Development of CVD Diamond Tracking Detectors for Experiments at High Luminosity Colliders

RD42 Status Report
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Outline of the Talk
✦ Introduction - 2004 LHCC Milestones
✦ Diamond Properties
✦ Radiation Hardness Studies with Trackers
✦ Pixel Results
✦ Beam Position Monitoring Studies
✦ Summary
✦ RD42 Plans and Request
The RD42 Collaboration


◊ Spokespersons

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

New groups joined RD42 from:

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

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
Priorities of Research in 2004

- Improve the charge collection distance of polycrystalline CVD (pCVD) material above 250 \( \mu m \)
- Pursue the development of single crystal CVD (scCVD) diamond material
- Test the radiation hardness of the highest quality pCVD and scCVD diamond
- Develop devices useful at the LHC by ATLAS and CMS
- Continue the development of systems for beam monitoring for the LHC

These points will be addressed in this talk.
**Characterization of Diamond:**

**Signal formation**

- $Q = \frac{d}{t} Q_0$ where $d =$ 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:

Signal formation

![Graph showing signal formation vs. exposure (K Gy).]

Signal versus applied electric field

![Graph showing signal versus electric field (V/µm).]

- Contacts on both sides - structures from µm to cm
- Contacts typically: Cr/Au or Ti/Au or Ti/W → non-carbide formers
- 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 on same diamond!
**Diamond Properties**

Recent polycrystalline CVD (pCVD) diamond.

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

Results of Research Program:

Wafers can be grown >12 cm diameter, >2 mm thickness.
Collection distance of this wafer 200µm (edge) to 310µm (center).
Diamond Properties

Recent single crystal CVD (scCVD) diamond.

New Research Program
Pulse height spectrum of various scCVD diamonds (t=210, 320, 435, 685 μm)
But along the way

Not that easy to make!
Recent single crystal CVD (scCVD) diamond.

Most Probable charge versus thickness

![Graph showing scCVD Charge versus Thickness](image-url)
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.
Preliminary Results: saturated velocity $v_e = 96$ km/s, $v_h = 141$ km/s
  lifetimes ≈ 34 ns >> transit time (charge trapping not the issue)
Radiation Hardness Studies with Trackers

Proton Irradiation - previously:

**Signal to Noise**

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

**Resolution**

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

- CDS-69
  - after 1E15 p/cm$^2$
    - $\sigma = 9.1$ µm
  - after 2.2 E15 p/cm$^2$ and re-metalization
    - $\sigma = 7.4$ µm
Proton Irradiation - new:

Left: Pulse height distributions before (blue curve) and after (red curve) the irradiation to $20 \times 10^{15}$ p/cm$^2$ (500Mrad)

Right: Summary of proton irradiation results for pCVD diamond (filled points) and first scCVD diamond (open points)
Applications

CVD Diamond Used or Planned for Use in Several Fields

✦ High Energy Physics
✦ Heavy Ion Beam Diagnostics
✦ Synchrotron Radiation Monitoring
✦ Neutron and $\alpha$ Detection

Applications Discussed Here

✦ Pixel Detectors
  ATLAS, CMS
✦ Beam Monitoring
  BaBar
  Belle
  CDF
  ATLAS
  CMS
Diamond Pixel Detectors

ATLAS FE/I Pixels (Al)

- Atlas pixel pitch 50µm × 400µm
- Over Metalisation: Al
- Lead-tin solder bumping at IZM in Berlin

CMS Pixels (Ti-W)

- CMS pixel pitch 125µm × 125µm
- Metalization: Ti/W
- Indium bumping at UC Davis

→ Bump bonding yield ≈ 100 % for both ATLAS and CMS devices

Radiation hard chips produced last year.
Diamond Pixel Detectors

Results from a single chip ATLAS pixel detector

1 Chip Assembly

Cadmium 109 deposits $\approx 1600e$
Diamond Pixel Detectors

Results from a single chip ATLAS pixel detector

1 Chip Beam Test (x-Resolution)

1 Chip Beam Test (y-Resolution)

Pitch is $50\mu m \times 400\mu m$

Spatial Resolution $12\mu m$; Efficiency 98%
Results from a single chip CMS pixel detector

- Results with 200 $\mu$m collection distance diamond
  
  Efficiency $\sim 94$

  Inefficient pixels due to bump bonding and/or electronics - shown in pulser tests

  Spatial resolution $\sim 31 \mu$m for 125 $\mu$m pitch
Constructing a Full ATLAS pixel module

Various stages of making a module
The diamond ATLAS pixel module test was cut short. (Non-ATLAS R&D?)
Excellent first results for a 4 hr run.
Module is now being tested at DESY.
Motivation:

→ Radiation monitoring crucial for Si operation/abort system of LHC
→ 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
✦ Examples: BaBar, Belle, CDF, CMS

✦ Single Particle Counting
✦ Requires fast readout (GHz range)
✦ Requires low noise
✦ Allows timing correlations
✦ Example: ATLAS
The BaBar/Belle/CDF Diamond Radiation Monitor Prototypes:

✦ Package must be small to fit in allocated space
✦ Package must be robust

Schematic View
The BaBar/Belle/CDF Diamond Radiation Monitor Prototypes:

- BaBar/Belle/CDF presently use silicon PIN diodes
- Leakage current increases 2nA/krad
- Large effort to keep working, BaBar PIN diodes will not last past 2005

BaBar device inside the silicon vertex detector. Belle device just outside the silicon vertex detector. CDF device just outside the silicon vertex detector.
Data Taking in BaBar, CDF:

System operating for 18 months in BaBar and works well!

Installation of full system in Winter 2006

System operating for 1 month in CDF and works well!
The CMS Diamond Radiation Monitor Program:

- Diamond activity has begun!
- Successful test beam emulating beam accident - unsynchronised beam abort - $10^{12}$ protons lost in 260 ns in CMS
- Worst case 100x unsynchronised beam abort over several turns - protection requires early detection
- Possible location in the CMS detector:

Simulation of a Beam Accident in CMS

![Simulation Diagram]
The ATLAS Diamond Radiation Monitor Program:

- Diamond activity has begun!
- Time of flight measurement to distinguish collisions from background
- Located behind pixel detector forward disks in pixel support tube
- Possible ATLAS scenario:

Beam Condition Monitor in ATLAS

![Diagram of beam condition monitor]

12 ns

Time difference
The ATLAS Diamond Radiation Monitor Program:

- Use 2 diamonds to double S/N
- System meets all ATLAS specs
- System will be installed in Fall 05
Further Progress in Charge Collection
- 300 μm collection distance diamond attained in wafer growth
- FWHM/MP ~ 0.95 – Working with manufacturers to increase uniformity
- This diamond process has been moved to production reactors
- Single Crystal diamonds look quite attractive
- Have 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 module
  - Bump bonding yield ≈ 100 %
  - Excellent correlation between telescope and pixel data
- Awaiting results on irradiated single chip devices
**Summary**

- **Beam Conditions Monitoring**
  
  Application of diamond successful in BaBar, CDF
  
  Successfully tested ATLAS and CMS BCM prototypes
  
  - have met all of the ATLAS specs
  
  ATLAS diamond BCM installation in Fall 2005
  
  Significant progress in the last year

- **RD42 Request to CERN/LHCC**
  
  RD42 is supported by many national agencies:
  
  - continuation of official recognition by CERN critical
  
  - 55kCHF from CERN/ 250kCHF from outside CERN
  
  RD42 requires access to CERN facilities:
  
  - maintain the present 20 m² of lab space (test setups, detector prep, ...)
  
  - maintain present office space
Proposed Research for RD42

✦ Charge Collection
Continue research program to improve material in progress:
  ○ collection distance → 325μm (Q = 11,700e)
  ○ → improved uniformity
  ○ → identification of trapping centers
  ○ compare scCVD with pCVD

✦ Radiation Hardness of Diamond Trackers and Pixel Detectors
Continue tracker irradiations in the next year, add pixel irradiations
With protons, pions, neutrons
Use pCVD and scCVD

✦ Beam Tests with Diamond Trackers and Pixel Detectors
Complete test of the first full ATLAS diamond pixel module

✦ Beam Condition Monitors
Continue development of BCM’s, work with ATLAS group to complete its BCM

✦ Material Research
→ CERN, Florence, OSU, Rome