2 Mc^2 + 2E}
\]

For creation of a stable defect the PKA has to acquire sufficient kinetic energy and travel a certain distance in order to avoid recombination.

The binding energy of an atom in Si or diamond is about 20 eV and depends on crystal directions.

There is not a big difference between diamond and Si.

For close displacement large probability of recombination.
Collision Cascade

Primary collision creates PKA which initiates further displacements until kinetic energy is exhausted

Clusters of displaced atoms may occur

Dimension of damaged region from a 40 keV Si can be 50 nm x 50 nm and it may contain 5-10 clusters with over 1000 defects

Crystal Defects in Silicon

Schottky defect: single vacancy V
Measurement of threshold energy for e- and defect introduction rate in Si

Threshold energy for di-vacancy V-V formation in high resistivity Si by electrons is ~ 600 keV
Vacancy-Oxygen is created at ~ 300 keV which indicates threshold for single vacancy creation
Non-Ionizing Energy Loss (NIEL)

The fraction of the energy deposition that is available as damage energy for displacements is limited at higher energies due to an increased fraction of ionization.

\[ \text{NIEL} = \frac{N}{A} \int_0^m \frac{dE}{dE_R} \]

The maximum damage energy in Si is about 300 keV independent of the energy of the Si recoiling target atom and This maximum increases with Z of the recoiling atom and eg. in GaAs 2 MeV is available.

Attempt to describe displacements in a unified approach for a variety of incoming particles and energies. Lindhard developed a theory of energy partitioning for the ionization by the recoiling atom in the lattice, as a function of the recoil energy.

Comparison of Lindhard calculation and some measurements.
Non-Ionizing Energy Loss

Comparison of calculations of protons and electrons in Si

The production of defects is not a constant fraction of the energy deposition
unlike the production of free carriers

Work on NIEL is being extended towards higher energies and including different projectiles
EPR and ENDOR Spectrometry

Paramagnetic resonance of unpaired electron spins in diamond before (a) and after irradiation (b)

\[ \Delta E = g \mu_B H \]

Transitions between split Zeeman levels in H field

ENDOR uses hyperfine interaction with nuclear spin of 4.7% abundant $^{29}\text{Si}$

Sensitivity EPR: $\sim 10^9$ spins in sample of 10 mm$^3$
12 possible orientations $\rightarrow 1.2 \times 10^{12}$ defects cm$^{-3}$

ENDOR is less sensitive: $6 \times 10^{15}$ defects cm$^{-3}$
Angular dependence of EPR signal for P-V with corresponding g-tensor values

The P-V complex can have different orientations in the lattice. Y in 1 must jump via 2 and 3 to 1.

EPR + ENDOR SPECTROMETER

- klystron
- variable phase shifter
- matched load
- crossguide coupler
- unidirectional coupler
- wave meter
- circulator
- crystal
- waveguide
- intermediate frequency
- low frequency
- NMR frequency

AMPLERAMAN DE WIT SIEVERTS AMSTERDAM (1978)

FIG 4-1 BLOCK SCHEME OF THE SPECTROMETER.
Double vacancy V-V in Si
can be created directly from large energy transfer
or by combination of single vacancies in high purity Si

V-V in orientation a-d in lattice

local distortion of the crystal: bonds b-c and b'-c' bent
electrons can be localized far away (using g-tensor)
dissociation between 200 - 300 °C

Charge state of defects
example: divacancy

Defects have one or several
characteristic energy levels in the bandgap

Charge state depends on position of the Fermi level
Divacancy can be donor-type eg. $V_2^0 \rightarrow V_2^+$
or acceptor type eg. $V_2^0 \rightarrow V_2^-$

Divacancy tends to compensate towards mid-gap
n-type or p-type doping

The spin of the unpaired electron can be used to
characterize the defect with EPR or ENDOR spectrum
TABLE 3-I: SURVEY OF EPR SPECTRA OBSERVED IN IRRADIATED SILICON, FOR WHICH ANY DEFECT MODEL HAS BEEN PROPOSED. A "SUBJECTIVE" ESTIMATE OF THE RELIABILITY OF THE MODELS IS GIVEN. A CLASSIFICATION AFTER THE FOUR TYPES OF SECTION 3.4 IS INDICATED.

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Model</th>
<th>Type</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>PSI₁</td>
<td>IV</td>
<td>*</td>
</tr>
<tr>
<td>A3</td>
<td>V₄⁻</td>
<td>III</td>
<td>***</td>
</tr>
<tr>
<td>A5</td>
<td>Si⁻Si₁</td>
<td>IV</td>
<td>*</td>
</tr>
<tr>
<td>A14</td>
<td>V₀⁺</td>
<td>I</td>
<td>***</td>
</tr>
<tr>
<td>A15</td>
<td>V₀⁺</td>
<td>III</td>
<td>***</td>
</tr>
<tr>
<td>B1</td>
<td>O⁻</td>
<td>III</td>
<td>*****</td>
</tr>
<tr>
<td>B3</td>
<td>(SiSi)₁</td>
<td>IV</td>
<td>**</td>
</tr>
<tr>
<td>G1</td>
<td>V⁺</td>
<td>III</td>
<td>*</td>
</tr>
<tr>
<td>G2</td>
<td>V⁻</td>
<td>III</td>
<td>*</td>
</tr>
<tr>
<td>G3</td>
<td>O⁻</td>
<td>III</td>
<td>**</td>
</tr>
<tr>
<td>G4</td>
<td>O⁻</td>
<td>III</td>
<td>**</td>
</tr>
<tr>
<td>G6</td>
<td>V₂⁺</td>
<td>I</td>
<td>***</td>
</tr>
<tr>
<td>G7</td>
<td>V⁻</td>
<td>I</td>
<td>***</td>
</tr>
<tr>
<td>G8</td>
<td>P⁺</td>
<td>I</td>
<td>***</td>
</tr>
<tr>
<td>G9</td>
<td>Al Clients</td>
<td>III</td>
<td>***</td>
</tr>
<tr>
<td>G10</td>
<td>B⁺</td>
<td>I</td>
<td>***</td>
</tr>
<tr>
<td>G11</td>
<td>(Co)⁺</td>
<td>IV</td>
<td>***</td>
</tr>
<tr>
<td>G12</td>
<td>(CoSi)⁺</td>
<td>IV</td>
<td>***</td>
</tr>
<tr>
<td>G15</td>
<td>CV⁺</td>
<td>II</td>
<td>*</td>
</tr>
<tr>
<td>G18</td>
<td>Al⁺⁺</td>
<td>II</td>
<td>***</td>
</tr>
<tr>
<td>G19</td>
<td>Al⁺⁺</td>
<td>II</td>
<td>***</td>
</tr>
<tr>
<td>G20</td>
<td>Al⁺⁺</td>
<td>II</td>
<td>***</td>
</tr>
<tr>
<td>G22</td>
<td>Ga⁺⁺</td>
<td>II</td>
<td>***</td>
</tr>
</tbody>
</table>

In this table, the impurity atoms in vacancy-impurity complexes are given behind the vacancy if they occupy their ordinary interstitial position and before if they occupy an ordinary substitutional site. Normally substitutional impurities are given a suffix i if they have become interstitial, a suffix s (substitutional) only if ambiguity may exist.

Structure from transitions in EPR:

- a) V⁺
- b) V⁻
- c) (V+P⁺)⁺
- d) (V+Al⁺⁺)⁻
- e) (V+Q⁻)
- f) (V+V)⁺

**Fig. 1.** Simple LCAO-MO treatment of the electronic structure of isolated and trapped vacancies.

Linear Combination of Atomic Orbitals (LCAO) G.D. Watkins
Electrical measurements on diodes

cryogenic TSC

Thermally Stimulated Current

traps are filled by forward current or light at low T
heating proceeds after change of Fermi level
under reverse bias

trapped charge is released
at a temperature that is related to trap energy

\[ T_{m} = 163 \text{ K} \]

LARGER DEPLETION
SOME OF THE TRAPS
HAVE TO BECOME
EMPTY: UNSTABLE,
ABOVE FERMI LEVEL

TRAP ENERGY \( E_{t} = -0.4 \text{ eV} \)
\( \sigma_{t} = 10^{-15} \text{ cm}^{2} \)
INTRODUCTION RATE .2 cm\(^{2}\) per muon
Principle of DLTS
Deep Level Transient Spectroscopy

Capacitance modulation of p-n junction by deep levels only traps in a relatively thin region are sensed both donor and acceptor traps can be detected

Example with defects from ion-implantation

DLTS measurement of irradiated diode

Peaks appear after irradiation and are characteristic for trap energies


S. POSPISIL CS. AND F. LEMEBLEUR

Curve INT33 proton dose $1.3 \times 10^{13} \text{ cm}^{-2}$

EH February 16, 1998
Characterization of defects

VIA THERMAL CHARACTERISTICS

ACTIVATION ENERGIES OF BULK DEFECT LEVELS CREATED BY NEUTRON IRRADIATION

\[
\begin{align*}
1000/T (K) &
\begin{array}{c}
10^3 \\
10^2 \\
10 \\
1
\end{array}
\end{align*}
\]

BC 57-7-2
DOSE: \(1.0 \times 10^{19}/cm^2\) (15 Mev NEUTRONS)

2 defect levels after 15 MeV n irradiation

N-1 \(E_C - E_T = 0.14\) eV introduction rate 1.1 cm\(^{-1}\)
N-2 \(E_C - E_T = 0.23\) eV introduction rate 0.8 cm\(^{-1}\)

N. Saks, Naval Research Laboratory

Defect Recovery by Thermal Anneal

Characteristic activation energy for rearrangement in the crystal lattice
defect transforms into a different defect structure:
eg. single vacancy is mobile above 46 K and: \(55^\circ K\)
2 vacancies combine into di-vacancy or vacancy combines with P into P-V

recovery stages for V, V-V, V4 and V5 in Si

annealing of P-V in diode is dependent on reverse bias

EH February 16, 1998
The reduction of minority carrier lifetime $\tau$ can be described using a damage constant $K$:

$$\frac{1}{\tau} = \frac{1}{\tau_0} + K \Phi$$

Shortening of the lifetime indicates enhanced recombination and generation of minority carriers, which leads to increase of generation current.

The increase of current can also be described by a damage constant, $\alpha$, which is related to $K$:

$$I_g = I_{g0} + \alpha \Phi \quad \alpha = \frac{q n_i}{2 K_{gen} x_d}$$
Annealing of reverse current

Dotted line is 21 MeV proton irradiation
Points are from 8 detectors in 24 GeV irradiation
Flux varied from $1 \times 10^{12}$ to $7 \times 10^{13}$ cm$^{-2}$
Steps indicate processes with different time constants
Initial leakage current is extrapolated backwards to time 0 and sometimes this value is quoted.
Damage Constant for Leakage Current

Introduction Rates of Defects

Introduction rate: \# defects cm\(^{-3}\) / incoming particle cm\(^{-2}\)
unit is cm\(^{-1}\)

usual range measured 0.1 to 1.0 cm\(^{-1}\)
so this results in \(~ 10^{12}\) defects cm\(^{-3}\)

Leakage current damage constant:
\(A \text{ cm}^{-3} / \text{incoming particle} \rightarrow A / \text{neutron}\)

Many measurements have been made over time and values range from \(~ 10^{-17}\) A per n to \(~ 10^{-16}\) A per n

Annealing can be taken into account

It is amazing how little the 'constant' varies with conditions
SUMMARY OF RESULTS
"DAMAGE CONSTANTS"

CURRENT \[ I = I_0 + \alpha \Phi \]
generation
RENORMALIZED \[ \text{nA.cm}^{-2} / \text{m.i.p.cm}^{-2} \]

TEST STRUCTURES \[ ^{60}\text{Co} \]
\[ 3 \times 10^{-12} \text{ nA cm}^{-1} \]
NO DISPLACEMENT DAMAGE
1 rad = \[ 4 \times 10^7 \text{ m.i.p.} \]

NFM PROTOTYPE TESTS \[ ^{60}\text{Co} \]
\[ 15 \times 10^{-8} \text{ nA cm}^{-1} \]
REACTOR NEUTRON DATA
GeV MUONS + SHOWER BEAM
bulk n-type \[ 3.4 \times 10^{-8} \]
bulk p-type \[ 1.8 \times 10^{-8} \]

UA2 (OSI)
IONIZATION \[ 8 \times 10^{-8} \text{ nA cm}^{-1} \]
NEUTRONS \[ 24 \times 10^{-8} \]

(I SI)
IONIZATION \[ 2.8 \times 10^{-8} \text{ PRELIMINARY} \]
NEUTRONS \[ 100 \times 10^{-8} \]

UNIV. HAMBURG
14 MeV N \[ 1.7 \times 10^{-7} \text{ nA cm}^{-1} \]
25 MeV p \[ 2.7 \times 10^{-7} \]

SUMMARY OF RESULTS
IN TERMS OF "DAMAGE CONSTANT"

LIFETIME \[ \frac{1}{\tau} = \frac{1}{\tau_0} + \kappa \Phi \]

CURRENT \[ I = I_0 + \alpha \Phi \]
\[ \alpha = \frac{q_n}{2K_n^2} \]
NORMALIZE CURRENT per cm\(^3\)

NEUTRONS \[ \text{nA/h} \]
IONIZING \[ \text{nA/m.i.p} \]

SRUQR (K:\text{\textbar}7) \[ 8 \times 10^{9} \text{ CCD} \]
\[ 0.65 \times 10^{-8} \text{ H2O} \]

KRAUKER \[ 2 \times 10^{6} \text{ ptn} \]

NAI - N\text{A32} \[ 1.3 \times 10^{-7} \]

KEK \[ 3 \times 10^{-8} \text{ p} \]

UA2 \[ 36 \times 10^{-8} \text{ n} \]
\[ 1.7 \times 10^{-8} \text{ p} \]

MUONS \[ 40 \times 10^{-8} \text{ p} \]
\[ 9 \times 10^{-8} \text{ sps} \]

TEST NFM \[ \leq 15 \times 10^{-8} \text{ reactivity} \]
\[ \leq 10^{-10} \text{ 6\text{Co} } \]
Charge Trapping/De-trapping
in silicon detectors

(a) Upper trace: detraping; Lower trace: normal detector. Each (nearly visible) division represents 50 ps.
(b) Upper trace: normal detector (SM48); Middle trace: detraping (SM41); Lowest trace: no beam.

Fig. 4.5 Comparison of detectors which do and do not show trapping/de-trapping of charge carriers. The horizontal scale of these oscilloscope pictures is time. The beam passage lasts in all cases 25 µs, the signal at the output of the charge integration circuit is displayed on the vertical axis, in 500 mV resp. 100 mV per division. The small vertical displacement visible in (b) and (c), is caused by a transient of the hold mode, but does not influence the real measured value.

(c) Two consecutive signals, showing de-trapping are compared with no beam (detector SM41). 500 µs per division.

The detector leakage current is slightly overcompensated, and this causes a slow decrease of the integrated signals with time (sect. 8.2.3).

F. Lemeilleur
RD 2
Carrier Removal by Neutrons

Change of Resistivity

for different starting resistivities 0.1 $\Omega$cm to 100 $\Omega$cm

The general perception has always been that irradiation is increasing the resistivity.

High dose neutron or proton irradiation of n-type Si at first increases the resistivity, then apparently the conduction type is inverted to p.

The curve is parametrized with constants $b, c$ as

$$N_{\text{eff}}(\phi) = N_D e^{-c\phi} - N_A - b\phi$$
Lecture 3
Mostly surface effects and ICs

Transition

The Si surface with dangling bonds and oxide

The Metal Oxide Semiconductor (MOS) capacitor

Radiation effects in the MOSFET gate oxide

The role of oxide in a silicon detector

Effects in sub-micron transistors

Hardness comparison of technologies

EH February 18, 1998
**Bipolar Transistor (Planar)**

- Junction-field surface-recombination region showing radiation-induced hole charge trapped in oxide
- Leakage channel region
- Interface states
- Emitter
- Oxide
- Base
- Collector
- Junction-field bulk-recombination region having recombination statistics similar to bulk silicon
- Junction-field bulk-recombination region having recombination statistics different from field-free bulk silicon

---

**Bipolar devices**

**Low dose rate effect: circuits**

[Graph showing relative damage in various transistors across different dose rates]

A.H. Johnston et al., JPL
Silicon Surface

$2 \times 10^5$ atoms/cm$^2$

$2 \times 10^7$ atoms/µm$^2$

Dangling Bonds

Surface States Can Trap Carriers

→ Recombination

Low Surface Mobility

Short Carrier Lifetime

Surface Current Generation

In modern CMOS processing, one can achieve $\sim 10^5$ to $10^{10}$ cm$^{-2}$ regularly improving!

→ Can be 1 trap per transistor!
MOS Capacitor

Oxide capacitance per unit area

$$C_{ox} = \frac{\varepsilon}{x_{ox}} \quad \varepsilon = 3.9 \times \varepsilon_0 = 0.345 \times 10^{-12} \text{ F cm}^{-1}$$

Capacitance in flat band condition at $V_{FB}$

$$C_{FB}(\psi_s = 0) = \frac{\varepsilon_e}{x + \left(\frac{\varepsilon_e}{\varepsilon_s}\right)L_D}$$

Debye length $L_D = \sqrt{\frac{kT\varepsilon_s}{q^2 N_D}}$

Maximum depletion in equilibrium

$$x_{d_{max}} = 2\sqrt{\frac{\varepsilon_{Si} kT}{q^2 N_D}} \ln \frac{N_D}{n_i}$$
High Frequency C-V curve MOS

 Capacitance (F)

\[ \frac{1}{C} = \frac{1}{C_{ox}} + \frac{1}{C_{min}} \]

max. depletion in equilibrium:

\[ x_{d,\text{max}} = 2 \sqrt{\frac{\varepsilon_i \cdot V_T \cdot \mu_n \cdot N_0}{\varepsilon_s \cdot N_0}} \]

Bias (V)

100 kHz

10^-12 10^-11 10^-10 10^-9

39:0804 <100> n-type 18-7-85

39:0809 <100> n-type 18-7-85

Capacitance (F) 1.1 mm², 100 nm
Si <111> n-type

accumulation

HF

100 kHz

Bias (V)

10^-12 10^-11 10^-10 10^-9
OXIDE CHARGES

MOSFET $V_{gs}$

POLY Si GATE

GATE OXIDE

$N^+$ Si SUBSTRATE P-type $N^+$

'FIXED' OXIDE CHARGE $Q_{ox}$

$\Delta V_T$ 'off' leakage

$I_{SD}$ $Q_{ox}$ log ($I_{SD}$) $N_{it}$

$V_{gs}$

INTERFACE 'TRAPPED' CHARGE

distortion of slope $N_{it}$

'off' leakage reduced mobility noise

MOS Flat Band Voltage and MOSFET Transistor Threshold Voltage

after before irradiation

(a) (b)

A. Holmes-Siedle and L. Adams, Handbook of Radiation Effects, Oxford

Shift of flat band voltage $V_{FB}$ in MOS capacitor is correlated with threshold shift $\Delta V_T$ in MOSFET

$$V_T \approx V_{FB} + 2 \psi_F$$
Figure 1. Band diagram illustrating physical processes governing the response of MOS devices to total-dose ionizing radiation. (After F. B. McLean et al., Ref. [2])

**Charge build-up in MOS structure**

**Energy loss in oxide**

Leads to electron-hole generation with 17 eV/pair

'Bandgap' in silicodioxide is 8.8 eV

Geminate recombination, fast electron evacuation

Slow hole drift towards traps near interface

hole mobility $\sim 2 \times 10^{-5}$ cm$^2$ V$^{-1}$ s$^{-1}$

this gives transit time of 0.5 $\mu$s in 100 nm oxide @ $10^6$ V cm$^{-1}$

electron-hole recombination at 'tunneling front' up to $\sim$ 5 nm from interface

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MOS Transistor Threshold

There are several methods for determining threshold:

Threshold voltage where certain $I_D$ is observed, e.g. 10 μA

Intersection with axis of tangent of straight part of $I_D$ vs $V_{gs}$

Idem with tangent taken where derivative $g_m$ is maximum see figure, $V_{DS}/2$ is subtracted, left diamonds shifted curves after 85 krad —

The threshold for conduction in the channel depends on the charge in the oxide + interface

$$g_D \propto V_q - V_T$$

$$V_T \propto V_{FB} = \phi_m - \frac{Q_f + Q_m + Q_{ot} + Q_{it}}{C_i}$$

$Q_f$: oxide fixed charge density

$Q_m$: mobile ionic charge density

$Q_{ot}$: oxide trapped charge density

$Q_{it}$: interface trapped charge density

$Q_f$: very close to interface

$Q_{it}$: at interface

Radiation > 5 MeV creates e-h pairs in oxide

Hole mobility ~ 2 x 10^{-5} cm^2 V^{-1} s^{-1}

Tranit time in 100 nm oxide, at 10^6 Vmm -> 0.5 μs

Holes are trapped near interface

→ shift of flat band voltage
HOLE TRAPPING IN OXIDE

DEFECT

NATURE OF THE TRAPPED HOLE IN SiO₂ AS DETERMINED BY ESR

GOOD

Strained Si-Si bond (Oxygen vacancy)

NORMAL S-O-S BOND

+ h⁺

Relaxed E⁺ center after hole capture

Qox

MODEL FOR FORMATION OF INTERFACE TRAPS (N₁ᵢ)

GATE SiO₂ SILICON

Vₕ > 0

Radiation

h → H → H⁻ → Si⁻

h₁ → H₁ → H⁻₁ → Si⁻₁

H plays big role in SiO₂

Creation of Interface Traps by Irradiation

EFFICIENCY OF Dᵢ CREATION

OX O₂/N₂O (900°C) O₂/N₂O (1000°C) N₂O (900°C) RNO OXI-NITRIDE

VARIOUS OXIDATION METHODS
CORRELATION OF OXIDE CHARGE WITH $1/f$ NOISE

$\Delta K_{1/f} \quad (V^2)$

$10^{-11}$

$10^{-12}$

$\Delta N_{ot} \quad (cm^{-2})$

$10^{11}$

$10^{12}$

IKEDA et al.

CORRELATION OF MOBILITY WITH INTERFACE TRAPS

$\frac{\mu_{post}}{\mu_{pre}}$

0.4

0.5

0.6

0.7

0.8

0.9

1.0

$\Delta N_{it} \quad (10^{11}/cm^2)$

0

0.5

1.0

1.5

2.0

2.5

3.0

IKEDA, MATSUMITA.

SEIKO SOI-CMOS (BESOI)
Separation of Effects from Interface Traps and Oxide Charge

**SUBTHRESHOLD CURRENT CURVES FOLLOWING $^{60}$Co IRRADIATIONS**

\[ I_D = \frac{W}{L} \mu_n C_{ox} \left( \frac{V_{th}}{V_{DD}} \right)^2 \frac{W}{L} \frac{2}{\beta N_A} \frac{L}{V_{th}^2} \left[ 1 - e^{-\beta V_{th}} \right] \]

\[ a = \frac{\sqrt{2} (\varepsilon_S / \varepsilon_o)}{C_{ox}} \]

\[ \psi = (V_D - V_{th}) - \frac{a_1}{2} \frac{1}{\psi} \left[ \left[ 1 + \frac{\psi}{a_1} (\beta V_D - B V_{th}) - 1 \right]^{\frac{1}{\psi}} - 1 \right] \]

\[ S = \ln_{10} \left[ \frac{dV_D}{d \ln I_D} \right] = \frac{kT}{2} \ln_{10} \left[ \left[ 1 + \frac{C_{sc}(\psi)}{C_{ox}} \right] \times \left[ 1 - \frac{a_2}{a_1^2} \left[ \frac{C_{sc}(\psi)}{C_{ox}} \right]^2 \right]^{-1} \right] \]

\[ = \frac{kT}{2} \ln_{10} \left( 1 + \frac{C_{sc}}{C_{ox}} \right) \text{ in } a \gg \frac{C_{sc}}{C_{ox}} \]
**Subthreshold Swing**

---

**Sandia Labs**

Schematic diagram showing subthreshold current vs. gate voltage for different doses. The graph illustrates how current changes with varying gate voltages and radiation doses (e.g., 1 Mrad, 30 krad (SiO2), 100, 300).

---

**Subthreshold Swing Analysis**

\[
C_{it}(\psi_s) = \frac{dQ_{it}(\psi_s)}{d\psi_s}
\]

\[
C_{it} = q_0 \cdot D_{it}(\psi_s)
\]

for band bending \(\psi_s\)

**Swing**

\[
S = kT \cdot \ln{10} \left( 1 + \frac{C_{sc}}{C_{ox}} \right)
\]

\[
S_{it} = S_0 \left[ 1 + \frac{C_{it}(\psi_s)}{C_{ox} + C_{sc}(\psi_s)} \right]
\]

stretch out factor

---

**Can be used to separate**

Not from N it

---

McWhorter & Winokur
Appl. Phys. Lett. 48 (1986) 133

van Overstraeten et al.
IEEE ED-22 (1975) 282
SOI TRANSISTOR WITH 5 TERMINALS

THRESHOLD SHIFT N-CHANNEL
W/L 30/2 μm
HS013-ND

CONTRIBUTION OF INTERFACE TRAPPED CHARGE OPPOSITE TO OXIDE TRAPPED CHARGE FOR N-CHANNEL

INTERFACE TRAPPED CHARGE INCREASES AFTERWARDS → REBOUND

USUAL BEHAVIOUR MOS NOT SPECIFIC FOR SOI

DRAWING: Fossum et al. Florida

THIN-FILM SOI 50 - 100 nm
THICK FILM SOI 200 - 500 nm
Dose Rate Effects

There are 2 competing processes:
1. Fast trapping of oxide charge near interface
   Oxide traps contain holes and contribute positive charge
2. Slow buildup of interface traps at the interface
   Interface traps contain electrons and are negative

Result: Threshold shift varies with time
Rebound: initial shift is (over)compensated later

Apparent threshold shift may vary nearly 10 x

Fig. 1. Threshold-voltage shifts versus dose at varying dose rates for n-channel transistors from lot GO239A. Irradiations were done with 10-V bias applied between gate and substrate.

WINDSOR et al (SANDIA)
IEEE 1387 p. 1448

\[
\begin{align*}
\text{CERN TEST POINT} & \text{ LOW RATE} \\
\text{CERN-MIETEC} & \text{ 70 krad T+m (300Gy)} \\
\text{PMOS} & \text{ BINS} \\
\text{AV} & -0.5 -0.3 -0.18 -0.23 \\
\text{AGE} & -18\% -10\% -30\% -30\% \\
\text{I_{0.1}} & <10^{-14} \rightarrow 3 \times 10^{-10}
\end{align*}
\]
Oxides in Si Detectors

a) Oxide is used to define diode implantation area
b) Oxide separates elements in segmented detectors
c) Oxide is edge protection at the termination of the Si

In p-n diode the oxide charging causes depletion or inversion and this improves separation between p implants
In n-p diode accumulation causes short circuit channels
What about interface trapped charge? Rebound?

Experience in Si with Si Microstrip

Radiation induced current in high flux ($3 \times 10^5$/pulse) (reversible phenomenon)

**Figure:**
- **a)** Graph showing current vs. voltage with stable regions at different voltage levels.
- **b)** Graph showing current vs. time with stable periods at various intervals.

**Edge-Sensitivity**

EH February 18, 1998
Figure 8. (Top) Parasitic leakage path between source and drain caused by inversion of p-type Si beneath thick field oxide. (Bottom) Cross-section showing LOCOS isolation used in commercial CMOS technology and radiation-induced leakage paths. (After F. B. McLean et al., Ref. [2])
TRENCH ISOLATION TECHNIQUE

EXAMPLE OF COMPLICATED TECHNOLOGY IN ORDER TO SAVE SPACE
Thermal anneal of oxide charge

Oxide charge and interface states become mobile at slightly elevated temperature: already at 150 °C

This is being used to anneal out the radiation damage from processing steps like plasma etching

Usually there is a 450 °C annealing under forming gas (N₂, 10% Hydrogen)
Radiation Damage in CCD

SINGLE DAMAGE EVENTS --- 99-MeV PROTONS

DEVICE #7
2.8 x 10^7 p/cm^2

DEVICE #8
2.8 x 10^9 p/cm^2

Current integration in CCD pixels reveals isolated incidents, presumably bulk damage, after proton irradiation.

Oxide damage affects mainly charge transfer efficiency in CCD through charge losses at interface traps.
Oxide Damage in Thin Oxides

Strong reduction with decrease of thickness

**OXIDE THICKNESS DEPENDENCE OF $\Delta V_{N_{ot}}$**

\[ \Delta V_{N_{ot}} \propto L_{ox}^{-n} \]

Dry Oxide: $n = 1.65$

Wet Oxide: $n = 1.65$

\[ E = 1 \, \text{MV/cm} \]
\[ \text{DOSE} = 1 \, \text{Mrad (Si)} \]

**OXIDE THICKNESS DEPENDENCE OF $\Delta V_{N_{it}}$**

\[ \Delta V_{N_{it}} \propto L_{ox}^{-n} \]

Dry Oxide: $n = 1.64$

Wet Oxide: $n = 1.61$

\[ E = 1 \, \text{MV/cm} \]
\[ \text{DOSE} = 1 \, \text{Mrad (Si)} \]

**Fig. 4.27** Advanced MOS design, 'Lightly doped drain': section of a MOSFET with lightly doped drain (after Palkuti et al. 1991). (a) Cross section of actual geometry; (b) idealized geometry, showing the structure of possible charge sheets; enlarged, the charge-sheet scheme discussed in Chapter 3, which all takes place in the gate oxide region.
THRESHOLD SHIFT OF GATE OXIDE

AFTER 1 MRAD

OXIDE TRAPPED CHARGE

\[ \Delta V_b \propto \frac{1}{E_{ox}^{1/2}} \]

\[ T = 80^\circ K \]
\[ E_{ox} = +2.0 \text{ MV/cm} \]

\[ \Delta V_b \propto \frac{1}{E_{ox}^{1/2}} \]

- Data from NSACKS 1985
  (NRL)

INTERFACED TRAPPED CHARGE

\[ \Delta D_p \propto t_{ox}^n \]

THIN OXIDE REGIME

THICK OXIDE REGIME

\[ n = 1.55 \]

\[ n = 1.01 \]

\[ 12 \text{ nm} \]

AS-GROWN OXIDES

+ +2.0 MV/cm

- -2.0 MV/cm

295°K

Oxide Thickness (nm)

nm

\[ 1 \quad 10 \quad 100 \quad 1000 \]

\[ 10^{-3} \quad 10^{-2} \]

\[ - \Delta V_b/10^6 \text{ RAD(SI)} \]

\[ 10^3 \quad 10^4 \quad 10^5 \]

\[ 100 \text{ mV} \]

\[ 1 \quad 10 \quad 100 \quad 10^2 \]

\[ 10^{-1} \quad 10^{-2} \]

\[ \text{V/RAD(SI)} \]

\[ 10^3 \quad 10^4 \quad 10^5 \]

\[ 10^{-1} \quad 10^{-2} \]

\[ \text{Gfv}_{1011} \text{ cm}^{-2} \text{ V-rad(SI)} \]

\[ 10^2 \quad 10^3 \quad 10^4 \]

\[ 10^{-1} \quad 10^{-2} \]

\[ t_{ox} (\text{nm}) \]

\[ 4 \quad 10 \quad 20 \quad 40 \quad 100 \]
HARDNESS COMPARISON

HOLMES-SIEBLE & ADAMS

Comparison of Technology

- Guaranteed Specifications
- Other Measured Device Parameters e.g. Noise
- Practical Aspects
  Hardware: Wafer Size, ..., Design Tool Compatibility, Models Available? Exportation Rules Turn Around Time Cost Yield

* Not Easy to Take All Factors Objectively Into the Balance. Depends on Special Boundary Conditions
Comparison of Technology

Interface state buildup
Guide lines shown are for Q_{ot} growth, d_{ox}=32nm, A=1 to 1E-4

4-Lane model for n-channel MOSFETs
Guide lines shown are for Q_{ot} growth, d_{ox}=32nm, A=1 to 1E-4

Which criteria?

n-ch
p-ch

A. Holmes-Siedle
& L. Adams
IEEE Trans 41(94) 2613
Lecture 4
LHC, what can one do

The radiation environment in the LHC experiments

Ionization-induced physical or logical destruction

ESD phenomena

Ionization density and transient effects in detectors

Hardening detectors and systems

Comparison of radiation environments in space and at the LHC

Hardening of readout chips

Use of commercial CMOS

Conclusions
**NEUTRON FLUENCE cm\(^{-2}\) year\(^{-1}\)**

$\geq 100$ keV

**ATLAS**

$10^9$ interactions s\(^{-1}\)

$10^9$ s/year

**FLUENCE OF CHARGED PARTICLES**

$\#$ cm\(^{-2}\) year\(^{-1}\)

- $10^{14}$
- $10^{13}$
- $10^{12}$
- $10^{11}$
- $10^{10}$

**FLAT DISTRIBUTION**

$\sim 10^{13}$ cm\(^{-2}\)

$\rightarrow 10^6$ cm\(^{-2}\) s\(^{-1}\)

5 cm bins

$\sim \frac{1}{R^2}$

in Si:

$4 \times 10^{13}$ mip cm\(^{-2}\)

$\sim 1$ Mrad

$4 \times 10^6$ mip cm\(^{-2}\) s\(^{-1}\)$
CMS DOSE GY/YEAR

Photon energy spectrum

Ex \( \Phi(E) \)

\( \text{cm}^{-2} \text{s}^{-1} \)

\( \text{MeV} \)

CUT OFF AT 30 keV

MAJORITY OF PHOTONS AT LOW ENERGY

\( 10^{-7} \text{cm}^{-2} \text{s}^{-1} \) IN INNER DETECTOR

\( \rightarrow \) OCCUPANCY
Reduction of neutron flux

Hydrogen containing material lining the calorimeter can significantly reduce the neutron flux: polyethylene or H₂O. This takes space (5 - 10 cm) and adds weight.

The neutron flux would be 10 x higher in some places if no moderator was applied.

CMS has adopted a moderator from the outset and fluxes in TDR are based on this.

Currently one tries to redistribute and reduce the amount in order to gain space, without losing the efficiency.

Ionization-induced physical or logical destruction (SEE)

A critical charge created in a small volume...#Gate rupture#Latchup#Burnout#Upset# ...

Originally discovered in space and attributed to heavy ions. All particles do it, as long as the recoil gives critical charge.

Neutron Spectrum at Fermilab locations (Top) compared to neutron spectrum at 40 000 ft (13 km)

The critical charge is in most cases of the order 10 MeV mg⁻¹cm² (units: MeV cm⁻¹ / g cm⁻³)

For Si this corresponds to 2.33 x 10⁶ μm⁻¹ or 6.4 x 10⁵ e-h pairs μm⁻¹.

All depends on the effective range of the recoiling atom.
Neutron-induced upsets

Is this a problem at LHC?

IBM conducted a 15-year study of logic upsets at different altitudes. Special issue IBM J. Res. Devpt. 40 (1996)

Case studies in different systems

Spectrum from 'cosmic' neutrons comparable to WNR Los Alamos

$E > 1 \text{ MeV at WNR}$

$3 \times 10^5 \text{ n cm}^{-2} \text{ s}^{-1}$ atm. 13 km

$2 \text{ n cm}^{-2} \text{ s}^{-1}$ ground level

$6 \times 10^{-3} \text{ n cm}^{-2} \text{ s}^{-1}$

$> 10 \text{ MeV}$

$5.4 \times 10^{-3} \text{ n cm}^{-2} \text{ s}^{-1}$

LHC (spectrum ?) $\sim 10^6 \text{ n cm}^{-2} \text{ s}^{-1}$

Power MOSFET Burnout with 10-200 MeV Protons and Neutrons

IRF360 is a 400V 0.62 cm$^2$ power MOSFET

Breakdown occurs between 300V and 400V with various incident particles, and the cross section has been determined.

It is amazing that 14 MeV n can cause breakdown:

$T_m$ for 14 MeV n to Si is 3.5 Mev and this gives an ionization of 150 fC or 940 000 e-h pairs (about 40 m.i.p.) but in a smaller volume.

Note that there may be an additional 8 MeV $\alpha$-particle produced.

EH February 16, 1998
SINGLE EVENT UPSET (SEU)

Figure 1: Ion track and current pulse induced by passage of a heavy ion through a depletion region of an integrated circuit. After J. C. Pickel, [9].

Figure 12: Circuit schematic of a 3-transistor DRAM memory cell. Information is stored as charge on the capacitor $C_{SN}$ and is accessed through transistors $Q_R$ and $Q_C$. The charge on $C_{SN}$ is written and refreshed through $Q_w$. After Pickel et al. [4].

-F. Sexton, 1992 NSACF SMART Course
Commercial Microprocessors Are Extremely Vulnerable to SEU

(After Sexton et al., IEEE TNS 38, 1521 (1991))

How Latch-up Occurs

3. Schematic of CMOS structure indicating current paths during latch-up.

84/SEMICONDUCTOR INTERNATIONAL APRIL 1997
ADAPT DETECTOR SYSTEM

- COOLING FOR REDUCED CURRENT
  SLOW REVERSE ANNEAL

- ALTERNATIVE MATERIAL FOR SENSOR

- COPE WITH LEAKAGE AND BIAS BY SEGMENTATION

Gettering of impurities

S.M. Sze, Semiconductor Devices, Physics and Technology, J. Wiley 1985

creation of a 'denuded' oxygen-free zone at the surface by oxygen evaporation during thermal processing
metal impurities move towards oxygen-related stacking faults deep in the wafer
denuded zone can be several 100 µm deep

Different gettering procedures integrated in process flow:
  intentional crystal defects
  implantation damage (eg P or He ions)
  backside roughness


EH February 16, 1998
USE OF GRAS OR DIAMOND

- Low leakage due to larger bandgap
  
  But: traps increase current

- Are these materials good detectors?
  
  Charge collection trapping in high flux

- Are they available and economical

PIXEL SIZE OF MICROPATTERN DETECTOR

- "Universal" degradation ~10^-8 nA
- After 10^3 cm² (1/4 M md)
- Detector thickness 0.3 mm
  
  1 cm² → 3 µA
  
  1 mm² → 30 nA
  
  100x100 µm → .3 nA

Amplifier may accept 100 nA
Status of silicon material and detector production for ROSE

1.- "Old" materials and samples

Samples produced in the past are still available at CERN

Distribution to ROSE institutes when requests were received

- **n-type FZ standard material** from Polovodice and Wacker processed in
  - planar technology by Canberra, SINTEF and ITE
  - mesa technology by DIOTEC.

- **n-type FZ oxygenated material** from Polovodice processed in
  - planar technology by SINTEF
  - mesa technology by DIOTEC.

- **n-type Epitaxial material** from MACOM (100 and 150 microns) processed in planar technology by Canberra.
  100 micron material has \(<111>\) orientation
  150 micron material has \(<100>\) orientation.

- **n-type Epitaxial material** from ITME (100, 150 and 200 microns) processed in
  - planar technology by Canberra
  - mesa technology by DIOTEC.

- **p-type Epitaxial material** from ITME (100, 150 and 200 microns) processed by DIOTEC in mesa technology.

- **p-type FZ standard material** from Topsil processed in planar technology by Canberra.
Concentrations as measured by SIMS (at EVANS Europa) or by FTIR:

- FZ oxygenated Polovodice material: \([O] = 7-10 \times 10^{15}\) at./cm^3
- Epitaxial MACOM material:  
  \([O] = 4-5 \times 10^{16}\) at./cm^3  
  \([C] = 3-4 \times 10^{16}\) at./cm^3
- Epitaxial ITME material:  
  \([O] = 4 \times 10^{16}\) at./cm^3  
  \([C] = 1.5 \times 10^{16}\) at./cm^3
- Mesa processed samples:  
  \([O] = 8 \times 10^{17}\) close to the surface and  
  \(2 \times 10^{17}\) at./cm^3 at 50 micron depth.

2.- Production of carbonated material

Polovodice did not succeed at increasing the carbon concentration in FZ using the gas method. They are trying now to inject carbon atoms during the FZ process from a highly doped CZ seed material.

3.- Production of oxygenated material

- ITME is working intensively on the production of highly oxygenated 3" FZ ingot using the quartz ring method.
  They have succeeded at growing a 2" ingot with an \([O]\) of about 2 \(10^{17}\) at./cm^3 but with a 500 Ohm cm resistivity. Wafers have been cut and polished to 200 \textmu m and are being processed by ITE.
  The next step is to obtain a 3" ingot with a higher resistivity and high \([O]\).

- A working program has started two months ago with Canberra and Diotec to produce diodes processed in mixed planar (junction side) / mesa (ohmic side) technology with the aim of benefiting from a clean planar process on the front side and diffusion of phosphorus and oxygen on the back side. We hope to have these available for distribution in April 1998.

- Oxygen diffusion has been performed by ITE, oxidizing 3" standard FZ wafers and heating (1150 deg.C) some of them for 24 hours, others for 48 hours and other ones for 72 hours.
  Oxygen concentrations are of the order of a few \(10^{17}\) at./cm^3.
  5x5 mm^2 planar diodes have been processed by ITE.

4.- Diode processing from various silicon materials

From various silicon materials handled by the Hamburg group, ITE has or will produced diodes with the planar technology.

- Old FZ Wacker 1" wafers, 500 microns, 4,000 Ohm cm with very low oxygen concentration ([O] < \(10^9\) at./cm^3).  
  5x5 mm^2 and 2.5x2.5 mm^2 diodes have been produced.

- FZ ITME 2" wafers, 275 microns, 110-130 Ohm cm.  
  5x5 mm^2 and 2.5x2.5 mm^2 diodes have been produced.

- CZ Polovodice 3" wafers, 240 microns, with an oxygen concentration close to \(10^9\) at./cm^3.  
  120 Ohm cm before processing, 40-50 Ohm cm after processing.  
  5x5 mm^2 diodes have been produced.

- FZ Wacker (?) 3" wafers, 500 Ohm cm, provided by BNL.  
  To be lapped down to 200 microns by ITME and processed by ITE.

5.- Production of silicon with tin

- A meeting held in January 98 with TOPSIL and Aarhus University for production of FZ silicon material with addition of tin atoms.

- ITME is working on a project for high temperature diffusion of tin in silicon.

6.- Future exotic silicon material production

Depends on the radiation hardness results achieved.

High temperature diffusion of other atomic impurities is possible.

Other ideas could come out from this Workshop.
## Radiation Performance of COTS & Rad-Hard

<table>
<thead>
<tr>
<th>Radiation Environment</th>
<th>COTS</th>
<th>Rad Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Dose</td>
<td>$10^3 - 10^4$ rads</td>
<td>$&gt; 1$ Mrad</td>
</tr>
<tr>
<td>Dose-Rate Upset</td>
<td>$10^6 - 10^8$ rads/s - Bulk</td>
<td>$&gt; 10^8$ rads/s - Bulk</td>
</tr>
<tr>
<td>Dose-Rate-Induced Latchup</td>
<td>$10^7 - 10^9$ rads/s - Bulk</td>
<td>$&gt; 10^{12}$ rads/s - Bulk</td>
</tr>
<tr>
<td>Neutrons</td>
<td>$10^{14} - 10^{15}$ n/cm$^2$</td>
<td>$10^{14} - 10^{15}$ n/cm$^2$</td>
</tr>
<tr>
<td>SEU</td>
<td>$10^3 - 10^6$ Errors/Bit-Day</td>
<td>$&lt; 10^{10}$ Errors/Bit-Day</td>
</tr>
<tr>
<td>SEL/SEB</td>
<td>$&lt; 20$ MeV-cm$^2$/mg (LET)</td>
<td>$&gt; 80$ MeV-cm$^2$/mg (LET)</td>
</tr>
</tbody>
</table>

- Technology Trends Are Not Encouraging for COTS Radiation Hardness
- COTS Hardness Varies Unpredictably From Part to Part and Lot to Lot
- Sources of Rad-Hard Are Diminishing

---

## What Does COTS-Plus Cost?

**Our problem:**

<table>
<thead>
<tr>
<th></th>
<th>Class B</th>
<th>Class S</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD589</td>
<td>$08.00 ea</td>
<td>$800.00 ea</td>
</tr>
<tr>
<td>AD590</td>
<td>$57.00</td>
<td>$906.00</td>
</tr>
<tr>
<td>OP-15</td>
<td>$10.00</td>
<td>$466.00</td>
</tr>
<tr>
<td>OP-97</td>
<td>$10.00</td>
<td>$600.00</td>
</tr>
</tbody>
</table>

What do we order for flight? Class B or Class S?

Some reports suggest the AD589 is only a 50 krad part?

What should we do? Buy Class B and test?
Qualification Procedures

How to simulate low dose-rate lifetime?

USA Mil-STD 883C, Test Method TM 1019.4
use of real devices, no need for test-structures

(a) $^{60}$Co irradiation to specified dose
under worst-case bias condition
at dose rate 50 to 300 rad(Si) s$^{-1}$

(b) Remove bias and maintain zero-bias
between irradiation and test

(c) Complete functional & parametric test within 2 hr

(d) If passed, irradiate again as in (a)
to 1.5 x specified dose (additional 50% of dose)

(e) Bake device
at worst-case static bias at 100°C for 168 hrs

(f) Complete functional & parametric test within 2 hr


TM 1019.4 should show the expected 'rebound' effects after 1 week anneal

Alternative procedure set up by ESA
Basic Specification BS 22900
50% overstress not required
Equilibrium Dose Theory

**Photons**

\[ D_1 = \Psi(\mu_{en}/\rho)_1 \]

\[ D_2 = \Psi(\mu_{en}/\rho)_2 \]

Therefore:

\[ \frac{D_1}{D_2} = \frac{(\mu_{en}/\rho)_1}{(\mu_{en}/\rho)_2} \]

Bragg-Gray Cavity Theory:

\[ D_3 = \Psi(\mu_{en}/\rho)_2(R_2/R_3) \]

Therefore:

\[ \frac{D_1}{D_3} = \frac{(\mu_{en}/\rho)_1}{(\mu_{en}/\rho)_2(R_2/R_3)} \]

**Electrons**

Let \( S_{col}/p \) be the mass collision stopping power, where superscripts pri and sec refer to the energy of primary and secondary electrons.

If Material 1 is thin to primary electrons, and Materials 2 and 3 are thick to secondary electrons, then:

\[ \Phi \]

\[ D_2 = \Phi(S_{col}^{pri}/p)_1 [S_{col}^{sec}(p)_2(S_{col}^{sec}(p)_1)] \]

\[ D_3 = \Phi(S_{col}^{pri}/p)_1 [S_{col}^{sec}(p)_2(S_{col}^{sec}(p)_1)] \]

Therefore:

\[ \frac{D_2}{D_3} = \frac{[S_{col}^{sec}(p)_2(S_{col}^{sec}(p)_1)]}{[S_{col}^{sec}(p)_2(S_{col}^{sec}(p)_1)]} \]

### Applicable ASTM Standards

**E666**


---

**Application of TLDs in Co-60 Testing**

**Applicability**

Type of Radiation: Cobalt-60 Gamma Radiation

Absorbed Dose Range: 10 mrad(Si) - 3 E5 rad(Si)

**Precautions**

Protect bare TLD from ultraviolet radiation (fluorescent light and sunlight.) Correct for fading.

**Use and Key Issues**

\[ \text{Al 2.2 mm} \]

\[ \text{Pb 1.61 mm} \]

\[ \text{Al 0.77 mm} \]

**Dosimeter**: CaF\(_2\) Mn or CaF\(_2\) Dy TLD

\[ D_{Si(eq)} = [(\mu_{en}/p)_Si / (\mu_{en}/p)_{CaF_2}] D_{CaF_2} \]

**Experimental Arrangement**

Device under test

Plane of device normal to incident radiation

Cobalt-60 Radiation

High-Z layers toward source

**Dosimeter**
General Characteristics

- Silicon On Insulator (SOI) + Trenches
- CMOS + NPN Bipolar + P JFET
- 5V Typical Technology
- Single Poly, Double Metal Layers
- 0.8μm and 1.2μm minimum drawn features
- Monitored Low Noise Performances
- 10Mrad & 1E14 neutrons/cm² Radiation Hardened
- Post 10Mrad parameter drifts for design simulation

SIMOX BURIED OXIDE

SUBSTRATE (Silicon)
DMILL BASIC PARAMETERS

General Features:
- SOI Substrate
- 0.8 μm minimum feature size
- 5.5 V maximum power supply voltage
- 24 masking levels
- Trench technology
- Silicided poly-Si
- LDD for NMOS and PMOS
- Aluminium double layer metallization

Topological and Electrical Parameters
- Trench: 0.9/1.1 μm
- Thin Oxide: 1/1.4 μm
- Poly1: 0.8/1 μm
- Contact: 1.0/1.2 μm
- Metal1: 1.1/1.2 μm
- Via1: 1.0/1.2 μm
- Metal2: 1.3/1.5 μm
- LeffN = 0.7 μm, LeffP = 0.7 μm
- VTN = VTP = ±0.8 V
- Thin Oxide = 17.5 nm
- IDS0.8 = 8.3 mA/μm
- IDSP0.8 = 4.6 mA/μm

Geneva, DMILL February 4th 1998
Large Scale production

- **DUAL USE approach**
  - Same set of equipment as for commercial large volume electronics
  - Back-end recipes derived from 0.6μm CMOS technology
  - Technology available whatever is the quality grade

- **Modern Quality tools**
  - ISO 9000 certification, QML soon
  - Statistical Process Control for all, critical parameters
    - faster reactivity &
    - technology capability based on mathematical representativeness of the distributions

- **Continuous Monitoring**
  - Basic failure mechanisms
  - Radiation hardness, noise, ...

---

Radiation Assurance (RHA)

- **100% of the wafer lots**
- **Wafer sampling**
- **Non destructive test at wafer level**
- **Use of existing standard with:**
  - Xrays at 1Krad(SiO2) / sec dose rate
  - 5V worst case bias during exposure
  - Individual device type measurement
- **Wafers delivered with CoC**
- **Post rad typical drifts available to assess design robustness**
RH: N Transistor

PARAMETRIC DRIFT AFTER 10Mrad (SiO2)

Delta Vt (mV)

N transistor
1Krad/sec
VGS=VGD=5.0V
VPS=VBS=0V
Ambient temp.

Batch Reference

CEA/MHS - Oct 97

Frost End Electronics Workshop, TAOS 5-7 November 1997

RH: P Transistor

PARAMETRIC DRIFT AFTER 10Mrad (SiO2)

Delta Vt (mV)

P transistor
1Krad/sec
VGS=VGD=VBS= -5.0V
VPS=0V
Ambient temp.

Batch Reference

CEA/MHS - Oct 97

Frost End Electronics Workshop, TAOS 5-7 November 1997
Noise: N Transistor

NOISE CALIBRATED AFTER 10Mrad (SiO)

CEA/MHS Octobre 97

Noise: P Transistor

NOISE CALIBRATED AFTER 10Mrad (SiO)

CEA/MHS Octobre 97
SCTA128 Architecture & Layout

⇒ Die size: 8.9x6.35

1. BiCMOS ampli-shaper
2. Analog Memory 128x112
3. Readout ampli+40Mhz analog mux
4. W/R Pipeline control logic
5. FIFO+sequencer

P. Jarron CERN. RD9 final report, LEB meeting 20/01/97

Preamp and noise measurement

\[
\text{Noise (2)} = \text{Noise (1)} + \beta \text{ decrease} \\
\text{Noise (3)} = \text{Noise (2)} + \text{memory non-uniformity} \\
\text{Noise (5)} = \text{Noise (3)} + \text{series noise} \ 6pF
\]

- Prerad and after 12 M
  1 » preamp Prerad: 620 el+ 33el/pF
  2 » preamp 12 Mrad 840 el+ 33el/pF
  3 » SCTA prerad 710 el @ 2pF
  4 » SCTA 10Mrad 810 el @ 2pF
  5 » SCTA +6cmSi-strip 860 el @ 8pF

- Full functionality at full specs verified after 12 Mrad, ultimate hardness much higher

1/11/96

Pierre Jarron CERN
Experience in ZEUS Calorimeter readout

Several iterations have been necessary

Strong field oxide leakage after 500 Gy (50 krad)

![Graph](image)

Modification of the layout of the transistors by adopting guard bands and extend gate oxide over this guard

FIELD OXIDE INVERSION- GUARD BANDS.


This worked!!

Results in ZEUS

1.2 μm non-radhard technology (Duisburg)

5 Gy = 500 krad

Analog Supply

Currents

\sim \text{CONSTANT}

Clocked

Digital Supply

Read only

Write only

Deviation of Pipeline gain

\sim -2.5 \% (OK)

S. Böttcher

Thesis
Charge build - up in MOS structure

Energy loss in oxide

TUNNELING

Leads to electron-hole generation with 17 eV/pair

'Bandgap' in silicon dioxide is 8.8 eV

Geminate recombination, fast electron evacuation

Slow hole drift towards traps near interface

hole mobility ~ $2 \times 10^{-5}$ cm$^2$ V$^{-1}$ s$^{-1}$ this gives transit time of

0.5 μs in 100 nm oxide @ $10^6$ V cm$^{-1}$

Tunneling current through the silicon dioxide

Electron-hole recombination at 'tunneling front'

up to ~ 5 nm from interface

BH February 18, 1998
Going to deep submicron

- 0.25 mm technology
- enclosed structures
- 30/0.4 (drawn)

Prerad and after 13Mrad

0.1 um CMOS - gate oxide 3.0 nm

poly - silicon
(crystallite)

3.0 nm SiO2

0.313 nm

IBM
Hardening by Layout

Source-Drain leakage along transistor gate, in bird’s beak region

Enclosed transistor layout (‘edgeless’, ‘re-entrant’)

eliminates the leakage path entirely
takes more space, becomes feasible in deep sub-micron

- NEEDS Multiple Metal Layers

0.7 mm $I-V_g$

Subthreshold currents before irradiation, after 3 Mrad and after 3 months annealing at room temperature. Worst case bias

Subthreshold current for $V_{ds}=7V$ before and after 1 Mrad for an edgeless device biased at the worst case
Enclosed geometry NMOS

$\text{Id}=f(\text{Vd})$ before and after 10 Mrad

Federico Faccio/CERN

Enclosed geometry NMOS

$\text{Id}=f(\text{Vg})$ before and after 10 Mrad

Federico Faccio/CERN
Enclosed geometry NMOS
Threshold voltage

PMOS
Threshold voltage
Standard geometry NMOS
Leakage current

Enclosed geometry NMOS
Leakage current
IRRADIATIONS LHC2-test

- 10 keV X-rays @ 4krad/min
- 1 chip gradually up to 800 krad
- 3 chips up to full dose at once (400, 600 and 800 krad), 1 day at room temperature, and 1 week at 100 degrees C
- behind target in NA50 experiment, slightly offset from beam
  - 1 chip gradually up to ~3.5 Mrad (dosimetry still to be confirmed)

W. Snoeys  CERN - ECP Division
CONCLUSIONS

- Silicon devices studied very extensively under radiation

- Efforts are diminishing rapidly for military applications

- New approaches needed for space and accelerators

- Problems usually come from unexpected sources

0.25 μm CMOS 32x16 = 512 μm²

'rad hard' layout used edgeless transistors + guard rings

0.7 μm 'rad hard' 45x48 = 2160 μm²

DENSE LAYOUT: D-FlipFlop

0.25 μm

1 μm²

0.7 μm

LAYOUT CONFIDENTIAL
Further Reading

Books
T.P. Ma & Paul V. Dressendorfer Ed. Ionizing Radiation Effects in MOS Devices & Circuits

G.C. Messenger & M.S. Ash The Effects of Radiation on Electronic Systems

S.M. Sze Physics of Semiconductor Devices 2nd ed
John Wiley

S.M. Sze Semiconductor Devices Physics and Technology

Andrew Holme-Siedle and Len Adams Handbook of Radiation Effects

V.A.J. van Lint et al. Mechanisms of Radiation Effects in Electronic Materials
Wiley-Interscience 1980 (out of print)

Semiconductors and Molecular Crystals

Sokrates T. Pantelides Deep Centers in Semiconductors

Proceedings
Series of Proceedings of IEEE Nuclear and Space Radiation Effects Conferences in:
December issues of IEEE Trans. Nucl. Sci. NS- from 1965 till present

Series of Proceedings of European Conf. on RADiation Effects on Components and Systems RADECs

Series of Proceedings of Int. Conf on Defects and Radiation Effects in Semiconductors
1964 Paris Royaumont Dunod 1965
1972 Reading IOP Conf Series 16 ISBN 0 85498 106 3
1974 Freiburg IOP Conf Series 23 ISBN 0 85498 113 6
1976 Dubrovnik IOP Conf Series ISBN 0 85498 xxxxx
1982 Amsterdam North Holland Reprint Physica 116 B+C

Emphasis in this conference moves with time from radiation effects towards solid state physics

Course Notes
Series of Short Course Notes presented at IEEE Nuclear and Space Radiation Effects Conferences
usually available only at the NSREC and a short period thereafter

Radiation Effects on Electronics in Space, ed. D.M. Fleetwood, Course Notes from courses given by
Fleetwood, Schwank, Sexton and Winokur from Sandia National Laboratories, Albuquerque, NM

EH February 16, 1998