Synthetic diamond based dosimetric systems for radiation therapy techniques

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Outline

- Introduction
- SCDD dosimeter (PTW microDiamond)
- Novel in-vivo dosimeter
- 2D array dosimeters
- Conclusions
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Dose measurements for radiotherapy

Measurements of the delivered dose in water are routinely performed in Radiotherapy wards:

- Treatment Planning System (TPS) commissioning
- Beam quality control

The quantity to be measured is the absorbed dose in water:

Energy per unit mass deposited in water by the radiation

\[ D_W = \frac{\Delta E_W}{\Delta m} \]
Dose measurements for radiotherapy

An ideal dosimeter should:

- measure the dose in water independently from the energy spectrum: it should have the same “energy response” as water
- not modify the radiation field: same interaction with radiation as water
- be small (small field dosimetry capability)
Dose measurements for radiotherapy

Reference dosimeters
Ionization Chambers
- Low sensitivity per unit volume
- High voltage
- Polarity correction needed
- Pressure and temperature correction needed
- Stopping power ratio correction needed (electrons)

Silicon diodes
- Small size
- Not “water equivalent”
- High energy dependence

Different dosimeters are needed depending on the utilized beam
Diamond properties

Diamond Properties

- HARDNESS: 9000 Kg/mm² (the highest)
- BAND-GAP: 5.5 eV
- YOUNG’S MODULES: 1012 N/m² (the strongest)
- FRICTION: 0.05 (the lowest)
- THERMAL CONDUCTIVITY: 20 W/cm K (5 times Cu)
- ELECTRICAL RESISTIVITY: $10^{16}$ Ωcm
- ELECTRICAL BREAKDOWN: $10^7$ V/cm (30 times GaAs)
- ELECTRON, HOLE MOBILITY: >2000 cm²/V s
- OPTICAL ABSORPTION: transparent from IR to IV (5.4 eV)
- MELTING POINT: 3350 °C
- RADIATION HARDNESS: very high
- CHEMICAL REACTIVITY: extremely low

Diamond applications

- Radiation detectors
  - Particle detectors
  - E-UV, V-UV sensors
  - Soft-X sensors
- Transistors
  - Fast FET
  - High power FET
- Quantum computing
- Chemical sensors
- Optical windows
- Biological application
- Cold cathodes / field emitters
- Heat spreaders
## Diamond properties compared to Si

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>Diamond</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bandgap</strong></td>
<td>1.12 eV</td>
<td>5.47 eV</td>
<td></td>
</tr>
<tr>
<td><strong>Density</strong></td>
<td>2.33 g cm(^{-3})</td>
<td>3.52 g cm(^{-3})</td>
<td></td>
</tr>
<tr>
<td><strong>Atomic Number</strong></td>
<td>14</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td><strong>Breakdown field</strong></td>
<td>0.3 MV/cm</td>
<td>10 MV/cm</td>
<td></td>
</tr>
<tr>
<td>(v_{\text{sat}}) (electrons)</td>
<td>0.86 x 10(^7) cm/s</td>
<td>2 x 10(^7) cm/s</td>
<td></td>
</tr>
<tr>
<td>(v_{\text{sat}}) (holes)</td>
<td>-- x 10(^7) cm/s</td>
<td>0.8 x 10(^7) cm/s</td>
<td></td>
</tr>
<tr>
<td><strong>Mobility (e(^-))</strong></td>
<td>1450 cm(^2) V(^{-1}) s(^{-1})</td>
<td>4500 cm(^2) V(^{-1}) s(^{-1})</td>
<td></td>
</tr>
<tr>
<td><strong>Mobility (holes)</strong></td>
<td>480 cm(^2) V(^{-1}) s(^{-1})</td>
<td>3800 cm(^2) V(^{-1}) s(^{-1})</td>
<td></td>
</tr>
<tr>
<td>(\rho_{\text{int}})</td>
<td>2.3 x 10(^5) (\Omega) cm</td>
<td>&gt; 10(^{11}) (\Omega) cm</td>
<td></td>
</tr>
<tr>
<td><strong>Displacement E</strong></td>
<td>25 eV</td>
<td>35-48 eV</td>
<td></td>
</tr>
<tr>
<td><strong>Specific sensitivity</strong></td>
<td>640 nC Gy(^{-1}) mm(^{-3})</td>
<td>240 nC Gy(^{-1}) mm(^{-3})</td>
<td></td>
</tr>
</tbody>
</table>

### Effects on dosimetric properties
- Z=6: weak energy dependence
- Wide gap: low leakage current
- High energy displacement threshold: high radiation hardness
- Density:
  - specific sensitivity about 7000 times higher than air
  - small size dosimeters
  - high spatial resolution
Energy dependence

Energy Response and tissue equivalence: scattering and absorption properties should match those of water for a given radiation

Relative mass absorption coefficient

- Photoelectric effect is dominant at low energy and proportional to $Z^3$

- High $Z$ results in an overestimation of dose at low-energy (scattered) radiation

Electron stopping power ratios

- Diamond / H$_2$O ratio is approximately constant in the whole range

- Good energy response at high energies
- No corrections needed for electrons
In summary, why a diamond dosimeter?

<table>
<thead>
<tr>
<th>Detector</th>
<th>Size for same response</th>
<th>Spatial Resolution</th>
<th>Energy dependence: Low energy</th>
<th>Energy dependence: High energy</th>
<th>Beam quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air filled Ionization Chamber</td>
<td>1</td>
<td>medium</td>
<td>excellent</td>
<td>corrections needed</td>
<td>Different ICs for photons, electrons and protons</td>
</tr>
<tr>
<td>Si-Diode</td>
<td>18000 smaller</td>
<td>excellent</td>
<td>bad</td>
<td>medium</td>
<td>Different Si-Ds for photons and electrons (no protons)</td>
</tr>
<tr>
<td>Diamond</td>
<td>7000 smaller</td>
<td>excellent</td>
<td>good</td>
<td>good</td>
<td>One single dosimeter for all?</td>
</tr>
</tbody>
</table>

From the theoretical point of view, diamond is a very suitable material for dosimetry applications in radiation therapy.
Natural diamond

Natural diamond dosimeter (PTW-Freiburg)

- Good energy response
- Near water-equivalent
- Good sensitivity per unit volume
- Small size

Drawbacks

- Limited availability (!)
- High cost
- Low reproducibility (!)
- Dose rate dependence
- LET dependence in proton dosimetry
Introduction

SCDD dosimeter (PTW microDiamond)

Novel in-vivo dosimeter

2D array dosimeters

Conclusions
SCDD: our device

Single crystal diamond grown by CVD microwave at the Rome Tor Vergata University Laboratories

SCDD: Single crystal diamond grown by CVD microwave at the Rome Tor Vergata University Laboratories.
PTW microDiamond T60019

Detectors

microDiamond

Highlights

- Worldwide first commercially available synthetic single crystal diamond detector for clinical radiation therapy
- Smallest sensitive volume (0.004 mm³) of all available detectors – perfect choice for small field dosimetry for electron, photon and proton beams
- High accuracy over a wide range of field sizes from 1 cm x 1 cm to 40 cm x 40 cm
- Significant advantages over commonly used silicon diode detectors: excellent radiation hardness, temperature independence; near-tissue equivalence; small directional dependence
- No high voltage required. Available for all connecting systems.

Type 60019

Developed by Marco Marinelli, Gianluca Verona-Rinati and their team at the Industrial Engineering Department of Rome Tor Vergata University, Italy

Commercialization – 01.08.2013

PTW-Freiburg leaflet: www.ptw.de
**microDiamond**

*Synthetic Diamond Detector*

<table>
<thead>
<tr>
<th>Specifications</th>
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<tbody>
<tr>
<td><strong>Type No.</strong></td>
</tr>
<tr>
<td><strong>Design:</strong></td>
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<tr>
<td><strong>Measuring quantity:</strong></td>
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<tr>
<td><strong>Nominal sensitive volume:</strong></td>
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<tr>
<td><strong>Reference point:</strong></td>
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<td><strong>Nominal response:</strong></td>
</tr>
<tr>
<td><strong>Detector bias:</strong></td>
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<td><strong>Radiation quality:</strong></td>
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<td><strong>Field size:</strong></td>
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<td><strong>Connectors:</strong></td>
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</table>
Commercial device presented for the first time at:

- AAPM 2013 conference (American Association of Physicist in Medicine)
- ESTRO 2014 conference (European Society for Radiotherapy and Oncology)
Pre-irradiation, stability and linearity

- **Pre-irradiation**: 0 – 5 Gy needed before daily use to reach a signal stability within ±0.5 %
- **Rise and decay times**: less than 0.1 s
- **Long term reproducibility**: 0.4% over 18 months
- **Dose linearity**: best fit with linear and allometric (Fowler) functions
- **Deviation from linearity**: about ±0.1%
Energy dependence: low energy

Response under low energy X-rays (100-280 KV) normalized to the response to $^{60}\text{Co}$ beam irradiation:

- SCDD response exhibits a very weak energy dependence at low energy (if any)
- This is obviously not the case for Si-D (response 5 times higher at 100 kV !)
Photons

- **PDDs**: SCDD vs PTW 31014 PinPoint in vertical orientation
- **Difference Plots**: PTW 31014 PinPoint – SCDD (SCDD with Tor Vergata PMMA housing)

**Photons**

- **Beam profiles**: SCDD vs PTW 31014 PinPoint in vertical orientation
- **Difference plots**: PTW 31014 PinPoint – SCDD (SCDD with Tor Vergata PMMA housing)
Electronic beams

No need of stopping power ratio correction of the as measured data from the SCDD
• The diamond dosimeter is recommended for an wide range of radiation quality and field sizes

Does it work reliably for proton therapy?
Proton therapy

- Proton therapy is a growing technique which make use of proton beams to irradiate tumors.
- The advantage of proton therapy is the ability to more precisely localize the delivered dose with respect to other external beam radiotherapy techniques.
Proton therapy

- Protons produce high local ionization density
- Solid state dosimeters can exhibit a strong energy dependence due to LET variation resulting in large error in dose determination
- Severe radiation damage reported for silicon diode dosimeters
- Plane parallel ionization chambers are recommended but they cannot be used for beam profile measurements


Proton therapy: linearity

- Good linear behavior: $R^2 = 1 \pm 10^{-6}$
- Deviations from linearity about $\pm 0.5\%$, well within experimental error
Proton therapy: Bragg peaks

14 x 14 cm$^2$ square aperture

- Good agreement with Markus parallel plate ion chamber
- Differences in the peak to plateau ratio lower than 2%
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Off line in-vivo dosimeter

Development and characterization of a novel prototype diamond cable free dosimeter for in-vivo applications.
Off line in-vivo dosimeter

Reading unit

Sensitive volume: $\approx 3.8 \times 10^{-3}$ mm$^3$
Sensitivity: $\approx 1$ nC/Gy
Off line in-vivo dosimeter

- Repeatability of the measurement: 3% for 49 consecutive irradiations.
- Fading effect: 1.5% after 30 min
- Good linearity with dose
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Single crystal diamond based multi-pixel dosimeter

- Fabrication of a 3×3 diamond matrix
- New version of the dedicated readout chip
- Embedded in epoxy resin
- Developed new control software
- Tested under linac beams at PTV
Single crystal diamond based multi-pixel dosimeter

Dose-map acquired by the pixel detector for three different configuration of the multileaf collimator

Dose rate dependence (central pixel)

Linearity plot (the central pixel)

Equation \( y = a + b \times x \)

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<tr>
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<th>Standard Error</th>
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**Conclusions**

- **PTW microDiamond™ type 60019** is the first (and only) commercially available synthetic single crystal diamond dosimeter for clinical radiation therapy. It is based on a SCDD produced in Rome “Tor Vergata” University laboratories.

- **Improvements with respect** to existing dosimeters have been demonstrated in terms of energy dependence of the response and spatial resolution.

- **SCDDs can be used for relative dosimetry in a very wide range of beam qualities (including proton beams) and irradiation conditions.**

- **Future work:**
  - Development and characterization of an off-line in vivo dosimeter based on single crystal CVD diamond.
  - Single crystal diamond based multi-pixel dosimeter.
| **Partners** |
|-----------------|---------------------------------|
| **Università di Roma “Tor Vergata”**  |
| INFN – Sezione Roma 2               |
| C. Di Venanzio                     |
| M. Marinelli                       |
| E. Milani                          |
| G. Prestopino                      |
| F. Pompili                         |
| A. Tonnetti                        |
| C. Verona                          |
| G. Verona Rinati                   |
| **Policlinico “Tor Vergata” Hospital**  |
| • Radiotherapy electron beams (Elekta) |
| M. D. Falco                        |
| R. Santoni                         |
| P. Bagalà                          |
| **INFN - LNS**                     |
| • Radiotherapy proton beams         |
| G. Cuttone                         |
| L. Raffaele                        |
| G.A.P. Cirrone                     |
| **LENA-Casaccia**                  |
| • $^{60}$Co and Monte Carlo simulations |
| M. Pimpinella                      |
| A. Guerra                          |
| A. Stravato                        |
| **Loma Linda University Medical Center**  |
| • Radiotherapy proton beams         |
| B. Patyal                          |
| A. Ghebremedhin                    |
| M. Anant                           |
| **“S. Filippo Neri” Hospital**     |
| • Radiotherapy photon beams (Varian) |
| R. Consorti                        |
| A. Petrucci                        |
Recent papers

- M. Pimpinella et al. “A synthetic diamond detector as transfer dosimeter for $D_w$ measurements in photon beams with small field sizes” Metrologia 49, (2012), S207


