Sapphire Detectors

Sergej Schuwalow, Uni Hamburg /DESY Zeuthen
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- Charge collection efficiency
- Radiation hardness
- Application at FLASH, signal shape
- Detection of MIPs
- Sensor configurations
- Test beam at DESY 08.2013
- Preliminary results
- Conclusions and outlook
Sapphire properties (Diamond)

- **Density**
  - Sapphire: 3.98 g cm$^{-3}$
  - Diamond: 3.52 g cm$^{-3}$

- **Dielectric constant**
  - Sapphire: 9.3 – 11.5
  - Diamond: 5.7

- **Breakdown field**
  - Sapphire: ~10$^6$ V cm$^{-1}$
  - Diamond: 10$^7$ V cm$^{-1}$

- **Resistivity**
  - Sapphire: $>10^{14}$ Ω cm
  - Diamond: $>10^{11}$ Ω cm

- **Band gap**
  - Sapphire: 9.9 eV
  - Diamond: 5.45 eV

- **Electron mobility**
  - Sapphire: ~600 (20°C)**
  - Diamond: 1800 cm$^2$ V$^{-1}$ s$^{-1}$

- **Hole mobility**
  - Sapphire: 30000 (400K)**
  - Diamond: 1200 cm$^2$ V$^{-1}$ s$^{-1}$

- **Average signal created**
  - Sapphire: 22 eh μm$^{-1}$
  - Diamond: 36 eh μm$^{-1}$

* Typical operation field ~10$^4$ V cm$^{-1}$

**Optical-Pump/THz-Probe Spectroscopy
Synthesis of sapphire (Al$_2$O$_3$)

- 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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<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>
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Melt, 2325 K

Pulling rod

Seed Crystal
Sapphire charge collection efficiency

Measured at $^{90}$Sr setup

SC Sapphire
10x10x0.5 mm$^3$
Metallization
Al+Ti+Au

Signal $\sim 600$ e$^-$

500 µm sample, MIP signal
Irradiation of sapphire and diamond sensors at 10 MeV electron beam

Single crystal CVD diamond

Leakage current after irradiation is still at few pA level

10 MGy ~ $5 \times 10^{16}$ MIPs ~ $2.5 \times 10^{15}$ [1 MeV neq] (NIEL, G.P.Summers)
4 artificial sapphire sensors
4pCVD diamond sensors

Analog signal from diamond sensor

Analog signal from sapphire sensor

Courtesy of A. Ignatenko, DESY-HH
Detection of MIPs

Typical thickness ~0.5 mm
~11K e-h pairs created
~5% CCE $\rightarrow$ 550 e signal
Very hard to detect
Detection of MIPs - 1

Typical thickness \( \sim 0.5 \text{ mm} \)

\( \sim 11K \) e-h pairs created

\( \sim 5\% \) CCE \( \rightarrow \) 550 e signal

Very hard to detect

\( a=10 \text{ mm} \) \( \Rightarrow \) 220K e-h pairs produced

\( \sim 5\% \) CCE \( \rightarrow \) \( \sim 11000 \) e signal, similar to scCVD diamond detectors.

Strongly reduced sensitivity to background!
Detection of MIPs - 2

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~5% CCE -> 550 e signal
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\[ a = 10 \text{ mm} \Rightarrow 220K \text{ e-h pairs produced} \]
\[ \sim 5\% \text{ CCE} \Rightarrow \sim 11000 \text{ e signal, similar to scCVD diamond detectors.} \]
Rad. Length: \( x/X_0 = 0.142 \)

Multiple scattering:

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<td>( 9.5 \times 10^{-6} )</td>
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Detection of MIPs - 3

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Possible sensor configurations

- Pad sensor
- Stack
- Segmented sensor ("pixel row")
- "No dead space" stack

And much more ....
Test beam at DESY 08.2013

- 5 GeV electrons + pixel telescope

~50% efficiency expected (hits in all trigger counters) (MC GEANT)

What we expect to see:

Detector - 8 sensors, 4 readout channels

Both carrier types contribute

Signal, arb.units

Polarization?
(expected to be small)

Only one carrier type

6 December 2013
Instrumentation Seminar, DESY, Hamburg
Test beam at DESY. EUDET telescope
Test beam at DESY. Detector installed

Detector in the holder

Shielding box
Telescope information only, XY of vertices

Work is going on
(PhD student at DESY Zeuthen)

Detector - 8 sensors, 4 readout channels
Sapphire detector signal, 500 V bias
DUT information only

Large pick-up of telescope trigger logical signals

Average of signals above the threshold

Average of signals below the threshold
Sapphire detector signal, 500 V bias
DUT information only

Large pick-up of telescope trigger logical signals
Sapphire detector signal vs bias voltage

HV = 800 V

Signal ~ 12000 e-

HV = 700 V

HV = 600 V

HV = 500 V

~9% of all events

The number of selected events as expected from geometrical probability

6 December 2013

Instrumentation Seminar, DESY, Hamburg
Sapphire detector signal vs bias voltage - 1

HV = 400 V

~ 0.7% of all events

HV = 300 V

1.1 MHz - close to DESY-II repetition rate

HV = 200 V

HV = 100 V

6 December 2013

Instrumentation Seminar, DESY, Hamburg
Sensor configurations

(i.e. Very Forward Tracking at LHC)
Sensor configurations

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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 sensors are successfully operating at FLASH, are to be installed at FLASH-2 and XFEL
- Sapphire sensors could be used for MIP detection in cases where tracker material budget is not critical (beam diagnostics, very forward tracking)
- Sapphire detector designed for MIP detection was tested at the DESY test beam. Preliminary results show expected performance.
- Further developments will follow.
Thank you!
Optical-pump/THz-Probe Spectroscopy

40 - 350 K

Ultrafast photo-excitation + THz time-domain spectroscopy

F. Wang et al., 2004
Irradiation of sapphire and diamond sensors at 10 MeV electron beam

**Single crystal CVD diamond**

So14_04 scCVD Diamond Irradiation

**Polycrystalline CVD diamond**

E6 samples CCD vs dose at 400V

Leakage current after irradiation is still at few pA level
Test of sapphire and quartz sensors at the 10 MeV electron beam

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

Silicon oxide

Aluminum oxide

Instrumentation Seminar, DESY, Hamburg 6 December 2013