Radiation Hardness Studies of Polycrystalline and Single-crystal Chemical Vapor Deposition Diamond for High Luminosity Tracking Detectors

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on behalf of

CDF Diamond Group
CMS BCM group
ATLAS BCM+Pixel groups
+ RD42 Collaboration
Outline

• Update on diamond as a detector material
  – Radiation Hardness of Polycrystalline and Single Crystal Diamond

• Diamond particle detectors
  – Recent results from diamond ATLAS pixel modules

• Diamond beam condition monitoring (BCM)
  – Babar, Belle
  – CDF
  – CMS
  – ATLAS
I. Update on Diamond as a Detector Material
The Challenge

Motivation: Tracking close to interaction region
- At SLHC (~$10^{35}$/cm$^2$/s) inner tracking layers receive fluence in excess of $\Phi_{eq} \sim 10^{16}$/cm$^2$ (5 years)
- Silicon based tracker maybe good to $\sim 10^{15}$/cm$^2$ (charge trapping)
- Frequent replacement of layers?
## Properties of Diamond

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap [eV]</td>
<td>1.12</td>
<td>5.45</td>
</tr>
<tr>
<td>Electron mobility [cm$^2$/Vs]</td>
<td>1450</td>
<td>2200</td>
</tr>
<tr>
<td>Hole mobility [cm$^2$/Vs]</td>
<td>500</td>
<td>1600</td>
</tr>
<tr>
<td>Saturation velocity [cm/s]</td>
<td>$0.8 \times 10^7$</td>
<td>$2 \times 10^7$</td>
</tr>
<tr>
<td>Breakdown field [V/m]</td>
<td>$3 \times 10^5$</td>
<td>$2.2 \times 10^7$</td>
</tr>
<tr>
<td>Resistivity [$\Omega$ cm]</td>
<td>$2 \times 10^5$</td>
<td>$&gt;10^{13}$</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>11.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Displacement energy [eV]</td>
<td>13–20</td>
<td>43</td>
</tr>
<tr>
<td>e–h creation energy [eV]</td>
<td>3.6</td>
<td>13</td>
</tr>
<tr>
<td>Ave e–h pairs per MIP per $\mu$m</td>
<td>89</td>
<td>36</td>
</tr>
<tr>
<td>Charge coll. dist. [$\mu$m]</td>
<td>full</td>
<td>~250</td>
</tr>
</tbody>
</table>

- **Low $I_{\text{leakage}}$, shot noise**
- **Fast signal collection**
- **Low capacitance, noise**
- **High radiation hardness**
- **Smaller signals**
- + **High thermal conductivity:** Room temperature operation

**CERN RD42 Collaboration:**
- Development of detector grade diamond
- Industrial partner: Element Six, Ltd.

*IPRD Siena - 3 Oktober 2008  Rainer Wallny - Diamond Tracking Detectors*
CVD Diamond Production

- Columnar growth of diamond crystal
- Si or diamond substrate
- Growth speed ~ few μm/hour
- Grains grow wider from substrate side
- Recently: single crystal diamond

Grain size: ~100–150μm

Columnar structure of polycrystalline CVD diamond (SEM picture M.Bruzzi)

IPRD Siena - 3 Oktober 2008  Rainer Wallny - Diamond Tracking Detectors
Polycrystalline CVD diamond

- detector grade pCVD wafers now routinely grown >12cm diameter and >2mm thickness
- finite charge collection distance (CCD)
  - charge trapping (grain boundaries, impurities …)
  - measure $\text{CCD} = \text{thickness} \times \frac{Q_{\text{measured}}}{Q_{\text{induced}}}$
- typical CCD 250μm (edge) to 310μm (center)
- RD42 goal was 200μm
- CCD saturates at around 1 V/μm
- Typically 9800 e-h pairs in 500μm sensor
Radiation Hardness of pCVD diamond

- pCVD detectors have been built as pixel, pad, strip detectors
  - Use strip detectors for irradiation tests
    - Charge and position

- Proton irradiation:
  - Observed 15% loss of S/N at $2.2 \times 10^{15} / \text{cm}^2$

- Leakage current (~ pA) decreases with fluence

- Resolution is found to improve 35% at $2.2 \times 10^{15} / \text{cm}^2$
  - Irradiated material appears to be more ‘uniform’

- New proton irradiation:
  - Still 25% of the signal (~2500 e−) after $1.8 \times 10^{16} / \text{cm}^2$ (500 Mrad)
  - Low noise performance still affords S/N >10
Single Crystal CVD Diamond

- Development of this material in collaboration with Element Six, Ltd
- scCVD diamond has been grown to 10mm x 10 mm with >1mm thickness
- Largest grown scCVD diamond is 14 mm x 14 mm
- scCVD diamond collects full charge
  - Tested up to ~ 1mm thickness
- Full charge collection at E=0.2V/µm!
- Signal and Noise well separate
  - FWHM/MP ~ 0.3–0.5
  - 1/3 of pCVD, 1/2 of silicon
  - Lower cutoff at 75% of MP signal

\[ d=320 \, \mu m \]
\[ Q_{MP}=9500e^- \]
scCVD Diamond Proton Irradiation

Narrow pulse height distributions before and after irradiation

$$\Phi = 1.5 \times 10^{15} \text{ p/cm}^2$$

unirradiated

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Preliminary summary of proton irradiation results for pCVD and scCVD diamond @ 1V/μm up to Φ=1.8x10^{16} p/cm^2 (500 Mrad): ‘Universal’ damage curve for pCVD and scCVD: 1/ccd = 1/ccd₀ + k Φ
New Manufacturers

RD 42 has begun to work with two companies (Germany, US) to develop detector grade material

First samples show CCD ~ 100 μm
II. Diamond Detector Application:
- Pixel Detectors
ATLAS Diamond Pixel Module

• Previous tests used 1–chip (CMS and ATLAS) pCVD diamond detectors
• full 16 chip pCVD diamond ATLAS module recently built
  − Element Six Ltd (crystal growth), OSU (metalization), IZM (bump–bonding), U Bonn (electronics, testing)
• Also first experience with 1–chip ATLAS scCVD pixel detector
• Irradiated to $1 \times 10^{14}$ (full) and $1 \times 10^{15}$ (single chip)
  Test beams performed at CERN and DESY
ATLAS Pixel Module Performance

Mean threshold: $1450e^{-}$
Noise: $\sim 140e^{-}$
Threshold spread: $25e^{-}$

Lower minimum threshold reachable than silicon
(mean threshold $2250$, noise $185e^{-}$
threshold spread $\sim 60e^{-}$)
ATLAS Pixel Module Resolution

Residual $\sim 14 \, \mu m$ after removal of residual telescope tracking contribution
ATLAS Single Crystal diamond pixel detector

- Single crystal diamond mounted on one pixel chip (~1cm x ~1cm)
- Hitmap (with trigger window) looks good (1 dead pixel)

- Nice pulse height distributions
- More 1–hit clusters as voltage is raised
- Analysis ongoing
ATLAS SLHC Pixel Upgrade Plans

- ATLAS approved SLHC Upgrade R&D on Diamond Pixel Detectors

Submitted May 2007
Approved Feb 2008
Technical Decision 2010

Abstract

The goal of this proposal is to construct diamond pixel modules as an option for the ATLAS pixel detector upgrade. This proposal is made possible by progress in three areas: the recent reproducible production of high quality polycrystalline Chemical Vapour Deposition diamond material in wafers, the successful completion and test of the first diamond ATLAS pixel module, and the operation of a diamond after irradiation to $1.5 \times 10^{16}$ p/cm$^2$. In this proposal we outline the results in these three areas and propose a plan to build 5 to 10 ATLAS diamond pixel modules, characterize their properties, test their radiation hardness, explore the cooling advantages made available by the high thermal conductivity of diamond and demonstrate industrial viability of bump-bonding of diamond pixel modules. Based on availability and size polycrystalline Chemical Vapour Deposition diamond has been chosen as the baseline solution. The use of single crystal Chemical Vapour Deposition diamond is reserved as a future option if the manufacturers can attain sizes in the range 16mm x 16mm.

ATU-RD-MN-0012, EDMS ID: 903424
III. Diamond Detector Application:
   – Beam Condition Monitoring (BCM)
   CDF, BaBar, Belle
Beam Accidents (Will) Happen

- Tevatron proton beam carries ~ 1 MJ of energy
  - A small truck at 100 km/h on a 30μm beam spot
- LHC proton beam ~ 350 MJ of energy
  - 80 kg of TNT (Steve Peggs)
- Dec 5th, 2003: Beam accident takes Tevatron down for 10 days
  - Beam aborted after 16ms
  - Decision to overhaul Tevatron Beam Loss Monitoring (BLM) System

20-30 TeV turns to drill these
Generic Specifications for Beam Condition Monitoring (BCM)

• Common Goal: measure interaction rates & background levels in high radiation environment
  - complementary to accelerator Beam Loss Monitoring (BLM) system

• Input to background alarm & beam abort

• "DC current"
  - Uses beam induced DC current to measure dose rate close to IP
  - Benefits from very low intrinsic leakage current of diamond
  - Can measure at very high particle rates

• Simple DC (or slow amplification) readout

  "Post mortem" analysis

  Single particle counting
  - Counts single particles
  - Benefits from fast diamond signal
  - Allows more sophisticated logic coincidences, timing measurements
  - Used at high particle rates

• Requires fast electronics (GHz range) with very low noise

Common Goal: measure interaction rates & background levels in high radiation environment.
diamond
beam current

diamond sensor
PIN diode

M. Bruinsma, Vertex 2004

- simple unamplified DC coupled sensors read out over ~40m of cable
• One prototype pCVD diamond in CDF since Fall 2004
• Since Summer 2006: System Running in Monitoring Mode
  – 8 pCVD diamonds in E and W Inside Tracking Station \( r=2\text{cm} \) from beamline at \( z=1.8\text{m} \)
  – 5 diamonds in calibration region outside tracking near BLMs
• Since October 2007: System is the default beam abort system!
Diamond Installation in CDF

- ATLAS style sensor 1cm x 1cm, Al based metalization (from RD42/Ohio State University)
- G10 package, wrapped in Cu foil shielding
- Triax cable DC readout (85m to counting room)
Readout electronics

- VME crate has “immediate” buffer, storing last 64K readings
- Three sliding sums:
  - Fast buffer stores the sum of readings over 1 ms
  - Slow buffer over 50 ms
  - Very slow buffer over 1 s
- On receipt of an abort or end-of-beam Tevatron event, crate freezes all buffers and writes them out for post-mortem analysis
Diamond Beam Condition Monitoring: A Tevatron Shot Setup

Comparison of inside and outside tracking diamonds during shot setup

- using final Tevatron BLM electronics (averaged 20μs buffer)
The first CDF Diamond Abort

Abort condition: 4 diamonds > 9000 units

Cause: B11 separator spark
- Tevatron BLMs in sector F4 confirmed diamond abort
  - relative abort timing difficult, but diamonds triggered first
  - F4 magnet still quenched
- Several trips in CDF muon system
- No significant dose measured in BLMs at CDF
III. Diamond Detector Application:
  – Beam Condition Monitoring (BCM)
    ATLAS, CMS
ATLAS Beam Condition Monitor

4 BCM stations on each side of the Pixel detector
- Mounted on Pixel support structure at $z = \pm 183.8$ cm, $r = 5.5$ cm (sensor center)
- Each station: $1\,cm^2$ detector element + Front-end analog readout

ATLAS Pixel

BCM-stations

Beam pipe

183cm

pCVD diamond

Agilent MGA-62653
500Mhz (22 dB)

Mini Circuits GALI-52
1 GHz (20 dB)
Distinction of Collisions from Beam Losses

- Distinguish collisions from background through time–of–flight measurement
- Measure number of charged particle/cm² using analog pulse height

Interactions: $\Delta t = 0, 25, \ldots \text{ns}$
Upstream background: $\Delta t = \frac{2z}{c} = 12\text{ns}$
ATLAS BCM Q&A

QA of all modules through production cycle
- Raw sensor characterization / ceramic module
  - I/V, CCD
- Module performance
  - Noise
  - Signal from $^{90}\text{Sr}$
- Thermal cycling:
  10 cycles from $-25^\circ\text{C}$ to $45^\circ\text{C}$
- Infant mortality test – 12h @ $80^\circ\text{C}$
Resulting S/N from 6.5 to 8.2 for perpendicular incidence
ATLAS BCM Test Beam Results

all modules tested in beam-test setup for
- signal & noise performance
- surface uniformity

size of diamond sensor (tilted 45°)
signal uniform over surface
**CMS BCM Units**

**BCM1L: Leakage current monitor**
- Location: \( z=\pm 1.9 \text{m}, r=4.5 \text{cm} \)
- 4 stations in \( \phi \)
- Sensor: 1cm\(^2\) pCVD Diamond
- Readout: 100kHz
- CDF/Tevatron-style electronics

**BCM1F: Fast BCM unit**
- Location: \( z=\pm 1.9 \text{m}, r=4.3 \text{cm} \)
- 4 stations in \( \phi \)
- Sensor: scCVD Diamond
- Electronics: Analog+ optical
- Readout: bunch by bunch

**BCM2: Leakage current monitor**
- Location: \( z=\pm 14.4 \text{m}, r=29 \text{cm} \)
- 8 stations in \( \phi \)
- Sensor: 1cm\(^2\) pCVD Diamond
- Readout: \(~20kHz\)
- Sensors shielded from IP
- Uses LHC BLM electronics

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**2 Sensor Locations, 3 Monitoring Timescales**
- total of 32 pCVD and 8 scCVD diamond sensors

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**IPRD Siena - 3 Oktober 2008**

Rainer Wallny - Diamond Tracking Detectors
Very tight space constraints!
Pixel Luminosity Telescope (PLT) can be installed later in same carriage
(see talk by D. Hits)
BCM1F Schematics and Performance

- scCVD Sensors
  - 5x5x0.504mm

- Amplifier:

  JK16 - CERN
  (IEEE TNS 52-2005 2713)
  0.25um CMOS rad-tolerant transimpedance
  4pF input capacitance
  20mV/fC ~ 60mV/MIP linear
  20ns peaking time

Sr90 spectra at 200V bias voltage. SN Ratio at amplifier output: ~25:1
After optical fibers: ~11:1
First CMS BCM1F Signals from 10. Sept
Summary

- **Polycrystalline CVD Diamond is detector grade material**
  - Radiation hardness proven up to $1.8 \times 10^{16} \text{ p/cm}^2$ – ready for SLHC challenge
  - Additional vendors becoming available

- **Single crystal diamond shows superior qualities**
  - Full charge collection/no trapping, narrow Landau distribution
  - Follows the same radiation damage curve as pCVD → same radiation hardness

- **ATLAS pCVD diamond pixel modules**
  - Full ATLAS module works well
  - Superior noise performance, comparable resolution to silicon system
  - Single crystal pixel detector prototype data very promising
  - ATLAS SLHC R&D on diamond pixel detectors approved

- **CDF has deployed the largest pCVD diamond BCM system so far**
  - First diamond beam abort system at a hadron collider

- **CMS uses pCVD and scCVD diamonds**
  - Several complementary branch systems for BCM (and luminosity measurement)
  - Fast branch uses scCVD diamonds

- **ATLAS BCM uses pCVD diamond with single particle detection capability**
  - Feasibility of ns resolution shown using suitable front end electronics

- **Diamond as detector material now well established with BCM as first large scale (HEP) application**
  - Detector application (pixel, strip, pad) demonstrated
• Backup Slides
Current CDF Beam Abort Hardware

- **Beam Loss Monitors:** Argon filled ionization chambers
- Output signal prop. to dose rate 70nA/(1 Rad/s)
- Amplified/digitized in CAMAC in control room
- FIFO electronics with 2048 210µs bin width (10 TeV turns)
- 210 µs is a long time – most aborts look like this.
- The CDF RADMON system never positively pulled the abort first – more like a post-mortem device.
- Chamber location dictated by detector size
  - Z=4.3m outside tracking
CVD: Chemical Vapor Deposition

High Pressure High Temperature (HPHT) Process causes high impurity concentration

- At 298 K and 1 atm pressure, graphite configuration is stable and diamond configuration is meta-stable: need 0.03 eV/atom but large activation energy barrier
- sp³–bonds are more energetically favorable than sp²–bonds.

=> Vacant surface site will prefer diamond lattice over graphite lattice
Diamond Particle Detectors

Operation of diamond detector:
- Bias voltage applied across diamond
  - ~500V for 500µm thick detector (1 V/µm)
  - both polarities possible
- Particle generate e–h pairs
- e–h pairs drift apart in E–field to electrodes
- AC–coupled particle detector:
  - detect charge pulses
  - fast, low noise detection
- DC–coupled radiation sensor:
  - measure induced current
  - ~pA leakage current

⇒ Solid State Ionization Chamber

Charge collection in diamond:
- Signal is limited by impurities and grain boundaries
- Signal increases with electric field with ‘knee’ around ~1 V/µm (pCVD diamonds)
- Current pCVD diamonds have charge collection distance d ~250–300 µm
‘Erratic’ Dark Currents

- Discovered by BaBar in pCVD diamond
- CDF observation:

BaBar experience:
- ~ 0.5 T B field ⊥ to E field stabilizes diamond
- Lowering bias stabilizes diamond
- Effect confirmed by bench studies

M. Bruinsma, Vertex 2004