Test and First Application of Sapphire Sensors

Alexandr Ignatenko
3rd ADAMAS Collaboration Meeting
Trento, Italy, November 20, 2014
Overview

- Introduction
- Sapphire sensors studies
- Application for the Beam Halo Monitor (BHM) at FLASH
- BHM for the European XFEL
- Summary
Introduction

Synthetic sapphire is an interesting sensor material
Commercially available

Low initial CCE values $\rightarrow$ Idea to improve the CCE by decreasing the impurity level or proper growth method

First application of sapphire sensors for the BHM at FLASH
Successful operation of the BHM at FLASH $\rightarrow$ BHM for the European XFEL
Sapphire sensors studies
Relevant sensor material properties

<table>
<thead>
<tr>
<th>Material property</th>
<th>Silicon</th>
<th>Diamond</th>
<th>Sapphire</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, g/cm³</td>
<td>2.32</td>
<td>3.52</td>
<td>3.98</td>
</tr>
<tr>
<td>Band gap, eV</td>
<td>1.12</td>
<td>5.45</td>
<td>8.8</td>
</tr>
<tr>
<td>Electron-hole pair creation energy, eV</td>
<td>3.62</td>
<td>13.2</td>
<td>24.6</td>
</tr>
<tr>
<td>Electron mobility, cm²V⁻¹s⁻¹</td>
<td>1350</td>
<td>1800-4500</td>
<td>~ 600</td>
</tr>
<tr>
<td>Hole mobility, cm²V⁻¹s⁻¹</td>
<td>480</td>
<td>1200-3800</td>
<td>n/a</td>
</tr>
</tbody>
</table>

- Wide band gap → no need for depletion
- Large electron-hole pair creation energy → smaller signal
- High radiation tolerance
- Fast signals
Sapphire sensors

Single crystal sapphire ($\text{Al}_2\text{O}_3$) with different impurity concentration from different manufacturers

1. CRYSTAL GmbH
   grown by Czochralski method, impurity level 33-39 ppm

2. RSA Le Rubis
   grown by Kyropolous method, impurity level 40 ppm

3. Kyocera
   grown by EFG method, impurity level 60 ppm

Cut [0001], dimensions $10\times10\times0.5$ mm$^3$

Metallization by Target laboratory @ GSI: 1 pad $8\times8$ mm$^2$ from each side
1 Al layer 200 nm thick or Al/Ti/Au layers respectively 50/50/200 nm
Sapphire sensors laboratory tests

I-V characteristic

Signal as a response to a single MIP is too low for detection

Signal as a response to particle flux from $^{90}\text{Sr}$ source
Irradiation studies

8.5 MeV electron beam
@ S-DALINAC

30 % of the initial value of the signal after 12 MGy
CCE of sapphire sensors

CRYSTAL

Bias voltage ramp up/down
0V -> 500V -> 0V -> -500V -> 0V

The sensors are pumped during the measurement (@ -500 V)

CCE in the pumped state is up to 50-100 % higher than that in the unpumped state

RSA Le Rubis

No strong dependency on the impurity concentration

Reaching high purity can be expensive

An alternative is to apply these sensors in specific applications or to use assemblies of such sensors with dedicated design

Kyocera No signal observed
Application for the Beam Halo Monitor (BHM) at FLASH
FLASH is the world's first soft X-ray free-electron laser available to the photon science user community for experiments since 2005. This is a user facility of the SASE FEL beam at DESY and also a test facility for the European XFEL and the ILC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge</td>
<td>0.2 – 1.2 nC</td>
</tr>
<tr>
<td>Energy</td>
<td>450 – 1250 MeV</td>
</tr>
<tr>
<td>Photon wavelength</td>
<td>4.1 – 40 nm</td>
</tr>
<tr>
<td>Bunch frequency</td>
<td>0.1 – 1 (3) MHz</td>
</tr>
<tr>
<td>Macro-pulse frequency</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Macro-pulse length</td>
<td>≤ 800 µs</td>
</tr>
<tr>
<td>Max. average beam power</td>
<td>100 kW</td>
</tr>
</tbody>
</table>
Beam accident during the “9 mA” run

Additional instrumentation was needed

The BHM is intended to detect beam displacements by registering the halo particles

Part of the electron beam dump diagnostics
BHM at FLASH

Sensor bias and signal readout scheme

BHM module carrying 4 pCVD diamonds and 4 synthetic sapphires
Operation experience

Analog signals from a diamond (left) and a sapphire (right) sensors as a response to 1 bunch

Shaped analog signal from a BHM sensor

Digitized signals for 30 bunches
Response to small beam displacements

Signal (in V) from a diamond sensor as a function of beam position

Signal (in V) from a sapphire sensor as a function of beam position

Sweeping frequency 1.1 Hz

The signals in the frequency domain
Calibration

The idea is to determine relationship between the signal from a sensor and the charge of the particles hitting the sensor

Energy 943 MeV
1 bunch per train (40 pC to 1 nC)
No defocusing in the dump section
Beam centered (as good as possible) in the dump section
Sweeper on, radius of 55 mm (beam pipe center – sensor center distance)

Signal from a BHM sensor (in V) as a function of beam position
Under normal conditions the sensors operate in the linear range. Sapphire sensors are capable to detect further worsening of the conditions thus increasing dynamic range of the BHM.
BHM for the European XFEL
European X-Ray Free-Electron Laser (XFEL) is a new international facility to generate extremely brilliant, ultra-short pulses of spatially coherent X-rays and to exploit them for experiments in a variety of disciplines.

<table>
<thead>
<tr>
<th>Charge</th>
<th>0.02 – 1 nC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>Up to 17.5 GeV</td>
</tr>
<tr>
<td>Bunch frequency</td>
<td>Up to 4.5 MHz</td>
</tr>
<tr>
<td>Macro-pulse frequency</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Macro-pulse length</td>
<td>≤ 600 μs</td>
</tr>
<tr>
<td>Max. average beam power</td>
<td>300 kW</td>
</tr>
</tbody>
</table>
BHM at the European XFEL

1, 3 and 7 – BPMs
2 – dipole steerer magnets
4 – OTR screen
5 – toroid
6 – BHM
8 – position of ionization chambers and BLMs

1,3 – quadruple magnets
2, 6 – BPM
4 – OTR screen
5 – toroid
7 – the last section with absorber
Intended to detect beam displacements by registering the secondaries along with primary halo particles
Each BHM module will provide alarm signals to MPS
Summary

- Synthetic sapphire is proven to be robust sensor material for application in high radiation fields up to several MGy and at high dose rates.

- To fully exploit their potential detailed studies are needed.

- Sapphire sensors were applied along with diamond sensors for the BHM, which has been designed, built, successfully commissioned and reliably operated at FLASH since Sept. 2009.

- The BHM at FLASH is considered as prototype of the BHMs designed for the European XFEL.
Thank you for your attention!

**Contributors:**

<table>
<thead>
<tr>
<th>Hans Henschel</th>
<th>Nicoleta Baboi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wolfgang Lange</td>
<td>Olaf Hensler</td>
</tr>
<tr>
<td>Wolfgang Lohmann</td>
<td>Dirk Nölle</td>
</tr>
<tr>
<td>Sergej Schuwalow</td>
<td>Michael Schmitz</td>
</tr>
<tr>
<td></td>
<td>Kay Wittenburg</td>
</tr>
</tbody>
</table>