Sapphire sensors for particles detection

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Contents

- Sapphire (Al$_2$O$_3$) properties (+diamond, GaAs, Si)
- Synthesis of sapphire
- Radiation hardness
- Application at FLASH, signal shape
- Charge collection efficiency
- Detection of MIPs with sapphire sensors
- Testbeam results
- Charge transport in sapphire
- Possible applications: tracker, TOF, calorimetry
- Conclusions and outlook
## Sensor material properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Sapphire</th>
<th>Diamond</th>
<th>GaAs</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cm³</td>
<td>3.98</td>
<td>3.52</td>
<td>5.32</td>
<td>2.33</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>9.3 – 11.5</td>
<td>5.7</td>
<td>10.9</td>
<td>11.7</td>
</tr>
<tr>
<td>Breakdown field, V/cm</td>
<td>~10⁶ *</td>
<td>10⁷</td>
<td>4.10⁵</td>
<td>3.10⁵</td>
</tr>
<tr>
<td>Resistivity, Ω·cm</td>
<td>&gt;10¹⁴</td>
<td>&gt;10¹¹</td>
<td>10⁷</td>
<td>10⁵</td>
</tr>
<tr>
<td>Band gap, eV</td>
<td>9.9</td>
<td>5.45</td>
<td>1.42</td>
<td>1.12</td>
</tr>
<tr>
<td>El. mobility, cm²/(V·s)</td>
<td>&gt;600 **</td>
<td>1800</td>
<td>~8500</td>
<td>1360</td>
</tr>
<tr>
<td>Hole mobility, cm²/(V·s)</td>
<td>-</td>
<td>1200</td>
<td>-</td>
<td>460</td>
</tr>
<tr>
<td>MIP eh pairs created, eh/μm</td>
<td>22</td>
<td>36</td>
<td>150</td>
<td>73</td>
</tr>
</tbody>
</table>

* Typical operation field ~1-2·10⁴ V cm⁻¹

** at 20°C, ~30000 at 40ºK
Synthesis of sapphire (Al₂O₃)

- Single crystals are grown by Czochralski process
- Growing speed ~100 mm/hour
- Up to 440 mm diameter crystals
- Crystal weight up to ~500 Kg
- World annual production >250 tons
- Used in chemistry, electronics, semiconductor industry, lasers, etc.

<table>
<thead>
<tr>
<th>Impurity</th>
<th>Na</th>
<th>Si</th>
<th>Fe</th>
<th>Ca</th>
<th>Mg</th>
<th>Ni</th>
<th>Ti</th>
<th>Mn</th>
<th>Cu</th>
<th>Zr</th>
<th>Y</th>
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</thead>
<tbody>
<tr>
<td>ppm</td>
<td>8</td>
<td>2</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>&lt;3</td>
<td>&lt;1</td>
<td>3</td>
<td>&lt;3</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Melt, 2325 K°
Irradiation of sapphire and diamond sensors at ~10 MeV electron beam

Single crystal CVD diamond

Single crystal sapphire

Leakage current after irradiation is still at few pA level

10 MGy ~ $5 \cdot 10^{16}$ MIPs ~ $2.5 \cdot 10^{15}$ [1 MeV neq] (NIEL, Summers)
Irradiation of sapphire and diamond sensors at ~10 MeV electron beam

Polycrystalline CVD diamond

E6 samples CCD vs dose at 400V

Single crystal sapphire

Irradiation of sapphire samples

Leakage current after irradiation is still at few pA level

$10 \text{ MGy} \sim 5 \times 10^{16} \text{ MIPs} \sim 2.5 \times 10^{15} [1 \text{ MeV neq}] \text{ (NIEL, Summers)}$

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Beam Halo Monitor at FLASH

4 artificial sapphire sensors
+ 4pCVD diamond sensors

Sapphire sensors

Diamond sensors

For more details, see talk by Alexandr Ignatenko at this workshop

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Sapphire charge collection efficiency

Measured at $^{90}\text{Sr}$ setup

- SC Sapphire
  - 10x10x0.5 mm$^3$
  - Metallization: Al+Ti+Au
- Very preliminary
- Signal $\sim$ 600 e$^-$
- 500 $\mu$m sample, MIP signal
Detection of MIPs

Typical thickness ~0.5 mm
~11K e-h pairs created
~5% CCE -> 550 e signal
Very hard to detect

a=10 mm => 220K e-h pairs produced
~5% CCE -> ~11000 e signal, similar to 100% efficient scCVD diamond detectors.
Test beam 2014, DESY
Stack of 8 sapphire plates

- 5 GeV electrons + EUDET pixel telescope
Stack image, scattered tracks

Sapphire detector image, constructed from scattered tracks, Z=0

Resolution ~10 µm
Sapphire charge collection efficiency

Electron beam 5 GeV

CCE linearly depends on the field strength

CCE for good plates ~5% at 1 V/µm
Charge collection mainly by electrons
Indication to the presence of polarization field
CCE as a function of sensor depth

Plates 5-8

Charge collection mainly by electrons
Indication to the presence of polarization field
Charge transport in sapphire

Space charge creation due to the trapped carriers

Space charge is a linear function of depth: \( \rho = p(2x - d) \)

Parabolic electric field

\[ E(x) = A \left( x - \frac{d}{2} \right)^2 + B \]

Collected charge for one carrier type:

\[ Q = \frac{N_0}{d} \int_{x_0}^{d} e \mu \tau \sqrt{AB} \left( \arctan \left( \frac{x_0 - \frac{d}{2}}{\sqrt{B}} \right) \right) dx \]

<table>
<thead>
<tr>
<th>Plate number</th>
<th>( B, \ V/\mu m )</th>
<th>( \mu \tau (e), \ \mu m^2/V )</th>
<th>Norm, %</th>
<th>( \mu \tau (h), \ \mu m^2/V )</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.328±0.011</td>
<td>79.4±1.0</td>
<td>52.4±0.4</td>
<td>4.7±0.2</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>1.207±0.011</td>
<td>62.0±1.0</td>
<td>47.0±0.5</td>
<td>5.7±0.2</td>
<td>59</td>
</tr>
<tr>
<td>3</td>
<td>1.274±0.009</td>
<td>66.7±0.9</td>
<td>53.2±0.5</td>
<td>6.1±0.2</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>1.243±0.010</td>
<td>76.6±1.0</td>
<td>48.6±0.5</td>
<td>2.3±0.2</td>
<td>35</td>
</tr>
<tr>
<td>5</td>
<td>1.441±0.010</td>
<td>61.0±1.0</td>
<td>48.6±0.8</td>
<td>2.4±0.3</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>1.297±0.011</td>
<td>40.5±0.9</td>
<td>44.2±0.9</td>
<td>4.2±0.3</td>
<td>67</td>
</tr>
<tr>
<td>7</td>
<td>1.521±0.006</td>
<td>18.7±0.3</td>
<td>60.4±1.4</td>
<td>2.3±0.2</td>
<td>17</td>
</tr>
<tr>
<td>8</td>
<td>1.314±0.009</td>
<td>14.2±0.5</td>
<td>46.3±1.9</td>
<td>1.9±0.3</td>
<td>46</td>
</tr>
</tbody>
</table>

Electric field distribution

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Sapphire possible application: tracker/TOF

Sensor thickness ~ 500µm
Strip pitch ~ 400µm
Expected resolution ~ 10µm

Tracker
CCD << d at room temperature
Large signals at adjacent strips
High sensitivity to the track XY position

TOF
Mobility of carriers gets much larger at low (cryogenic?) temperatures
Very fast signals, higher CCE expected, although spatial resolution gets worse, being comparable with strip pitch.
BeamCal sensor requirements

BeamCal should be compact, small Moliere radius needed:
- sampling calorimeter with solid state sensors, tungsten as absorber.

Severe load at small radii due to beamstrahlung:
- radiation hard sensors (up to 1 MGy annual dose)

Bunch-by-bunch operation:
- fast response of sensors

Test beam studies, physical calibration:
- sensitivity to MIPs
Modification of BeamCal design for sapphire sensors application
Dynamic range needed for BeamCal Readout (high energy electrons/MIPs)

Baseline design

- Entries: 1657469
- Mean: 0.4655E-02
- RMS: 0.1945E-01

New sapphire design

- Entries: 1307920
- Mean: 0.7331E-02
- RMS: 0.2477E-01

Factor ~2300

- Entries: 3009050
- Mean: 0.1857E-03
- RMS: 0.8717E-04

Factor ~220

- Entries: 120973
- Mean: 0.4137E-02
- RMS: 0.2524E-02

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BeamCal energy resolution

200 GeV electrons, GEANT3 Monte Carlo

Baseline design. $\delta E/E = 1.6\%$

New design. $\delta E/E \sim 8\%$

Response nonuniformity in the direction, perpendicular to the strips, depends on relative layer positioning. Further optimization is needed.
Conclusions and outlook

- Sapphire (single crystal Al$_2$O$_3$) is a very promising wide-bandgap material for HEP applications.
- Produced in large quantities for industrial purposes, large size wafers are available (~25 cm, up to 40 cm diameter is possible), not expensive.
- Perfect electrical properties, excellent radiation hardness, but presently low charge collection efficiency (~ 5%, probably due to high level of impurities).
- For many applications, where radiation hardness is an issue (large particle fluxes), sapphire could be used as it is, i.e. leakage current sensors, detection of particle bunches, calorimetry etc.
- Sapphire detector designed for MIP detection was tested at the beam. Results are in agreement with expectations, will be published soon.
- Preliminary design of the ILC BeamCal, based on sapphire sensors, is presented. First Monte Carlo simulations show promising results.
- Further plans: optimization, prototyping, test beam measurements …
Backup slides
Irradiation of GaAs sensors

10 MeV electrons

Few µA leakage current after 1 MGy dose (extra noise!)
Test of sapphire and quartz sensors at the 10 MeV electron beam

Quartz Crb3 Sample

Test samples 10 x 10 x 0.5 mm$^3$

Beam current $\sim 5$ nA

Sapphire Crb2 Sample

Strong polarization, seems like electric field is fully compensated. No charge collection.

Normal charge collection
Other two samples. Some recovery effect for sapphire during beam interruptions.

Silicon oxide

Aluminum oxide