Diamond Pixel Modules

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for the RD42 Collaboration

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Outline of the Talk

✦ Introduction
✦ Radiation Hardness Studies with Trackers
✦ Pixel Module Studies
✦ Material and Manufacturing Developments
✦ Summary
Motivation: Tracking Devices Close to Interaction Region of Experiments at the SLHC

Scale is $\sim 10^{16} \text{ cm}^{-2}$ → Annual replacement of inner layers perhaps? → No
Motivation: Tracking Devices Close to Interaction Region of Experiments

Look for a Material with Certain Properties:

✦ Radiation hardness (no frequent replacements)
✦ Low dielectric constant $\rightarrow$ low capacitance
✦ Low leakage current $\rightarrow$ low readout noise
✦ Good insulating properties $\rightarrow$ large active area
✦ Room temperature operation, Fast signal collection time $\rightarrow$ no cooling

Presented Here:

✦ Radiation hardness tests of the highest quality pCVD and scCVD diamond
✦ Beam tests results to characterize quality
✦ Pixel Module preparation
✦ Manufacturing Developments
✦ See also talk by A. Gorišek - ATLAS Diamond BCM and BLM

♦ Reference $\rightarrow$ http://rd42.web.cern.ch/RD42
♦ Diamonds supplied by/in collaboration with Diamond Detector Ltd./Element Six Ltd.
Radiation Hardness

- binding energy
- displacement energy
- elastic, inelastic, total cross section
Radiation Hardness Studies with pCVD and scCVD Trackers

pCVD Diamond Trackers:

- Patterning the diamond → pads, strips, pixels!
- Successfully made double-sided devices; could be made edgeless.
- Use trackers (strip or pixel) in radiation studies - charge and position.
Polycrystalline CVD (pCVD) Diamond irradiations at $1.4 \times 10^{15}\text{p}/\text{cm}^2$

- Application is pixel detectors
- At LHC (FE-I3), Thresholds are $\sim \text{noise}(1400e) + \text{overdrive}(800e)$
- PH distributions look good after irradiation of $1.4 \times 10^{15}\text{p}/\text{cm}^2$. 
**Single Crystal CVD (scCVD) Diamond Irradiations at $1.5 \times 10^{15}$**

PH distributions look narrow before and after irradiation.

PH distributions after $1.5 \times 10^{15}$ p/cm$^2 \rightarrow \epsilon > 99\%$. 

<table>
<thead>
<tr>
<th>Clustered Landau Distribution minus Multiple Cluster Events</th>
<th>Mean</th>
<th>RMS</th>
<th>Constant</th>
<th>MPV</th>
<th>Sigma</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS 23849</td>
<td>1393</td>
<td>383.7</td>
<td>293.5 ± 3.0</td>
<td>1178 ± 1.1</td>
<td>79.18 ± 0.65</td>
</tr>
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<tr>
<td>PS 15611</td>
<td>837.3</td>
<td>284.2</td>
<td>276.7 ± 3.7</td>
<td>710.4 ± 1.0</td>
<td>52.82 ± 0.58</td>
</tr>
</tbody>
</table>
24GeV Proton Irradiation Summary 2009:

- **Red Data**: strip scCVD (x-shifted by -3.8)
- **Open Red**: pixel scCVD (x-shifted by -3.2)
- **Blue Data**: strip pCVD
- **Black data**: new CD113
- **Black curve**: \( \frac{1}{ccd} = \frac{1}{ccd_0} + k \phi \)

New results from pixel modules - diamond and electronics irradiated!

Irradiation results up to \(1.8 \times 10^{16} \text{ p/cm}^2\) (\(~500\text{Mrad}\)).

- pCVD and scCVD diamond follow the same damage curve:
  \( \frac{1}{ccd} = \frac{1}{ccd_0} + k \phi \).
Work in Progress 2009:

- Irradiations already performed awaiting test beam:
  - Sendai - $1 \times 10^{16}$ 70MeV protons/cm$^2$
  - Ljubljana - $1 \times 10^{16}$ neutrons/cm$^2$

- Irradiations in progress:
  - Karlsruhe - 25MeV protons

In diamond 70MeV protons have $\sim 3x$ larger damage constant than 24GeV
pCVD and scCVD Pixel Detectors

- signal
- noise, threshold, overdrive
- charge sharing, signal over threshold
Recall: Full 16 Chip and 1 chip ATLAS diamond pixel modules

- Single chip and full modules bump-bonded at IZM (Berlin), constructed and tested in Bonn
- Operating parameters (FE-I3): Peaking Time 22ns, Noise $140\text{e}$, Threshold $1450-1550\text{e}$, Threshold Spread $25\text{e}$, Overdrive $800\text{e}$
Results: Bare Noise $\sim 140e$, Bare Mean Threshold $\sim 1500e$, Bare Threshold Spread $\sim 25e$. 
ATLAS pCVD Diamond Pixel Detectors

The full ATLAS diamond pixel module - Noise, Threshold

Results: Noise $\sim 137e$, Mean Threshold $1454e$, Threshold Spread $\sim 25e$. Noise, threshold, threshold spread do not change from bare chip.

→ Advantage of low capacitance, no leakage current
Recall: Full ATLAS diamond pixel module - Efficiency, Resolution

- Excellent correlation with telescope, efficiency > 97%
- Residual ~ 18µm - remove telescope tracking contribution → 14µm.
New: First Full Diamond Pixel Module Made in Industry

- Begin with a tested raw diamond
- Clean → IZM in Berlin
- Receive finished, metalised, bump-bonded module!
New: First Full Diamond Pixel Module Made in Industry

Diamond sensor pixel metallisation

Status after electroplating of pad metallisation and lithography for pixel metallisation patterning

result after pixel metallisation patterning
The First scCVD ATLAS diamond pixel detector

- The hitmap plotted for all scintillation triggers with trigger in telescope.
- The raw hitmap looks good - ~1 dead pixel
:: ATLAS scCVD Diamond Pixel Detectors

Last Year: The First scCVD ATLAS diamond pixel detector - Charge Sharing

✦ Charge sharing as expected

Cluster size

\[ S_{\text{seed}} / \sum S_{\text{cluster}} \]
New This Year: Cluster Signal

- As voltage is raised → more 1-hit clusters
- Larger drift speed → less lateral diffusion
- Cluster signal as expected
New This Year: Spatial Resolution (1-pixel and 2-pixel $\eta$)

- Plot contains all scintillator triggers with “track” trigger in telescope
- Diamond pixel resolution 8.9 $\mu$m for normal incidence
- Lower threshold $\rightarrow$ more charge sharing observed $\rightarrow$ better spatial resolution.
New This Year: Irradiated scCVD Diamond Pixel Module

TOT comparison (Oct.06 – Jul.08)

- Full module irradiated - electronics and diamond.
- Data falls on expected damage curve!
Next Steps

On the basis of these results ATLAS officially approved Upgrade R&D on Diamond Pixel Detectors

Proposing Institutes:

✦ Carleton University (Canada)
✦ University of Toronto (Canada)
✦ University of Bonn (Germany)
✦ Jožef Stefan Institute (Slovenia)
✦ CERN
✦ Ohio State University (US)

✦ Submitted May 2007
✦ Approved Feb 2008
✦ Technical Decision 2010

Reference → ATU-RD-MN-0012, EDMS ID: 903424
Next Steps Checklist

✦ Re-Test ATLAS Pixel Module at CERN - Done
  Data analysis → Thesis

✦ Irradiate scCVD and pCVD diamonds - Done
  pCVD to $2 \times 10^{16}$ and scCVD to $2 \times 10^{15}$ p/cm$^2$

✦ Irradiate scCVD pixel modules (chip and detector) - Done
  Up to $\sim 10^{15}$

✦ Move Metalization to Industry - Done
  Cleaner facilities
  Metalization and bumping done at one facility
  This should be easy ... IZM is interested

✦ Produce 5-10 Modules - ongoing
  Evaluate production process
  Full measure of efficiency, noise, etc.

✦ Test of Modules - beginning
  Beam test of production modules
  Radiation hardness test of production modules

→ Progress on many fronts!!!
CVD Diamond Material Status

- collection distance
- polycrystalline, single crystal
- new manufacturers
**Material Status - Polycrystalline CVD Diamond**

**pCVD Material: pCVD Diamond Measured with a $^{90}\text{Sr}$ Source**

- Contacts on both sides - structures from $\mu$m to cm
- Usually operate at $E=1$-$2V/\mu m$
- Test Procedure: dot $\rightarrow$ strip $\rightarrow$ pixel on same diamond!

![Graph 1](image1.png)

- $Q_{MP} = 8500$-$9000e$
- Mean Charge $= 11300e$

![Graph 2](image2.png)

- Source data well separated from 0
- Collection Distance now $\approx 300\mu m$
- Most Probable Charge now $\approx 9000e$
- 99% of PH distribution above $4000e$
- FWHM/MP $\approx 0.95$ — Si has $\approx 0.5$
- Six wafers grown with this quality
Recent Polycrystalline CVD Diamond

Recent pCVD wafers ready for test - Cr/Au dots are 1 cm apart

✦ New wafers continually being produced.
✦ Wafer collection distance now typically 250\(\mu\)m (edge) to 310\(\mu\)m (center).
✦ Contract for material with ccd > 275\(\mu\)m \(\rightarrow\) 300\(\mu\)m.
✦ Samples available by contacting DDL
RD42 continues to develop and test this material.

scCVD diamond can be grown $\approx 10 \text{ mm} \times 10\text{mm}$, $>1 \text{ mm}$ thickness.
Largest scCVD diamond grown $\approx 14 \text{ mm} \times 14\text{ mm}$.
First results from irradiated scCVD pixel module.
**Material Status: Additional Manufacturers**

**Status:**
RD42 has begun working with two companies (Germany, US) to develop detector grade diamond material.

- First samples from companies show charge collection distance $\sim 100 \mu m$
- RD42 is working with these manufacturers on both pCVD and scCVD
✦ **Radiation Hardness of Diamond Trackers**
   Using trackers allows a correlation between S/N and Resolution
   With Protons:
   - Dark current decreases with fluence
   - pCVD and scCVD have same damage curve

✦ **Diamond Pixel Detectors**
   Successfully tested a complete ATLAS pCVD module and scCVD module
   Five full pCVD modules in production
   Diamond R&D Approved by ATLAS for LHC Upgrade

✦ **Further Progress in Charge Collection**
   pCVD - 320 $\mu$m collection distance diamond attained in wafer growth
   pCVD - 275-325 $\mu$m collection distance for modules
   scCVD - Full charge collection, fast, large signals, Getting larger?

✦ **Beam Conditions Monitoring**
   see A. Gorišek Talk on ATLAS diamond BCM and BLM
   Application of diamond successful in BaBar, CDF, Alice, ATLAS, CMS, LHCb.
Summary

CVD Diamond Used in High Energy Physics Experiments

Summary of Diamonds in HEP Experiments

Year

Number

BaBar

CDF

ATLAS

CMS

Blue data installed; black data planned. Diamond use is on the rise!