Non-Silicon Solid State Detectors

Harris Kagan
Ohio State University

42nd INFN Eloisatron Workshop
Sep 29, 2003 - Erice, Italy

Outline of the Talk

- Introduction
- Status of Diamond Research
- Status of SiC Research
- Radiation Monitoring - a new application
- The Future
- Summary
Motivation: Tracking Devices Close to Interaction Region of Experiments

LHC + SLHC Issues:

→ Inner tracking layers must survive!
→ Inner tracking layers must provide high precision tracking to tag b, t, Higgs, …
→ Annual replacement of inner layers perhaps?

Material Properties:

• Radiation hardness
• Low dielectric constant → low capacitance
• Low leakage current → low readout noise
• Room temperature operation, Fast signal collection time → no cooling

Material Presented Here:

• Chemical Vapor Deposition (CVD) Diamond
• Silicon Carbide

Reference → http://rd42.web.cern.ch/RD42
→ http://rd50.web.cern.ch/RD50
# 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>$10^1$</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>
</tr>
<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>
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:

- Metalization was typically Cr/Au or Ti/Au or Ti/W → new
- Polycrystalline CVD diamond typically “pumps” by a factor of 1.5-1.8
- Usually operate at 1V/µm → drift velocity saturated
- Test Procedure: dot → strip → pixel
Diamond

Growth side of a recent polycrystalline CVD (pCVD) diamond.

(Courtesy of Element Six)
In 2000 RD42 entered into a Research Program with Element Six to increase the charge collected from pCVD diamond.

**Latest Diamonds Measured with a $^{90}\text{Sr}$ Source:**

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

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

The Research program worked!
Diamond

History of Diamond Progress

Charge Collection in DeBeers CVD Diamond

Collection Distance (microns)

Time (year)

RD42 Goal

Non-Silicon Solid State Detectors (page 8)
Recent pCVD diamond wafer ready for test:
**CERN Testbeam Setup for Diamond Telescope:**

- 4 diamond strips in frame 1
- 3 diamond strips in frame 2
- Plastic scintillation trigger
- Pion beam 100 GeV/c
- Direction of strips: H=horizontal, V=vertical
- 7 planes of CVD diamond strip sensors each 2cm × 2cm
- 50μm pitch, no intermediate strips → new metalisation procedure
- 2 additional diamond strip sensors for test
- Several silicon sensors for cross checks
- Strip Electronics (2 μsec) → ENC ≈ 100e + 14e/pF
Diamond - Tracking Studies

Photograph of Two Planes of the Telescope:
Diamond - Tracking Studies

PH Distribution on each Strip

Residual versus Track Position

- 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 - Tracking Studies

Residuals

Diamond Detector Plane
CDS-83-P1

Residuals perpendicular to Strips

Residuals along Strips

Diamond Detector Plane
CDS-83-P1

CDS-83-P1
Nent = 23513
Mean x = -0.965
Mean y = 1494
RMS x = 20.33
RMS y = 1867
Integ = 2.04e+04

CDS-83-P1
Nent = 23513
Mean x = -0.9702
Mean y = 190.9
RMS x = 20.31
RMS y = 1906
Integ = 2.039e+04
Next advance → take advantage of charge sharing:

Use intermediate strips to force charge sharing.
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 → $S/N > 8/1$
- Efficiency will be measured in test beams at 40 MHz clock rate
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 a CMS pixel detector

- Results with 200\(\mu m\) collection distance diamond
  
  Efficiency \(\sim 94\%
  
  Spatial resolution \(\sim 31\mu m\) for 125\(\mu m\) 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!
Diamond Radiation Hardness Studies with Trackers

Proton Irradiation Studies with Trackers:

Signal to Noise

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

Resolution

- Signal from Irradiated Diamond Tracker
- Resolution improves at $2 \times 10^{15}/\text{cm}^2$
Pion Irradiation Studies with Trackers:

Signal to Noise

- Dark current decreases with fluence
- 50% loss of S/N at $2.9 \times 10^{15}/\text{cm}^2$
- Resolution improves 25% at $2.9 \times 10^{15}/\text{cm}^2$
Diamond Future: Single Crystal CVD Diamond

Could we make a CVD diamond with improved characteristics?

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

This is single crystal CVD (scCVD) diamond: [Isberg et al., Science 297 (2002) 1670].

![Graph showing signal size (electrons) vs. number per 400 electrons.](image)
High quality scCVD diamond collects all the charge at $E=0.2V/\mu$!
High quality scCVD diamond does not pump!
Structures in 4H-SiC:

The properties of silicon carbide are in some sense the geometric mean between silicon and diamond. As a result one hopes to take advantage of the strengths of both. Two types of SiC structures have been studied:

In Semi-insulating material the charge collection depends on native defects; Epitaxial material has low native defects but only exists in thin layers.
Characterization of SiC:

Source Setup

- Source: $^{90}\text{Sr}$, $0.1\text{mCi}$
- S+PM trigger
- Noise = $300e + 10e/\text{pF}$
- Amptek
- Acquisition system

Graph showing noise vs. $C(\mu\text{F})$.

42nd INFN Eloisatron Workshop
Sep 29, 2003 - Erice, Italy

Non-Silicon Solid State Detectors (page 25)

Harris Kagan
Ohio State University
Semi-insulating SiC works but has problems with defects, full charge collection and stability.
Silicon Carbide

Charge Distributions from Epitaxial 4H-SiC:

- circular Schottky contact
  \( \text{Ni}_2\text{Si} \phi = 1.5 \text{ mm} \)

- \( n \), 4H – SiC, 40 \( \pm \) 2 \( \mu \)m
  epitaxial 4H-SiC

- \( n^+ \), 4H – SiC, 360 \( \mu \)m
  substrate

- Ohmic contact -
  \( Ti/Pt/Au \)

Signal to Noise of 7:1 attained with Epitaxial SiC. Signal just separated from the pedestal.
Silicon Carbide

Charge Distributions from Epitaxial 4H-SiC:

Epitaxial SiC has been shown for thin layers to collect all the charge at electric fields of \( \sim 1.5 \text{V/}\mu\text{m} \).
Motivation:

- Radiation monitoring crucial for silicon operation/abort system
- Abort beams on large current spikes
- Measure calibrated daily and integrated dose
- 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/Belle PIN diodes will not last past 2004-05
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:

Photo of Belle Prototype Device

Photo of Packaged Belle Prototype
The BaBar/Belle Diamond Radiation Monitor Prototypes:

BaBar device inside the silicon vertex detector.
Belle device just outside the silicon vertex detector.
The CMS Diamond Radiation Monitor Program:

- Diamond activity has begun!
- Test beam emulating beam accident in Autumn 2003
- Possible location in the CMS detector:

Simulation of a Beam Accident in CMS
Results on Calibration in BaBar:

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

Calibration repeatable but so far limited by systematics
Data Taking in BaBar:

System operating for 4 months in BaBar and works well!
Leakage Current in BaBar

- Diamonds have received 250kRad $^{60}$Co plus 250kRad while installed
- No observed change in leakage current ($<0.1\text{nA}$) or fluctuations (30pA)
- Data directly from BaBar SVTRAD system
- Electronic noise ($\approx 0.5\text{nA}$) subtracted off

![Graphs showing leakage current changes over time](image-url)
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 for Fast Abort
An attempt at final packaging

Ceramic Package
The Future

- Diamond and silicon carbide have very promising futures.
- Diamond work is being pursued by RD42 pCVD → scCVD.
- SiC work is being pursued by RD50 epi layers → 100μm.
- Present pCVD diamonds should surpass the performance of present silicon at around $10^{15}$ p/cm$^2$.
- Semi-insulating SiC will require lots of engineering.

![Graph](chart.png)

Data: Gianluigi Capea; 1st Workshop on Radiation hard semiconductor devices for high luminosity colliders; CERN; 28-30 November 2002.
Summary

- **Charge Collection in Diamond**
  - 270 $\mu$m collection distance diamond attained in pCVD research contract
  - MP signal $\approx 8000$ $e$
  - 99% of charge distribution above 3000 $e$
  - Attained S/N=60/1 with 2$\mu$s shaping time; 8/1 at 25ns
  - FWHM/MP $\sim 0.95$ – Working with manufacturers to increase uniformity
  - This diamond process now in production reactors
  - Single crystal CVD diamond is here: $>450$ $\mu$m collection distance attained
  - MP signal $\approx 13000$ $e$
  - 99% of charge distribution above 10000 $e$
  - FWHM/MP $\sim 0.30$

- **Charge Collection in Silicon Carbide**
  - 40 $\mu$m collection distance epitaxial SiC attained
  - Full charge collection at $E \sim 1.5V/\mu$m
  - Attained S/N of 7/1 with 2$\mu$s shaping time using a source
  - Wafer diameters up to 3 cm and thicknesses up to 100$\mu$m soon
  - Tracking devices now being fabricated
Summary

- **Radiation Hardness of Large Bandgap Semiconductors**
  - 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
  - Tests must be repeated with more trackers and latest pCVD and scCVD diamonds and Epitaxial 4H-SiC

- **Radiation Monitoring**
  - Successfully tested BaBar and Belle devices
  - CMS performing tests this summer

Radiation monitoring should lead to the development of the next level radiation hard devices
Future Plans for RD42

- **Charge Collection**
  Continue research program to improve pCVD material:
  - collection distance → 300µm ($\bar{Q} = 10,800e$)
  - 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$^2$
  With Pions:
  - $5 \times 10^{15}$/cm$^2$
  With Neutrons:
  - $5 \times 10^{15}$/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
Goals: Define optimal materials and device structures to ensure best radiation tolerance.

- **Defect Engineering of Si**
  - Oxygen, Oxygen dimmers, etc

- **New Materials**
  - SiC, GaN

- **New Geometries**
  - 3D, thin detectors

- **Defect Modeling and Device Simulation**

Detectors should (soon) be able to handle the highest luminosities of the SLHC!