How can we use SiC?

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IFD2015 Torino

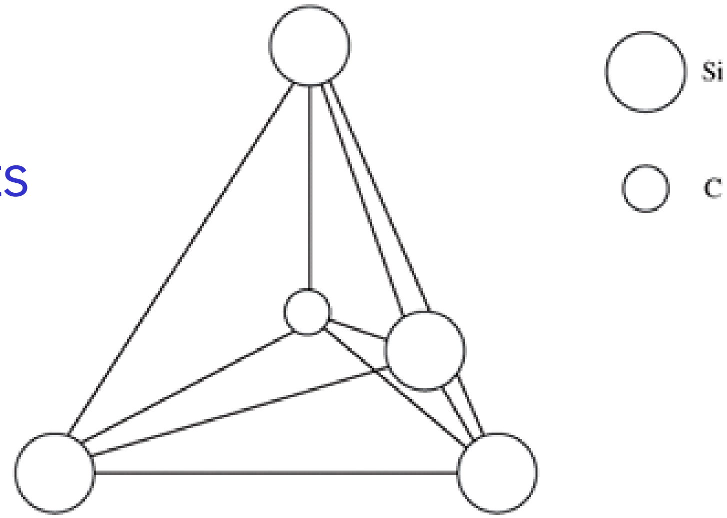
16th December 2015

SiC @ INFN

- Two initiatives within INFN-CSN V
  - CLASSiC: Cherenkov Light detection with silicon carbide
    - Financed as grant for young researchers within CSN V
    - PI: PL, **Firenze**
  - SiCILIA: Silicon Carbide detectors for Intense Luminosity Investigations and Applications
    - Financed as CSN V "call"
    - PI: Salvo Tudisco, **Catania**
- Overall **7 sezioni and national laboratories** involved
- Main manufacturing involved in these projects: CNR-IMM (**Catania**)
- Industries: ST, FBK

What is special about SiC?

- Wide bandgap semiconductor
  - → visible blind
  - → low thermally generated currents
- Fast
  - High drift velocity at saturation
- More radiation resistant than silicon

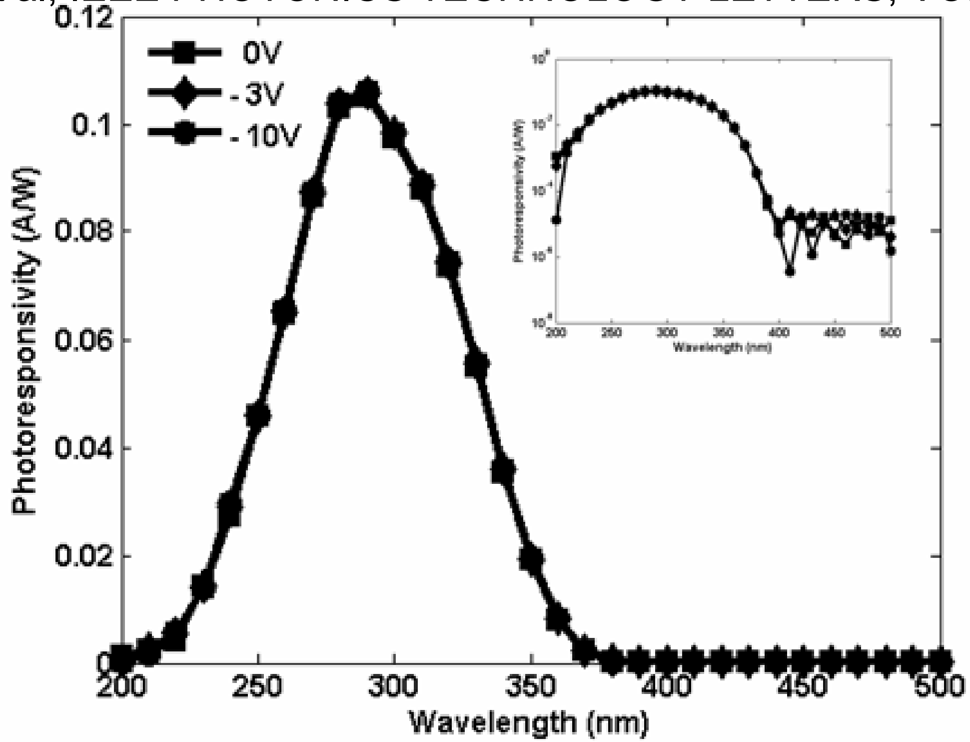


Material	Gap (eV)	ε (eV)	υ_s (10^6cm/s)	energy for defect (eV)
Si	1.1	3.7	10	12.8
4H-SiC	3.3	7.8	22	25

SiC optical properties

- Thanks to the higher band-gap wrt silicon SiC is insensitive to visible light (beyond 400 nm)
  - Useful for applications in which visible light is contaminating the environment
    - e.g Cherenkov detection in scintillating crystals
    - Neutron and charged particle detection in plasmas

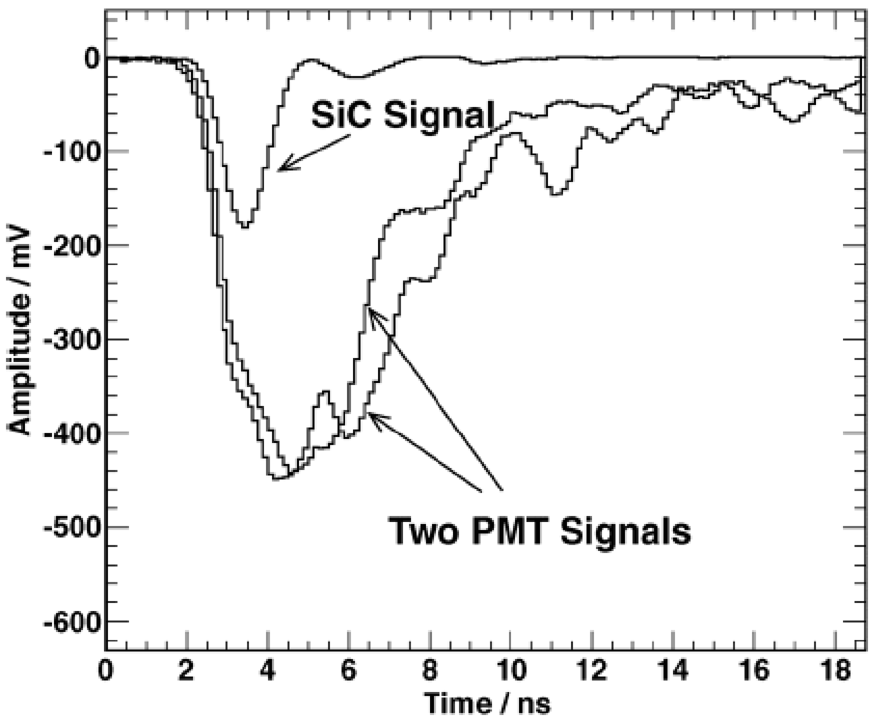
A. Sciuto et al, IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 21, NO. 23



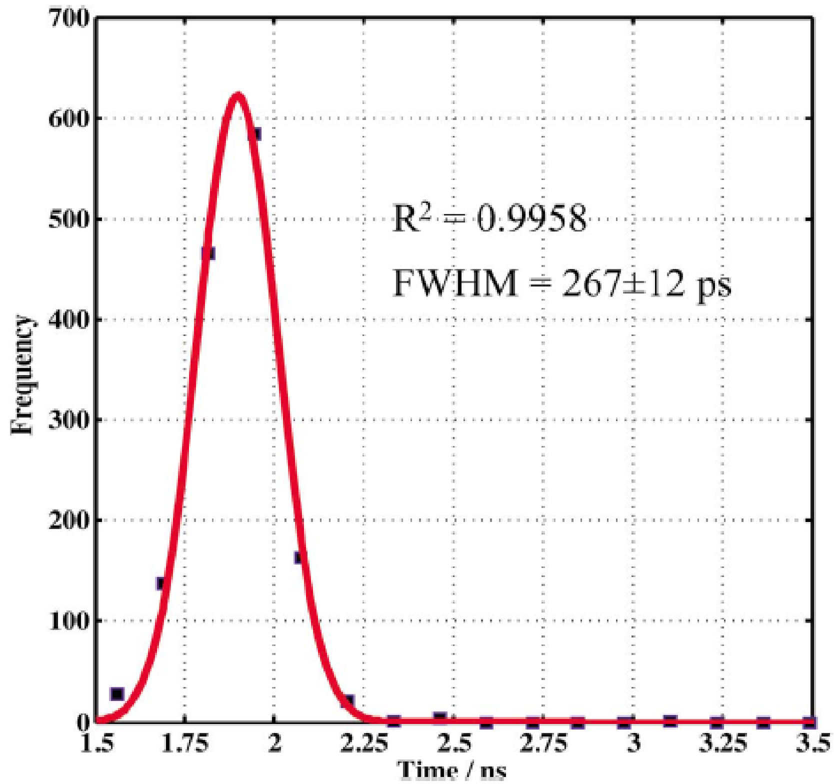
SiC Timing properties

- Suitable for extreme timing applications
  - Example of alpha detection in 100 um Schottky SiC diode

Xiaodong Zhang IEEE Trans. Nucl. Scie. VOL. 60, NO. 3, JUNE 2013



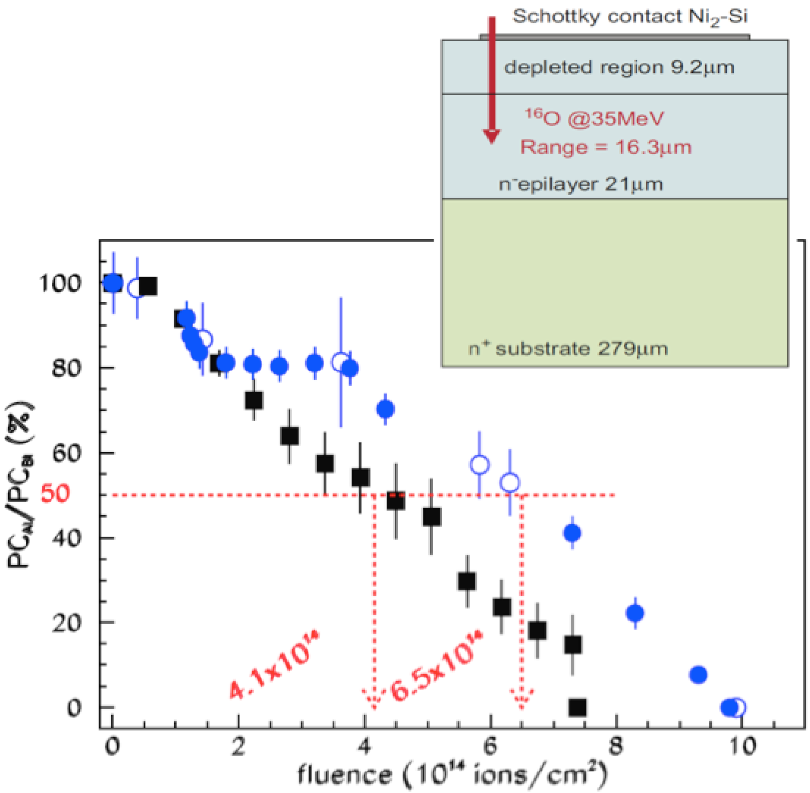
Snapshot of signals obtained from the SiC detector and the two PMTs



SiC radiation hardness

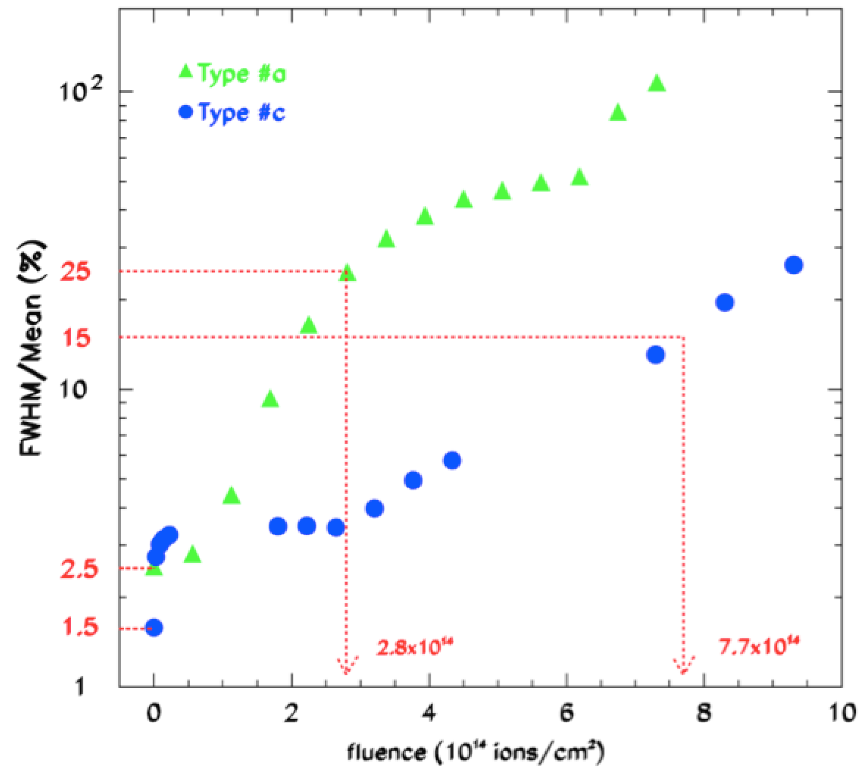
- Studies on Schottky diodes

M. De Napoli et al. NIMA 600 (2009) 618



Ratio of peak centroid of ^{16}O energy spectrum after (PC_{Al}) and before irradiation (PC_{BI}) fro two SiC detector samples

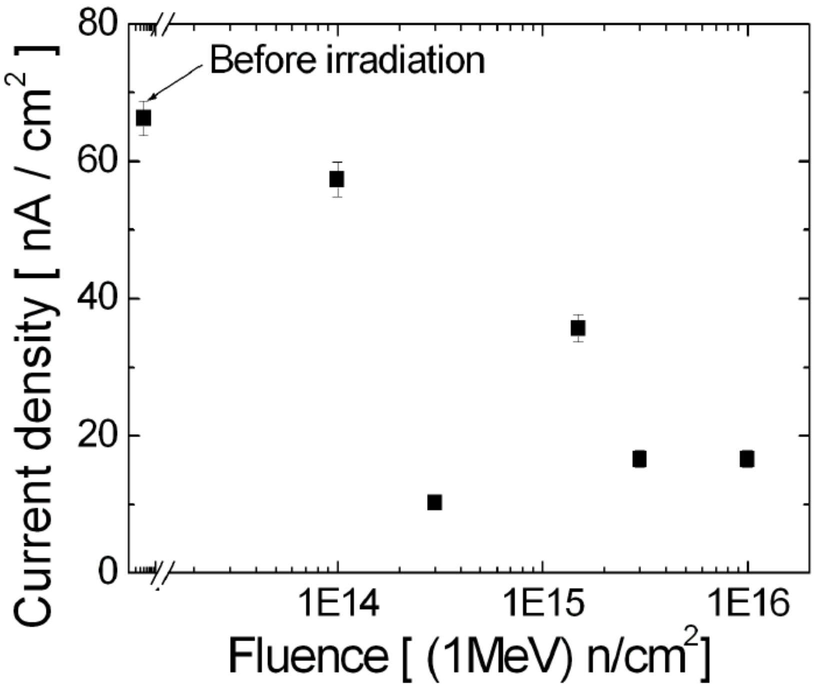
G. Raciti et al. Nuclear Physics A 834 (2010) 784

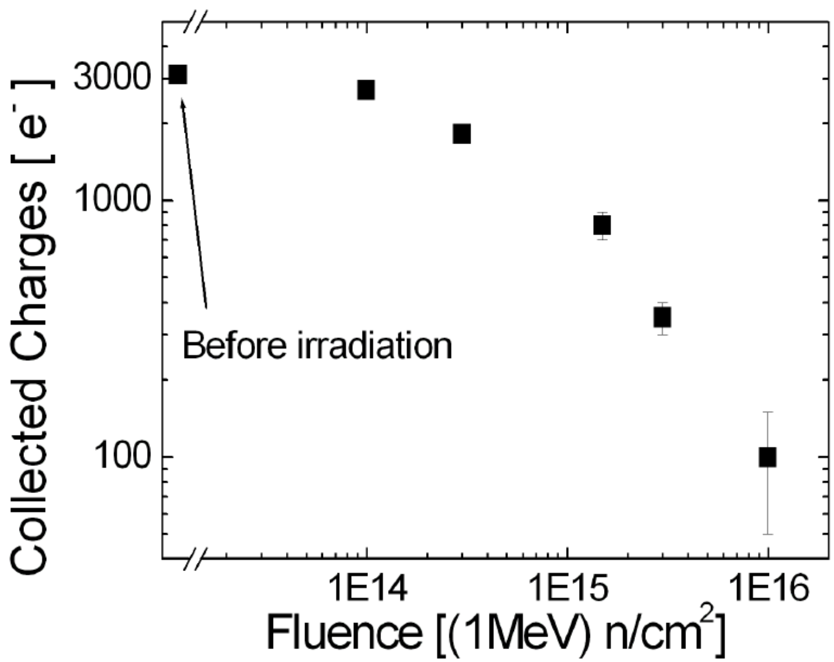


Relative Energy resolution for two types of Schottky SiC detectors with different dopant concentration

SiC radiation hardness

- Studies on p-n SiC junctions up to 10^{16} neutrons/cm^2
  - High charge collection efficiency up 10^{15} neutrons/cm^2
  - Leakage current stays low up to 10^{16} neutrons/cm^2





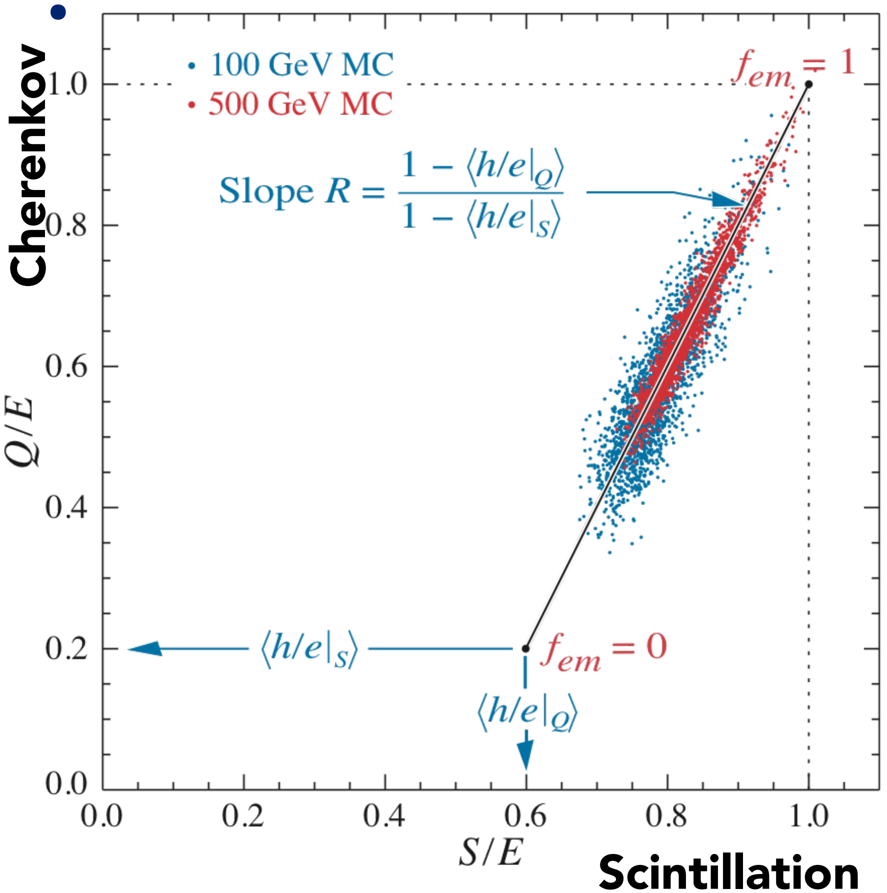
Moscatelli et al, 2005 IEEE Nuclear Science Symposium Conference Record

CLASSiC

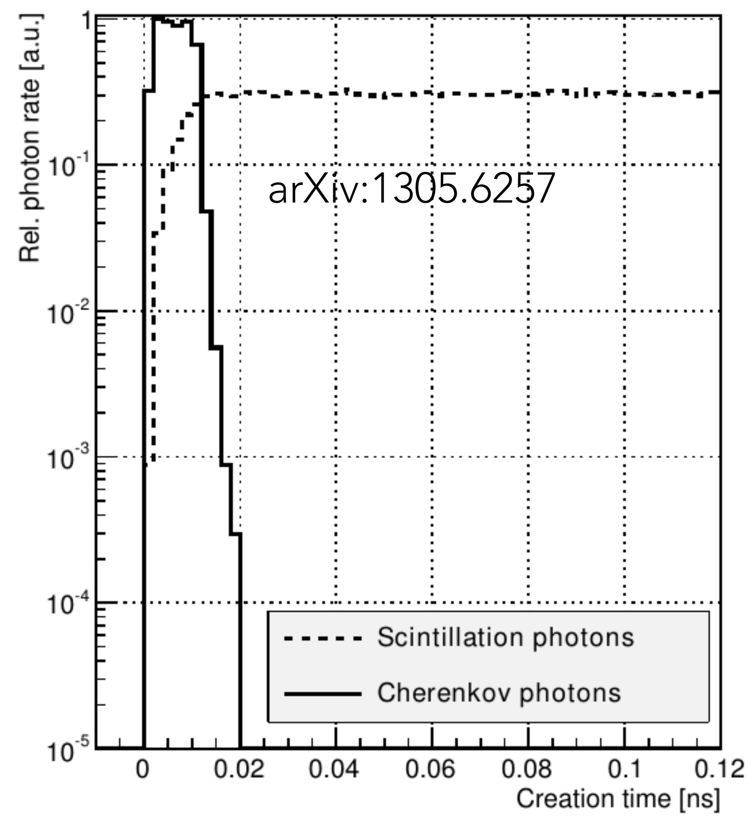
- Aims at the development of a **SiC based avalanche photodiode**
  - Few to **single photon detection** capability
  - Detect **Cherenkov light in the presence of visible radiation**
    - Typically Cherenkov light produced in a scintillating crystal
- Two applications were originally foreseen in the proposal
  - **Dual readout calorimetry** (DREAM calorimetry concept)
  - **Fast timing in ToF-PET**
- **Multiple impact**
  - **Pave the way to pixelated SiC Detectors**
  - **SiCPM?**
- Project started in **February 2015**

Motivations of CLASSIC

- Exploit correlation of Cherenkov with em fraction as a means to measure em fraction event by event
  - → e/h compensation
-

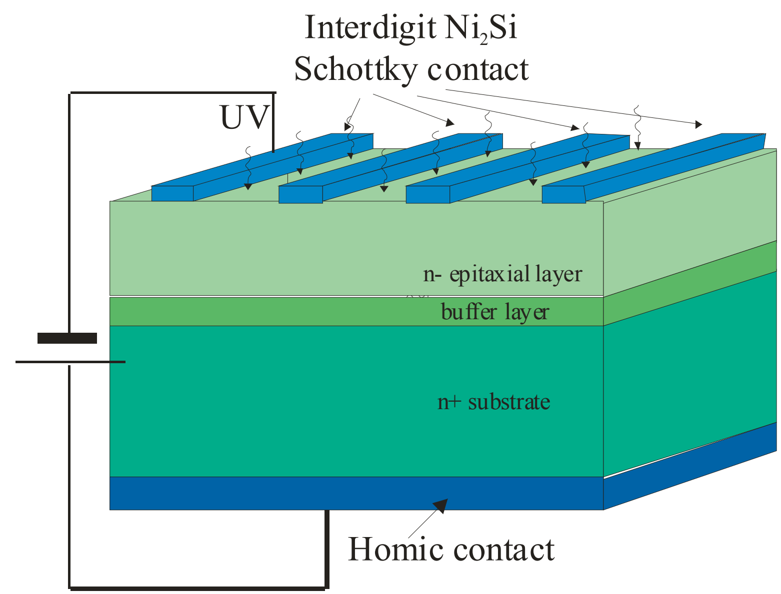


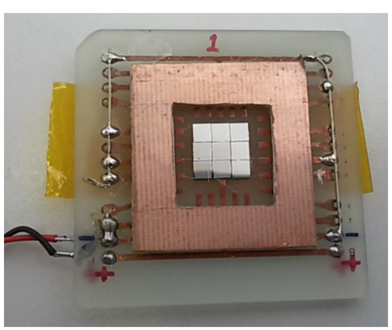
- Exploiting the fast Cherenkov signal from electrons emitted after photoelectric absorption of the 511keV photon



Starting point

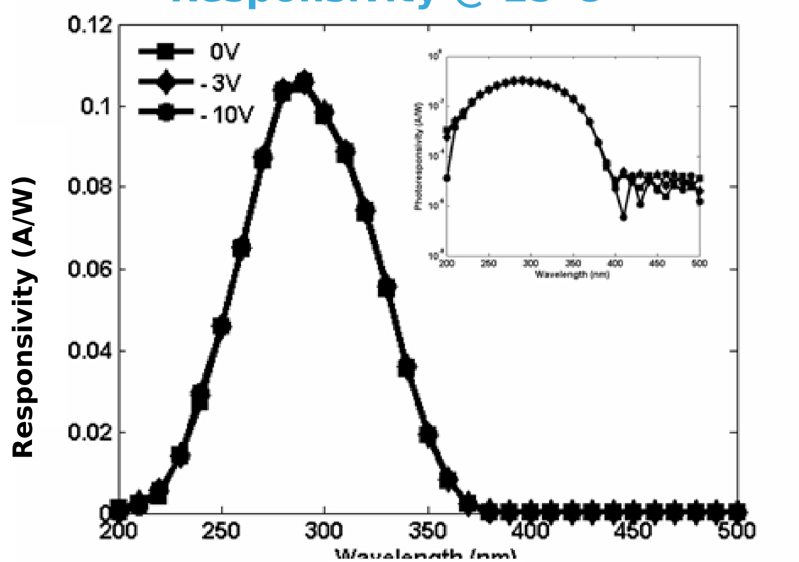
- Schottky UV photodiodes with interdigitated metal
  - To expose more area to incident radiation
- Initially developed in CNR-IMM CT then industrialised by ST microelectronics
- Peak **QE 45%**
- Dimensions: **3 X 3 mm^2**
- Capacitance **~100 pF**
- Dark current: **1pA/mm^2** @ 25 °C
- Visible rejection ratio
  - QE (400nm)/QE(290nm): 2X10^{-4}





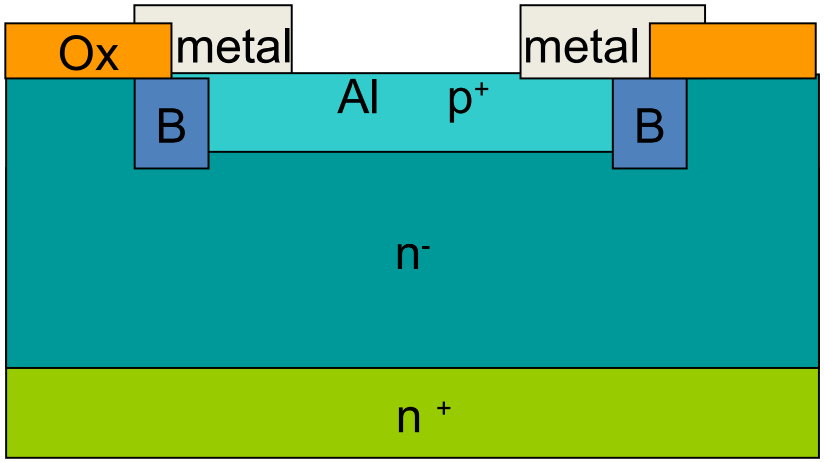
Matrix of 9 3X3mm^2 diodes

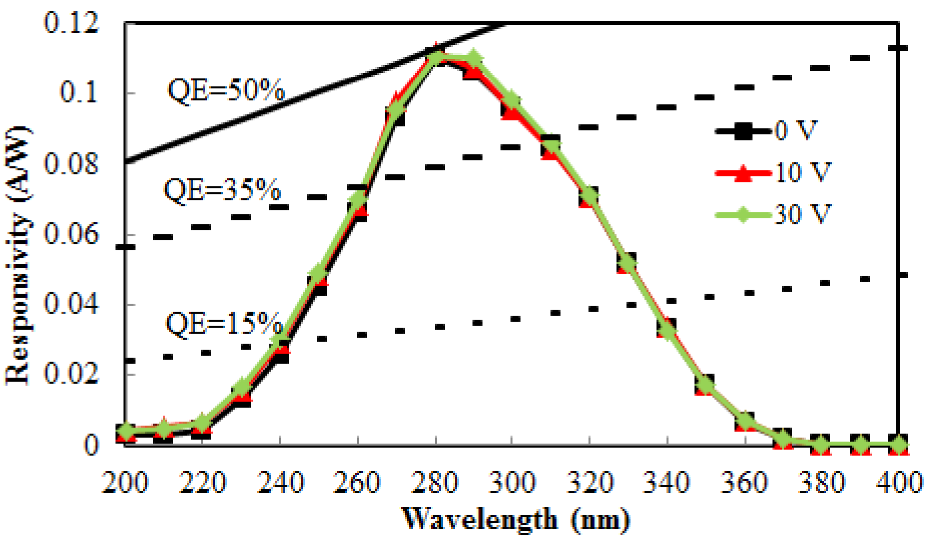
Responsivity @ 25°C



The road to multiplication

- First step
  - Develop p-i-n diode
- We have investigated several p-i-n diode structures
- Studies in literature mostly rely on epitaxial junction
  - Thicker junction → less transparent to UV radiation
- We concentrated on ion implantation techniques
  - Several structures considered
  - Best results obtained with a thin planar junction
    - Interdigitation of the junction is possible but yielded worse results

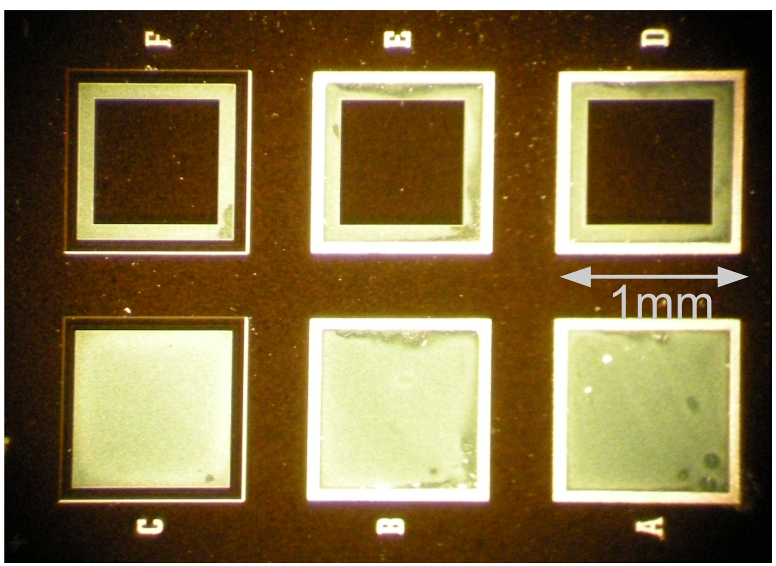


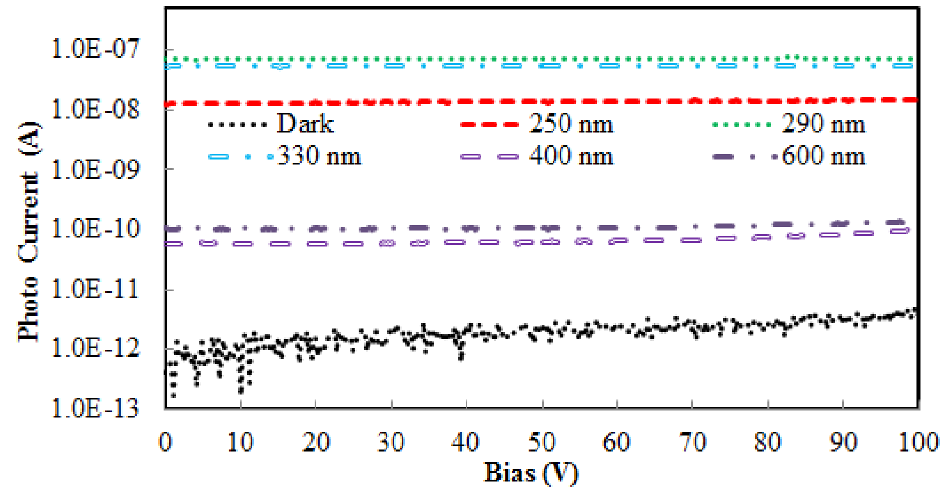


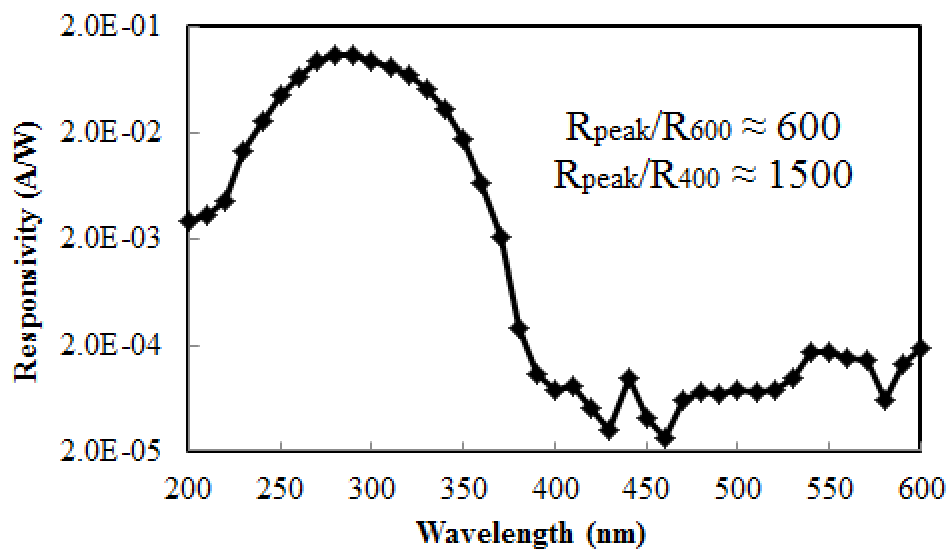
Detectors manufactured at CNR-IMM CT

The road to multiplication

- The material is very high quality
  - Charge collection efficiency essentially independent of the applied voltage
  - High charge carrier lifetime
- V_{br} ~ 600 V
- Very good visible rejection power
  - Same as in Schottky diodes

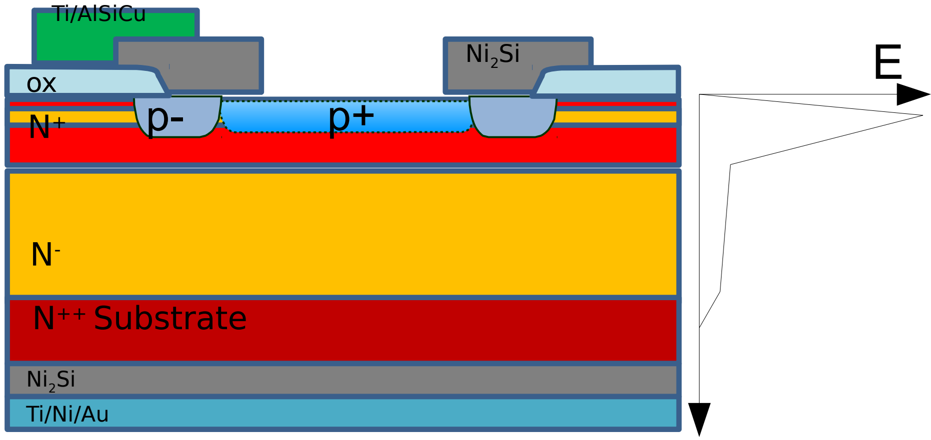






Multiplication

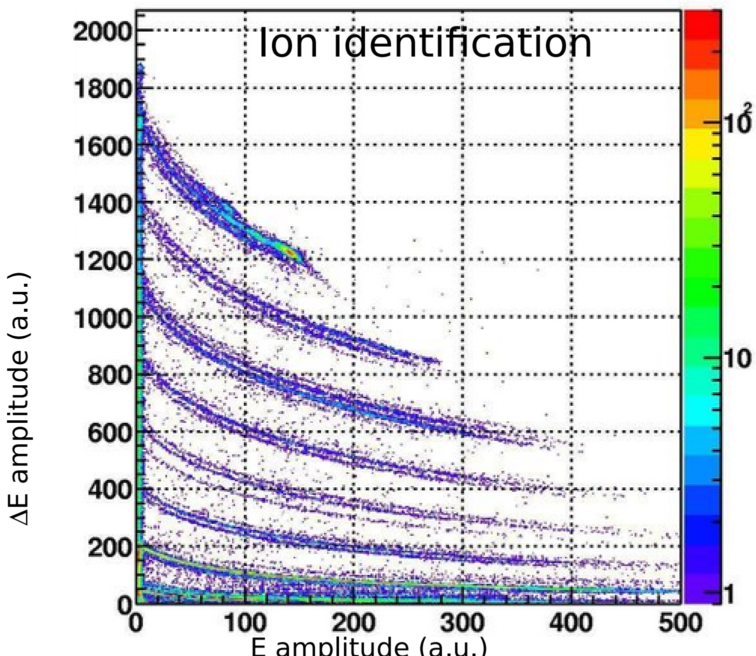
- **Critical field in SiC is much higher than silicon (~3MV/cm)**
  - We aim at achieving multiplication while keeping the reverse bias to reasonable level
- Design studies and simulations have been performed
  - Doping concentration such that the critical field is achieved with ~100 V reverse bias



- Main design features
  - P+/N+/N- structure
    - Thin p+ layer by ion implantation
  - p- implanted edge ring to tame electric field at the edges
  - **Planar structure** in view of a possible "pixelisation" evolution
- **P-on-n structure** has been chosen because holes impact ionization rate in SiC is one order of magnitude higher than electron ionization rate
- **First batch currently in production**

SICILIA

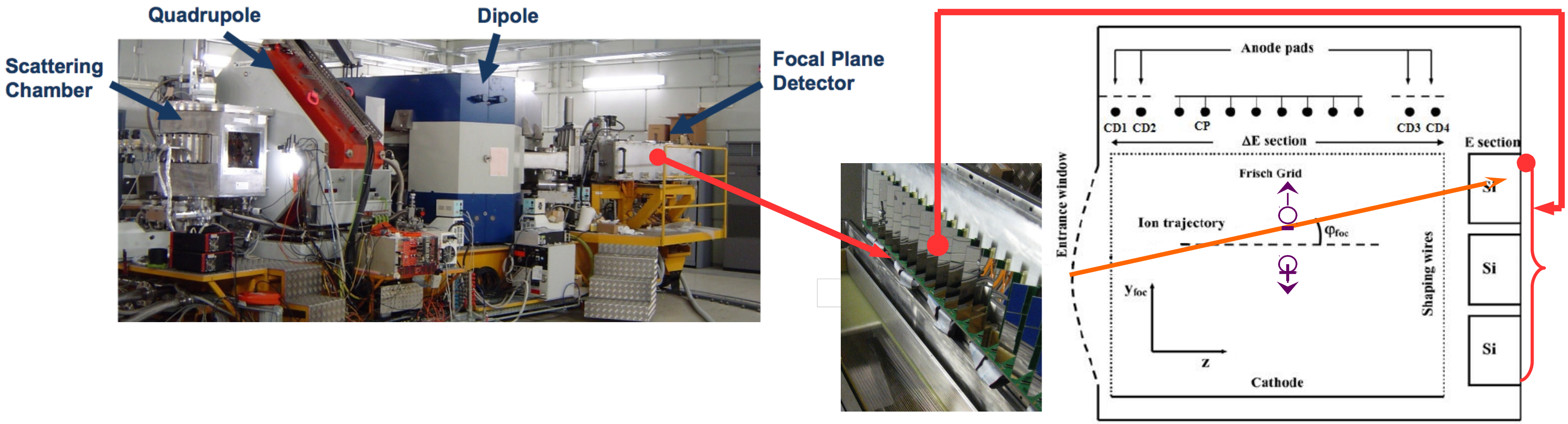
- Use SiC for radiation hard detectors in nuclear physics experiments
- Main objective:
  - SiC ΔE-E telescopes for ion identification
- Need to grow epitaxial layers with **unprecedented thickness and purity**
- **Industrial impact**
  - Know-how transfer
    - Rely on FBK and AdvanSiD for Schottky devices
  - Interact with ST for new developments (p-n junctions)



SiCILIA applications (I)

- **NUMEN** experiment:
  - experiment for the extraction of nuclear matrix elements for $0\nu\beta\beta$ from double charge exchange reactions

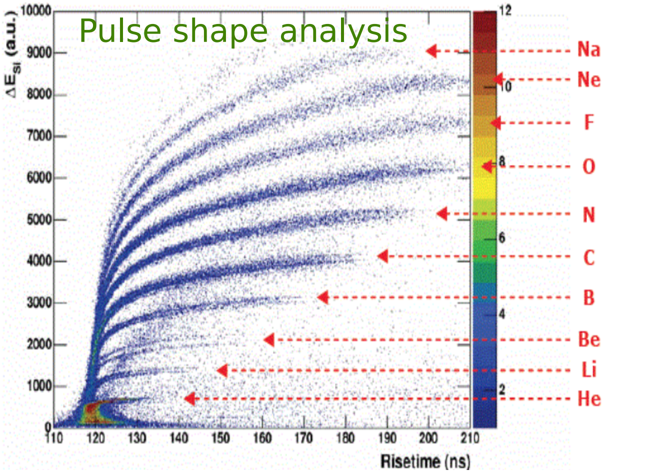
Multiwire gas tracker and ΔE stage

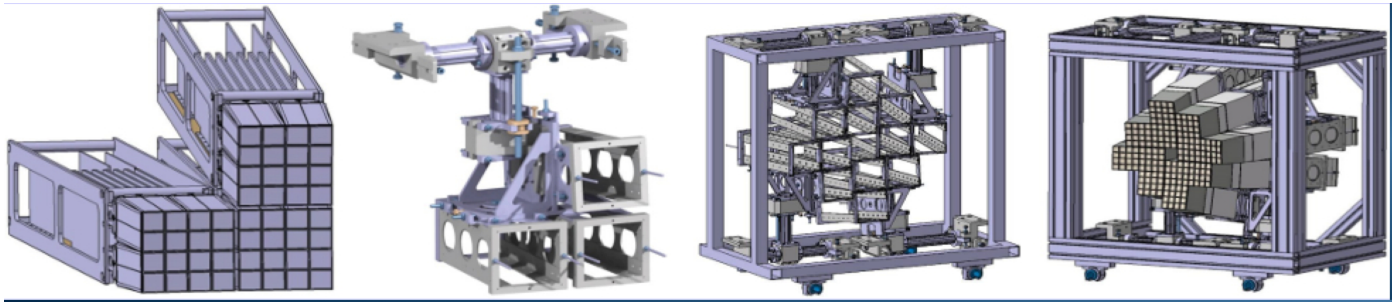


- **Upgrade of the silicon wall** plus multiwire gas tracker needed: **10^{14} ions/cm^2 in ten years of activity**
  - **Silicon dead @ 10^9 ions/cm^2**
- **Unprecedented thickness needed 1cmX1cm**
  - > 100 um for ΔE stage
  - 500-1000 um for E stage

SiCILIA applications (II)

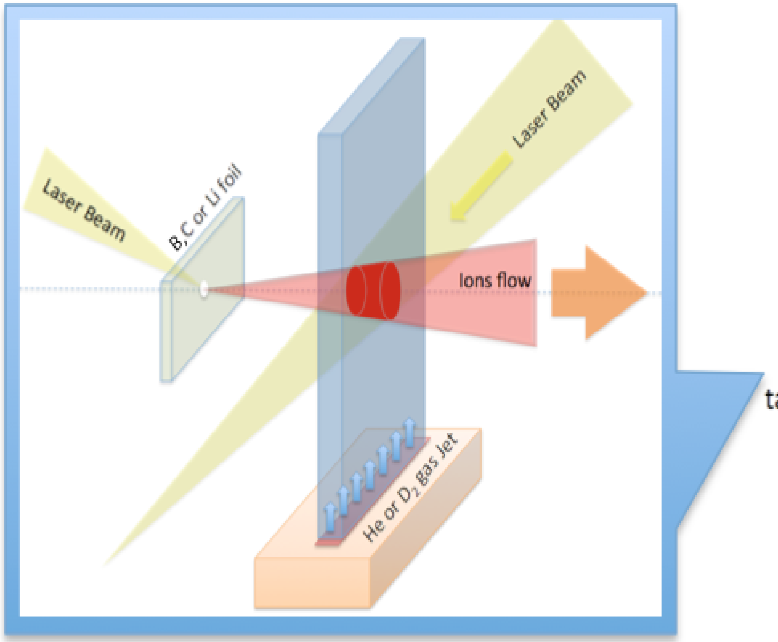
- Facility for heavy ion induced reactions around and below the Fermi energy
- Aiming at 4 pi coverage
- High granularity and high radiation hardness
- With pulse shape capabilities for ion identification
  - SiC suitable for pulse shape analysis thanks to different electron and holes mobilities

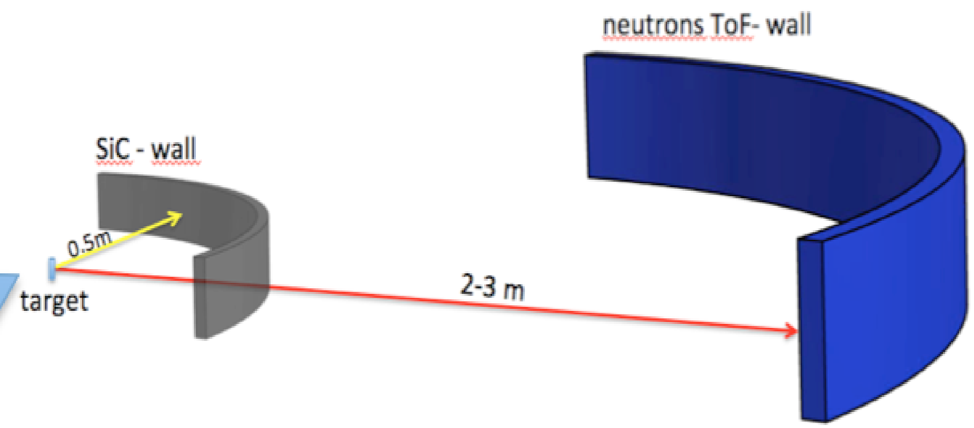




SiCILIA applications (III)

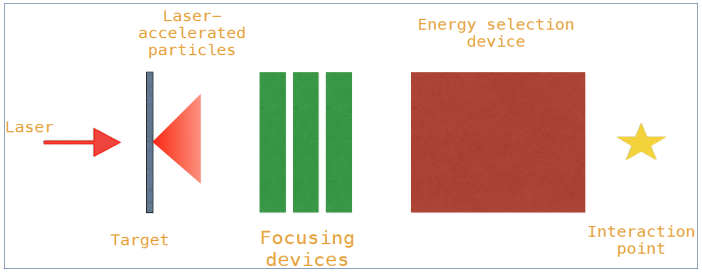
- Nuclear Reactions in Laser Plasmas @ ELI-NP





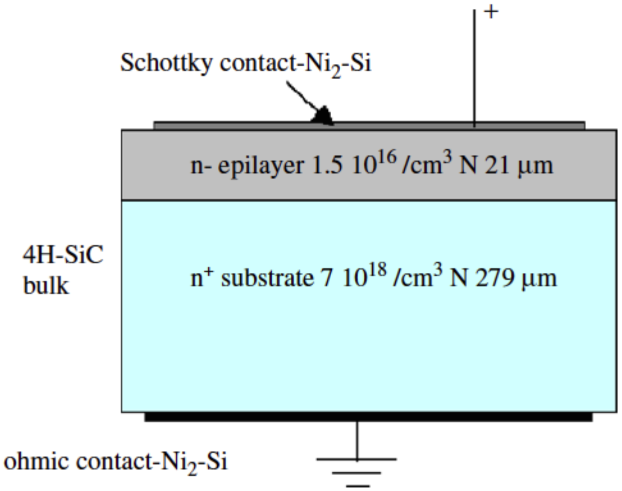
- Key advantages of SiC based detectors
  - Radiation hardness
  - Visible blindness
  - Timing performances
  - X-ray sensitivity
  - Neutron sensitivity

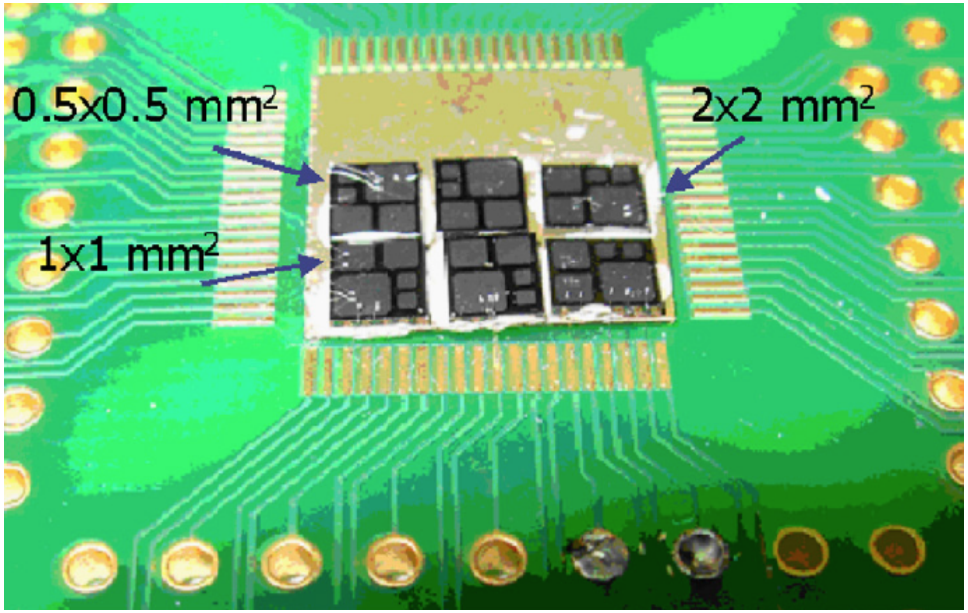
- Possible applications also in ELI-MED
  - Similar requirements in terms of visible blindness



SiCILIA starting point

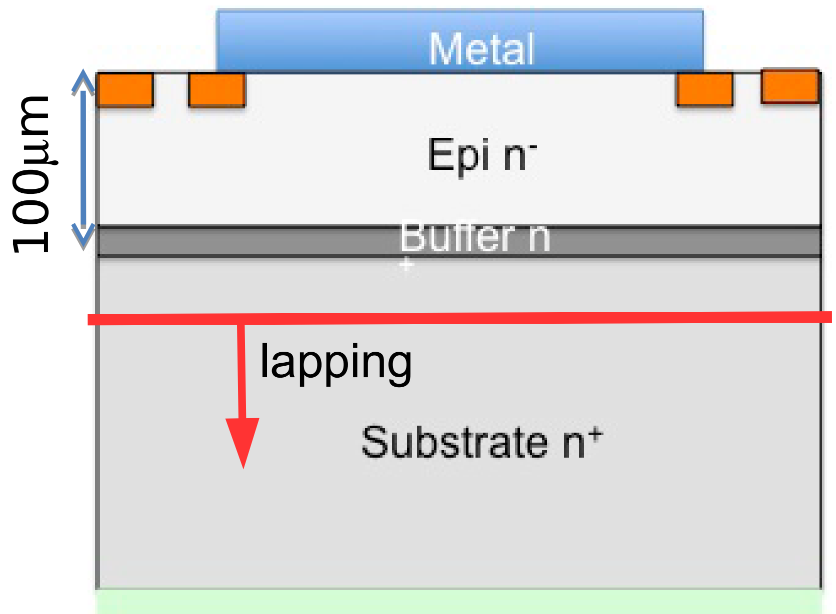
- Schottky diodes epitaxial layer growth onto high purity 4H-SiC n- type substrate
  - Active thickness: 80 um
  - 4H-SiC bulk: 250 um
  - Active area: 2X2 mm^2

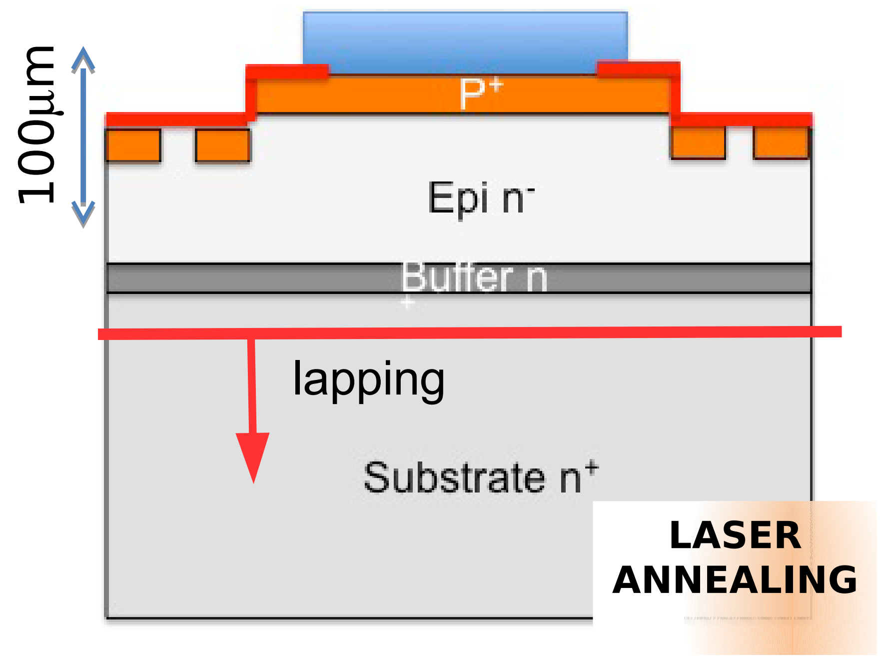




SiCILIA strategy (ΔE det)

- Schottky junction
  → FBK
- P-n junctions
  → ST microelectronics

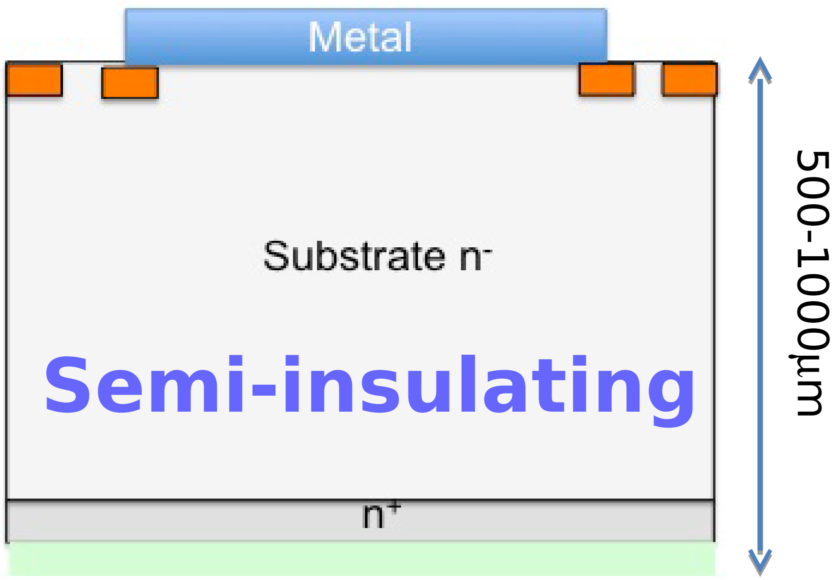


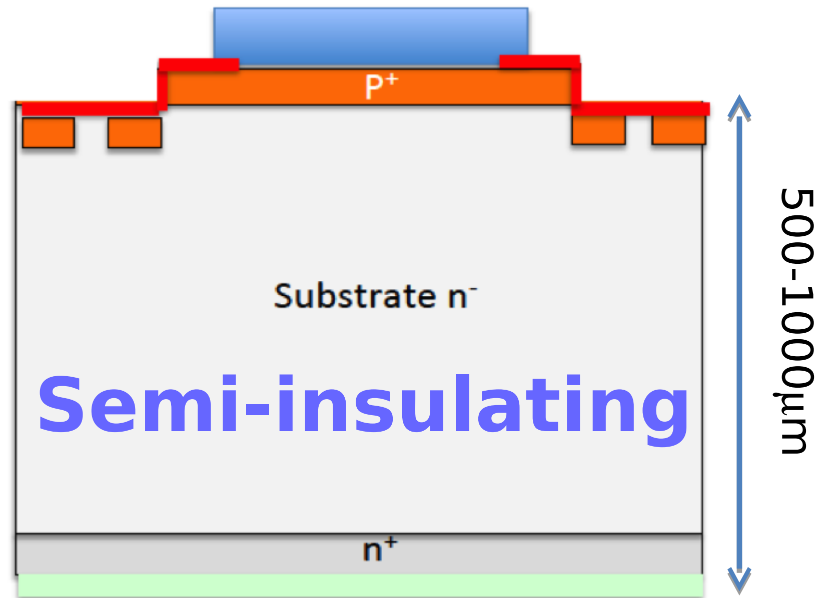


- The thick substrate is removed mechanically after the junction is manufactured
- The contact on the back is realized with cold processes
  - Laser annealing

SiCILIA strategy (E det)

- Schottky junction
  → FBK
- P-n junctions
  → ST microelectronics





- Epitaxial layer this thick do not exist
- SiCILIA will use semi-insulating substrates in place of epitaxial ones for the E detector

CLASSiC and SiCILIA

Investigate SiC detectors from complementary points of view

CLASSiC		SiCILIA
Light detection	Applications	Particles detection
- Complex p-n junction - Multi-layer - ion implantation	Junction	- Schottky - epitaxial p-n
Thin substrates	Substrate	Thick, high purity substrates
In house CNR-IMM (with opportunistic use of ST facilities)	Manufacturing	P-n junctions @ ST Schottky @ FBK

Conclusion

- SiC stands out as a promising material for future detectors
  - Visible blind
  - Radiation hard
  - Fast
- Two CSN V initiatives studying SiC detectors for both light and particle detectors
  - CLASSiC:
    - Research and Development of SiC APDs technology and manufacturing processes
  - SiCILIA:
    - Develop SiC epitaxial growth techniques
    - Know-how transfer to industries
- Promising preliminary results
- Good interaction with industries

Backup

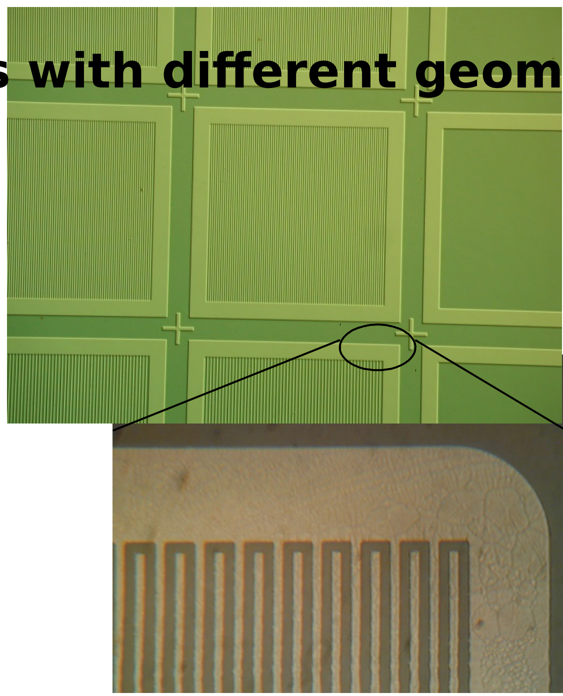
Schema e foto di un diodo Schottky con anodo interdigitato

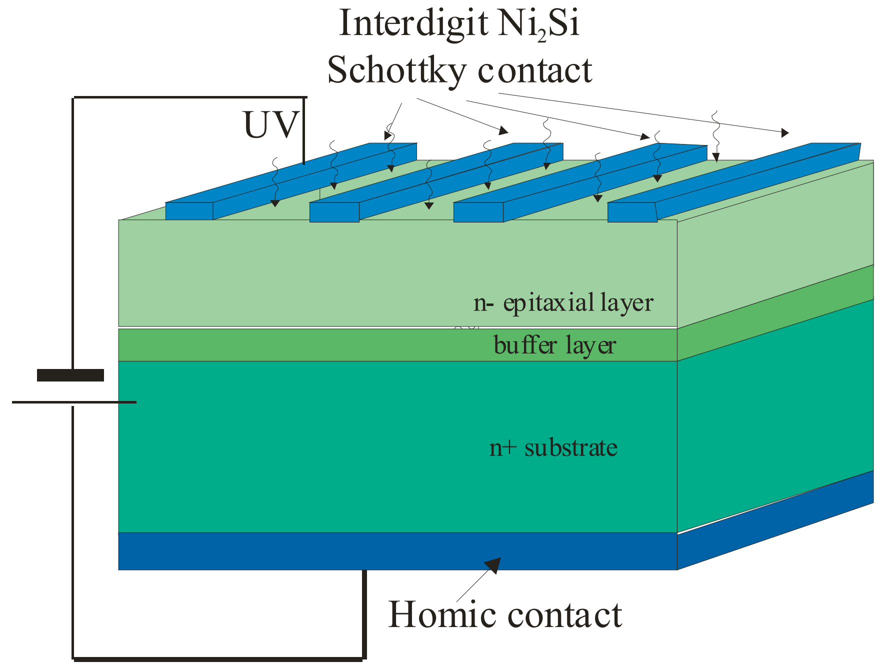
our first approach

Ni$_2$Si on 4H-SiC Schottky diode from Ni

Deposition and annealing process

diodes with different geometries

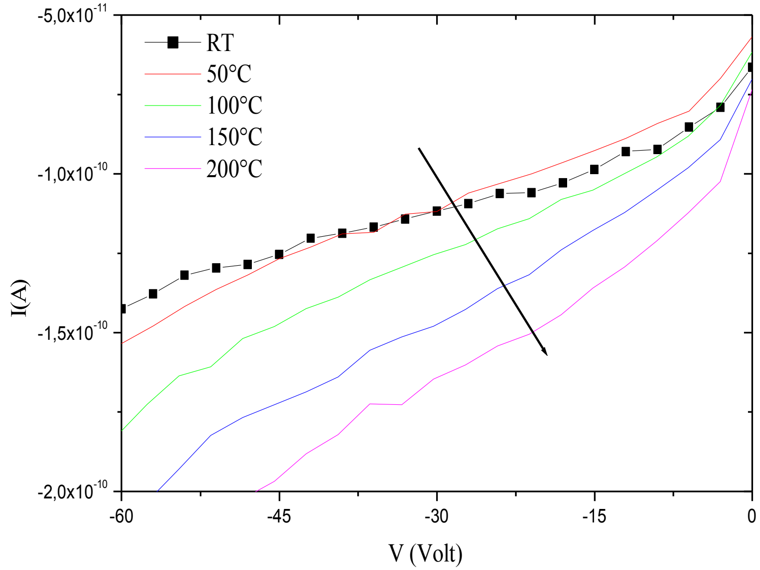




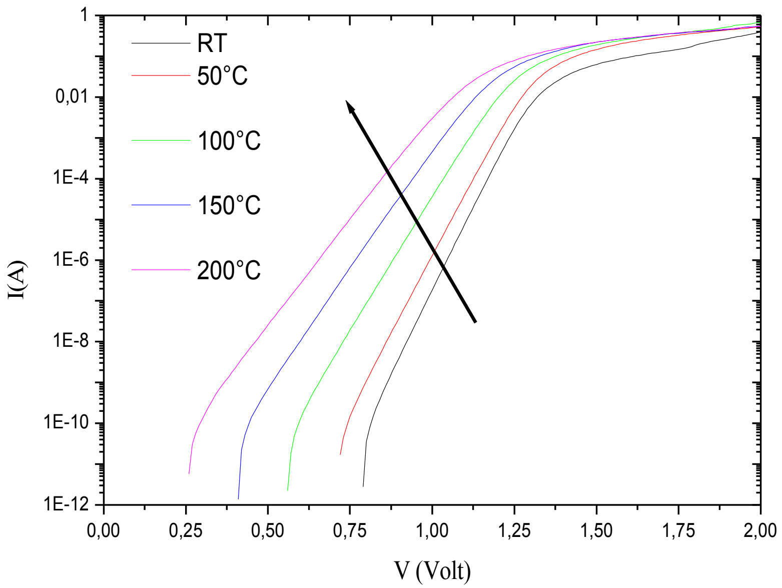
Direct exposure of Optically Active Area and vertical electrical operation

Electrical characterization

Leakage current



Forward I-V characteristic



dark current < 200 pA @ -50 V

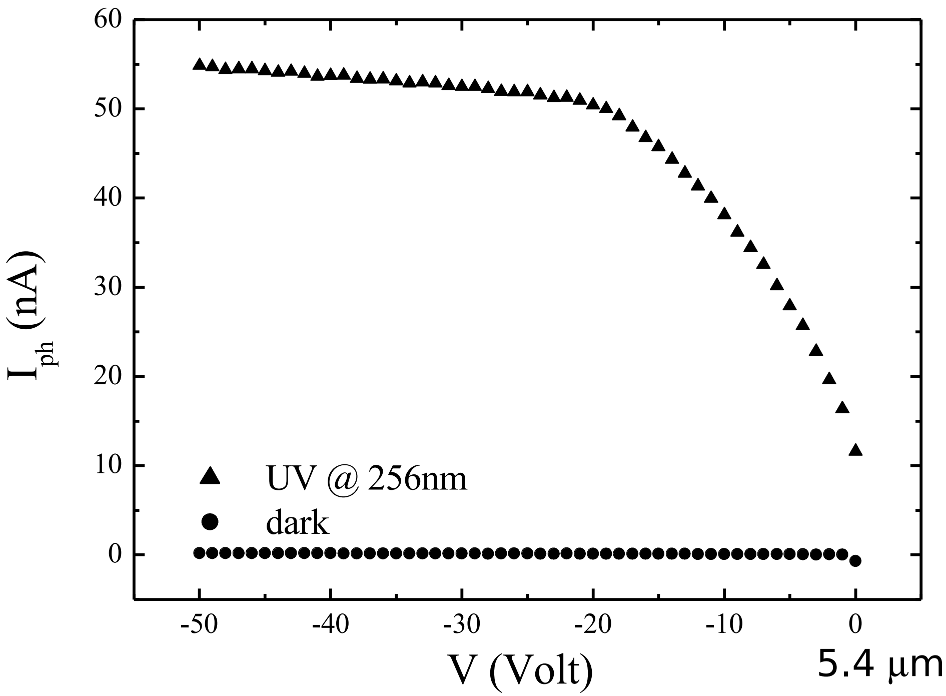
From I-V characteristics

Φb: 1.66 ± 0.02 eV
n: 1.04 ± 0.01

Ridcharson constant A*: 5 A/cm²/K²

Electro-optical characterization

I_{ph} quasi-saturation*
due to pinch-off



Pinch-off @ -20V

I_{ph} increase due to
OAA increase with bias

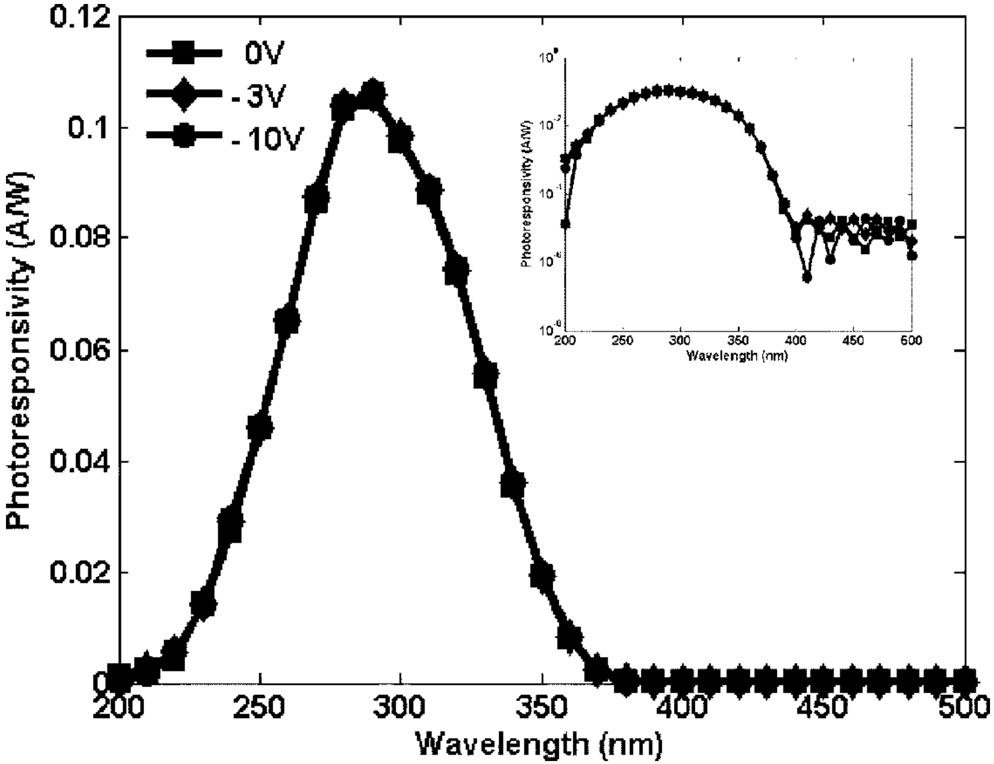
5.4 μm spaced strips

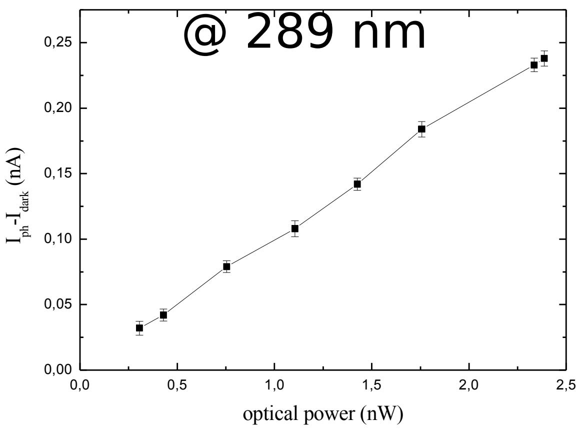
I_{dark} < 200 pA @ -50 V

I_{ph}/I_{dark} > 2E2 @ pinch-off
with optical irradiance < 0.1 mW/cm²

*I_{ph} quasi-saturation probably
due to internal gain mechanism

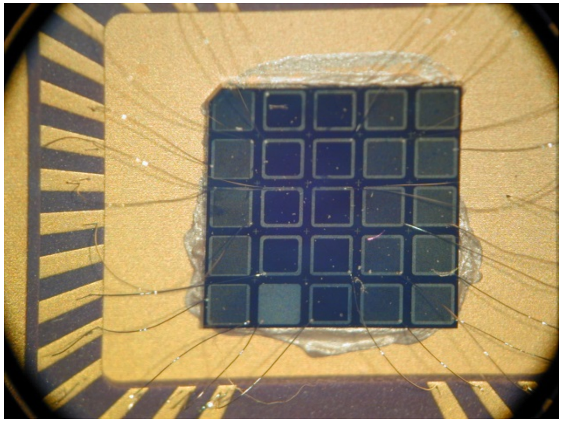
Electro-optical characterization

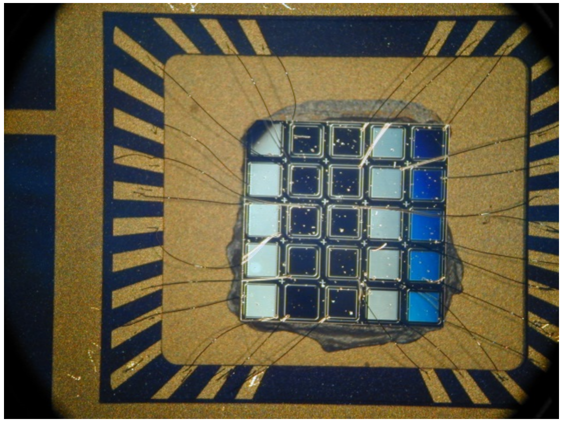


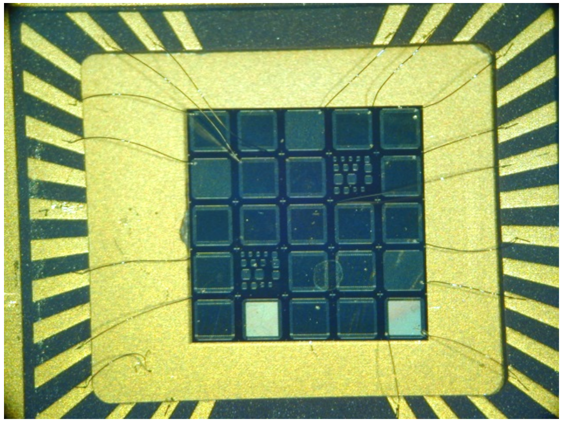


optical response has a linear trend with incident optical power

Foto di array di rivelatori realizzati in passato con anodo interdigitato

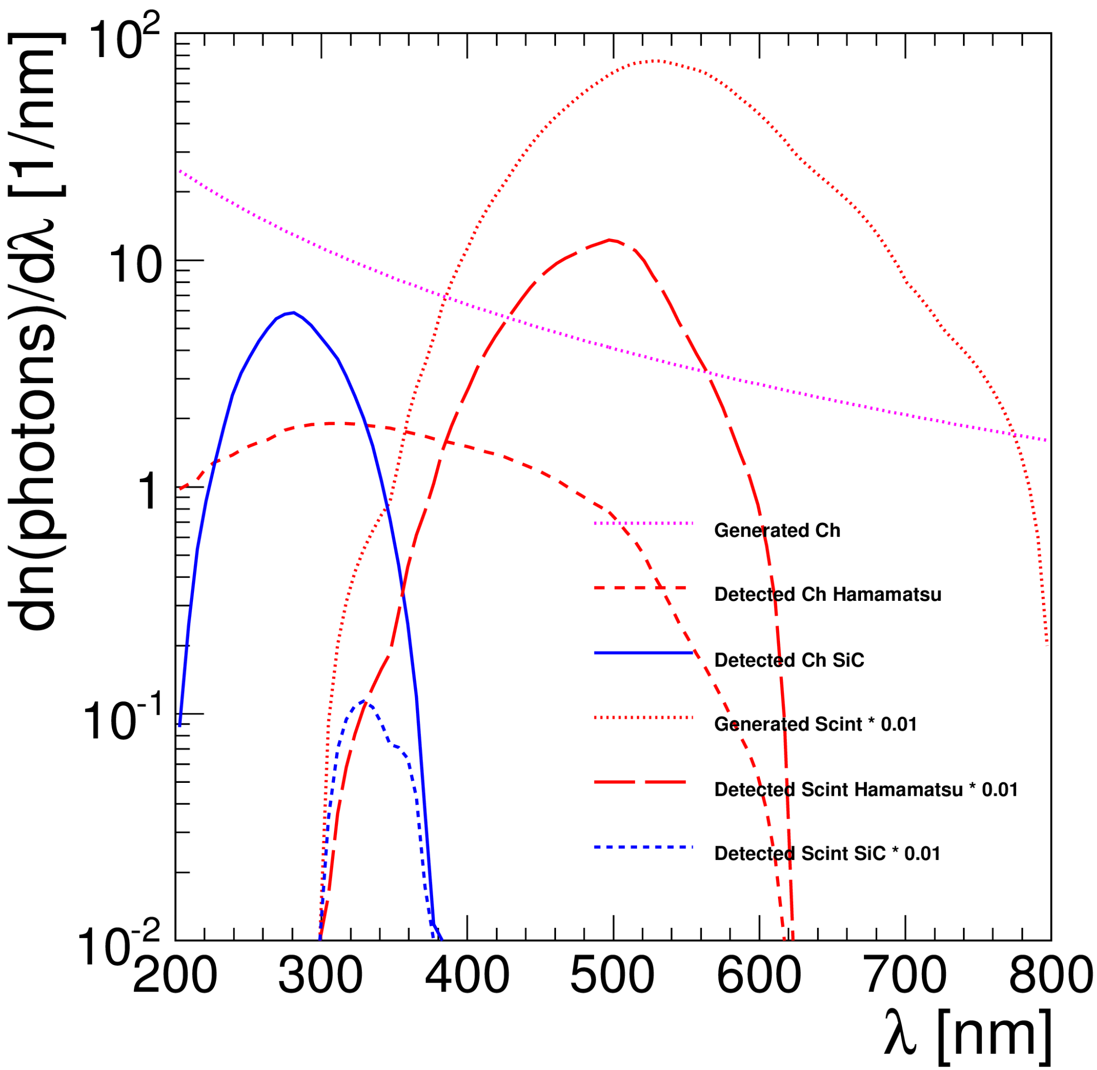






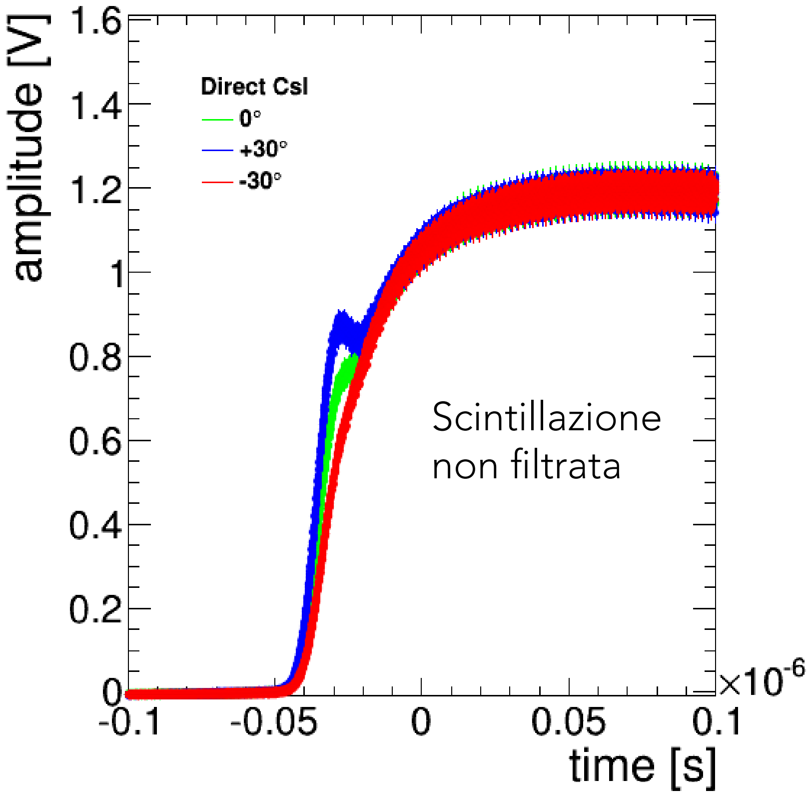
Esempio: CsI(Tl)

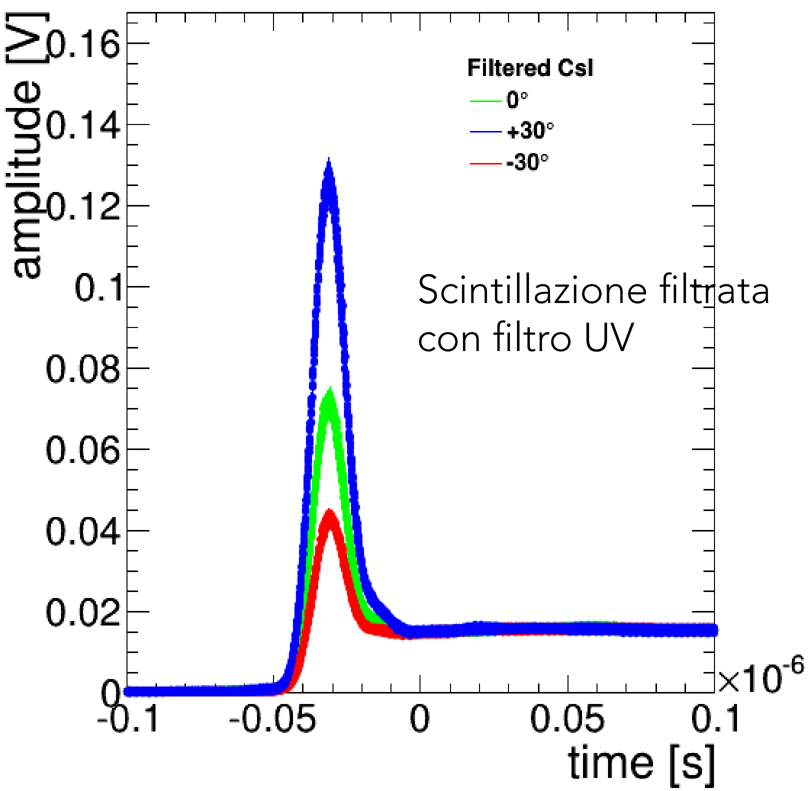
- Radiazione Cherenkov e scintillazione in CsI(Tl)
- Simulando una MIP in 4 cm di CsI(Tl)
- Confronto tra spettri di scintillazione e Cherenkov rivelati da
  - un rivelatore SiC
  - un fototubo ottimizzato per UV
- Sovrapposizione tra gli spettri di assorbimento della radiazione Cherenkov e della scintillazione estremamente ridotta rispetto al fototubo



Cherenkov and scintillation

- Test beam measurement of 50 MeV electrons on a CsI(Tl cube)
- Cherenkov light only evident with a dedicated UV filter
  - A SiC based detector would naturally be insensitive to scintillation light





APD Campbell

- IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 43, NO. 12, DECEMBER 2007
- IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 45, NO. 3, MARCH 2009

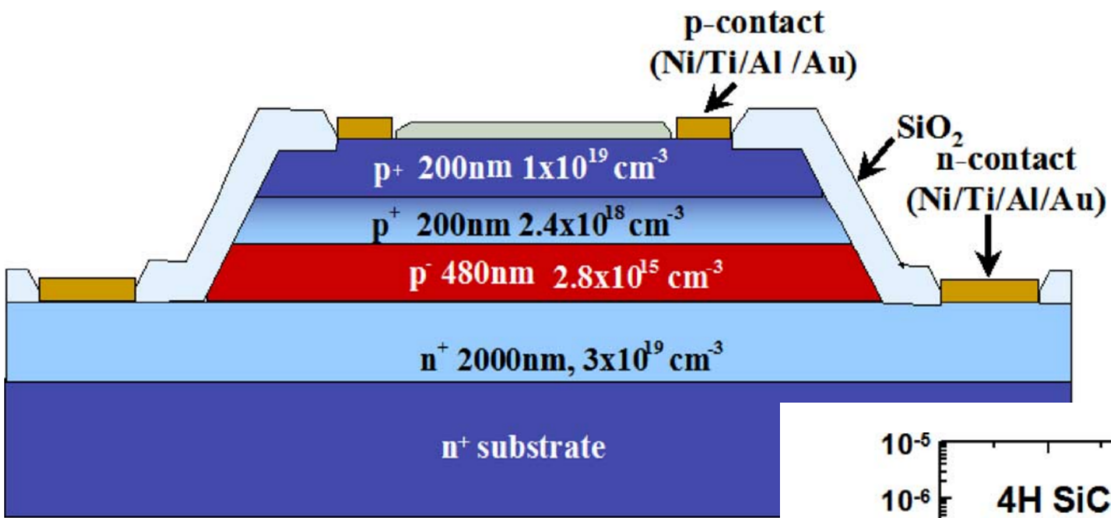
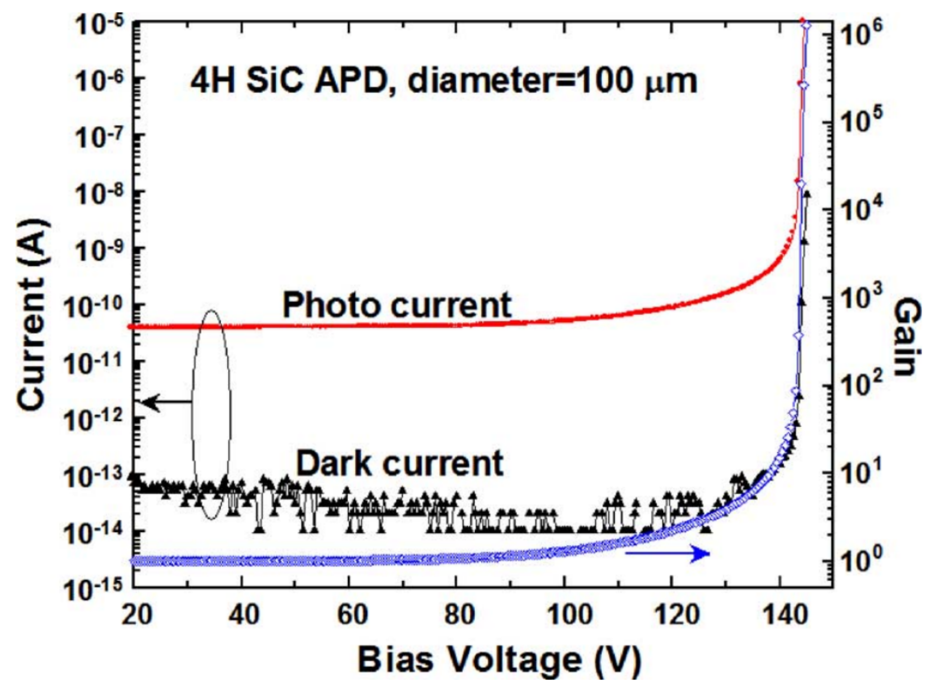


Fig. 1. Schematic cross section of 4H-SiC APDs.



APD SAM (separate absorption and multiplication)

8 H. Zhu et al. / Solid-State Electronics 53 (2009) 7–10

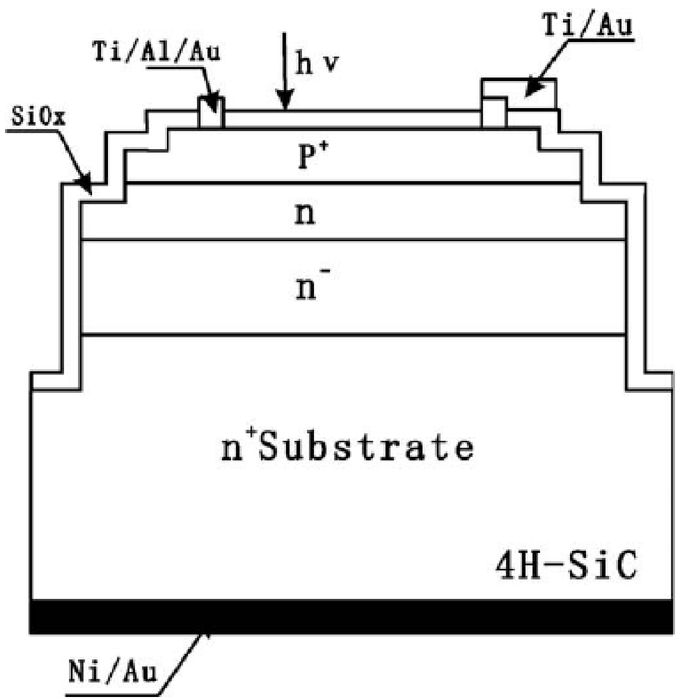


Fig. 1. Schematic cross-section of the 4H–SiC SAM-APD.

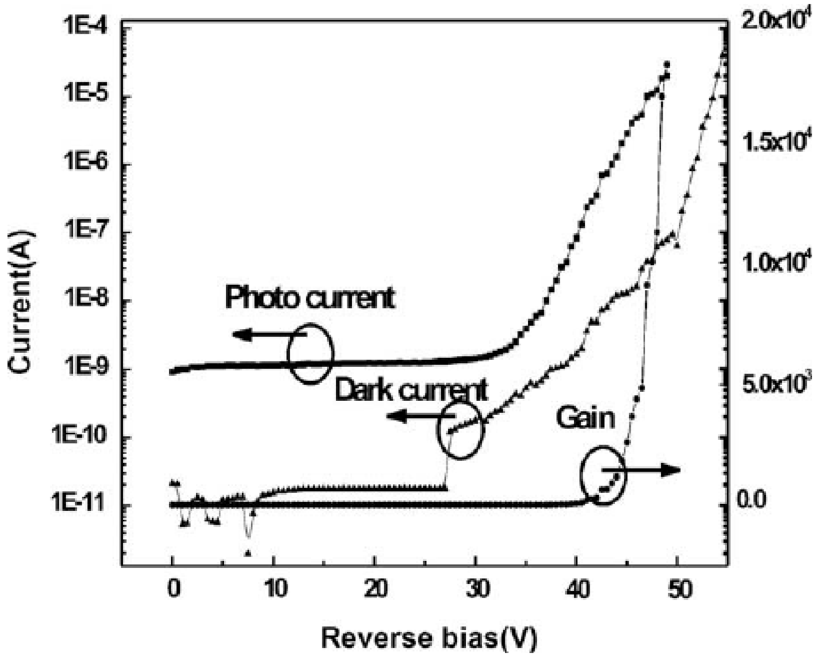


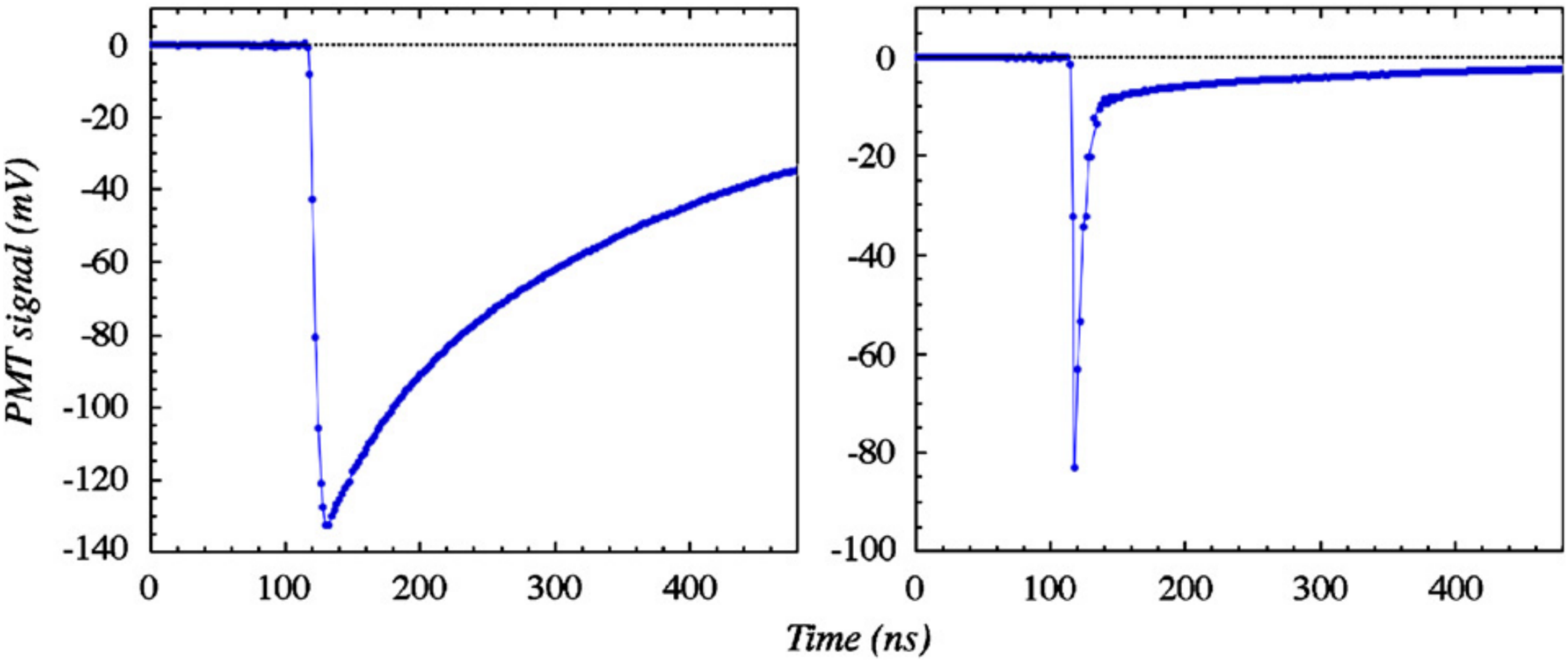
Fig. 2. *I–V* characteristics and gain of 4H–SiC APD.

DREAM

Discriminazione segnali

Con filtro giallo
Scintillazione

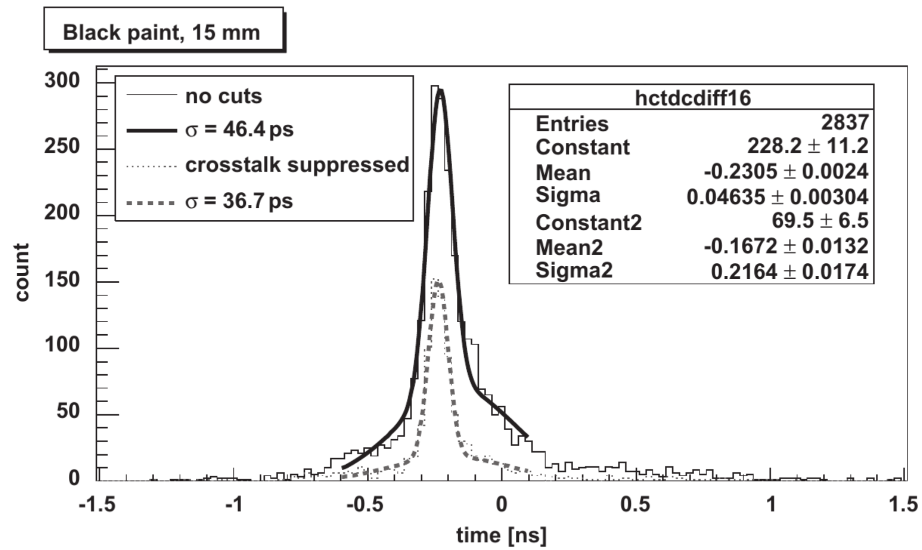
Con filtro UV
Cherenkov+ coda scintillazione



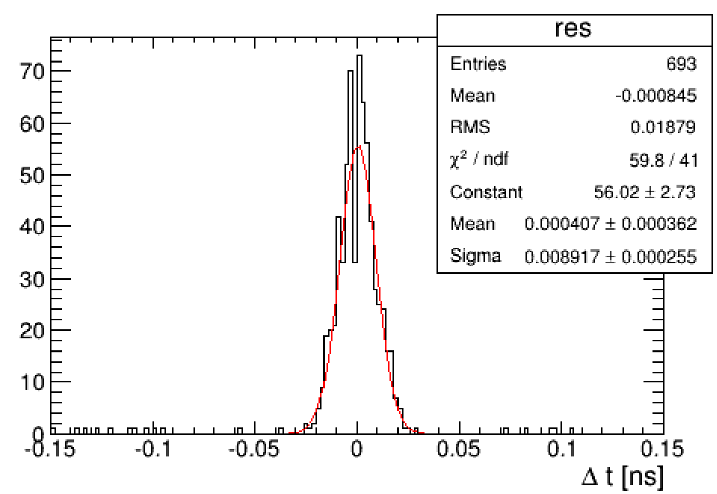
Applicazione TOF-PET

- Risoluzione in tempo di TOF-PET limitata dai tempi del processo di scintillazione
  - Miglioramento se si rivelano i fotoni Cherenkov emessi dagli elettroni prodotti per effetto fotoelettrico
  - 36.7 ps da test in letteratura con MCP
- Un rivelatore basato su SiC in grado di rivelare il singolo fotone permetterebbe di:
  - Migliorare efficienza di rivelazione rispetto a MCP
    - Migliore matching con lo spettro Cherenkov
  - Migliorare la separazione rispetto alla scintillazione

In letteratura, usando MCP



Dalla nostra simulazione di LuAG (Ce)
Trascurando la risoluzione del fotorivelatore



Altro sul SiC

RESMDD06, Florence, 10-13 October 2006

SiC properties

Wide Bandgap

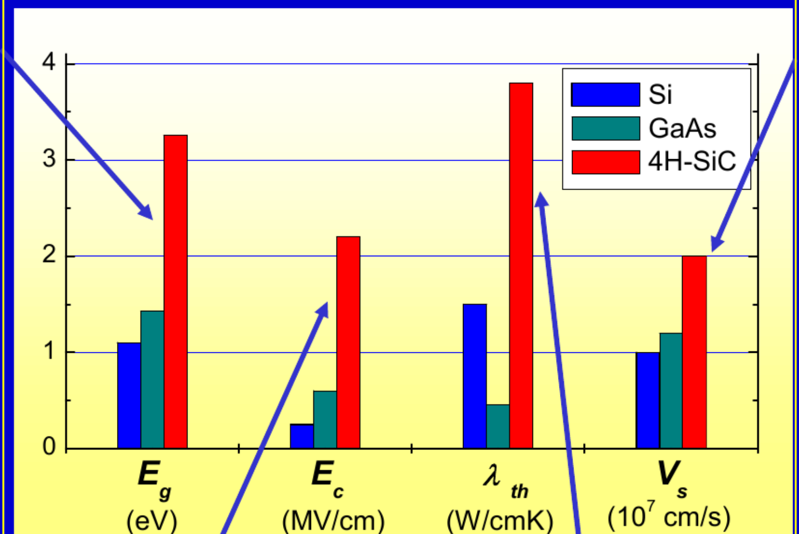
E_G=3.2 eV

⇩

Low thermally generated currents

⇩

Room temperature operation



High saturation velocity

v_S = 200 µm/ns

⇩

High frequency/speed devices

⇩

Short transit time

Low trapping probability

High Critical Field

E_C = 2 MV/cm

⇩

High Voltage devices

High thermal conductivity

⇩

High Power devices

3

Diamante-SiC

- SiC esiste in forma cristallina da più tempo dei diamante
- Materiale più maturo, proprietà ottiche migliori del diamante policristallino

PROPERTY	Si	GaAs	4H-SiC	Diamond
Z	14	31/33	14/6	6
Density (g/cm^3)	2.33	5.32	3.2	3.5
Band Gap (eV)	1.12	1.43	3.3	5.5
Room Temperature μ_e / μ_h	1350/480	8500/400	800/115	1800/1200
Max electric field (10^5 V/cm)	3	4	40	100
Saturation drift velocity of electrons (10^7 cm/s)	0.8	0.8	2.0	2.2
Average energy for e-h pair (eV)	3.62	4.21	7.8	13-17
e-h pairs/μm for MIPs	9000	13000	5100	3600
Thermal conductivity (W/cm·K)	1.5	0.5	4.9	20
Dielectric constant	11.9	13.1	9.7	5.7
Mono-crystalline	yes	yes	yes	yes
Minimum energy for defect creation (eV)	12.8	9	25	43

GOOD

BAD

(2005)

Involvement

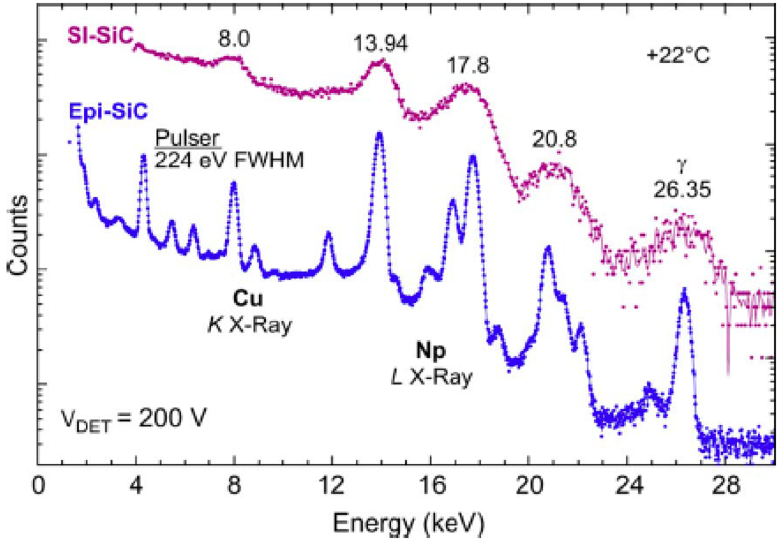
- CLASSIC:
  - Firenze
    - Lenzi, Adriani, Starodubtsev
  - Catania & CNR-IMM
    - Albergo, Falci, Sciuto (CNR-IMM & INFN)

Involvement

- SICILIA
  - LNS
  - Catania-Messina
  - Bicocca
  - Milano
  - Firenze
  - Trento
  - Pisa

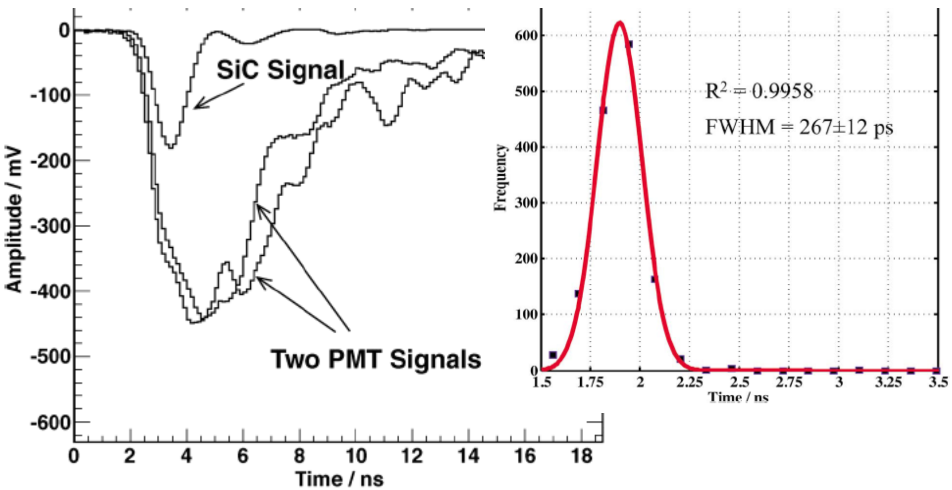
SiC performance

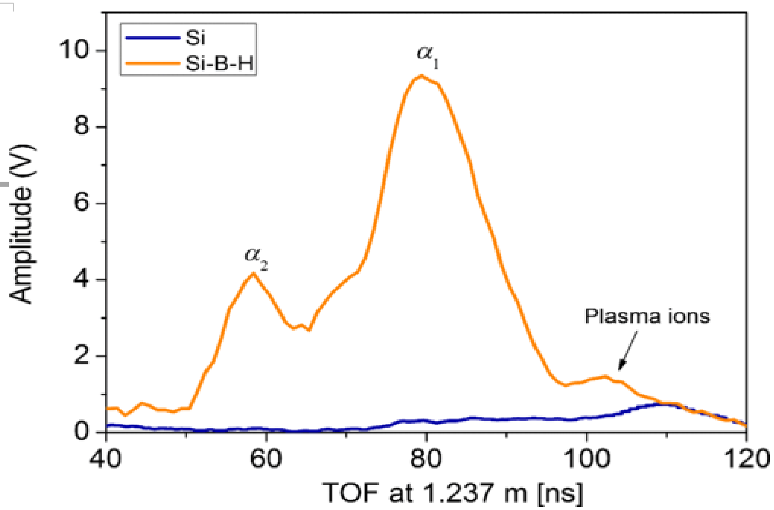
- ✓ Low leakage current → high energy resolution → X-rays detection
- ✓ Timing → sub-nanoseconds → ToF application
- ✓ Insensible to visible light → neutrons and charged particles detection in plasmas



G. Bertuccio et al. IEEE Trans. Nucl. Scie. 60, NO. 2, APRIL 2013

Xiaodong Zhang IEEE Trans. Nucl. Scie. VOL. 60, NO. 3, JUNE 2



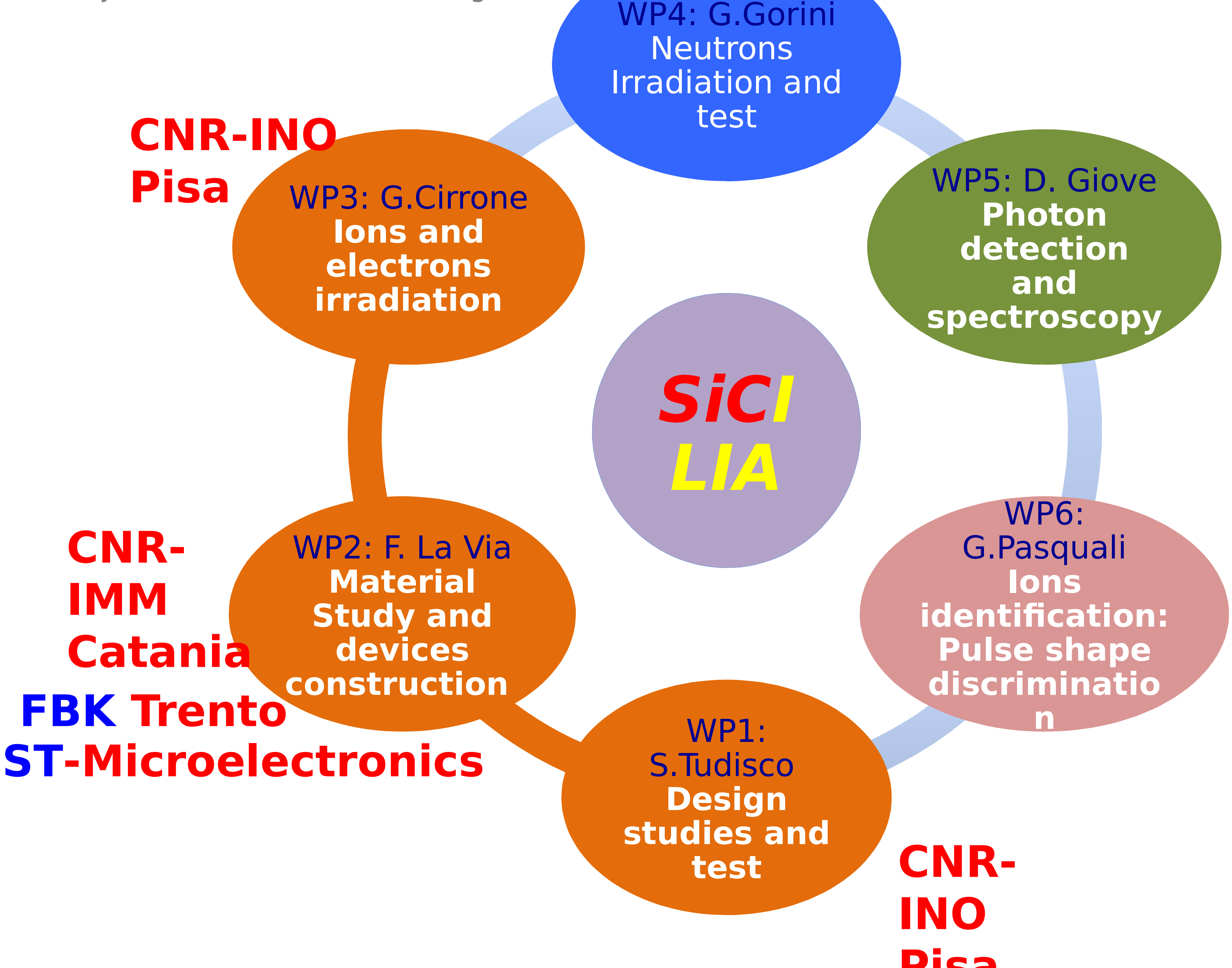


A. Picciotto et al. Phys. Rev. X 4, 031030 (2014)

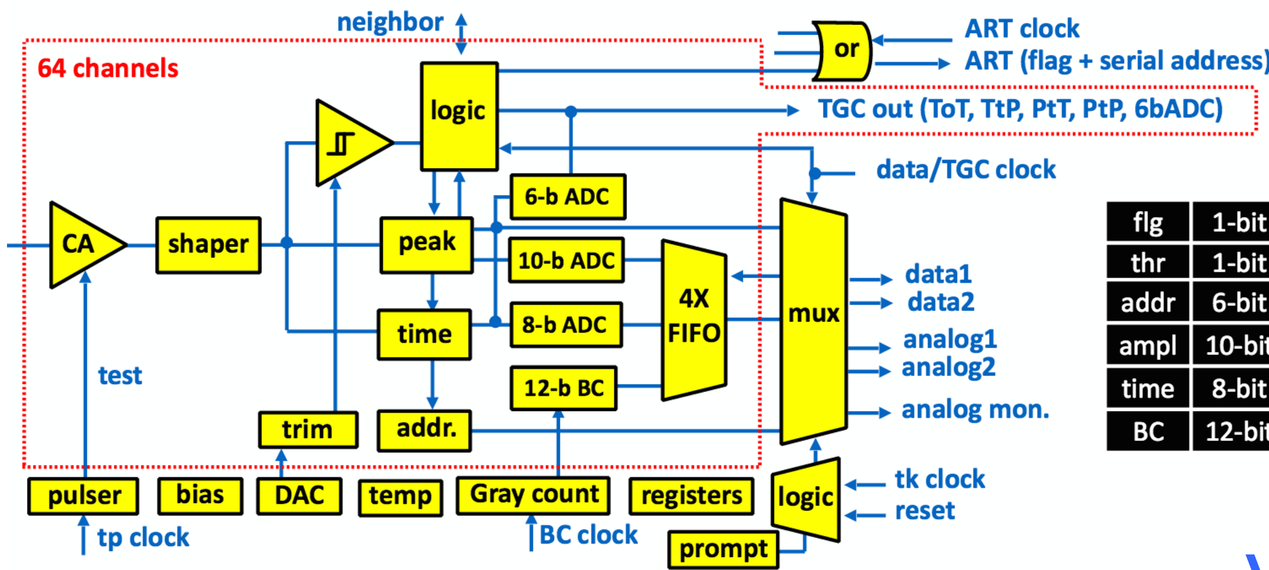
TOF distribution measured by the SiC detector for the Si-H-B (orange curve) and Si (blue curve) targets

Work packages organization

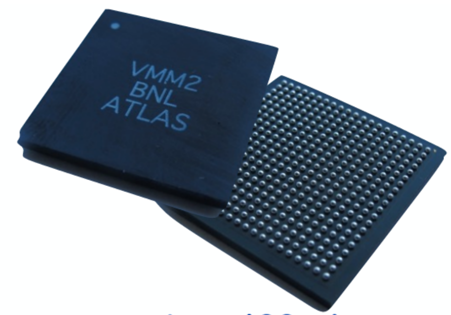
WP1 – Project coordinator and management



SiC Wall



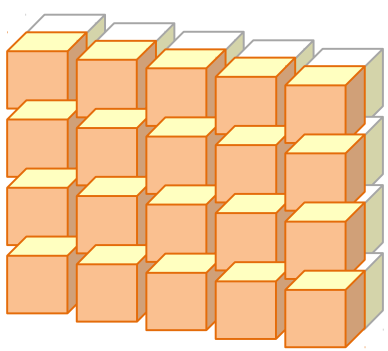
flg	1-bit
thr	1-bit
addr	6-bit
ampl	10-bit
time	8-bit
BC	12-bit



custom 400-pin

21 x 21 mm² BGA

VMM2



SiC Wall