CVD Diamond Radiation Sensors For Application In Very High Radiation Environments

Seminar presented at University of Geneva

30. 11. 2005

Peter Weilhammer, for the RD42 Collaboration

CERN Physics Dept. and INFN and University of Perugia, Perugia, Italy
RD42 Collaboration: 28 institutes on joined development of CVD diamond detectors

http://rd42.web.cern.ch/rd42/

Industrial Partner:
Element Six Ltd
H. Murphy, D. Twitchen, A. Whitehead
(Element Six, UK)
RD42 Collaboration:

**Goal: Development of Diamond as a Detector Material**


Institutes from HEP, Heavy Ion Physics, Hadron Therapy Centers and Solid State Physics

Still growing: new groups joined in 2004 and 2005

Desy-Zeuthen, Ioffe Institute St. Petersburg, Fachhochschule fuer Technik, Vienna, ITEP Moscow

IN THIS TALK I WILL PRESENT AN OVERVIEW AND SOME RECENT RESULTS

Content of this presentation:

1. INTRODUCTION AND SOME BASIC FACTS ON CVD DIAMOND

2. POLYCRYSTALLINE CVD DIAMOND (pCVD)
   - Charge Collection, Results from Irradiations, Applications: the ATLAS Pixel Module, Beam diagnostics and Monitoring with Diamonds

3. SINGLE CRYSTAL CVD DIAMONDS (sCVD)
   - Charge Collection, Charge Carrier Properties via TCT
Introduction
Attraction of Semiconductor Sensors for Radiation Detection and for Tracking

For modern detectors in particle physics (and in particular close to the interactions region of colliders) detectors need to …

- Have fast signals and be able to tolerate high rates
  - High drift velocity and short drift path

- Ionization is localized and can achieve very high segmentation

- Are free standing with an absolute minimum of “dead” material

- Are relatively radiation hard and easy to operate
  - to survive many years of operation without access or replacement: in colliders, in space,….

The central tracking detectors of present and future collider facilities use nearly only semi-conductor detectors (Silicon)
Many astrophysics detectors in orbit have silicon trackers: GLAST, AMS,…
Challenge for future detectors: Development of Radiation Detectors for Future Hadron and Linear Colliders which can survive long enough severe radiation environments without bad performance deterioration.
What do we expect:

What are the radiation environments to be expected after initial LHC running: SEVERE!!

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**Graph:**

- **SUPER - LHC (5 years, 2500 fb⁻¹):**
- **Axes:**
  - Vertical: Total fluence $\Phi_{eq}$ [cm⁻²]
  - Horizontal: Distance $r$ [cm]
- **Data Points:**
  - Neutrons $\Phi_{eq}$
  - Pions $\Phi_{eq}$
  - Other charged hadrons $\Phi_{eq}$
- **Areas:**
  - ATLAS Pixel
  - ATLAS SCT - barrel (microstrip detectors)
- **Annotations:**
  - Total fluence expected after 5 years of operation: $\sim 10^{16}$ pions/cm² at the innermost radius of LHC interaction regions

**From:** M. Moll, Pixel2005, Bonn

**Scenario for 5 years running SLHC**

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Development of ultra-radiation hard semiconductor detectors for the luminosity upgrade of the LHC to $10^{35}$ cm$^{-2}$s$^{-1}$ ("Super-LHC").

Challenges:
- Radiation hardness up to $10^{16}$ cm$^2$ required
- Fast signal collection (Going from 25ns to 10 ns bunch crossing ?)
- Low mass (reducing multiple scattering close to interaction point)
- Cost effectiveness (big surfaces have to be covered with detectors!)

For silicon detectors and other materials (except diamond) this is done in RD39 and RD50.
One way to go: Make Silicon Detectors more radiation-hard:

**Main adverse effects in Si after irradiation:**

1. **Bulk (Crystal) damage** due to Non Ionizing Energy Loss ("NIEL"): *displacement damage, built up of crystal defects* –
   - Change of effective doping concentration (higher depletion voltage, under-depletion)
   - Increase of leakage current (increase of shot noise, thermal runaway)
   - Increase of charge carrier trapping (loss of charge)
2. Surface damage due to Ionizing Energy Loss (IEL)

- accumulation of positive charge in the oxide (SiO2) and the Si/SiO2 interface –

  affects: interstrip capacitance (noise factor), breakdown behavior, …
What happens in physical terms to a silicon detector (equivalently to other semiconductor detectors) which stays for a long time in an high radiation environment:

The effective doping concentration \( (n^-) \) changes and eventually becomes p-doping (type inversion) \( \Rightarrow \) increasing voltage of full depletion

Moreover: this process goes on with time when irradiation stopped

\[ \text{U}_{\text{dep}} [\text{V}] (d = 300\mu\text{m}) \]

\[ \Phi_{\text{eq}} \left[ 10^{12} \text{ cm}^{-2} \right] \]

\[ |N_{\text{eff}}| \left[ 10^{11} \text{ cm}^{-3} \right] \]

\[ \Delta N_{\text{eff}} \left[ 10^{11} \text{ cm}^{-3} \right] \]

\[ \text{annealing time at } 60^\circ\text{C} [\text{min}] \]

\[ g_C \Phi_{\text{eq}} \]

\[ N_A \]

\[ N_C \]

\[ N_Y \]

[Data: R. Wunstorf, PhD thesis 1992, Uni Hamburg]

[Data: M.Moll, PhD thesis 1999, Uni Hamburg]
The leakage current goes up by orders of magnitude with a total fluence of $10^{15}\text{ cm}^{-2}$.

Charge trapping energy levels inside the band gap are created which eat up the electron hole pairs when drifting across the detector before they can be fully collected $\Rightarrow$ 70% charge loss at $8 \times 10^{15}$. 
Remedies for Silicon:

Material engineering

Device engineering

Change of detector operational conditions

Maybe new materials:

4H-SiC, 6H-SiC, GaN, GaAs, CZT, a-Si(H), ….CVD Diamond

So far lots of progress to improve radiation hardness of Si based sensors

However to get enough charge after irradiation and not to have the signal dominated by noise: quite extreme running conditions required (in Silicon case):

Low temperatures, very high bias voltage,…….
In this situation it is interesting to study CVD diamond as a detector material; at least for the areas with the highest integrated radiation fluxes
Basic material constants of CVD diamond in comparison

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>4H-SiC</th>
<th>Si</th>
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<tr>
<td>Band Gap [eV]</td>
<td>5.5</td>
<td>3.3</td>
<td>1.12</td>
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<td>Breakdown field [V/cm]</td>
<td>$10^7$</td>
<td>$4 \times 10^6$</td>
<td>$3 \times 10^5$</td>
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<td>Resistivity [Ω-cm]</td>
<td>$&gt; 10^{11}$</td>
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<td>Intrinsic Carrier Density [cm$^{-3}$]</td>
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<td>1800</td>
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<td>Saturation Velocity [km/s]</td>
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<td>Displacement Energy [eV/atom]</td>
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<td>Energy to create e-h pair [eV]</td>
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New Results on this ...
Important Properties of CVD diamond for Tracking:

**GOOD**

Both electron and hole mobilities are high, signal collection fast
At $E = 1 \text{ V/}\mu\text{m}$ high
Drift velocities $v_d$

$\Rightarrow$ Diamond $v_d = 1.67 \times 10^7 \text{ cm/sec}$
$\Rightarrow$ Silicon $v_d = 3.80 \times 10^6 \text{ cm/sec}$

Load capacitances of sensor 2.1 times lower than for Si (lower dielectric constant epsilon)

Diamond has 1.3 times less radiation length compared with Si

“Good” CVD Diamond is an insulator (high band gap) with resistivity greater than $10^{14} \Omega\text{cm}$.
Leakage current: $I_{\text{leak}} \sim 1 - 10 \text{ pA/sqcm}$ for a $500\mu\text{m}$ thick sample.

$\Rightarrow$ Low load capacitances are limiting electronic noise
NOT SO GOOD, but maybe possible to live with

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 (typical silicon sensor thickness):

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): signal loss in bulk by trapping in non-irradiated material
The Material: single crystals a few micron across at substrate side up to a few 100 µm across on top of growth side (~500 to 800 µm thick)

Deposited by Chemical Vapor Deposition in Microwave plasma
Charge Collection and Radiation Hardness of pCVD Diamond
Principle of detector operation

\[ Q = \frac{d}{t} Q_0 \]

\[ d = \mu E \tau \]

\[ \varepsilon = \frac{Q}{Q_0} \]

collected charge

“collection distance”

collection efficiency

\[ \mu = \mu_e + \mu_h \]

\[ \tau = \frac{\mu_e \tau_e + \mu_h \tau_h}{\mu_e + \mu_h} \]

\( \mu \) and \( \tau \) are “effective” mobility and lifetime

Growth-Side

Substrate-Side
Examples of Detectors made in RD42

• Diamond Pixel Detectors for ATLAS and CMS

ATLAS FE/I Pixels (Al)                  CMS Pixels (Ti-W)

- Atlas pixel pitch $50\mu m \times 400\mu m$
- Over Metalisation: Al
- Lead-tin solder bumping at IZM in Berlin

- 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.
Diodes for ATLAS Beam Conditioning Monitor
Saturation above 1 V/mm.

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

Metallization typically is a carbide former plus over-metal like Cr/Au, Ti/Au, Ti/Pt/Au, Ti/W
New better process used recently: Non carbide former
Results are very regular

A particular effect is “priming” in pCVD diamonds: When a sample is first biased with a e. g. field of 1 V/micron and with radiation impinging the collected charge will increase with time in average by $\sim 60\%$ after 30 to 60 mins
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

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

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Thinning Experiment
Leakage Current in pCVD Diamonds for ATLAS Beam Monitoring System

Leakage currents in 1/10 pA region up to +/- 500 V (No guard ring on this devices)
Leakage current for a very recent pCVD Diamond samples with Guard ring around dot
Positive Polarity

Leakage current for pCVD Diamond samples with Guard ring around dot
Negative Polarity
Radiation Hardness Measurements
Summary on Irradiation Studies done over last few years

Studied with Protons, Neutrons and Pions on pCVD Strip Detectors

Fluences of $2-3 \times 10^{15}$ 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 $2.9 \times 10^{15}$ pions/cm$^2$.
- 15% loss of S/N at $2.2 \times 10^{15}$ protons/cm$^2$

No loss seen for EM radiation up to 10MGy.

Sample CDS-69 had originally ~ 160µm ccd, 520 µm thick

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 $2.2 \times 10^{15}/\text{cm}^2$
- Resolution improves 35% at $2.2 \times 10^{15}/\text{cm}^2$
Irradiation with protons up to $\sim 2 \times 10^{16}$!

Sample: $t = 490 \, \mu m$, $ccd = 225 \mu m$

*Proton Irradiation - new:*

**Pulse Height**

**Summary**

Left: Pulse height distributions before (blue curve) and after (red curve) the irradiation to $18 \times 10^{15} \, p/cm^2$ ($\sim 500$Mrad)

Right: Summary of proton irradiation results for pCVD diamond at fixed $V$
Results from Irradiations with pions

Landau Distribution before and after irradiation

Spatial Resolution

52% loss of S/N at 2.9 $10^{15}$ p/cm²
Some Applications
A full ATLAS Pixel Module with pCVD Diamond

Most of this done by the Bonn Pixel group in RD42:
M. Mathes, F. Huegging, J. Weingarten, N. Wermes and H. Kagan (OSU)
Constructing a full ATLAS Diamond Pixel Module - new:

Various stages of making a module
Very short test in the high energy ATLAS test beam at CERN

Module equipped with 16 fully radhard IBM readout chips

Beam profile
All channels are working
The full diamond pixel module at DESY - Hitmap

Analysis in Progress.
Hitmap looks good - can easily see scintillator edge.
The full ATLAS diamond pixel module - Noise, Threshold

Results - Noise $\sim 137e$, Mean Threshold $1454e$, Threshold Spread $\sim 25e$. 
The full ATLAS diamond pixel module - Correlation, Resolution

Excellent correlation with telescope
Resolution dominated by multiple scattering.
Preliminary residual \( \sim 23 \mu m \) - includes contribution from multiple scattering.
Beam Diagnostics and Monitoring with pCVD Diamonds
Beam Diagnostics & Monitoring with Diamonds (ATLAS, CMS, CDF, Belle, BaBar)

- **Common Goal:** measure interaction rates & background levels in high radiation environment
- **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**

- **Examples:**
  - BaBar
  - Belle, CDF
  - Similar method planned for CMS

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

- **Requires fast electronics (GHz range) with very low noise**

- **Examples**
  - Atlas Beam conditions monitor
ATLAS Beam Conditions Monitor @ LHC

- 4 BCM stations on each side of the Pixel detector
  - Mounted on Pixel support structure at $z = \pm 183.8 \text{ cm}$ and $r = 7 \text{ cm}$
  - Each station: $1 \text{ cm}^2$ detector element + Front-end analog readout
Ten ATLAS BCM Modules with double sensor mounting and GHz readout ready for mounting
CVD diamonds and fast amplifiers at ATLAS

- Benefits from very fast signal in diamond
- Radiation hard and requires no cooling

MIP signal distribution:
Average signal = 6.3 mV
$S_{mp} = 5.2 mV$
$SNR_{mp} \sim 8:1$

- Single MIP time response:
  - After 16 m analog readout
- Rise-time: 0.9 ns
- Pulse width: 2.1 ns

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Timing of background vs. interactions

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

Interactions: $\Delta t = 0, 25, \ldots$ ns
Upstream background: $\Delta t = 2z/c = 12$ ns

Normal operation flux
1-2 MIPs/cm²/BCO

Single Crystal CVD Diamonds

Some first results on charge collection and carrier properties
Recent single crystal CVD (scCVD) diamond.

Pulse height spectrum of various scCVD diamonds (t=210, 320, 435, 685 µm)
Recent single crystal CVD (scCVD) diamond.

Most Probable charge versus thickness
Charge carrier properties in Single Crystals

- Measure charge carrier properties important for signal formation
  - electrons and holes separately
- Use $\alpha$-source (Am 241) to inject charge
- Injection
  - Depth about 14\(\mu\)m compared to 470\(\mu\)m sample thickness
  - Use positive or negative drift voltage to measure material parameters for electrons or holes separately
  - Amplify ionization current

The pulse shape of the induced current is recorded (Transient Current Technique)
Ionization current in a sCVD sample

- Drift time and mobility
- Charge Lifetime
- Internal electrical field

- Transit time of charge cloud
  - Signal edges mark start and arrival time of drifting charge cloud
- Two effects determine the shape during the drift
  - Charge trapping during drift if any
  - Space charge: decrease of current for holes / increase for electrons with time

\[ i_{e,h}(t) \propto e^{\frac{-t}{\tau_{\text{eff},e,h}}} - \frac{t}{\tau_{e,h}} \]

\[ \tau_{\text{eff},e,h} = \frac{\varepsilon \varepsilon_0}{\varepsilon_0 \mu_{e,h} |N_{\text{eff}}|} \approx \frac{\varepsilon \varepsilon_0 t_c V}{\varepsilon_0 d^2 |N_{\text{eff}}|} \]
The measured drift velocity

- Average drift velocity for electrons and holes
  \[ v_{dr_{e,h}}(E) = \frac{d}{t_c} \]

- Extract \( \mu_0 \) and saturation velocity
  \[ v_{dr} = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_s}} \]

\( \mu_0 \) for this sample:
  - Electrons: 1714 cm²/Vs
  - Holes: 2064 cm²/Vs

- Saturation velocity:
  - Electrons: \( 0.96 \times 10^7 \) cm/s
  - Holes: \( 1.41 \times 10^7 \) cm/s
The “effective mobility”

• Deduce a calculated mobility from the measured velocity (normally mobility is defined only at low fields with linear relation between field and velocity)

• Taking space charge into account:

\[ \mu_n = -\frac{d^2}{2t_e V_c} \ln \left( \frac{V + V_c}{V - V_c} \right) \]

\[ \mu_e = -\frac{d^2}{2t_e V_c} \ln \left( \frac{V - V_c}{V + V_c} \right) \]

• Normal operation in region close to velocity saturation

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Preliminary carrier lifetime measurements

- Extract carrier lifetimes from measurement of total charge

Charge trapping doesn’t seem to limit signal lifetime -> full charge collection (for typical operation voltages and thickness)

Net effective space charge

» TCT probes the internal field configuration

• Allows precise measurement of space charge if present

• On this sample e.g.
  – Signal decrease due to decreasing electrical field
  – Negative space charge $N_{\text{eff}} = -2.8 \times 10^{11} \text{ cm}^{-2}$

Voltage necessary to compensate for $N_{\text{eff}}$
Summary

- **Further Progress in Charge Collection**
  - 300 $\mu$m collection distance diamond attained in wafer growth
  - FWHM/MP $\sim$ 0.95 – Working with manufacturers to increase uniformity
  - This diamond process works in 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 $2.2 \times 10^{15}$/cm$^2$, 25% signal at $20.0 \times 10^{15}$/cm$^2$
    - Resolution improves 35% at $2.2 \times 10^{15}$/cm$^2$

- **Diamond Pixel Detectors**
  - Successfully constructed a complete ATLAS diamond module
    - Bump bonding yield $\approx$ 100 %
  - Analyzing Module data from DESY
    - Excellent correlation between telescope and pixel data
    - Noise, Threshold, Efficiency, Resolution look good

Beam Conditions Monitoring

Application of diamond successful in BaBar, Belle, CDF
Successfully tested ATLAS BCM prototypes
  - have met all of the ATLAS specs
ATLAS diamond BCM system in production (10 modules)
ATLAS diamond BCM installation in Fall 05/Winter 2006

First results obtained with single crystal CVD diamonds:

- Full charge collection in material up to 1mm thick
- Mobility of electrons and holes measured with TCT; very high hole mobility
- Carrier lifetimes are bigger than 40 nsec ➔ full charge collection
CVD Diamond is very promising material for Radiation Detectors up to fluences where other solid state detectors will no more have required performance using acceptable service and running conditions