Diamonds for Beam Instrumentation

TIPP 2011, Chicago, 9.6.2011
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CERN and CIVIDECE Instrumentation
Overview

• Diamond Detectors
• Physics
• Application Examples
• Summary
The Diamond Detector
Substrate

Diamond Substrate:

pCVD = 10x10 mm$^2$ x 0.5 mm
sCVD = 5x5 mm$^2$ x 0.5 mm
pCVD Substrate

Crystal boundaries, 100 – 200 um
Charge-collection distance 200 um
→ Trapping
→ Reduction of ionization charges
Diamond Detectors

pCVD

sCVD
Diamond Beam Monitor

Detector  AC/DC Splitter  2 GHz Amplifier
Physics
Principle of Ionization

13 eV/eh-pair
1.6 fC/MIP
Modes of Operation

Counting Mode

Calorimetric Mode

\[ i_0 = \frac{Q}{2} \cdot \frac{v_a}{d} \]

\[ t_d = \frac{d}{v_d} \]

\[ i_0 = \frac{Q}{2} \cdot \frac{v_d}{d} \]

\[ t_d = \frac{d}{v_d} \]
Proton Interaction

E > 10 MeV: protons traverse detector

E < 10 MeV: protons penetrate the detector (calorimetric mode)

→ Direct measurement of the ionization charge.

→ Single protons, efficiency = 100%
Proton Interaction

![Graph showing stopping power vs. initial energy for protons. The graph displays a peak at a certain initial energy.]
Proton Interaction
Proton Interaction

![Graph showing the relationship between initial energy and generated charge. The graph is a 2D plot with the x-axis labeled 'Initial energy, MeV' and the y-axis labeled 'Charge, fC'. The graph is divided into two regions: one for low charge and high energy, and one for high charge and low energy. The region of interest is marked by a red circle at 10 MeV and 100 fC.]
Proton Interaction

[Graph showing the relationship between generated charge and initial energy for single particles.]
Proton Interaction

![Graph showing proton interaction with generated charge and initial energy. The x-axis represents initial energy in MeV, ranging from $10^{-4}$ to $10^{6}$. The y-axis represents charge in fC, ranging from $10^{-2}$ to $10^2$. The graph is color-coded with green, yellow, and blue sections, indicating different ranges of charge and energy.](image)
Electron Interaction

E > 400 keV: electrons traverse detector

E < 400 keV: electrons penetrate the detector (calorimetric mode)

→ Direct measurement of the ionization charge.

→ Single electrons, efficiency = 100%
Electron Interaction

Generated charge

Charge, fC

Initial energy, keV

10

10^2

10^3

400
Neutron Interaction

E < 6 MeV: Converter foil (B, Gd) and measure n → α conversion products

E > 6 MeV: Direct measurement of n → α interaction of neutrons and detector

→ Direct and indirect measurement of the n → α ionization charge.

→ Single neutrons, efficiency << 100%
→ Neutron flux, efficiency = 100%
Photon Interaction

$E > 5.5\ \text{eV}$: Photo excitation current

$2\ \text{keV} < E < 50\ \text{keV}$: Fluorescence monitors

$E > 50\ \text{keV}$: Ionization $\rightarrow$ direct measurement, single photon detection

$\rightarrow$ Direct and indirect measurement of the ionization
$\rightarrow$ Direct measurement of the excitation

$\rightarrow$ Single photons, efficiency $<< 100$
Photon flux, efficiency $= 100\%$
Photon Interaction

Secondary e- generated by Geant4

Excitation

Ionization

Number of e- per 100,000 photons

Initial energy, MeV
Applications
Beam Instrumentation Detectors

Protons
- Beam Loss / Position / Profile Monitors

Electrons
- Beam Loss Monitors

Photons
- Beam Position Monitors (SLS, XFEL)

Neutrons
- Flux monitors (14 MeV fusion, radiation protection)
Application Example 1:

PROTONS
Proton Therapy

IBA Cyclotron in Orsay
Proton Therapy

Energy calibration

IBA Cyclotron
Proton Therapy

Beam structure

200 MeV protons, 106 MHz RF
9 ns RF period

100 mV/div
20 ns/div

IBA Cyclotron
Proton Therapy

Phase measurement

200 MeV protons, 106 MHz RF

10 ns/div

Phase histogram → Phase $\phi$ → Maximum → Half maximum
Proton Therapy

Phase measurement

200 MeV protons, 106 MHz RF

10 ns/div

10 ps phase resolution

3° = 80 ps phase stability

IBA Cyclotron
CERN ISOLDE – Heavy Ions
Heavy Ions

Calorimetric spectroscopy

23 MeV C-ions

dE/E = 0.6%
Energy resolution

REX ISOLDE
LHC - Diamond Beam Loss Monitor

LHC – Collimation Area – IP7
LHC - DBLM

Unexpected beam abort ("UFO")
LHC - DBLM

Loss profile

Turn clock

1 ms

← Ionization Chambers

← DBLM
LHC - DBLM

Zoom for next transparency

Turn clock

1 ms

DBLM

 Ionization Chambers
LHC - DBLM

Zoom x10

19 bunch trains, 192 bunches

100 us
LHC - DBLM

Zoom x100

8 bunches

Bunch trains

8 bunches 8 bunches

10 us
LHC - DBLM

Zoom x10'000

Single bunch signal

FWHM = 6 ns

100 ns
Application Example 2:
Neutrons
Neutron Measurement

n_TOF experiment at CERN: thermal to GeV neutrons
Neutron Measurement

6 MeV to GeV neutron time-of-flight

n_TOF at CERN
Neutron Measurement

Measurement of $n \rightarrow \alpha$ and $n \rightarrow p$ interactions

Pulse shapes of interactions
Application Example 3:

Photons
Medical LINAC

AKH Vienna
X-rays: 6 MV – 25 MV
Dose-rate: 4 Gy/min
Courtesy: D. Georg

Diamond Detector

Water phantom
10 MeV Photons

2.5 ms bunch rate

Depth-dose profile measurement

1% agreement with a reference Thimble Ionization Chamber

rms = 0.126
0.012
Summary

• Radiation resistance
• Fast $\rightarrow$ 10 ps time resolution, 360 ps for single particles
• High sensitivity $\rightarrow$ single particles with +40 dB
• High dynamic range $\rightarrow$ attenuation -40 dB
• Protons – electrons – neutrons – photons
• BLM, BPM, Counter, Spectroscopy, Phase
• Many other potential applications.....
Conclusion

- Compact
- Fast
- Radiation hard

DIAMONDS
Thank you for your attention!
# CVD Parameter

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>Silicon</th>
<th>Advantage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap [eV]</td>
<td>5.5</td>
<td>1.12</td>
<td>Low leakage</td>
</tr>
<tr>
<td>Breakdown field [V/cm]</td>
<td>$10^7$</td>
<td>$3 \cdot 10^5$</td>
<td></td>
</tr>
<tr>
<td>Intrinsic resistivity @ R.T. [Ω cm]</td>
<td>$&gt; 10^{11}$</td>
<td>2.3 $\cdot$ 10$^5$</td>
<td></td>
</tr>
<tr>
<td>Intrinsic carrier density [cm$^{-3}$]</td>
<td>$&lt; 10^3$</td>
<td>1.5 $\cdot$ 10$^{10}$</td>
<td></td>
</tr>
<tr>
<td>Electron mobility [cm$^2$/Vs]</td>
<td>1900</td>
<td>1350</td>
<td></td>
</tr>
<tr>
<td>Hole mobility [cm$^2$/Vs]</td>
<td>2300</td>
<td>480</td>
<td></td>
</tr>
<tr>
<td>Saturation velocity [cm/s]</td>
<td>e$^-$: $0.9 \cdot 10^7$</td>
<td>0.82 $\cdot$ 10$^7$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>holes: $1.4 \cdot 10^7$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Density [g/cm$^3$]</td>
<td>3.52</td>
<td>2.33</td>
<td>Low capacitance</td>
</tr>
<tr>
<td>Atomic number - Z</td>
<td>6</td>
<td>14</td>
<td>Radiation hard</td>
</tr>
<tr>
<td>Dielectric constant - ε</td>
<td>5.7</td>
<td>11.9</td>
<td>Heat spreader</td>
</tr>
<tr>
<td>Displacement energy [eV/atom]</td>
<td>43</td>
<td>13-20</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity [W/m.K]</td>
<td>$\approx$ 2000</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>Energy to create e-h pair [eV]</td>
<td>13</td>
<td>3.61</td>
<td>Low signal,</td>
</tr>
<tr>
<td>Radiation length [cm]</td>
<td>12.2</td>
<td>9.36</td>
<td>Low Noise</td>
</tr>
<tr>
<td>Interaction length [cm]</td>
<td>24.5</td>
<td>45.5</td>
<td></td>
</tr>
<tr>
<td>Spec. Ionization Loss [MeV/cm]</td>
<td>6.07</td>
<td>3.21</td>
<td></td>
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<tr>
<td>Aver. Signal Created / 100 μm [e$_0$]</td>
<td>3602</td>
<td>8892</td>
<td></td>
</tr>
<tr>
<td>Aver. Signal Created / 0.1 X0 [e$_0$]</td>
<td>4401</td>
<td>8323</td>
<td></td>
</tr>
</tbody>
</table>
Radiation Hardness

Preliminary Summary of Proton Irradiations

- Red Data: strip scCVD (x-shifted by -3.8)
- Open Red: pixel scCVD (x-shifted by -3.2)
- Blue Data: strip pCVD
- Black curve: $ccd = ccd_0/[1+k \cdot \phi \cdot ccd_0]$