RD42 STATUS REPORT

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

presented by

P. Weilhammer
CERN/Ohio State University/University of PERUGIA

For the RD42 COLLABORATION
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1 HEPHY, Vienna, Austria
2 GSI, Darmstadt, Germany
3 LENS, Florence, Italy
4 University of Florence, Italy
5 LEPSI, IN2P3/CNRS-ULP, Strasbourg, France
6 Rutgers University, Piscataway, U.S.A.
7 INFN, Milano, Italy
8 UMM, Cracow, Poland
9 II.Inst. f. Exp. Physik, Hamburg, Germany
10 NIKHEF, Amsterdam, Netherlands
11 University of Torino, Italy
12 Ohio State University, Columbus, OH, U.S.A.
13 CERN, Geneva, Switzerland
14 MPI f. Kernphysik, Heidelberg, Germany
15 FNAL, Batavia, IL, U.S.A.
16 Polytechnico Milano, Italy
17 University of Toronto, Canada
18 Universitaet Bonn, Bonn, Germany
19 Universitaet Karlsruhe, Karlsruhe, Germany
20 University of Roma, Italy

* Spokespersons
Outline

• Motivation

• A Short Course on Synthetic Diamond

• Summary of RD42 Results: Old and New

• First R&D to use diamonds as beam monitors
  • In HEP
    • Beam steering
    • Beam abort
  • For Hadron Therapy: beam positioning

• Summary
Main Motivation for R&D on CVD Diamond Material

• At LHC and SLHC radiation levels for inner tracking layers are predicted to be extremely high

• CVD Diamond material has promise to be exceptionally radiation hard

• Good material candidate for development of tracking detectors surviving significantly higher radiation doses than warm ("cool") silicon.

• Tracking information as close as possible to the interaction point is most valuable, especially for vertex finding:
  • Diamond pixel detector
  • Beam monitoring and abort
A Short Course on Synthetic CVD Diamond
### Some Material Properties of Diamond

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Gap [eV]</td>
<td>5.47</td>
<td>1.12</td>
</tr>
<tr>
<td>Resistivity [$\Omega \text{cm}$]</td>
<td>$&gt;10^{11}$</td>
<td>$2.3 \times 10^5$</td>
</tr>
<tr>
<td>Ionisation Energy [eV]</td>
<td>13</td>
<td>3.6</td>
</tr>
<tr>
<td>Ionisation Density MIP [eh/mm]</td>
<td>36</td>
<td>89</td>
</tr>
<tr>
<td>Break-down Field [V/cm]</td>
<td>$10^7$</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>$\mu_e$ [cm$^2$/Vs]</td>
<td>1800</td>
<td>1450</td>
</tr>
<tr>
<td>$M_h$ [cm$^2$/Vs]</td>
<td>1200</td>
<td>480</td>
</tr>
<tr>
<td>Density [g/cm$^3$]</td>
<td>3.52</td>
<td>2.33</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>5.7</td>
<td>11.9</td>
</tr>
<tr>
<td>Radiation Length</td>
<td>12.2</td>
<td>9.4</td>
</tr>
<tr>
<td>Average charge created/100$\mu$m</td>
<td>3600</td>
<td>8900</td>
</tr>
<tr>
<td>Charge lifetime (un-irradiated)</td>
<td>Short</td>
<td>Infinite</td>
</tr>
<tr>
<td>Leakage current (~ T = 300Deg)</td>
<td>extr. Low</td>
<td>low. But with dose</td>
</tr>
</tbody>
</table>
Important Properties for Tracking:

**GOOD**

Both electron and hole velocities are high
At $E = 1 \text{ V/\mu m}$
  - Diamond = $1.7 \times 10^7 \text{ cm/sec}$
  - Silicon = $\sim 8 \times 10^6 \text{ cm/sec}$

Load capacitances of sensor 2.1 times lower than for Si (lower epsilon)
Diamond has 1.3 times less radiation length compared with Si

“Good” CVD Diamond is an insulator with Resistivity greater than $10^{14} \Omega \text{ cm}$.
Leakage current: $I_{\text{leak}} \lesssim 100 \text{pA/cm}^2$ for a $500\mu\text{m}$ thick sample.

- Low load capacitances are limiting electronic noise
The generated charge in diamond is 3600 electron-hole pairs per 100 µm compared with 10600 electron hole pairs in Si. Slightly more favorable when one compares generated charge per .3% of radiation length:

Diamond: ~13900 mean charges in 361 µm
Silicon: ~26800 mean charges in 282 µm

Lifetime of both holes and electrons is smaller than the transit time at 1V/µm (in un-irradiated silicon lifetime is 10’s of ms)
• Diamond material
  – Synthetic diamond
  – Chemical Vapour Deposition
  – Polycrystalline films
Growth Side of a recent polycrystalline CVD diamond

"DeBeer Industrial Diamonds" has become "Element6"
• Large Wafer Production (5") possible
Signal Formation and Collection Distance

- $Q = \frac{d}{t} Q_0$ 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 $\tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h}$
Signal versus applied Field:

Saturation above 1 V/µm.

Shape governed by $\mu(E)$ dependence.

Metallization typically is a carbide former plus over-metal like Cr/Au, Ti/Au, Ti/Pt/Au, Ti/W.

New much better process used recently: Non carbide former
Results are very regular
Types of DETECTORS RD42 IS WORKING WITH

• Dot detectors
  – Characterization
• Strip detectors
  – Tracking
  – Slow VA2 for beam test and fast SCTA LHC electronics
  – Irradiated and non-irradiated
• Pixel detectors
  – Tracking
  – CMS and Atlas patterns / electronics
• Diamond Pixel Detectors

- ATLAS FE/I Pixels (Al)
  - Atlas pixel pitch $50\mu m \times 400\mu m$
  - Over Metalisation: Al
  - Lead-tin solder bumping at IZM in Berlin

- CMS Pixels (Ti-W)
  - CMS pixel pitch $125\mu m \times 125\mu m$
  - Metalization: Ti/W
  - Indium bumping at UC Davis

→ Bump bonding yield $\approx 100\%$ for both ATLAS and CMS devices

*New radiation hard chips produced this year.*
Next Step:
Biased intermediate strips to benefit from charge sharing. 
Should improve resolution.

Data have been taken recently.
Analysis still to be done
Overview of RD42 Results: Old and New
Thinning Experiment

Gain knowledge on CCD properties during growth
A diamond sample from one of the recent productions

In 2000 RD42 entered into a Research Program with Element Six to increase the charge collected from pCVD diamond.

Latest Diamonds Measured with a $^{90}$Sr Source:

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

- Source data well separated from 0
- Collection Distance now 275$\mu$m
- Most Probable Charge now $\approx 8000e$
- 99% of PH distribution now above 3000$e$
- FWHM/MP $\approx 0.95$ — Si has $\approx 0.5$
- This diamond available in large sizes

The Research program worked!
At CERN the diamond characterization station has been rebuilt. Full automatic readout of wave forms. Wave form analysis

Collection distance as a function of time
Radiation Hardness

• Studied with Protons, Neutrons and Pions on pCVD Strip Detectors

• Fluences of 2-3 $10^{15}$ particles/cm$^2$

• Generally decrease of leakage current with dose observed.

• Resolution of Strip detectors gets better with fluence.

• 300 MeV Pions damage more than 27 GeV protons.
  
  ➔ 50% loss of S/N at 2.9 x $10^{15}$ pions/cm$^2$.
  ➔ 15% loss of S/N at 2.2 x $10^{15}$ protons/cm$^2$

• No loss seen for EM radiation up to 10MGy.
Pion Irradiation Results

Landau Distribution before and after irradiation

- CDS-38 at 0.6 V/µm
- before irradiation
  - mean 66
  - most prob. 44
  - FWHM 58
- after 2.9 E 15 π/cm² and re-metalization
  - mean 28
  - most prob. 21
  - FWHM 27

52% loss of S/N at 2.9 10^15 p/cm²

Spatial Resolution

23% improvement in resolution
Proton Irradiation Results

Landau Distribution before and after irradiation

Spatial Resolution

Residual Distributions, Proton Irradiated Diamond

Diamond CDS-69 at 0.9 V/\mu m
- Before irradiation:
  - Mean: 57
  - Most probable: 41
  - FWHM: 54
- After 1 \times 10^{15} protons/cm^2:
  - Mean: 49
  - Most probable: 35
  - FWHM: 41
- After 2.2 \times 10^{15} protons/cm^2 and re-metalization:
  - Mean: 47
  - Most probable: 35
  - FWHM: 36

CDS-89
- After 1 \times 10^{15} p/cm^2:
  - Mean: 9.1
  - FWHM: 9.1
- After 2.2 \times 10^{15} p/cm^2 and re-metalization:
  - Mean: 7.4
  - FWHM: 7.4
Uniformity in Charge Collection of CVD Diamonds

CVD Diamond, Mean Signal Map

UTS-5
run 945, 954, 955, 961, 962

$\delta_u \times \delta_v = 25 \times 25 \mu m^2$
mean entries / bin = 11.5

[Image of a graph showing uniformity in charge collection of CVD diamonds]
Radiation Hard Diamond Tracking Modules:

- Large (2cm × 4cm) Module constructed with new metalisation
- Fully radiation hard SCTA128 electronics → 25ns peaking time
- Tested in a $^{90}$Sr → ready for beam test and irradiation
- Charge distribution cleanly separated from the noise tail → S/N > 8/1
- Efficiency will be measured in test beams at 40 MHz clock rate

Landau distribution measured with source with LHC-type radiation hard front-end electronics: the SCTA chip.

Beam test performed this autumn but not yet analysed
• Results from Atlas Diamond Pixel Detectors

- $\sigma = 14 \mu m$
- $\sigma = 115 \mu m$

- Efficiency = 80%
- Resolution = digital
• Results from CMS Diamond Pixel Detectors

$\sigma = 31\mu m$

- Efficiency = 90%
- Resolution = digital
Weaknesses of polycrystalline CVD diamond:

- Many grain boundaries -> defects
- Non-uniformity of collection properties

Mono-crystalline CVD diamond could be a solution:

- No grain boundaries -> less defects
- Uniform collection properties
- First samples available
NEW!! Single Crystal CVD Diamond

CD135 - Both Sides - Pumped (Sr-90 source)

• Mono-crystalline CVD

Collection Distance as Function of El. Field for 2 Samples

- Saturation already at 0.2 V/mm
- Collection Distance equals Thickness
- ~100% efficient

Diamond Sample CD135
Diamond Sample CD71415b
Applications in HEP and other Fields

- Vertex Pixel Detectors with CVD Diamond are a realistic option for LHC detector upgrades.

- For Beam monitoring CVD Diamond is an option for the LHC experiments. Under study.

- BaBar and BELLE employ already CVD Diamond in their beam monitoring system.
Initial R&D to use diamonds as beam monitors
Beam loss and conditions monitor for CMS and Atlas

- CMS and Atlas investigate diamond as a sensor for a beam loss and conditions measurements close to the beam pipe.
- Same type of device considered by CMS & Atlas inside their tracker
  - CMS: $\sim z=\pm 1.8m$ and $r=4cm$
  - Atlas: $\sim z=\pm 3.5m$ close to beam pipe
- Act as part of a radiation monitoring system for equipment safety and radiation level/beam monitoring
- A beam conditions monitor can in particular address the following issues:
  - Allow to protect equipment during instabilities / accidents
  - Providing feedback to the machine thereby helping them to routinely provide optimum conditions
  - Monitor the instantaneous dose during operation
- Advantages of diamond for this application
  - Radiation hard, low leakage currents at room temperature, fast signal response
- The goal is to detect signs of beam losses and monitor beam conditions
Test of response to beam loss: T7 PS testbeam

Beam intensity: $8 \times 10^{11}$ protons per spill
Fluence: $4 \times 10^{10}$ protons/cm$^2$/spill at the centre of the beam spot -
$1 \times 10^8$ protons/cm$^2$/spill in the halo
Train of 40ns-wide bunch extracted from PS with 260ns gap.
Use RD42 diamond samples for first CMS and Atlas tests:

Read out through 16m long RG58 cable connected directly to diamond
(no electronics close to beam).
Diamond signal response to high intensity bunch

Single pulses from diamond
Bias on Diamond = +1 V/μm
Readout of signal:
  16m of cable
  no electronics
  20dB attenuation on signal
  cable (factor 10)

Signal maintained over the duration of the spill
Almost identical diamond response to PS beam monitor response (pulse length 40ns)
High-speed single-particle beam monitor

Use high-speed single-particle COUNTER
Beam conditions monitor to track instantaneous rate for CMS and Atlas (under study)
Beam monitor for Hadron-Therapy in proton accelerators (use as beam diagnostic tool and monitoring of beam intensity and time structure in MedAustron)

Based on diamond: It benefits from fast signal response due to high drift velocity combined with short charge live time of polycrystalline CVD diamond and radiation hardness

Principle: Benefit from fast signal by reading out the direct ionization CURRENT signal (no integration) using a 2GHz bandwidth current amplifier
First test results of this high-speed beam monitor

Test in a high intensity proton accelerator at IUCF, Indiana, US
Test with a beam typically used for proton-therapy:

- Proton kinetic energy 55-200MeV
- Beam measured by recording SINGLE particles
- Single particle ionization signal = 2.3 to 6.3 x MIP

Used 2 RD42 polycrystalline diamonds with ccd=190mm (after pumping)
- One diamond with Pad size 7.5x7.5mm²
- One diamond with 3x3 padarray with pad size 2.5x2.5mm²

Diamonds are readout using 3 stages of a 2GHz bandwidth current amplifier (amplification approximately 1500 total), amplifier HFK-2GHz (FOTEC, Austria)
Amplifier analog output readout via 15m cable to scope or signal processing electronics for rate monitoring
Diamond assembly used during high-speed monitor test
The analog pulse from a single particle:

Beam momentum 330MeV/c, recorded single pulses in LeCroy Wavemaster digital scope (5GHz analog bandwidth, 20Gs/s)
Peak current distribution

protons 55 MeV

detector UT31P5 V=1000V
$S_{mp} = 280 \text{mV}$, $<S> = 396 \text{mV}$, Noise r.m.s. = 19mV

S/N most probable: 15:1
BaBar beam monitor

So far Si PIN diodes have been used.
- $U_{bias} = 50V$, leakage increases with 1nA/krad
- After 100fb-1, noise 50mA, signal 10nA
Since 4 month CVD diamond beam monitor prototype installed
Package must fulfill space constraints
Robustness
CVD Diamond installed and working in BaBar
BaBar beam monitor

Promising results!

Stable operation
Follows closely diode signal
BELLE Diamond Beam Monitor

CVD diamond is installed and working
Summary

• Further progress with polycrystalline CVD diamond samples has been achieved: Collection Distance increased to 225 µm – 250µm for some samples

• Thinning experiment successfully terminated: understanding of CCD properties in growth process

• Work is ongoing to produce 6 x 2 cm² pixel module with latest rad hard ATLAS pixel chip (in coll. With IZM Berlin and Bonn)

• 2 fully automated diamond characterization stations have been brought into operation at CERN

• Data taken in test beam with rad-hard SCTA128 ATLAS analog chip with full LHC architecture

• New single crystal CVD diamond successfully developed by Element6, has been tested: close to full charge collection
Summary continued

• Applications of CVD diamond extended into beam monitoring/beam abort systems for
  • LHC experiments
  • $e^+e^-$ B-factories: monitors installed and running
• Tests underway to do very fast (Gigahertz bandwidth) single particle counting for hadron therapy facilities and maybe for LHC beam monitoring
Proposed Research Program for 2004

The overall goal for the year 2004 and beyond is to continue in developing and stabilise the process for the best electronic grade polycrystalline CVD diamond material in collaboration with Element6. In particular:

- Further improve and characterize material with a CCD of 250 µm and above
- Perform more irradiations with this quality material
- More material studies: defects, mobilities, lifetime of carriers, etc.
- Build and test tracking detectors, in particular real size pixel modules with finalised ATLAS/CMS fully radiation hard .25 µm front-end chips.
- Exploit new ohmic contact technology
Proposed Research Program for 2004, continued

• Development with Element6 and characterization of single crystal CVD diamond material. A research contract with Element6 is starting still in 2003.

• Irradiation studies with sc-diamond

• Continue development of systems for beam monitoring around LHC and B-factories

• Similar work for hadron therapy installations
Request to CERN

- Further extension of the RD42 project as a recognized CERN R&D

- Four 4-day test beam periods in 2004; two could be parasitic

- Maintain the present 20 m² of laboratory space in building 15 for test set-up, two characterization stations, detector preparation and some electronics development

- Maintain the present minimal office space for full time visitors and visiting members of the RD42 collaboration