Sviluppo di dosimetri con materiali avanzati per radioterapia clinica

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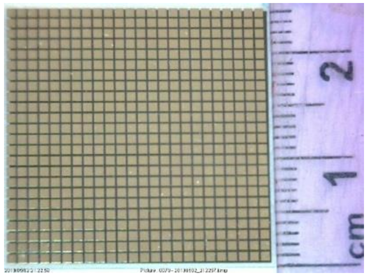
Outline

1. Motivation
2. Advanced materials and devices in clinical radiotherapy dosimetry
- epitaxial silicon
- SiC
- polycrystalline diamond
- perovskites PERO2

4. Conclusions

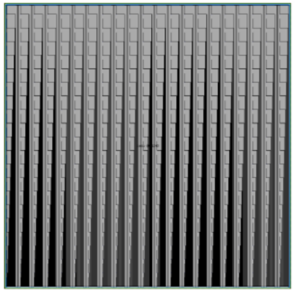
Esperimenti finanziati nel corso degli anni da INFN CSN5 presso la sezione di Firenze per lo sviluppo di dosimetri per radioterapia clinica



- **Diamante policristallino**

IDDD (96-98) / CANDIDO (99-02) /

DIAPIX (11-13) / IRPT MIUR (14-17) / 3DOSE (17/19)

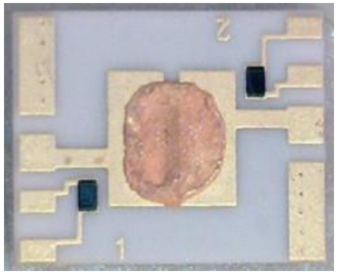


- **Si ossigenato, SiC, diamante**

CONRAD (03-05)

- **Si epitassiale**

PRIMA (04-09)



- **perovskite inorganica**

PERO/PERO2 (19-21)

Motivation

Radiotherapy with external beams with high energy (X, γ, electrons, protons, ions) produced by particle accelerators

- immobilization techniques allow for positioning patient during the treatment with always increasing accuracy,

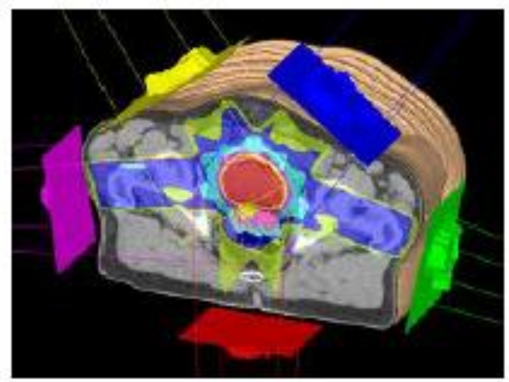
- accelerators equipped with beam modifying devices able to get dose distributions closely shaped on the target volume.

Advanced, highly accurate imaging and dose verifications systems must match with increased accuracy of irradiation techniques

Intensity Modulated Radiation Therapy (IMRT)

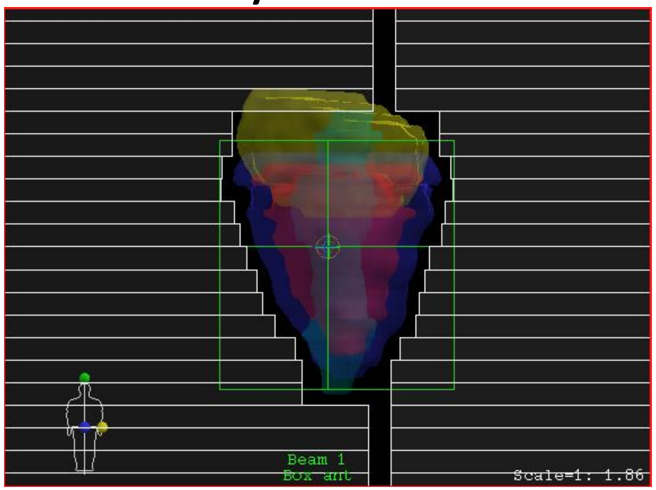
To spare surrounding healthy tissues released dose shaped along an irregular field conformed to the tumor volume

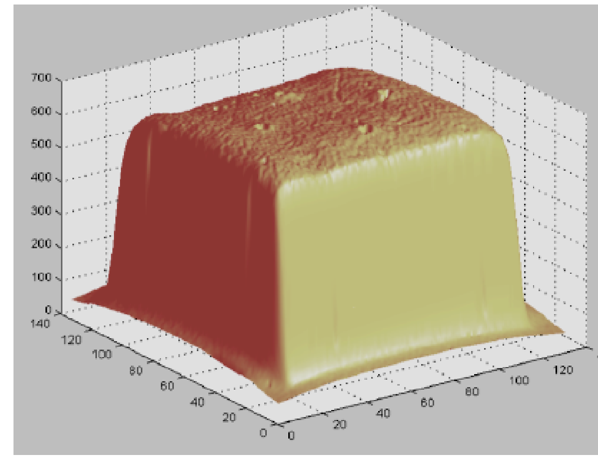
Intensity Modulated Radiation Therapy (IMRT) : a few radiation beams, generally from 2 to 9, produced by the same linear accelerator and directed towards the tumor from different angles, in order to concentrate the dose released on the volume of the tumor.

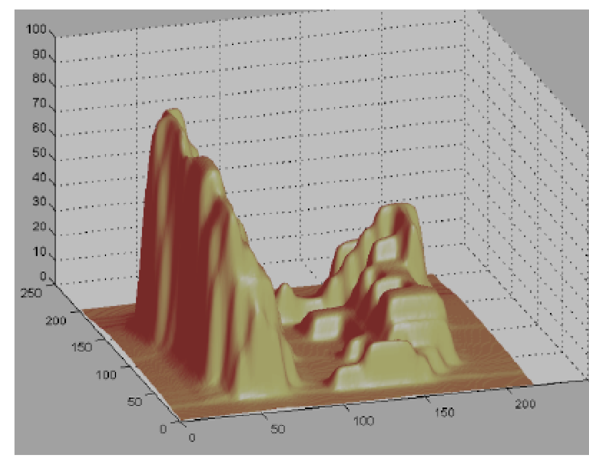


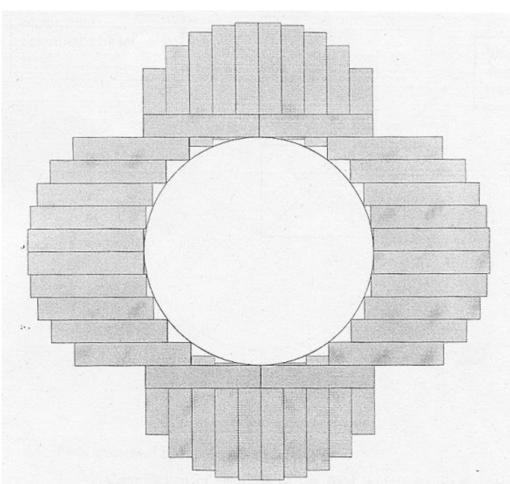
Multi Leaf Collimators (MLC)

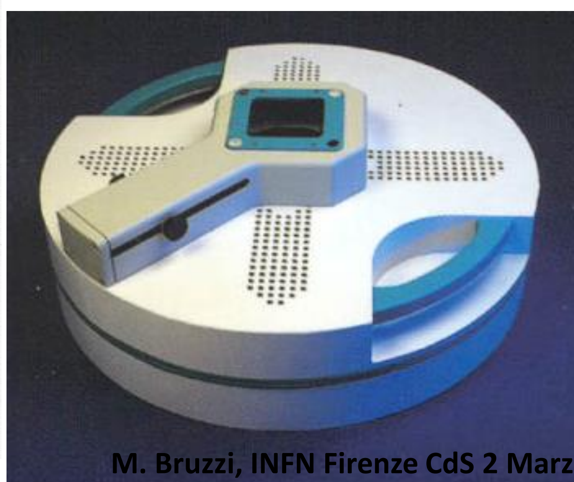
Dose conformation obtained using Multileaf Collimators with sets of mobile lamellas in W mounted externally on the LINAC head





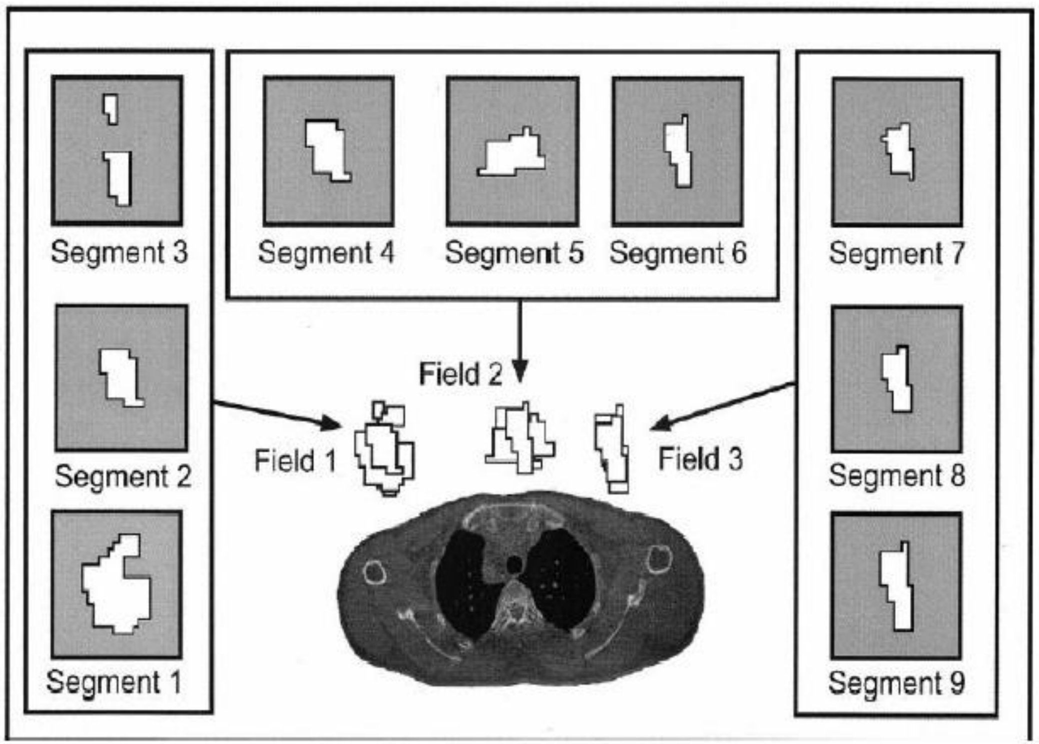


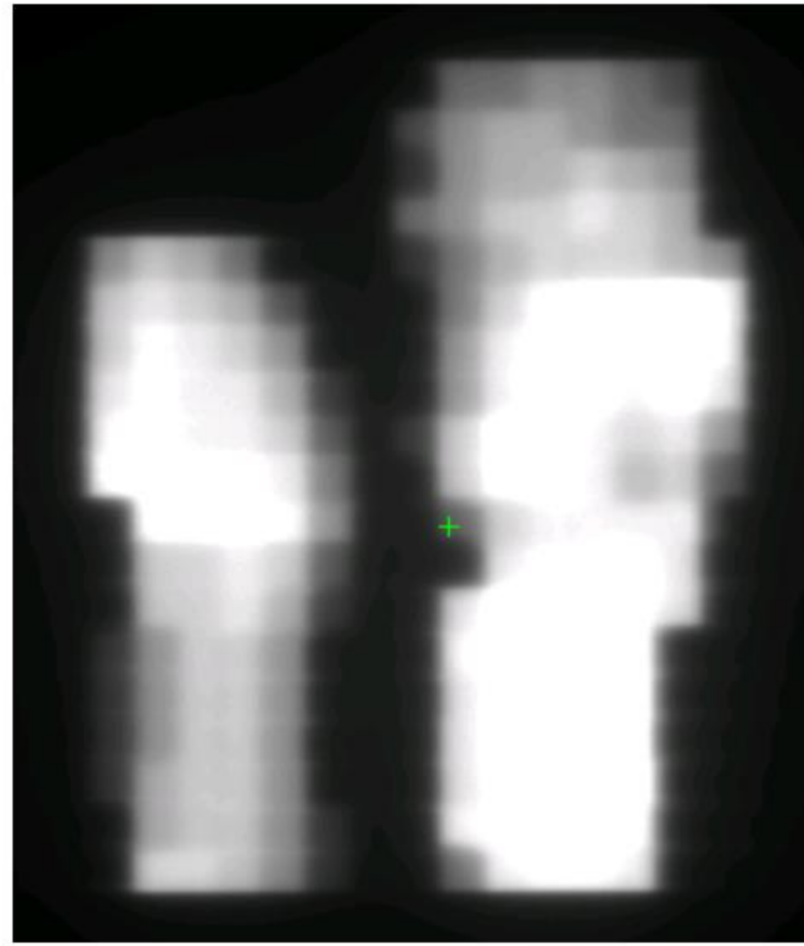




Example: IMRT irradiation in step and shoot modality, the total dose is released as a sum of nine segments, each corresponding to a particular arrangement of the MLC lamellas (left). Beam is off during their movement.

Total dose is obtained as the sum of the dose released by each segment (right).





VMAT (*Volumetric Modulated Arc Therapy*)

- Able to focus more accurately at tumor tissues, ensuring greater preservation of healthy ones.

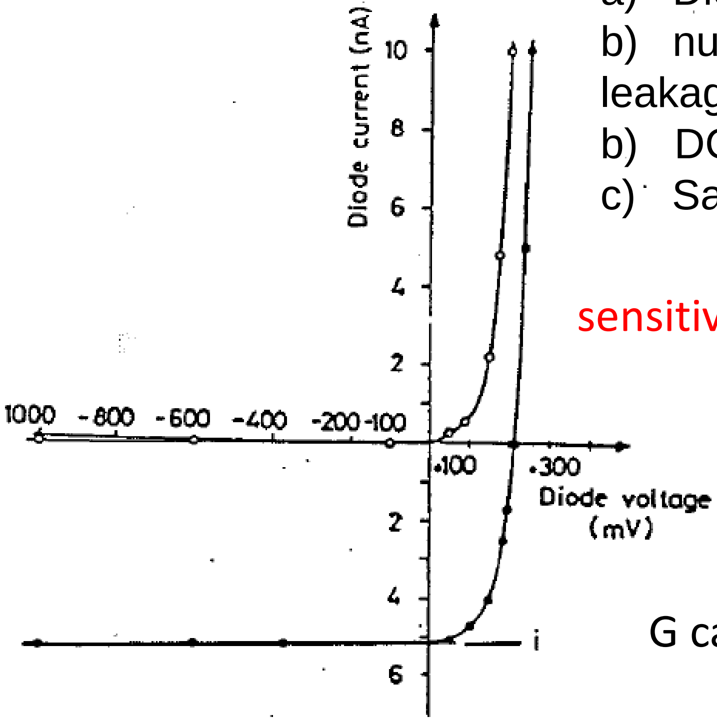
- Modulating not only the amplitude and velocity of the MLC, but also **rotation speed of the Gantry and Linac dose-rate**.

- **continuous rotation of the accelerator head during irradiation for maximum focusing** of radiation on tumor tissues, which are thus affected by all possible angles.

- **significantly reducing duration of treatments** compared to IMRT: about 5-7 minutes compared to traditional times which are around 20 minutes per session.

- **useful when treatment focus must be maximum to preserve nearby organs**: tumors of the head / neck, as larynx, pharynx and oral cavity; tumors of the pelvis, as prostate and rectum; tumors of the lung and breast.

Working principle of a on-line dosimeter



a) Diode / resistor
b) null bias or low bias (to minimize leakage current and polarization effects).
b) DC coupling.
c) Sampling time and reset fixed by digital electronics (t ≥10ms).

sensitivity $$S = \frac{Q}{D\,Volume} = \frac{qG}{R}$$

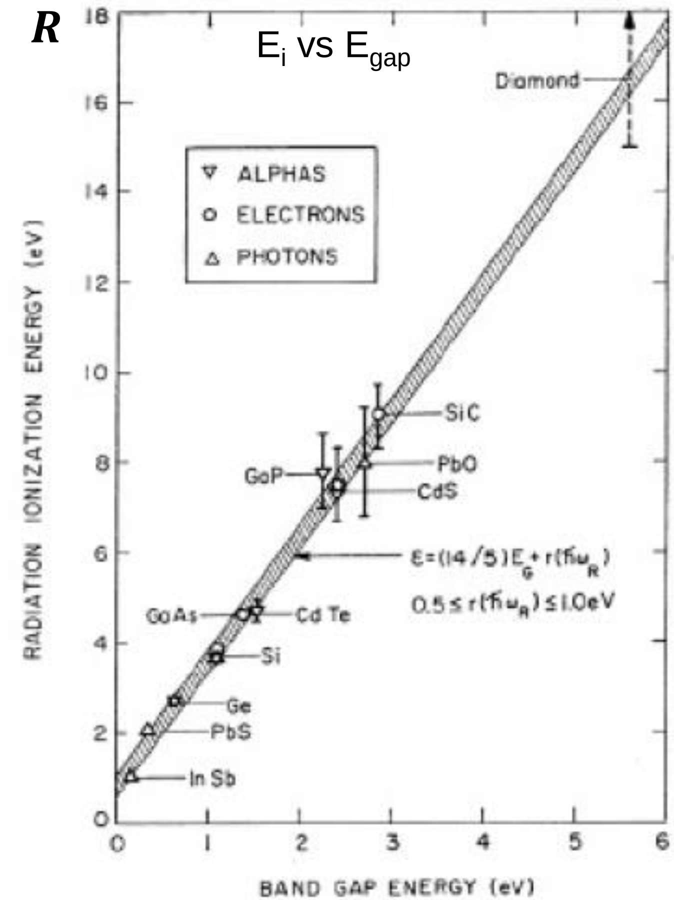
R,: dose rate;
Q: released charge;
D: delivered dose;
q: elementary charge

G carrier generation rate:

$$G = \frac{R\rho}{E_i}$$

$$\rightarrow \quad S = \frac{q\rho}{E_i}.$$

ρ: density;
E_i: mean ionization energy.



	IC(AIR)	SILICON	DIAMOND	CsPbBr3
ρ [g/cm³]	1.29x10^{-3}	2.33	3.52	4.55
E_i [eV]	34.00	3.60	16.20	5.30
Sensitivity [nC/Gymm³]	0.038	647.22	217.28	860

Dosimetry Challenges

Highly accurate imaging and dose verifications systems must match with increased accuracy of the irradiation techniques .

- **Response independent of energy** - often Charged Particle Equilibrium (CPE) lacks (a phenomenon associated with the range of secondary particles and hence dependent on the beam energy, composition and density of the medium);
- **small volume and high sensitivity** - to get enough spatial resolution;
- **response independent of dose rate,** continuously changing during VMAT;
- **Real time invivo detectors** - european community require dose delivery to be verified experimentally **directly during irradiation** (Article 56 of COUNCIL-DIRECTIVE-2013/59/EURATOM).

State-of-art commercial dosimetric devices used in clini radiotherapy

	IC (AIR)	SILICON	DIAMOND
ρ [g/cm^3]	1.29x10^{-3}	2.33	3.52
E_i [eV]	34.00	3.60	16.20
S [nC/Gymm^3]	0.038	647.22	217.28
Area [mm^2]	25.00	0.64	3.80
thickness [mm]	5.00	0.03	0.001
volume [mm^3]	125	0.019	0.0038
Array	OCTAVIUS PTW	MAPCHECK SunNuclear	-
Detector	729 PTW	SunPoint® Diode Detector	microDiamond type 60019 PTW
Reference	APL Mater. 7, 051101 (2019); doi: 10.1063/1.5083810		

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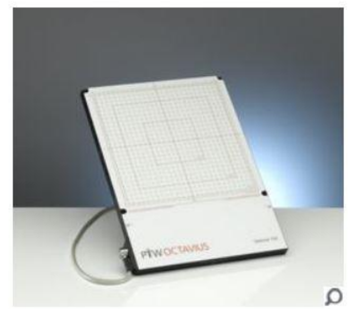
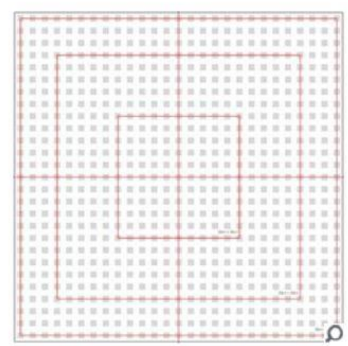
OCTAVIUS 729 | Specifications | Learn more

OCTAVIUS Detector 729

Detector type:	Plane-parallel vented ionization chambers
Detector design:	cubic
Number of detectors:	729
Detector size:	0.5 cm x 0.5 cm x 0.5 cm ($0.125\ cm^3$)
Detector spacing:	10 mm center-to-center, 5 mm edge-to-edge
Max. field size:	27 cm x 27 cm
Reproducibility:	≤ ± 0.5%
Dead time:	zero
Repetition rate:	200 ms
Measured quantities:	absorbed dose to water (Gy), absorbed dose rate to water (Gy/min)
Resolution:	0.1 mGy or 0.1 mGy/min
Measurement range:	(0.5 ... 48 Gy/min)
Reference point:	7.5 mm below the surface of the array
Housing material:	GRP
Dimensions:	30 cm x 42 cm x 2.2 cm (W x D x H)
Weight:	5.7 kg
Power supply:	(100 ... 240) VAC; (50 ... 60) Hz
PC connection:	Ethernet, RS232
Part No.:	L981378



OCTAVIUS® 729 - 2D ionization chamber array for patient and machine QA with OCTAVIUS 2D/4D



729 cubic ionization chambers uniformly arranged on 27 cm x 27 cm

ArcCHECK® & 3DVH®

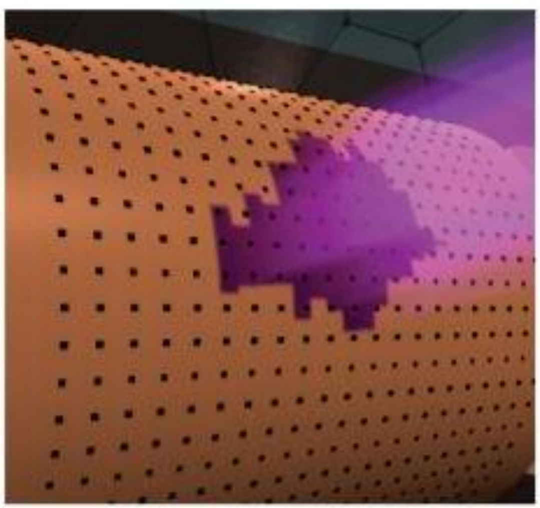
The Ultimate 4D Patient QA Solution

Helical Detector Grid

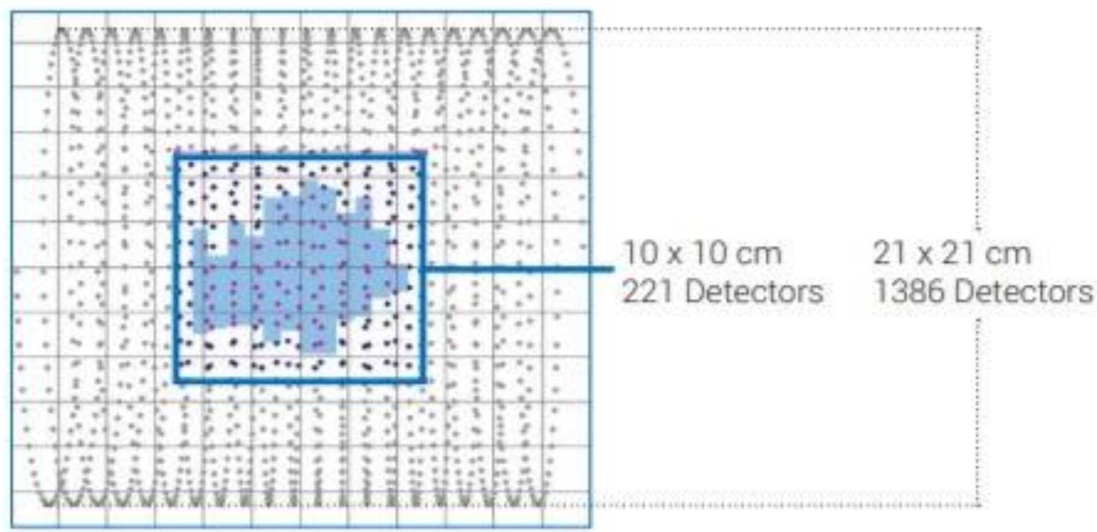
Detectors are arranged on a HeliGrid™ which increases the sampling rate and reduces BEV detector overlap and shadowing.

- An ArcCHECK 10 x 10 cm² area contains 221 detectors; equivalent to the detector density in a MapCHECK® 2
- Entrance and exit dose are measured, effectively doubling the detector density in the measurement field

Beam Delivery



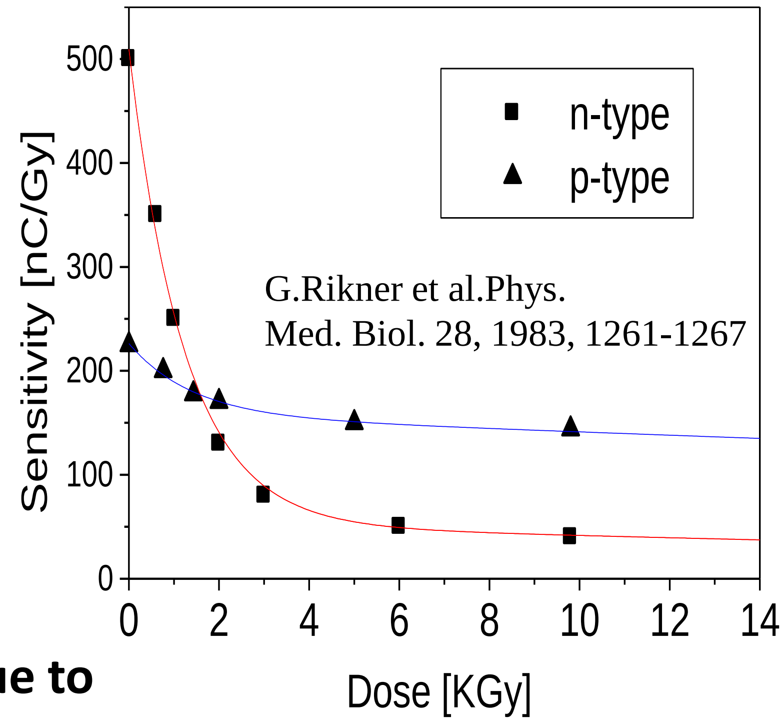
ArcCHECK Detector



The Silicon Choice

Advantages:

- **High sensitivity (18000 times higher than IC).**
- **Well developed manufacture technology.**
- **high spatial resolution.**
- **work in null bias mode (in-vivo).**

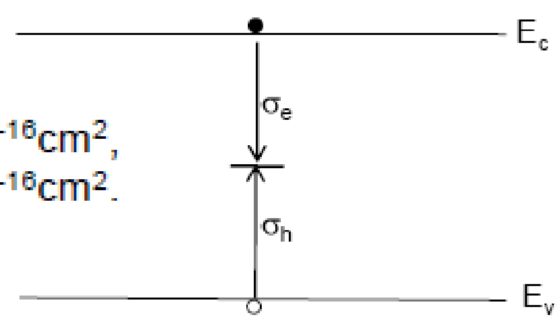


Drawbacks:

- **Sensitivity decrease with accumulated dose due to increase of concentration of recombination centers (recalibrations needed).**
- **Dose rate dependency due to centers saturation at high dose rates.**
- **Energy dependence: Si not "water equivalent".**

Radiation Resistant ?
p-type radiation harder material

$\sigma_e = 1.62\text{x}10^{-16}\text{cm}^2$,
$\sigma_h = 8.66\text{x}10^{-16}\text{cm}^2$.



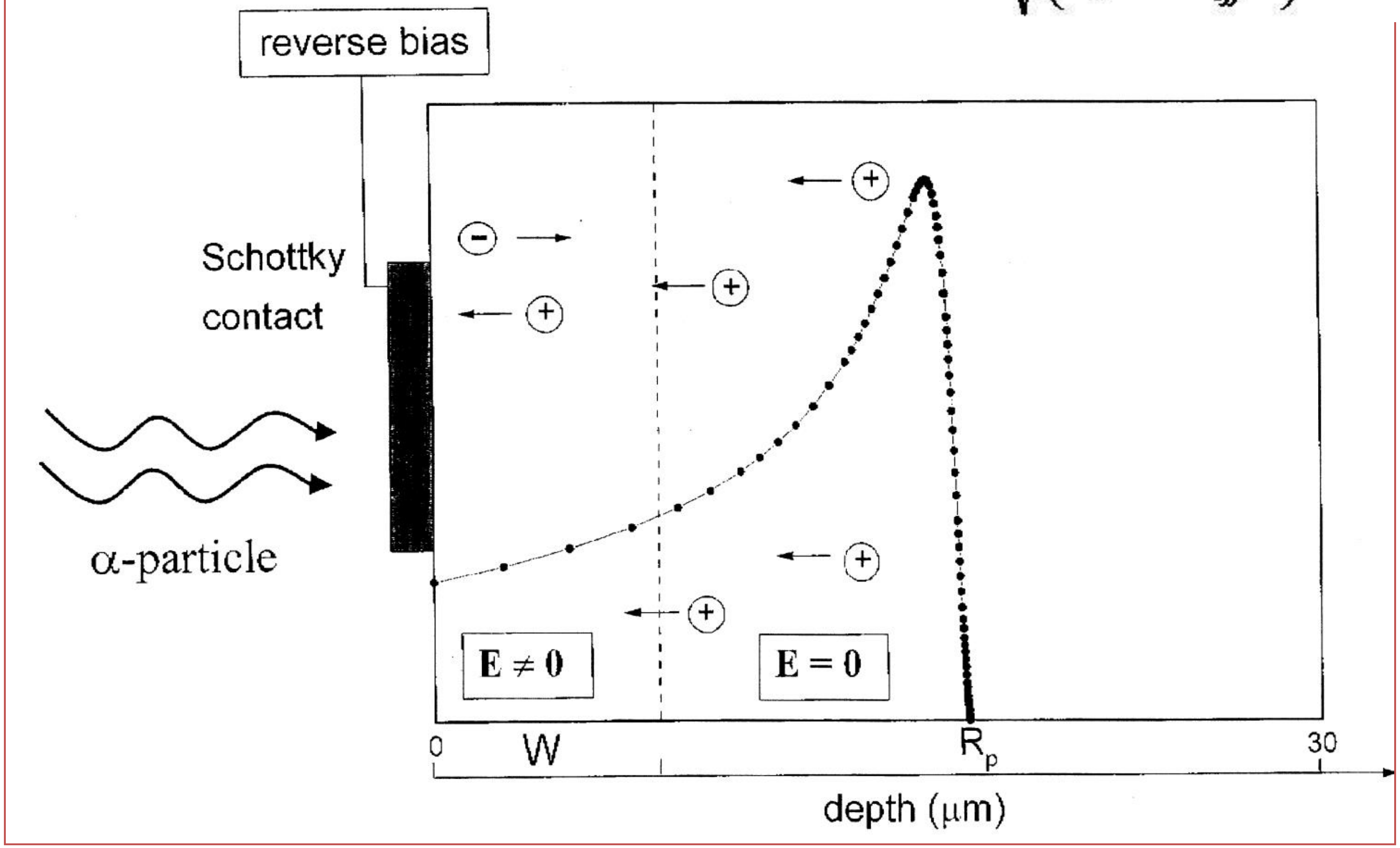
hole capture more efficient -> Lifetime for minority carriers higher in case of electrons.

Dosimeter active region

W = depletion thickness R_p = particle range

L = diffusion length

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

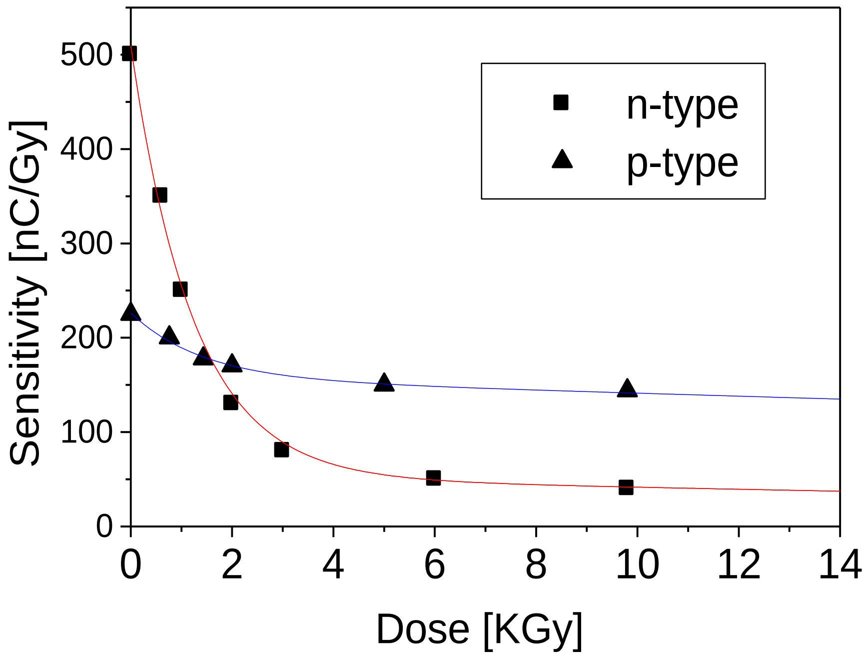


The neutral region contributes (diffusion of minority carriers into the depletion region) to the signal

Radiation damage in standard Si dosimeters (thickness 300um)

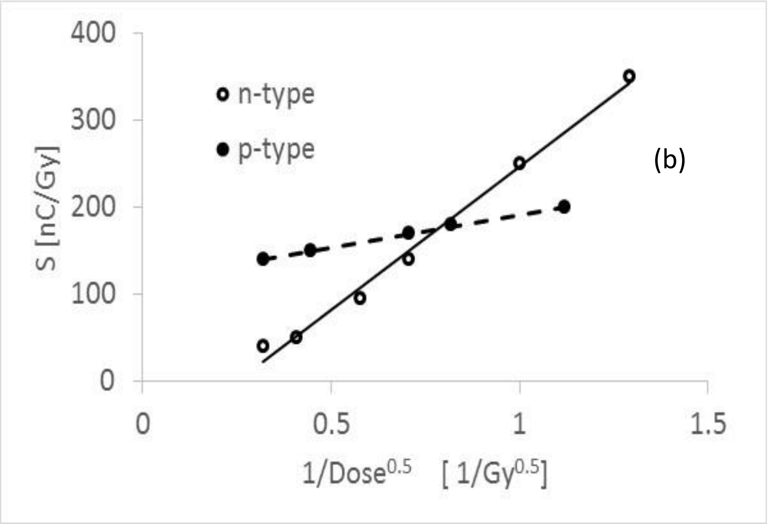
Sensitivity as a function of trap concentration in a Si dosimeter

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



N_t linearly increasing with dose so:

$$S \propto \frac{1}{\sqrt{Dose}}$$

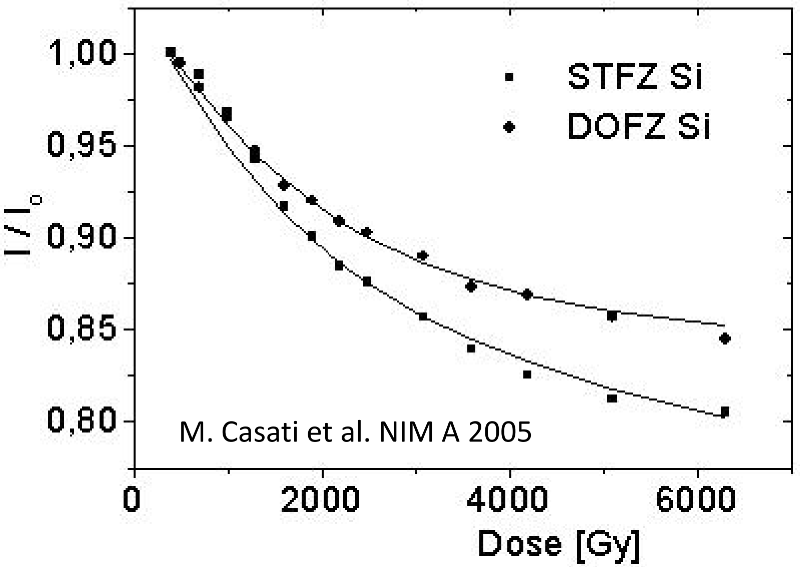


M. Bruzzi, NIMA 809, 2016 Novel Silicon Devices for Radiation Therapy Monitoring, 105-112

Pre-irradiation (≈10kGy) to reduce the dependence of the signal on the dose.

Material engineering concepts have been applied also to Silicon dosimeters for radiotherapy

Improved radiation hardness of DOFZ Si



Decrease in sensitivity with the accumulated dose due to the generation of a dominant trap acting as lifetime killer.

$1/\tau - 1/\tau_0 = \sigma\, v_{th}\, N_t$, $N_t = a\ \phi$; a = trap generation rate

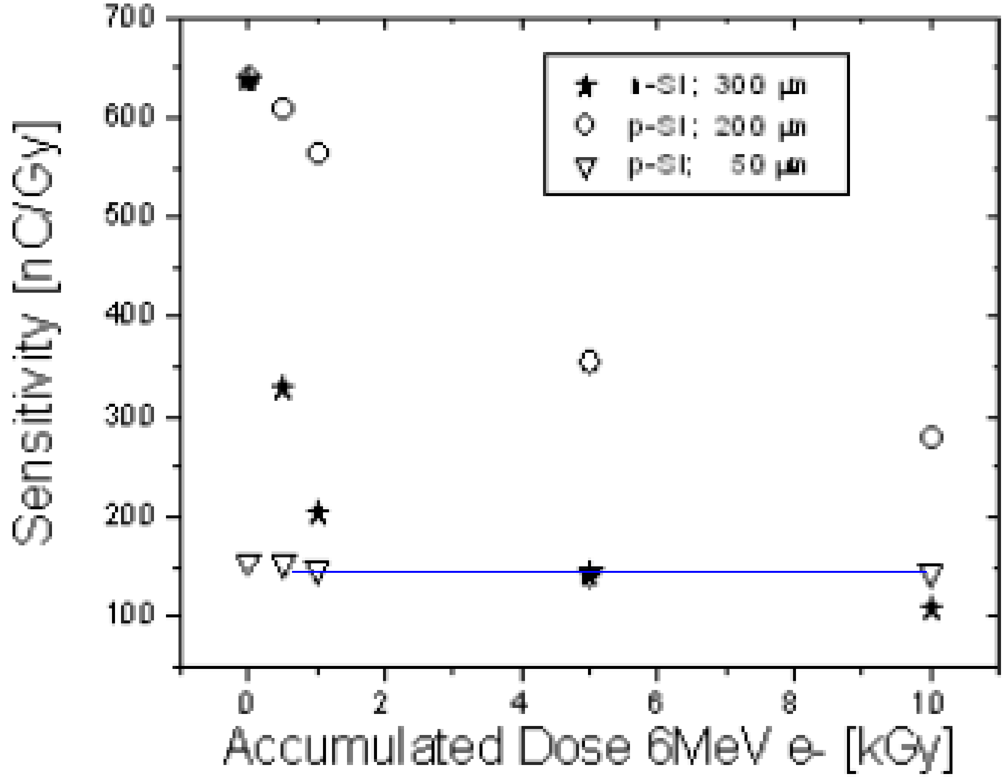
σ capture cross section ; v_{th} carrier thermal velocity. N_t trap concentration.

$a_{DOFZ} < a_{SFZ}$ $\Rightarrow$ increased radiation hardness of the device to radiotherapic beams.

$$a_{DOFZ} = 5.0\text{x}10^{7}\ \text{cm}^{-3}\text{Gy}^{-1},\ a_{STFZ} = 8.1\text{x}10^{7}\text{cm}^{-3}\text{Gy}^{-1}$$

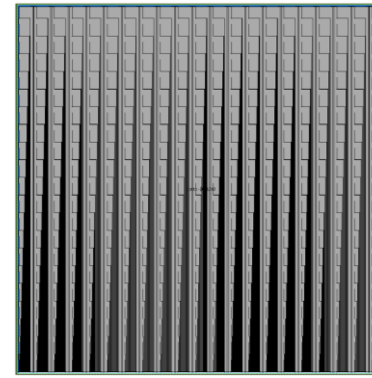
Our recipe: epitaxial p-type Si on MCz substrates to limit active thickness

Active region is limited in any direction to a value shorter than L_n at the highest dose of interest. Epitaxial Layer is used to limit active depth, guard-ring to limit active area.



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

Si bidimensional dosimeter

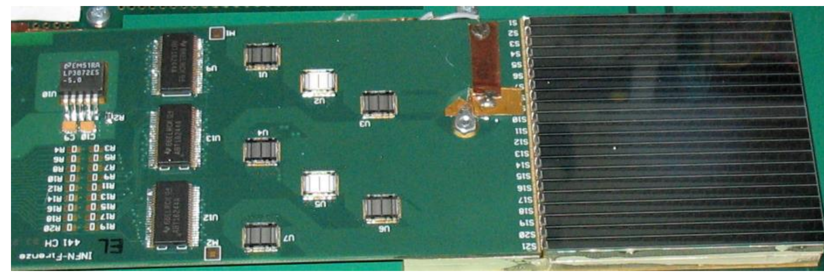


Matrix: 21x21pixels

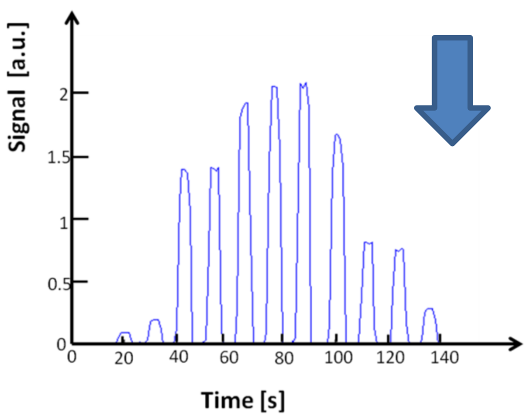
Pixel: 2x2mm Pitch: 3mm
Detector size: 6.3x6.3cm^2

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

Covered area 20×20 cm^2
~4k channels

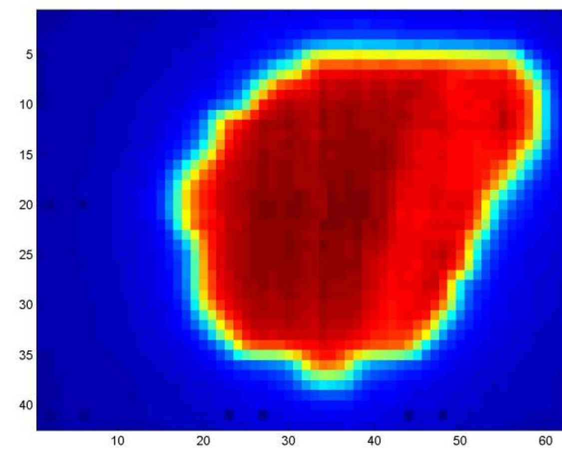


Measured time structure of dose segments



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.

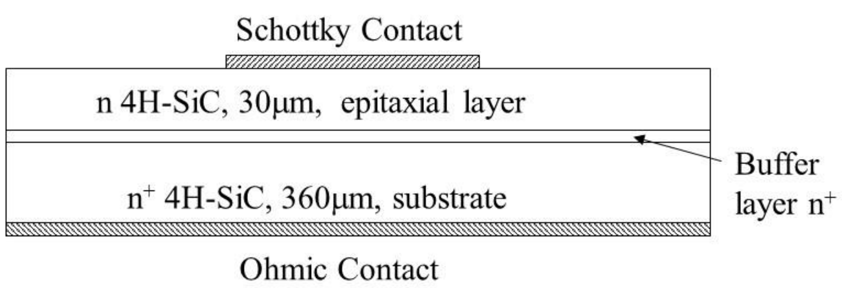


United States Patent (10) **Patent No.: US 8,563,936 B2**
Bruzzi et al. (45) **Date of Patent: Oct. 22, 2013**

The SiC choice

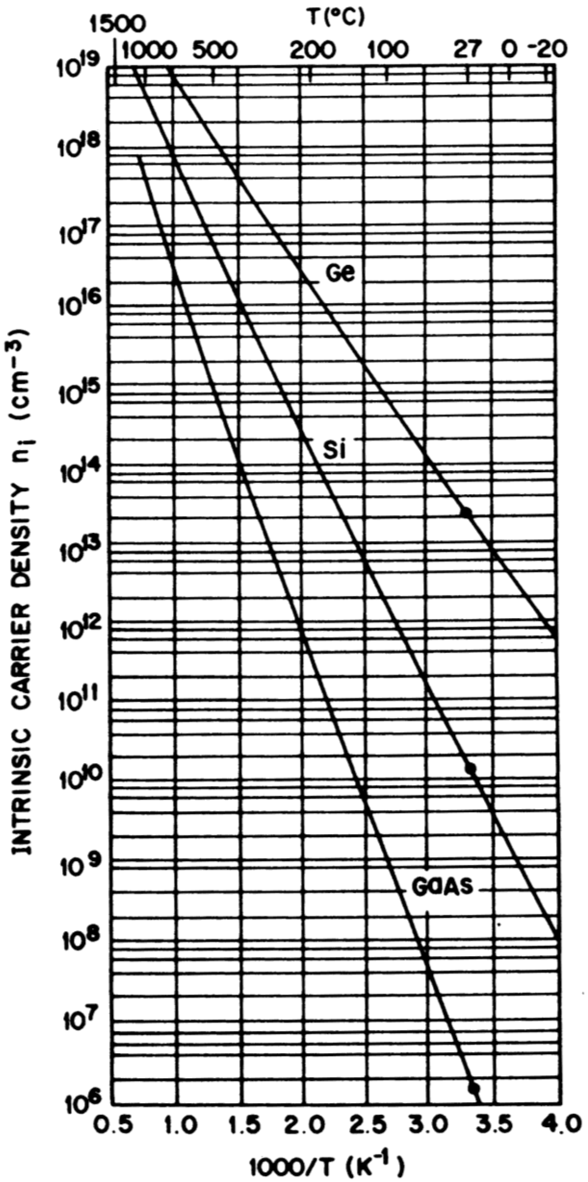
- ☺ Low Leakage Current
- Working without applying bias
- Very low active volume
- Fast Response
- More tissue equivalent than Si
- ♠ Radiation resistance ?

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

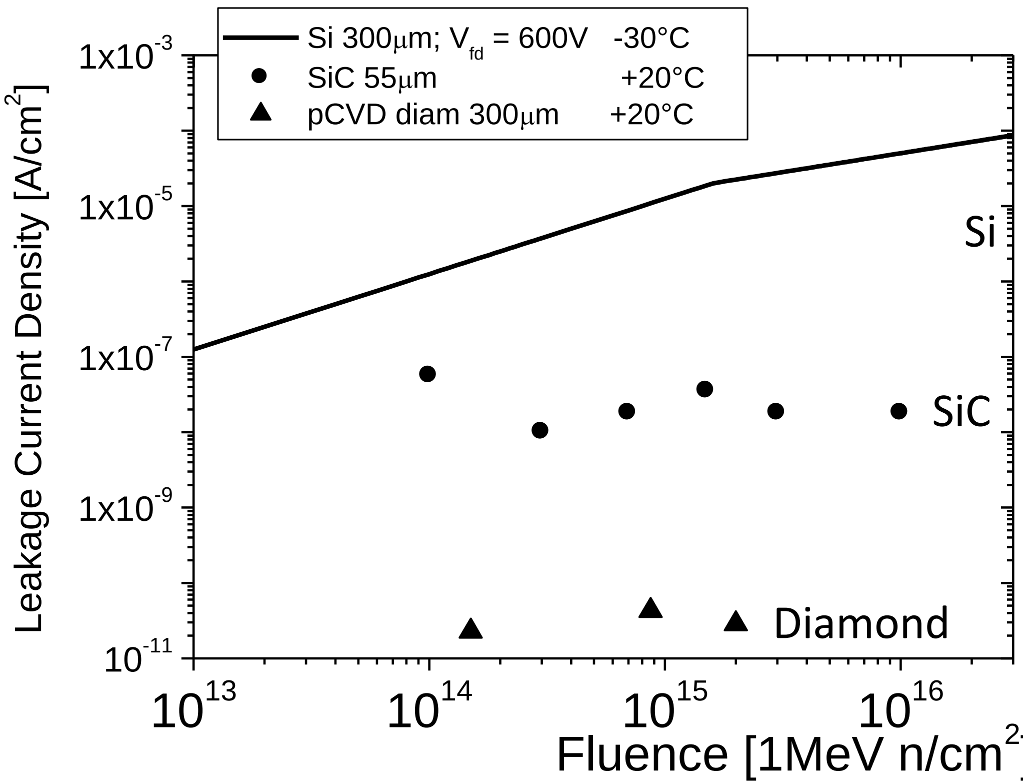


High bandgap semiconductors: generation always negligible → intrinsically radiation hard

$$J_{gen} \propto \frac{n_i}{\tau_g} W \qquad n_i \;\alpha\; T^{\frac{3}{2}} e^{-\frac{\varepsilon_g(T)}{2K_B T}}$$



T = -30°C; V = 600V, W = 300μm

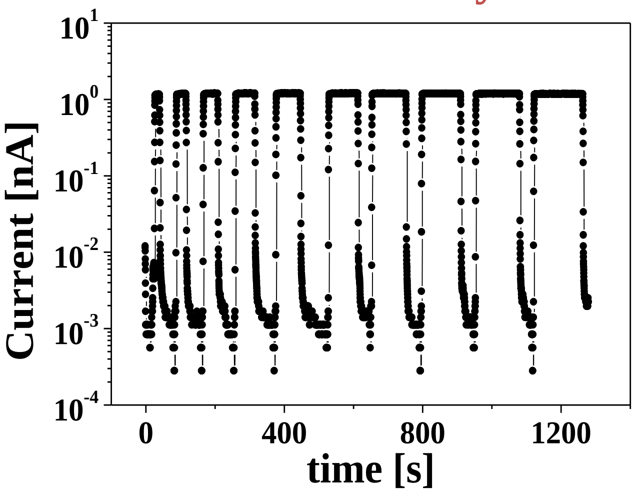


M. Bruzzi ;H. Sadrozinski ; A.Seiden NIM A 579 2 754 (2007)

Dosimetric Characterisation

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

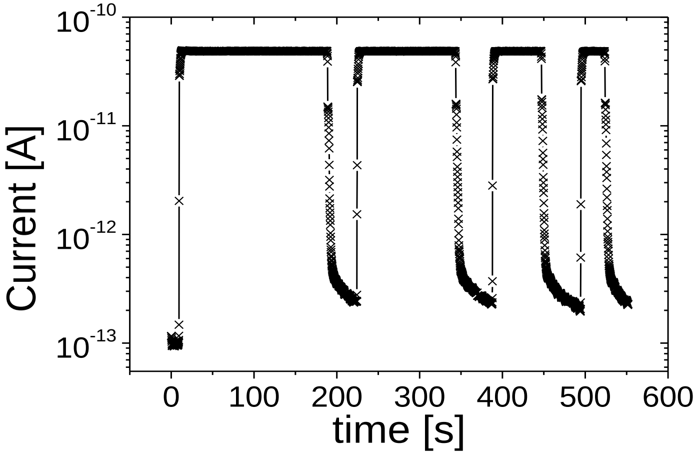
22 MeV Electrons
dose-rate 4.2Gy/min



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

Co^{60} γ

dose-rate 0.21Gy/min



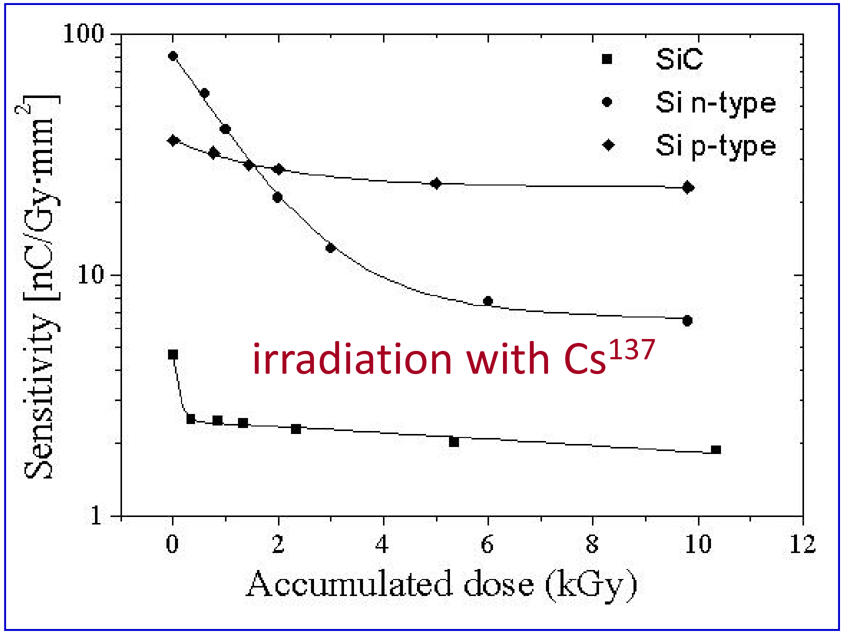
V_{rev} = 0 Volt I_{signal} ~ 50pA
I_{dark} ~ 0.1pA

M. Bruzzi, F. Nava, S. Pini, S. Russo, App. Surf. Sci, 184 (2001) 425-430

Comparison between Epitaxial SiC and standard dosimeters

Device	bias [V]	Vol. [mm^3]	S [nC/Gy]	S per unit volume [$nC/(Gy \cdot mm^3)$]
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**

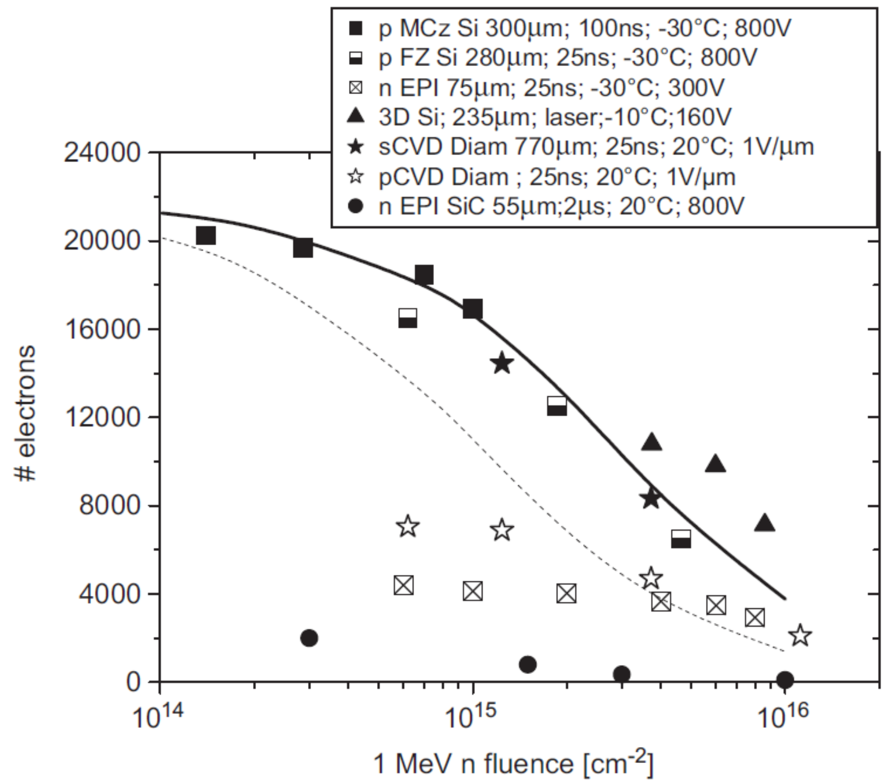
Problem: SiC is not defect tolerant



M. Bruzzi, F. Nava, S. Pini, S. Russo, App. Surf. Sci, 184 (2001) 425-430

Worse sensitivity vs. Accumulated Dose than Si

Worse cce vs. fluence than Si



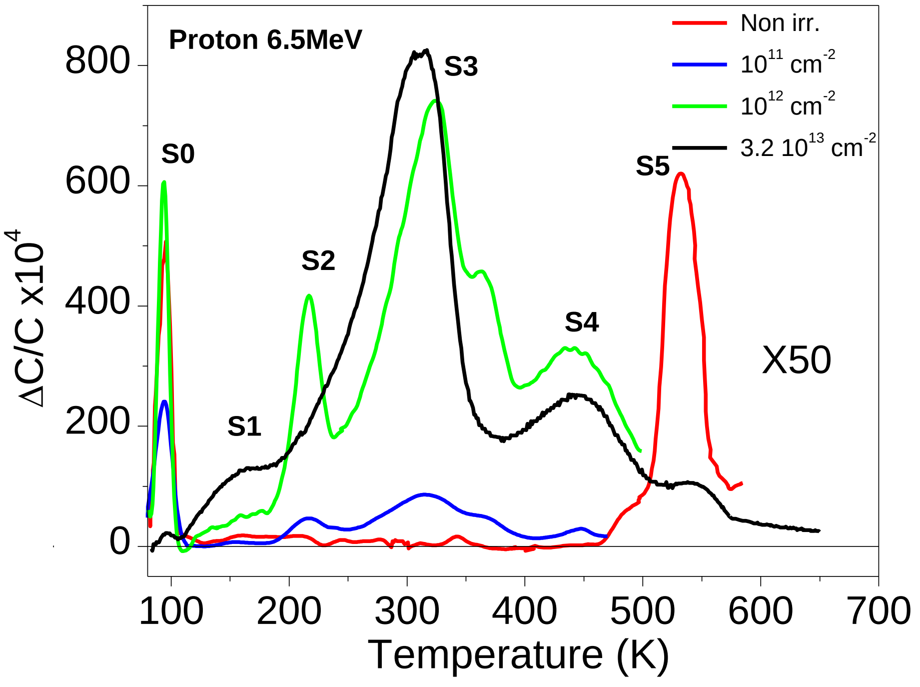
M. Bruzzi et al. NIMA 579 (2007) 754-761

Microscopic radiation damage si responsible of the reduced charge collection of SiC with respect to Si and Diamond

- n epilayer 7μm
- $N_{eff} \sim 7\times10^{15}cm^{-3}$
- Schottky Barriers Ti or Ni
- Ohmic contacts Ti/Ni/Ag
- Deep levels by C-DLTS
- 6.5MeV p up to 6.4x$10^{13}cm^{-2}$

Six traps detected after irradiation

- $E = 0.18 - 1.22eV$
- $\sigma = 10^{-13}-10^{-18}cm^{-2}$
- $N_t = 10^{11}$ - $5x10^{14}$ cm^{-3}



Data from A. Castaldini, A. Cavallini et al.

The Diamond Choice

☺
- 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
- it can be used as TL dosimeter (off-line) or for on-line applications

♠
- high defect density - priming effects – instability of the signal
- high voltage required
- high production costs

Overview | Specifications | Learn more

Nearly as good as water.

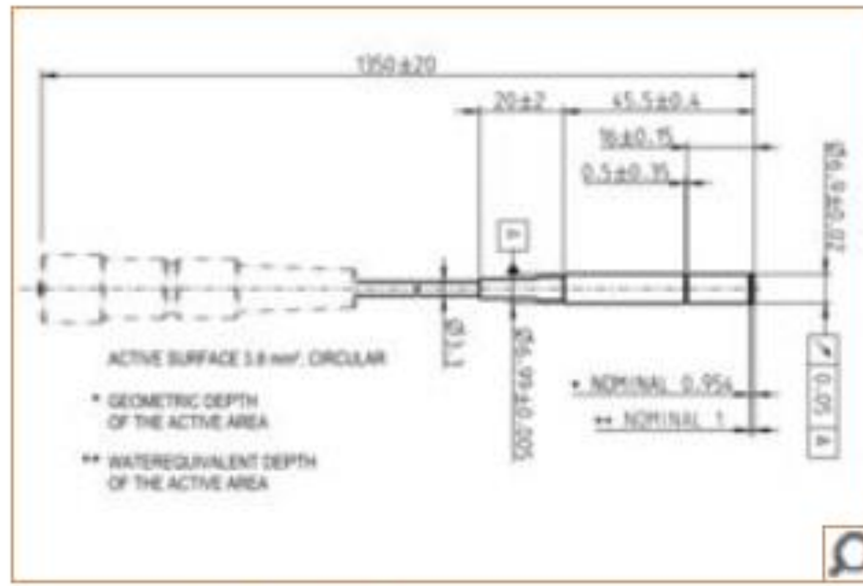
microDiamond

microDiamond
Synthetic Diamond Detector

Key Features

- Nearly water equivalent for all beam energies
- Very small sensitive volume (0.004 mm³) - perfect choice for small field dosimetry
- Suitable for all field sizes up to 40 cm x 40 cm
- Precise, accurate measurements in photon, electron and proton fields
- Excellent radiation hardness, minimal energy, temperature and directional dependence
- No high voltage required. Suitable for all connecting systems (BNT, TNC, M)

Type No.	60019
Design:	waterproof, disk-shaped, sensitive volume perpendicular to detector axis
Measuring quantity:	absorbed dose to water
Nominal sensitive volume:	0.004 mm³, radius 1.1 mm, thickness 1 µm
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 (6 ... 25) MeV electrons (70 ... 230) MeV protons
Field size:	(1 x 1) cm² ... (40 x 40) cm²
Connectors:	BNT, TNC or M

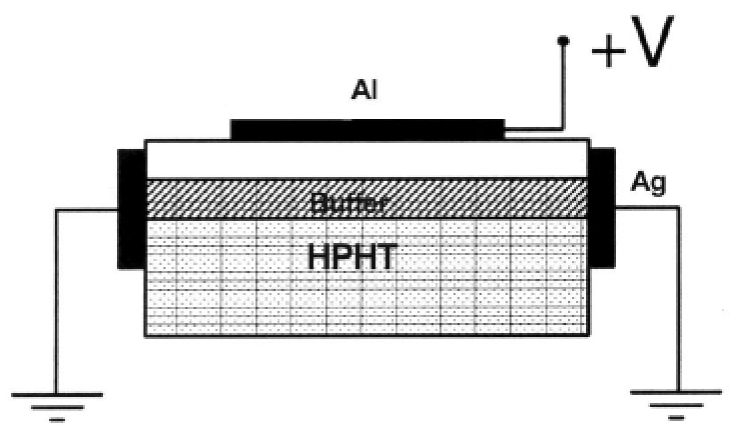


microDiamond Detector Design

Single Crystal Diamond Dosimeter

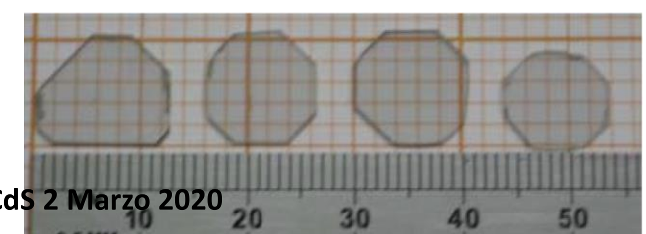
device manufactured by Università di Roma Tor Vergata

Schottky barrier Vrev = 0



- HPHT p+ boron doped substrate - 300 μm thick
- 35 μm thick p+ buffer layer (CVD)
- Active epilayer 17 μm thick
- Al 100 nm ϕ 2mm upper electrode
- Buffer layer contacted at the perifery with Ag paste

Problem : No large area array available



The Polycrystalline diamond Choice

- **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**

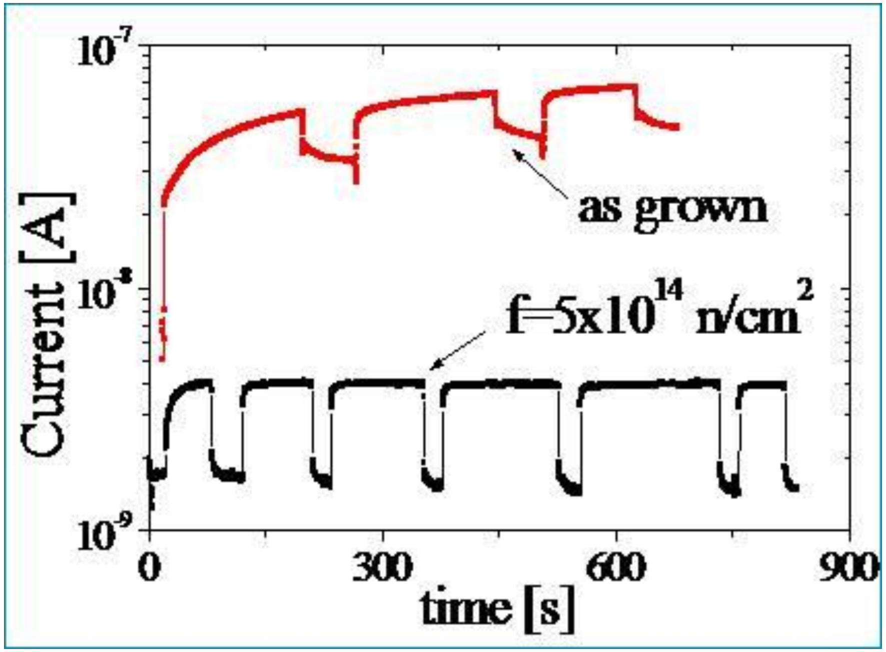
Polycrystalline CVD diamond

ability to produce large area wafers of 3-5"

- **persistent currents due to trapping → slow dynamics**

Neutron irradiation in pCVD diamond beneficial as removes dominant defect and increase recombination centres, bringing to faster dynamics

Measurements of pCVD diamond photoresponse under different cycles of X-ray irradiations – deactivation of the peak at 1eV probably responsible of the current instability.



M. Bruzzi et al., Appl. Phys. Lett, (2002)

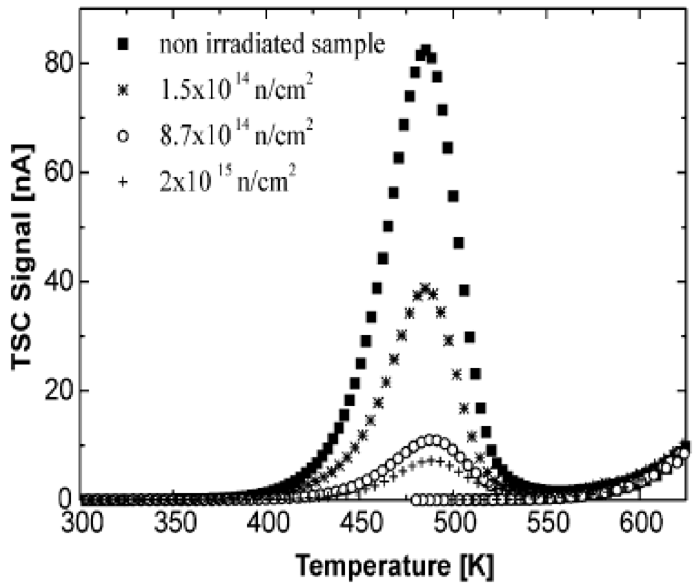
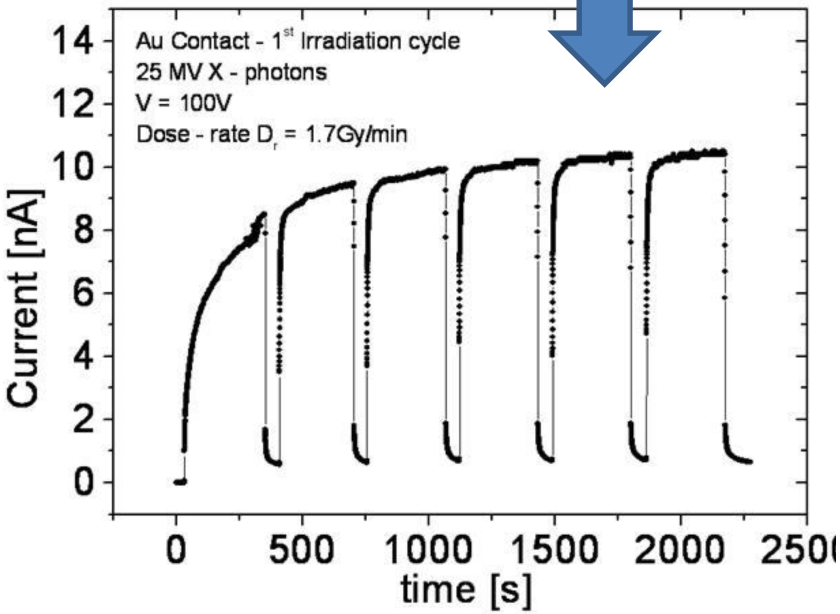


Fig. 1. TSC signal vs. temperature for non-irradiated and irradiated samples, after filling with UV xenon lamp for 20 min. The samples are biased with 100 V. The heating rate is 0.15 K/s. The neutron fluences are indicated in the legend.

Problem in polycrystalline diamond: priming and instability effects due to defects at grain boundaries

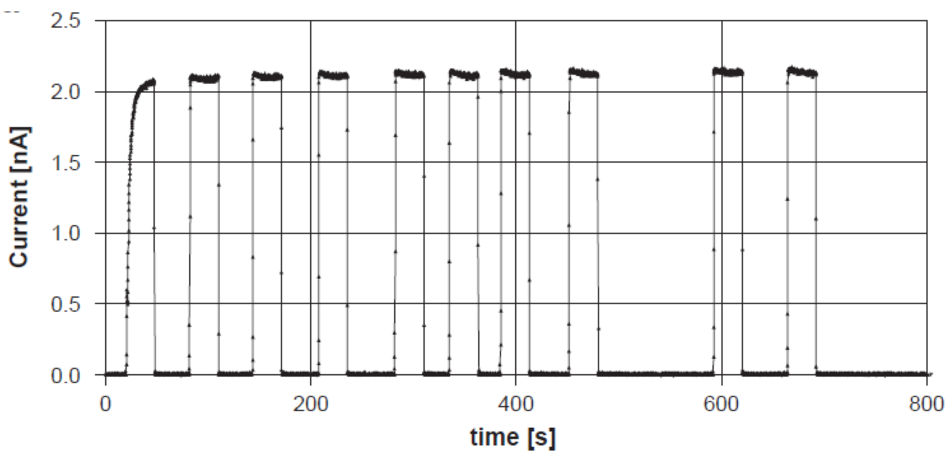
High voltage application
Ohmic contacts



Current response of the unirradiated sample (Au contact) showing the priming effect during the first 6 successive irradiations.

Our Solution to get STABLE SIGNAL

- back to back schottky barriers
- low/null bias



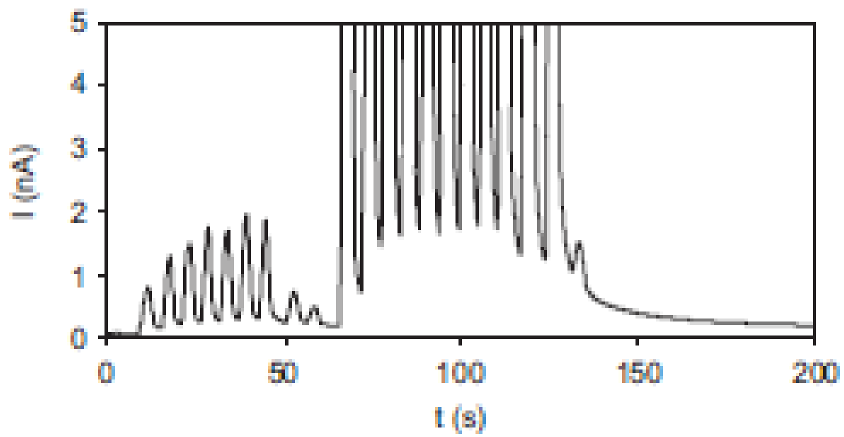
Diamond & Related Materials 20 (2011) 84–92

Zero-bias operation of polycrystalline chemically vapour deposited diamond films for Intensity Modulated Radiation Therapy

M. Bruzzi [a,*], C. De Angelis [b], M. Scaringella [a], C. Talamonti [c], D. Viscomi [b], M. Bucciolini [c]

Priming and instability effects due to trapping and polarization in pCVD are dominant at high voltage with ohmic contacts and high electric field applied.

Slow dynamics due to persistent currents in pCVD in conventional beam and in IMRT modality



C. De Angelis et al. / Nuclear Instruments and Methods in Physics Research A 583 (2007) 195–203

Polarization is negligible at low/zero bias operation when using Schottky contacts.

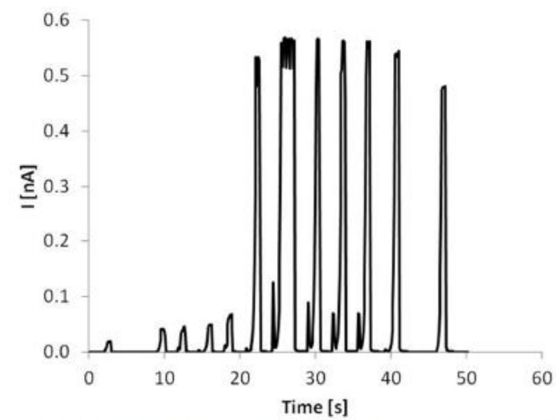
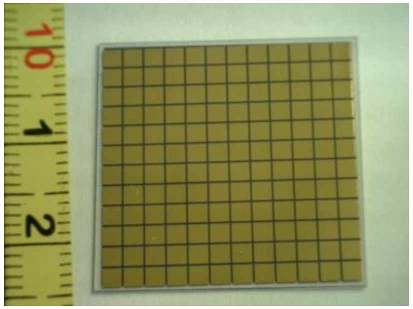


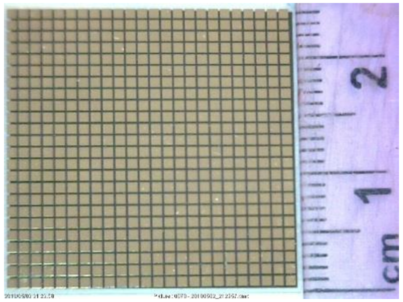
Fig.5 Time structure of the IMRT segments as measured by one of the pCVD diamond pixels under an IMRT prostate cancer treatment.

M. Scaringella et al. / Nuclear Instruments and Methods in Physics Research, A, 796, 2015, 89-92

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

polycrystalline diamond segmented dosimeter prototype made in Florence





- Material

- Up to three polycrystalline diamond films $2.5\text{x}2.5\text{cm}^2$ active area each, $300\mu\text{m}$ thick;
- Premium Detector Grade Element Six, UK

- Contacts

• Schottky Barriers produced @ University of Florence
•12 x 12 matrix, pixel size: $1.8\text{x}1.8\ \text{mm}^2 \rightarrow$ 288 pixels in total

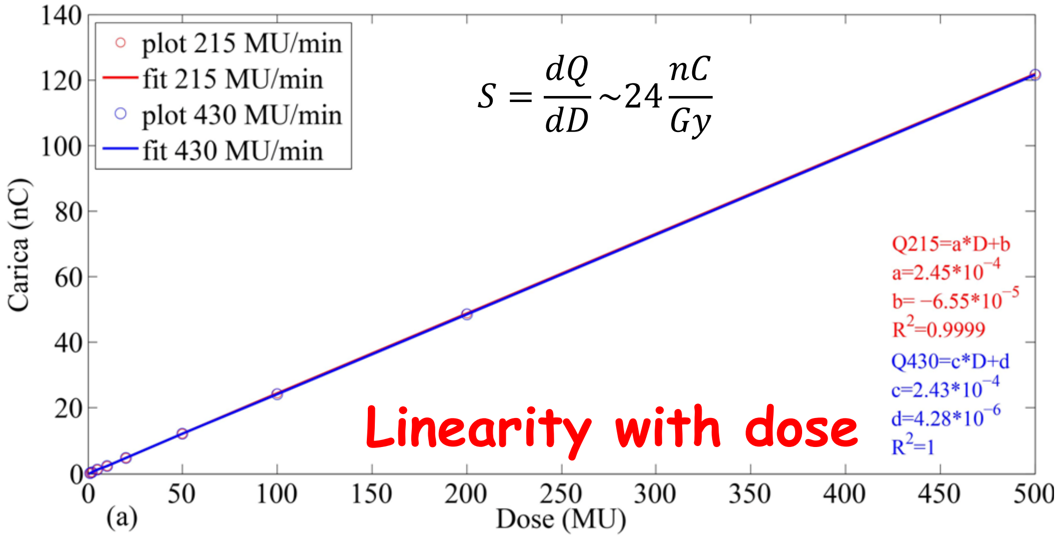
- Read Out Electronics

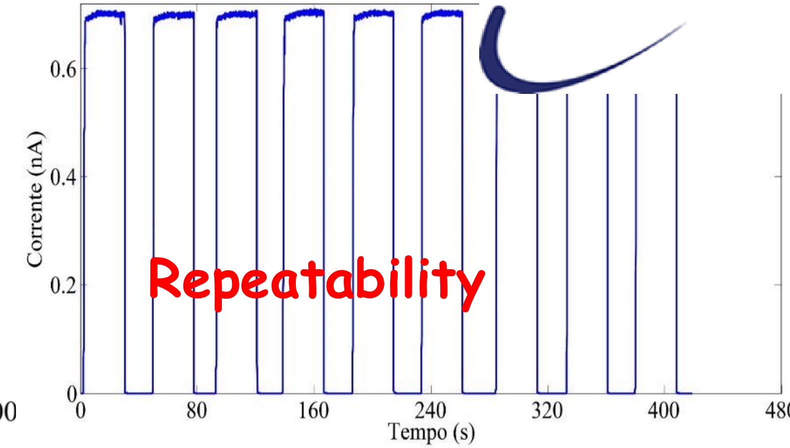
•four 64 channels 20 bit current-input analog to digital converter chips able of measuring currents from fAs to mAs; $160\mu\text{s}$-1s integration time (50ms)
•custom printed circuit board;
•semi-rigid silver-polymer pin-contacts produced by us connecting each pixel of the 144 matrix connecting vias on PCB .

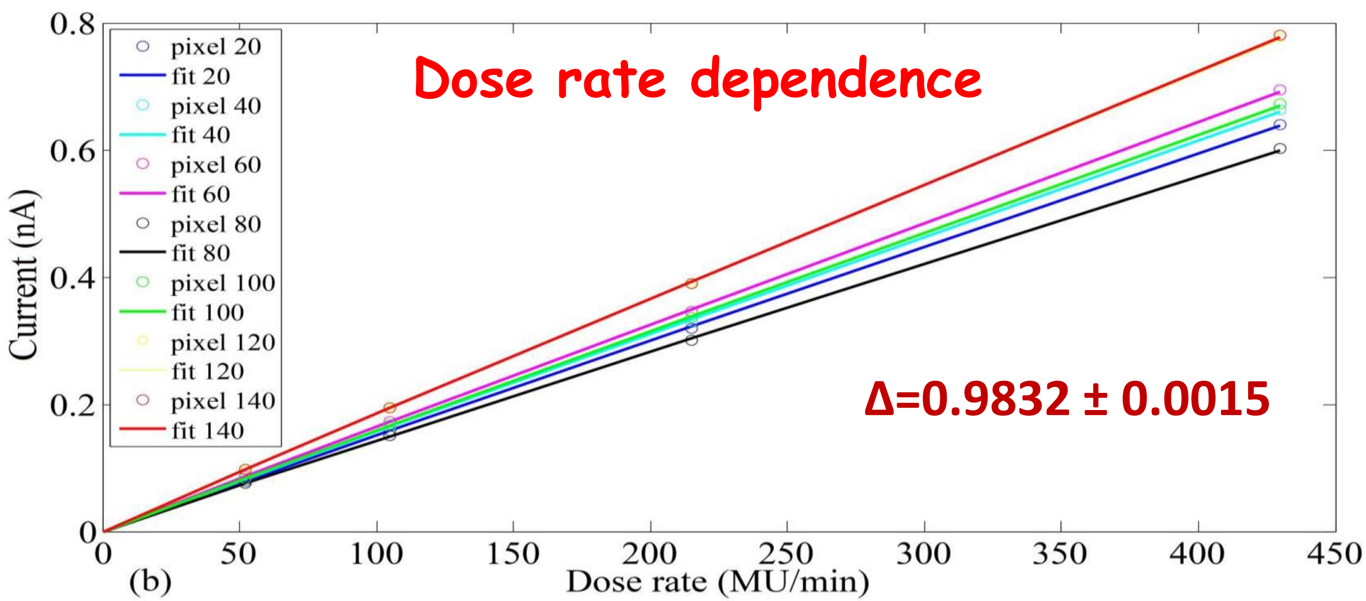
-Measurement

•Low voltage to get fast and reproducible signals;
•Device can be moved in x-y directions to cover a
•wider radiation field area.

pCVD Diamond test under linac



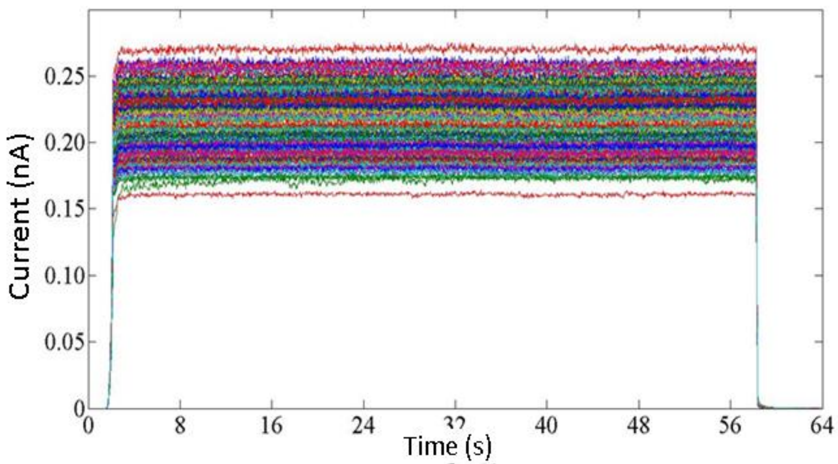




Bartoli et al. 2017 JINST 12 C03052

Performance under conventional and IMRT radiotherapy beam

Current response of all pixels in a conventional X-ray beam (V_{app} = 1V) Dose-rate 50 Mu/min



Bartoli et al. 2017 JINST 12 C03052

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

Current response of one pixel under an IMRT beam in step and shoot modality

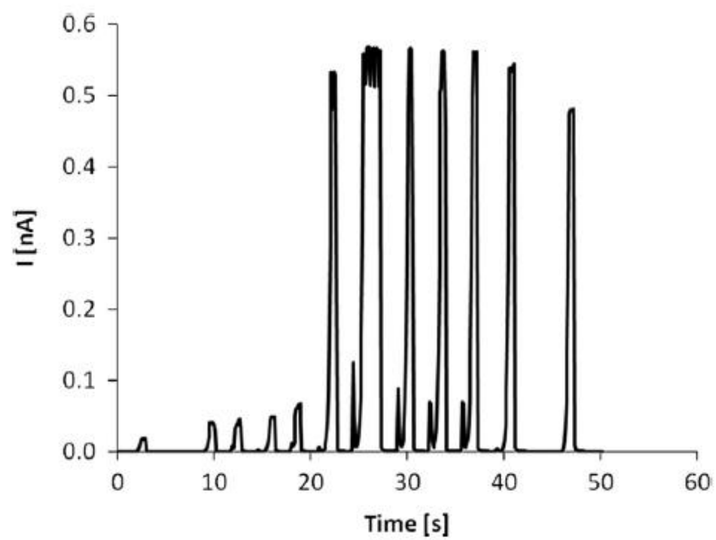


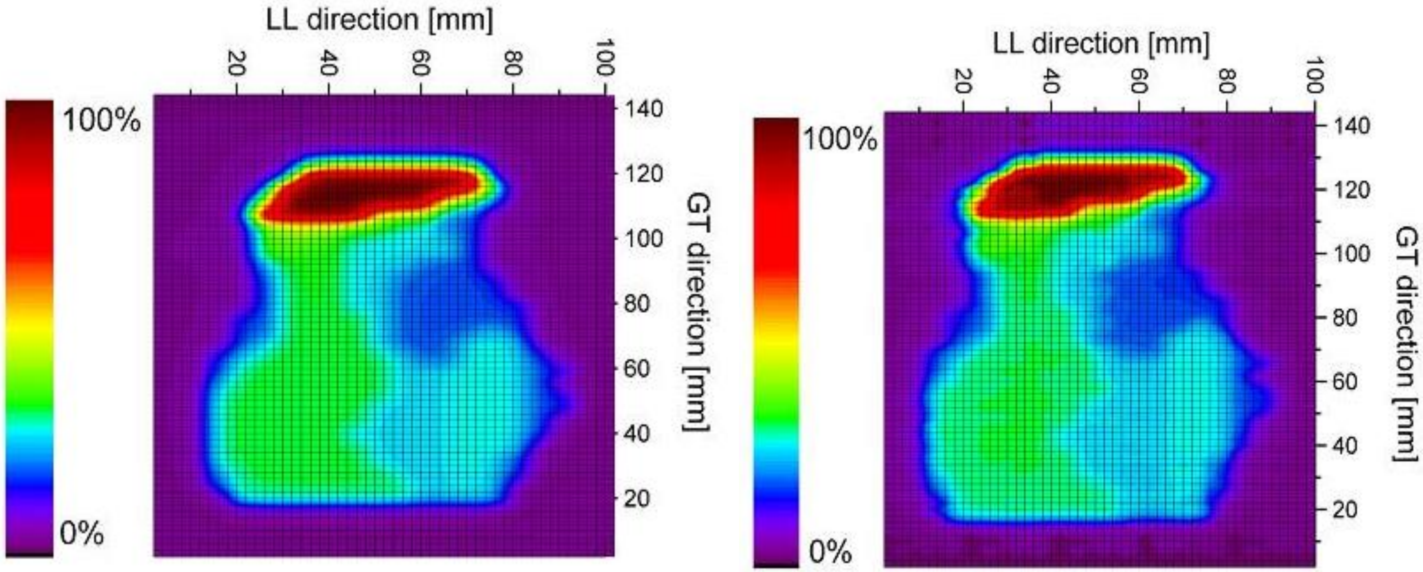
Fig. 5. Time structure of the IMRT segments as measured by one of the pCVD diamond pixels under an IMRT prostate cancer treatment.

M. Scaringella et al.

Nuclear Instruments and Methods in Physics Research A 796 (2015) 89–92

First IMRT map with Diamond Device

2.5x2.5cm^2 pCVD Diamond prototype
IMRT map 14x10cm^2
measured by shifting the diamond dosimeter



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.

M. Scaringella et al. / Nuclear Instruments and Methods in Physics Research A 796 (2015) 89–92

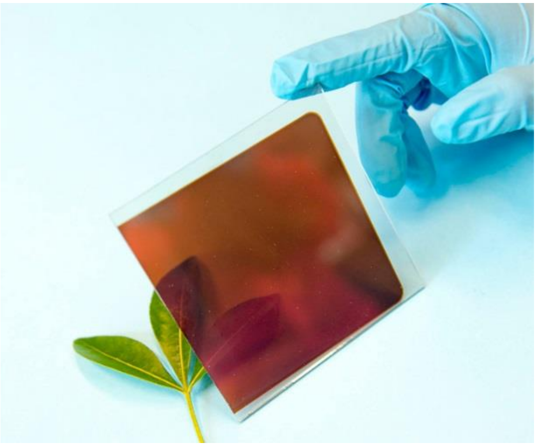
The Perovskite Choice

Perovskites are emerging materials for large-area and flexible optoelectronic device systems

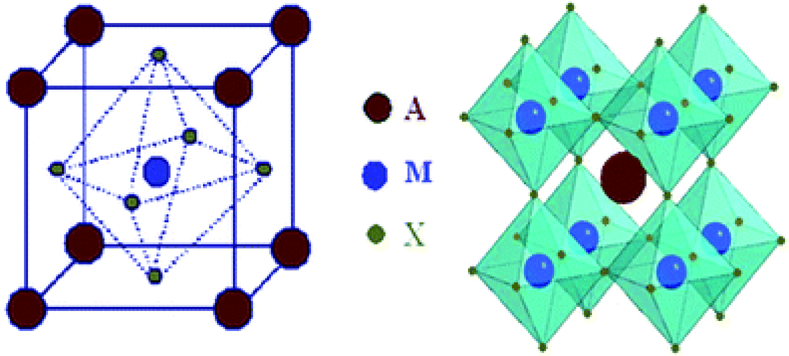
AMX_3 (X = oxide, halide anion such as Cl, Br and I, M = metal cation).

Organo-metallic halide perovskites recently proposed for printable large area flexible X-ray detectors in medical imaging applications (Nature 2017 550(7674): 87-91; Physics in Medicine, Vol. 5, 2018 20-23.).

All-inorganic perovskites, $CsPbX_3$ (X=Cl, Br, and I) attracting alternatives due to their improved chemical stability, they can be produced in form of single crystals, nano-crystals and micro-crystalline thin films.



A 15% perovskite solar cell made in University of Oxford

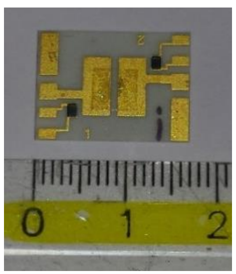


The $CsPbBr_3$ Choice

- More sensitive than silicon
- Easy deposition methods
- Potentially defect tolerant

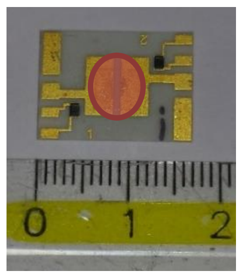
	SILICON	CsPbBr3
Eg [eV]	1.12	2.30
ρ [g/cm³]	2.33	4.55
E_i [eV]	3.60	5.30
S [nC/Gymm³]	647.22	860

Sample preparation and characterization in Florence



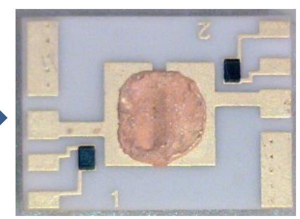
Our custom PCB

$CsPbBr_3$ sat. in DMSO



Deposition of the saturated solution of CsBr and $PbBr_2$ in DMSO (1:1)

Heating treat. 150 °C



Evaporation of the solvent and formation of perovskite

PMMA cover to protect against moisture

New: single crystals cm size

- Possibility to deposit directly on any kind of substrates, even flexible

- Spin coating, magnetron sputtering, dropcast – polycrystalline and single crystals

Defect Tolerance of $CsPbBr_3$

Conventional semiconductors as GaAs, CdSe, InP, are defect intolerant as they are prone to mid-gap states very active as trap states.

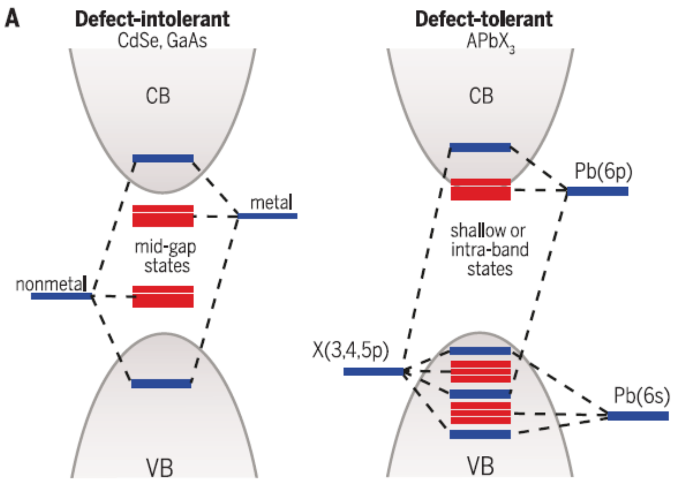
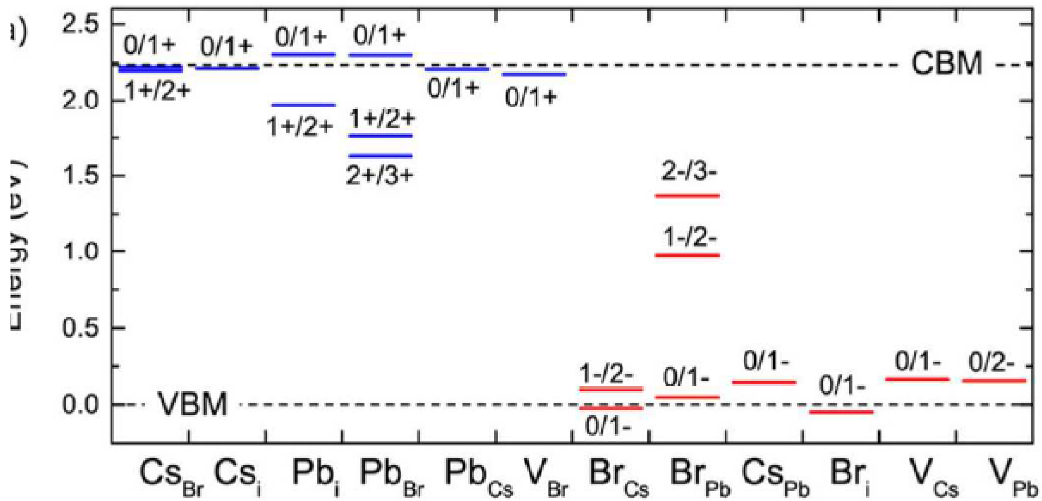


Fig. 4. Defect tolerance in LHP NCs. (**A**) Schematics comparing electronic structures that are defect-intolerant, such as for conventional semiconductors (for example, CdSe, GaAs, and InP), and defect-tolerant, such as for LHPs (*27*). Defects do not act as trap states in LHPs and are therefore benign toward their electronic and optical properties. [Adapted from (*27*)] (**B**) Electronic structure diagrams for $CsPbBr_3$ NCs at the DFT/PBE level of theory (*26*), where PBE is Perdew-Burke-Ernzerhof exchange-correlation functional. Each line

Kovalenko *et al.*, *Science* **358**, 745–750 (2017)

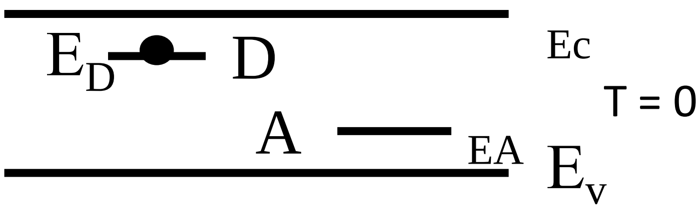
defects in $CsPbBr_3$



J. Kang, L.-W. Wang, *J. Phys. Chem. Lett.* **2017**, *8*, 489–493.

$CsPbBr_3$ potentially defect tolerant: mostly shallow and intermediate defect states.

Shallow levels: The hydrogen-like model



Donor (e.g. P in Si) is seen as a complex Si + H, an hydrogen atom is added at a site of the silicon lattice.

$$E_{Dn} = -\frac{e^4 m^*}{2(\varepsilon_0 \varepsilon_r)^2 \hbar^2} \frac{1}{n^2} \approx 10\text{-}60\,\text{meV}$$

→ fully ionized at moderate temperatures → Doping

$$a^*_n = \frac{\varepsilon_0 \varepsilon_r \hbar^2}{m^* e^2} n^2$$

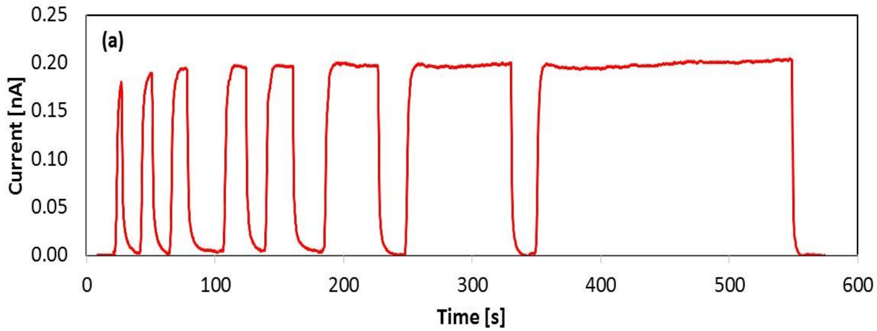
a_o = 0.529 Å Bohr radius, a_{Si} ~ 30 Å ; a_{Ge} ~ 80 Å

→ delocalized wave functions

$$E_n \propto -\frac{m^*}{{\varepsilon_r}^2}$$

A level e.g. that in silicon is a few tens of meV reduces to few meV in $CsPbBr_3$ ($m^* = 0.13m_0$ and $\varepsilon_r = 29.37$)

Polycrystalline: linear dependence of collected charge/current on adsorbed dose and dose rate



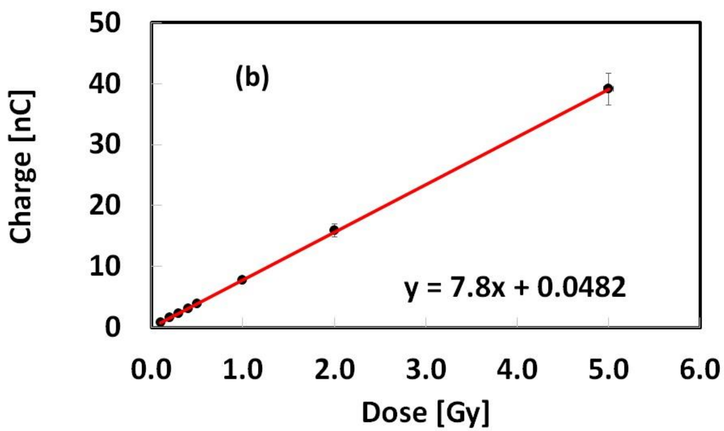
→Active thickness reduced due to defects

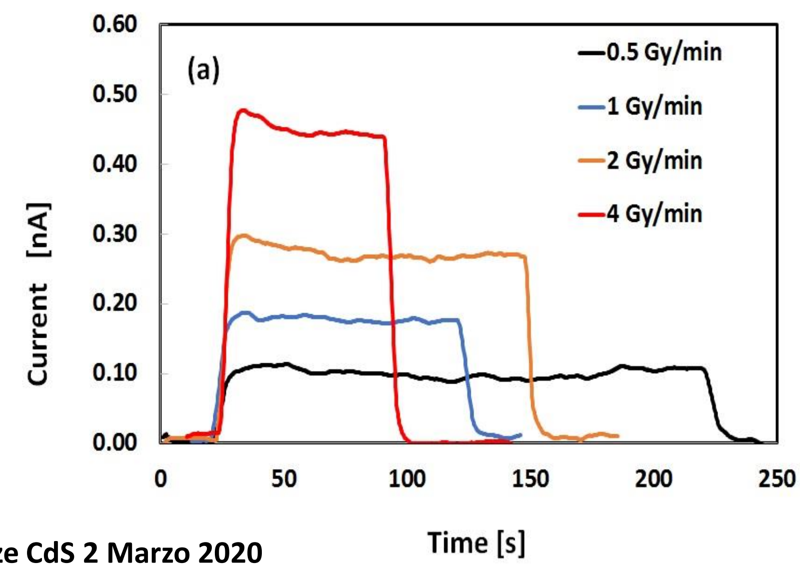
$S_{CsPbBr3}$ ~ 70 nC / (Gymm^3)

S_{Si} = 637 nC / (Gymm^3)

S_{air} = 35 pC / (Gymm^3)

S_{diam} ~ 4 nC/(Gymm^3)





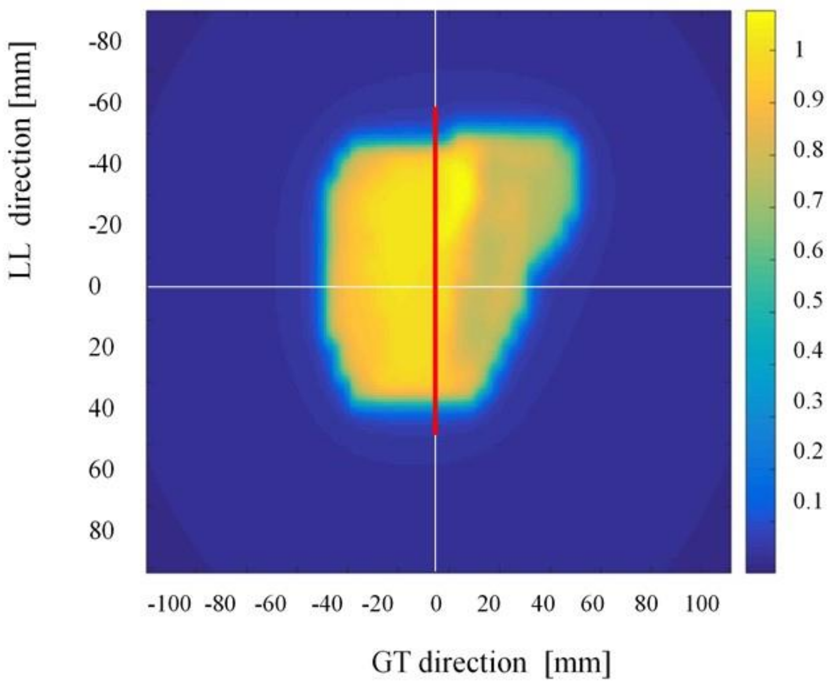
APL Materials

First proof-of-principle of inorganic perovskites clinical radiotherapy dosimeters

Cite as: APL Mater. 7, 051101 (2019); https://doi.org/10.1063/1.5083810
Submitted: 30 November 2018 . Accepted: 02 April 2019 . Published Online: 03 May 2019

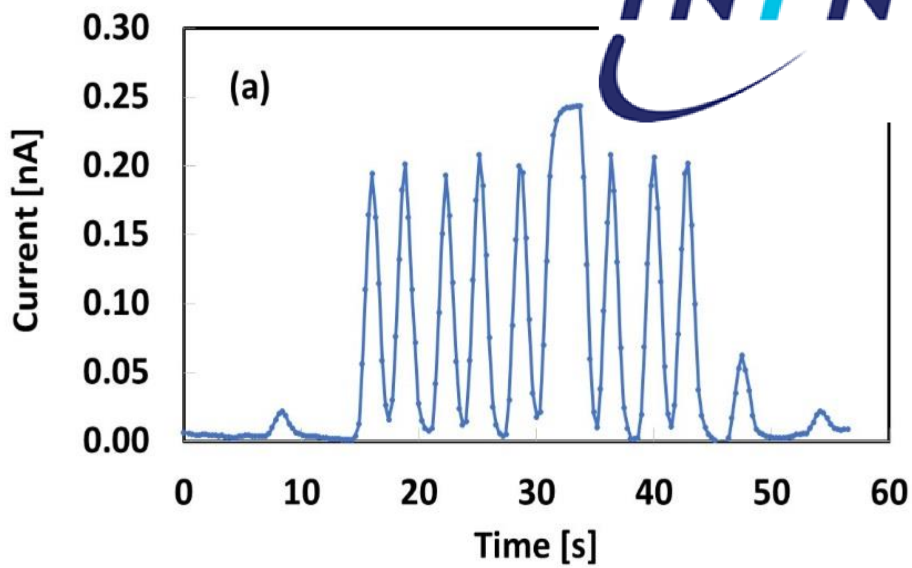
Mara Bruzzi, Cinzia Talamonti, Nicola Calisi, Stefano Caporali, and Anna Vinattieri

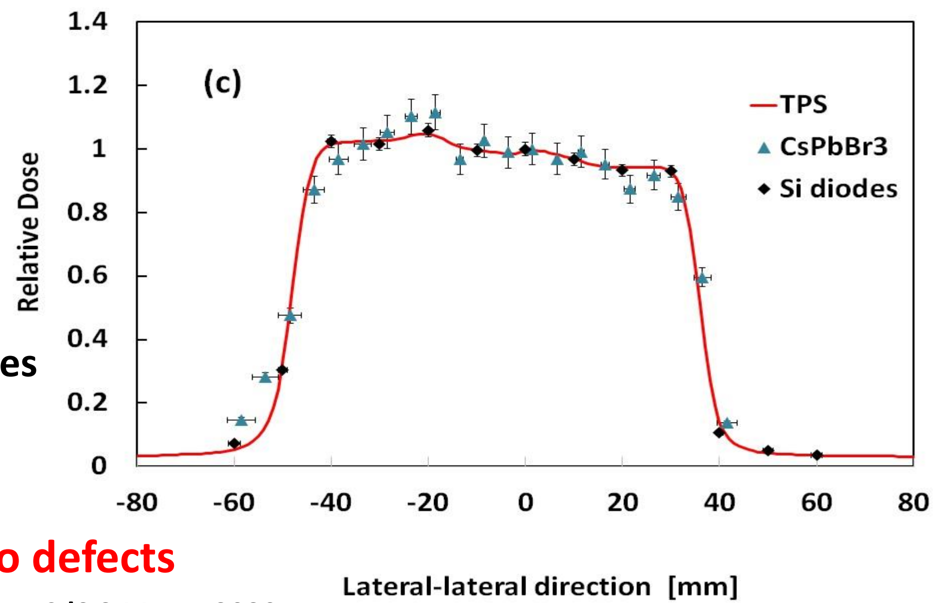
$CsPbBr_3$: promising with IMRT beams; Response comparable to silicon , but slower dynamics



Bruzzi et al. **APL Mater. 7, 051101 (2019)**

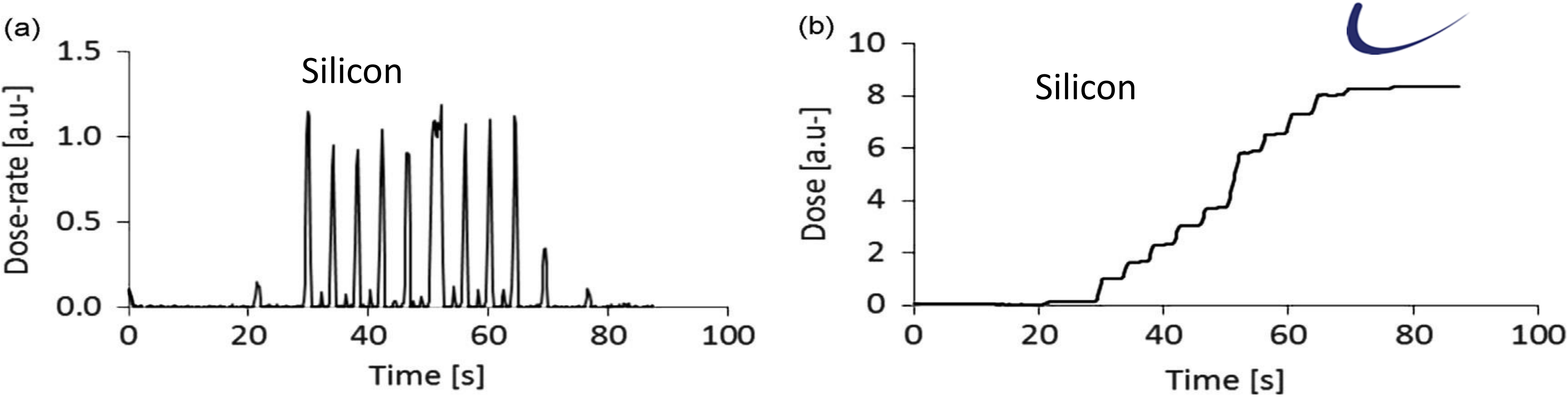
TPS dose map for prostate cancer treatment
GT = Gantry Target direction; LL=lateral–lateral direction (isocenter at intersection red line evidences the profile measured with silicon and perovskite dosimeters



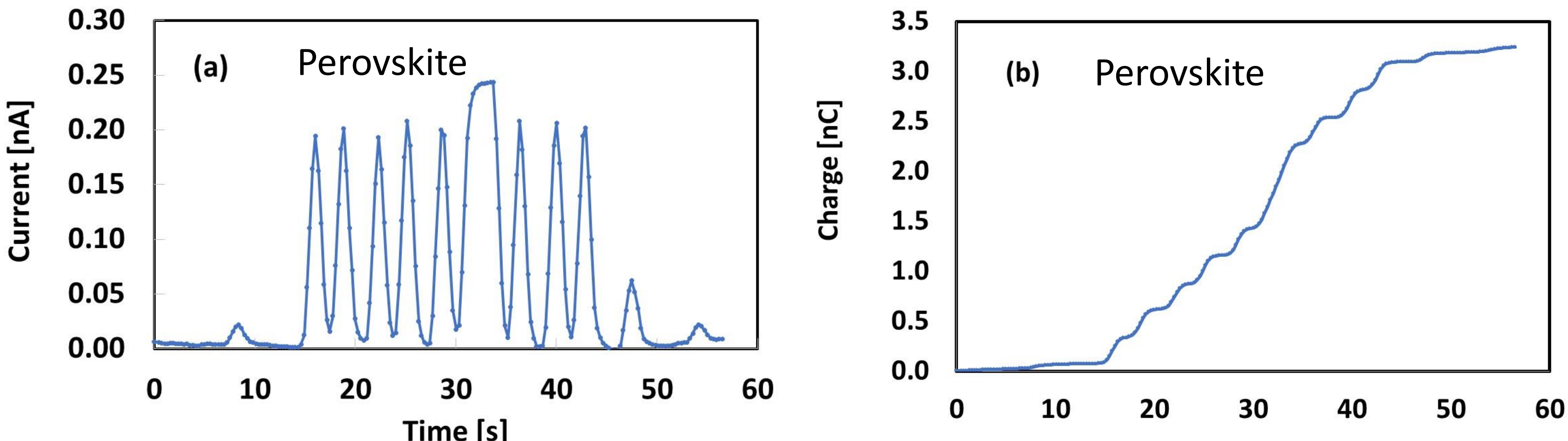


Open Issue →higher rise/decay times due to defects

Open issue: effect of native and radiation induced defects



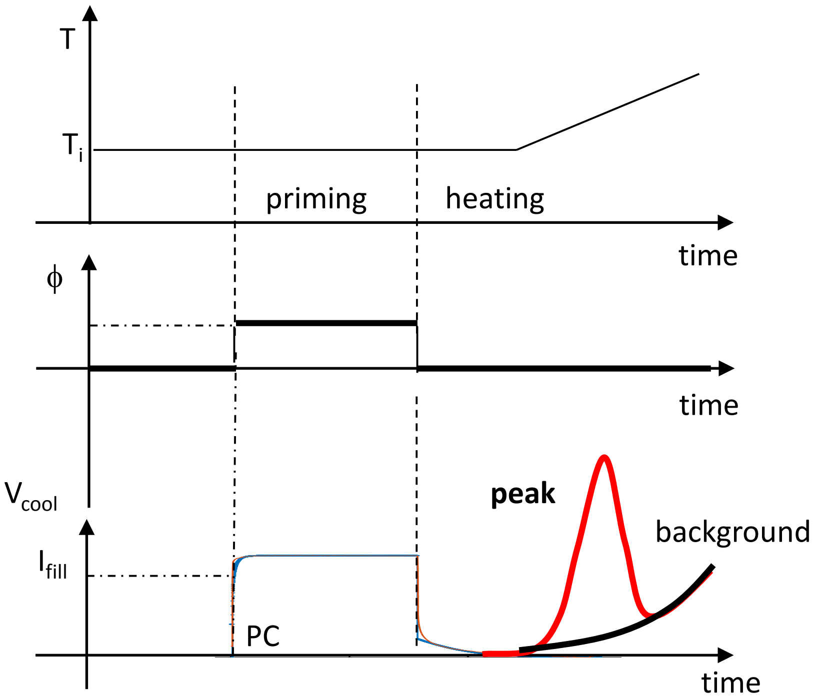
M. Bruzzi, NIMA 809, 2016 Novel Silicon Devices for Radiation Therapy Monitoring, 105-112

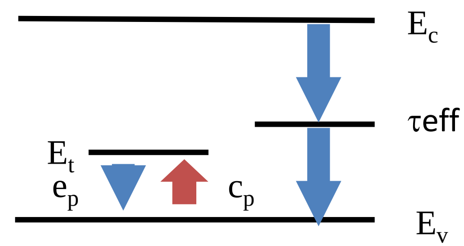


APL Mater. 7, 051101 (2019);

Slower rise/decay times when radiation switches. This effect should be minimized to increase dose measurement accuracy

Thermally Stimulated Current (TSC)
to reveal native and radiation induced traps





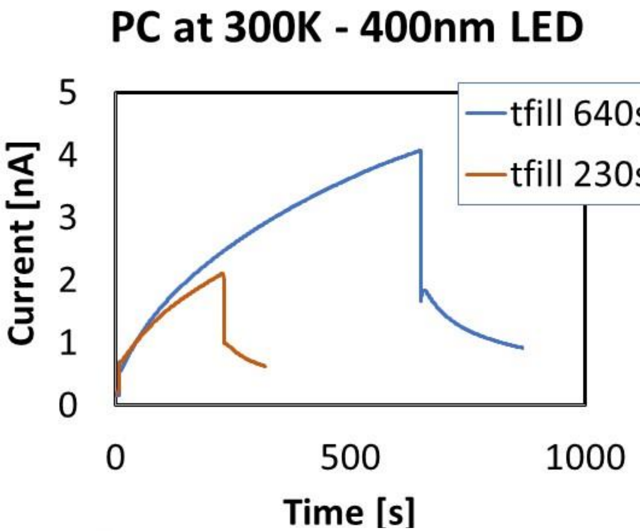
- V_{bias} applied
- Cooling to initial temperature T_i
- Filling traps with light source pulse
- heating at constant rate $\beta = {dT}/{dt} = \text{const}$
- cooling at constant rate

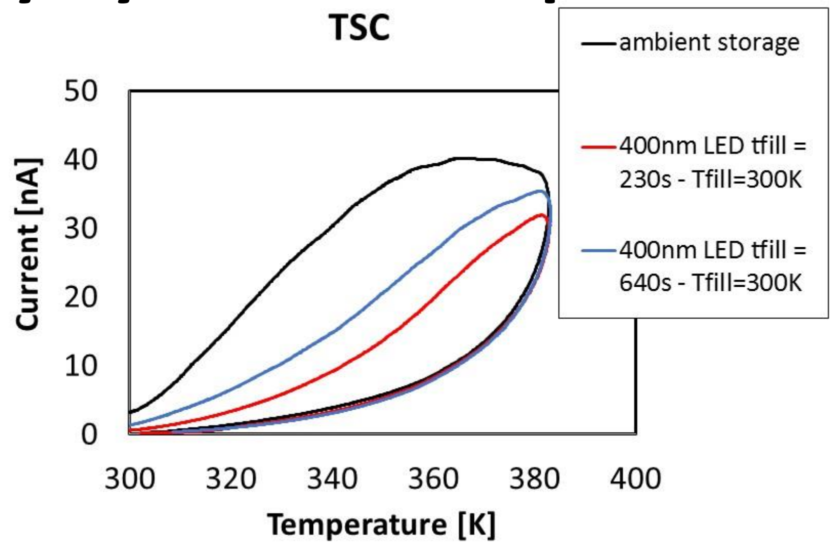
Thermally Stimuated Current:

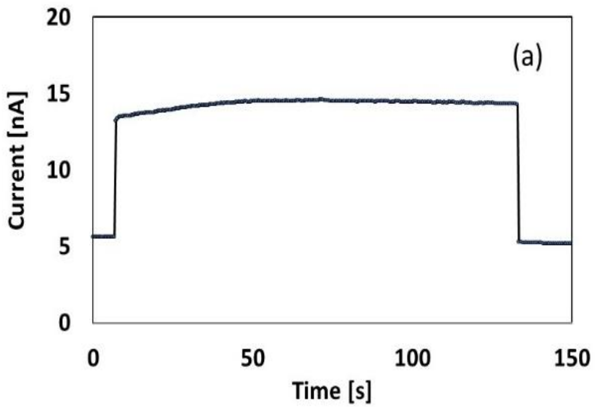
- **Peak due to charge emitted from trap only during heating;**
- **Background due to thermal generation rate, same during heating and cooling.**

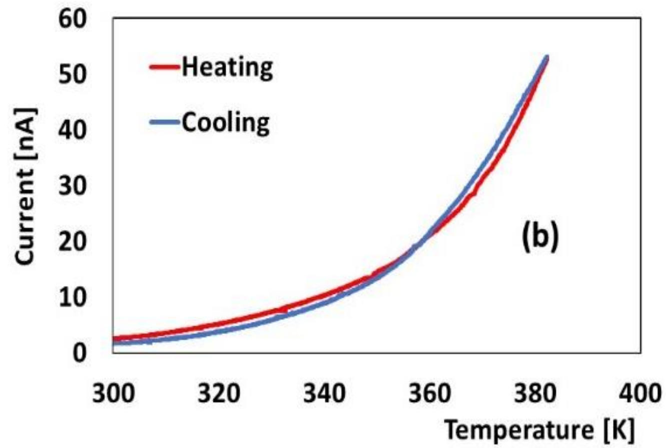
$$I_{TSC}(T) = e\,\mu_p\,F\,A\,\tau_{eff}\,p_{t0}\,e_p(T)\,e^{-\frac{1}{\beta}\int_{T_i}^{T} e_p(T)dT}.$$

New results: Main defect active at RT 0.45eV. Present only in polycrystalline samples





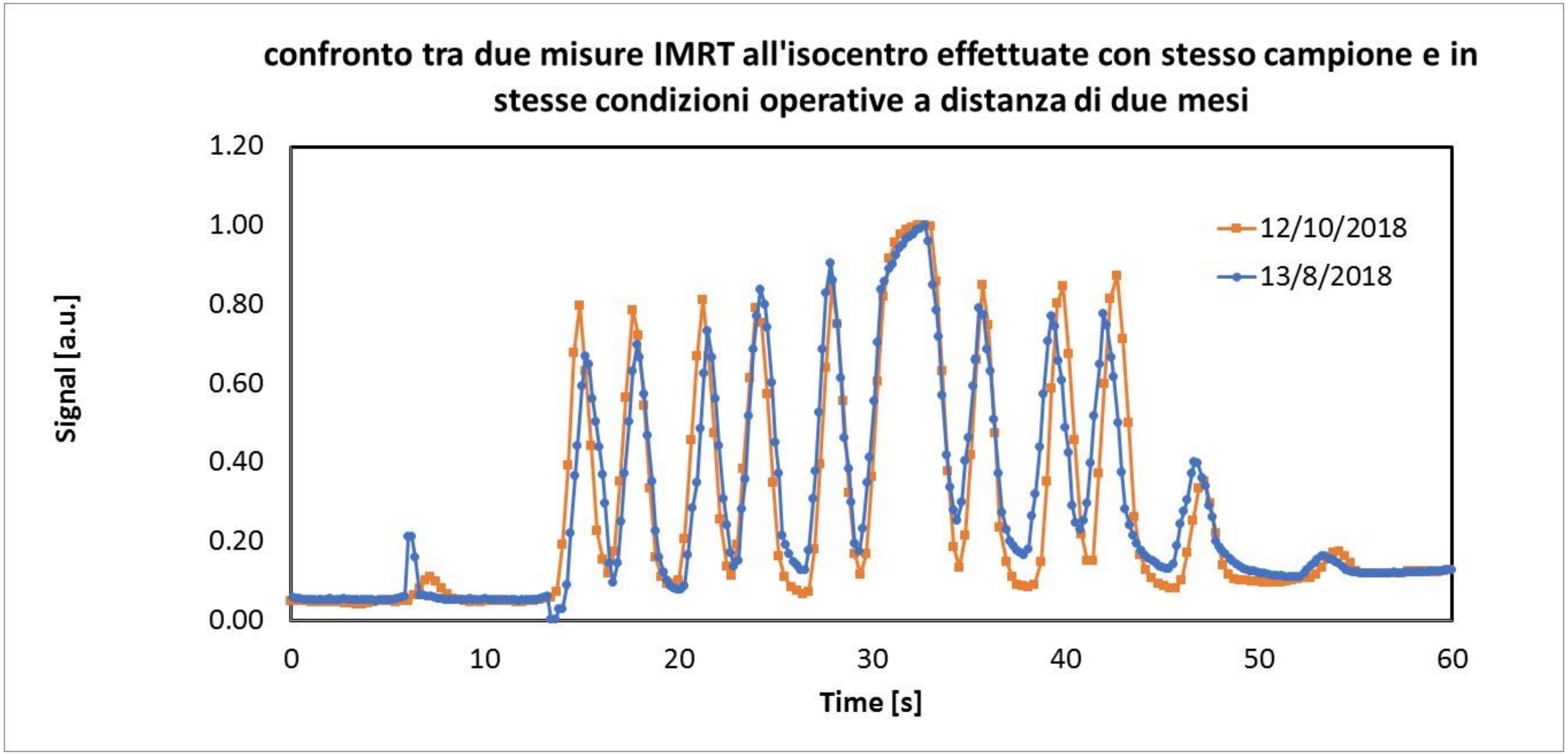




Mara Bruzzi, Naomi Falsini, Nicola Calisi, Anna Vinattieri, **Electrically active defects in polycrystalline and single crystal metal halide perovskite,** submitted to Energies, feb. 2020, section: Advanced Energy Materials, issue: Progress in Inorganic Halide Perovskites; Inorganic Perovskites.

Open issues

- **Reproducibility;**
- **Radiation Hardness;**
- **Single crystal performance under X-ray beam**
- **Schottky barrier devices to increase S/N**



Conclusions

- **Advanced imaging and dosimetry systems needed to get increased accuracy in radiotherapy treatment plans;**
- **State-of-art segmented detectors made with silicon (epitaxial, Italian patent)**
- **Diamond potentially best suited for X-ray radiotherapy due to energy independence of its response (tissue equivalence); segmented dosimeters not yet available commercially; Florence prototype shows excellent performances under IMRT and VMAT treatment plans;**
- **Volumetric dosimetry : next generation of high sensitivity – flexible geometry systems based on perovskite materials under development,**
  - **open issues: optimizing deposition techniques and device engineering, influence of defects on dosimetric properties, radiation hardness.**