Characterization of Single-Crystal Diamond Sensors for Radiation Monitoring in the Belle II Experiment

L. Bosisio, P. Cristaudo, B. Gobbo, C. La Licata, L. Lanceri, L. Vitale
INFN and University of Trieste
G. Cautero, D. Giuressi
Elettra Sincrotrone Trieste SCpA

7th ADAMAS Workshop – 13-14 December 2018 – Vienna - Austria
Belle II and its Vertex Detector

Belle II Detector at the SuperKEKB $e^+e^-$ collider

$L_{\text{peak}} = 8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

$L_{\text{int}} = 50 \text{ ab}^{-1}$ by 2025

Silicon Vertex Detector (SVX)
- Two layers of DEPFET pixels (PXD)
- Six layers of double-sided microstrips (SVD)
Radiation Detection System

Dual-purpose system:

1. Providing long-term monitoring of integrated radiation doses at several places in the vertex detector

2. Providing interlock signals for beam abort in case of potentially damaging radiation levels

Sensor current is measured and sampled, providing fast (100 kHz, higher dynamic range) and a slow (10 Hz, higher sensitivity) data output streams
28 Diamond Sensors installed

20 sensors at the SVX

6 + 6 sensors close to SVD L3 support rings

4 + 4 sensors at PXD-beam pipe

Plus 4 + 4 sensors at the nearest quadrupoles

=> 28 Diamond Sensors in total
Diamond Sensors + Package

- Diamond sensors supplied by Cividec
- (4.5 x 4.5 x 0.5) mm³ single-crystal diamond
- Ti + Pt + Au metallization (100 + 120 + 250) nm

Shielding is completed by a thin Al cover

Miniature coaxial cables 2.5 m long + standard cables 25 m long

Shielded diamond sensor in package

Diamond crystal with metallized electrodes

Ball-bonded gold wires

Ceramic-like rogers package

Voltage source (150÷500 V)

pA–meter

14-12-2018
L. Bosisio – ADAMAS-2018 Workshop – Vienna
Readout Electronics

DCU: Diamond Control Unit (4 channels)

I/O:
- Ethernet
- DAC + 4 HV modules: HV bias to diamond sensors
- 4 Amplifiers + ADCs: currents digitization at 50 MHz

FPGA:
- HV setting, Amplifier range selection, thresholds
- Moving sums and abort logics at 100 kHz
- Monitoring data at 10 Hz

Developed by
Elettra Sincrotrone Trieste ScpA

Back panel: connectors
Diamond Current Unit

- Eth
- FPGA
- ADC & DACs
- Amplifiers
- HV bias
Cividec provided data sheets for each sensor, including:

- Alpha-TCT
- \( I-V \) dark
- \( I-t \) stability with Beta irradiation
  \((\pm 100 \text{ V}, -200 \text{ V}, 10 \text{ min}, +200\text{V}, 1h)\)
Our measurements – outline

- $I$-$V$ dark current
- Alpha TCT
- Current stability under steady beta irradiation
- $I$-$V$ with beta irradiation
- Current to dose-rate calibration:
  - $I$ vs $d$ (source distance)
  - Fluka simulation of $I$ vs dose-rate
  - $\Rightarrow$ Effective Gain factor
Dark $I$-$V$ measurements

- Measured up to 800 V, both polarities

Large variations, but:
- measurement not slow enough to reduce memory effects
- all currents within a few pA at 500 V
Alpha TCT: Set-Up

HV Power Supply (-800 V ÷ +800 V)

Power Supply for Amplifier (12 V)

Signal to Oscilloscope

Holder of Diamond Sensor and Alpha Source

BIAS-T (1) and AMPLIFIER (2) (by Particulars d.o.o.)
Examples of TCT measurements - 1

Scope screenshot, + 200 V bias => hole drift

- $E = 200 \text{ V}/0.5 \text{ mm}$
  - $= 4.0 \times 10^3 \text{ V/cm}$
- $\nu_{\text{drift}} = 0.5 \text{ mm}/10.6 \text{ ns}$
  - $= 4.7 \times 10^7 \text{ cm/s}$
- $\mu_h = 1.2 \times 10^3 \text{ cm}^2/(\text{V} \cdot \text{s})$
- Amplifier voltage gain:
  - $G_{\text{amp}} = 52 \text{ dB} \approx 400$
- Amplifier $Z_{\text{in}} = 50 \Omega$

- $Q_{\text{collected}} = \text{Pulse Integral}/G_{\text{amp}}/Z_{\text{in}} = 5.45 \times 10^{-14} \text{ C}$
- $Q_{\text{gen}} = q_e \cdot 5.17 \times 10^6 \text{ eV} / 13 \text{ eV} = 6.36 \times 10^{-14} \text{ C}$
- $\text{CCE} = \frac{Q_{\text{collected}}}{Q_{\text{gen}}} = 86\%$

But there is some uncertainty in amplifier gain and $Z_{\text{in}}$, plus some attenuation (~ 1dB ?) from the 2.5 m long, thin cable

=> under investigation
Examples of TCT measurement-2

Measurement at $\pm 800$ V bias

- Higher drift speed consistently obtained for holes
- Trailing edge has rather long tail
  - cannot be explained by carrier diffusion (much smaller effect)
  - possibly due to parasitics introduced by the sensor assembly
Examples of TCT measurement-3

• Some signals show spikes at the rising or falling edge, or both:
Examples of TCT measurement-4

- By rising the trigger level, we can single-out these signals

Possible explanation:
- Charge build-up in localized areas and close to the surfaces?
- Edge effects due to insufficient collimation of alpha particles?
Carrier Mobilities from TCT

- From the TCT measurements we obtain the ‘field-dependent mobilities’

```
Mobilities vs electric field
```

- holes
- electrons
Current stability under beta irradiation

The current is measured vs time at +/- 100 V bias, for times of ~ 1 day, with beta irradiation giving ~ 1 nA current. Results are used to choose the bias polarity to be used for each sensor.

![Graphs showing current stability under +100 V and -100 V bias](stability_DC19_100V_27_03_2017)
I-V curves under beta irradiation

- Measured from 0 to ± 500 V and back to 0 V
- Source at short distance to the sensor (~ 2 mm)

- Some sensors show lack of saturation and hysteresis effects
- These curves are also used to select the bias polarity for each sensor
Dose-rate vs current calibration

Obtained with beta irradiation, by:

- Measuring the current versus source-detector distance $d$, at ±100 V bias
- Simulating with FLUKA the energy deposited in the sensor per unit time, and converting it into current, assuming $\epsilon_{e-h} = 13$ eV
- Comparing the two currents, to get an ‘effective’ gain $G$, accounting for both the photoconductive gain and a possible defect in CCE
- Relating the simulated energy deposit to dose, using the sensor mass
Measured and simulated currents

Measured current $I_m$ vs distance, 
\approx point-like source:

$$I_m(d) \propto \text{solid angle}$$

Simulated energy deposit (dose rate) 
⇒ Simulated current $I_s$ vs distance 
⇒ assuming gain $G = 1$

Average energy deposit per emitted β electron

$$I_s(d) = \frac{\langle E(d) \rangle}{\varepsilon_{e-h}} A q_e$$

Source activity (3.2 MBq) 
elementary charge 

Average energy deposit per generated e-h pair, assumed to be 13 eV
Current to Dose-Rate Conversion

Current is measured vs source-detector distance and confronted with simulation

‘Effective’ photo-conductive gain $G$
(includes also possible CCE defect):

$$\frac{I_m(d)}{I_s(d)} = G > 1$$

Electron drift
Hole drift

Conversion: current => dose-rate:

$$\frac{dD}{dt} = \frac{F}{G} I^m$$

$$F = \frac{\varepsilon_{e-h}}{m} \frac{1}{q_e}$$

sensor mass
Calibrations summary on 26 detectors

- $F = 36.5$ (mrad/s)/nA
- $G \approx 2 - 3$

(very approximately)

$$\frac{dD}{dt} \left[ \text{mrad/s} \right] \approx 10 \left[ \frac{\text{mrad/s}}{\text{nA}} \right] \times I_m \left[ \text{nA} \right]$$

Temporary estimate of systematic relative uncertainty on $F/G$: about 17% (under study)

<table>
<thead>
<tr>
<th>Origin of systematic uncertainty</th>
<th>$\delta G / G$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source-diamond sensor distance</td>
<td>10</td>
</tr>
<tr>
<td>Diamond sensor active volume</td>
<td>10</td>
</tr>
<tr>
<td>Diamond sensor priming or pumping</td>
<td>5</td>
</tr>
<tr>
<td>Source activity</td>
<td>7</td>
</tr>
<tr>
<td>FLUKA simulation statistics</td>
<td>1</td>
</tr>
<tr>
<td>HV reproducibility</td>
<td>1</td>
</tr>
<tr>
<td>Combination in quadrature</td>
<td>17</td>
</tr>
</tbody>
</table>
Example of diamond results at SuperKEKB

Correlation between beam currents and diamond dose-rates during Phase 3 commissioning of SuperKEKB and Belle II

Beam currents and diamond dose-rates

- HER current
- LER current
- BWD CH0 - phi = 55°
- BWD CH1 - phi = 125°
- BWD CH2 - phi = 235°
- BWD CH3 - phi = 305°

The spikes from diamonds are due to transient increases of radiation during injections

14-12-2018
L. Bosisio – ADAMAS-2018 Workshop – Vienna
Conclusions

• A relatively large number of diamond sensors has been procured, assembled and characterized for radiation monitoring in Belle II experiment.

• The application required measuring sensor currents, and a very compact sensor package, with long, thin cables.

• Characterization emphasis was on measurement of radiation-induced current, not on single-particle signals, for which the sensor assembly was not well suited.

• More detailed investigations of sensor characteristics are planned, together with a comparison with SiC sensors.