Diamond Sensors

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Vertex2010
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June 6-11, 2010
Outline

• From LHC to SLHC – the $10^{16}$ ballpark
• Diamond as sensor material
• Radiation hardness: RD-42
• Diamond sensor applications (focus on ATLAS)
  – ATLAS BCM/BLM
  – Pixel modules
  – ATLAS dPIX project
• Diamond sensor vendors
From LHC to SLHC

- Chamonix 2010 brought (cruel) reality into LHC luminosity forecast

“Standard” LHC/sLHC scenario (not-so-far-pre-Chamonix)

730 fb\(^{-1}\) not reached by 2020

M. Lamont: Chamonix 2010

Vertex2010, Loch Lomond, June 8, 2010

Marko Mikuž: Diamond Sensors
SLHC sensor requirements

- Small radii: 3-5 cm
- Main constraint: radiation damage after $6000 \text{ fb}^{-1}$ (by 2030)
  - Ballpark fluence $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$
  - Could be a factor 2-3 more, depending on exact radius ($\sim 1/r^2$), flat along z
  - Predominantly pions (>90 %)
  - Broad energy spectrum peaked at $O(100 \text{ MeV})$
Order of magnitude higher than LHC sensors designed for 730 fb\(^{-1}\) with ballpark fluence \(10^{15}\)

- Remember, sensors believed to be fit for LHC only following a decade-long R&D campaign
- Pixel B-layer planned to be replaced at \(\frac{1}{2}\) fluence

Despite slow LHC ramp up, time is in short supply
- ATLAS plans for IBL sensor choice early next year
- \(5 \times 10^{15} n_{eq}/cm^2\) benchmark!
Sensors contending $10^{16}$

- Planar silicon
  - Exploiting charge multiplication
- 3-D silicon
  - Novel silicon processing
- Diamond
  - New material

- All three options rely on technology / mode of operation not utilized in HEP so far
  - Obviously, there is no free lunch
## Diamond as sensor material

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap [eV]</td>
<td>5.5</td>
<td>1.12</td>
</tr>
<tr>
<td>Breakdown field [V/cm]</td>
<td>$10^7$</td>
<td>$3 \times 10^5$</td>
</tr>
<tr>
<td>Intrinsic resistivity @ R.T. [Ω cm]</td>
<td>$&gt; 10^{11}$</td>
<td>$2.3 \times 10^5$</td>
</tr>
<tr>
<td>Intrinsic carrier density [cm⁻³]</td>
<td>$&lt; 10^3$</td>
<td>$1.5 \times 10^{10}$</td>
</tr>
<tr>
<td>Electron mobility [cm²/Vs]</td>
<td>1900</td>
<td>1350</td>
</tr>
<tr>
<td>Hole mobility [cm²/Vs]</td>
<td>2300</td>
<td>480</td>
</tr>
<tr>
<td>Saturation velocity [cm/s]</td>
<td>1.3(ɛ)-1.7(h)×10⁷</td>
<td>1.1(ɛ)-0.8(h)×10⁷</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>3.52</td>
<td>2.33</td>
</tr>
<tr>
<td>Atomic number - Z</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td>Dielectric constant - ɛ</td>
<td>5.7</td>
<td>11.9</td>
</tr>
<tr>
<td>Displacement energy [eV/atom]</td>
<td>43</td>
<td>13-20</td>
</tr>
<tr>
<td>Thermal conductivity [W/m.K]</td>
<td>~2000</td>
<td>150</td>
</tr>
<tr>
<td>Energy to create e-h pair [eV]</td>
<td>13</td>
<td>3.61</td>
</tr>
<tr>
<td>Radiation length [cm]</td>
<td>12.2</td>
<td>9.36</td>
</tr>
<tr>
<td>Spec. Ionization Loss [MeV/cm]</td>
<td>6.07</td>
<td>3.21</td>
</tr>
<tr>
<td>Aver. Signal Created / 100 μm [eₒ]</td>
<td>3602</td>
<td>8892</td>
</tr>
<tr>
<td>Aver. Signal Created / 0.1 Xₒ [eₒ]</td>
<td>4401</td>
<td>8323</td>
</tr>
</tbody>
</table>

- Low leakage
- Fast signal
- Low capacitance
- Radiation hard
- Heat spreader
- Low signal
Sensor types - pCVD

- Polycrystalline Chemical Vapour Deposition (pCVD)
  - Grown in μ-wave reactors on non-diamond substrate
  - Exist in Φ = 12 cm wafers, >2 mm thick
  - Small grains merging with growth
  - Grind off substrate side to improve quality
    → ~500-700 μm thick detectors
  - Base-line diamond material for pixel sensor
Sensor types - scCVD

- Single Crystal Chemical Vapour Deposition (scCVD)
  - Grown on HTHP diamond substrate
  - Exist in ~ 1 cm$^2$ pieces, max 1.4 cm x 1.4 cm, thickness > 1 mm
  - A true single crystal

😊 Fall-forward for sLHC pixel upgrade (single chips, wafers ?)
  - Needs significant improvement in size & price
  - After heavy irradiations properties similar to pCVD, headroom ~3x10$^{15}$ p/cm$^2$

😔 Recent developments in adverse direction
  - Concentrate on max. ~5x5 mm$^2$ pieces & packaging, main target market: dosimetry
Signal from CVD diamonds

- No processing: put electrodes on, apply electric field
- Trapping on grain boundaries and in bulk
  - much like in heavily irradiated silicon
- Parameterized with Charge Collection Distance, defined by

\[ CCD = \frac{< Q_{col} >}{36 \frac{e_0}{\mu m}} \]

- CCD = average distance e-h pairs move apart
- Coincides with mean free path in infinite \((t \gg CCD)\) detector

\[ Q_{col} = Q_{created} \frac{d}{t} \]
\[ d = d_e + d_h \] - distance e - h move apart
\[ t \] - detector thickness

CCD measured on 1.4 mm thick pCVD wafer from E6

@ 2 V/ \(\mu m\)

CCD of BCM 0.5 mm thick pCVD detectors

ccd of recent diamonds

E6 Wafer 1

Collection Distance (um)

Electric Field (V/um)
Charge collected in pCVD diamonds

- Electrodes stripped off and reapplied at will
  - Test dot → strip → pixel on same diamond
  - Charge collection usually done with strip detectors and VA chips in SPS high-energy pion test beam

- Non-irradiated detectors
  - MIP spectrum well separated from pedestal
    - $<Q_{col}> = 11300 \text{ e}$
    - $<Q_{MP}> \sim 9000 \text{ e}$
    - 99% of events above 4000 e
  - FWHM/MP ~ 1 (~ 0.5 for Si)
    - Consequence of large non-homogeneity of pCVD material

- Irradiated detectors
  - FWHM/MP < 1
    - Trapping in bulk starts to dominate
    - Radiation homogenizes pCVD material
Charge collected in scCVD diamonds

- CCD = thickness at $E > 0.1 \text{ V/\mu m}$
  - Collect all created charge
  - “CCD” hardly makes sense
- FWHM/MP ~ $1/3$
  - scCVD material homogenous
  - Can measure diamond bulk properties with TCT

scCVD measured in Ljubljana
e-injection with $\alpha$-particles

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Radiation damage in diamond

<table>
<thead>
<tr>
<th>Radiation induced effect</th>
<th>Diamond</th>
<th>Operational consequence</th>
<th>Silicon</th>
<th>Operational consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakge current</td>
<td>small &amp; decreases</td>
<td>none</td>
<td>$I/V = \alpha \Phi$</td>
<td>Heating</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\alpha \sim 4 \times 10^{-17} \text{ A/cm}$</td>
<td>Thermal runaway</td>
</tr>
<tr>
<td>Space charge</td>
<td>~ none</td>
<td>none</td>
<td>$\Delta N_{\text{eff}} \approx -\beta \Phi$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\beta \sim 0.15 \text{ cm}^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Charge trapping</td>
<td>Yes</td>
<td>Charge loss Polarization</td>
<td>$1/\tau_{\text{eff}} = \beta \Phi$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\beta \sim 4-7 \times 10^{-16} \text{ cm}^2/\text{ns}$</td>
<td></td>
</tr>
</tbody>
</table>

- At extreme fluences charge trapping the paramount radiation damage effect
- Difference O(10) in x-section between charged/neutral traps
  - Filled (neutral) traps trap less (of the opposite carrier)
  - Basics of “pumping”
- $E_{\text{gap}}$ in diamond 5 times larger than in Si
  - Many processes freeze out
  - Typical emission times order of months
- Works also in Si at 300/5 = 60 K – “Lazarus effect”

\[
\frac{1}{\tau_{\text{eff}}} = \sum_t N_t (1 - P_t) \sigma_t v_{\text{th}}
\]
Radiation damage studies: RD-42


♦Spokespersons

87 Participants

27 Institutes

1 Universitat at Bonn, Bonn, Germany
2 INFN/University of Catania, Catania, Italy
3 CERN, Geneva, Switzerland
4 Wiener Neustadt, Austria
5 INFN/University of Florence, Florence, Italy
6 Department of Energetics/INFN, Florence, Italy
7 FNAL, Batavia, USA
8 GSI, Darmstadt, Germany
9 Ioffe Institute, St. Petersburg, Russia
10 IPHC, Strasbourg, France
11 ITEP, Moscow, Russia
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13 Universitat at Karlsruhe, Karlsruhe, Germany
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23 Czech Technical Univ., Prague, Czech Republic
24 University of Colorado, Boulder, CO, USA
25 Syracuse University, Syracuse, NY, USA
26 University of New Mexico, Albuquerque, NM, USA
27 University of Manchester, Manchester, UK
Test beam studies

- Preferred way of radiation damage assessment
  - Test beam before and after irradiation
  - Using strip detectors of 50 μm pitch, read out by VA2 electronics in a tracking telescope
- Reliable & reproducible results on pulse spectrum, efficiency and position resolution

Strip pattern on diamond

Test beam assembly
PS protons

For mean free path in infinite detector expect

\[ \frac{1}{CCD} = \frac{1}{CCD_0} + k \times \Phi \]

With \( CCD_0 \) initial trapping on grain boundaries, \( k \) a damage constant

- Larger \( CCD_0 \) performs better (larger collected charge) at any fluence
- Can turn \( 1/CCD_0 \) into effective “initial” fluence, expect \( CCD_0 \sim \infty \) for SC
- pCVD and scCVD diamond follow the same damage curve
- \( k \sim 0.7 \times 10^{-18} \, \mu \text{m}^{-1} \text{cm}^{-2} \)

Test beam results
70 MeV protons (Sendai)

- Recent irradiations with 70 MeV protons at Cyric Facility in Sendai, Japan
- 3x more damaging than PS protons
  \[ k \sim 2 \times 10^{-18} \, \mu m^{-1}cm^{-2} \]
- NIEL prediction
  - factor of 6
  - NIEL violation ?!

Test beam results
800 MeV protons (LANL)

- 800 MeV protons in LANL, December 09
- Appear approximately 2x more damaging than PS protons
- Source results only, test beam ongoing now

Source results – test beam in progress
More (recent) irradiations

- pCVD (2) with reactor neutrons up to $1.3 \times 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ (in 6 steps)
  - $k \sim 3 \times 10^{-18} \mu\text{m}^{-1}\text{cm}^{-2}$
  - Discrepancy between source and test-beam data
  - Source overestimates damage

- pCVD with PSI 200 MeV pions up to $6 \times 10^{14} \pi/\text{cm}^2$
  - $k$ consistent with $\sim 1 \times 3 \times 10^{-18} \mu\text{m}^{-1}\text{cm}^{-2}$

Source data
NIEL/DPA calculations

  - Protons
    - Ratio 800 MeV / 24 GeV: ~ 2 ✓
    - Ratio 70 MeV / 24 GeV: ~ 6 !!
  - Neutrons
    - 10 MeV n ~ 24 GeV p !!

- Recent calculation by S. Mueller based on displacement per atom (DPA) value given by FLUKA (development version, preliminary)
  - Proton ratios: 1.2; 5 (800; 70 MeV)
  - p(24 GeV)/n(10 MeV) ratio: 6 ✓
Some resemblance of NIEL/DPA results to measurements
- Don’t expect miracles, NIEL scaling is broken in Si trapping, too!

For sLHC, and especially IBL
- No time left to disentangle discrepancies, no headroom

Need pions in the $n \times 100$ MeV energy ballpark
- Applied for beam at PSI (with RD-50)
  - Use scCVD to maximize damage effect
  - Campaign starts August 15
- Negotiate very simple pion line at LANL
  - If approved, could reach sLHC fluences
  - Quick evaluation with strip detectors in 800 MeV proton beam
Diamond sensor applications

• All LHC exp’s use diamonds for beam monitoring & accident protection
  – Current and counting mode operation, TOF capability
  – $O(100)$ diamond sensors employed
• CMS is building Pixel Luminosity Telescope
  – 48 scCVD pixel modules (5 mm x 5 mm)
• Upgrade plans include diamond as candidate for innermost pixel tracker layer(s)
• Elaborate on two projects
  – ATLAS BCM
  – ATLAS DPix
ATLAS BCM

2 x 4 modules

Agilent MGA-62653 500Mhz (gain: 22 dB, NF: 0.9dB)

2 x 1 cm² pCVD diamond

Mini Circuits GALI-52 1 GHz (20 dB)
BCM performance

- Time difference hit on A side to hit on C side
- Most of data reconstructed offline
- Sub ns resolution of BCM clearly visible (0.69 ns) without offline timing corrections applied

- Beam dump fired by BCM during LHC aperture scan
  - Too sensitive at current conditions
    - Beam monitoring only
    - Measures to restore abort functionality

1177 LHC orbits — ~100 ms after BA is fired the buffer is recorded for additional 100 LHC orbits (~10 ms)
Diamond pixel modules

- Full modules built with I3 pixel chips @ OSU, IZM and Bonn
Diamond pCVD Pixel Module – Results

- pCVD full module
  - Tests show no change of threshold and noise from bare chip to module
    - A consequence of low sensor $C$ & $I$
    - Noise 137 e
    - Threshold: mean 1450 e, spread 25 e
    - overdrive 800 e
  - reproduced in test beams

Many properties (e.g. resolution, time-walk) scale with S/N and S/T!
Diamond tracker upgrade proposal

DPix Collaboration
- Bonn
- Carleton
- CERN
- Ljubljana
- Ohio State
- Toronto
- Approved by ATLAS EB Mar’08
- EDMS: ATU-RD-MN-0012

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 1.8x10^16 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 10mm x 16mm.

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Checked by: W. Trischuk (University of Toronto)

Approved by: W. Trischuk (University of Toronto)

Distribution List

Vertex2010, Loch Lomond, June 8, 2010
Marko Mikuž: Diamond Sensors
Original R&D proposal goals

• Industrialize bump bonding to diamond sensors (make 5-10 modules)
• Quantify radiation tolerance of full ATLAS pixel modules
• Optimisation of front-end electronics
• Lightweight mechanical support – exploit minimal cooling requirement
• Financial resources to make 10 parts:
  ✔ Diamond sensors
  ✔ Bump-bonding contracts
  ❌ 200 FE-I3 + 25 MCC’s
  ❌ Module support prototypes
  ❌ Three year beam-test program (2008-2010)
• Aimed at tracker upgrade, bidding for IBL
Industrialization: 2\textsuperscript{nd} full pixel pCVD module

- 1\textsuperscript{st} module to be built in industry
- All steps from polished sensor to bump-bonding performed at IZM Berlin

- Embedding in a ceramic wafer
- Wafer scale metallization & UBM process
- Removal from the ceramics
- Backside metallization & cleaning
- Flip chip
Industrialization hic-up

- Edge of diamond left metalized – module damaged
  - Voltage short across edge

**Before applying 10 V**

- Threshold (e): VCAL scan without sensor bias - BARE 1.
  - Module "pCVDP"
  - 93352 out of 46080 pixels with good fit

**After applying 10 V**

- Threshold (e): VCAL scan without sensor bias.
  - Module "MS/0156"
  - 25913 out of 46080 pixels with good fit

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Industrialization: repair @ IZM

- 7/16 chips stopped functioning
- Back to IZM for re-build
  - Module taken apart – visual damage to sensor and chips
  - Backside metallization redone
  - Improved cleaning of the module rim by using plasma etching
  - All FE chips replaced

- Successful re-build proves concept of diamond sensor recycling in case of module QA failure!
  - Successfully done before on single-chip assemblies
Diamond vendors: DDL (E6)

- Our (and RD-42) long-term supplier – considered qualified
  - Reproducible material
  - Quote for 500 pcs (900 kGBP)
- Have 4 18 mm x 64 mm sensors for the original dPix programme based on I3
  - CCD was guaranteed above 275 µm
    - Achieved on one part only
    - Others 250-270 µm, rejected,
    - Refurbished, not a big change (235-250 µm)
    - DDL agreed to re-evaluate their polishing procedures
- Have 4 I4 shaped sensors at hand
  - Ordered as 17.4 mm x 20.6 mm
  - Measured at 17.5 mm x 20.7 mm
    - 10-20 um RMS spread = cutting precision
    - Can be thinned & trimmed to envelope
  - Measured CCD between 240 and 260 µm
Diamond vendors: II-VI

- New US producer
  - Large company (sold eV products to El recently) based in Saxonburg, PA
  - Interested in electronic grade diamonds to enrich their product line
  - Working closely with OSU on development for HEP
  - Produced a 1.5 mm thick 5” wafer in their “normal” process
    - Not tailored to HEP applications at all
  - 4 I4-shaped pieces delivered to OSU for testing
    - As grown – no processing at all
II-VI (cont.)

- Really as grown, 1.5 mm thick
- Surprisingly good results
  - CCD uniform across all samples
  - 220-230 µm @ 0.7 V/µm, not saturated
    - Error in metallization, CCD lower limit
- Suspect very good intrinsic CCD
- Start working on a programme to (im)prove it
  - Take off substrate side in steps
    - First 50 µm step done, CCD increase ~20 µm
  - Go to higher fields
- Work with II-VI to optimize further
  - Reduce growth rate
- Ultimate goal : 300³
  - 300 USD/cm², 300 µm CCD, 300 µm thick
  - 400 average will also do (e.g. 400, 300, 500)
II-VI (latest)

- Last news
  - Got a 5” wafer for evaluation
    - Not for HEP applications
    - 2 mm thickness at centre
    - 2.5 mm at rim
  - Spectacular CCD results
    - 300 \( \mu \text{m} \) at 0.5 V/\( \mu \text{m} \)!
  - Starting to grow a wafer for us
  - Eagerly awaiting delivery
    - Suspect close to scCVD quality when thinned down to 500 \( \mu \text{m} \)
- Could change the whole perception of pCVD diamond
Summary

• Recent progress in the diamond world
  – Improved understanding of radiation damage
  – Application in all LHC experiments
  – Building of pixel modules in industry
  – New producer with VERY promising initial performance

Very interesting times with promises of spectacular performance ahead of us!
Backup
Diamond scCVD Pixel Module – Results

scCVD single chip module
- Analysis (M. Mathes PhD, Bonn) of SPS test beam data exhibits excellent module performance
  - Cluster signal nice Landau
  - Efficiency 99.98 %, excluding 6/800 problematic electronic channels
  - Unfolded track resolution using η-algorithm from TOT exhibits \( s \approx 8.9 \text{ mm} \)
  - Charge sharing shows most of charge collected at high voltage on single pixel – optimal for performance after (heavy) irradiation
IBL pCVD diamond sensor cost estimate

- IBL = 14 staves of 32 (= 448) single-chip sensors
- Active sensor: 16.8 mm x 20 mm
- Count on 20 % loss during production (recycling) => need ~0.2 m² of diamond
- Budgetary estimate – DDL quote for 500,1000 20x20 mm² pCVD diamond sensors
  - Cost 900 kGBP for 500 pcs
  - 1.5 MGBP for 1000 pcs
8x8 mm² 0.5 mm thick diamond sensors used
6 sensors on each side (A and C) installed on ID End Plate
Readout adopted from LHC BLM system with minor modifications
Redundant system to BCM – safety only

- 7 TeV p on TAS collimator gives ~1 MIP/BLM module → ~1 fC of charge
  - 25 pA of current “spike” for single occurrence (possible with pilot bunch)
  - 40 nA of current for continuous loss (only when full LHC bunch structure)

- Diamond dark currents
  - In magnetic field, should be O(10 pA)
  - Erratic currents, several nA w/o magnetic field

- Require 2 ch. above threshold simultaneously

\[ \sim 50 \text{ nA increased to } 500 \text{ nA} \]