Radiation damage in diamond detectors

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for CERN-RD 42 collaboration
Outline

- Diamond as detector material
  - Properties
  - Suppliers and availability

- Radiation damage
  - Challenges
  - Review of the damage caused by different particles
  - Validity of NIEL/DPA scaling and comparison to silicon
  - Prediction on signal

- Pumping and polarization
  - Polarization and space charge probing
  - TCT on single crystalline detectors – polarization effects

- Conclusions

The use of diamond detectors at present/future experiments will not be discussed. See previous vertex talks…
# Diamond as Sensor Material

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>Silicon</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap [eV]</td>
<td>5.5</td>
<td>1.12</td>
<td></td>
</tr>
<tr>
<td>Breakdown field [V/cm]</td>
<td>10⁷</td>
<td>3x10⁵</td>
<td>Low leakage</td>
</tr>
<tr>
<td>Intrinsic resistivity @ R.T. [Ω cm]</td>
<td>&gt; 10¹¹</td>
<td>2.3x10⁵</td>
<td>Fast signal</td>
</tr>
<tr>
<td>Intrinsic carrier density [cm⁻³]</td>
<td>&lt; 10³</td>
<td>1.5x10¹⁰</td>
<td></td>
</tr>
<tr>
<td>Electron mobility [cm²/Vs]</td>
<td>1900</td>
<td>1350</td>
<td></td>
</tr>
<tr>
<td>Hole mobility [cm²/Vs]</td>
<td>2300</td>
<td>480</td>
<td></td>
</tr>
<tr>
<td>Saturation velocity [cm/s]</td>
<td>1.3(e)-1.7(h)x 10⁷</td>
<td>1.1(e)-0.8(h)x 10⁷</td>
<td>Heat spreader</td>
</tr>
<tr>
<td>Density [g/cm³]</td>
<td>3.52</td>
<td>2.33</td>
<td>Low capacitance</td>
</tr>
<tr>
<td>Atomic number - Z</td>
<td>6</td>
<td>14</td>
<td>Radiation hard</td>
</tr>
<tr>
<td>Dielectric constant - ε</td>
<td>5.7</td>
<td>11.9</td>
<td>Heat spreader</td>
</tr>
<tr>
<td>Displacement energy [eV/atom]</td>
<td>43</td>
<td>13-20</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity [W/m.K]</td>
<td>~2000</td>
<td>150</td>
<td>Low capacitance, Low signal</td>
</tr>
<tr>
<td>Energy to create e-h pair [eV]</td>
<td>13</td>
<td>3.61</td>
<td></td>
</tr>
<tr>
<td>Radiation length [cm]</td>
<td>12.2</td>
<td>9.36</td>
<td></td>
</tr>
<tr>
<td>Spec. Ionization Loss [MeV/cm]</td>
<td>6.07</td>
<td>3.21</td>
<td></td>
</tr>
<tr>
<td>Aver. Signal Created / 100 µm [e₀]</td>
<td>3602</td>
<td>8892</td>
<td></td>
</tr>
<tr>
<td>Aver. Signal Created / 0.1 X₀ [e₀]</td>
<td>4401</td>
<td>8323</td>
<td></td>
</tr>
</tbody>
</table>
**Diamond Manufacturers**

- Detector grade polycrystalline diamonds are grown with CVD technique on non-diamond substrate (sapphire).
- Many large (~2 cm x 2 cm) polycrystalline CVD sensors delivered in the last year:
  - Diamond Detectors Ltd, UK - ceased operations, but the “mother” E6 will fulfill the contracts
  - II-VI Infrared, USA (e.g. ATLAS Pixel sensors ordered and some received)
- Up to 2 mm thick wafers

Probing points for testing the wafer homogeneity before sensors are cut
Single Crystal Chemical Vapour Deposition (scCVD)
- Grown on HTHP diamond substrate
- Exist in ~ 1 cm² pieces, max 1.4 cm x 1.4 cm, thickness > 1 mm
- A true single crystal

😊 Fall-forward for HL-LHC pixel upgrade (single chips, wafers ?)
- Needs significant improvement in size & price, ideas are around
- After heavy irradiations properties similar to pCVD, headroom ~3x10^{15} p/cm²

気軽に集めて、可能ならマーケットを拡大

)Mathematical expression: $\text{PRODUCT} = \text{SUM} \times \text{DIVISION}$

Recent commercial developments in adverse direction
- Concentrate on max. ~5x5 mm² pieces & packaging, main target market: dosimetry
- Used on large scale in CMS PLT project
The main challenge

Sensors for 1\textsuperscript{st} (& 2\textsuperscript{nd} ?) tracking layer of experiments at the LHC and more importantly at the HL-LHC

- Diamond offers:
  - Radiation Hardness in terms of signal
    - Survive to the end of the experiment
  - Low dielectric constant
    - Low capacitance $\rightarrow$ low noise
  - Low leakage current
    - Decreases with irradiation
    - Low readout noise
  - Room temperature operation
    - Low mass construction
  - Fast signal collection

- Fluence of interest is $O(10^{16}) \text{ cm}^{-2}$
  - For 1\textsuperscript{st} pixel layer at $R \sim 4$ cm
  - For $R < 25$ cm charged particles dominate, but $\sim 10\%$ contribution comes from neutrons also at $R \sim 4$ cm
Signals from CVD Diamonds

- No processing: put electrodes on, apply electric field
  - Surface preparation and metallization are non-trivial and crucial for operation

- Trapping on grain boundaries (pCVD) and in bulk
  - Much like in heavily irradiated silicon

- Parameterized with Charge Collection Distance, defined as

\[ \text{CCD} = \frac{\langle Q_{\text{col}} \rangle}{36 \frac{e_0}{\mu m}} \]

\(\text{\textbullet mean not }\)
\(\text{most probable}\)

- \(\text{CCD}\) = average distance e-h pairs move apart

CCD vs. field for (pCVD and scCVD)

1.4 mm thick pCVD (E6)
thinned to 0.8 mm
Radiation Damage Parameterization

- Radiation-induced traps in fact decrease the mean free path *mfp*
  - CCD~ *mfp_e*+*mfp_h* = *v_e*τ_e+*v_h*τ_h in thick detectors *t* >> *mfp*, CCD
  - CCD degradation formula not applicable to scCVD since *CCD_0* = *t*; *mfp_0* → ∞
  - Also for high-quality pCVD *CCD_0* → *t*

- Traditionally CCD was fitted with the ansatz
  - We measure CCD
  - Relation CCD ↔ *mfp* for homogeneous material

For lack of data assume *mfp_e* = *mfp_h*

- Symmetry of strip CCD to field reversal supportive of the assumption, but more studies are needed
- *k_mfp* robust to *mfp_e* / *mfp_h* variation anyway

\[
\frac{1}{mfp} = \frac{1}{mfp_0} + k_{mfp} \times \Phi
\]

\[
\frac{1}{CCD} \approx \frac{1}{CCD_0} + k \times \Phi
\]
Irradiation: 24 GeV Protons (PS)

- CCD evaluated with strip detectors in CERN test beam
- For mean free path expect

\[
\frac{1}{mfp} = \frac{1}{mfp_0} + k_{mfp} \times \Phi = k_{mfp} \cdot (\Phi + \Phi_{\text{shift}})
\]

- With \( mfp_0 \) initial trapping, deduced from \( CCD_0 \)
- \( k_{mfp} \) the damage constant
  - Can turn \( 1/ mfp_0 \) into effective “initial” fluence (x-shifts)
  - expect \( mfp_0 \sim \infty \) for scCVD
- pCVD and scCVD diamond follow the same damage curve
  - \( k_{mfp} \sim 0.66 \times 10^{-18} \mu m^{-1} cm^2 \)
Irradiation: 70 MeV Protons and 800 MeV Protons

Recent irradiations with 800 MeV protons at LANSCE Facility in Los Alamos, US

- \( k_{mfp} \sim 1.2 \times 10^{-18} \ \mu\text{m}^{-1}\text{cm}^2 \)
- \( \sim 1.8 \)x more damaging than PS protons
- Consistent with NIEL prediction

Irradiations with 70 MeV protons at Cyric Facility in Sendai, Japan

- \( k_{mfp} \sim 1.7 \times 10^{-18} \ \mu\text{m}^{-1}\text{cm}^2 \)
- \( \sim 3 \)x more damaging than PS protons
- NIEL prediction
  - factor of 6
  - NIEL violation ?!
Recent irradiations with 25 MeV protons at Karlsruhe, Germany

- $k_{mfp} \sim 2.6 \times 10^{-18}$ $\mu$m$^{-1}$cm$^2$
- 4x more damaging than PS protons
- NIEL prediction
  - factor of 15
  - NIEL violation!
- Work in progress – more data needed.
**Irradiation: 300 MeV pions**

pCVD and scCVD with Pions up to $10^{15}$

- **pCVD with PSI 300MeV $\pi$**
  - up to $6 \times 10^{14}$ p/cm$^2$ tested in CERN test beam
    - $k_{\text{ccd}} \sim 1.8 \times 10^{-18} \, \mu \text{m}^{-1} \text{cm}^2$
  - $^{90}\text{Sr}$: $k_{\text{ccd}} \sim (1.26 \pm 0.8) \times 10^{-18} \, \mu \text{m}^{-1} \text{cm}^2$

- **scCVD up to $1 \times 10^{15}$ $\pi$/cm$^2$**
  - samples tested in source and CERN test beam
    - $k_{\text{ccd}} \sim 2.2 \times 10^{-18} \, \mu \text{m}^{-1} \text{cm}^2$

Pions are $\sim 3x$ as damaging as 24 GeV protons

One would expect a factor of 2 from DpA
Irradiation: reactor neutrons

- **pCVD**: large decrease of CCD
  - $^{90}$Sr: $k_{\text{CCD}} \sim (4.2 \pm 0.8) \times 10^{-18} \, \mu m^{-1} cm^2$
  - Test beam data give somewhat smaller damage constant

- **sCVD**:
  - $^{90}$Sr: $k_{\text{mfp}} \sim 3.9 \times 10^{-18} \, \mu m^{-1} cm^2$
  - But measurement is based on a single measurement at $10^{14} \, cm^{-2}$

NIEL prediction:
Neutrons should be approximately as damaging as 24 GeV protons, **but the difference is a factor of ~4-6**.

Already 10% of neutrons at R~4 cm can result in significant contribution in signal degradation!

Two samples irradiated in steps – no intentional high temperature annealing inbetween.
Damage in terms of mean free path degradation deviates from the calculated NIEL scaling:

- For low energy protons - measured is lower than calculated (scale normalized to 24 GeV p)
- Large difference also for neutrons - measured seems to be larger than calculated
- If scaling with silicon is applied then also for 300 MeV pions?
**Diamond Radiation Tolerance - DpA**

DpA based on Displacement Energy: Si:~25eV; Diamond~42eV

DpA scaling seems to describe charge collection measurements better.

From: S. Mueller thesis

RD42 data

- neutrons
- pions
- protons

Scale normalized to 24 GeV protons
How much charge can we expect

- Less signal at all fluences of interest in diamond, but also less noise
- With present FE-I4 in time threshold of around 800-1500 a “thumb rule” says around 3000 e is required for good efficiency – at the limit for pions

Solid blue markers – n irradiated FZ-p Si – most probable charge

- 24 GeV protons
- 300 MeV pions
- Reactor neutrons

Don’t forget diamond has other advantages over silicon.

~2 GeV pions should be similar to 24 GeV protons

Si data:
I. Mandic et al., NIMA 603 (2009) 263.
Operation of diamond detectors is similar to operation of silicon detectors at cryogenic temperatures – governed by the ratio $E_g/k_bT$.

- **Priming – pumping – trap filling** (exposure to ionizing radiation)
- **Polarization effects (in E field)**

Steady state operation condition which is reproducible is not so easy to achieve:

- pCVD diamonds: both present already before irradiation
- scCVD diamonds: only after irradiation

In most applications priming is done without bias – re-emission times are such that the detector remains primed for a long time.

In real situations priming is done during bias applied = both effects are at the same time:

- rate of particles
- time of exposure
**Pumping procedure - example**

Pumping at 1kV at with weak source:
- Small initial drop (polarization of grain boundaries - reduction of field?)
- Rise of the signal (passivation of traps)
- Non-irradiated detector – stable after few h

Pumping with strong source:
- Signal regularly measured – voltage scans start when stationary state is reached
**Polarization**

Non-irradiated detector in stationary state at -1 kV (negative pulse after preamp-shaping amp.)

Bias changed to -100 V
- time dependence of signal
- Initially different polarity of the signal which indicates that internally the electric field is different

The change persists over a long time (rate dependent) – only ~1/3 of the detector has field orientation of that at 1 kV after the bias was switched to 0V.

37MBq source 3 cm away

The signal has opposite polarity as for +/-1 kV
Explanation of the signal

1.) Stationary field profile (+1 kV) indicated by
2.) If bias is changed rapidly by $\Delta V_{bias}$ the profile changes
3.) The direction of the drift is different in different parts of the detector leading to redistribution of the space charge

Dependence of the CCD on the bias change (from +/-1kV)

- Opposite sign of CCD indicates that majority of the detector has different field orientation.
- If electric field is symmetric with respect to the contacts its gradient can be derived from the slope

$$\frac{dE}{dx} \sim \frac{1}{W} \frac{d\Delta V_{bias}}{dCCD} \sim \frac{e_0 N_{eff}}{\varepsilon_c}$$

Effective space charge is this case is of the order $2 \cdot 10^{12}$ cm$^{-3}$
Probing the field - pumping without bias

Pumping to reference/reproducible state:
>20 h of 37 MBq $^{90}$Sr at ~3 mm without bias

scCVD
1e14 cm$^{-2}$

Probing with positive bias
Electrons

Probing with negative bias
Holes

- The charge collection measurements are reproducible within ~5%!
- Small difference in collected charge – between holes and electrons – similar trapping, although significantly less charge is induced than for non-irradiated detectors (around 20% less)
- The slope of the induced currents point to trapping and (small) space charge

$^{90}$Sr
$^{241}$Am

$37 \text{ MBq}$

$<55 \text{ kBq}$
Pumping & probing the field

>20 h of 37 MBq $^{90}$Sr without bias

- polarization of the detector (0,5,10 min) – double peak
- more complex form at later stages
  - Effect of alpha particles?
  - Slow charging of the traps?
- At ±1kV the charge remains stable within 10% at all stages

scCVD neutron irradiated to $10^{14}$ cm$^{-2}$

-1kV bias

-1000 V

time=0 (pumped unbiased)
time~5 min (d=2.5 cm)
time~add. 10 min (d=1 cm)
time~add. 220 min(d=1 cm)
time~add. 700 min(d=0.5 cm)

HOLE signal

Probing the field - pumping under bias

Pumped under bias >20h (37MBq) -> source removed -> $^{241}\text{Am}$ scans performed from 1kV

- Complex field – different from that when pumping is done without bias
  - two peaks are visible for both electron and hole signals - some indication on predominant negative space charge

- Charge collection efficiency at high bias voltages is equal than for the reference state in spite of longer signals
  - Stronger voltage dependence of charge collection for electrons than for holes
Conclusions

- The understanding of damage in diamond detectors has improved:
  - the charge collection degradation has been measured for neutrons, pions and protons – the latter at different energies
  - NIEL is violated, but the agreement with DpA seems to be better
- Diamond offers several advantages over the silicon, but two things need to be resolved:
  - signal after high fluences of charged hadrons – wishfully pions
  - availability of the diamond (QA, price)
- The understanding of detector operation is complex:
  - undergo strong polarization effects – pCVD even before irradiation
  - pumping under bias produces different electric field
  - At high bias voltages (2V/μm) this seem not to influence charge collection efficiency

Very interesting times for diamond in HEP ahead of us
Can the polarization effect be reduced by alternating the bias voltage

After the bias switch the electric field profile has a more favorable distribution

- The CCD increases because of more appropriate field distribution which overcompensates for increase of trapping probability near the edges (large cross-section for capturing carriers of the opposite charge)

- Clear hysteresis effect because of polarization
- Larger effect at low bias voltages

- The difference in stationary and non-stationary state is around 20-30%
- At lower voltages the difference may be larger
Applications in HEP: wrap-up

![Diagram showing active area in square centimeters over years for different collaborations like ATLAS DBM, Particle trackers, Beam monitors, Babar, CDF, and CMS. The diagram illustrates the growth and evolution of these collaborations over time.]
Detrapping