Terzo Incontro Nazionale di Fisica Nucleare

INFN2016

Silicon Carbide for Nuclear Physics applications

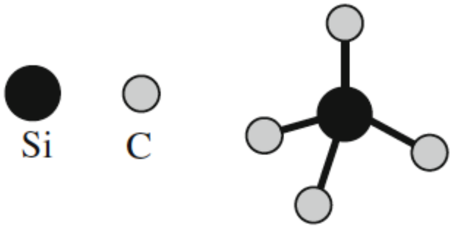
Salvo Tudisco

14-16 Novembre 2016 *Laboratori Nazionali di Frascati*

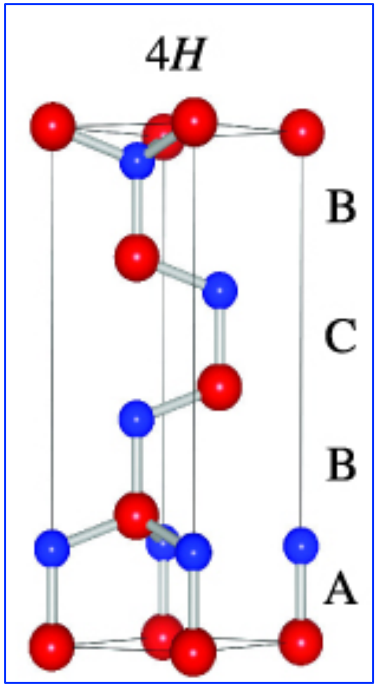
Silicon Carbide Material

Was discovered in 1824 by **Jons Berzelius (**Swedish scientist) in the same year when he also discovered elemental Silicon.

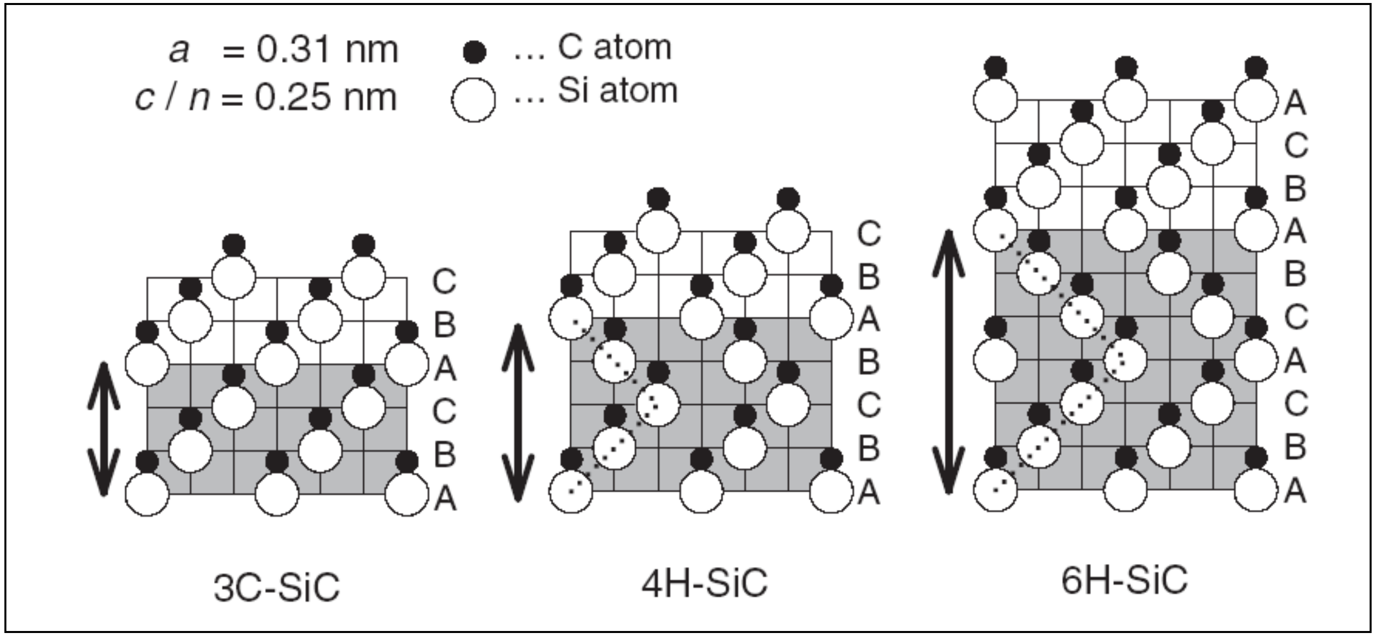
Tetrahedra of Carbon and Silicon atoms with strong bonds in the crystal lattice. **Very hard and strong material**!



strong bonds !

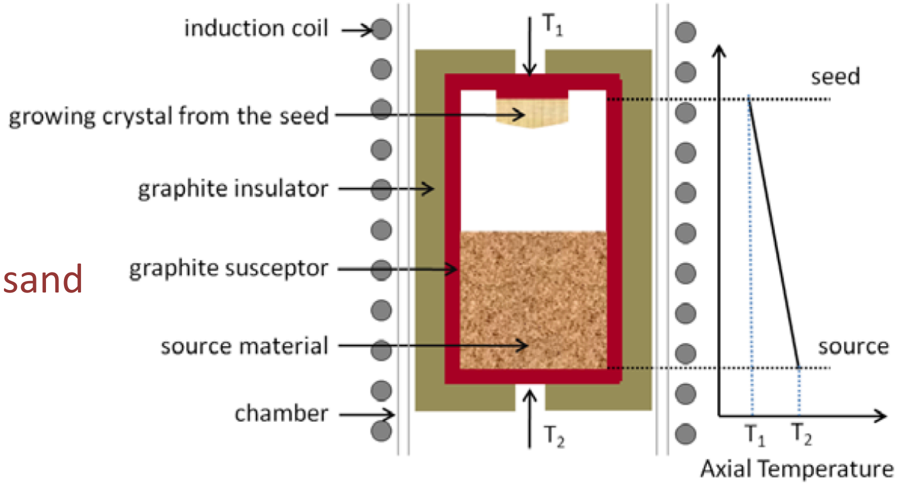


Lattice structure



SiC - Polytypism

Unlike of Si, **SiC** does not show a liquid phase,
The only way to synthesize, purify and grow SiC raw material is by means of gaseous phases



SiC Growth

high temperature electro-chemical reaction reducing sand (SiO_2) in presence of excess carbon (Acheson in 1891).

General Properties of SiC

- **high thermal conductivity**
- **low thermal expansion**
- **high strength (hardness)**
- **chemical inertness**

⇨ **Exceptional thermal shock resistant qualities**

SiC wide-band-gap semiconductor

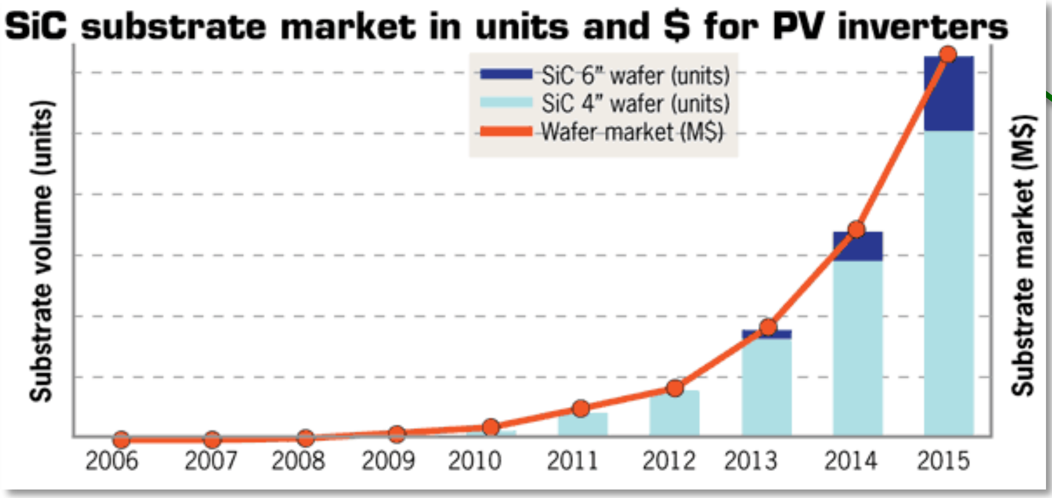
Energy gap => E_{SiC}=3.28 eV > E_{si}=1.12 eV
Breakdown Field => BF_{SiC}=3-4 MV/cm > BF_{si}=0.3 MV/cm
Saturated electron velocity => $v_{SiC} > v_{Si}$

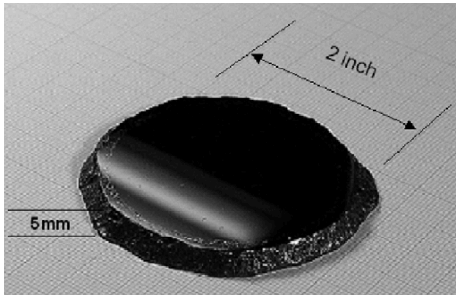
Applications on ELECTRONIS DEVICES

- High power
- High frequency
- High temperature
- Radiation detectors

BULK GROWTH

Challenge in the growth of bulk SIC is the possibility to grow large single crystals in high quantities

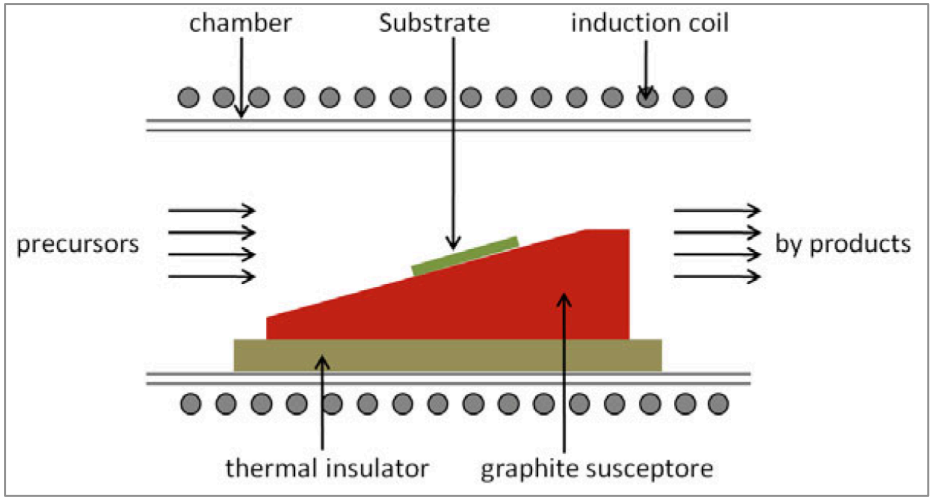




extended material defects
(**micro-pipes**, **dislocations**, etc.)

EPITAXIAL GROWTH

Bulk wafers are mainly used as a substrate to support the **Epitaxially** grown active layers.



Epitaxy allows a precise control of:
layer thickness, doping and homogeneity, imperfections

Dopants are provided by gaseous precursors
n-type by N or P and **p**-type by Be, B, Al, or Ga

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Defects in Silicon Carbide

Macroscopic defects

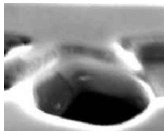
- polytype inclusions
- micropipes
- comets, carrots

Microscopic defects

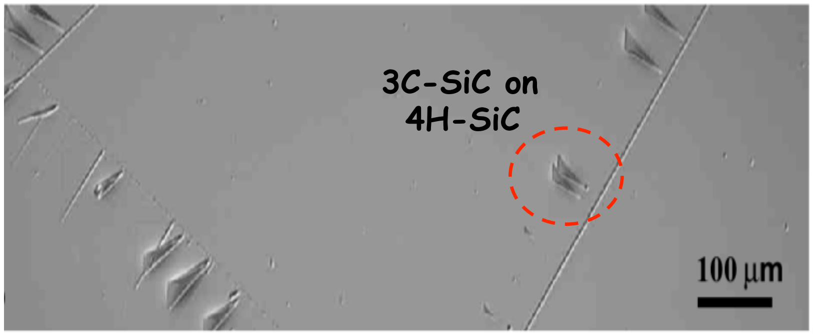
- dislocations
- stacking faults
- interstitial, vacancies
- divacancies, antisites

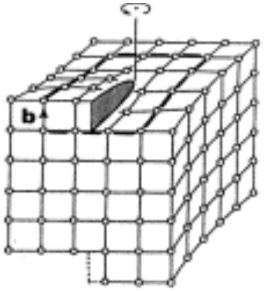
Extended defects

Micro-pipe

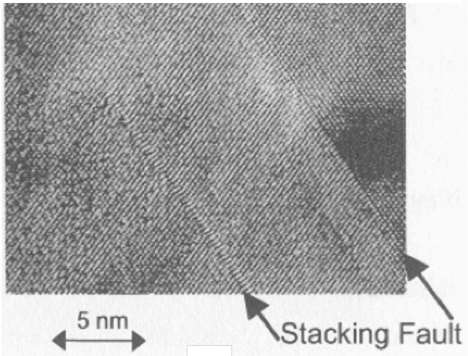


polytype inclusions

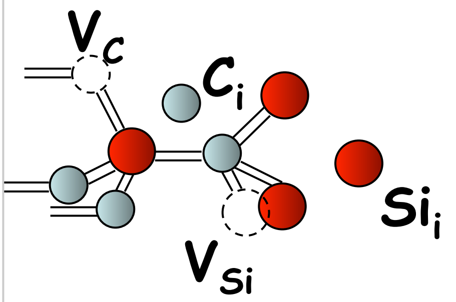




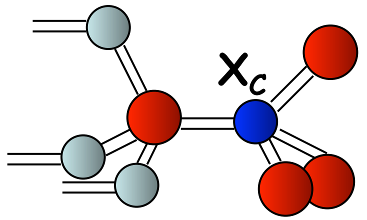
dislocations



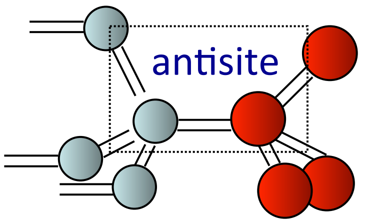
Point and Point-like defects



Vacancies and interstitials



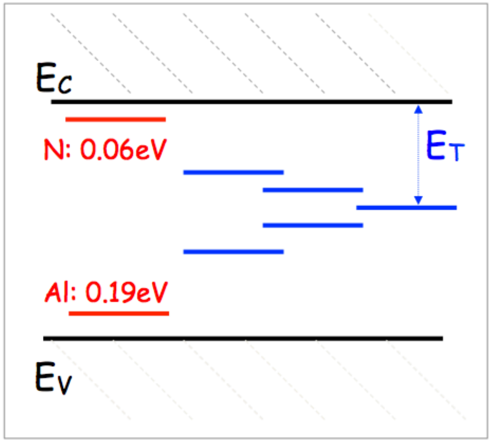
Substitional impurity



Donor & Acceptor Impurities

Deep levels in the gap =>

Defect-Levels



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SiC for radiation detection

Property	Diamond	GaN	4H SiC	Si
E_g [eV]	**5.5**	**3.39**	**3.28**	**1.12**
$E_{breakdown}$ [V/cm]	10^7	$4 \cdot 10^6$	$3\text{-}4 \cdot 10^6$	$3 \cdot 10^5$
μ_e [cm^2/Vs]	1800	1000	800	1450
μ_h [cm^2/Vs]	1200	30	115	450
v_{sat} [cm/s]	$2.2 \cdot 10^7$	-	$2 \cdot 10^7$	$0.8 \cdot 10^7$
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**	**30-40**	**13-15**

- Wide band-gap (3.3eV)

⇒ Visible blind

⇒ Lower Leakage current

- High Breakdown

⇒ Advantage for Radiations hardness

- Different e-h mobility

⇒ Charge Identification pulse shape analysis

- Fast devices

⇒ Timing applications

- Signal

⇒ Less charge than Si, SiC≈Si/2

⇒ A problem for MIP!

Diamond	36 e/µm
SiC	51 e/µm
Si	89 e/µm

⇒ No problem in all other case

- Higher displacement threshold

⇒ Radiation harder then Silicon

Applications

- UV - Soft-X detection
- Charged Particle detection and identification
- Neutron detection

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Radiation Hardness

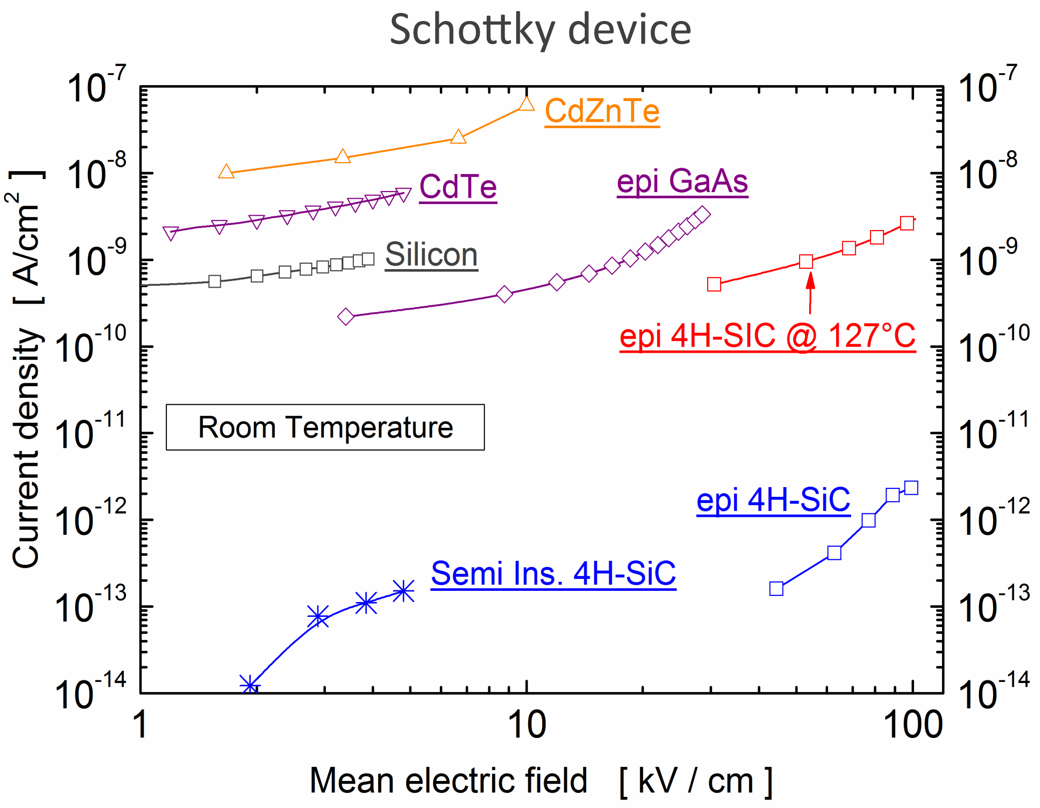
- Lower Leakage current

p-n => $J_L = J_{diff} + \boxed{J_{gen}}$

Schottky => $J_L = J_S + \boxed{J_{gen}}$

$J_{gen} \approx N_t \, (V_{bi}+V)^{1/2}$

N_t = traps density
V_{bi} = internal potential
V = external bias


Schottky device

$$\boxed{J_S \approx A^{**}T^2 \exp\left(-q(\Phi_B+\Delta\Phi_B)/KT\right)}$$

$\Delta\Phi_B = (qE_m/4\pi\varepsilon)^{1/2}$
=> $E_m = (2qN_D/\varepsilon * (V+V_{bi}-KT/q))$

T= temperature
Φ=Schottky potential
E_m=max electric field

$$\boxed{J_{L}^{(SiC)} \approx 10^{-3} J_{L}^{(Si)}}$$

$$\boxed{J_{diff} \approx T^{(3+\gamma/2)} \exp\left(-E_g/KT\right)}$$

E_g=energy gap
N_D=doping concentration

$$\boxed{J_{L}^{(SiC)} \approx 10^{-4} - 10^{-5} J_{L}^{(Si)}}$$

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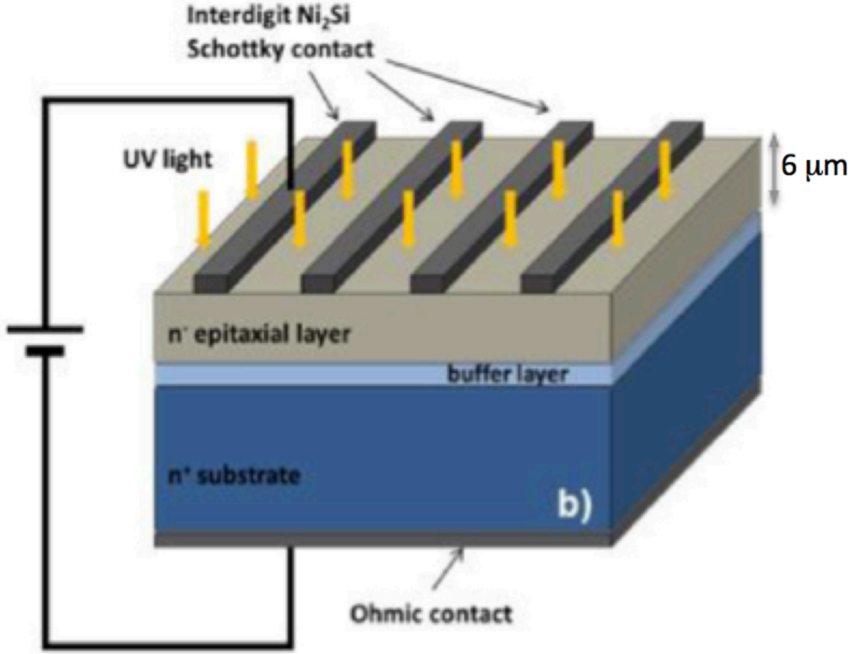
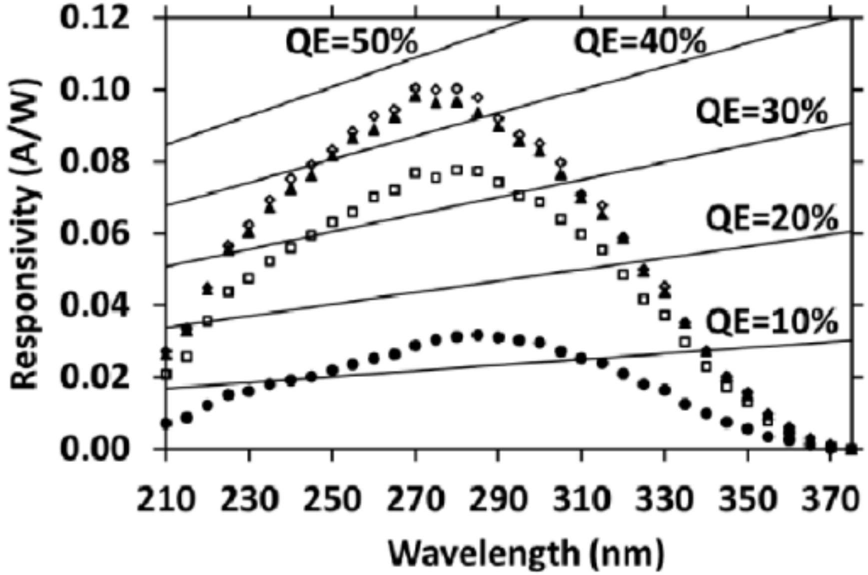
SiC detector: state-of-Art

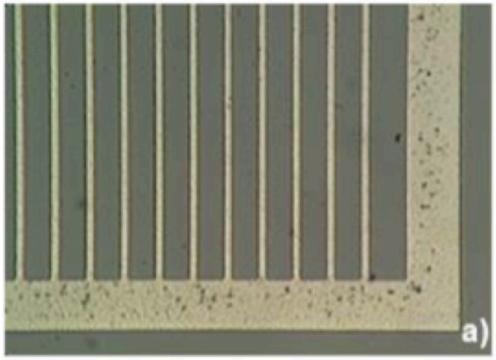
- Schottky junctions
- Small size devices (2-3 mm^2)
- Thin Epi-layers (60-80 μm)



SiC Visible-blindness!

UV photo-detector applications



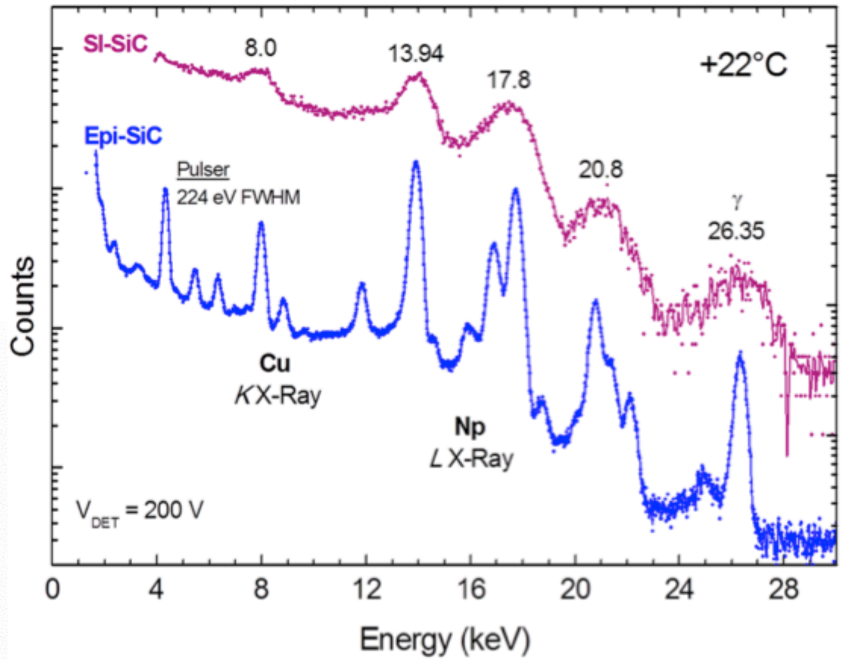


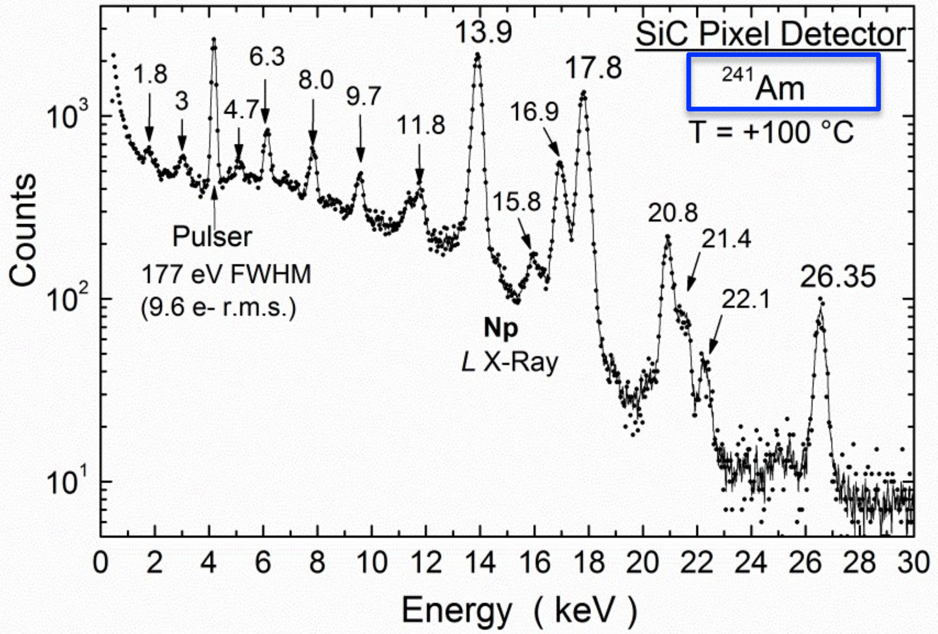
Optics Express Vol. 23, Issue 17, pp. 21657-21670 (2015)

SiC detector: state-of-Art

- ⇒ Lowest dark current
- ⇒ Efficient transport of charge
- ⇒ Fast response
- ⇒ high purity and low defectivity
  (minimize charge trapping or recombination)

X-ray photo-detection and spectroscopy

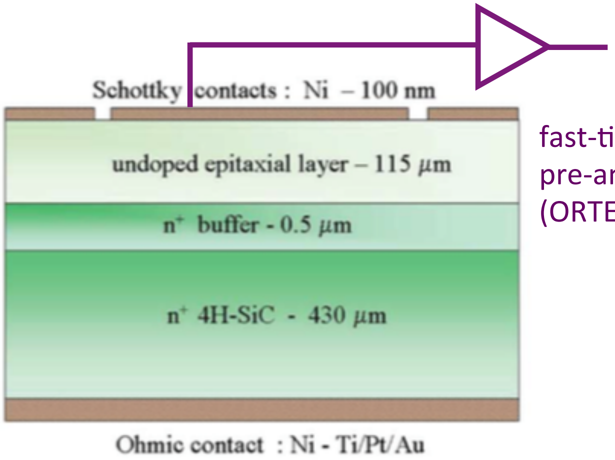




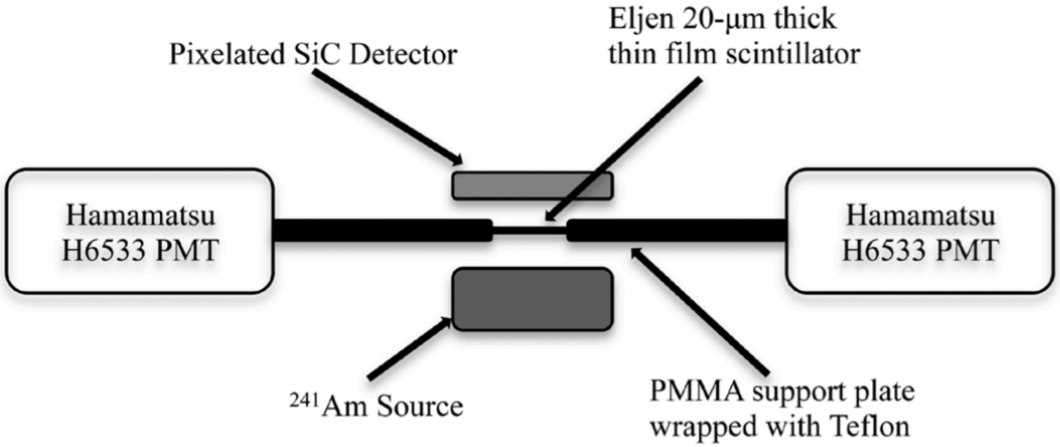
G. Bertuccio et al. NIM A 652 (2011) 193–196
G. Bertuccio et al IEEE Trans. on Nucl.. Sci. 60 n° 2 (2013) 1436–1441

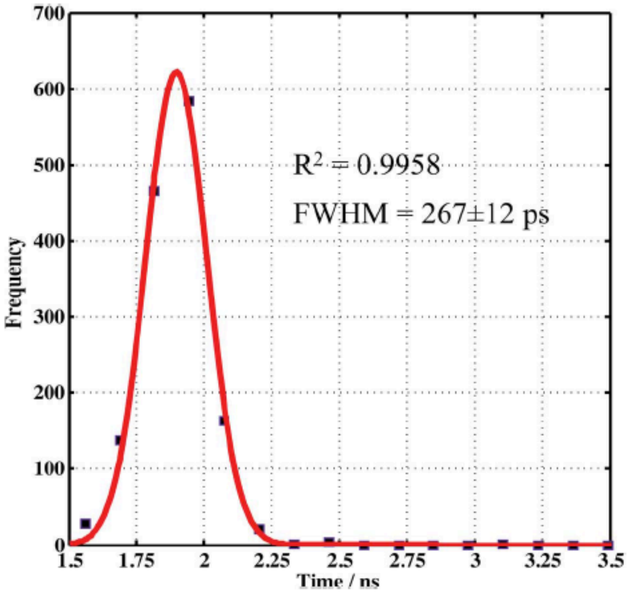
SiC detector: state-of-Art

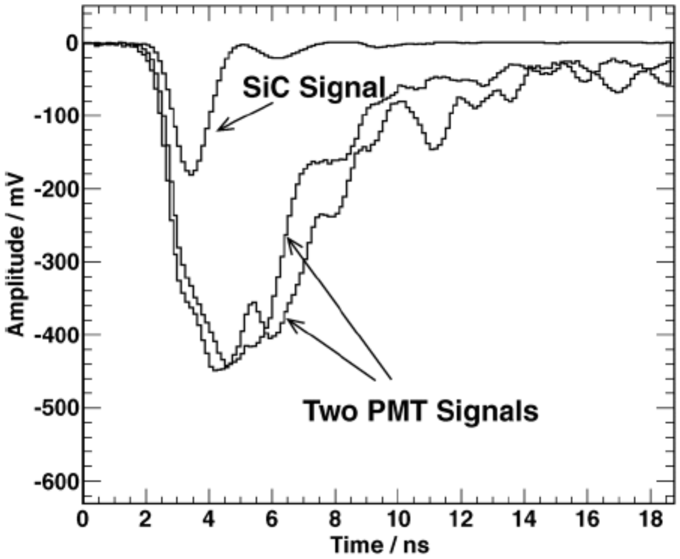
- ✓ Timing



fast-timing pre-amplifier (ORTEC VT120B)





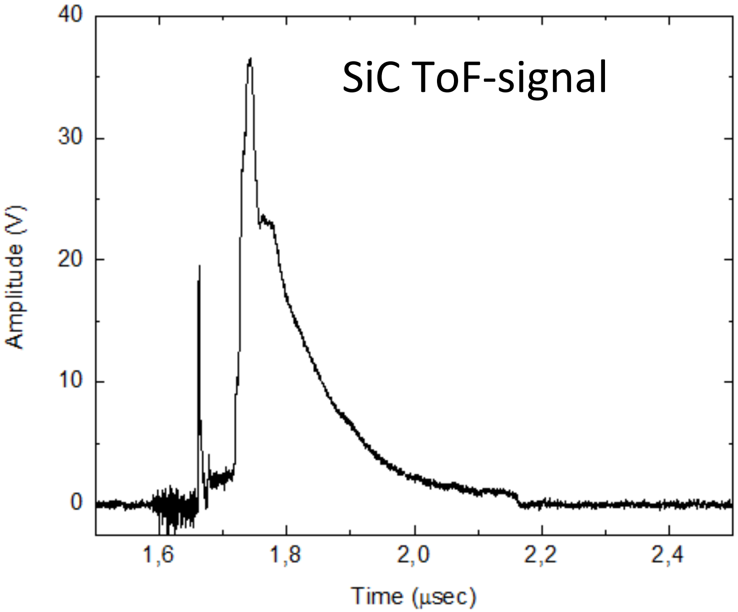


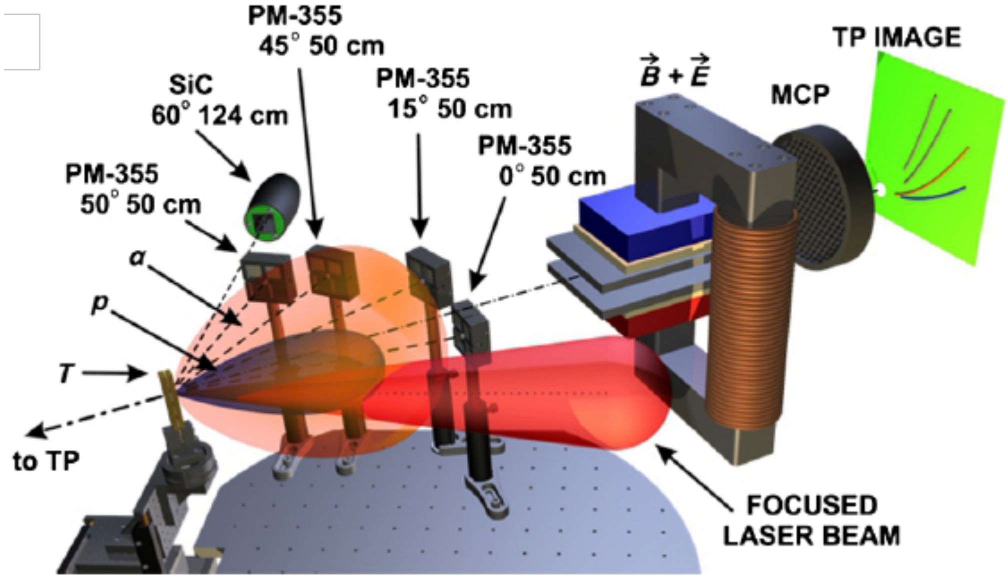
Snapshot of signals obtained from the SiC detector and the two PMTs.

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

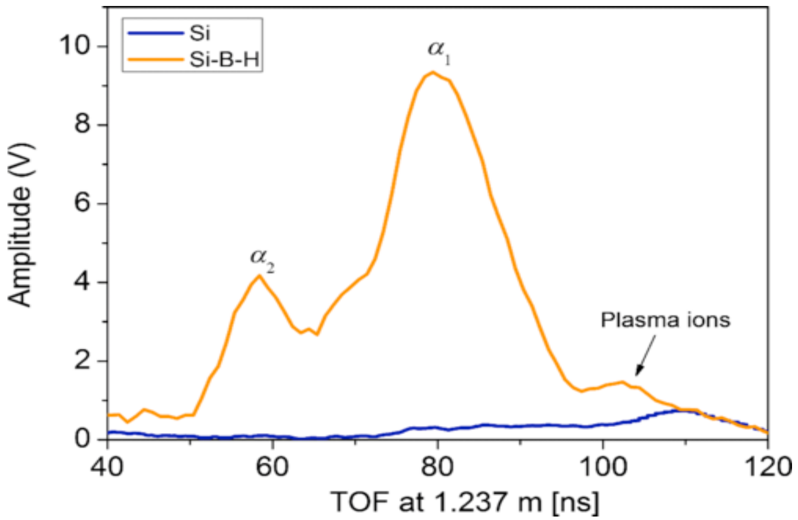
SiC detector: state-of-Art

- ✓ neutrons and charged particles detection in plasmas





$^{11}B + p \rightarrow 3\alpha + 8.7$ MeV



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

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

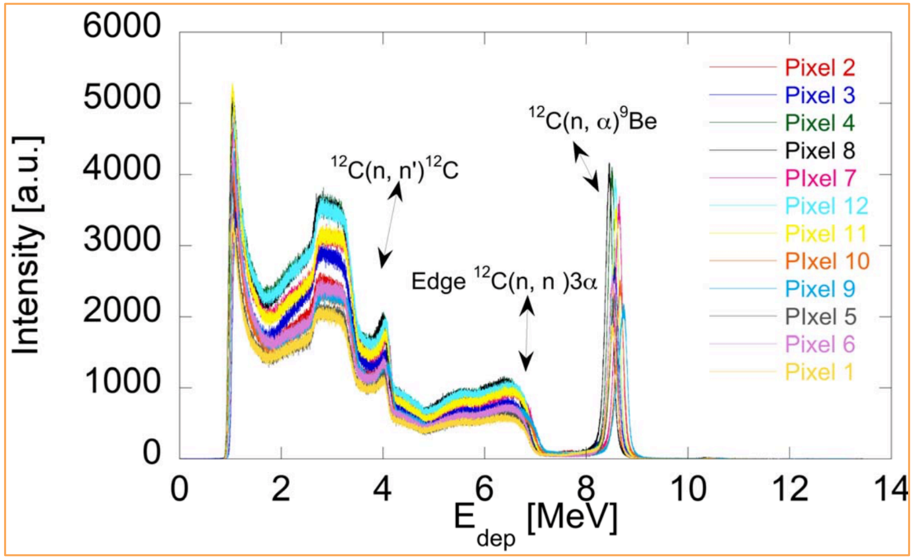
SiC detector: state-of-Art

- ✓ Neutron detection →
  - Fusion application (14 MeV DT neutrons)
  - Neutron flux and fluence measurements (Spallation Source)

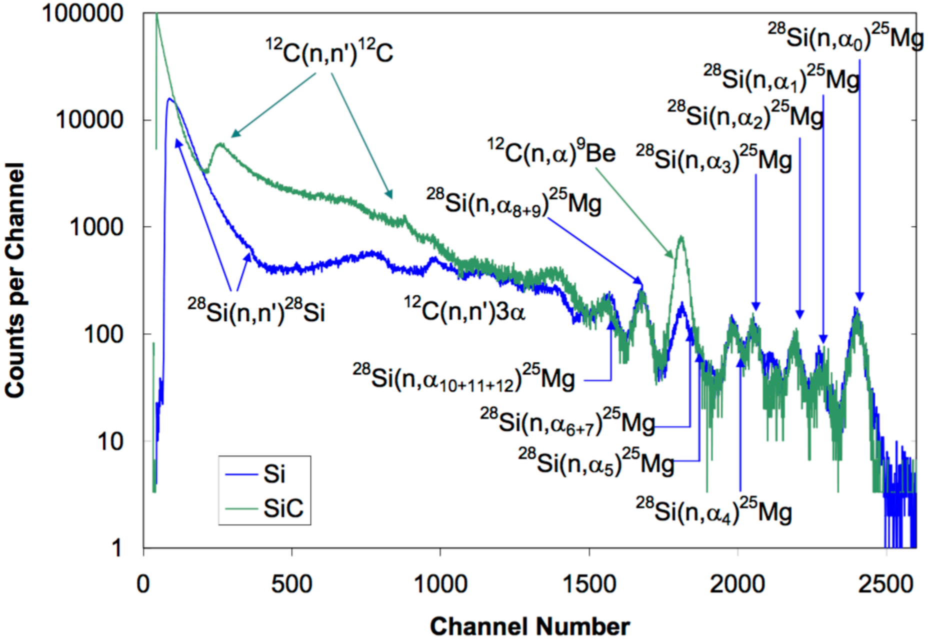
Single crystal diamond detectors →

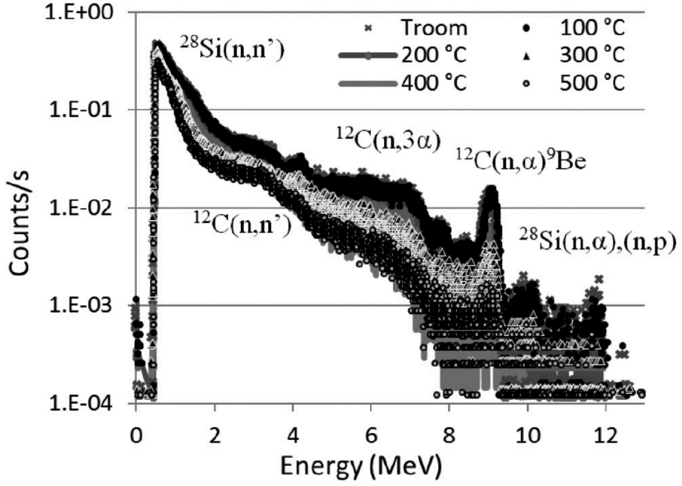
(R.H., low Leakage-Current, negligible T dependence)

Gain stability problem (Charge Trapping)!



14 MeV, 10^{10} n/s



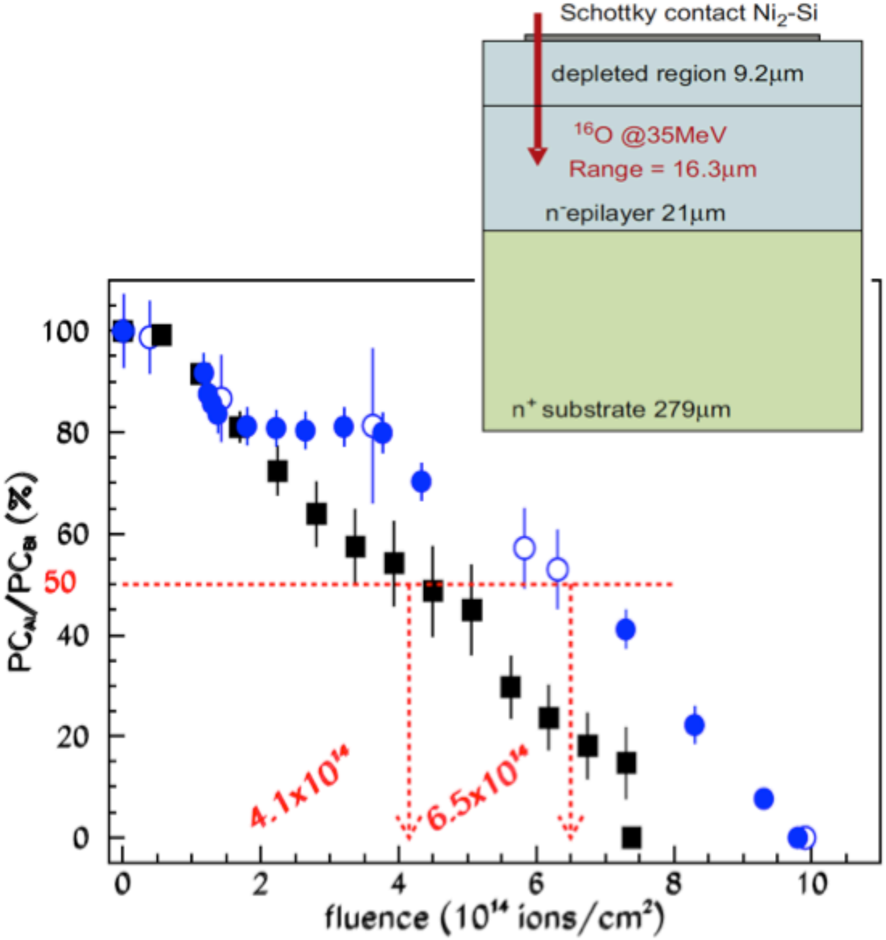


F. Franceschini and F. H. Ruddy, Properties and Applications of Silicon Carbide, InTech Book

D. Szalkai et al. IEEE TRANS. ON NUCL. SCIE., 63, NO. 3, (2016)

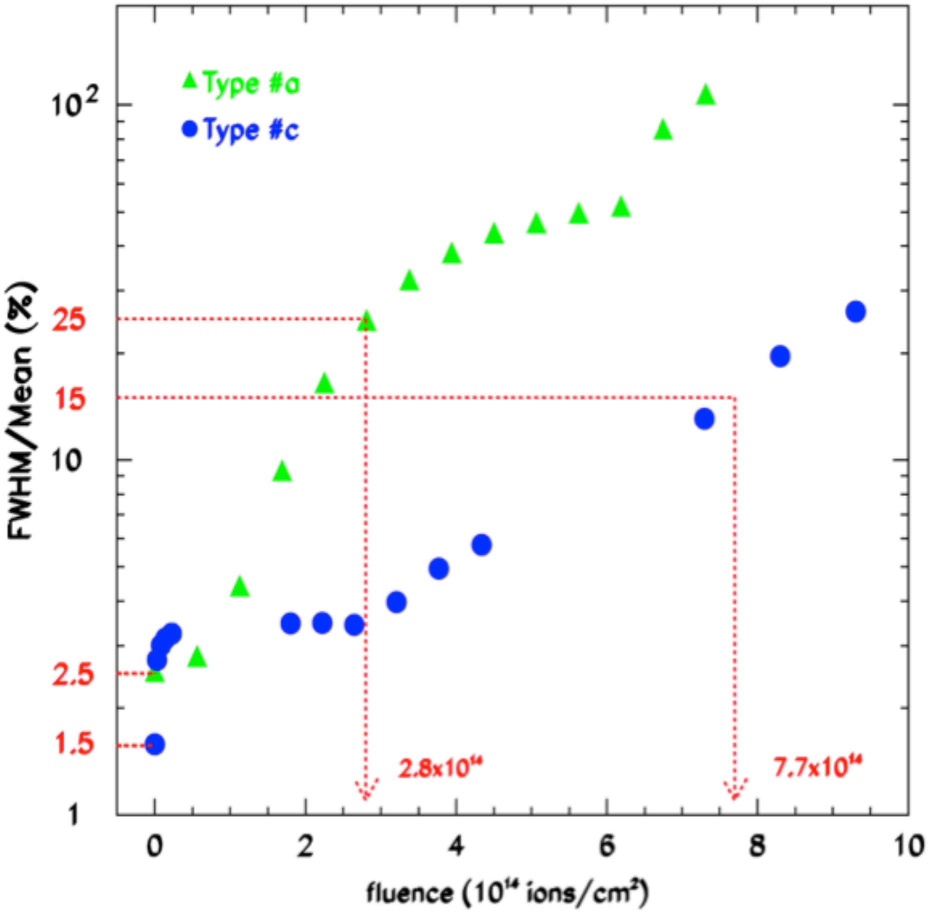
SiC detector: state-of-Art

✓ Radiation Hardeness



Ratio of peak centroid of ^{16}O energy spectrum after (PC_{Al}) and before irradiation (PC_{Bl})

^{16}O @ 35 MeV

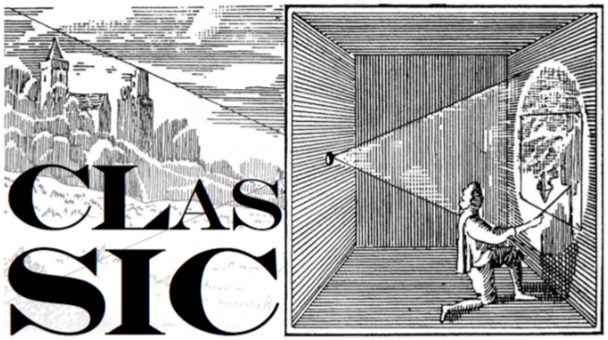


Relative Energy resolution

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

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

INFN Activities on SiC



Cherenkov **L**ight detection with **Si**licon **C**arbide

FIRB-INFN 2015

Silicon **C**arbide Detectors
for **I**ntense **L**uminosity **I**nvestigations and **A**pplications

Call INFN 2016

Aims at the development of a SiC based, visible-blind, avalanche photodiode

Single (or few) photon detection capability

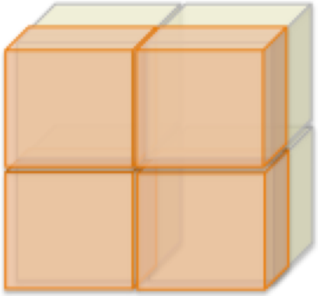
to detect Cherenkov light in the presence of visible radiation

(typically Cherenkov light produced in a scintillating crystal)

Two applications:

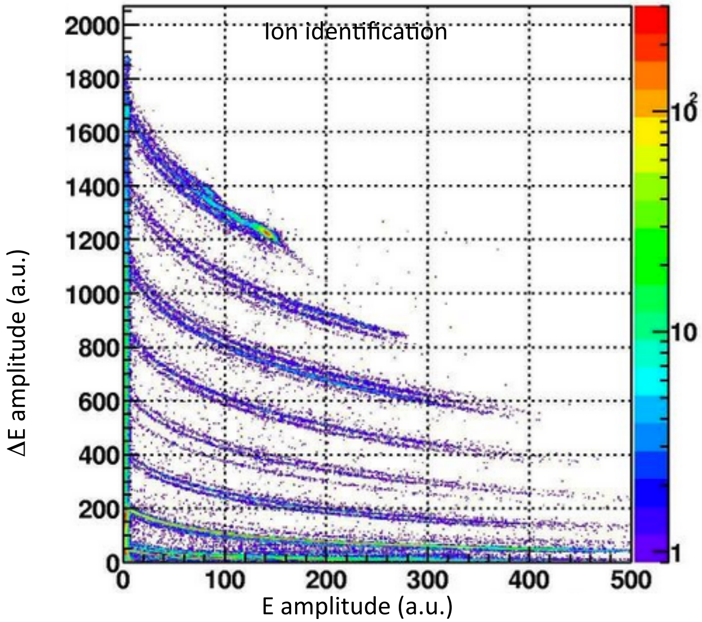
- Dual readout calorimetry (DREAM calorimetry concept)
- Fast timing in ToF-PET

Silicon **C**arbide Detectors for **I**ntense **L**uminosity **I**nvestigations and **A**pplications



SiC *ΔE-E* telescopes

- ✓ Active area 1 cm^2
- ✓ *ΔE* stage thickness ≥ 100 μm
- ✓ *E* stage thickness 500 ÷ 1000 μm



SiCILIA Strategy

Epitaxial growth SIC: beyond the state of the art (small number of defects)

New Tecnology

Schottky junctions → FONDAZIONE BRUNO KESSLER

p-n junctions → STMicroelectronics

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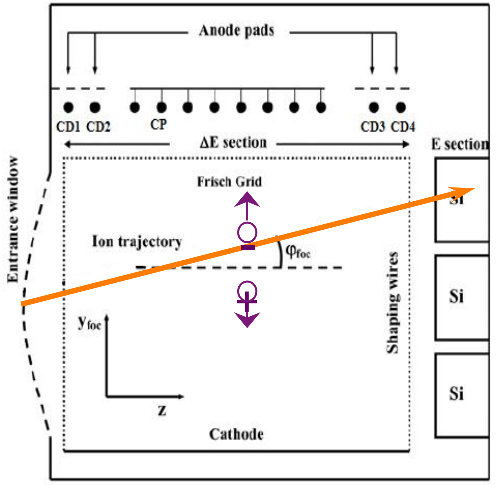
NUMEN project

NUclear **M**atrix **E**lements of **N**eutrinoless Double Beta Decays by Heavy Ion **D**ouble **C**harge **E**xchange Reactions

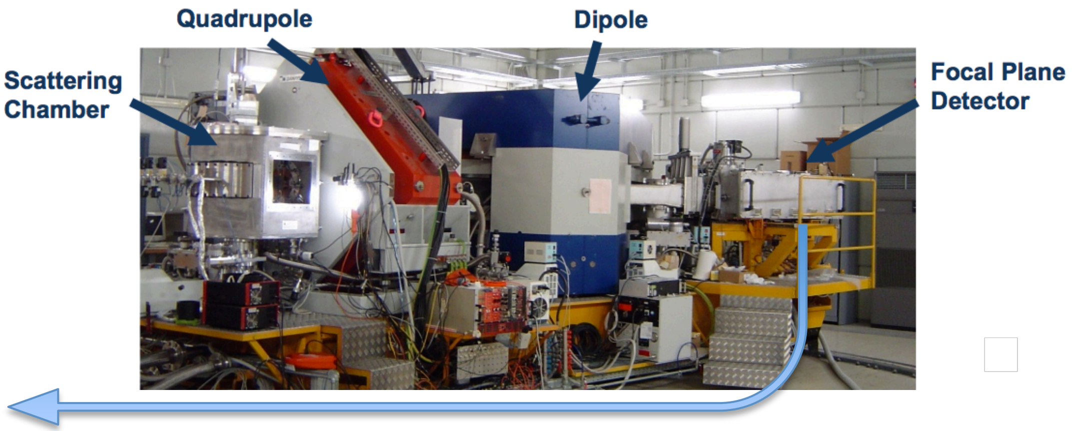
DCE => ^{12}C, ^{18}O, ^{20}Ne to energies between 15 and 30 MeV/u

MAGNEX

Multiwire gas tracker and ΔE stage

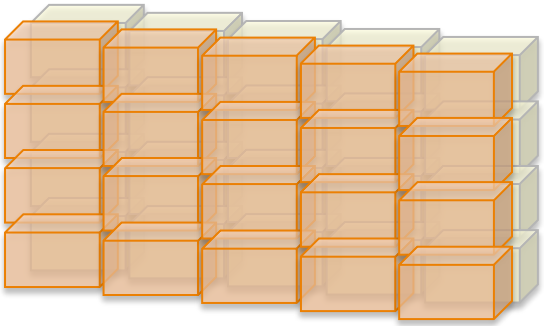


limited to 1 kHz



From Multiwire gas tracker → to GEM gas tracker

From 7 X 5 cm^2 silicon Wall → **to 1 cm^2 telescopes wall**



1 cm^2 *ΔE-E* telescope

R. H. → 10^{14} ions/cm^2 in ten years of activity

(Si detector dead @ 10^9 implanted ions/cm^2)

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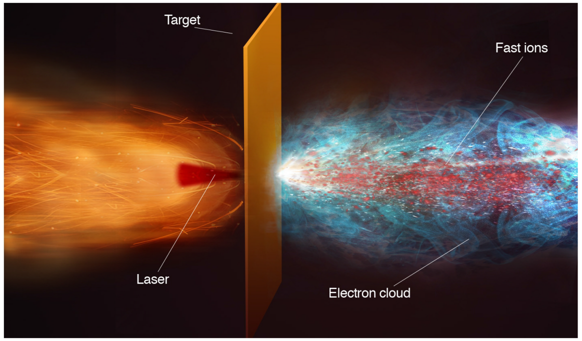
Applications

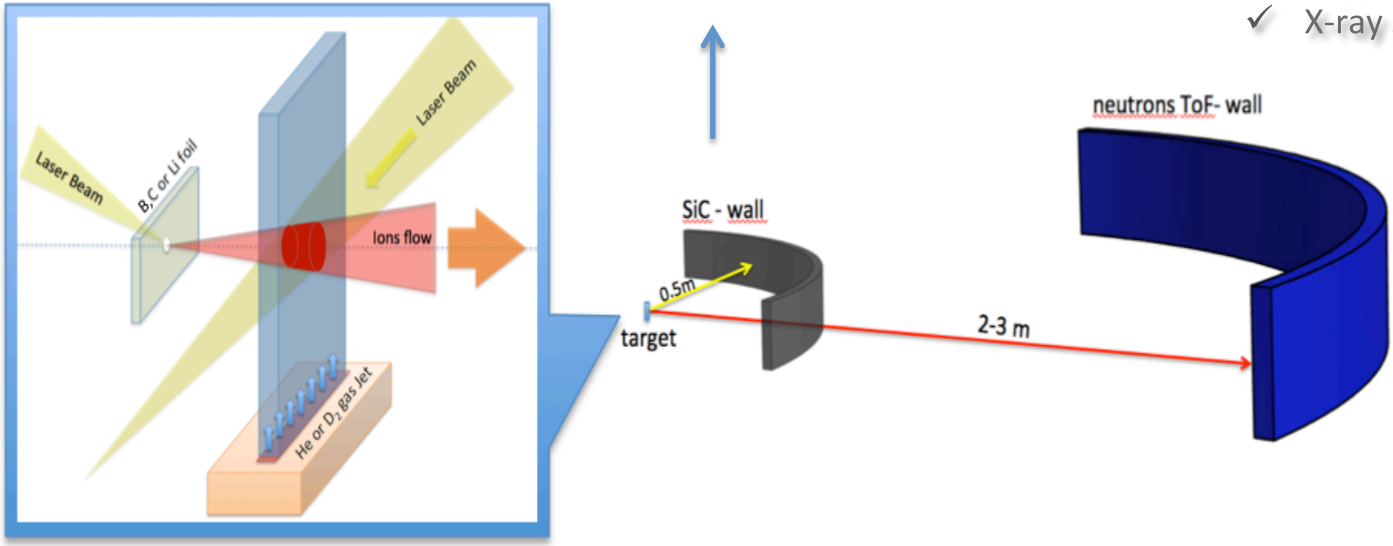
Nuclear Reactions in Laser Plasmas



Detectors working in plasmas environment =>

Requirements

- ✓ Radiation Hardness
- ✓ Timing
- ✓ Insensibility to the visible radiation
- ✓ X-ray sensitivity



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SiCILIA

Participating INFN research units

*INFN Laboratori Nazionali del Sud di Catania (**LNS**)*

*INFN Sezione di Catania and “Gruppo collegato di Messina” (**CT-ME**)*

*INFN Sezione di Milano Bicocca (**MI-B**)*

*INFN Sezione di Milano (**MI**)*

*INFN Sezione di Firenze (**FI**)*

*INFN Sezione TIFPA (**TN**)*

*INFN Sezione Pisa (**PI**)*

External institutions

CNR-IMM – Catania
CNR-INO – Pisa

Companies

Fondazione Bruno Kessler (**FBK**) – Trento
ST Microelectronics – Catania
LPE – Catania (**LPE**)

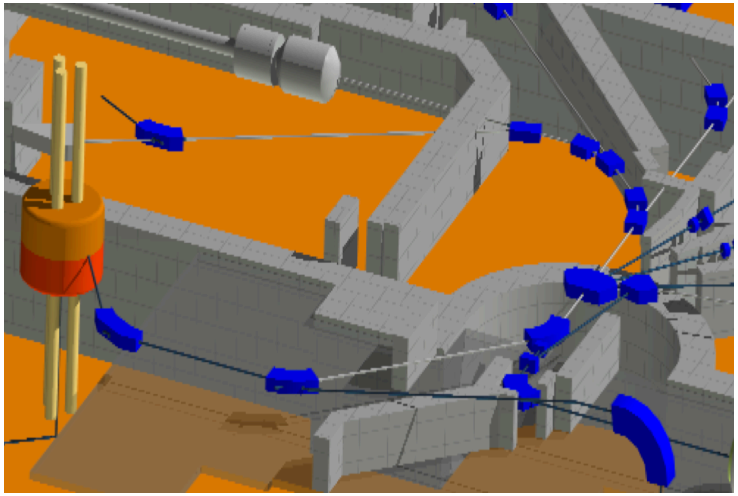
Global Deliverables

- Tens of detectors: epitaxial grow SiC (50-150 µm thick) semi-insulating SiC (500-1000 µm thick)
- Study of the performance in the electrons and ions detection (radiation hardness, energetic resolution, timing, etc.)
- Study of the performance in the neutrons and X-ray detection
- Study of the ions identification through the pules shape analysis
- A wall of tens of SiC telescopes equipped with a VMM ASIC front-end as demonstrator
- Performance of demonstrator in operative conditions

SiCILIA activities 2016

- ✓ **Epitaxial grows**
- ✓ **Simulations**
- ✓ **Flow chart** (p-n and Schottky junction)
- ✓ **Test bench** (electrical and physical characterization)
- ✓ **Irradiation beam-lines preparation** (INFN-LNS, UniMe, ILIL-Pi)

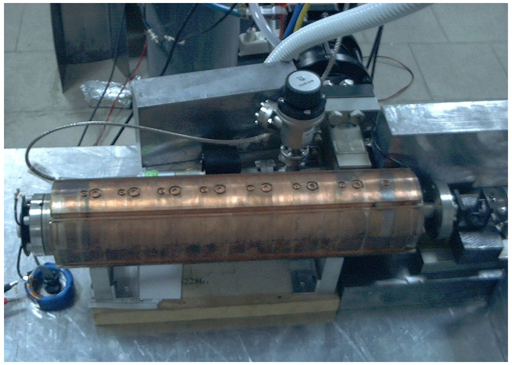
LNS Sample irradiation beam-line



* 0 degree beam-line

- Transported beams: p, He, C, O, Ne, Ar, Kr, Xe, …
- Fast and easy positioning systems
- In-air and in-vacuum irradiations

LINAC @ UniMe



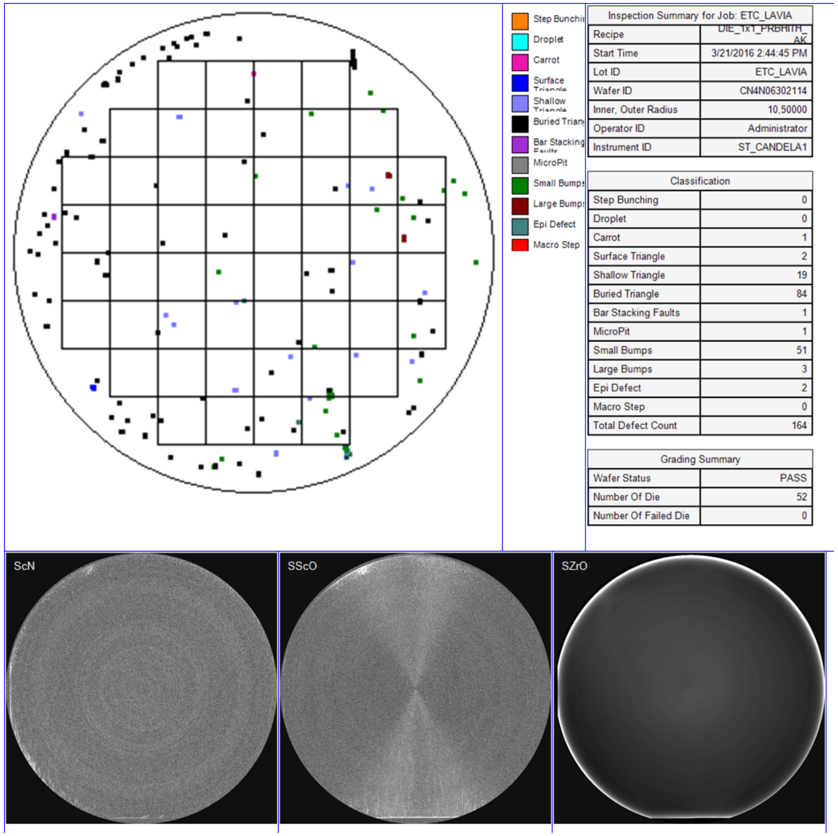
Electrons irradiation

- Energy	5 MeV
- Current	1-200 mA
- Rep. Rate	1-300 Hz
- Pulse duration	3 μsec

SiCILIA activities 2016

Epitaxial grows

10 μm epitaxial layers grown in LPE



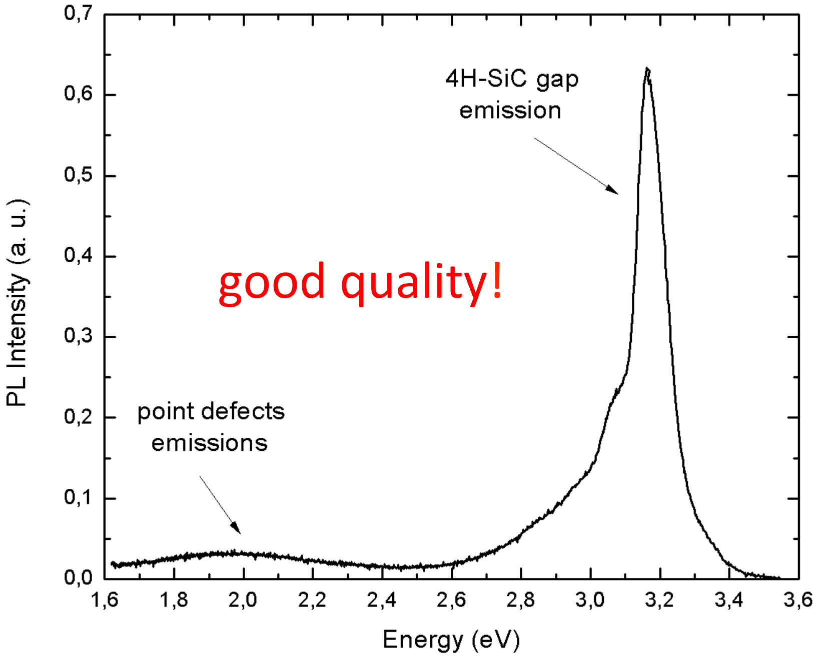
Inspection Summary for Job: ETC_LAVIA	
Recipe	DIE_1x1_PRBHITH_AK
Start Time	3/21/2016 2:44:45 PM
Lot ID	ETC_LAVIA
Wafer ID	CN4N06302114
Inner, Outer Radius	10,50000
Operator ID	Administrator
Instrument ID	ST_CANDELA1

Classification	
Step Bunching	0
Droplet	0
Carrot	1
Surface Triangle	2
Shallow Triangle	19
Buried Triangle	84
Bar Stacking Faults	1
MicroPit	1
Small Bumps	51
Large Bumps	3
Epi Defect	2
Macro Step	0
Total Defect Count	164

Grading Summary	
Wafer Status	PASS
Number Of Die	52
Number Of Failed Die	0

CANDELA Analysis

PL Spectroscopy @325 nm



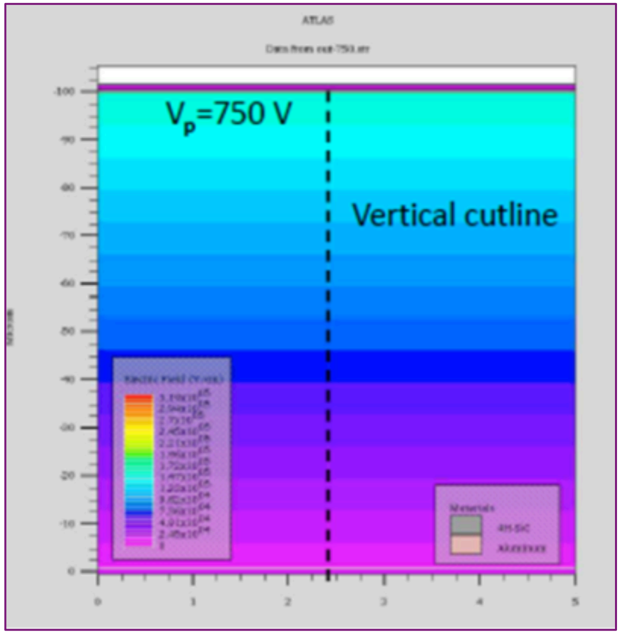
STM - New Candela device for defects mapping @266nm

New system for PL spectroscopy @266nm for thick EPI-layer analysis

Expected Yield 85 -100 % @ 10 μm Epi => 50% @ 100 μm Epi

SiCILIA activities 2016

Simulations



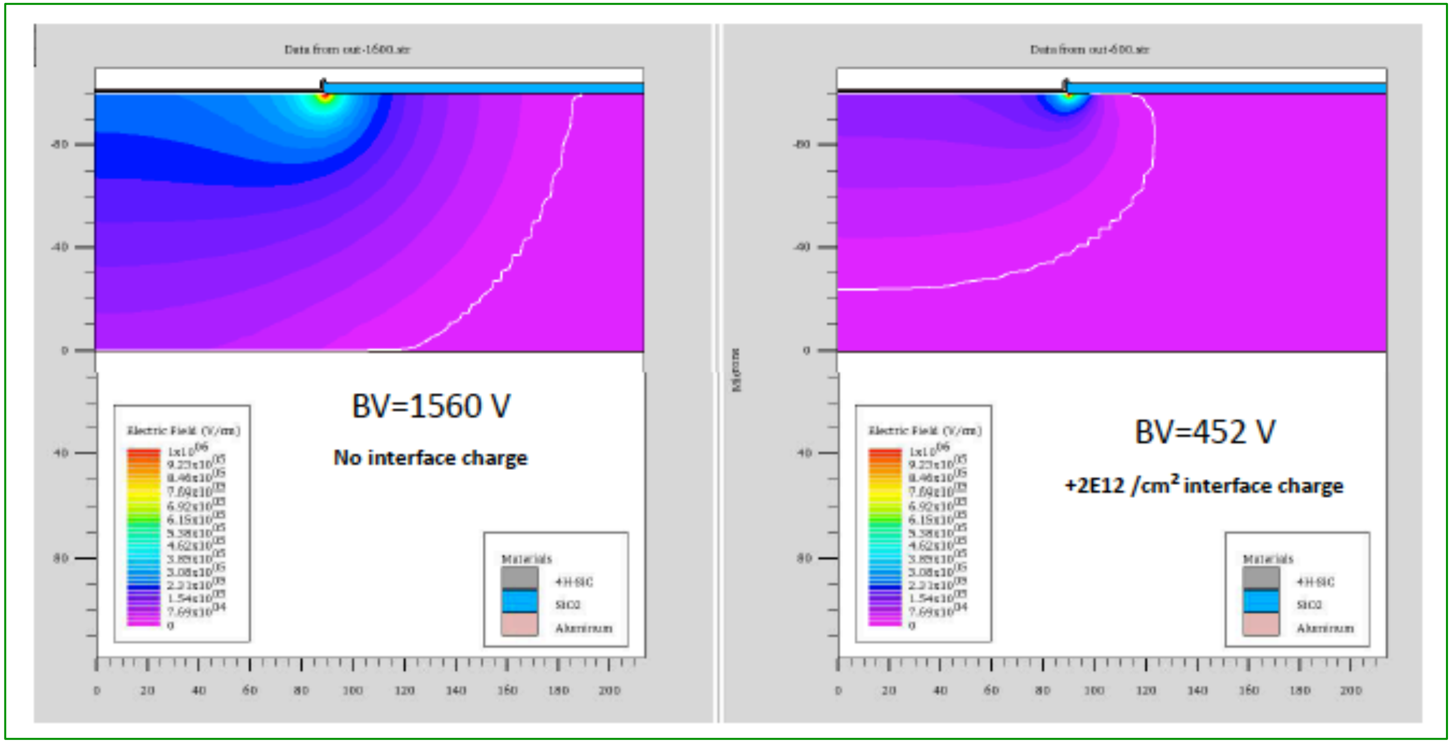
V_p=750 V

Vertical cutline

Depletion Voltage for 100 micron EPI is 750 V

Breakdown > 10kV infinite planar junction

Oxide and Interface Trapped Charges



BV=1560 V

No interface charge

BV=452 V

+2E12 /cm^2 interface charge

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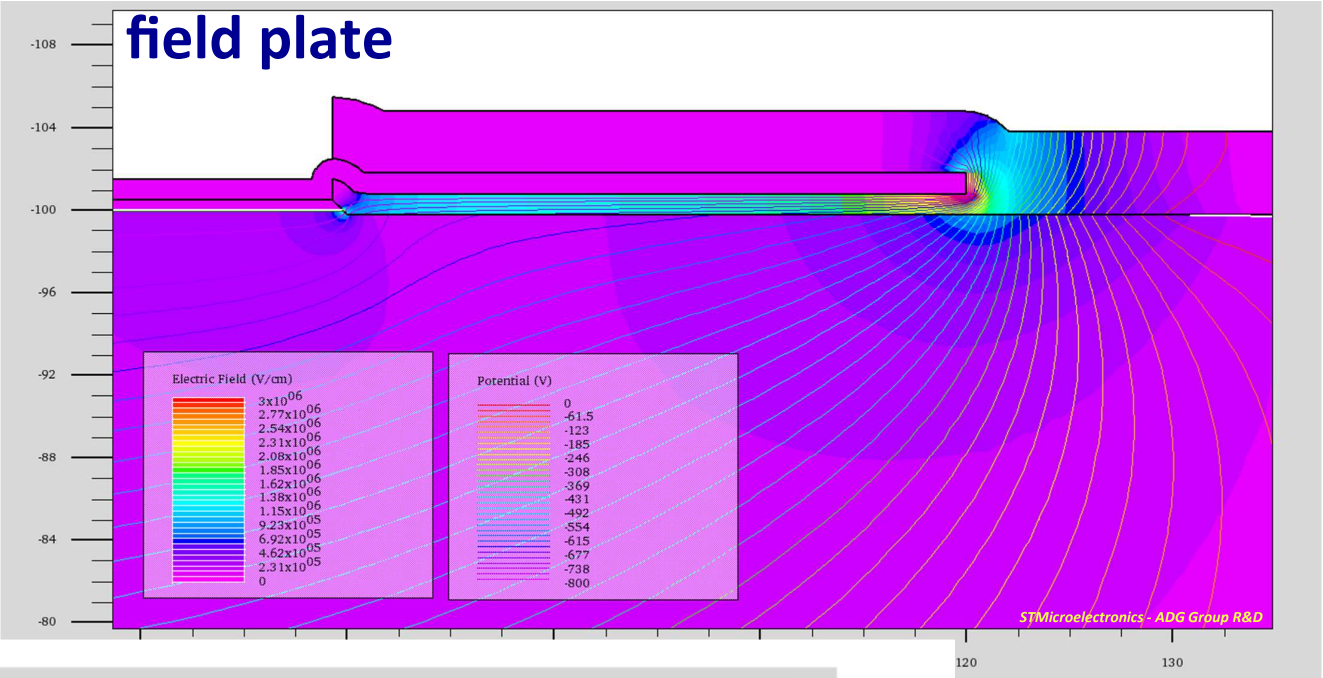
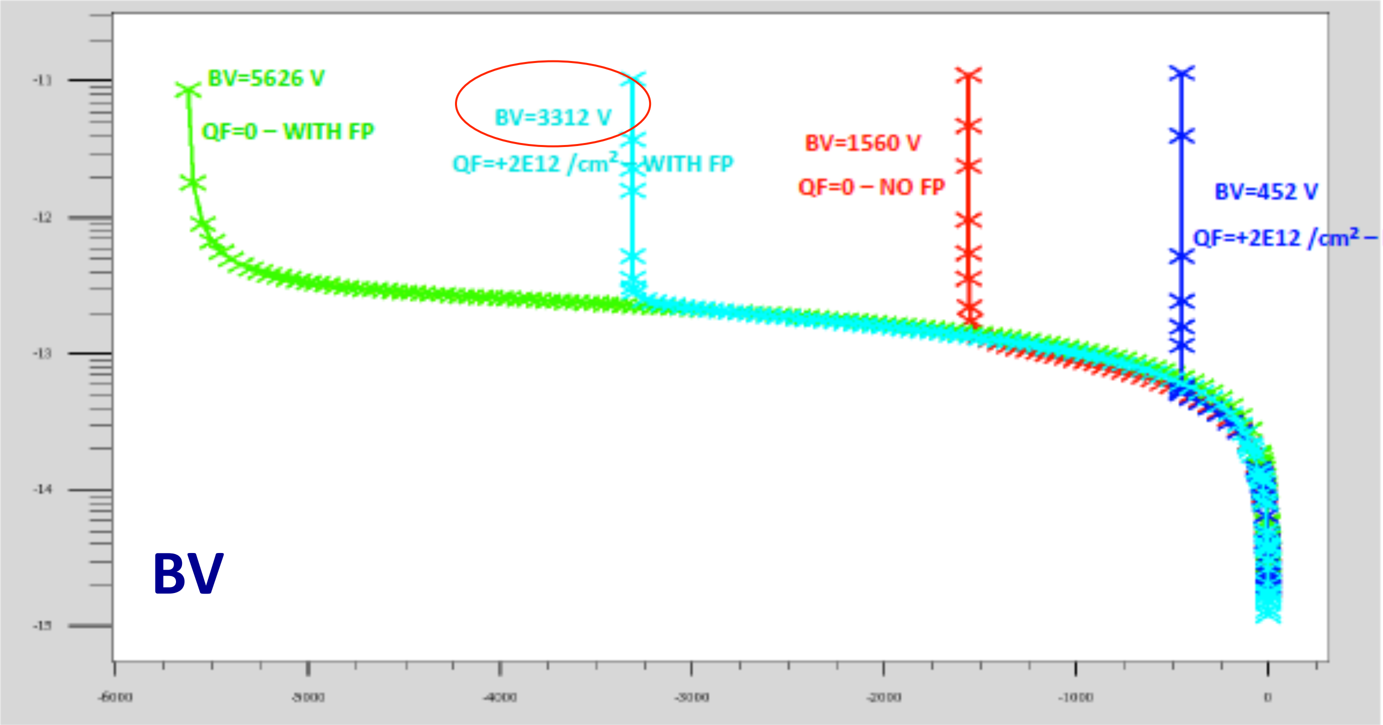
SiCILIA

Simulations





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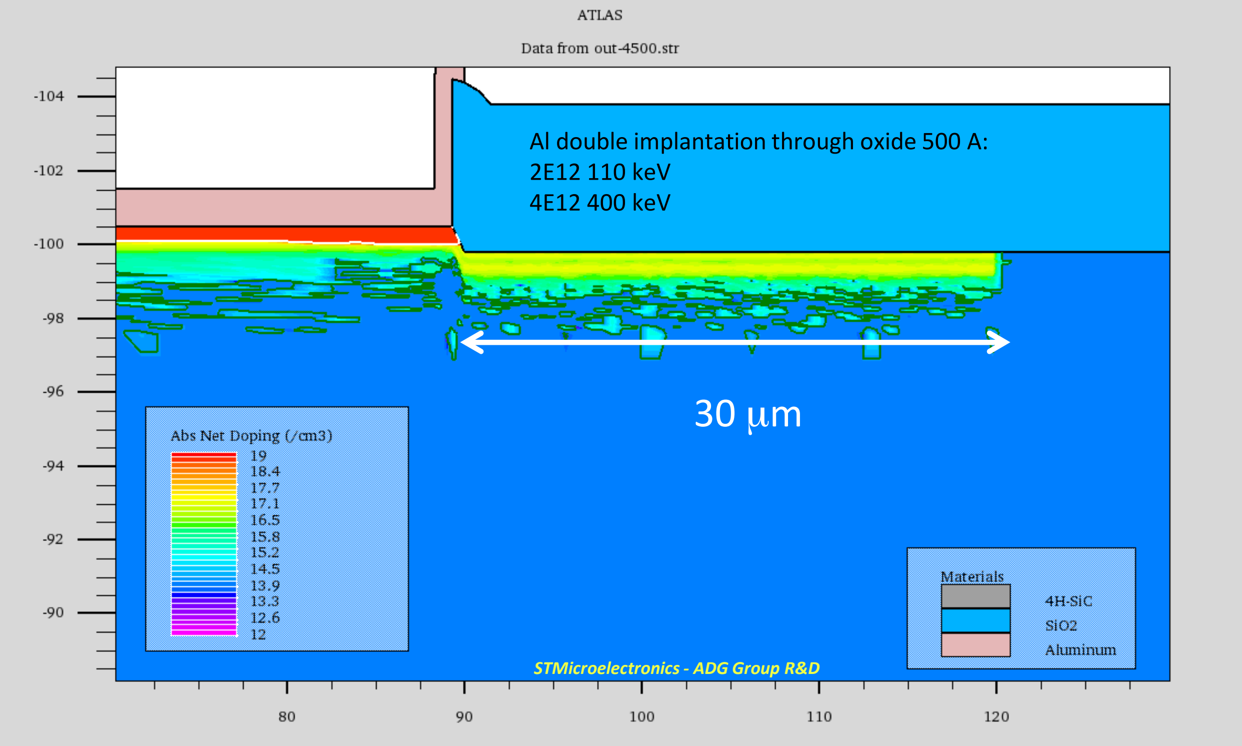
Simulations

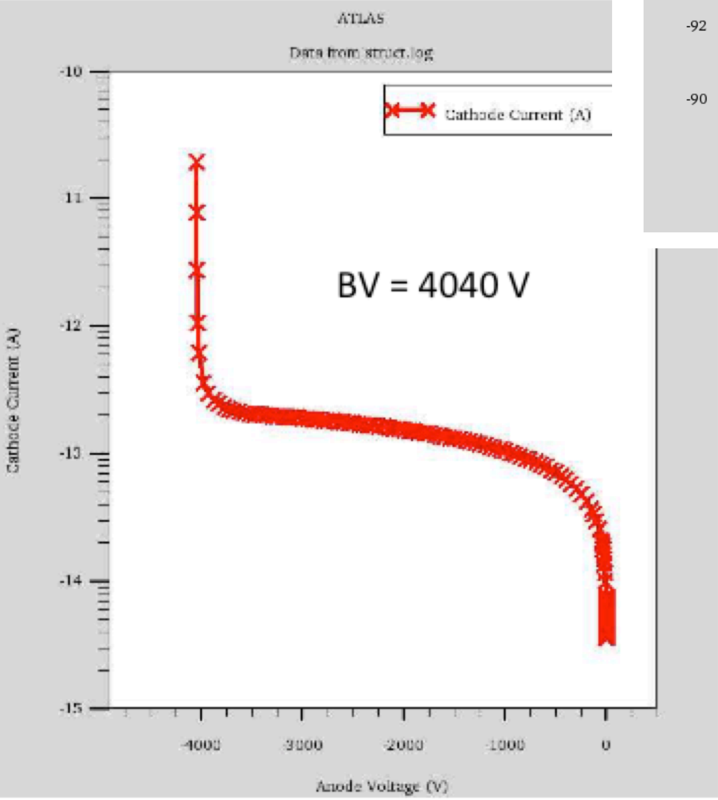
JTE- structure


Al double implantation through oxide 500 A:
2E12 110 keV
4E12 400 keV

30 µm

STMicroelectronics - ADG Group R&D

Q= $2 \times 10^{12}/cm^2$


BV = 4040 V

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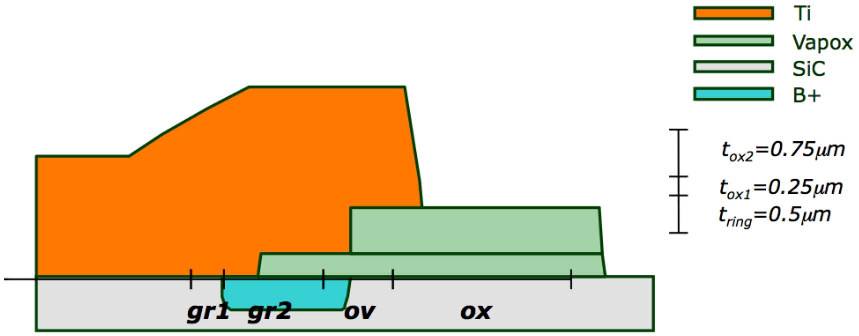
SiC processing, some of the standard steps are missing (RTA, Ni deposition, …)

Strategy

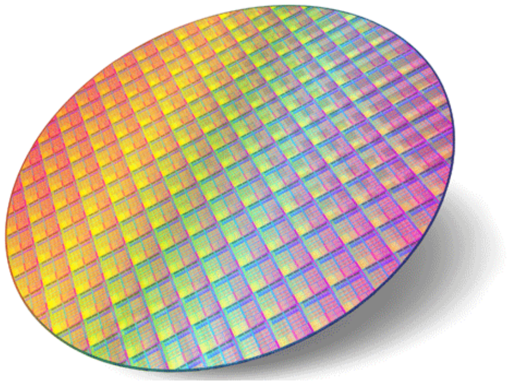
Starting from a consolidate IMM lay-out, new flow-chart accessible to FBK technology has been defined.



gr1	*anello di guardia (sotto il contatto)*	*20 µm*
gr2	*anello di guardia (sotto l'ossido)*	*50 µm*
ov	*overlap*	*40 µm*
ox	*ossido libero*	*100 µm*

Work in progress on Simulations, Flow-Chart

Silicon Carbide detectors



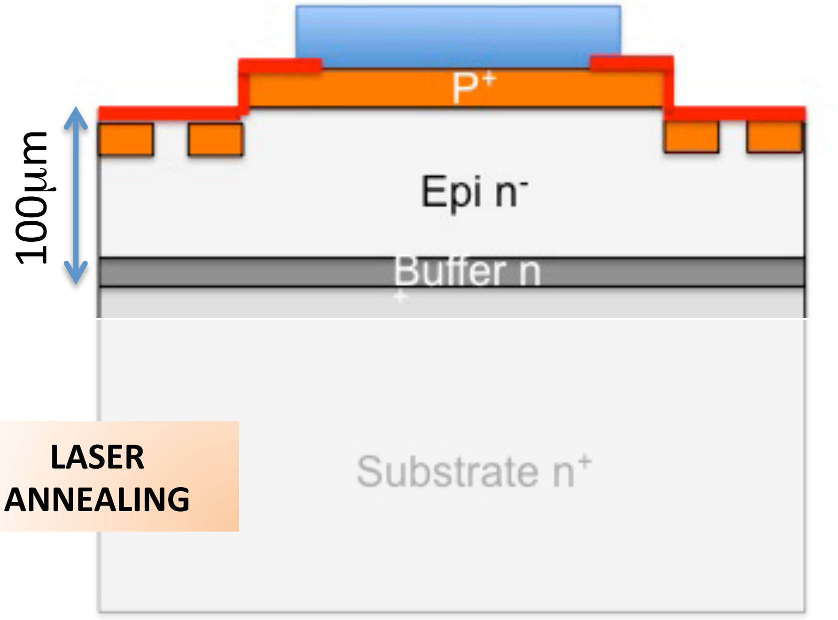
Grazie per l'attenzione!

SiCILIA Strategy

Schottky junctions => FONDAZIONE BRUNO KESSLER

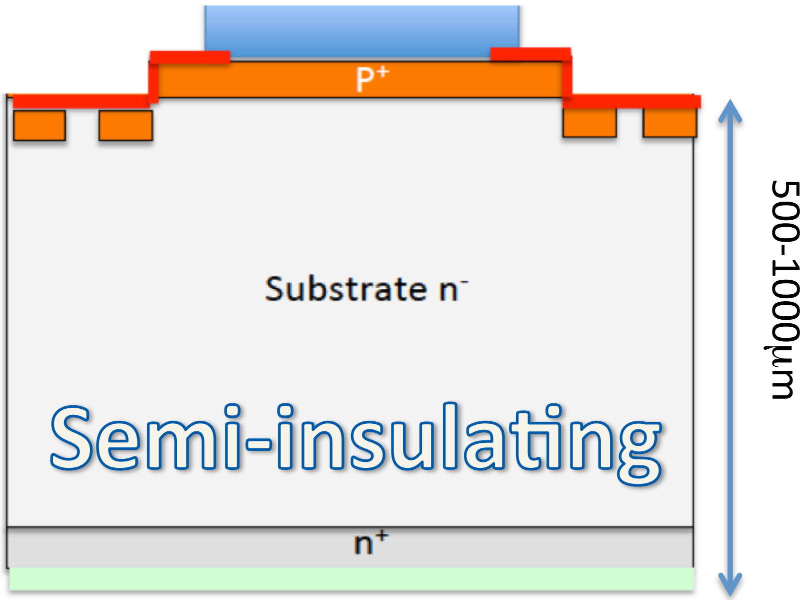
p-n junctions => STMicroelectronics

Detector Δ E



reduction thickness and metallization back

Detector E



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