ATLAS Diamond Pixel Modules

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for the RD42 Collaboration
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Outline of the Talk

✦ Introduction - Diamond Properties
✦ Radiation Hardness Studies with Trackers
✦ The First ATLAS Diamond Pixel Module
✦ The ATLAS Diamond Beam Conditions Monitor
✦ Summary
The RD42 Collaboration

Goal: Development of Diamond as a Detector Material


◊ Spokespersons

Institutes from HEP, Heavy Ion Physics, and Solid State Physics

Still growing - new groups joined RD42 last year:

DESY-Zeuthen, St. Petersburg, Fachhochschule für Wirtschaft und Technik-Vienna
**Introduction**

**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?

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![Graph showing total fluence $\Phi_{eq}$ for different regions at ATLAS and other experiments](image-url)

**SUPER - LHC (5 years, 2500 fb⁻¹)**

- Pixel (?)
- Ministrip (?)
- Macropixel (?)
- Total fluence $\Phi_{eq}$
- Neutrons $\Phi_{eq}$
- Pions $\Phi_{eq}$
- Other charged hadrons $\Phi_{eq}$

**ATLAS Pixel**

**ATLAS SCT - barrel (microstrip detectors)**
Motivation: Tracking Devices Close to Interaction Region of Experiments

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
**Characterization of Diamond:**

**Signal formation**

![Diagram of signal formation with charged particle, electrodes, diamond, e-h creation, amplifier, and collection distance](image)

- $Q = \frac{d}{t} Q_0$ 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 $\tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h}$

for the RD42 Collaboration

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Properties - Polycrystalline CVD Diamond

pCVD Diamond Measured with a $^{90}$Sr Source:

✦ Contacts on both sides - structures from $\mu$m to cm
✦ Usually operate at $E=1V/\mu$m $\rightarrow$ drift velocity saturated
✦ Test Procedure: dot $\rightarrow$ strip $\rightarrow$ pixel on same diamond!

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

✦ Source data well separated from 0
✦ Collection Distance now $\approx 300\mu$m
✦ Most Probable Charge now $\approx 8000e$
✦ 99% of PH distribution above 3000$e$
✦ $FWHM/MP \approx 0.95$ — Si has $\approx 0.5$
✦ This diamond available in large sizes
Recent Polycrystalline CVD Diamond

Left: Recent pCVD wafer ready for test - Cr/Au dots are 1 cm apart
Right: Collection distance from a dot in the pCVD wafer

Wafers can be grown >12 cm diameter, >2 mm thickness.
Collection distance of this wafer 200μm (edge) to 310μm (center).
Recently Single Crystal CVD (scCVD) Diamond has been Fabricated

RD42 has a research contract with Element Six to develop this material.

scCVD diamond can be grown $\approx 10 \text{ mm} \times 10\text{mm}$, $>1 \text{ mm}$ thickness. Largest scCVD diamond grown $\approx 14 \text{ mm} \times 14 \text{ mm}$.
Properties - Single Crystal CVD Diamond

scCVD Diamond Measured with a $^{90}\text{Sr}$ Source:

Pulse height spectrum of various scCVD diamonds ($t=210, 320, 435, 685 \, \mu m$)
High quality scCVD diamond can collect full charge for thickness $800\mu m$

Width of landau distribution is $\approx 1/2$ that of silicon, $\approx 1/3$ that of pCVD diamond
High quality scCVD diamond collects all the charge at $E=0.2\text{V}/\mu$!

High quality scCVD diamond does not pump!

But...
Properties - Single Crystal CVD Diamond

Along the way

Not that easy to make!
Properties - 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.

**Properties - Single Crystal CVD Diamond**

**Drift Velocity and Lifetime:**

- Average drift velocity for electrons and holes: \( v_{e,h} = \frac{d}{t_c} \)
- Extract \( \mu_0 \) and saturation velocity: \( v = \frac{\mu_0 E}{1 + \mu_0 E / v_s} \)
- For this sample:
  - \( \mu_{0e} = 1714 \, \text{cm}^2/\text{Vs} \)
  - \( \mu_{0h} = 2064 \, \text{cm}^2/\text{Vs} \)
  - \( v_{se} = 0.96 \times 10^7 \, \text{cm/s} = 96 \, \text{km/s} \)
  - \( v_{sh} = 1.41 \times 10^7 \, \text{cm/s} = 141 \, \text{km/s} \)
- From the drift velocity deduce the lifetimes \( > 35 \, \text{ns} \rightarrow >> \) transit time so charge trapping not the issue
Radiation Hardness Studies with pCVD Trackers

Diamond Proton Irradiation - previously:

Signal to Noise

Diamond CDS-69 at 0.9 V/µm

- before irradiation
  - mean 57, most prob. 41
  - FWHM 54
- after 1 E15 protons/cm²
  - mean 49, most prob. 35
  - FWHM 41
- after 2.2 E15 protons/cm² and re-metalization
  - mean 47, most prob. 35
  - FWHM 36

Resolution

Residual Distributions, Proton Irradiated Diamond

- before irradiation
  - σ = 11.5 µm
- after 1E15 p/cm²
  - σ = 9.1 µm
- after 2.2 E15 p/cm² and re-metalization
  - σ = 7.4 µm

- Data taken over a period of 2 years
- Dark current decreases with fluence
- 15% loss of S/N at $2.2 \times 10^{15}$/cm²
- Resolution improves 35% at $2.2 \times 10^{15}$/cm²
Radiation Hardness Studies with pCVD Trackers

Proton Irradiation - new:

Pulse Height

Summary

CD113 Charge - Before, After Irradiation

Preliminary Summary of Proton Irradiation

Left: Pulse height distributions before (blue curve) and after (red curve) the irradiation to $18 \times 10^{15}$ p/cm$^2$ ($\sim$500Mrad)

Right: Summary of proton irradiation results for pCVD diamond at fixed V
Results from a single chip ATLAS pixel detector - previously:

1 Chip Assembly

Cadmium 109 deposits ≈ 1600e
Beamtest results from a single chip ATLAS pixel detector

1 Chip Beam Test (x-Resolution)

1 Chip Beam Test (y-Resolution)

Pitch is 50μm × 400μm
Spatial Resolution 12μm; Efficiency 98%
Various stages of making a module
The ATLAS Diamond Pixel Module Test was cut short (4 hrs).
Excellent start for a 4 hr run.
Module and Telescope were moved to DESY for testing.
The ATLAS Diamond Pixel Module tested at DESY using 4-6 GeV electrons.
The full diamond pixel module at DESY - Hitmap

Hitmap looks good - can easily see scintillator edge.
Analysis in progress - preliminary results shown here.
Problems with low energy electrons, multiple scattering, etc.
Telescope Resolution at CERN and DESY

Telescope resolution CERN $\sim 7\mu m$; DESY $\sim 37\mu m$. 
Results: Noise $\sim 137e$, Mean Threshold $1454e$, Threshold Spread $\sim 25e$. 
Excellent correlation with telescope
Resolution dominated by multiple scattering.
Preliminary residual $\sim 23\mu m$ - includes contribution from multiple scattering.
Preliminary efficiency >97.5%
- still need to correct for dead or missing channels.
- still need to do correct tracking.
**Motivation:**

→ Radiation monitoring crucial for Si operation/abort system
→ 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, CDF, CMS
✦ Example: ATLAS
Idea: Time of flight measurement to distinguish collisions from background
Testbeam Results:

Atlas BCM prototype module
double diamond assembly
500 MHz FE electronics

1.9 ns FWHM
Results: Attained >8/1 S/N

Fig 6. Normalized signal amplitude distribution (hatched histogram) in comparison to the noise distribution (open histogram) for the double-diamond assembly in the test beam.
Further Progress in Charge Collection

- 300 μm collection distance pCVD diamond attained in in production reactors
- pCVD FWHM/MP ~ 0.95 – Working with manufacturers to increase uniformity
- Single Crystal diamonds look attractive – Full charge collection, FWHM/MP~0.3
- RD42 has scCVD research contract in operation until 2006

Radiation Hardness of Diamond Trackers

- Using trackers allows a correlation between S/N and Resolution
- With Protons:
  - Dark current decreases with fluence
  - 15% loss of S/N at $2.2 \times 10^{15} \text{/cm}^2$, 25% signal at $20.0 \times 10^{15} \text{/cm}^2$
  - Resolution improves 35% at $2.2 \times 10^{15} \text{/cm}^2$

Diamond Pixel Detectors

- Successfully constructed a complete ATLAS diamond module
- Excellent correlation between telescope and pixel data
  - Noise, Threshold, Efficiency, Resolution look good

Beam Conditions Monitoring

- Successful application in BaBar, Belle, CDF → ATLAS