Advances in Synthetic Diamond Detectors Dosimetry

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Outline

• Introduction

• Overview of novel synthetic diamond detectors

• Single crystal diamond diode and PTW microDiamond

• Diamond diode dosimetric characteristics

• Diamond diode results in clinical beams

• Conclusions
Introduction

• **Diamond detectors**: solid state dosimeters with high spatial resolution and low energy dependence, suitable for small field dosimetry

• **Synthetic diamond detectors**: introduced to overcome the high cost and long delivery time of detectors based on natural gems

• **Polycrystalline CVD diamonds**: major drawbacks of detectors are high-dose pre-irradiation, poor stability, slow dynamic response (all drawbacks related to the presence of a significant amount of impurities in the diamond crystal)

• **Single crystal CVD diamonds**: in recent years detectors have been fabricated starting from high-purity synthetic crystals. However, the detector performance does not depend only on the crystal quality.
Single crystal diamond detectors

• Detectors fabricated in a sandwich structure metal-diamond-metal using commercial single crystal diamond plates

    ▪ detector-grade quality diamond by Diamond Detector Ltd (500 μm – 4.7x4.7 mm²)
    ▪ diamond-like carbon /platinum /gold ohmic contacts (3-16-200 nm – Ø 3 mm)
    ▪ valuable results only for one detector operated with -10 V polarizing voltage

    ▪ electronic-grade diamond from Element Six Ltd (165 μm – 1 x 1 mm²)
    ▪ aluminium electrodes (100 nm thickness)
    ▪ good results with a detector operated with a bias voltage of 50 V
High sensitivity 44.5 nC Gy$^{-1}$
Dose rate dependence within 1%
Low energy dependence (1.2 % from 6 to 18 MV)

Reproducibility of detector properties among different samples has not been investigated
Single crystal diamond diode (SCDD) developed at Rome “Tor Vergata” University

- Sensitive volume 0.004 mm³
- Sensitive volume diameter 2.2 mm
- Sensitive volume thickness 1 μm
- Sensitivity ~1 nC/Gy

A built-in potential at the metal-to-intrinsic diamond interface allows the device to work as a Schottky diode

Very favourable results have been obtained with an early dosimeter prototype
From SCDD to microDiamond

- **Engineered dosimeter (pre-market prototype)**
  - PTW-like housing developed in conjunction with PTW-Freiburg
  - Changes in metallic contacts
  - Changes in HPHT substrate dimensions

- **microDiamond PTW No 60019, the first commercially available synthetic diamond dosimeter**
  - Design: waterproof, disk-shaped, sensitive volume perpendicular to detector axis
  - Measured quantities: absorbed dose to water
  - Nominal sensitive volume: 0.004 mm³
  - Reference point: on detector axis, 1 mm from detector tip, marked by ring
  - Nominal response: 1 nC/Gy
  - Detector bias: 0 V
  - Radiation quality: 100 keV ... 25 MV photons and (6 ... 25) MeV electrons
  - Field size: (1 x 1) cm² ... (40 x 40) cm²
SCDD: pre-irradiation, signal stability and reproducibility in Co-60 beam

- Signal stability within 0.5% after a pre-irradiation with a dose of 2 Gy
- Measurement repeatability ≤ 0.1 %
- Short term (1 day) reproducibility ≤ 0.2%
- Long-term (1 year) reproducibility within ± 0.5%
**Dose-rate and dose-per-pulse dependence**

- $y = 1.2759 \times 10^{-11}x + 1.0010 \times 10^{00}$
  - $R^2 = 1.0000 \times 10^{00}$

- $y = 1.3125 \times 10^{-11}x + 1.0011 \times 10^{00}$
  - $R^2 = 1.0000 \times 10^{00}$

**60Co beam**: dose rate from 0.2 Gy min$^{-1}$ to 1.3 Gy min$^{-1}$ varying the source-to-detector distance

**Accelerator beams**: dose rate from 0.8 Gy min$^{-1}$ to 5.8 Gy min$^{-1}$ varying the Linac pulse repetition frequency

**Linearity index equal to unity within 0.2%**

- Reference dosimeter: Farmer type IC
- Measurements performed in a megavoltage photon beam with SSD in the range $75 \div 322$ cm

The **SCDD response is independent of dose-per-pulse within ± 0.6%**
The SCDD response is measured against a Farmer type ionization chamber (PTW type 30013) in reference conditions.

Response variations are less than 1% from 6 MV to 15 MV photon beams.

\[ D_{w\_ref} = M_{IC} \, N_w \, k_{Q\_TRS398} \]

\[ D_{SCDD} = M_{SCDD} \, N_w \]

\( N_w \) determined in Co-60 beam.
SCDD energy dependence in electron beams

\[ D_{w\_ref} = M_{IC} N_w k_{Q\_TRS398} \]

\[ D_{SCDD} = M_{SCDD} N_w \]

N\(_w\) determined in Co-60 beam
Measurements performed at z\(_{ref}\) in water

The SCDD response is measured against a plane-parallel ionization chamber (type 34001 Roos) calibrated in terms of D\(_w\) in Co-60 beam

From 6 MeV to 18 MeV the SCDD response is independent of energy within 1%
Field-size dependence in photon beams (EGSnrc Monte Carlo calculations)

MC calculations indicate an over-response in field sizes below 2 cm

The uncertainty bars are the statistical uncertainties of MC calculations

(1) Pimpinella et al, *A synthetic diamond detector as transfer dosimeter for $D_w$ measurements in photon beams with small field sizes*, Metrologia 49 (2012) S207-10
• Measurement performed in Co-60 beam at 5 cm depth in water
• Similar results have been obtained in high energy photon (1) and electron beams
• Variations < 0.5% for ± 30° tilt (in axial irradiation)

Excellent agreement between SCDD (early prototype) and a PinPoint ionization chamber (PTW 31014 in axial orientation)
**Electron beams: PDD and profile measurements**

**Characterization of a synthetic single crystal diamond Schottky diode for radiotherapy electron beam dosimetry**


**Radiotherapy electron beams collimated by small tubular applicators: characterization by silicon and diamond diodes**


**Good agreement with different types of ICs in PDD measurements**

**Excellent agreement with an unshielded silicon diode (PTW 60017) in profile and PDD measurements**
Comparison of relative output factors (ROF) for square fields with side from 2 cm to 40 cm
Reference dosimeter:
Farmer type IC from 5 cm to 40 cm
PinPoint chamber from 5 cm to 2 cm
Output factors by SCDD and IC agree within ± 1% from 2 cm to 40 cm field sizes
A comparison in FFF beams is described in ESTRO 33 EP-1468
Photon beams: measurements in small fields

Metrologia 49 (2012) S211-214

Comparison of $D_w$ measurements by alanine and synthetic diamond dosimeters in photon beams with $1 \text{ cm} \times 1 \text{ cm}$ field size

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Radiother Oncol 2013; 109(3): 356-360

Detector comparison for small field output factor measurements in flattening filter free photon beams

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Dose response is measured for various microdetectors including microDiamond against alanine dosimeters in 10 - 6 MV FFF and FF beams with field sizes from 10×10 to 0.6×0.6 cm$^2$

The microDiamond dose response ratio ranges from unity in large fields to 1.042 in the smallest field size

Br J Radiol 2014; 87:20130768

Evaluation of a synthetic single-crystal diamond detector for relative dosimetry measurements on a CyberKnife™

A CHALKLEY, MSc, BSc and G HEYES, PhD, MSc

ROF are measured in beam with diameter from 6 cm to 0.5 cm using different detectors including microDiamond

In the smallest fields, correction factors are closer to unity for the microDiamond compared to other dosimeters
Photon beams: dose verification

Med. Phys. 40 (9), September 2013

A synthetic diamond diode in volumetric modulated arc therapy dosimetry

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- **Point dose measurements by SCDD (PTW-like housing prototype) compared to ionization chamber (Exradin A1SL) measurements and dose calculations by TPS (Philips Pinnacle Smart Arc)**

- **Comparable values from SCDD and ionization chamber for dose difference (DD) and distance-to-agreement (DTA)**

- **SCDD measurements in better agreement with TPS calculations, especially in the high gradient region**
Proton beams measurements

Med. Phys. 40 (12), December 2013

Evaluation of the dosimetric properties of a synthetic single crystal diamond detector in high energy clinical proton beams

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ESTRO 33-2014 EP-1469

SCDD compared to Markus p-p chamber
Differences in peak-to-plateau ratio lower than 2%

SCDD compared to an Exradin A16 micro-chamber
Smaller penumbra values by SCDD
Proton beams: small fields

126 MeV proton beam, circular brass collimators, beam diameter 1, 2 and 3 cm


SCDD compared to an Exradin A16 IC
Differences in the peak to plateau ratio lower than 1%
Conclusions

• The first commercially available synthetic diamond dosimeter, PTW microDiamond type 60019, is based on a single crystal diamond diode, SCDD, produced in Rome “Tor Vergata” University laboratories.

• Dosimetric properties of SCDD detectors have been favourably evaluated in a wide range of measurements conditions including photon, electron and proton beams with small field sizes.

• SCDD performance is comparable to that of well assessed dosimeters for measurements in standard conditions.

• Advantages of SCDD have been demonstrated in challenging dosimetry when high spatial resolution and energy independence are required.
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