Development of innovative SiC detectors for harsh environments

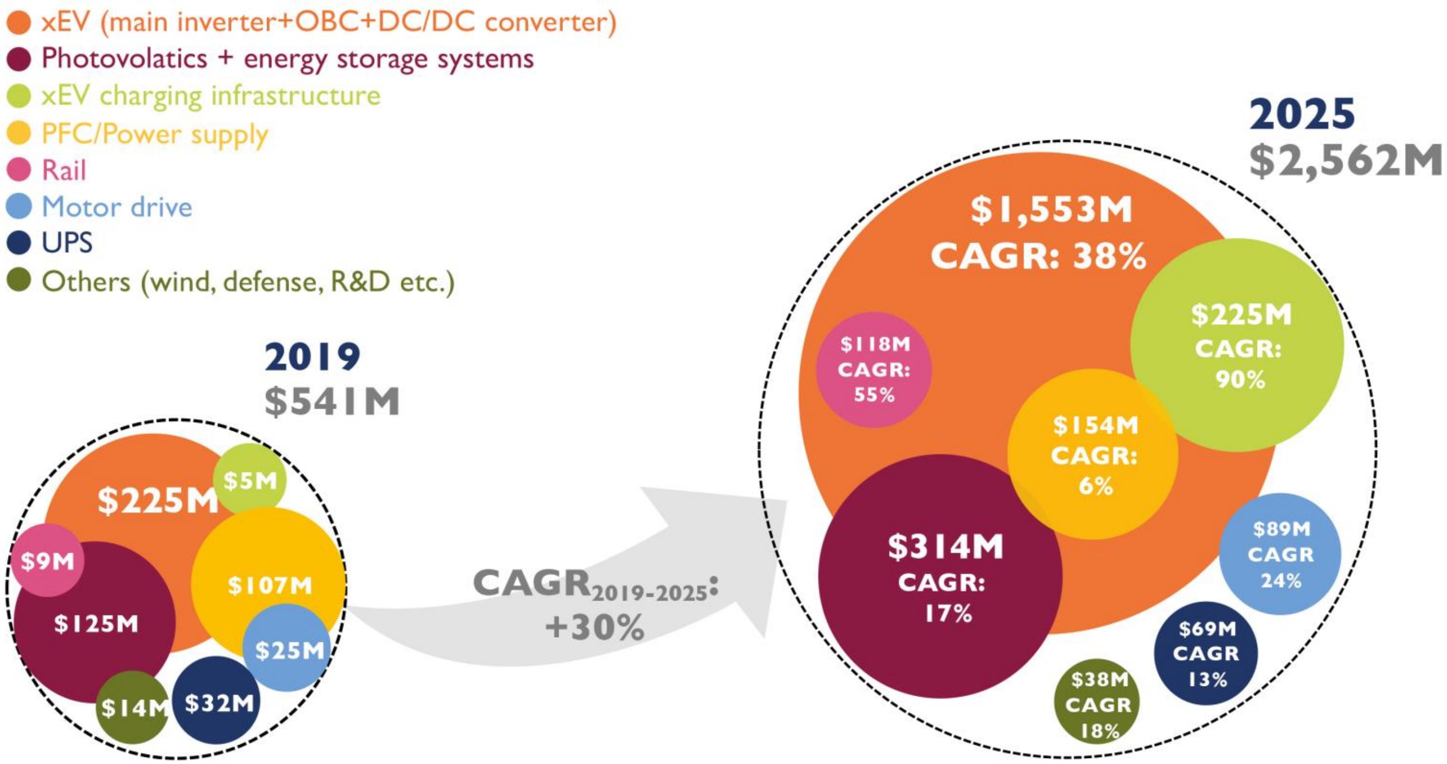
Centro Nacional de Microelectrónica IMB

CSIC Consejo Superior de Investigaciones Científicas

G. Pellegrini

2019-2025 power SiC market forecast split by application

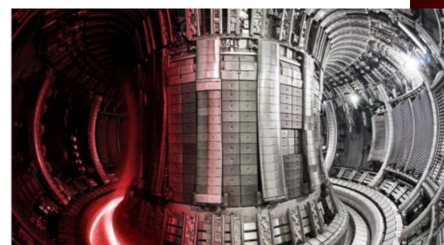
(Source: Power SiC: Materials, Devices and Applications 2020 report, Yole Développement, 2020)

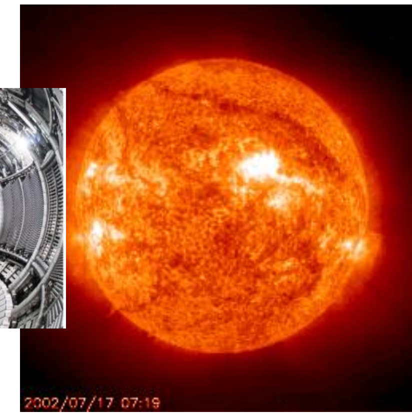


High quality, low defect density SiC is available up to 200 mm wafers

Compound Annual Growth Rate (CAGR)

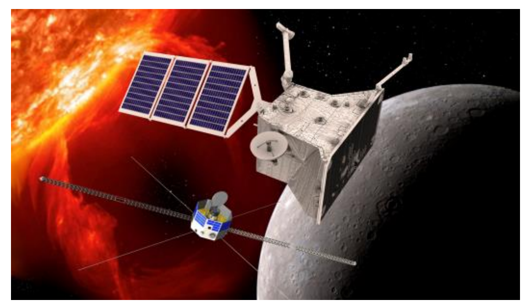
Many potential applications in sensors





Nuclear fusion reactors

-Plasma diagnostic



Aerospace

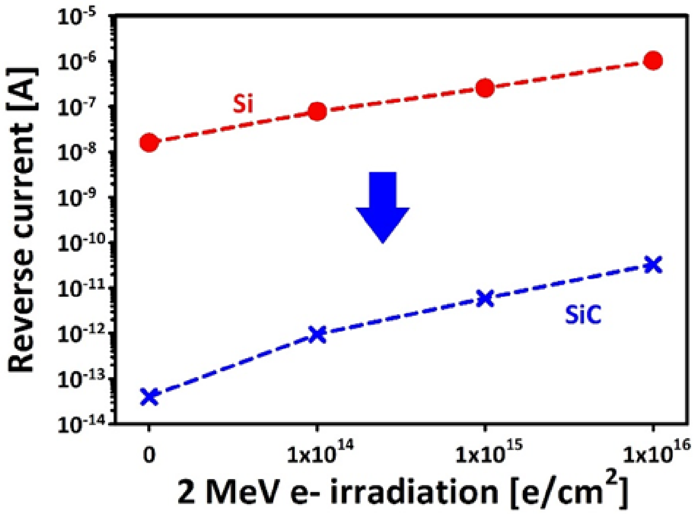
-Sensors and electronics

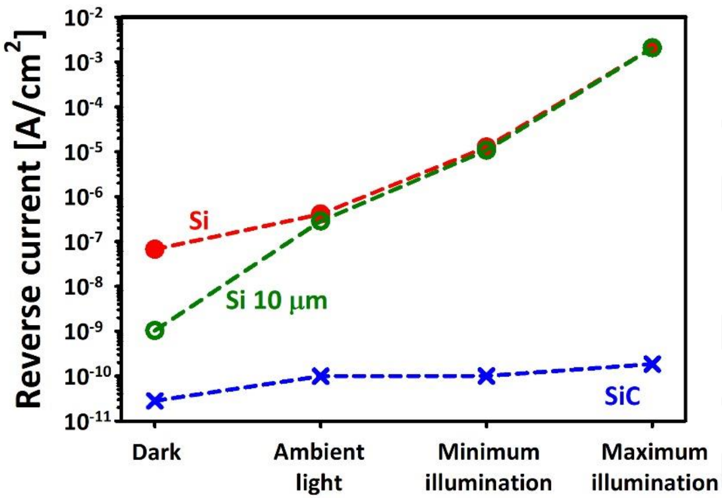
Medical

-Dosimetry in FLASH therapy and microdosimetry

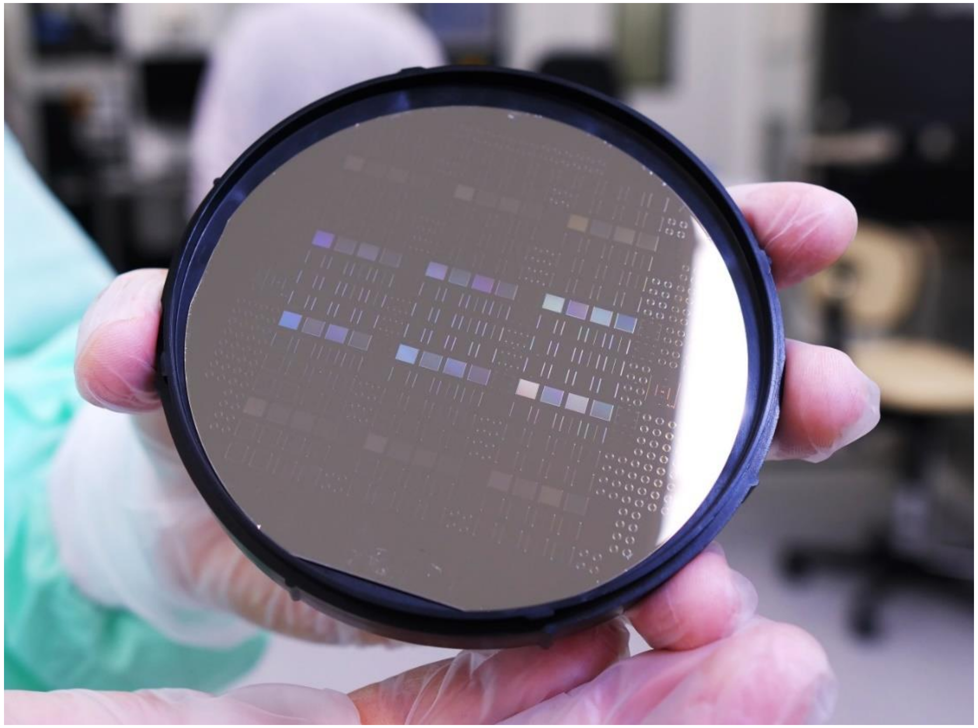
Advantage of using SiC

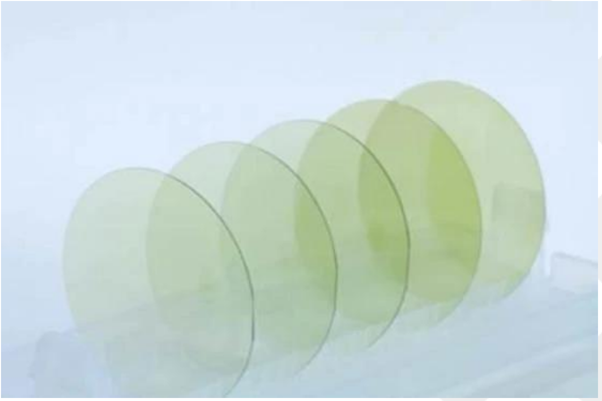
- Wide bandgap that reduces the leakage current, maintaining ***low noise*** levels even ***at high temperatures***.
- Insensitive to visible light.
- High atomic displacement threshold (~20 eV for C, and ~40 eV for Si), ***which should make the material more radiation resistant***;
- ***Fast saturated electron drift velocity*** (2x10^7 cm/s at room temperature), twice faster than silicon;
- ***High thermal conductivity*** (490 $Wm^{-1}K^{-1}$), which is three times higher than that of Si, and ten times higher than that of GaAs.





SiC detectors fabricated at the IMB-CNM clean room





Technology based on :

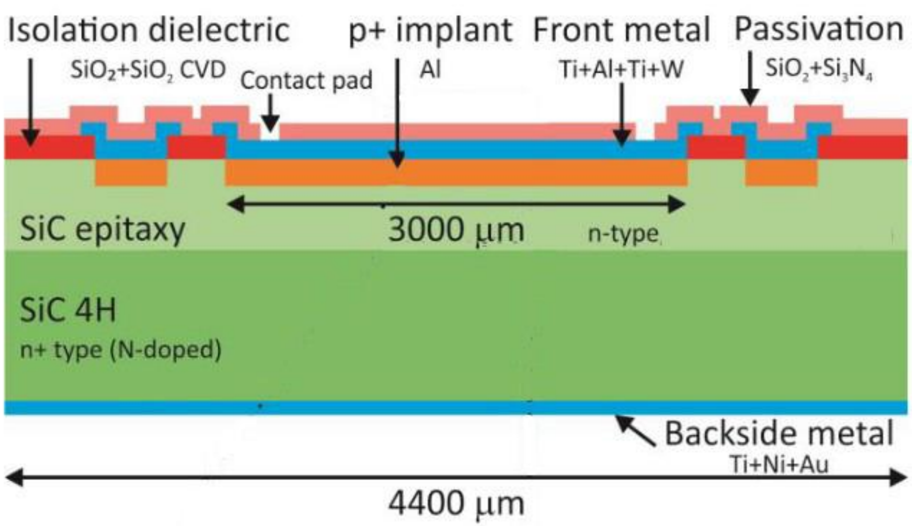
SiC rectifiers for space

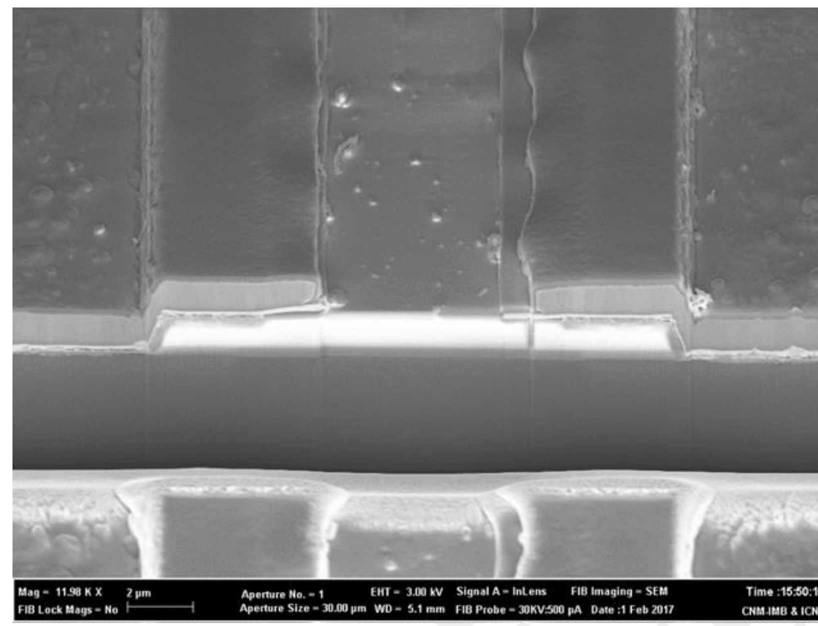
Bepi-Colombo & Solar orbiter missions

Main contractors EADS, Airbus, ALTER

DOI: 10.1109/TDMR.2009.2029090

Detector technology SiC



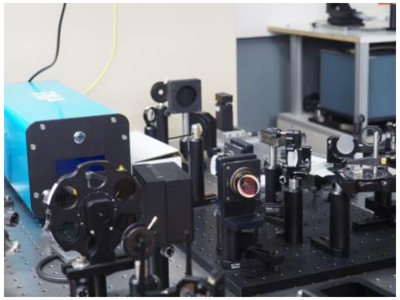


- SiC based "P on N" diode fabricated on 4H-SiC on a 50um high resistivity n-type doped epi-layer. 100 or 150mm wafers.
- The technology has been optimized with high temperature processers and metal contacts.

J.M. Rafí et al 2018 JINST 13 C01045

Testing at different facilities

- SiC measurements at high temperature at the 3 MeV **Tandem**.



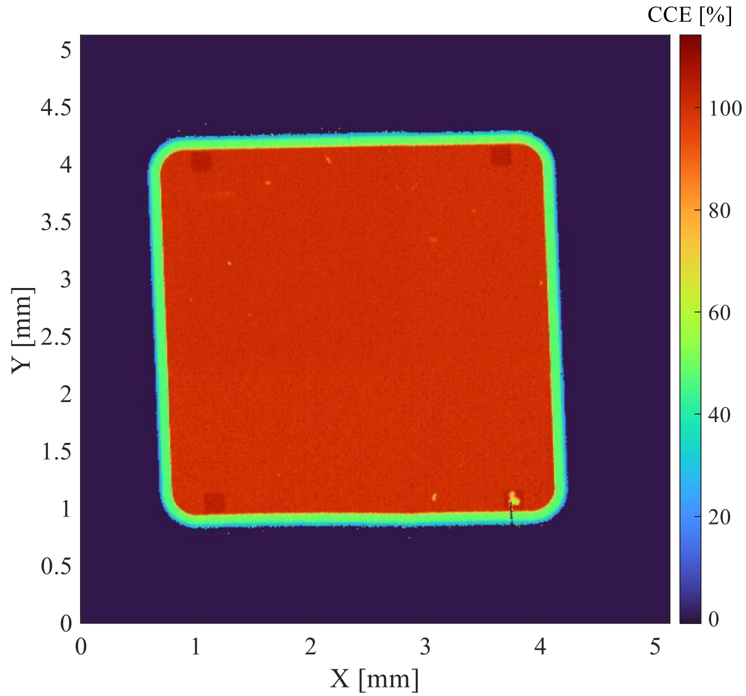
- **TPA-TCT**, with two photons *producing one electron-hole pair, and the energy is deposited at the laser focal point, so this permits a 3D spatial resolution.*

- ***FLASH effect conditions**** *: Irradiations with con Ultra-High Dose Rate pulsed radiation reduce adverse effects in healthy tissues. Tested in PTB, Germany electron FLASH.*

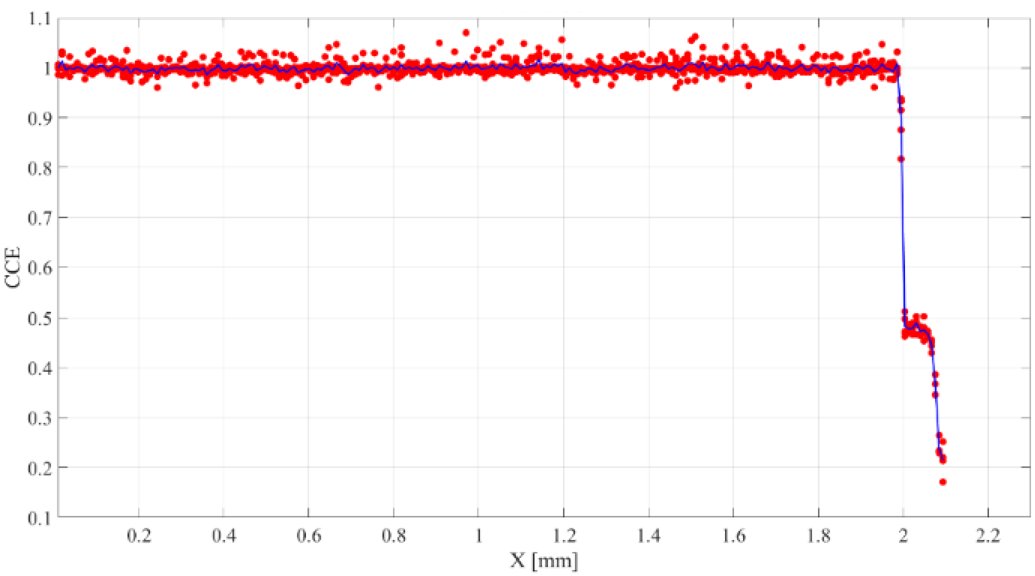
*Favaudon et al., Sci Transl Med 6 (2014)

CCE homogeneity study

CNA Centro Nacional de Aceleradores
Infraestructuras Científicas y Técnicas Singulares



M.C. Jiménez-Ramos, J. García López , A. García Osuna



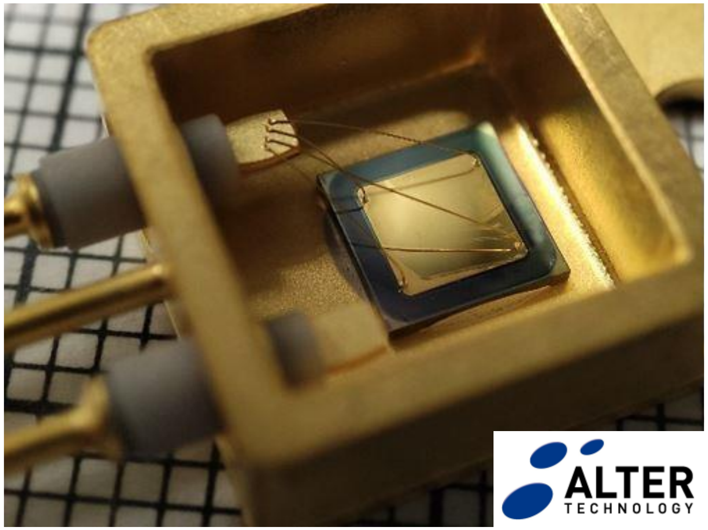
Homogeneity IBIC measurements on the microprobe line at CNA with He^{2+} @ 3.5 MeV.
The mean standard deviation is ~1%.

Jiménez-Ramos M.C et al., Radiation Physics and Chemistry 177 (2020) 109100b

High temperature setup

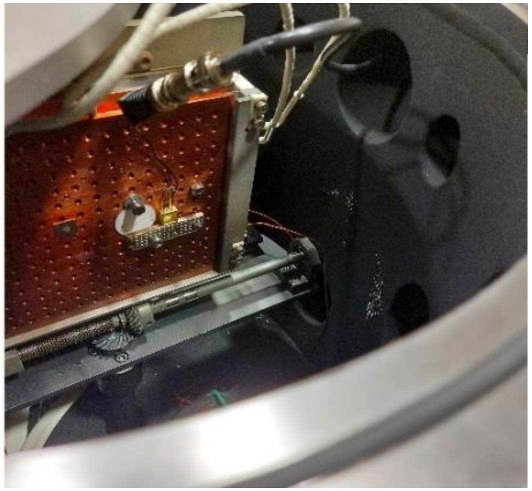
Centro Nacional de Aceleradores
Infraestructuras Científicas y Técnicas Singulares

Vacuum chamber for high temperature measurements. Furnace accommodated inside the chamber (RT-500 ºC)

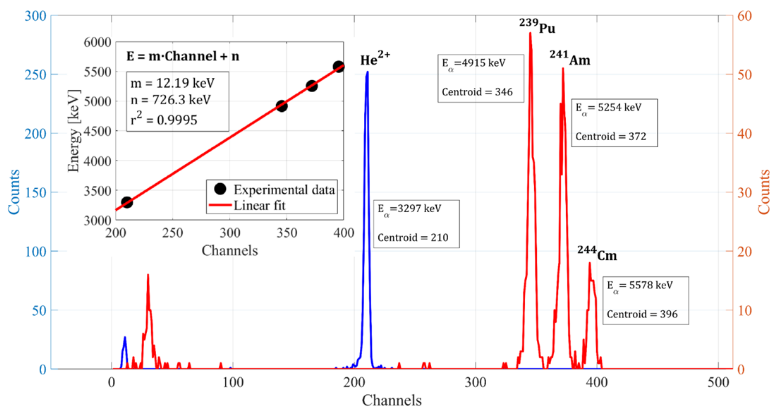


Detectors mounted on a special package certified for high temperature.
Tested with thermal cycles during various days.

- TO257 package
- Ag Sintering
- Gold bondings



Calibration with He2^{+} ions



Alpha source measurement at RT for setting the operation voltage

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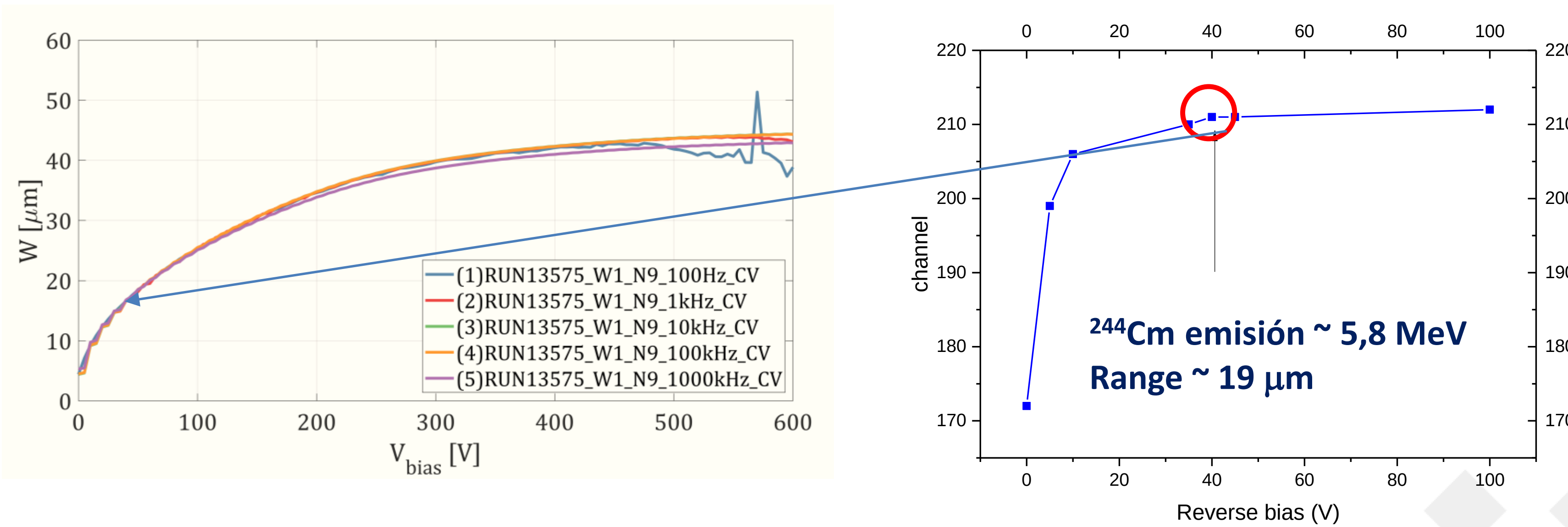

At 40 V the depletion zone is thick enough to completely stop the 5.8 MeV alpha particles and the CCE signal saturate.

Both electronic noise and reverse current increase at higher voltages during high temperature measurements, so it was decided to perform the experiments at 40 V.

Measurements done at : TAMARA Temperature Analysis Measurements And Radiation Applications

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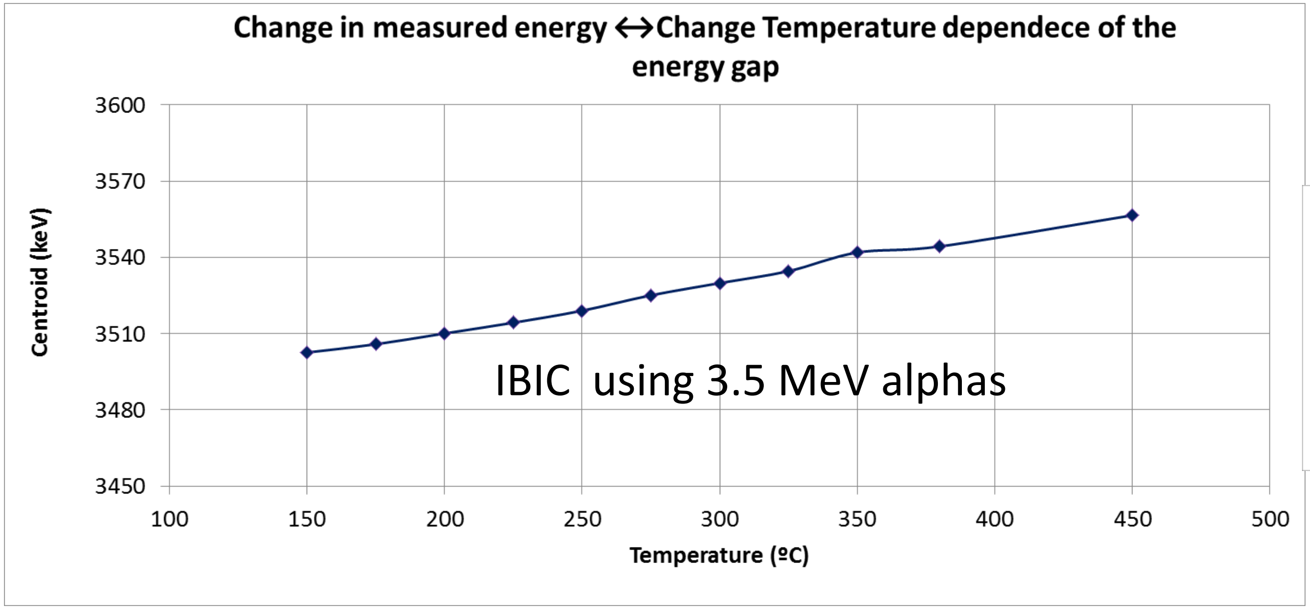
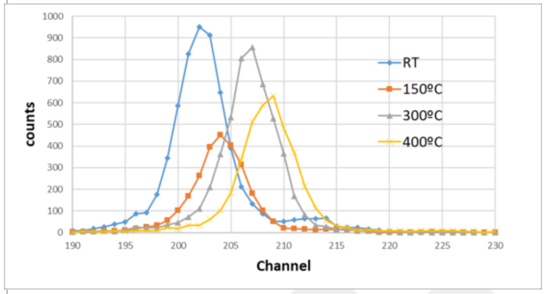
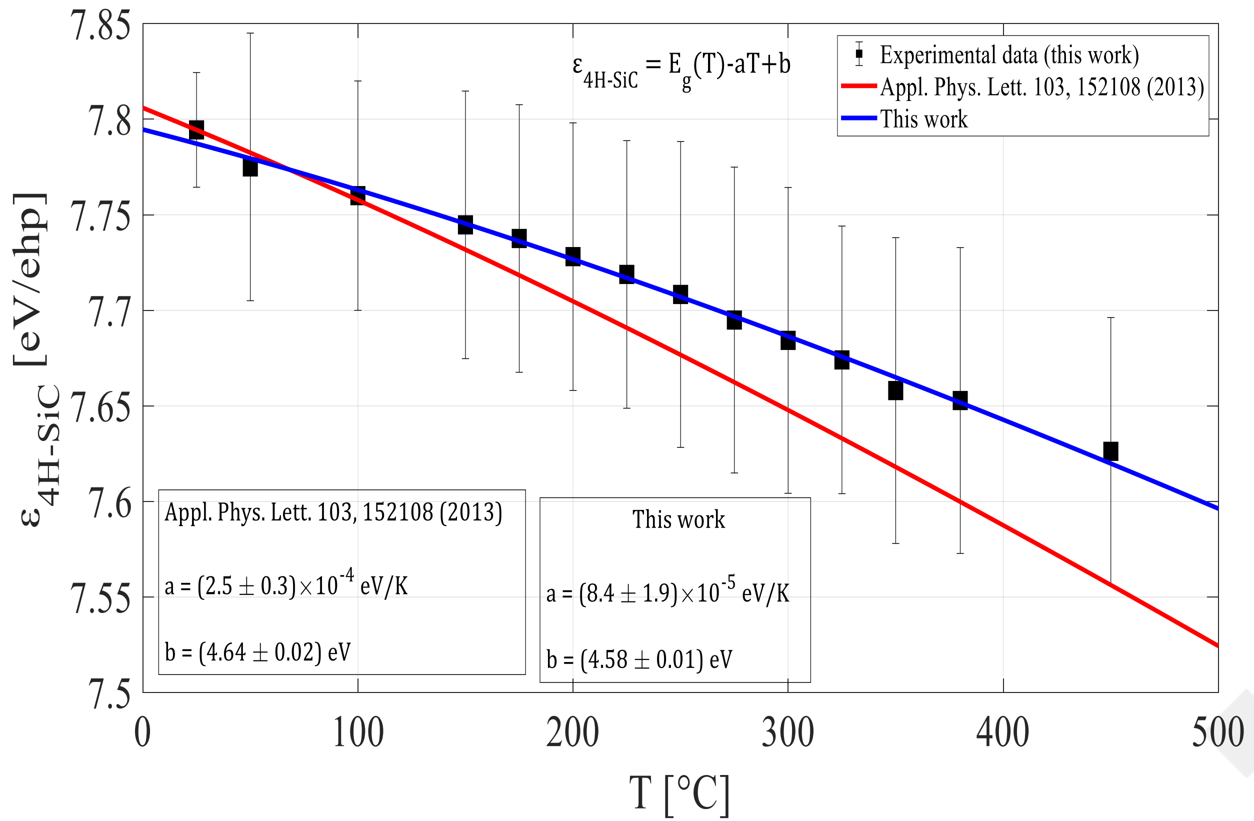
Infraestructuras Científicas y Técnicas Singulares



Measurements from RT to 450ºC



Pair creation energy vs T

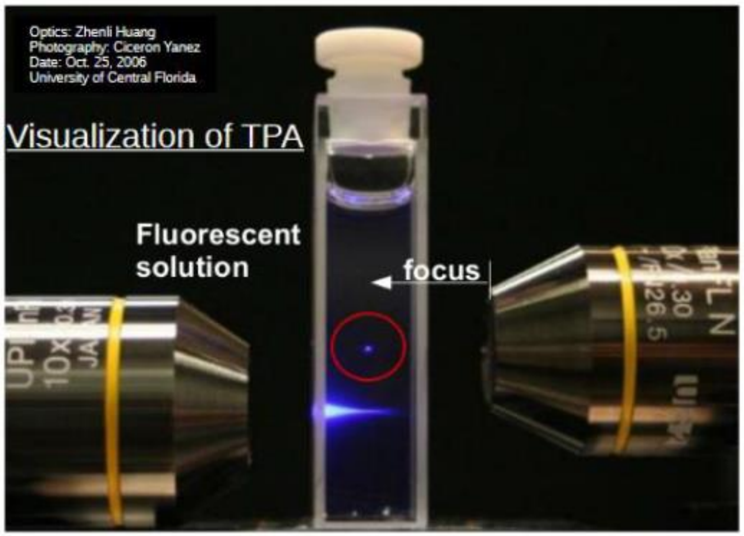


The increase of energy collected vs T is excepted:
Pressure and Temperature Dependence of Energy Gap in SiC and Si 1-x Ge x.
DOI: [10.33899/rjs.2019.163296](10.33899/rjs.2019.163296)

Two Photon Absorption TPA

RD50

Single Photon Absorption
Continuous energy deposition along beam direction



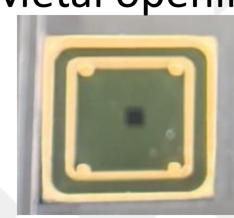
Two Photon Absorption

Absorption only at focal point

Confine photons in **time (femto-second laser)** and in **space (microfocusing)** for Two Photon Absorption

- 12th of March 2013, first TPA-TCT measurement at SGIker facility of UPV, Bilbao
- November 2014: Presentation of TPA-TCT at 25th CERN RD50 workshop
- 2013 – 2017: TPA-TCT measurements at UPV, Bilbao

Metal opening



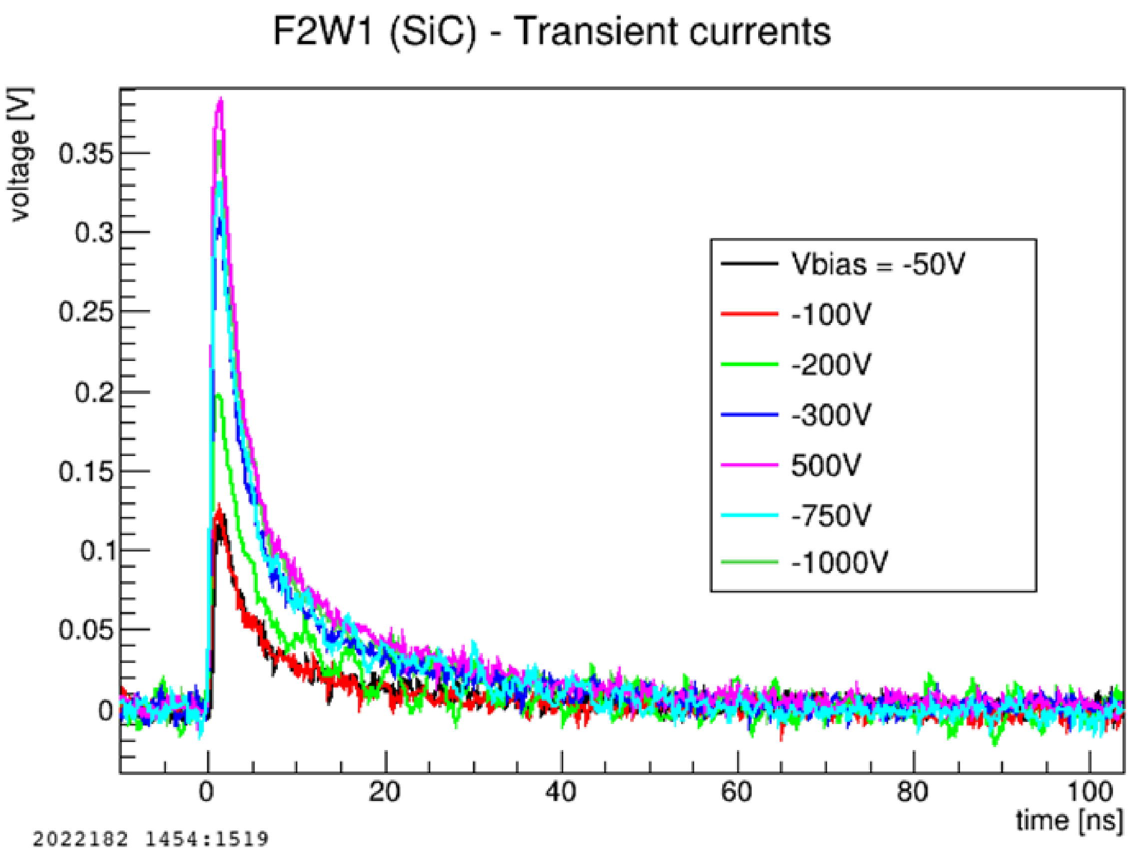
Wave length (800nm) adapted to the SiC bandgap for the TPA

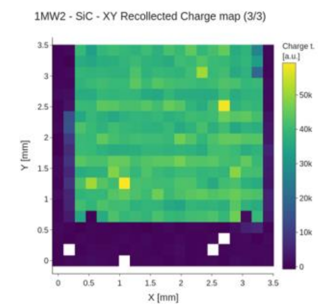
I. Vila et al., “TPA-TCT: A novel transient current technique based on the two photon absorption (TPA) process,” in Proc. 25th RD Workshop. Geneve, Switzerland: CERN, 2014, pp. 17–19.

Esteban Curras et al., Caracterization of neutron irradiated IMB-CNM SiC planar diodes with TPA-TCT, RD50 workshop 2022

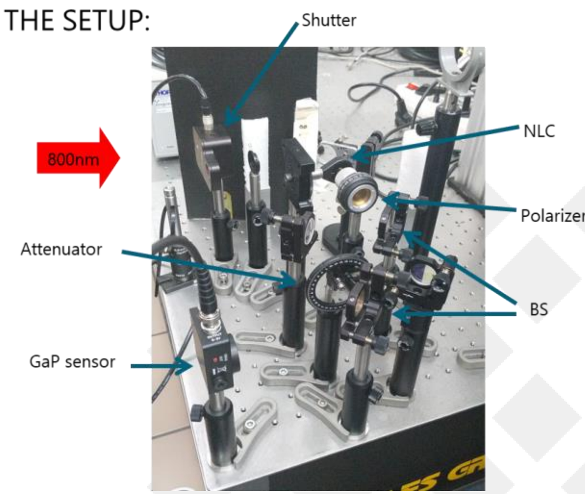
First measurements of SiC diodes with TPA

iFCA
UPV EHU





THE SETUP:

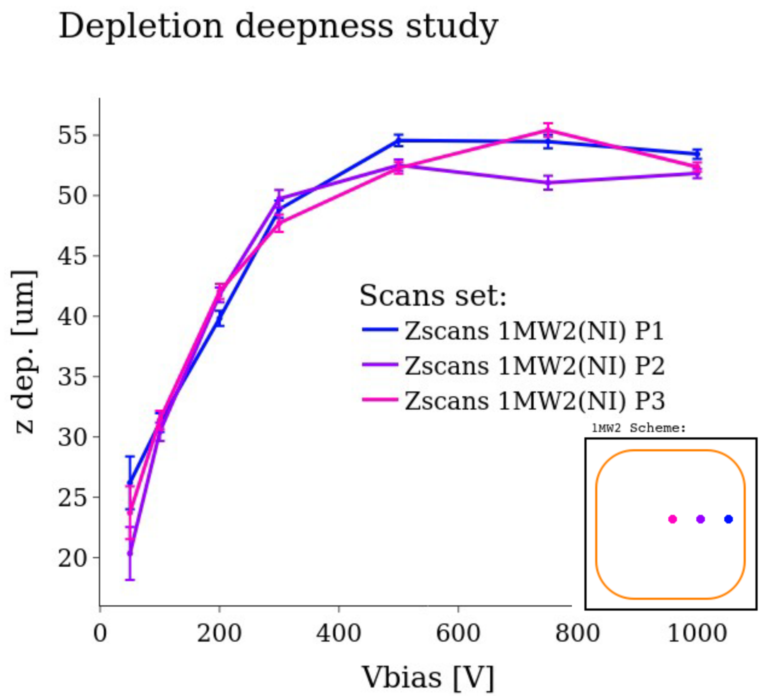


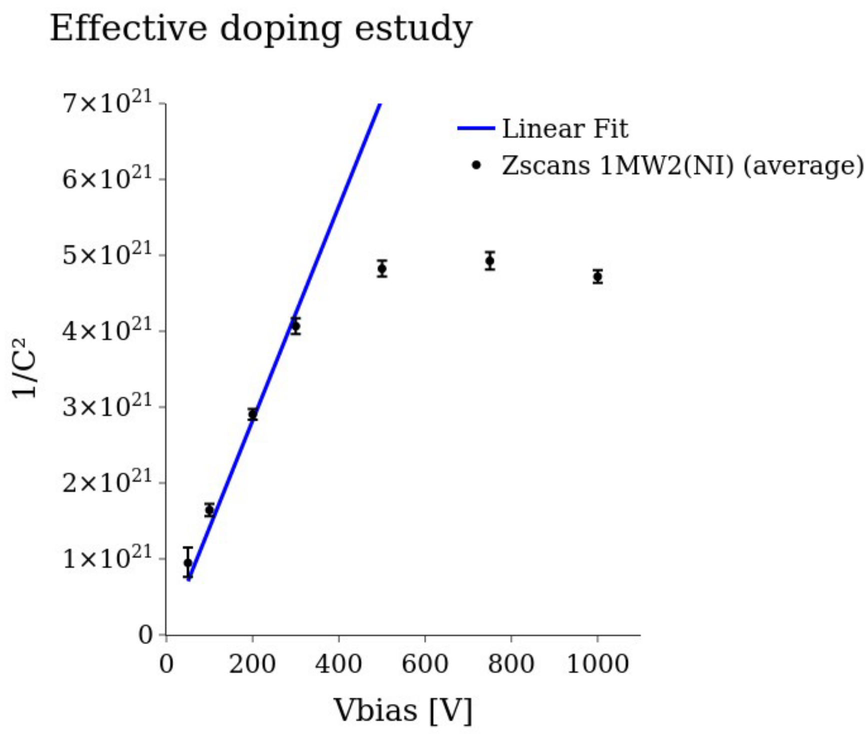
Rise time on the order of few hundreds of ps

C. Quintana, I. Vila, R. Montero

Ref: http://dpnc.unige.ch/seminaire/talks/fernandez.pdfhttp://dpnc.unige.ch/seminaire/talks/fernandez.pdf

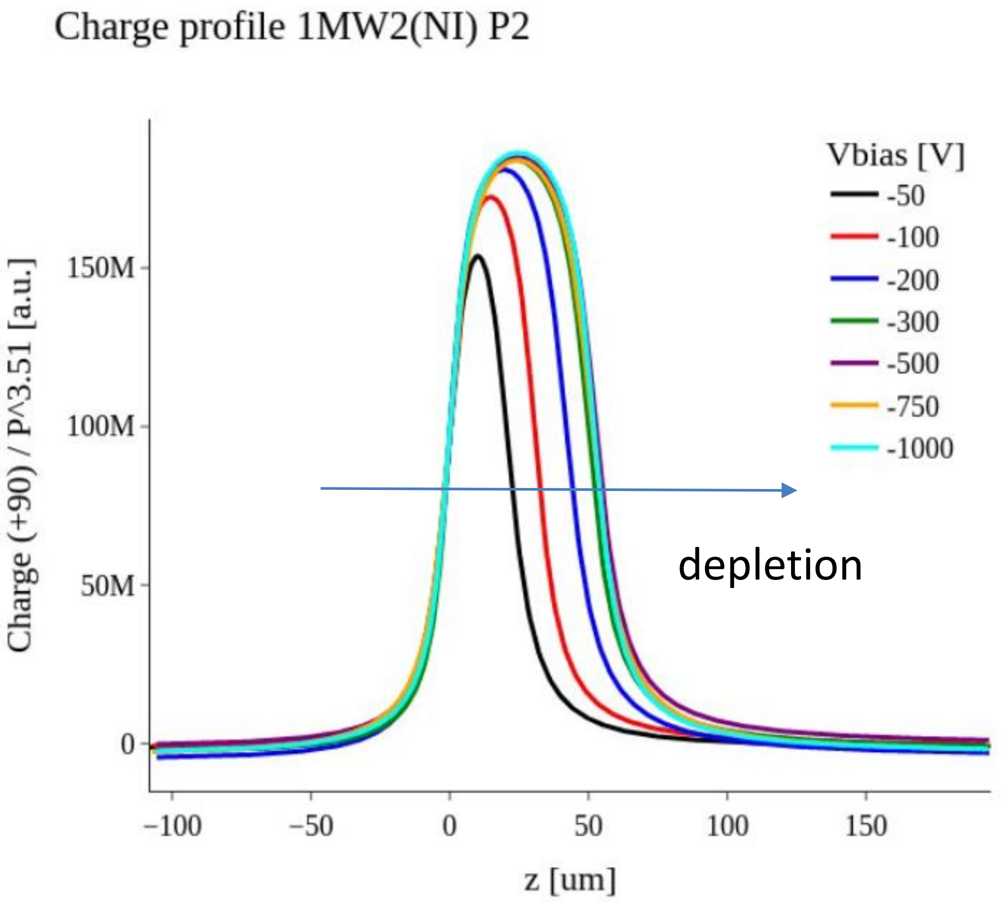
Depletion width vs bias: non irradiated

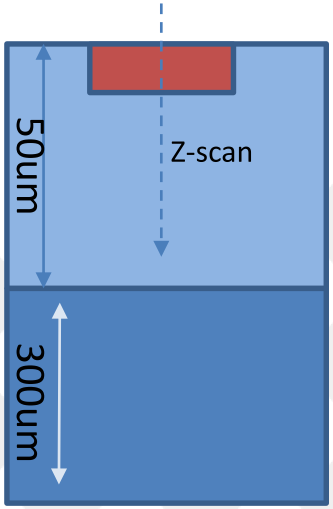




- Neff=1.3 E14/cm2 in agreement with the nominal doping
- Diode fully depleted between 300-500 volts
- Homogeneity in the sensor depletion

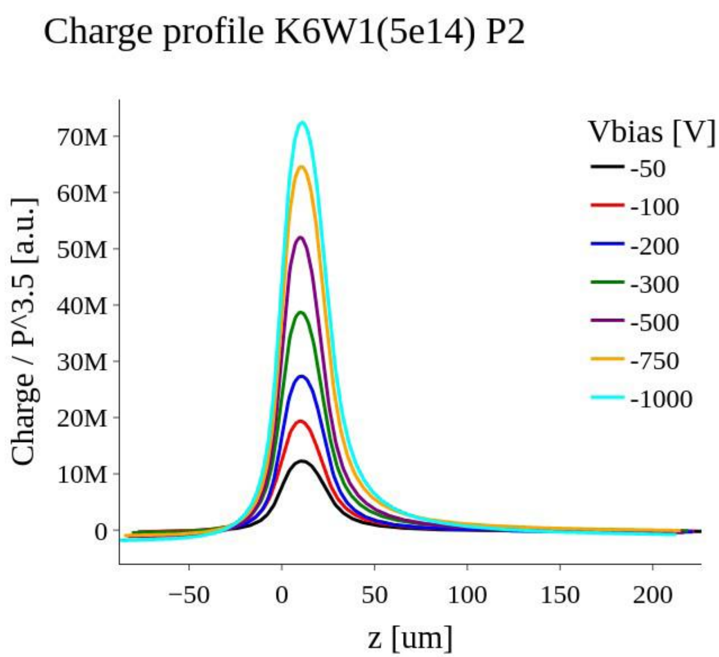
Z-scan charge profiles: non-irradiated diodes

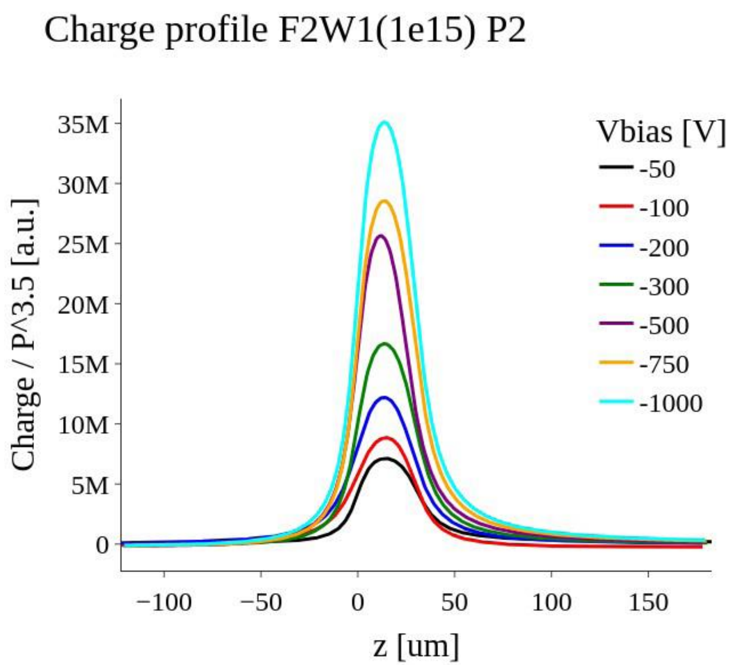




Detector is 50um thick, nominal value

Z-scan charge profiles: irradiated diodes

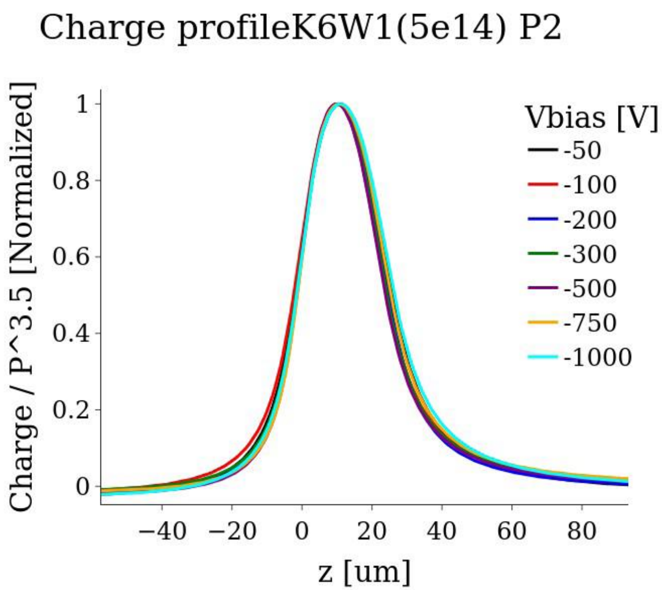


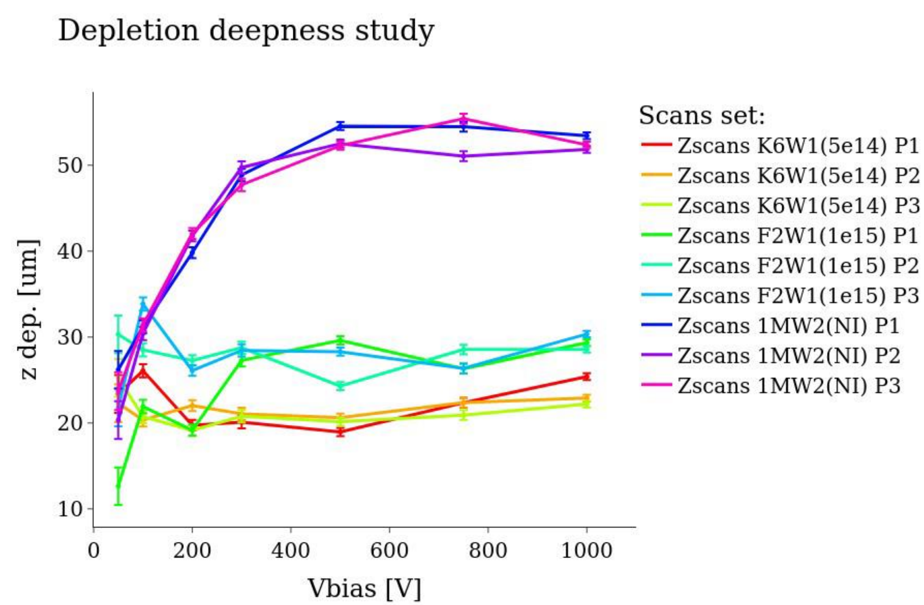


Neutron-irradiated (ATI Vienna) July/Aug 2021
Fluences are in 1MeV neutron equivalent /cm2

- The diode behavior lost!
- Capacitor-like charge collection
- No charge collection saturation with bias voltage

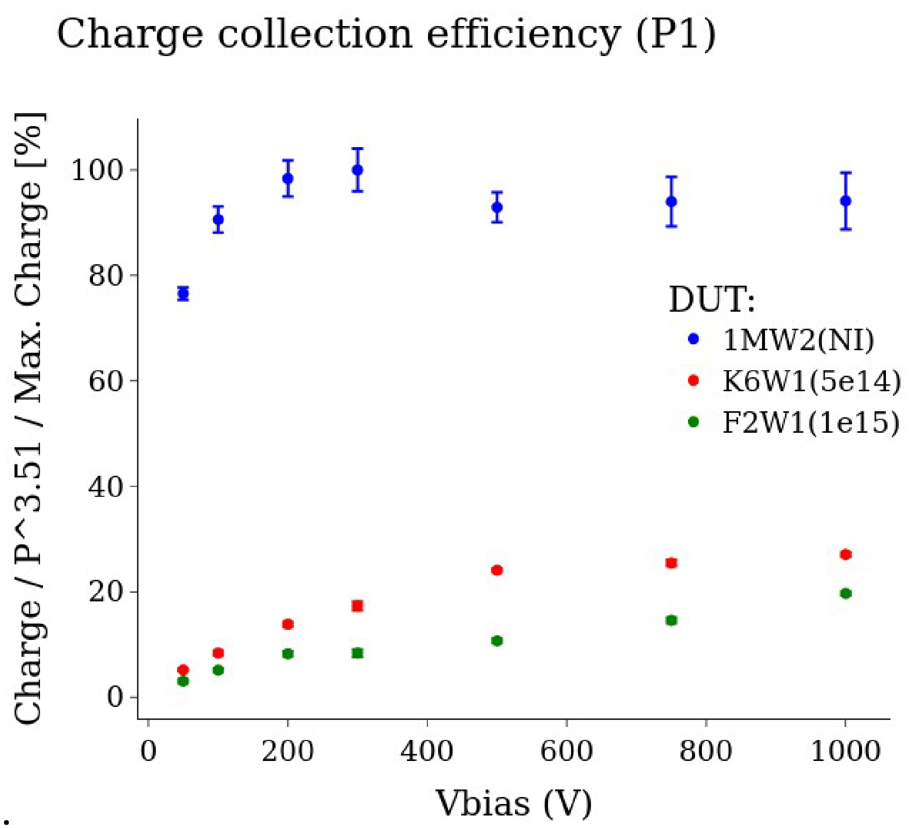
Depletion width vs bias: irradiated





- Both figures show that the depletion width is constant for the irradiated detectors.
- The depletion width is different if we compare irradiated and non-irradiated detectors, but also between the irradiated ones

Charge collection efficiency



Dependence with irradiation:

- Charge collection increases with bias
- Charge collection decreases with irradiation.
- Lost of charge due to signal trapping in the resistive electrode (metal opening for TPA)

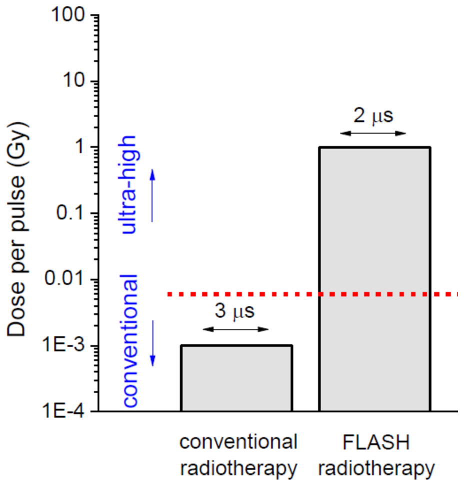
FLASH radiotherapy: dosimetry

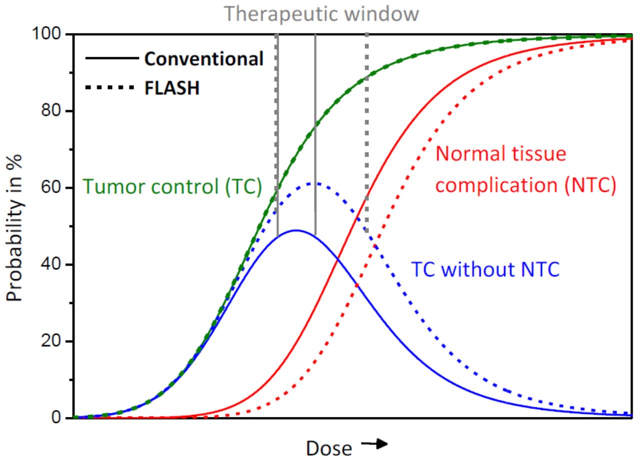
FLASH effect (*Favaudon et al., Sci Transl Med 6 (2014)*): Irradiations with con Ultra-High Dose Rate pulsed radiation reduce adverse effects in healthy tissues.

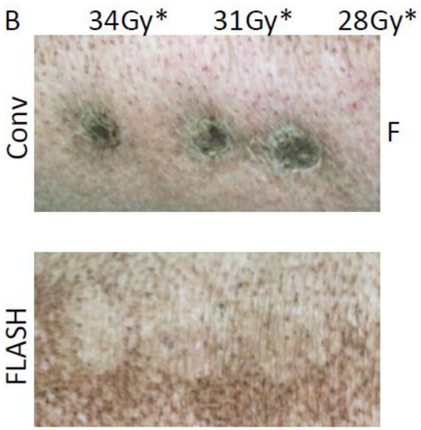
- Need real-time, highly precise dosimeters
- CNM is a partner in the European project EMPIR-UHDPulse (2019-2023) for metrology in UHDR beams

UHDpulse

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States







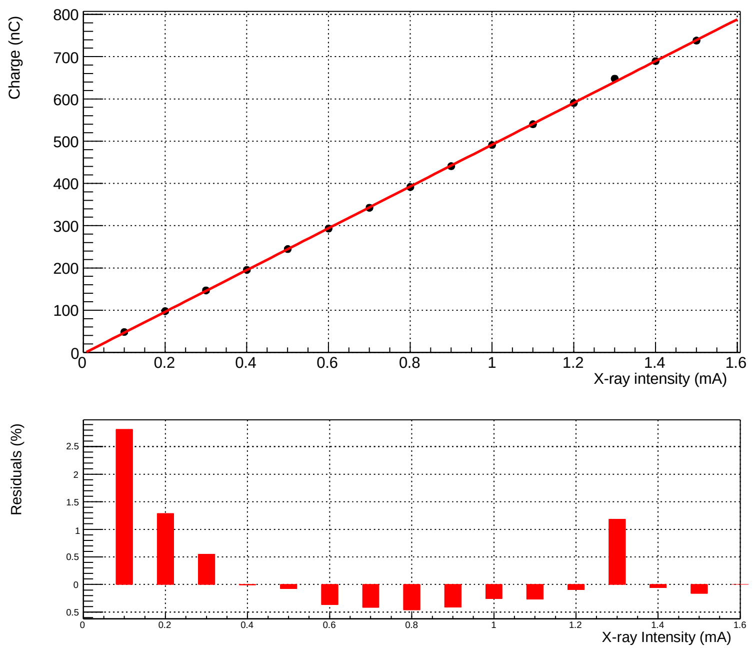
FLASH: h(> 40Gy/s) while keeps same tumor control & "need real-time, highly precise dosimeters since standard dosimeters saturate"

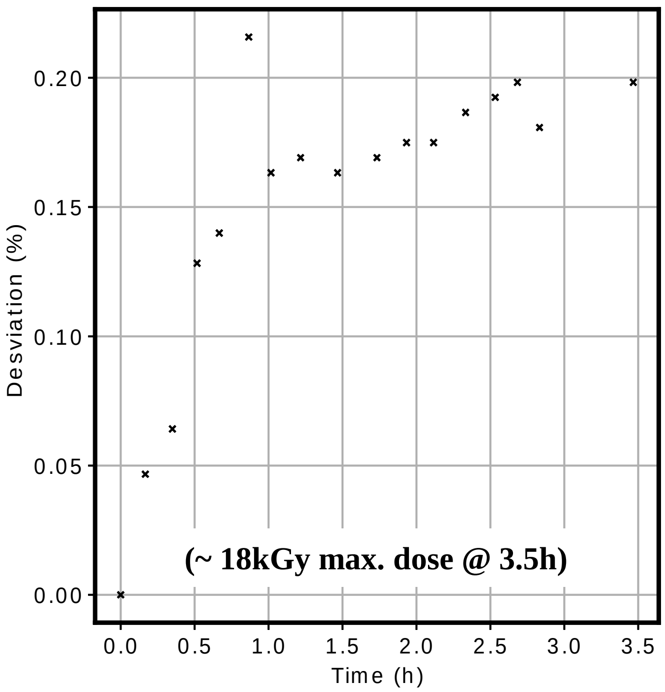
First tests of CNM's SiC diodes in conventional RT dosimetry

50kV X-rays, 0 V bias

USC Universidade de Santiago de Compostela

F. Gomez USC





✓Linearity deviation with 50 kV X-rays integrated dose delivered is less than 1.5%

✓ Medium-term stability with integrated dose up to 18 kGy X-rays is better than 0.3%

Electron beam

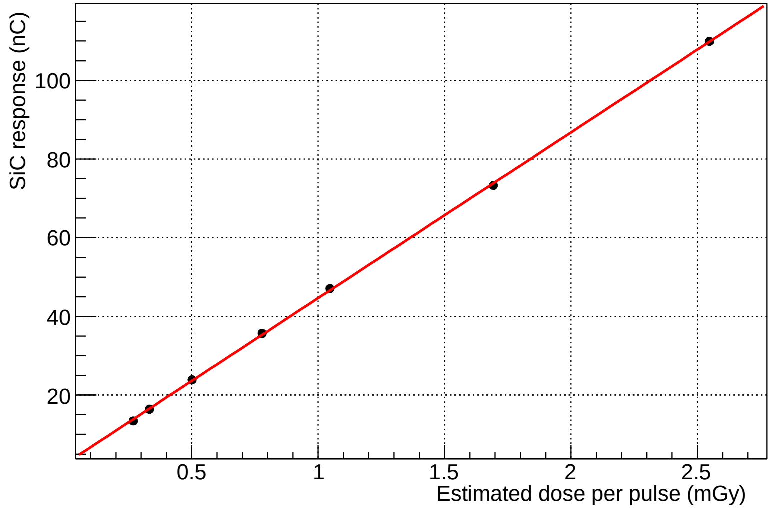
USC Universidade de Santiago de Compostela

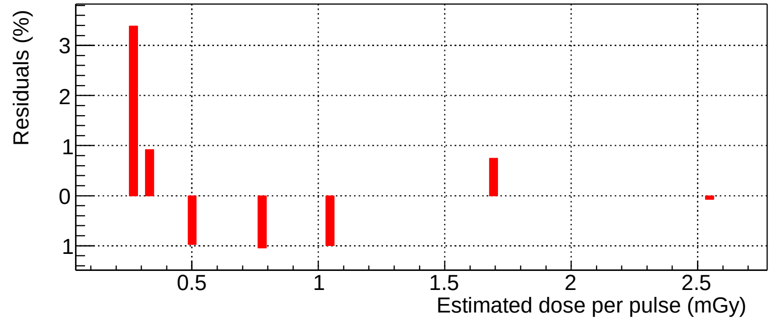
SiC diodes fabricated at CNM show **good performance as dosimeters in conventional RT beams** where they are a promising alternative to other semiconductor materials.

Currently tests are being performed to **evaluate their capabilities in Ultra-High Dose Rate beams**.

F. Gomez USC

9 MeV electrons, 40 V bias.
Reference dosimeter: PPC40 @ -400 V

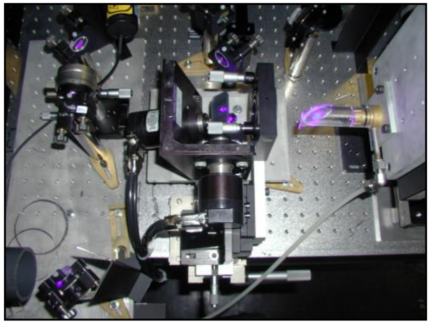




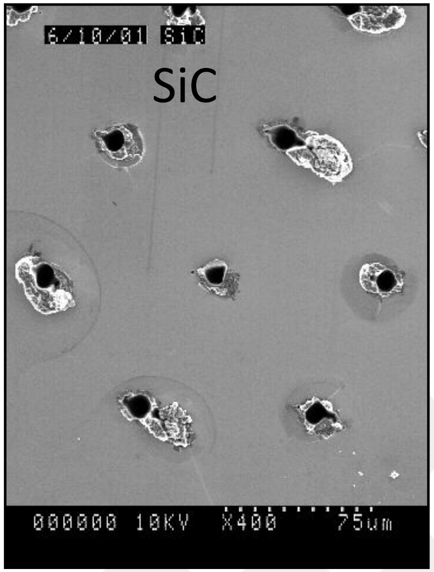
✓ Linearity deviation with dose per pulse of 9 MeV electrons up to 2.5 mGy is less than 1.5%

3D in SiC material

- Reduce electrode distance keeping a thick substrate
- New Deep RIE for Si and SiC materials will be available soon in our Clean Room
- Laser drilling seems a possible solution
- Possibility to fabricate 3D detectors or other MEMS structure



Laser drilling [1]



- diameter : *8 μm.*
- depth : *300 μm.*

1. G. Pellegrini, “Technology development of 3D detectors for high energy,” PhD Thesis, University of Glasgow, 2003.
2. S. Nida et al., “Silicon carbide X-ray beam position monitors for synchrotron applications,” Journal of Synchrotron Radiation, vol. 26, no. 1, pp. 28-35, 2019.

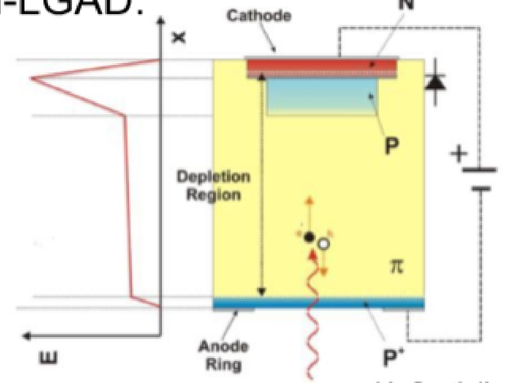
SiC-LGAD: The Idea

- Signal height in Silicon carbide very small
  - 57 vs. 72 e/µm
  - 50µm (epi-layer) vs. 300µm (float zone) active thickness
  - Signal speed already in planar material very high

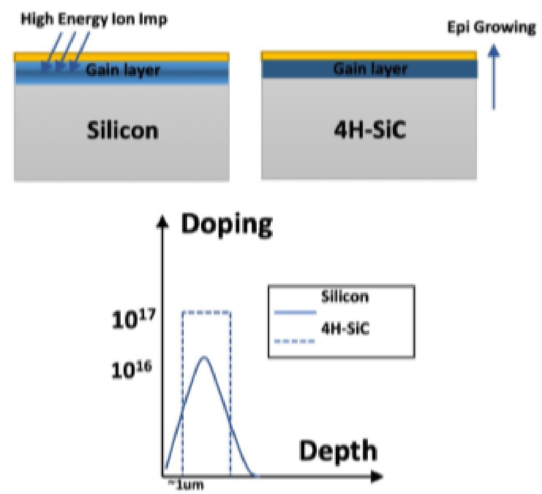
➢ **Implement a gain layer into Silicon Carbide to mitigate the small signals**
  - Impact ionization in multiplication layer produces gain → signal large
  - SiC-LGAD presumably ultra radiation hard as gain-reducing acceptor removal strongly suppressed

- Challenges:
  - Creation of deep gain layer not possible by ion implantation (as usually done for Si-LGAD) due to high displacement energy and thermal conductivity of SiC
  - Gain layer need to be implemented during epitaxial growth → involvement of wafer supplier necessary in formation of gain layer
  - We know that wafer supplier can grow sandwich of N-/P layers. They already grown layers with thicknesses down to 0.5um for CNM

Si-LGAD:



N. Cartiglia



Yang Tao, 39th RD50 workshop

RD50

Future work

Fusion :

- Test irradiated detectors at high temperature
- Understand the use of Graphene as a contact (TPA, high T, etc…)
- Explore other application related to fusion (IFMIF –DONES)
- Test sensors in fusion facilities (DIII-D San Diego, CA,).

Medical Flash:

- Study the limit of SiC dosimetry in FLESH therapy (in collaboration with PTW)
- Fabricate new sensors for micro-dosimetry to measure LET (National project submitted, NEWDOSI project started in 2022 and UHDR EU project TWAC for development of compact electron accelerators
- Large strip SiC sensors and LGAD for beam monitoring (U. if Vienna and MedAustron)

HEP:

- Test beam of irradiated detectors : strip configuration.
- Understand the annealing at high temperature.
- Fabricate SiC detectors with internal gain (LGAD)
- Exploratory detector concepts based on 2D materials, e.g. grapheme

Thank you for your attention

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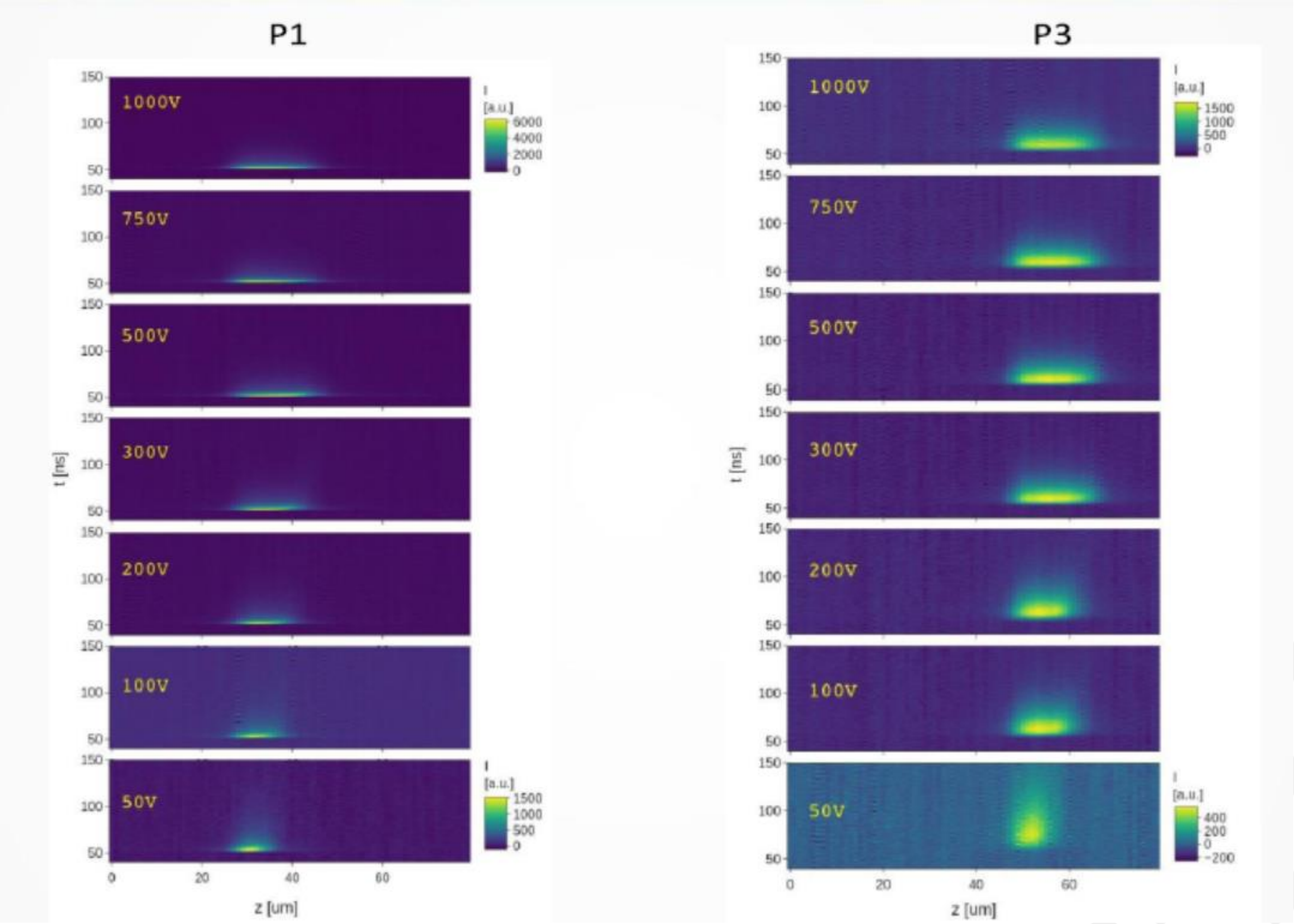
https://rdg.imb-cnm.csic.es/

@imb_cnm


P1
1000V
750V
500V
300V
200V
100V
50V
t [ns]
z [um]
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P3
1000V
750V
500V
300V
200V
100V
50V
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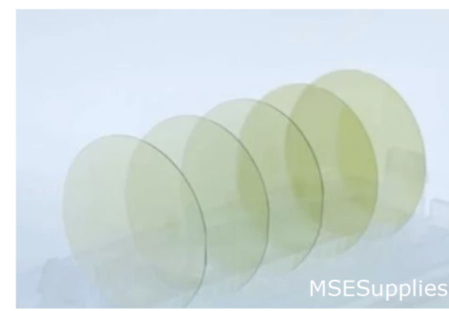
Silicon Carbide (SiC)

Material properties and benefits

- Wide band gap material
- Low leakage current even after irradiation
- High breakdown voltage
- Possibility to work at room temperature after irradiation
- High saturation velocity
  - Potential for timing applications

Properties	Si	4H-SiC
Crystal Structure	Diamond	Hexagonal
Energy Gap : E_G (eV)	1.12	3.26
Electron Mobility : μ_n (cm^2/Vs)	1400	900
Hole Mobility : μ_p (cm^2/Vs)	600	100
Breakdown Field : E_B (V/cm) $X10^6$	0.3	3
Thermal Conductivity (W/cm°C)	1.5	4.9
Saturation Drift Velocity : v_s (cm/s) $X10^7$	1	2.7
Relative Dielectric Constamt : ε_S	11.8	9.7

ROHM, *SiC Power Devices White Paper*



Potential for fabrication of 3D detectors and other MEMS structures

Irradiation campaign

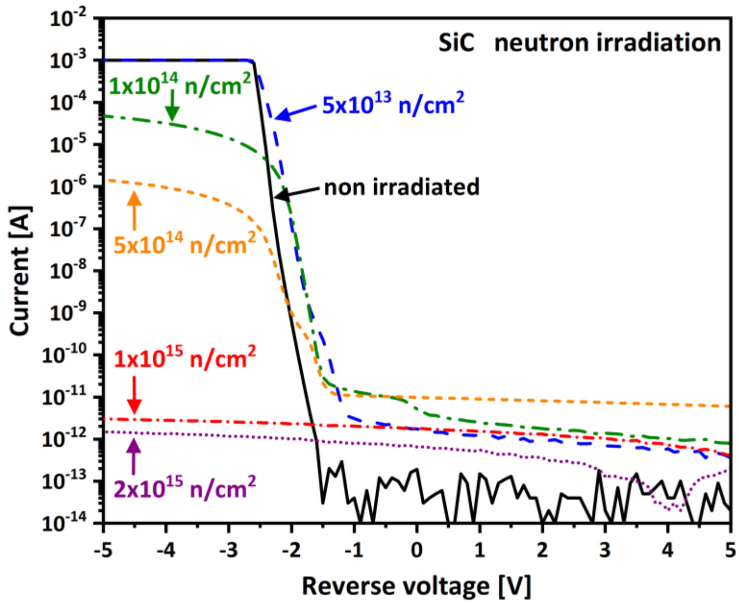
2 MeV electron irradiation (e/cm²)				
$1x10^{14}$	$1x10^{15}$	$1x10^{16}$		
Neutron irradiation (n/cm²)				
$5x10^{13}$	$1x10^{14}$	$5x10^{14}$	$1x10^{15}$	$2x10^{15}$
24 GeV/c proton irradiation (p/cm²)				
$8.6x10^{13}$	$1.5x10^{14}$	$1x10^{15}$	$1.7x10^{15}$	$2.5x10^{15}$

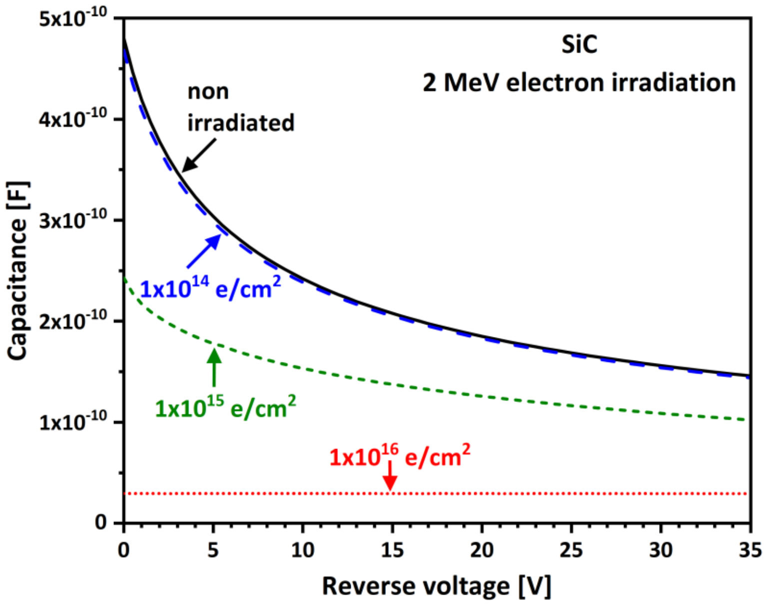
- 2 MeV electron irradiations were carried out at Takasaki-JAEA electron accelerator in Takasaki, Japan.
- Neutron irradiations were performed at JSI research reactor in Ljubljana, Slovenia
- 4 GeV/c proton irradiations were carried out at CERN PS-IRRAD facility in Geneva, Switzerland.

This project has received partial funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168.

AIDA 2020

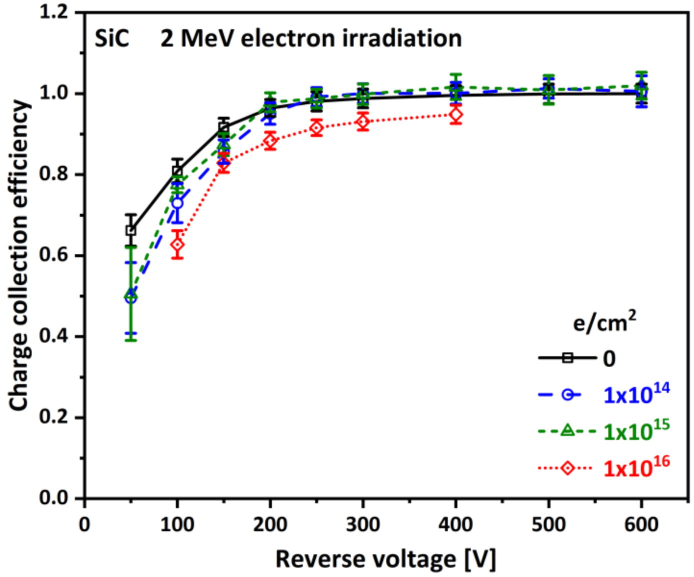
Electrical characterization after irradiation

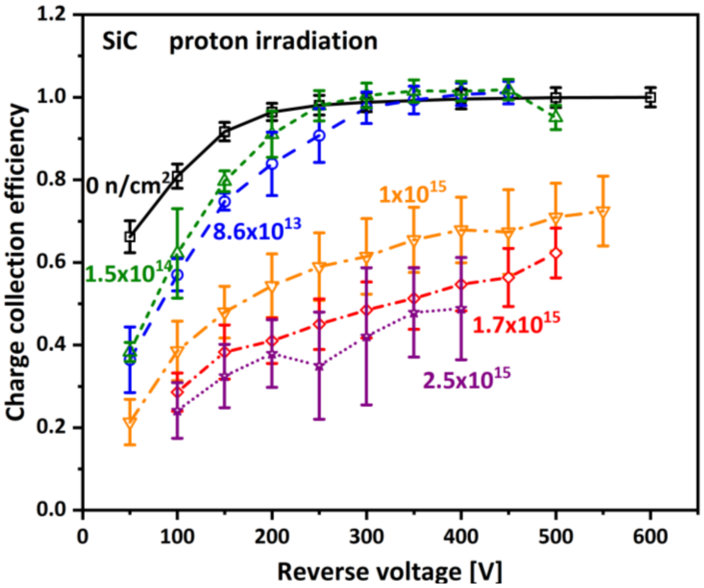


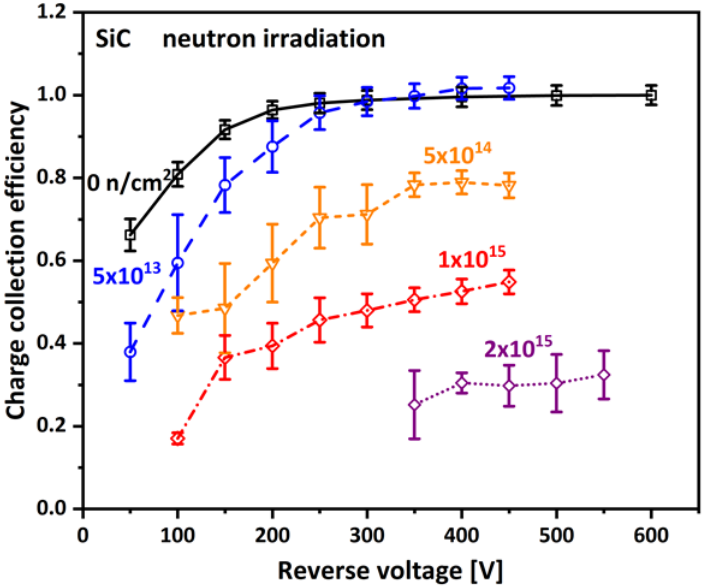


J.M. Rafí et al 2018 JINST 13 C01045

CCE characterization







Detectors tested with 5MeV alpha particles and at room temperature

J.M. Rafí et al IEEE TNS, vol. 67, no. 12, december 2020

Centro Nacional de Microelectrónica IMB

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

24th-28th October

22

Ecosystem

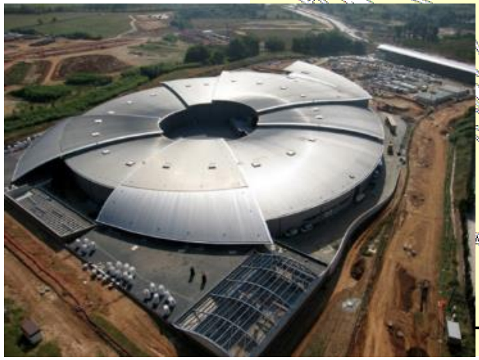
PRUAB
Spin-off Incubator

IMB-CNM(CSIC)

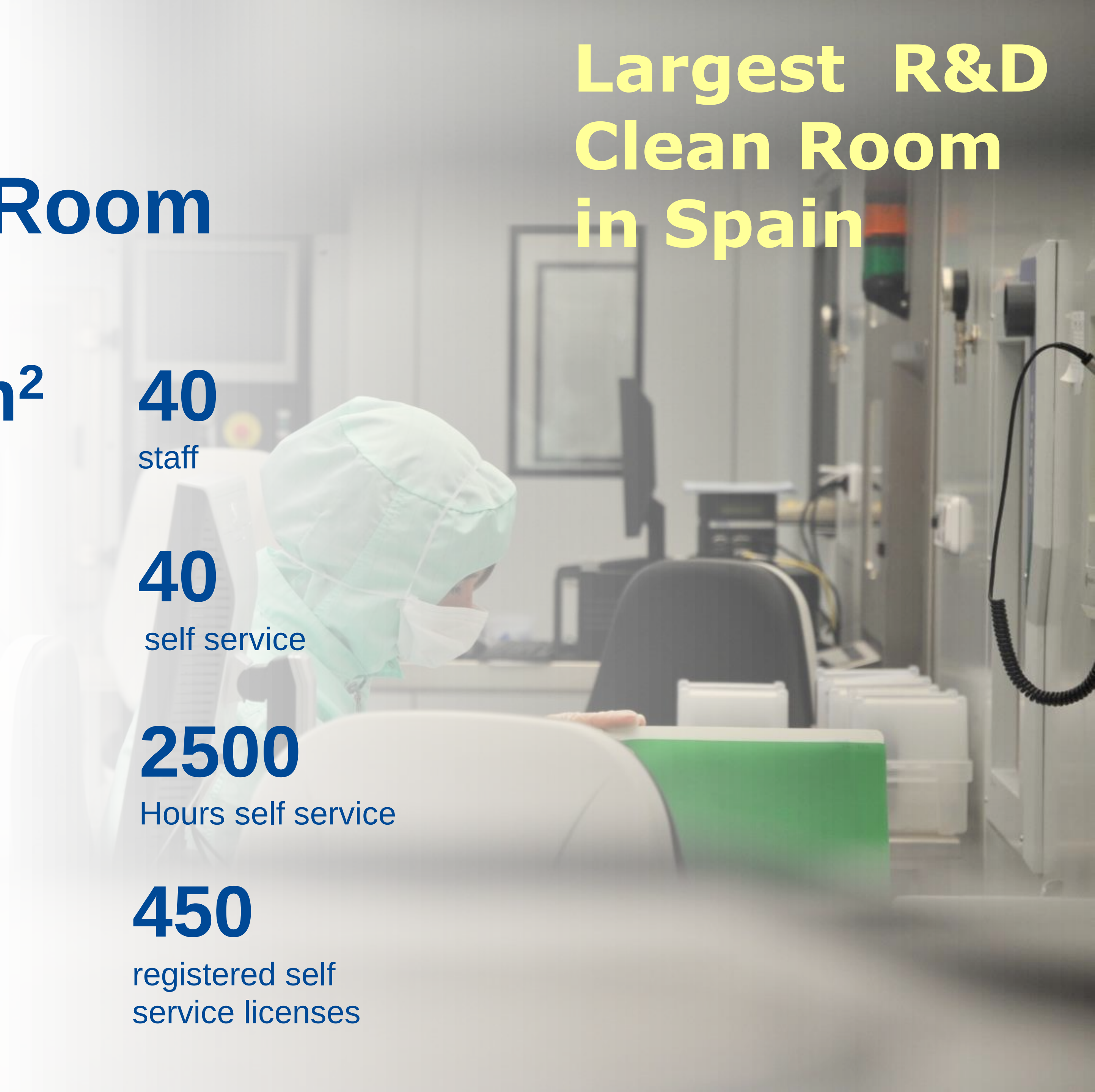
Sciences (UAB)

Materials Science Institute (CSIC)

ICN2



Alba Synchrotron



Clean Room

Largest R&D Clean Room in Spain

1,500 m²
total area

40
staff

190
equipment units

40
self service

3000
Wafers/year

2500
Hours self service

550
Runs/year

450
registered self service licenses

Integrated Micro & Nano Fabrication Clean Room

The main activities of IMB-CNM is basic and applied research and development, education and training in micro and nanotechnologies, components and systems.

Clean room

- class 100 to 10.000
- Technologies for Micro y Nano fabrication
- 3 Areas:
  - ✓ CMOS (high purity, no contaminants)
  - ✓ MNC (Noble Metals contaminants for Si)
  - ✓ Nanolithography
- Process size: 4'' and 6” wafers
- Technologies: CMOS, MEMS/NEMS, power devices, radiation detectors
- Silicon Micromachining

Microelectronic Packaging Area

- 200 m2, class 100
- Wafer cutting, wire-bonding, bump-bonding

Clean Room Equipment

- Thermal processes, CVD and ALD
- Ion Implantation
- PVD and Metallisation (Sputtering and Evaporators)
- Optical Lithography:
  - Proximity Aligners: single and double side
  - Steppers: g-line and i-line
  - Direct laser writing
- Nano-lithography (e-beam, NIL, FIB and AFM)
- Dry etching
- Wet and dry micromachining
- Wet etching and cleaning
- On-line test
- Conventional and advanced packaging
- Electrical characterization

Experience in production

SiC rectifiers for space

Bepi-Colombo & Solar orbiter missions
Main contractors EADS, Airbus, ALTER
400k€/year (2,800 k€ accumulated)

Beam monitors for Synchrotron accelerators

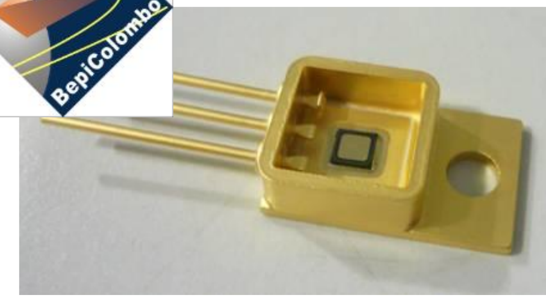
position and intensity thin sensors (Alba cell, Alibava)

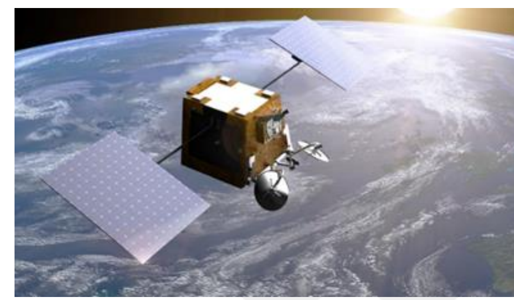
Radiation detectors

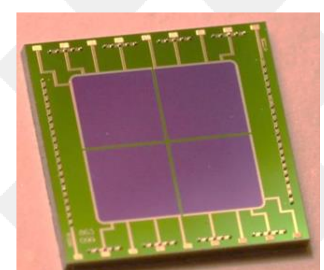
Main contractor CERN (ATLAS experiment, RD50, TOTEM
Other contractors: INFN, BNL, DESY, GSI, Xian University, .

Four Quadrant diodes for space

Main contractor non disclosed
In orbit since February 2019, full contract 650 k€







THE INCREASE OF CHARGE COLLECTED VS T IS EXPECTED

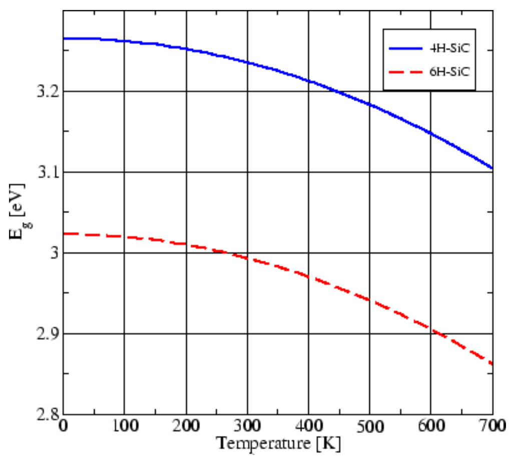
Measurements from RT to 450ºC → **Change in the BandGap energy** → **Change in the pair creation energy** → **Change in measured energy**

Properties of Advanced Semiconductor Materials: GaN, AIN, InN, BN, SiC, SiGe. John Wiley & Sons. (2001).

$$E_g(T) = 3.265 - 6.5 \times 10^{-4} \frac{T^2}{T + 1300} \ (eV)$$

$$\varepsilon_{4H-SiC}(T) = \varepsilon_{4H-SiC}(RT) \frac{E(RT)}{E(T)}$$

https://www.iue.tuwien.ac.at/phd/ayalew/node61.html



38