Synthetic single crystal diamond dosimeters for radiotherapy

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INFN – DIARAD Project (2008-2010)

Università di Roma “Tor Vergata”
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- Diamond growth
- Device fabrication
- Tests

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“S. Filippo Neri” Hospital
- Varian accelerator facility
- Clinical tests

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- Design and realization of on-chip electronics

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- Electronic properties

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- Electronic properties

C. Manfredotti
Outline

✓ Why diamond?
✓ State of the art:
  ▪ Natural diamond (ND)
  ▪ HPHT diamond (HPHT)
  ▪ Polycrystalline diamond (PCVD)
✓ Our devices: dosimetric characterization
✓ Our devices: IMRT characterization
✓ Conclusions
Diamond properties

**ELECTRONIC PROPERTIES**

- Band gap: 5.4 eV
- Electrical resistivity: $10^{16} \ \Omega \text{cm}$
- Electrical breakdown: $10^7 \ \text{V/cm}$
- Electron mobility: $1800 \ \text{cm}^2/\text{V s}$
- Hole mobility: $1600 \ \text{cm}^2/\text{V s}$
- Max velocity of electrons: $2.7 \times 10^7 \ \text{cm/s}$

**“DOSIMETRIC” PROPERTIES**

- Solid state ionization chamber
- Tissue equivalence
- High spatial resolution
- Photovoltaic regime operation
- Radiation hardness
- High T working capability

**Low noise, high speed detectors**

**Application in radiotherapy and proton therapy**
Which Diamond?

- Natural
  - ND-D
- HPHT
  - HPHT-D
- Single-crystal CVD
  - SCVD-D
- Polycrystalline CVD
  - PCVD-D
**State of the art: ND-D**

- **Pre-irradiation process needed in order to stabilize the detector signal before daily use**
- **10-15 Gy (sample dependent)**

**Response time (sample dependent)**
A sublinearity is usually observed in NDD and fitted according to the Fowler model: $I = I_{\text{dark}} + R D^\Delta$

Once the $\Delta$ value has been determined, the sublinearity is accounted for by software correction of the measured dose.

The $\Delta$ coefficient is sample dependent and must be carefully determined for each sample.
State of the art: HPHT - D

A study of radiation dosimeters based on synthetic HPHT diamond

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Photoluminescence topographs of two different HPHT samples
HPHT-D: dose rate dependence

The fabrication process is not reproducible, the concentration of contaminants and impurities may differ considerably from sample to sample.

<table>
<thead>
<tr>
<th>Sensitivity (nC/Gy)</th>
<th>Gain (G)</th>
<th>d (μm)</th>
<th>Slope (Δ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>28.62</td>
<td>0.46</td>
<td>128</td>
<td>0.94(2)</td>
</tr>
<tr>
<td>26.05</td>
<td>0.30</td>
<td>89</td>
<td>0.88(2)</td>
</tr>
<tr>
<td>19.53</td>
<td>0.22</td>
<td>62</td>
<td>0.85(2)</td>
</tr>
<tr>
<td>41.34</td>
<td>0.57</td>
<td>180</td>
<td>0.97(2)</td>
</tr>
<tr>
<td>6.58</td>
<td>0.11</td>
<td>29</td>
<td>0.84(2)</td>
</tr>
<tr>
<td>3.87</td>
<td>0.06</td>
<td>16</td>
<td>0.76(6)</td>
</tr>
<tr>
<td>4.46</td>
<td>0.1</td>
<td>24</td>
<td>0.68(1)</td>
</tr>
<tr>
<td>6.55</td>
<td>0.07</td>
<td>21</td>
<td>0.49(5)</td>
</tr>
</tbody>
</table>
State of the art: PCVD -D

Diamond dosimetry: Outcomes of the CANDIDO and CONRAD INFN projects

M. Bucciolini$^{a,b}$, E. Borchia$^a$, M. Bruzzi$^b$, M. Casati$^a$, P. Cirrone$^b$, G. Cuttone$^b$, C. De Angelis$^b$, I. Lovik$^a$, S. Onori$^a$, L. Raffaele$^c$, S. Sciorino$^b$

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Available online 1 July 2005

✓ Grain boundaries and structural defects
✓ Memory effects and persistent conductivity

Priming needed and slow response times
**Motivation summary**

Natural diamond dosimeters already in the market (PTW – Freiburg) for absolute and relative dosimetry (IAEA certified)

- **Natural diamonds:**
  - differences between different natural stones (NDD)
  - very low yield of the selection process (1 good out of 4000 !)
  - high cost (~15 k€)
  - very long delivery times (more than 1 year)

- **HPHT and PCVD synthetic (SCD) diamonds:**
  - Simply not good enough
**Goal**

SCVD synthetic diamond based dosimeter with as many as possible of the following features:

- No priming effect
- Stability
- Fast response time
- Linearity with dose and dose rate
- Response independent from the radiation energy
- Tissue equivalence
- High sensitivity
- Small size (high spatial resolution)
- Low bias voltage
- Radiation hardness
- Low cost
- Comparable with IC
- Response independent from dose rate
- Reliable and reproducible

High reproducibility of the fabrication process is a major issue.
**SCVD-D: scheme of our device**

- High quality Synthetic Single Crystal CVD Diamond
- Tissue equivalent
- No bias voltage needed ($V_b=0$ V)
- Highly reproducible manufacturing
- Compact (5x5x0.5 mm)
- Low cost

Electrons, Photons, Protons

- Ag contact
- Al contact
- Output
- CVD Intrinsic
- CVD B-doped
- HPHT substrate
Images

Waterproof casing and connector

X-ray image
• **Pre-irradiation performed before daily use** (black curve)

• **Less than 1% fluctuations after the pre-irradiation procedure** (red curve)

• **10-15 Gy needed for stable operation** (same as NDD)
After pre-irradiation, the signal is stable within (much) less than 1%
**SSCD: stability**

- Very small priming (if any) and no repriming
- Excellent stability (short and long term !)
- Very fast response time
- High S/N

"Synthetic single crystal diamond diodes for radiotherapy dosimetry"
- **Time behaviour of the SCD current during a multi-step irradiation process**
- The dose rate was changed so to deliver different doses in the same step duration
- No overshoot observed
- Good S/N ratio (200-1000)
- Fast response time (< 0.1 s)
- Very low dark current (< 100 fA)
Linearity: dose dependence

10 MV Photons

SSCD measured dose as compared with the given dose

Equation: $y = a + b \times x^c$

Adj. R-Square: 0.99998

<table>
<thead>
<tr>
<th>Value</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.00446</td>
</tr>
<tr>
<td>b</td>
<td>0.00936</td>
</tr>
<tr>
<td>c</td>
<td>1.00245</td>
</tr>
</tbody>
</table>

SSCD Dose (nC) vs Delivered Dose (Gy)

Deviation from linearity (%)

Delivered Dose (Gy)

Dose (Gy)
• The Dose Rate was evaluated by changing the accelerator pulse repetition frequency (PRF).

• In all cases a linear behavior was observed, with 0.99<\(c\)<1.01.

• This is NOT observed in NDD. They need a software correction factor to take into account this problem.

![Graph showing dose rate dependence](image)

Equation: \( y = a + b \cdot x^c \)

<table>
<thead>
<tr>
<th>Value</th>
<th>Standard Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>4.54186E-4</td>
</tr>
<tr>
<td>(b)</td>
<td>0.03003</td>
</tr>
<tr>
<td>(c)</td>
<td>1.00871</td>
</tr>
</tbody>
</table>

Adj. R-Square: 0.99998
Energy dependence

- Tests have been done with all of the available radiation qualities.
- Energy dependence of the order of ± 1% was observed.
- The sensitivity is quite low if compared with NDD, but similar to the one of commercial "pin point" ionization chambers.
PDD: electrons

A perfect agreement is found between SSCD and IC with no need of any dose rate correction of the as measured data from the SSCD.
Reproducibility (6 MV photons)

- Two different devices were separately measured and the measurements were both repeated after about one month.
- No difference observed between the response from the two devices.
- No changes observed after a prolonged no-use period.

Many samples were produced with nearly identical properties. Reproducibility seems to be no longer a concern.
IMRT

✓ IMRT (Intensity Modulated Radiation Therapy) is a computer-designed modulation of the intensity across a radiation beam during clinical radiotherapy treatments of cancer disease

✓ IMRT is accomplished by dividing the treatment into several beamlets, delivered by a “Step and Shoot” technique

✓ Each beamlet is computer-programmed to hit areas within the target for a specific amount of time, until the entire coverage objective has been met
IMRT: step & shoot technique
IMRT

- Test performed by using a prostate cancer IMRT treatment, consisting of 10 complex shape segments
- Each segment is made of several "step and shoot" sequences
- A highly conformed dose profile is achieved
- IMRT is characterized by high dose gradients and lack of charged particle equilibrium

STRINGENT REQUIREMENTS ON THE DOSIMETER DETECTION CAPABILITY
Diamond dosimeters:
- Polycrystalline CVD diamond (Poly-CVD)
- Natural Single Crystalline Diamond (NSCD)
- Synthetic Single Crystalline CVD Diamond (SSCD)

"Present limitations of CVD diamond detectors for IMRT applications"
“Real” dosimeters

PTW Semiflex IC
(SF in the following)
- Ionization Chamber
- Volume: 125 mm³
- Sens.: 3.29 nC/Gy
- V bias: 400 V
- Application: absolute dosimetry in radiotherapy beams
- Waterproof

PTW Pinpoint IC
(PP in the following)
- Ionization Chamber
- Volume: 15 mm³
- Sens.: 0.41 nC/Gy
- V bias: 400 V
- Application: dosimetry in high-energy photon beams with high spatial resolution
- Waterproof

Diamond Dosimeter
(SSCD in the following)
- Single crystal diamond
- Volume: < 0.1 mm³
- Sens.: 4.10 nC/Gy
- V bias: 0 V
- Application: under evaluation and certification
- Waterproof
SSCD vs. PP: sensitivity

SCD dosimeter vs. Pinpoint IC

Current (pA) vs. time (s)
**Spatial resolution: wedge adsorber**

Profile of the beam shaped by a stainless steel wedge absorber

Better spatial resolution than commercial IC
Characterization of SSCD diamond based dosimeters for application in radiotherapy

Results comparable with the ones widely reported in literature for commercial (PTW) natural diamond based dosimeters

- No energy dependence (tissue equivalent)
- Limited dose rate dependence ($\Delta \approx 1$)
- Small dimensions (good spatial resolution)

Advantages

- Synthetic diamond
- Very high reproducibility of the whole fabrication process
- Relatively low cost and large scale production
- Good control of the structural and physical properties of the raw material
- Zero bias voltage as a "standard" operating condition
Conclusions

- **Characterization of SSCD dosimeters for IMRT radiotherapy**

- **Results comparable with the reference commercial IC, but:**
  - Better spatial resolution than the Semiflex IC
  - Much higher sensitivity than the Pinpoint IC (“designated” IMRT detector)

- **Our prototypes are currently under evaluation and certification by two leader companies in the market of radiotherapy dosimetry**
**SSCD vs. SF: spatial resolution**

![Graph showing the comparison between SCD, Pinpoint IC, and Semiflex IC over time.](image)
SSCD: reliability
Comparison

![Graph showing normalized dose vs position with different markers for SCD dosimeter, Pinpoint IC, Semiflex IC, Map Check, and Nominal Dose.]

<table>
<thead>
<tr>
<th>Position</th>
<th>Coordinates (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(0, 0)</td>
</tr>
<tr>
<td>2</td>
<td>(40, 0)</td>
</tr>
<tr>
<td>3</td>
<td>(80, 0)</td>
</tr>
<tr>
<td>4</td>
<td>(-40, 0)</td>
</tr>
<tr>
<td>5</td>
<td>(-80, 0)</td>
</tr>
<tr>
<td>6</td>
<td>(0, 40)</td>
</tr>
<tr>
<td>7</td>
<td>(0, 80)</td>
</tr>
<tr>
<td>8</td>
<td>(0, -40)</td>
</tr>
<tr>
<td>9</td>
<td>(0, -80)</td>
</tr>
</tbody>
</table>
SSCD vs SF: spatial resolution

X direction

Y direction
PCVD-D: time dependence

Slow response times, dose, dose rate and energy dependence are usually observed in the case of Poly-CVD detectors
The hospital facility

**Experimental setup:**
- Varian DHX accelerator
- Water phantom (PTW)
- Tandem electrometer (PTW)
- Unidos electrometer (PTW)
- Mephisto software (PTW)

- The on-site acquisition system is used
- No need of dedicated electronics