Recent Developments in Diamond Tracking Devices

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Outline of the Talk
✦ Introduction
✦ Tracking Studies
✦ Diamond Pixel Detectors
✦ Radiation Hardness Studies
✦ Radiation Monitoring - a new application
✦ Summary and RD42 Plans
Institutes from HEP, Heavy Ion Physics, and Solid State Physics
Introduction

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?

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

Tracking Detector Implementation:
- Based on Chemical Vapor Deposition (CVD) Diamond
- Material goes Beyond Silicon in Radiation Hardness
- Signal Size and Uniformity?
- Performance of Trackers?
- Pixel Detector Performance?
- Radiation Hardness?

Reference → http://rd42.web.cern.ch/RD42
**Characterization of Diamond:**

**Signal formation**

- $Q = \frac{d}{t} Q_0$  
  where $d = \text{collection distance} = \text{distance e-h pair move apart}$

- $d = (\mu_e \tau_e + \mu_h \tau_h)E$

- $d = \mu E \tau$

  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
Introduction

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

(Courtesy of Element Six)
Introduction

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

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

- System Gain = 124 $e$/mV
- $Q_{MP} = 62$mV = 7600$e$
- Mean Charge = 79mV = 9800$e$
- Source data well separated from 0
- Collection Distance now 275$\mu$m
- Most Probable Charge now $\approx$ 8000$e$
- 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!*
Introduction

History of Diamond Progress

Charge Collection in DeBeers CVD Diamond

Collection Distance (microns)

Time (year)

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Recent pCVD diamond wafer ready for test:
**Recent Tracking Studies**

**CERN Testbeam Setup for Diamond Telescope:**

- **100 GeV/c pion/muon beam**
- **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**
Recent Tracking Studies

Photograph of Two Planes of the Telescope:
Recent Tracking Studies

**PH Distribution on each Strip**

**Diamond Tracker CDS-90, Signal Charge on Strips**

![Graph showing signal charge distribution on strips]

**Residual versus Track Position**

**Diamond, 2-Strip Non-Linear Eta Residuals**

![Graph showing residual distribution between two strips]

- 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 $\sim 6500 \ e$
Recent Tracking Studies

Residuals

Residuals perpendicular to Strips

Diamond Detector Plane
CDS-83-P1

\[ \text{Residuals} = \mu \times \text{entries per 120 entries} \]

\[ \begin{align*}
\text{Mean } x & = 0.9702 \\
\text{Mean } y & = 190.9 \\
\text{RMS } x & = 20.31 \\
\text{RMS } y & = 1906 \\
\integ & = 2.039 \times 10^4
\end{align*} \]

Residuals along Strips

Diamond Detector Plane
CDS-83-P1

\[ \text{Residuals} = \mu \times \text{entries per 120 entries} \]

\[ \begin{align*}
\text{Mean } x & = 0.965 \\
\text{Mean } y & = 1494 \\
\text{RMS } x & = 20.33 \\
\text{RMS } y & = 1867 \\
\integ & = 2.04 \times 10^4
\end{align*} \]
Next advance → take advantage of charge sharing:

Use intermediate strips to force charge sharing.
Recent Tracking Studies

Radiation Hard Diamond Tracking Modules:

- Large (2cm \times 4\text{cm}) Module constructed with new metalisation
- Fully radiation hard SCTA128 electronics $\rightarrow$ 25ns peaking time
- Tested in a $^{90}\text{Sr}$ $\rightarrow$ ready for beam test and irradiation
- Charge distribution cleanly separated from the noise tail $\rightarrow$ 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.*
Results from an ATLAS pixel detector

Spatial Resolution – Short Direction

Spatial Resolution – Long Direction

✦ Excellent correlation between beam telescope and pixel tracker data!
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

- Diamond CDS-69 at 0.9 V/µm
  - Before irradiation: mean 57, most prob. 41, FWHM 54
  - After 1E15 protons/cm$^2$: mean 49, most prob. 35, FWHM 41
  - After 2.2E15 protons/cm$^2$ and re-metalization: mean 47, most prob. 35, FWHM 36

- Residual Distributions, Proton Irradiated Diamond
  - CDS-69 before irradiation: $\sigma = 11.5$ µm
  - After 1E15 p/cm$^2$: $\sigma = 9.1$ µm
  - After 2.2E15 p/cm$^2$ and re-metalization: $\sigma = 7.4$ µm

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Recent Developments in Diamond Tracking Devices (page 18)
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Radiation Hardness Studies with Trackers

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 $2.9 \times 10^{15} / \text{cm}^2$
The 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].
HV characteristics

![scCVD HV Curve](chart.png)
Radiation Monitoring - A New Application

Motivation:

→ SVT monitoring crucial for silicon operation/abort system
→ Abort beams on large current spikes
→ Measure calibrated daily and integrated dose
→ Presently use silicon PIN diodes at 50V, leakage current increases 2nA/krad
→ After $100\text{fb}^{-1}$ signal $\approx 10\text{nA}$, noise $\approx 1-2\mu\text{A}$
→ Large effort to keep working, system will not last past 2004-05
The BaBar Diamond Radiation Monitor Prototypes:

✦ Package must be small to fit in allocated space
✦ Package must be robust
✦ Package of choice - shown below

Schematic View

Photo of Installed Device
Radiation Monitoring

Calibration:

✦ 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
Radiation Monitoring

Data Taking:

System operating for 4 months and works well!
**Radiation Monitoring**

**Leakage Current**

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

![Graphs showing leakage current over time](image-url)
Radiation Monitoring

**Very Fast Time Scale (ns)**

- 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
Summary

✦ Charge Collection
  270 $\mu$m collection distance diamond attained in pCVD research contract
  MP signal $\approx 8000$ $e$
  99% of charge distribution above 3000 $e$
  FWHM/MP $\approx 0.95$ – 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 $\approx 0.30$

✦ Tracking Results
  Operated a 7 plane telescope with 50 $\mu$m pitch detectors
  Attained high efficiency and tracking precision of 10-20 $\mu$m
  A rad-hard module with DMILL electronics was constructed with S/N=8/1
  Source tests indicate high efficiency at 40 MHz
  Beam test and irradiation → this summer!
  Constructed first diamond detector with intermediate strips → test this July!
Summary

✦ **Radiation Hardness of Diamond Trackers**
   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
   All tests will be repeated with more trackers and the latest pCVD and scCVD diamonds

✦ **Diamond Pixel Detectors**
   Successfully tested ATLAS and CMS pixel patterns
   - Bump bonding yield \( \approx 100 \% \)
   - Excellent correlation between telescope and pixel data
   - Reasonable spatial resolution attained
   Radiation hard chips have arrived and work
   Single chip and module tests this summer

More progress this Summer
Future Plans for RD42

✦ **Charge Collection**

Continue research program to improve pCVD material:

- collection distance $\rightarrow 300 \mu m$ ($\bar{Q} = 10,800e$)
- $\rightarrow$ improved uniformity
- $\rightarrow$ 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:

$\rightarrow 5 \times 10^{15} / \text{cm}^2$

With Pions:

$\rightarrow 5 \times 10^{15} / \text{cm}^2$

With Neutrons:

$\rightarrow 5 \times 10^{15} / \text{cm}^2$

✦ **Beam Tests with Diamond Trackers and Pixel Detectors**

$\rightarrow$ trackers with intermediate strips, SCTA128 electronics

$\rightarrow$ pixel detectors with ATLAS and CMS radhard electronics now available!

$\rightarrow$ construct the first full ATLAS diamond pixel module

✦ **Material Research**

$\rightarrow$ Florence, OSU, Paris, Rome