Diamond Sensors for Future High Energy Experiments

Felix Bachmair on behalf of the RD42 collaboration
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129 Participants
Overview

- Diamond as a sensor material
  - Newest developments in chemical vapor deposition (CVD) diamonds
  - Radiation tolerance
- Overview of diamond detectors in HEP
- Latest experiences for
  - CMS PLT pilot run
  - ATLAS DBM
- 3D diamond detectors
  - Single-crystalline (sc)CVD diamond
  - Polycrystalline (p)CVD diamond
Why diamond?

- advantages of diamonds w/r/t silicon
  - large displacement energy
  - large bandgap
  - high thermal conductivity

- there are some disadvantages though
  - Large bandgap
  - Size of diamonds (scCVD)

  - Radiation hard
  - less leakage current & noise
  - less cooling, good heatspread

  - less signal
  - Material more expensive than Si
Diamond Manufacturers

- In the past diamonds via DDL from ElementSix (De Beers)
  - DDL out of business, now directly via ElementSix
- New suppliers
  - IIa-Technologies (scCVD)
  - II-VI Incorporated (pCVD)
- IIa has delivered O(10) samples for evaluation
  - committed their self to
    - Further improvement of material
    - pCVD growth
- II-VI improved quality of pCVD over the last years
  - Delivered growing number of final finished parts to CMS and ATLAS
  - Now typically deliver 275 - 300 µm collection distance
Radiation Hardness

- 24 GeV protons
- $k_\lambda = 0.62 \pm 0.07 \times 10^{-18} \mu m^{-1} cm^{-2}$
- Polycrystalline diamond sample offset by $\Phi \sim 5 \times 10^{15}$ to account for existing traps.
- Poly and single crystal diamond show consistent damage constants.

$$\lambda_{e/h} (\Phi) = \frac{\lambda_0}{1 + \lambda_0 \cdot k \cdot \Phi}$$

$e/h (\Phi) = 1+ \frac{\lambda_0}{k \Phi}$

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More high energy diamond experiments

- **CMS:**
  - BCM1F: for online background and luminosity measurements
    - 24 scCVD diamond sensors, 48 Channels
    - Fast MIP counter, trigger-less readout
  - BCM1L/BCM2L: Beam abort system
    - Based pCVD diamond sensors

- **ATLAS:**
  - BCM:
    - 4 x 2 pCVD diamonds on each side
    - Single particle counting with $\sigma = 0.7\text{ns}$.
CMS Pixel Luminosity Telescope (PLT)

- High precision bunch-by-bunch luminosity measurement with an array of eight 3-plane telescopes
  - Pilot Run: Diamond sensors
  - Final Installation: Silicon sensors
- Pilot Run while LHC Run 1 in Castor region: 14.5m from IP
  - Total exposure 20fb$^{-1}$
    - $5 \times 10^{13}$ n/cm$^2$ and $5 \times 10^{13}$ charged hadrons/cm$^2$
- In the Pilot Run:
  - Strong rate dependency for this diamonds after a small amount of irradiation
- Major effort was started to understand this issue
PSI beam test campaign

- Multiple beam tests at PSI
- Compact Si telescope based on CMS pixel chip PSI46v2
  - Scalable trigger size
  - Readout of pad detectors with Amplifier + DRS4 Evaluation board
- Testing pCVD and scCVD
  - irradiated/non-irradiated/ Pilot Run
  - Pad detectors:
    - Quick detector fabrication and turn around
    - study sensors w/o threshold effect
  - Pixel detectors:
    - Study effects of pixel threshold
    - Study effects of pixel charge sharing

<table>
<thead>
<tr>
<th>PSI</th>
<th>Paul Scherrer Institute</th>
</tr>
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<tbody>
<tr>
<td>Beamline</td>
<td>HIPA/PiM1</td>
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<tr>
<td>Beam Energy</td>
<td>250 MeV/c</td>
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<tr>
<td>Particles</td>
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<tr>
<td>Flux</td>
<td>O(1kHz/cm²) – O(10 MHz/cm²)</td>
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Pixel Results for rate studies

- Testing irradiated scCVD pixel detector
  - Using PSI46v2 readout chip
  - 5x10^{13} \text{n/cm}^2 and 5x10^{13} \text{charged hadrons/cm}^2 (PLT pilot run diamond)

- 50% drop in charge with flux
- Similar effect as seen in PLT pilot run
PAD Results for rate studies

- scCVD unirradiated and pCVD irradiated show less than few % signal variation up to O(MHz/cm²)
- scCVD irradiated with neutrons and in CMS (PLT pilot run 2012) show similar behavior:
  - ~10% drop in signal at flux > 100 kHz/cm²
- pCVD does not show a rate effect
Rate dependency summary

- Also tested irradiated/unirradiated scCVD diamonds from IIa Technology
  - Seems to show less rate dependence than E6 diamonds
- Investigation of rate dependencies is continuing with an improved readout system with
  - Faster amplifiers for PAD readout
  - Lower threshold ROC for Pixel measurements
  - Longer data taking capabilities
- Up to now:
  - **No rate dependence for pCVD diamonds** irradiated with $5 \times 10^{13}$ neutrons/cm$^2$ up to 2 MHz/cm$^2$
  - Rate dependence seems to be a growth dependent
Effect of surface treatment on a leakage current
Lessons learned – leakage current

- Observed large erratic currents for several diamonds
  - This diamonds could not hold high bias fields
  - Some scCVD diamonds were not collecting full charge @ 1V/µm
  - Different results for positive and negative polarity

Can’t go above 700V
Lesson learned – leakage current

- Surface treatment with reactive ion etching (RIE)
  - Fixing HV problems
    - More stable currents
    - Higher voltages/electric fields
  - More symmetric charge collection
  - Improving charge collection

Can go to 1000V
ATLAS Diamond Beam Monitor (DBM)

- **Purpose:**
  - Bunch-by-bunch luminosity monitor (aim <1% per BC per LB)
  - Bunch-by-bunch beam spot monitor
    - Pixelated sensors allow (limited) tracking to distinguish collision tracks from beam halo

- **Design:**
  - 4 telescope of three FE-I4 modules at $\eta \approx 3.2$ per side $\Rightarrow$ 24 modules
  - On each side
    - 3 diamond telescopes with diamonds from 2 suppliers (E6 & II-VI) bump bonded at IZM
    - 1 silicon telescope
DBM status

- Powered since early February for ATLAS cosmic/commissioning runs
  - Included in ATLAS central data-taking since mid of February
- Sensors biased at
  - 50 V (silicon telescopes)
  - 500 V (diamond telescopes)
- Thresholds tuned to 2500e for diamond
  - Plan to tune to 1500e
- New experiences with
  - bump bonding
  - Installation
Experience DBM Bump Bonding
Lessons learned – Bump bonding issues

- FE-I4 – Biggest Pixel chip ever bump bonded to a diamond
  - 26880 pixels with an active area of 341 mm$^2$
- Bump bonding of diamonds in four batches
  - Batch 1 & 4: Similar bump bond efficiencies as for silicon
  - Batch 2 & 3: Low bump bond efficiencies
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- Issues related to the persons and machines used for bonding the chips
- Able to bump bond FEI-4 readout chips to diamond with similar efficiencies as to silicon
Experience DBM Installation
Lesson learned – installation issues

- ‘Lost’ 3 DBM modules in 2 telescopes during operation
  - 1 diamond module
  - 2 Si modules

- Left modules in an unconfigured state
- Probably wire bonds broke due to high currents and magnetic field

- Investigation is in progress but definitely not a sensor related issue
3D diamond detectors
3D diamond detectors

- 3D geometry to shorten the drift distances

- For 3D geometry using a femto second laser (100fs) with a wavelength of 800 nm
  - phase change of diamond into a combination of diamond-like carbon, amorphous carbon and graphite

- Sizes:
  - Planar strip pitch 50 µm
  - 3D Cell size: 150 x 150 µm²

- Optical and resistivity measurements show a yield for micromachining columns of ~ 90 %

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3D diamond detectors

- 3 different regions on one diamond for comparison
  - Planar strip @ 500V, pitch 50 µm
  - 3D phantom @ 25V, size 150 x 150 µm²
  - 3D detector @ 25V, size 150 x 150 µm²
- Missing charge around ~9 broken readout columns
  - In agreement with other measurements
- See effects of missing bias columns
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3D diamond detectors

- Remarkable agreement between signal in 3D and planar strip geometry for a good cell region
- Full charge at lower avrg. E Field
3D pCVD diamond detectors

- 3D pCVD diamond has been tested in beam tests at CERN this summer
- Same layout/mask as for 3D scCVD diamond with Planar Strip/3D-Phantom/3D-Detector
  - Smaller yield in fabrication of columns than for scCVD
  - Smaller yield in contacting the columns with the metallization than for scCVD
- Preliminary result without calibration to electrons
  - 3D-Detector & 3D-Phantom biased @ 75V, planar strip @ 500V
  - Comparison between 3D detector and planar strip
  - Looking at single working cells
Poly 3D

- Red line: estimate for MP of full charge collection (500 µm)
- Collecting more charge than planar strip detector
- ~ 77% of Full charge collection @ 75V
- Highest charge collection ever measured for pCVD diamonds
Summary

- New diamond suppliers, IIa & II-VI, improved situation on the market
- Quality of diamonds has improved strongly over the last years
  - Now reaching 275 - 300 µm CD in pCVD diamonds
- New experiences in using diamonds on bigger scales in CMS PLT Pilot Run and Atlas DBM
  - Most problems has been understood and solved
- Rate dependency still under study,
  - seems to be growth dependent
  - We did not observed a rate dependence for pCVD diamonds
- 3D diamond detectors show a great promise
  - 3D pCVD shows 2.5x the charge of a planar pCVD strip detector at 75V.
Outlook

- Further improvement of diamond quality in cooperation with suppliers
- Continue Rate studies with improved setup
  - Faster amplifiers for PAD readout
  - Lower threshold ROC for Pixel measurements
  - Longer data taking capabilities
- Working on thinner diamond detectors
- R&D for HL-LHC: innermost layer of Tracker
- R&D on 3D devices
  - Improve fabrication of 3D device
    - Higher yield
    - Bigger detectors
  - Test different structures
  - Studies of irradiated 3D CVD diamonds
  - Measure 3D pCVD at higher bias voltages.