An Insight into
Radiation Tolerance of scCVD-DD
First Irradiations with
26MeV p and ~20MeV n

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4th NoRHDia Workshop at GSI, 08/06/2008
Aim of the Study

Novel Radiation Hard(?) Diamond Detectors for Hadron Physics
1. Introduction
   - Non Ionizing Energy Loss - NIEL
   - Radiation induced effects

2. Material and Methods
   - scCVD diamond
   - irradiation conditions - 26MeV p, ~20MeV n, on-line monitoring

3. Characterization
   - identification of radiation induced defects - optical characterization
   - dark current and TL
   - trapping time - TCT technique
   - trapping related phenomena - polarization, priming etc.
   - CCE and CCD of primed detectors

4. Summary

5. Outlook - How to proceed
NIEL - Non Ionizing Energy Loss in Diamond

Radiation damage at **LOW energy** dominated by elastic cross section. C-nuclei have factor two smaller Z than Si and higher displacement energy ($\approx 40 \text{eV} (?)$ vs 20 eV)

Radiation damage at **HIGH energy** dominated by inelastic cross section. C-nuclei smaller and more stable than Si. Diamond order of magnitude better than Silicon.
NIEL – Radiation induced effects

Silicon

- dark current $\rightarrow \alpha \Phi$ - NIEL scalable
- space charge $\rightarrow -\beta \Phi$ - depletion voltage
- charge trapping $\rightarrow 1/\tau$ - NIEL violation
- induced defects are mobile at RT - annealing

Diamond

Gap $\sim 5x$ silicon $\sim$ at RT Diam $\sim$ Si at 60K

- dark current - none or decreases if present
- space charge - none(?)
- charge trapping - yes $\rightarrow$ space charge, pumping Polarization
  
pumping, priming $\rightarrow$ 'Lazarus effect'

Induced defects are not mobile at RT
interstitials $\sim 1.6$ eV, vacancies $\sim 2.3$ eV
**CCE and CCD**

**CCE - charge collection efficiency**  \( \text{CCE} = \frac{Q_{\text{coll}}}{Q_{\text{gen}}} \)

\[
Q_{\text{coll}} = Q_{\text{gen}} \tau_{e,h} / t_{tr-e,h} \left(1 - \exp\left(-\frac{t_{tr-e,h}}{\tau_{e,h}}\right)\right)
\]

\[
Q_{\text{gen}} = \sim 36e^{-h} / \mu m \times d
\]

where \( t_{tr} = v_{dr} / d \) and \( d \)-sample thickness in \( \mu m \)
- thickness dependent
- bias dependent

**CCD - charge collection distance**
(averaged 'Schubweg' \( \rightarrow e + h \))

\[
\text{CCD} = \mu_{e,h} \times \tau_{e,h} \times E - \text{ohmic transport}
\]

better

\[
\text{CCD} = v_{dr-e,h}(E) \times \tau_{e,h}
\]

at high \( E \) \( v_{sat} \sim \text{constant} \)

\[
\frac{1}{\tau} = \frac{1}{\tau_{\text{intr}}} + \frac{1}{\tau_{\text{rad-ind}}} \quad \text{and} \quad \frac{1}{\tau_{\text{rad-ind}}} = \beta \phi
\]

Bad quality samples eg. pcCVD (or thin) appear more rad-hard when looking at CCE

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scCVD diamond

**Samples:**
- single crystal CVD diamond – producer e6
- free standing thin films 3-5 x 3-5 x 0.05 - 0.5 mm³
- <100> oriented

**Atomic impurities:**
- extremely low concentration of N (<5ppb) and B (<1ppb)

**Macroscopic impurities:**
- most of the samples contains threading dislocations

**Detector fabrication:**
- cleaning and wet oxidation
- electrodes sputtering using shadow masks
- pad motive of ‘sandwich’ geometry
- Cr(50nm)Au(100nm)+annealing or Al(100nm)

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scCVD diamond

**Transport properties:**

- can be operated at drift saturation velocity $\sim 10 \text{ V/}\mu\text{m}$
- velocities for e and h $\sim 140 \text{ µm/ns } @ \text{ 10 V/µm}$
- lifetime approaching 1µs $\rightarrow$ CCD approaching several cm

![Graphs and diagrams related to transport properties and output signal vs. time.]

'Spectroscopic' grade

- Data on electronic and hole mobilities, drift velocities, and energy spectra with peaks at various energies (e.g., 5.443 MeV, 5.449 MeV).

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26 MeV protons irradiation

Proton beam in Karlsruhe:

- 26 MeV
- beam current 500nA - 40µA
- beam radius 1mm – 1cm
- temperature ~-10 °C (cold N2)
- time for 1e14p/cm² on 12x12cm²: ~2min

Dosimetry well established (RD50 Si irradiation):
- initially calibrated
- nickel foil activation (dose verification if needed)

<table>
<thead>
<tr>
<th>sample</th>
<th>beam current [µ A]</th>
<th>irradiation time [min]</th>
<th>integral fluence Φ [26 MeVp/cm²]</th>
<th>integral fluence Φ [26 MeV p/cm²]</th>
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<td>BDS14</td>
<td>0.6</td>
<td>2</td>
<td>5.35 × 10¹³</td>
<td>6.38 × 10¹³</td>
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<td>2</td>
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<td>6.11 × 10¹⁴</td>
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<td>BDS13</td>
<td>12</td>
<td>22</td>
<td>1.07 × 10¹⁶</td>
<td>1.18 × 10¹⁶</td>
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<tr>
<td>s256-05-06</td>
<td>0.2</td>
<td>6 × 3</td>
<td>1.07 × 10¹⁴</td>
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</table>

annealed Cr(50nm)Au(100nm)

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SETUP AND EXAMPLES OF CURRENT SIGNALS

~20 MeV neutrons irradiation
(thanks to Otilia Militaru)

High flux fast neutron line in Louvain-la-Neuve:

- ~ 20 MeV
- max. flux $6.6 \times 10^{12}$ n sr$^{-1}$ s$^{-1}$
- contamination gammas~2.4%, charged ~0.03%
- temperature ~-10C (cold N2)
- irradiation time about 6h

Dosimetry well established (RD50 Si irradiation):
- initially calibrated
- PAD (dose verification)

<table>
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<th>sample</th>
<th>Integrated fluence</th>
<th>current int.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PAD dosimetry</td>
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<td>BDS12</td>
<td>$1.14 \times 10^{14}$</td>
<td>$1.16 \times 10^{14}$</td>
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<tr>
<td>BDS12</td>
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<tr>
<td>john100</td>
<td>$2.05 \times 10^{15}$</td>
<td>$2.63 \times 10^{15}$</td>
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</tbody>
</table>

Al 100nm

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~20 MeV n – on-line monitoring

- tunnel card developed for BML system of LHC (Steffen Mueller talk)
- biased detectors with DC current read-out
- Hamamatsu Si diode irradiated in parallel

- drop of the current and unexpected low CCD/CCE (bias induced polarization)
- however.... beam induced I ~ two orders of mag. over the dark current
- Si → self-heating leads to thermal runaway

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Optical Absorption – 26MeV p irradiation
(thanks to Prof. Schwartz)

- low sensitivity but absolute estimation of the concentration of the defects possible
- RT and cryo measurements

- only three ZPL; GR1-neutral mono-vacancy, R2, R11- split self-intersitial
- using ESR calibration constant of proportionality (Twitchen et al.) \( \rightarrow \sim 10^{17} \, V^0/cm^3 \)
- about 20x lower than expected from NIEL

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Photoluminescence - ~20MeV n irradiation

- high sensitivity but only relative comp.
- LNT measurements
- mainly GR1 (neutral mono-vacancy)
- residual defects (NV\(^0\), R2, some others)
- linear introduction rate

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Electronic Characterization

**Transient Current Technique:**
short range $\alpha$-source (Am241-~5.5 MeV)
50Ω impedance DBA II, bandwidth 2.4 GHz, gain ~120
Digital Scope, bandwidth 3GHz, 20GS/s

**Charge Collection Efficiency (primed state):**
Sr-90 $\beta$-source - triggered $\varepsilon > 1.5$ MeV - ~MIP eq.
Low noise CSTA2 (Darmstadt) and A250CF (Amptek) preamplifier - shaping time 1μs
Classical electronics chain
Cross calibrated pulser + Si detector (known $\varepsilon$)

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Dark Current and TL

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Transient Current Signals

26 MeV p irradiation; Cr(50nm)Au(100nm) annealed electrodes

velocity didn’t change
no additional scattering
No space charge

\[ \phi = 6.38 \times 10^{13} \text{ p/cm}^2 \]
\[ \tau_e = 11 \text{ ns} \]

\[ \phi = 1.07 \times 10^{14} \text{ p/cm}^2 \]
\[ s256-05-06 \]
\[ E = 1.32 \text{ V/\mu m} \]
\[ \tau_e = 5.9 \text{ ns} \]
\[ \tau_h = 6.3 \text{ ns} \]

\[ \phi = 6.11 \times 10^{14} \text{ p/cm}^2 \]
\[ E_{\text{ext}} = 1.6 \text{ V/\mu m} \]
\[ \tau_e = 1.33 \text{ ns} \]
\[ \tau_h = 1.7 \text{ ns} \]

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Bias-induced polarization

20 MeV n irradiation; Al(100nm)

Similar effect observed in CdTe and irradiated cryo Si (reverse biased)

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Transient Current Signals

~20 MeV n irradiation; remetallized Cr(50nm)Au(100nm) annealed contacts

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TCT $\rightarrow$ trapping time (unprimed state)

$\beta_n = \beta_p$ - non-scalable with NIEL

$\beta$ - about twice higher than in Si(!) - no re-trapping

**$V^0$ cross-section for trapping**

$$\tau_{e, n} = \left( \sigma v N \right)^{-1} \quad \sigma_{V^0} \approx 6 \times 10^{-15} \text{ cm}^{-2}$$

---

**26MeV p**

![Graph showing $\tau_{e, n}$ vs. $E$ for 26MeV protons with different symbols for different datasets.](image1)

**~20MeV n**

![Graph showing $\tau_{e, n}$ vs. $E$ for 20MeV neutrons with different symbols for different datasets.](image2)

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TCT $\rightarrow$ trapping related effects

BDS14 $d=490$ $\mu$m after $6.39 \times 10^{13}$ 26 MeV proton/cm$^2$

Stopped $\rightarrow$ polarization traversing $\rightarrow$ priming

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Charge Collection for MIP

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Charge Collection

Are the detectors fully depleted?

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CCE $\rightarrow$ CCD

Hecht

$\delta/d$

$CCE - Q_{in}/Q_0$

$CCE = Q_{in}/Q_0$

$CCD$ [$\mu m$]

$RT$

$10^14$ $10^15$ $10^16$

$\Phi_{26\text{MeV} p}; 20\text{MeV n}$ [cm$^{-2}$]

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Summary

We’ve damaged eight scCVD:

- no increase of the dark current after irradiation
- mainly neutral mono-vacancy (other complex defects(?))
- no space charge is observed after irradiation (CrAu electrodes)
- bias-induced polarization appears for samples metallized with Al
- no degradation of charge carriers velocity or mobility, only trapping
- effective trapping time proportional to the fluence
- equal $\beta$ for 26MeV p and 20MeV n - NIEL violation

- after irradiation - priming and polarization phenomena are observed
- about $\times$ 2.3 increase in CCD of primed detectors
- shape of the Landau distribution remains constant (up to $10^{15}$) but MPV drops
- after $1.2 \times 10^{16}$ 26MeV/p well separated signal above the noise

- scCVD (as a material) is not less radiation hard than pcCVD
Open questions

During irradiation:
- Self-annealing - is 43eV at RT valid?
- flux influence on self-annealing
- influence of biasing during irradiation

After irradiation:
- contacts influence - bias induced pol.
- polarization of primed detectors
- other defect - optically non-active
- light, temp sensitivity

How to compare with silicon? → S/N, no cooling etc.

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Outlook or How to Proceed

NIIEL verification:
- low fluence irradiation (<5x10^{14} part/cm^2) + TCT
- PL relative comparison of V^0 introduction rate (other defects)

Limits of diamond:
- more high fluence irradiations (>10^{15} part/cm^2)

Contact influence:
- try various metallization to explore bias-induced polarization

Defects spectroscopy:
- TL and TSC - too deep levels (?)
- PL extended range
- others ...DLTS(?)

Numerical simulations:
- priming, polarization etc.

How to improve:
- injecting contact for irradiated detectors? (cryo Si CID)
- light illumination, temperature
- go 3D
TRANSIENT CURRENT SIGNALS

\[ i(t) = Q_{gen} \frac{V_{dr}(E_{in})}{d} \cdot e^{-t/\tau_{e,h}} \]

\[ Q_{col-e,h}(E) = \int_{0}^{t} i_{e,h}(E,t)dt \]

CLOSE TO “IDEAL” TRANSIENT CURRENT SIGNALS

NEGATIVE SPACE CHARGE \((N_{eff} \approx 2.8 \times 10^{11} \text{ cm}^{-3})\)

CHARGE TRAPPING

APPROACHING SILICON DETECTORS

$^{241}\text{Am} \alpha$-particle spectrum measured using CS electronics

ORTEC Silicon detector

$d=100\mu m$

$\tau_c \sim 1\text{ms}$

$\tau_r = 4\text{ns}$

“OUR” SILICON DETECTOR

Silicon detector

$HV = -120\text{V}$

$14\text{keV}$

$\tau_c \sim 1\text{ms}$

$\tau_r = 10\text{ns}$

SC CVD DIAMOND DETECTOR

$17\text{keV}$

$d=480\mu m$

$5.486\text{MeV}$

$\tau_h \sim 968\text{ns}$

$\tau_r = 4.5\text{ns}$

$\Delta E (\text{FWHM}) < 25\text{ keV}$

How to improve: grow better quality crystals or use thin detectors

At RT resolution of Si detector is governed by electronic noise due to leakage current and capacitance

$\Delta E = 2.355 \sqrt{F E_0 \varepsilon_i + (\Delta e / 2.355) + a_1 E_0^{a_2}}$

PhD seminar at GSI, 07/02/2007
CHARGE COLLECTION - $Q_{\text{col}}$
LIFETIME, $Q_{gen}$ and $\epsilon_{avg}$

Hecht: \[
CCE = \frac{Q}{Q_0} = \left(\frac{\tau_{e,h}}{\tau} \right) \left(1 - \exp^{-\frac{\tau}{\tau_{e,h}}} \right)
\]

\[
\tau_{e, h} >\gg \text{transient time}
\]

$Q_{gen} = 68.6 \text{ fC} (\pm 0.2) \rightarrow \epsilon_{avg} = 12.8 (\pm 0.05) \text{ eV/e-h}$

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IRRADIATION 26MeV PROTONS

Irradiation in Karsruhe with 26 MeV protons

Homogeneous energy deposition, dose well known

Optical Absorption spectra at 7K

only GR1 and R11 → no other zero-phonon lines e.g related to N, or aggregates

Leakage current decreases

-Leakage current at the detection limit (I < 10^{-13} A/mm²) up to 2V/µm

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$T_{\text{eff}}$ - effective trapping time

$$Q_{\text{coll}} = Q_{\text{gen}} \cdot \exp\left(-\frac{t}{\tau_{\text{eff}} - \epsilon, k}\right)$$

A good parameter $\tau_{\text{eff}}$...... and even better one... $t_{\text{tr}}/\tau_{\text{eff}}$

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IRRADIATION 26MeV PROTONS

stopped particles $\rightarrow$ polarization

- pulse high decreases with time for alpha particles

traversing particles $\rightarrow$ priming

- stable operation
- $CCE(CCD)$ increases due to deep traps filling

defects can be annealed

- about 70% (holes) 50% (electrons) electrically active
defects annealed out after 3h at 1000°C (sample BDS14)

...obviously insufficient statistics
we need some more samples
to be destroyed!

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Radiation damage at **LOW energy** dominated by elastic cross section. C-nuclei have factor two smaller Z than Si and higher displacement energy ($\approx 40$ eV vs $20$ eV)

Radiation damage at **HIGH energy** dominated by inelastic cross section. C-nuclei smaller and more stable than Si. Diamond order of magnitude better than Silicon.

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START DETECTOR FOR ToF SYSTEMS

New RH and fast start detector needed

PRINCIPLE OF TIMING MEASUREMENT

\[ \sigma_{\text{intr}} < 50\text{ps} \]

REQUIREMENTS FOR START DETECTOR:

\[ \sigma_{\text{ToF}} = \frac{\sigma_N}{\left| \frac{dV}{dt} \right| \text{thr}} \]

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RESULTS FOR $^{27}$Al 2AGeV - FoPi

TIME DIFFERENCE D1 vs D2

INTRINSIC RESOLUTION: $\frac{\Delta t_{D1} - \Delta t_{D2}}{\sqrt{2}}$

$\sigma_{\text{intr}} = 28\text{ps}$

limited only by electronics (TDC 50ps/bin)

FOR MIP p SC DIAMOND ONLY HOPE

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FRAGMENTATION AT FRS OF GSI

PhD seminar at GSI, 07/02/2007
FRS - PRELIMINARY RESULTS

132-Xe 740 AMeV fragmentation spectrum

SC-CVD-DD
E=2V/micron

Z=47

Z=48

Z=49

Z=50

ADC channel [a.u.]

measured signal SCL

calculated total current non-SLC (τ=210ps)

Traversing particle --> Q₀=20.05 pC

Sample thickness d=400µm

HV = 500V

measured

EVEREST simulated

simulated after APLAC (see diagram)

500V

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MORE DATA

Relativistic protons (1-2 GeV) (timing)
- stable operation over a week (rates up to 1MHz)
- 100% separation from electronic noise (d=400µm)
- unsatisfactory timing → electronics development needed

Low energy (6 MeV/u) ions (p, He, Li) (timing, ΔE)
- good energy resolution ~1% (limited by experimental set-up)
- very good timing properties σ_{intr} ~ 30ps

Heavy ion beams Ta, Al, C, Ca (timing, ΔE) (FoPi)
- good energy resolution ~1%
- very good timing properties σ_{intr}~30 ps
SUMMARY and CONCLUSIONS

SC CVD Diamond as \( \Delta E \) detector:
- lifetime of charge carriers >> transient time \( \rightarrow \) CCE \( \sim 100\% \) at low E
- stable detection
- max. energy resolution (17keV/5.5MeV)
- \( \epsilon_{\text{avg}} = 12.8 \text{ eV/e-h} \)

homogeneous material suitable for energy loss spectroscopy

SC CVD Diamond as Timing detector:
- high mobility (\( e^- 1300-3100; h^-2400 \) [\( \text{cm}^2/\text{Vs} \)])
- transient signals 1 \( \text{ns}/100\mu\text{m} \), uniform \( t_{rs} < 150\text{ps} \)
- very good intrinsic time resolution (\( \sigma_{\text{int}} \sim 28 \) ps) (heavy ions)

fast device perfect for start detectors

Heavy irradiations with 26 MeV protons
- leakage current drops (no electronics noise), CCE drops, polarization and priming phenomena
- diamond is expected to be at least 10x more radiation hard than Si at higher energies

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OUTLOOK

**X-ray microbeam mapping at ESRF** - to find possible correlation with macroscopic defects (May'07)

**MIP timing** measurements with "stacked" diamonds using BB and fast CS electronics (May'07)

**Detailed radiation hardeness tests** --> irradiation with protons (26MeV) in Karlsruhe

  fast neutrons in (~1MeV) Ljubljana ( ~10MeV) Leuven

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PARTICIPANTS

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ENERGY NEEDED TO CREATE e-h PAIR

Rule \sim 3\times E_g \text{ is not valid for diamond}

Various values reported up to now for diamond:

- From 19 eV/e-h $\rightarrow$ 13.1 eV/e-h
- From calculation 11.8 eV/e-h diamond

Charge creation is not a random process

$\sigma = \sqrt{N}$

$\sigma = \sqrt{F \times N}$ - intrinsic resolution
where $F < 1$ is the fano factor

general trend measured $\epsilon$ decreases when charge carriers lifetime increases
CCE mapping – ion microbeam at GSI