Latest Results on the Radiation Tolerance of Diamond Detectors

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G. Kramberger, HSTD12, Hiroshima 2019
Radiation bulk damage poses a major problem for semiconductor detector operation at future colliders (HL–LHC, FCC, …). Dominant contribution from pions/charged hadrons close to the IP and neutrons further out ($r>30$ cm).

Diamond has been looked at for a very long time as a replacement for Si and is in fact the only other material up to now used at LHC as semiconductor sensing material (beam monitors, telescopes):

- **large band gap** ($5.5 \text{ eV}$) – large $E_g/k_B T$ also means that (G–R) processes can be very slow and state of operation can depend on the history (similar to Si at cryogenic temperatures)
- **low leakage current** $\rightarrow$ **low noise**
- lower signal ($\sim 1/2$ of Si)
- **drift velocities** of e and h are larger (comparable) to silicon
- low **capacitance** $\rightarrow$ **low noise**
- high **thermal conductivity** $\rightarrow$ good heat spread
- very high resistivity – no need for junction

Is it more radiation hard than silicon – displacement energy is larger than for Si ($42\text{ eV}$ vs. $25\text{ eV}$), but the defects that formed matter?

There is no general statement on that as it depends very much on application!
Production of the sensors

Production of material with Chemical Vapour Deposition Technique. Choice of right substrate (HTHP for sCVD, sapphire for pCVD) is important:

- sCVD: expensive and limited area (very pure, high CCD)
- pCVD: less expensive, larger growing area but more intrinsic charge traps

Thickness of typical diamond detectors ~400–1000 μm.

Metallization plays and important role for the detector operation (proprietary procedures):

- accumulation of charge underneath the electrodes
- resistivity of the electrode
- mechanical/chemical properties

Any kind of electrode is possible, in recent years also 3D diamond detectors – see talk from Harris Kagan.

Unlike silicon – diamond can be reused – metallized many times!

Unfortunately the number of producers is limited – at least those interested in diamond detectors
Diamond as particle detector

- Operation as any other semiconductor detector
- Trapping on grain boundaries (pCVD) and in bulk (scCVD and pCVD) determines most of the detector properties
- Historically the performance is parameterized with Charge Collection Distance
  \[ CCD = \frac{<Q_{col}>}{36 \text{ e–h/\mu m}} \text{ (for mip)} \rightarrow \text{average distance e–h pairs move apart} \]
- In high quality scCVD CCD doesn’t depend on E

![Diamond as particle detector diagram](image)

**CCD vs. field for (pCVD and scCVD)**

- scCVD 395\(\mu\)m
- pCVD 800\(\mu\)m
Test beam measurements

- irradiated diamond samples with various particle species and energies (5x5 mm\(^2\) (scSVD) and 10x10 mm\(^2\) (pCVD)
- metalized as strip detectors with 50 μm pitch
- characterization of irradiated devices in beam tests 120 GeV p, π at CERN
- transparent (unbiased; 5 largest strips/10 strips ROI) hit prediction from telescope
- tracking precision at detector under test: ~ 2–3 μm

- sensors pumped with \(^{90}\text{Sr}\) source to fill lattice traps (“reset” the diamond)
- test of leakage current, I < 10 nA
- signal charge corrected for pedestal, noise, common mode noise
- signal calibration (ADC to electrons)
- measurement done with two polarities (at ± 1 V/μm and ± 2V/μm)
Radiation Damage Parameterization

- Radiation-induced traps decrease the mean free path
  \[ \lambda = \lambda_e + \lambda_h = V_e \tau_e + V_h \tau_h \]

  \[
  \frac{ccd}{t} = \sum_{i=e,h} \frac{\lambda_i}{t} \left[ 1 - \frac{\lambda_i}{t} \left( 1 - \exp\left( -\frac{t}{\lambda_i} \right) \right) \right]
  \]

- Relation \( CCD \leftrightarrow \lambda \) for homogeneous material

\[ n = n_0 + k' \phi \]
\[ \frac{1}{\lambda} = \frac{1}{\lambda_0} + k \phi \]

- Due to lack of data we assume \( \lambda_e = \lambda_h \), but for pad geometry it is quite robust
- Similar \( CCD \) for strip detectors after field reversal support the assumption, but more studies are needed
Fast charged hadrons

$k_{800 \text{ MeV } p} = 1.04 \\
\pm 0.02 \text{(stat.)} \pm 0.05 \text{ (syst.)} \times 10^{-18} \text{ cm}^2 / (p \mu \text{m})$

due to initial traps in poly

$1/k = \frac{1}{\lambda (1/\mu \text{m})}$

$\phi (p/\text{cm}^2) \times 10^{15}$

800 MeV proton

$24 \text{ GeV proton}$

$24 \text{ GeV } p = 0.62 \\
\pm 0.01 \text{(stat.)} \pm 0.06 \text{ (syst.)} \times 10^{-18} \text{ cm}^2 / (p \mu \text{m})$

Single $k$ used in fits to all the data points – pCVD data are simply offset for the initial traps in the material
“Slow” charged hadrons and neutrons

\[
k_{70\text{ MeV} p} = 1.76 \\
\pm 0.10 \text{ (stat.) } +0.18^{\text{ -0.23 (syst.)}} \cdot 10^{-18} \text{ cm}^2 / (\text{p } \mu\text{m})
\]

Measurements done in the past also with 26 MeV p (KIT) – less accurate:

\[
k_{26\text{ MeV} p} \sim 2.6 \cdot 10^{-18} \text{ cm}^2/(\text{p } \mu\text{m}) \text{ for pCVD}
\]

Measurements done in the past with 200 MeV pions

\[
k_{200\text{ MeV} \pi} \sim 2 \cdot 10^{-18} \text{ cm}^2/(\pi \mu\text{m}) \text{ for pCVD}
\]

\[
k_{\text{fast } n} = 3.05 \\
\pm 0.23 \text{ (stat.) } \pm 0.14 \text{ (syst.)} \cdot 10^{-18} \text{ cm}^2 / (\text{n } \mu\text{m})
\]
pCVD and scCVD undergo the same degradation of performance with fluence – \( k_i \) is the same

Initial \( \lambda_{0,i} \) can be seen as shift in the fluence \( \Phi_{0,i} \)

equivalent fluence defined with respect to 24 GeV p instead of 1 MeV neutrons

\[
\phi_{0,i} = \frac{1}{\lambda_{0,i} k_i}
\]

\[
\phi_{eq.} = \frac{k_i}{k_{24\text{ GeV protons}}} \times \phi_i
\]
comparison shown only up to $\sim 10^{15}$ cm$^{-2}$ --> reliable trapping time data from RD50

- detectors can be depleted with $\langle E \rangle = 2V/\mu$m (oxygen rich silicon material)
- In terms of $\lambda$ diamond is better than silicon for charged hadrons and worse for neutrons
- In silicon the MFP starts exhibit saturation with fluence; seems not in diamond not for the investigated fluence range

Damage doesn’t follow NIEL calculations.
Less signal at all fluences of interest in diamond, but also less noise.

Roughly around 3000 e is required for good efficiency (ok for 24 GeV p, on the limit for PSI π).

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.
Nonhomogeneous collection over the surface – widening of the spectrum
pCVD samples
- $FWHM/MP$ decreases with fluence
sCVD samples
- Smaller initial $FWHM/MP$
- $FWHM/MP$ is flat with dose

Determines the required threshold on readout chip – long tails!

800 MeV $p$: $0-13.4 \times 10^{15} \, p/cm^2$

+HV

-HV

reactor neutrons
**Uniformity of response in pixel sensor**

$\Phi_{24\text{GeVp}}$

$\text{CCD}_0 = 239 \, \mu\text{m}$

- **FWHM/MP** is a measure of the uniformity of the material.
- Observe regions of different signal ($\lambda$) in un-irradiated poly-crystalline diamond.
- Derivative of damage equation:
  \[ \frac{d\lambda}{d\phi} = -k\lambda^2 \]  
  portions of material with the largest $\lambda$ have faster decrease.
Rate effects
Study the pulse height dependence on the particle flux

- Characterization in 260 MeV $\pi^+$ beam at PSI
- 5 years ago published rates up to 300 kHz/cm$^2$
- 4 years ago with new electronics, rates up to 10–20 MHz/cm$^2$
- Recently measured rate after fluences up to $8 \times 10^{15}$ n/cm$^2$
- Pad detectors tested in ETH (CMS Pixel) telescope

19.8 ns bunch spacing clearly visible
Irrad. pCVD diamond shows no rate effect (<2 %) up to 20 MHz/cm²
Irrad. pCVD diamond shows no rate effect (<2 %) up to $8 \times 10^{15}$ n/cm²
Rate effects observed are very likely related to surface effects (cleaning and remetalizing of the surface cures the problem)
Conclusions

Quantified understanding of radiation effects

- radiation damage up to fluences relevant for tracker application in HL–LHC experiments
- analysed signal uniformity of single- and poly-crystalline CVD diamond after irradiation

The decrease of the mean free path doesn’t follow NIEL.

Quantified understanding of rate effects @2 V/μm

- Irrad. pCVD diamond shows no rate effect (<2 %) up to 20 MHz/cm²
- Irrad. pCVD diamond shows no rate effect (<2 %) up to $8 \times 10^{15}$ n/cm²
Repair of Rate Dependence

- Very large rate dependence of PH for some diamonds at first measurement (>90%)
- After reprocessing and surface cleaning with RIE, very stable behavior (2%)
- This is clearly a surface issue
- Feasible to “fix” some fraction of diamonds with rate dependent PH
- Less than 20% of the diamonds show rate dependence >10%

(a) First measurement

(b) After reprocessing