Diamond (Radiation) Detectors Are Forever!

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Outline of the Talk
- Introduction to Diamond
- Recent Results
- Applications
- Summary
Motivation: Tracking Devices Close to Interaction Region of Experiments

Use at the LHC/SLHC (or similar environments e.g. BaBar, Belle):

→ Inner tracking layers must provide high precision tracking (to tag b, t, Higgs, . . .)
→ Inner tracking layers must survive! → what does one do?
→ Annual replacement of inner layers perhaps?

Look for a Material with Certain Properties:
- Radiation hardness (no frequent replacements)
- Low dielectric constant → low capacitance
- Low leakage current → low readout noise
- Room temperature operation, Fast signal collection time → no cooling

Material Presented Here:
- Polycrystalline Chemical Vapor Deposition (pCVD) Diamond
- Single Crystal Chemical Vapor Deposition (scCVD) Diamond

On Behalf of RD42:
- Reference → http://rd42.web.cern.ch/RD42
### Comparison of Various Materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>4H-SiC</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Gap [eV]</td>
<td>5.5</td>
<td>3.3</td>
<td>1.12</td>
</tr>
<tr>
<td>Breakdown field [V/cm]</td>
<td>$10^7$</td>
<td>$4 \times 10^6$</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>Resistivity [$\Omega$-cm]</td>
<td>$&gt;10^{11}$</td>
<td>$10^{11}$</td>
<td>$2.3 \times 10^5$</td>
</tr>
<tr>
<td>Intrinsic Carrier Density [cm$^{-3}$]</td>
<td>$&lt; 10^3$</td>
<td>$10^{11}$</td>
<td>$1.5 \times 10^{10}$</td>
</tr>
<tr>
<td>Electron Mobility [cm$^2$V$^{-1}$s$^{-1}$]</td>
<td>1800</td>
<td>800</td>
<td>1350</td>
</tr>
<tr>
<td>Hole Mobility [cm$^2$V$^{-1}$s$^{-1}$]</td>
<td>1200</td>
<td>115</td>
<td>480</td>
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<tr>
<td>Saturation Velocity [km/s]</td>
<td>220</td>
<td>200</td>
<td>82</td>
</tr>
<tr>
<td>Mass Density [g cm$^{-3}$]</td>
<td>3.52</td>
<td>3.21</td>
<td>2.33</td>
</tr>
<tr>
<td>Atomic Charge</td>
<td>6</td>
<td>14/6</td>
<td>14</td>
</tr>
<tr>
<td>Dielectric Constant</td>
<td>5.7</td>
<td>9.7</td>
<td>11.9</td>
</tr>
<tr>
<td>Displacement Energy [eV/atom]</td>
<td>43</td>
<td>25</td>
<td>13-20</td>
</tr>
<tr>
<td>Energy to create e-h pair [eV]</td>
<td>13</td>
<td>8.4</td>
<td>3.6</td>
</tr>
<tr>
<td>Radiation Length [cm]</td>
<td>12.2</td>
<td>8.7</td>
<td>9.4</td>
</tr>
<tr>
<td>Spec. Ionization Loss [MeV/cm]</td>
<td>4.69</td>
<td>4.28</td>
<td>3.21</td>
</tr>
<tr>
<td>Ave. Signal Created/100 $\mu$m [e]</td>
<td>3600</td>
<td>5100</td>
<td>8900</td>
</tr>
<tr>
<td>Ave. Signal Created/0.1% $X_0$ [e]</td>
<td>4400</td>
<td>4400</td>
<td>8400</td>
</tr>
</tbody>
</table>

→ Low dielectric constant - low capacitance
→ Large bandgap - low leakage current
→ Large energy to create an eh pair - small signal
Diamond Growth:

Diamonds are “synthesized” from a plasma
The diamond “copies” the substrate
Characterization of Diamond:

Signal formation

- \( Q = \frac{d}{t} Q_0 \) where \( d \) = collection distance = distance e-h pair move apart
- \( d = (\mu_e \tau_e + \mu_h \tau_h) E \)
- \( d = \mu E \tau \)

with \( \mu = \mu_e + \mu_h \)
and \( \tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h} \)
Diamond Properties:

**Signal formation**

- Contacts on both sides - structures from $\mu$m to cm
- Contacts typically: Cr/Au or Ti/Au or Ti/W $\rightarrow$ non-carbide formers
- Polycrystalline CVD diamond typically “pumps” by a factor of 1.5-1.8
- Usually operate at $1V/\mu$m $\rightarrow$ drift velocity saturated
- Test Procedure: dot $\rightarrow$ strip $\rightarrow$ pixel on same diamond!

**Signal versus applied electric field**
Recent polycrystalline CVD (pCVD) diamond.

Left: Enhanced surface of pCVD diamond
Right: Recent pCVD wafer ready for test - Dots are 1 cm apart

Wafers can be grown >12 cm diameter, >2 mm thickness.
In 2000 RD42 entered into a Research Program with Element Six to increase the charge collected from pCVD diamond.

**Research Program Diamond Measured with a $^{90}$Sr Source:**

- System Gain = 124 e/mV
- $Q_{MP} = 7600e$ (62mV)
- Mean Charge = 9800e (79mV)

- Source data well separated from 0
- Collection Distance now 275µm
- Most Probable Charge now $\approx 8000e$
- 99% of PH distribution now above 3000e
- FWHM/MP $\approx 0.95$ — Si has $\approx 0.5$
- This diamond available in large sizes

**The Research program worked!**
History of Diamond Progress

Charge Collection in DeBeers CVD Diamond

Collection Distance (microns)

Time (year)

RD42 Goal

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Diamond (Radiation) Detectors Are Forever! (page 9)
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Diamond Tracking Planes:

- Use same electronics as Silicon
- Uniform signals on all strips → new metalisation
- Pedestal separated from “0” on all strips
- 99% of entries above 2000 $e$
- Mean signal charge $\sim 8640$ $e$ → new metalisation
- MP signal charge $\sim 6500$ $e$
Diamond Radiation Hardness Studies with Trackers

Proton Irradiation Studies with Trackers:

Signal to Noise

- Dark current decreases with fluence
- S/N decreases at $2 \times 10^{15}$/cm$^2$
- Resolution improves at $2 \times 10^{15}$/cm$^2$

Resolution

Irradiation to $10^{16}$ protons/cm$^2$ presently underway!
Pion Irradiation Studies with Trackers:

Signal to Noise

- Dark current decreases with fluence
- 50% loss of S/N at $2.9 \times 10^{15}$/cm$^2$
- Resolution improves 25% at $2.9 \times 10^{15}$/cm$^2$
Diamond - Tracking Studies

Radiation Hard Diamond Tracking Modules:

- Large (2cm × 4cm) Module constructed with new metalisation
- Fully radiation hard SCTA128 electronics → 25ns peaking time
- Tested in a $^{90}\text{Sr}$ → ready for beam test and irradiation
- Charge distribution cleanly separated from the noise tail → S/N > 8/1

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New Type of CVD Diamond: Single Crystal CVD Diamond

Could we make a CVD diamond with improved characteristics?

- Remove the grain boundaries, defects, charge trapping etc.
- Lower operating voltage.
- Eliminate pumping.

This is single crystal CVD (scCVD) diamond: [Isberg et al., Science 297 (2002) 1670].
High quality scCVD diamond collects all the charge at $E=0.2\text{V}/\mu\text{m}$!

High quality scCVD diamond does not pump!

But…
Single Crystal CVD Diamond

But for Other Diamonds

Not that easy to make!
Single Crystal CVD Diamond

Largest scCVD Diamond:

- Began with 4mm × 4mm
- Today 7mm × 7mm
- Well on our way to 8mm × 8mm sizes!

Impurities, Defects and Dislocations: Photo-Luminescence Measurements

Left Image: High purity, no nitrogen, no dislocations.
Middle Image: Contains nitrogen - NV centre, 575 nm PL.
Right Image: Contains dislocations, broad band blue PL.

May be able to unravel the complexity of the CVD process!
Single Crystal CVD Diamond

Charge Collection Properties: Transient Current Measurements (TCT)

- Measure charge carrier properties separately for electron and holes
- Use α-source (Am241) to inject charge
  - penetration ≈ 14 μm (thickness of diamonds ≈ 470 μm)
  - use positive and negative applied voltage
- Amplify ionization current

Extracted parameters: Transit time, velocity, lifetime, space charge, pulse shape, charge.

Preliminary Results: saturated velocity \( v_e = 96 \text{ km/s} \), \( v_h = 141 \text{ km/s} \)
  lifetimes ≈ 34 ns >> transit time (charge trapping not the issue)
Applications

**CVD Diamond Used or Planned for Use in Several Fields**

- High Energy Physics
- Heavy Ion Beam Diagnostics
- Synchrotron Radiation Monitoring
- Neutron and $\alpha$ Detection

**Applications Discussed Here**

- Pixel Detectors
  - ATLAS, CMS
- Beam Monitoring
  - BaBar
  - Belle
  - ATLAS
  - CMS
Diamond Pixel Detectors

**ATLAS FE/I Pixels (Al)**
- Atlas pixel pitch $50\mu m \times 400\mu m$
- Over Metalisation: Al
- Lead-tin solder bumping at IZM in Berlin

**CMS Pixels (Ti-W)**
- CMS pixel pitch $125\mu m \times 125\mu m$
- Metalization: Ti/W
- Indium bumping at UC Davis

→ Bump bonding yield $\approx 100\%$ for both ATLAS and CMS devices

*New radiation hard chips produced this year.*
Diamond Pixel Detectors

Results from an ATLAS pixel detector

1 Chip Assembly

2x8 Chip Assembly (Module)

1 Chip IV Curve

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Diamond Pixel Detectors

Results from an ATLAS pixel detector

1 Chip Source Test (Am241)

Map of hits from TOT meas. chip 0

1 Chip Source Test (Cd109)

Map of hits from TOT meas. chip 0

Americium 241 deposits $\approx 4600e$
Cadmium 109 deposits $\approx 1600e$
Diamond Pixel Detectors

Results from an ATLAS pixel detector

1 Chip Beam Test (x-Resolution)

1 Chip Beam Test (y-Resolution)

Pitch is 50\(\mu m\) \(\times\) 400\(\mu m\)
Spatial Resolution \(\approx\) pitch/\(\sqrt{12}\)
Results from a CMS pixel detector

- Results with 200μm collection distance diamond
  - Efficiency ~ 94%
  - Spatial resolution ~ 31μm for 125μm pitch
Diamond Pixel Detectors

Results from a CMS pixel detector

Efficiency vs Pixel

- Inefficient pixels due to bump bonding and/or electronics - shown in pulser tests
- Excellent correlation between beam telescope and pixel tracker data!
Motivation:

→ Radiation monitoring crucial for Si operation/abort system of BaBar, Belle, LHC
→ Abort beams on large current spikes
→ Measure calibrated daily and integrated dose

Style:

- DC current or Slow Readout
- Requires low leakage current
- Requires small erratic dark currents
- Allows simple measuring scheme

- Single Particle Counting
- Requires fast readout (GHz range)
- Requires low noise
- Allows timing correlations

- Examples: BaBar, Belle, CMS
- Example: ATLAS
The BaBar/Belle Diamond Radiation Monitor Prototypes:

- Package must be small to fit in allocated space
- Package must be robust

Schematic View

- Ground Braid
- Kapton Insulation
- Copper Shield
- Diamond
- HV Insulation
- Au Contact
- In Solder
The BaBar/Belle Diamond Radiation Monitor Prototypes:

→ BaBar/Belle presently use silicon PIN diodes, leakage current increases 2nA/krad
→ After 100fb⁻¹ signal≈10nA, noise≈ 1-2μA
→ Large effort to keep working, BaBar PIN diodes will not last past 2005

Photo of BaBar Prototype Devices  Photo of Installed BaBar Device

BaBar device inside the silicon vertex detector.
Radiation Monitoring - Belle

The BaBar/Belle Diamond Radiation Monitor Prototypes:

Photo of Belle Prototype Device

Photo of Installed Belle Device

Belle device just outside the silicon vertex detector.
Results on Calibration in BaBar:

- In BaBar during injection relative to silicon diodes: 5.9mrad/nC (Feb)
- In BaBar during injection relative to silicon diodes: 5.8mrad/nC (Apr)
- Correlation coefficient unchanged over several months

Calibration repeatable over many months
**Data Taking in BaBar:**

System operating for 18 months in BaBar and works well!
Leakage Current in BaBar

- Diamonds have received 250kRad $^{60}$Co plus 750kRad while installed
- No observed change in leakage current ($<0.1$nA) or fluctuations (30pA)
- Data directly from BaBar SVTRAD system
- Electronic noise ($\approx 0.5$nA) subtracted off
It is observed the diamond current increases as the magnetic field goes off. This happens every time the field goes off in BaBar. The Erratic Dark Currents have been reproduced in the laboratory!
Discovery of Erratic Dark Currents

Eratic Dark Currents go away every time the magnetic field is turned on! Origin is still a mystery
Radiation Monitoring

Very Fast Time Scale (ns) in BaBar

- Use a fast amplifier to look at PIN-diode and diamond signals
- Trigger on the PIN-diode signal
- Look at fast spikes: red = diamond, black = PIN-diode

Diamond is fast enough (< 20 ns) → now used in BaBar abort system
Installation of full diamond system possible in summer 2005
The CMS Diamond Radiation Monitor Program:

- Diamond activity has begun!
- Test beam emulating beam accident - unsynchronised beam abort - $10^{12}$ protons lost in 260 ns in CMS
- Worst case 100x unsynchronised beam abort over several turns - protection requires early detection
- Possible location in the CMS detector:

Simulation of a Beam Accident in CMS
The ATLAS Diamond Radiation Monitor Program:

- Diamond activity has begun!
- Time of flight measurement to distinguish collisions from background
- Located behind pixel detector forward disks in pixel support tube
- Possible ATLAS scenario:

Beam Condition Monitor in ATLAS

12ns

Time difference
CVD Diamond as Radiation Tolerant Detectors

- High Quality pCVD diamond (ccd up to 275 μm) are readily available in large sizes
  - MP signal ≈ 8000 e
  - 99% of charge distribution above 3000 e
  - Attained S/N=60/1 with 2μs shaping time; 8/1 at 25ns
- Radiation Tests show tolerance up to $2 \times 10^{15}/\text{cm}^2$
  - Using trackers allows a correlation between S/N and Resolution
    - Dark current decreases with fluence
    - Some loss of S/N with fluence
    - Resolution improves with fluence
- Present pCVD diamonds should surpass performance of silicon at around $10^{15}\text{p/cm}^2$

scCVD Diamonds May Overcome the Limitation of pCVD Material

- Full signal collection at $E<<1\text{V}/\mu\text{m}$
- Long charge lifetime
- Very little trapping- uniform detector

Many Applications Benefit from use of Diamond

- Beam Monitoring Now - BaBar, Belle
- Strip or Pixel detectors for the future
**Future Plans for RD42**

- **Charge Collection**
  Continue research program to improve pCVD material:
  - collection distance $\rightarrow 300\mu$m ($Q = 10,800e$)
  - improved uniformity
  - identification of trapping centers
  Begin research program on scCVD diamond

- **Radiation Hardness of Diamond Trackers and Pixel Detectors**
  Continue tracker irradiations this year, add pixel irradiations
  - With Protons:
    - $5 \times 10^{15}$/cm$^2$ $\rightarrow$ Now
  - With Pions:
    - $5 \times 10^{15}$/cm$^2$

- **Beam Tests with Diamond Trackers and Pixel Detectors**
  - trackers with intermediate strips, SCTA128 electronics
  - pixel detectors with ATLAS and CMS radhard electronics now available!
  - construct the first full ATLAS diamond pixel module

- **Material Research**
  - Florence, OSU, Paris, Rome