SiC devices for applied physics

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Outline

- Motivations
- Experiments – Collaborations on the development of Si detectors
- Development of SiC devices as real-time dosimeters;
- Alternative strategies (epi Si – Diamond)
- Application of SiC detectors for solar UV monitoring
- Conclusions

Motivation
SiC a material btw Si and Diamond

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.3**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4\cdot10^6$	$2.2\cdot10^6$	$3\cdot10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2\cdot10^7$	-	$2\cdot10^7$	$0.8\cdot10^7$
Z	6	31/7	14/6	14
ε_r	5.7	9.6	9.7	11.9
e-h energy [eV]	**13**	**8.9**	**7.6-8.4**	**3.6**
Density [g/cm3]	3.515	6.15	3.22	2.33
Displacem. [eV]	**43**	**≥15**	**25**	**13-20**

- Wide bandgap (3.3eV)

Þ lower leakage current than silicon

- Signal:
  Diamond 36e/mm
  SiC 51e/mm
  Si 89e/mm

Þ more charge than diamond

- Higher displacement threshold than silicon

Þ radiation harder than silicon (?)

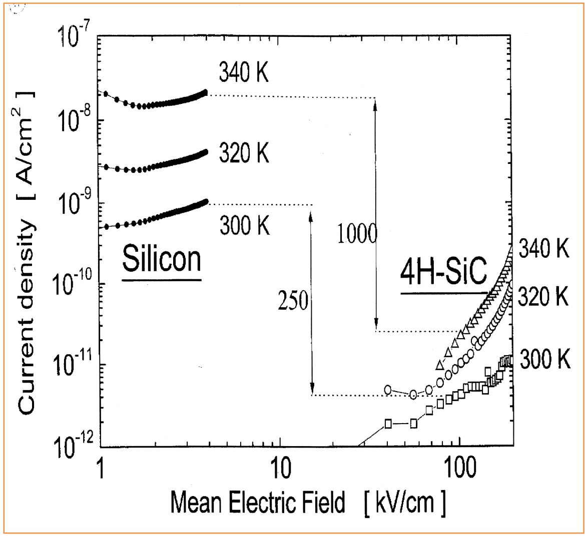
R&D on diamond detectors:
RD42 – Collaboration
http://cern.ch/rd42/

SiC, as all undoped high band gap crystalline materials, is intrinsically radiation hard because even at high fluences of the leakage current is < 1pA/cm²

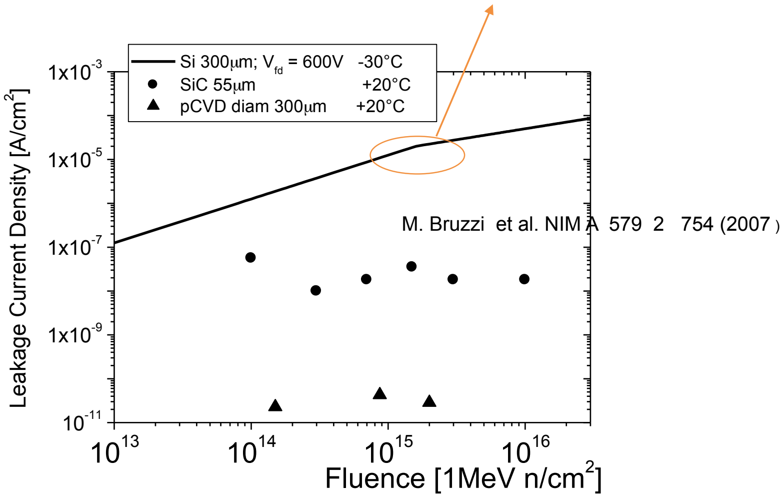
Silicon: $J(\Phi) = \alpha \cdot \Phi \cdot d$

T = -30°C; V = 600V, W = 300mm

$$I(T)\ \alpha\ T^2 \exp\left(-\frac{E_g}{KT}\right)$$



Partial depletion



Experiments – Collaborations on SiC devices

EPICS sviluppo di rivelatori EPItassiali di Carburo di Silicio INFN CSN5 (00-02) INFN Firenze, Politecnico di Milano, Modena-Bologna.

CONRAD INFN CSN5 (03-05) development of dosimeters con CONformed RADiotherapy: Firenze, Laboratori Nazionali del Sud e di Legnaro, Istituto Superiore di Sanità di Roma.

CERN RD50 Collaboration (02-06) Development of ultra radiation hard detectors for HL-LHC: Firenze, Modena-Bologna, Vilnius, Perugia.

Collaboration with **Fondazione Osservatorio Ximeniano** (08-10) Development of SiC devices for solar UV monitoring.

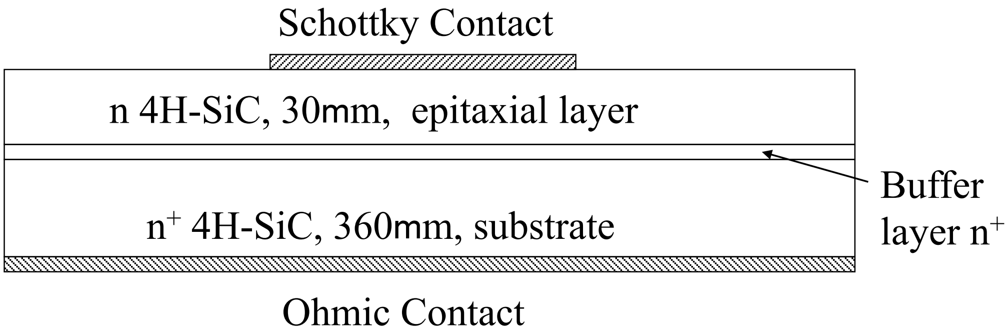
Memorandum of understanding signed (14-16) for common research on the development of medical sensors and nanotechnology btw Dipartimento di Fisica e Astronomia, Università di Firenze - Korea Electrotechnology Research Instititute (KERI). Application for **significant bilateral projects** MAE (2015) - A Feasibility Study for Application of SiC Semiconductor to Medical Dosimetry System. Applicants: Dipartimento di Fisica e Astronomia, Università di Firenze and Korea Electrotechnology Research Instititute (KERI).

INFN CSN5: EPICS (00-02) & SICPOS

Epitaxial SiC Schottky Barriers

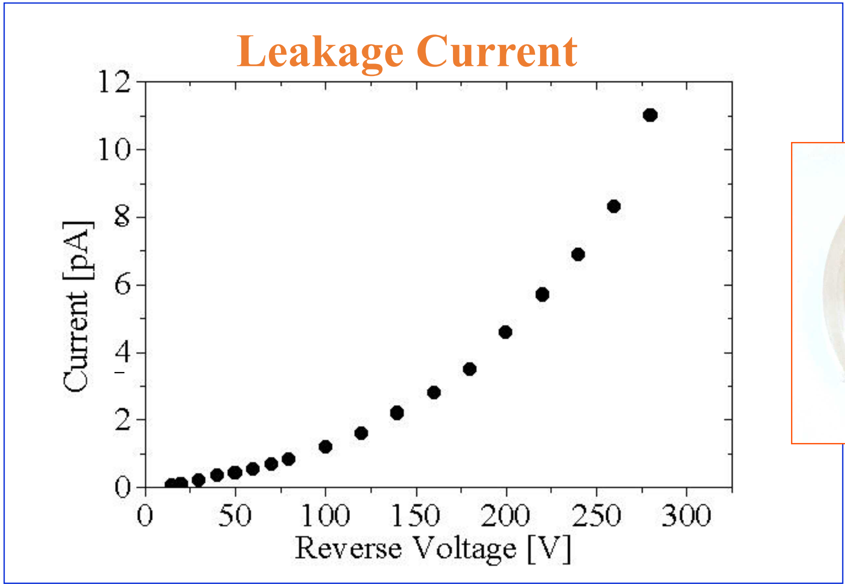
Epitaxial 4H-SiC Wafer from CREE (USA)

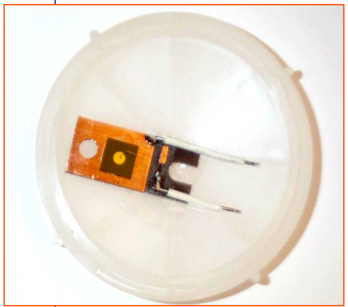
<u>Epitaxial n</u>	thickness: 20-50 mm,	N: 2.2-0.5x10^{15} cm^{-3}
<u>substrate n$^+$</u>	thickness: 320-360mm,	N: 6.8x10^{18} cm^{-3}



M. Bruzzi et al. Recent results on radiation and particle detection with epitaxial SiC Schottky diodes, NSS-MIC Symposium, Norfolk, Virginia, Nov. 10-16, 2002

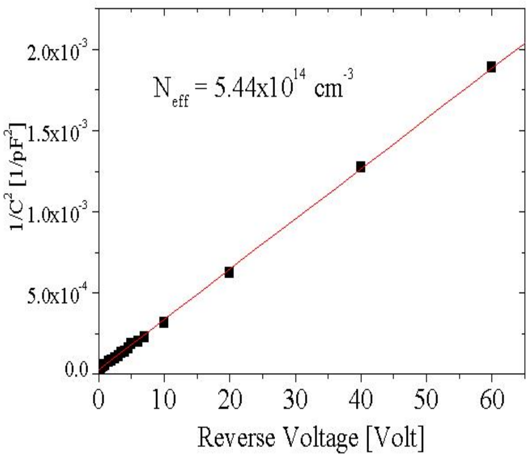
Ohmic Contact ➡ Ti/Au thin films
Schottky Contact ➡ Au (1000Å) Ø 2mm
produced by:
C.Lanzieri, Alenia Systems, Roma, Italy

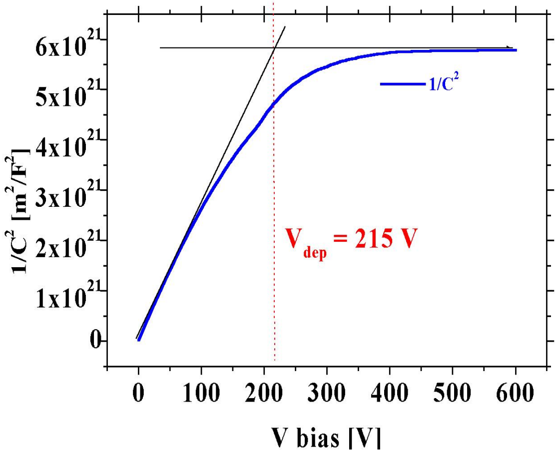




Capacitance - Voltage Characteristics

Good Uniformity up to 100V. Saturation @ 400V
Active Thickness ~ 20mm





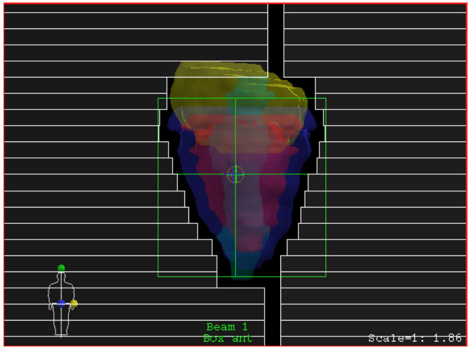
M. Bruzzi et al. Recent results on radiation and particle detection with epitaxial SiC Schottky diodes, NSS-MIC Symposium, Norfolk, Virginia, Nov. 10-16, 2002

Modern radiotherapy techniques : dose-delivery conformal to tumors to spare healthy tissues

- ✓ **Intensity Modulated RadioTherapy – IMRT**
- ✓ **Volumetric Modulated Arc Theraphy - VMAT**

→ high spatial gradients, strong variations in space and time of dose rate and energy spectrum.

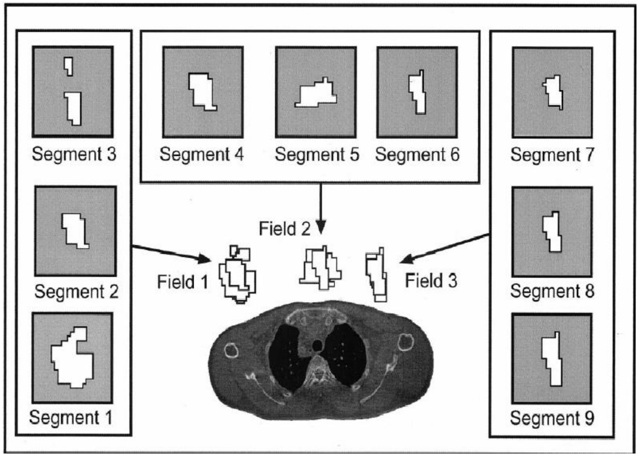
Requirement: Tissue equivalent bidimensional dosimeter for pre-treatment verifications

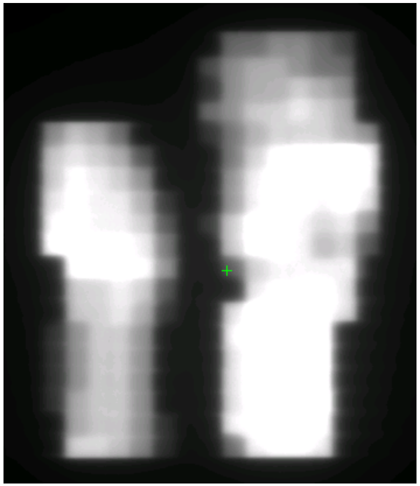


Multi Leaf Collimator (MLC) mounted on the linear accelerator head

IMRT: Step and shoot modality

Non uniform fluence distribution obtained by a sequence of static irradiations (segments) characterized by different MLC configurations. Beam is switched off during MLC rearrangement.





VMAT*: Continuous delivery modality

Intensity modulation is obtained thanks to MLC, variable dose rate and variable rotation velocity of gantry

Gantry moving continuously without dead times due to repositioning

VMAT / IMRT comparable in terms of target covering and sparing of healthy tissues ;

VMAT reduced treatment time (10-15 times)

*Cedric X Yu , **Intensity-modulated arc therapy with dynamic multileaf collimation: an alternative to tomotherapy** , Physics in Medicine and Biology 40, 1435-1449, 1995.

SiC as a real time clinical dosimeters

☺ Low Leakage Current

Working without applying bias

Very low active volume

Fast Response

High radiation resistance ?

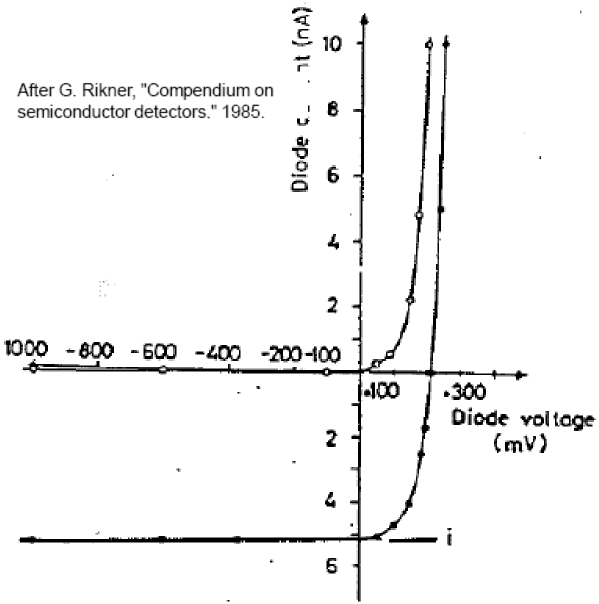
Non tissue-equivalent*, but better than Si

$Z_{SiC} \sim 10 < Z_{Si}$

High production costs

materiale	Z
aria	7.78
acqua	7.51
muscolo	7.64
grasso	6.46
ossa	12.31
carbonio	6
silicio	14
SiC	10

example of an I-V characteristics of a Si dosimeter in dark and under irradiation with a 1.5Gy/min dose-rate



After G. Rikner, "Compendium on semiconductor detectors." 1985.

Operating:

-V = 0 to miminize dark current
- sampling time T≥10ms
- measurement of the integrated charge, directly proportional to dose

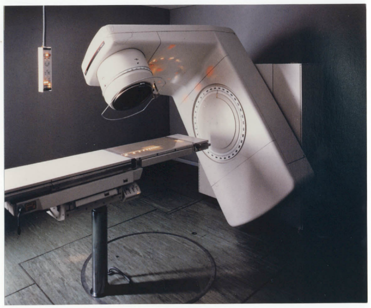
sensitivity ⟶ $s = \frac{dI}{dD}$

Radiation Facilities

Detector Characterization

Radiotherapy Unit-
University of Florence

1. 4-22MeV electrons from linear accelerator
   dose: 1-10Gy
2. 6MV photons from linear accelerator
   dose: 1-10Gy
   dose-rate 2-10Gy/min
3. Co^{60} source
   dose: 0.1-1Gy
   dose-rate 0.1-0.3Gy/min



Radiation Hardness

•CNR Bologna

• 8.2MeV electrons linear accelerator dose: 2-40MRad

• Co^{60} source dose: 2-40MRad

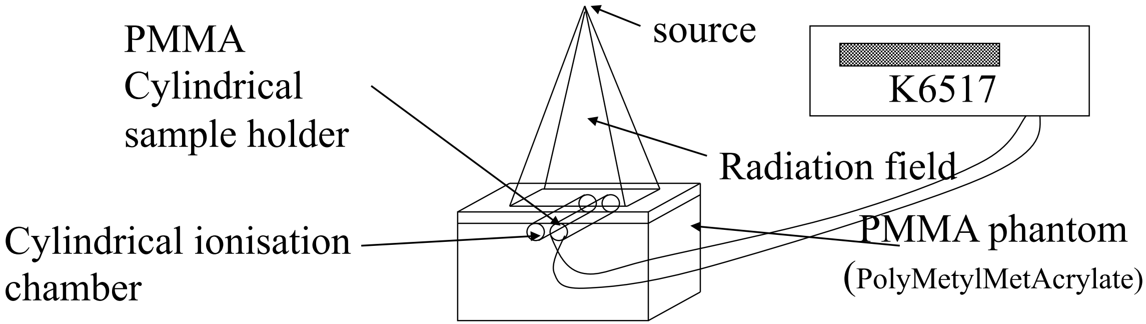
Dip. di Fisiopatologia Clinica - Firenze

• Cs^{137} source
  dose: 0.1-1kGy
  dose-rate: 200 Gy/h

CERN Geneve

• 24GeV/c protons fluence up to 10^{14} cm^{-2}

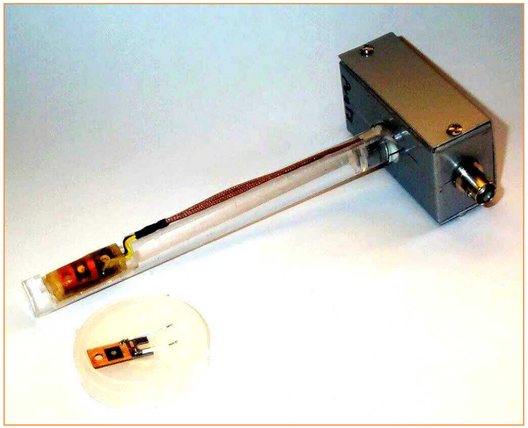
4. Dosimetric Characterisation



source-surface distance: 70-100 cm

Radiation field : 20x20 cm^2

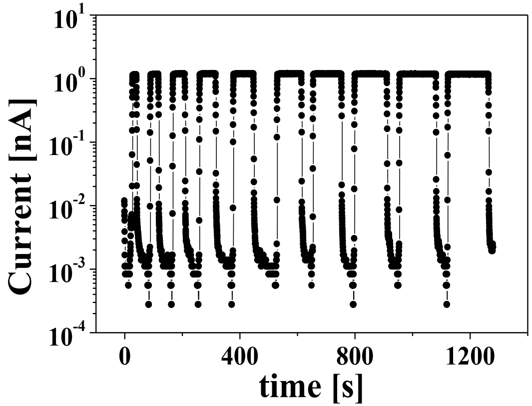
SiC embedded in tissue equivalent to eliminate the contribution of air to the signal →



Dosimetric Characterisation

Stable signal - high S/N ratio - no priming effects

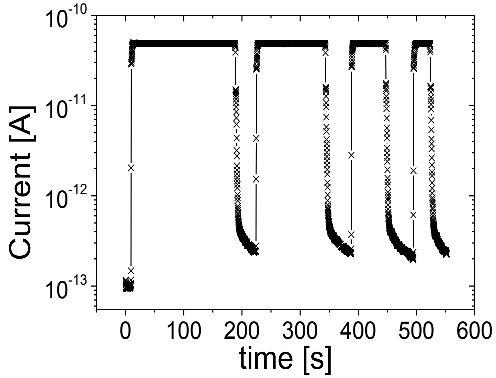
22 MeV Electrons
dose-rate 4.2Gy/min



V_{rev} = 150 Volt I_{signal} ~ 1nA I_{dark} ~0.1pA

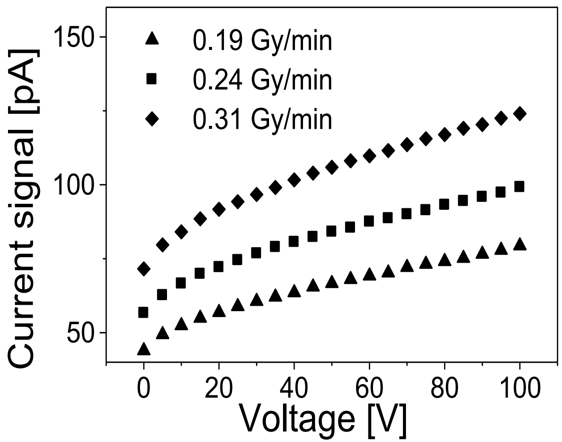
Co^{60} g

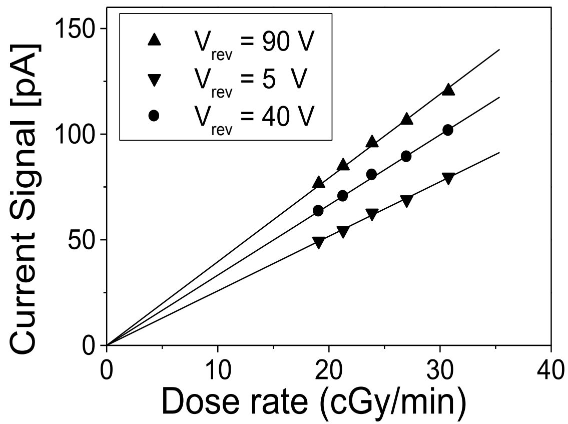
dose-rate 0.21Gy/min



V_{rev} = 0 Volt I_{signal} ~ 50pA I_{dark} ~ 0.1pA

IV characteristics during irradiation with Co^{60}





- **Current response dependent on the square root of reverse voltage V_{rev}**

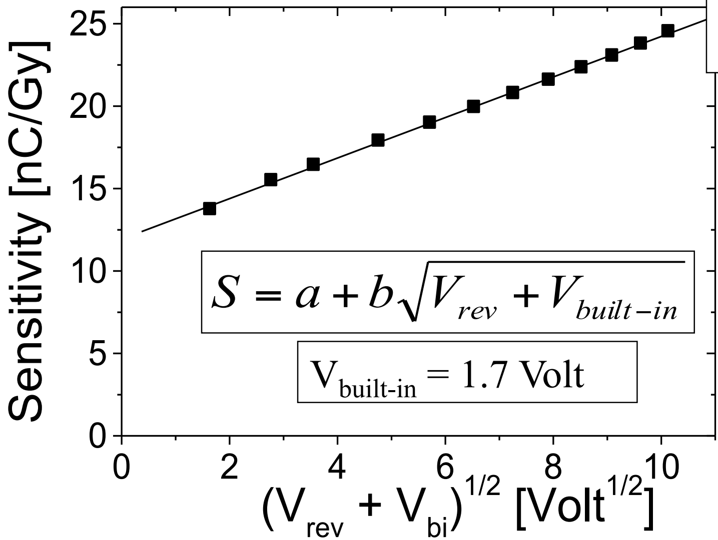
- **Signal linearly dependent on dose-rate**
- **sensitivity: ➡ slope of the linear fit**

Sensitivity as a function of V_{rev}

$$W = W_0 + L = \sqrt{\left(\frac{2\varepsilon \cdot V_{bi}}{q \cdot N_{eff}}\right)} + \sqrt{D_h \cdot \tau_h}$$

Active depth at V_{rev} = 0

Minority carrier diffusion length



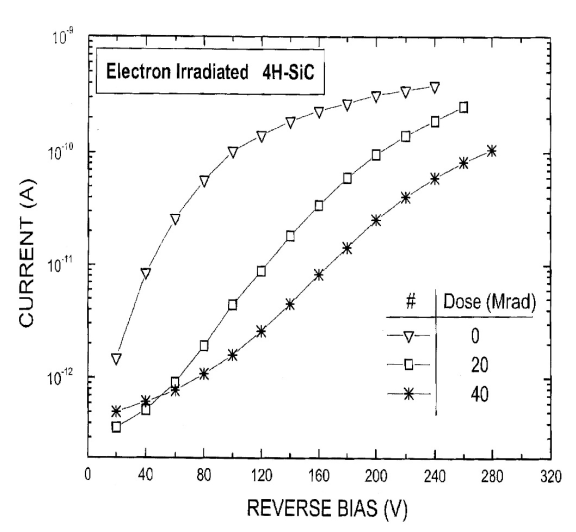
t_h ~ 500ns
$D_h = m_h K \cdot T/e$
$D_h = 2.98 cm^2/s$
$m_h = 115\ cm^2/V \cdot s$

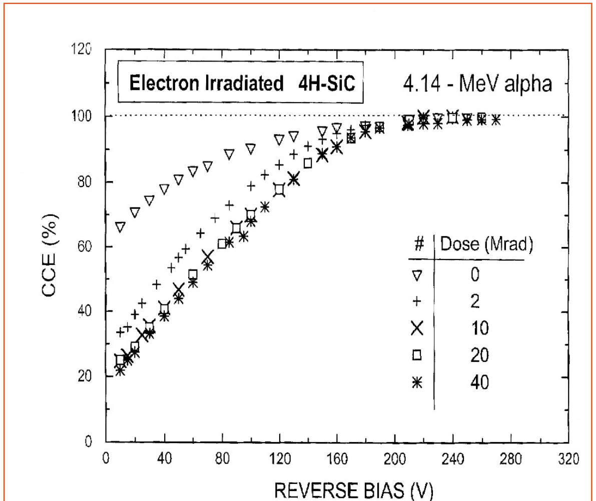
W_0 ~ 1mm
L ~ 10mm

Comparison between Epitaxial SiC and standard dosimeters

Device	bias [V]	Vol. [mm^3]	S [nC/Gy]	S per unit volume [nC/(Gy·mm^3)]
Standard Farmer Ionisation chamber	300	600	**21.5**	**0.036**
Miniature Farmer Ionisation chamber	300	50	**1.38**	**0.028**
Scanditronix GR-p BS **Silicon**	0	0.295	**140**	**474**
Scanditronix SFD stereotactic **Silicon**	0	0.017	**6**	**353**
Epitaxial SiC diode	0	0.0415	**14.1**	**340**

_Irradiation with 8.2MeV electrons and g Co^{60} up to 40MRad





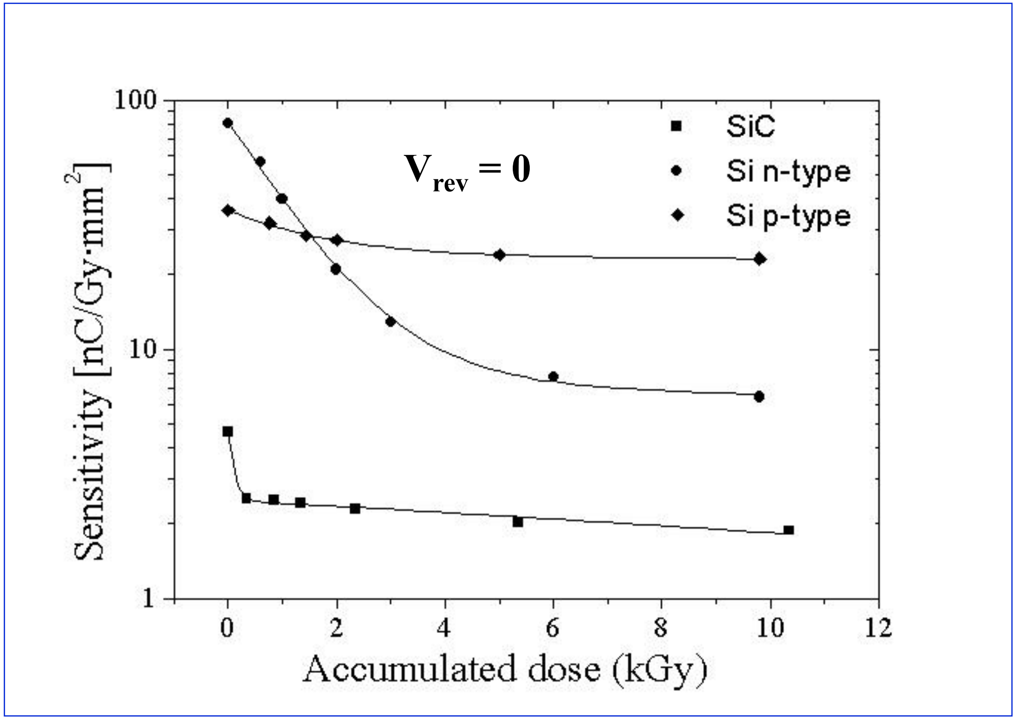
F. Nava et al, RESMDD02, 2002

No increase in the leakage current

Slight decrease of the min. carrier diff. length: L =10 [?] 1mm

100% CCE after a dose of 40 MRad

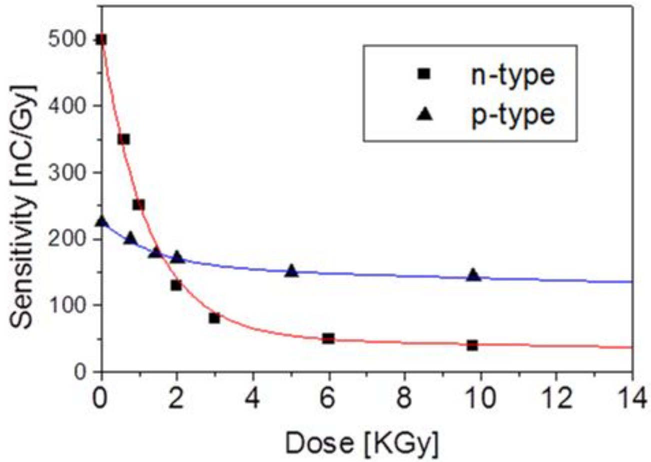
Dosimetry: Sensitivity vs. Accumulated Dose after irradiation with Cs^{137}



Thick Si dosimeter - sensitivity dependence on accumulated dose

$$S = \frac{q\rho_{Si}}{E_i}\sqrt{\frac{D_e}{\sigma_e v_e N_t}} \propto N_t^{-1/2}.$$

N_t grows with irradiation → t_e and L_e decrease with accumulated dose → decrease in sensitivity S during device lifetime → need of periodic recalibration.

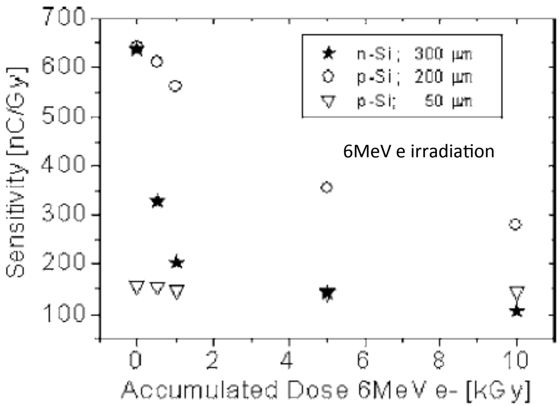


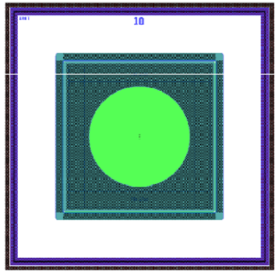
Grusell and Rikner , 1984, Acta Radiologica Oncology 23, 465-469.
Rikner G. et al., 1983, Nucl. Instr. and Meth. A, 217, 501-5.

Since S is proportional to $N_t^{-1/2}$, irradiation reduce the slope of sensitivity vs dose curve.

Overcoming thick Si limitations with epitaxial Si

Research carried out by University of Florence in the framework of European Integrated Project MAESTRO (2004-2009) with the support of IBA dosimetry (from 2009). Active region limited in any direction to a value shorter than L_e at highest dose of interest. Epi layer used to limit active depth, a guard-ring to limit active area.





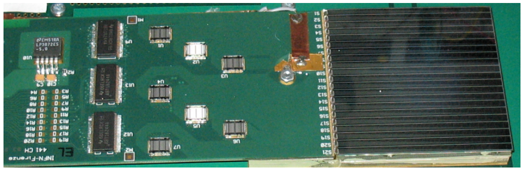
Active area	~9mm²
pad-grd distance:	10-500 µm
Epi layer:	50µm thickness
	50Ωcm resistivity
	p type

M. Bruzzi et al., "Epitaxial silicon devices for dosimetry applications," Appl. Phys. Lett., vol. 90 (2007) 172109 1-3.

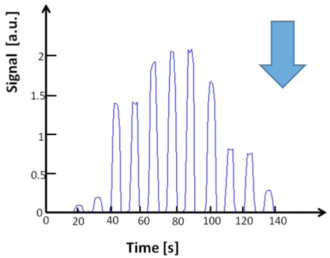
Si bidimensional dosimeter

In the framework of the MAESTRO EU Integrated project the Florence group designed and manufactured a high performance cost-effective device based on epitaxial p-type silicon (radiation-hard, no dependence on the accumualted dose), designed to get a high resolution matrix of macropixels (2x2mm^2). Module:6.3x6.3cm2, 441ch.

C.Talamonti, M.Bruzzi et al. 2011 Nucl. Instr. Meth A, vol. 658, p. 84-89.

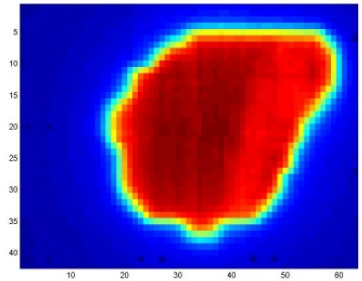


Measured time structure of dose segments



Large area IMRT covered by mosaic composition and/or shifting modules along x-y axes.

Dose map of an IMRT field for prostate cancer as measured by the Epi-Si 2D silicon dosimeter.



Patent : US2010176302 (A1) — 2010-07-15

Diamond Dosimeters

☺

- **it is almost water equivalent**
  it doesn't perturb the radiation field → small fields
  the energy is absorbed as in the water → no correction factors
- **high radiation hardness** → long term stability
- high density → high sensitivity → small dimensions
- non toxic

Natural diamond

- **very high production costs, difficult to select stones with proper dosimetric response**

Single crystal CVD (Chemically Vapour Deposited) diamond

- **grown on HPHT diamond, not available in large areas**

Polycrystalline CVD diamond

☺ ability to produce large area wafers of 3-5"

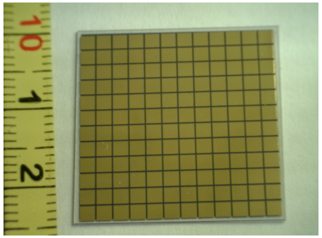
- zero/low voltage to reduce polarization effects*

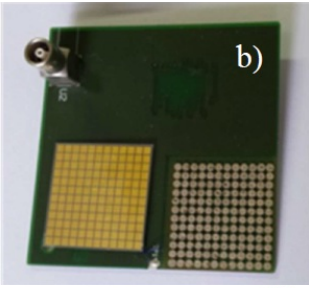
*M. Bruzzi et al., Diamond & Related Materials 20 (2011) 84–92

Diapix Experiment CNS5 10-13

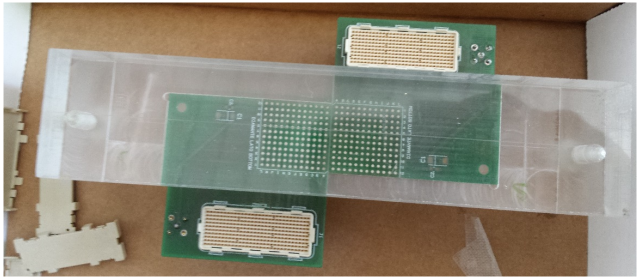
Device manufacturing

- **Material**
•Premium Detector Grade polycrystalline diamond pCVD
•Element Six, UK 300mm thick;
Two prototypes: 2.5x2.5cm^2, 5.0x2.5cm^2 active area
•Contacts
•produced by the University of Florence as Schottky barriers;
•12 x 12 matrix, pixel size: 1.8x1.8 mm^2
-Electronics
•electronics read out applied with four 64 channels 20 bit current-input analog to digital converter chips
•custom printed circuit board designed and manufactured;
•Electronic read-out and software developed starting from an evaluation kit

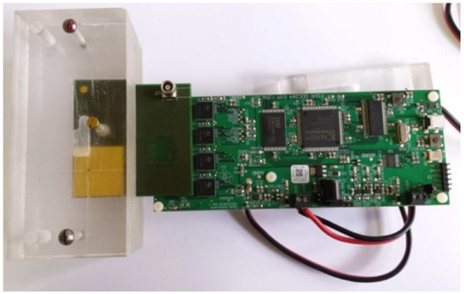




IRPT MIUR WP8 (14-16)



5.0x2.5cm^2 active area prototype under development now

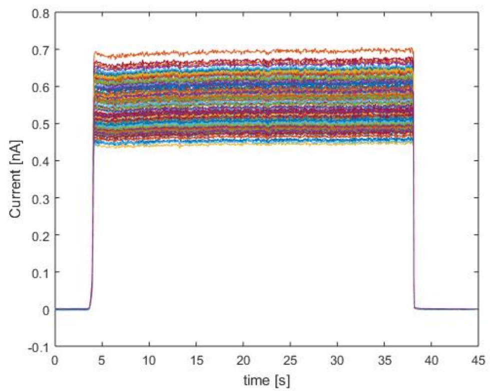


2.5x2.5cm^2 active area prototype with evaluation kit – ready for test

Performance under conventional radiotherapy beam

Charge response in a conventional 10MV X beam (V_{app} = 1V)
Dose-rate 1.73Gy/min

IRPT MIUR WP8 (14-16)

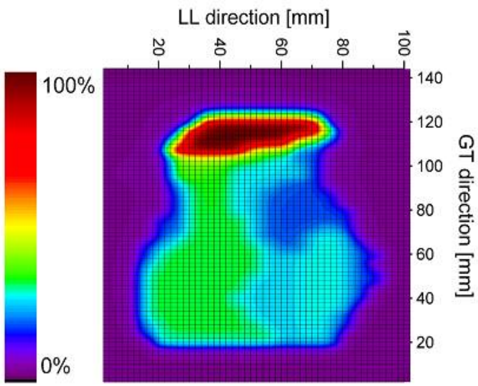


$S = dQ/dD \sim 20 nC/Gy$

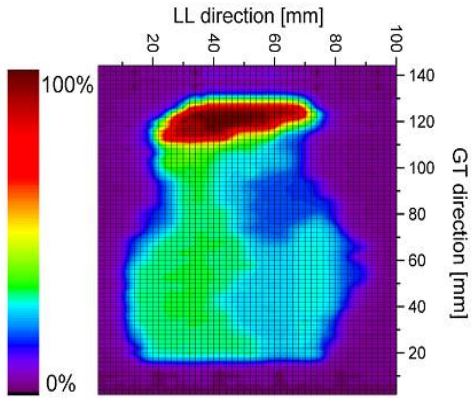
$s = dQ/dD \; 1/A \sim 6 nC/Gy \cdot mm^2$

- ✓ negligible dark current → high S/N
- ✓ negligible polarization effects → stable response , fast dynamics

IMRT map 14x10cm^2 measured with a diamond dosimeter 2.5x2.5cm^2, 144 pixels



IMRT breast cancer map **as measured by the pCVD Diamond .**

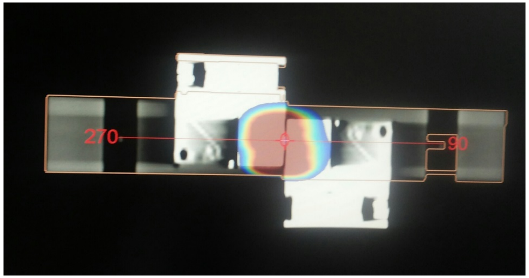


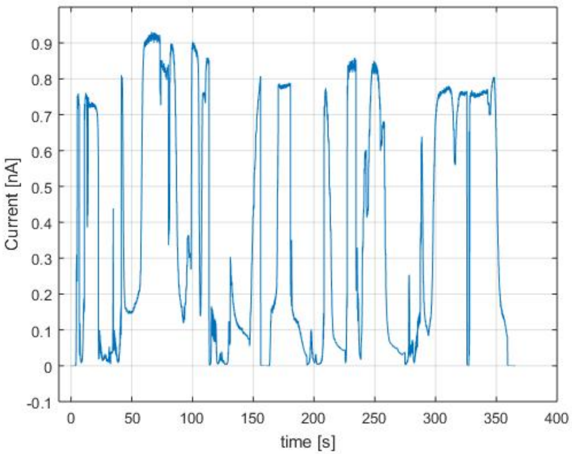
IMRT breast cancer map **as calculated by the TPS (treatment planning system)**

(GT = gantry target direction; LL = lateral-lateral direction) Grid spacing 3 mm.

VMAT Experimental Test

- lung cancer treatment
- 2 polycrystalline diamond dosimeters
- Active area: 5.0x2.5cm^2
- moved ±2.0cm in the y-direction to cover field

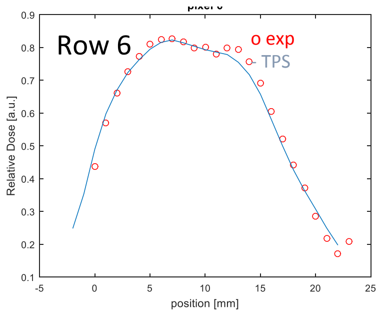


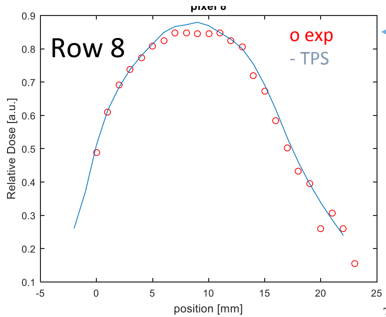


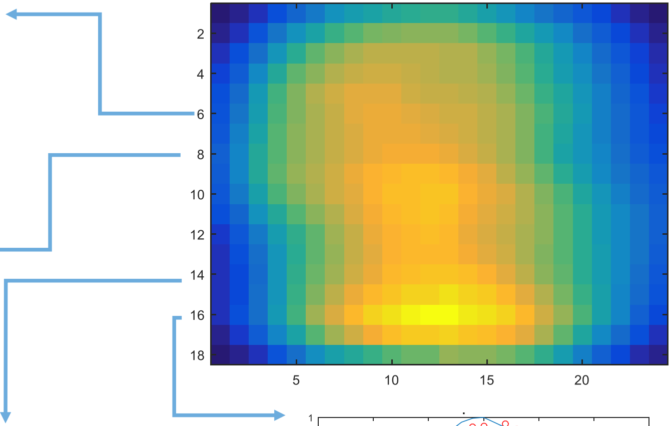
Time structure of VMAT delivery as measured by one pixel of the pCVD diamond dosimeter

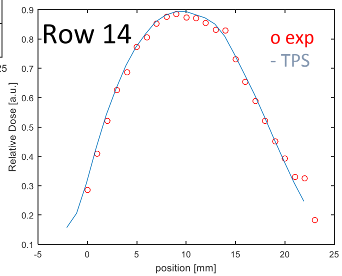
IRPT MIUR WP8 (14-16)

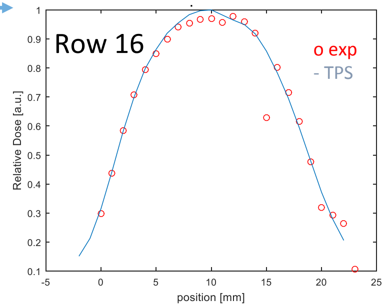
Profiles relative to maximum dose in TPS











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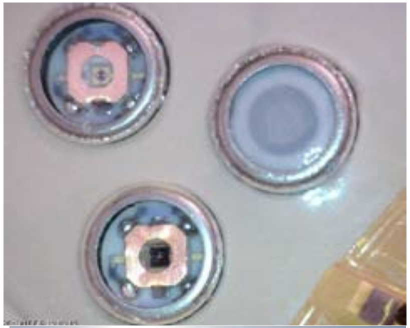

SiC devices for UV light measurements in environmental monitoring

3 Commercial SiC photodiodes JIC137A, JIC167B, JEC-1 I-DE designed by Institut für Fügetechnik und Werkstoffprüfung (IFW, Jena) and produced by Electro Optical Components, Inc. (Santa Rosa, U.S.A.) mounted in hermetically sealed TO-5 package with UV-glass windows.

JIC137A, JIC167B equipped with filters to cover respectively the ranges UVA and UVB

JECF 1 I-DE produced by Boston Electronics Corporation, MA-USA equipped with a specific filter to obtain a spectral response to measure directly the UV index

Sensor	λ peak (nm)	Area (mm^2)	Nominal max resp. (mV/nW)	λ_{max} (nm)	λ_{min} (nm)
JIC137A	340	0.22	0.3	400	315
JIC167B	305	0.965	0.4	315	280
JECF 1 I-DE	285	1	2.1	400	250

Temperature coefficient < 0.06%/K

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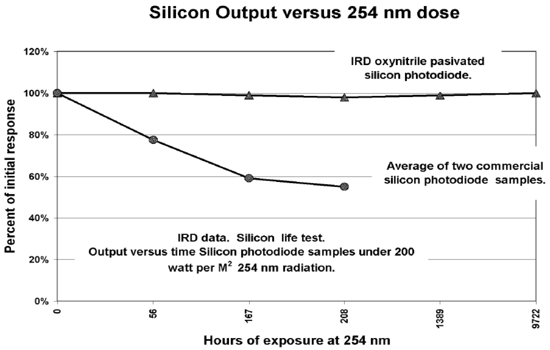
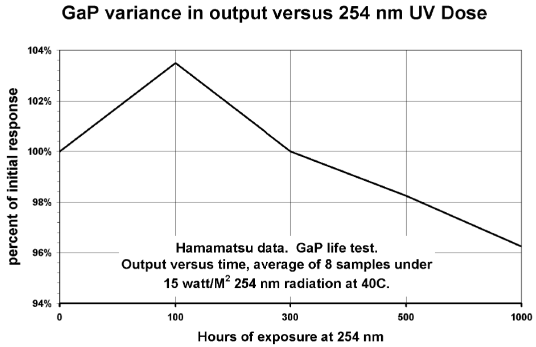
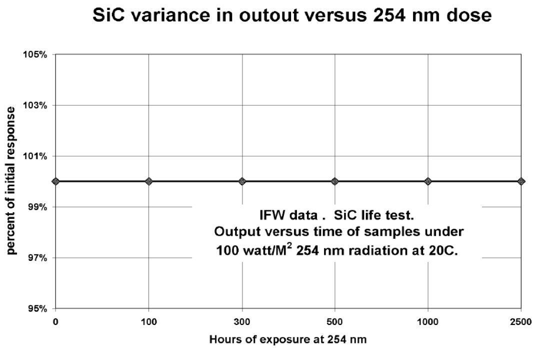
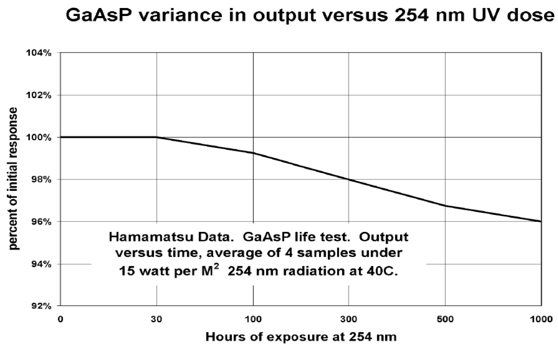
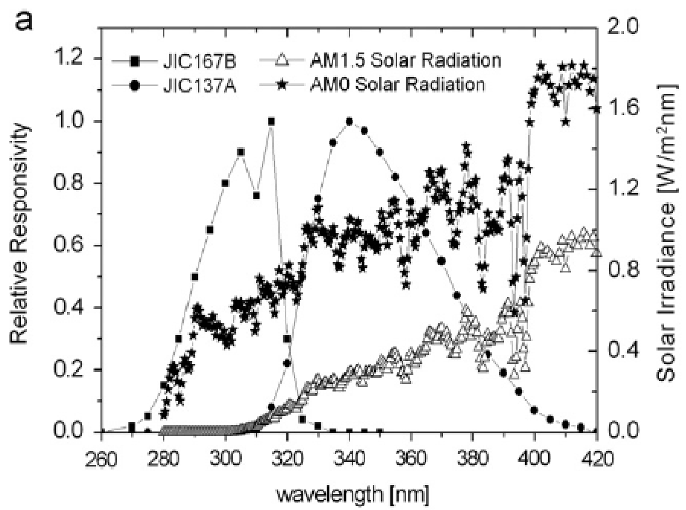
Good radiation resistance as UV photodetector, extremely stable for long periods of time even when exposed to high doses of UV radiation of up to 100W/m²

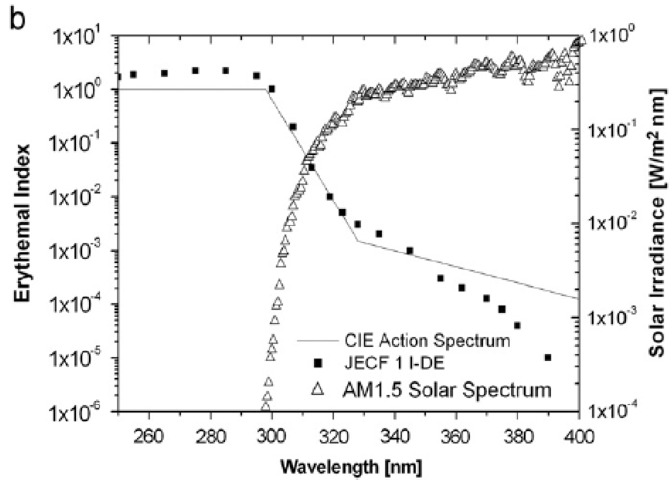












(a) Relative responsivities of the SiC photodiodes JIC137A-JIC167B as compared to the AM0 and AM1.5 Solar irradiance spectrum [10]; (b) JECF 1 I-DE responsivity as compared to the ideal erythemal spectrum and AM1.5 Solar spectrum [11].

(b) JECF 1 I-DE responsivity as compared to the ideal erythemal spectrum and AM1.5 solar spectrum

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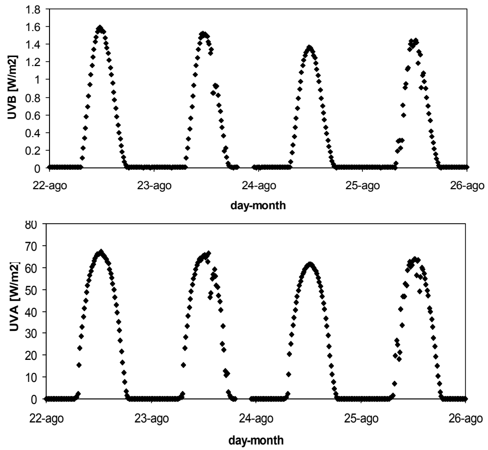
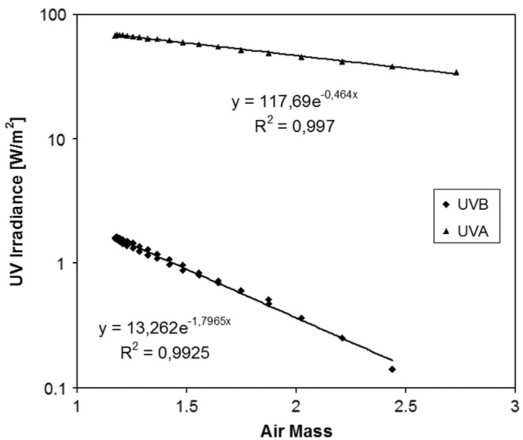


Integral irradiance (UVA and UVB signals) vs GMT measured with the JIC137A and JIC137B SiC photodiodes mounted on a Sun tracker near Florence, Italy.



Evaluation of the the total atmospheric optical thickness t:

$I = I_0 \exp(-t\mathrm{AM})$

I measured radiation intensity at ground level, I_0 intensity of radiation before entering the atmosphere, AM = Air Mass.

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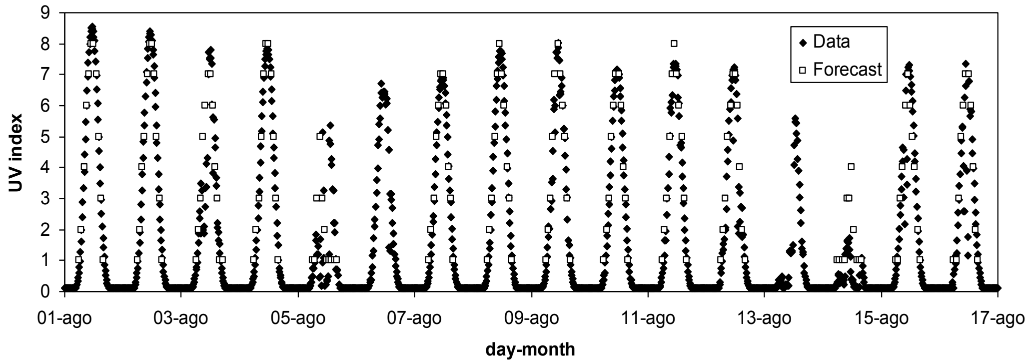
UV index monitoring with the JECF 1 I-DE SiC device



UV index measured by the JECF 1 I-DE with the on August 1-17 2010 in Ponte Buggianese, Tuscany as compared with values from DWD (Deutscher Wetterdienst, German Meteorological Service, Human Biometeorology, Stefan-Meier-Freiburg, Germany http://orias.dwd.de/promote/data/www_UV_forecast.pdf)

E. Borchi, R. Macii, M. Bruzzi, M. Scaringella, Nuclear Instruments and Methods in Physics Research A 658 (2011) 121–124

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Conclusions

- In modern radiotherapy, there is a need to developing optimised dosimeters for pre-treatment verifications. Schottky barriers on epitaxial SiC proved to have good performances as real-time dosimeter in conventional radiotherapy beams, nonethelss, a decrease of the sensitivity with the accumulated dose was observed.

- Best solutions as dosimeters for pretreatment verifications are up to now coming from systems made of segmented epitaxial Si junctions and Schottky barriers on single crystal and polycrystalline diamond films.

- However, Si is non-tissue equivalent, single crystal diamond is limited by a small area and in general diamond is a high-cost material. So, SiC could be considered as a an efficient solution in modern radiotherapy dosimetric systems, as a good compromise between Si and diamond devices.

- SiC devices can be viable solutions in other applications, especially when working in harsh environments (SiC is already extensively used for solar UV monitoring - UV index). It could find application as a sensor in Wireless Sensor Networks (WSN) to increase the ubiquity of the Internet (Internet of Things INTERNATIONAL JOURNAL OF COMMUNICATION SYSTEMS *Int. J. Commun. Syst.* 2012; **25**:1101–1102)