

Rivelatori a base di carburo di silicio

Alessandro Lo Giudice
(Ricercatore CNR-INFM)

Caratterizzazione di semiconduttori per mezzo di tecniche spettroscopiche e nucleari

Claudio Manfredotti

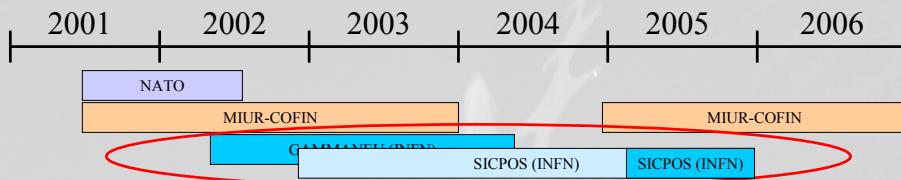
Ettore Vittone

Alba Zanini

Yiuri Garino, Elisabetta Colombo
(Dottorandi)

Paolo Olivero, Floriana Fasolo
(ex-dottorandi)

Progetti inerenti rivelatori a base di SiC con coinvolgimento del gruppo di Torino



NATO: “Research of Charge Transport Properties in SiC by Nuclear Microbeam Techniques”. Principal Investigators: M. Jaksic, R. Boskovic Institute, Zagreb, Croatia; E. Vittone, Univ. Torino

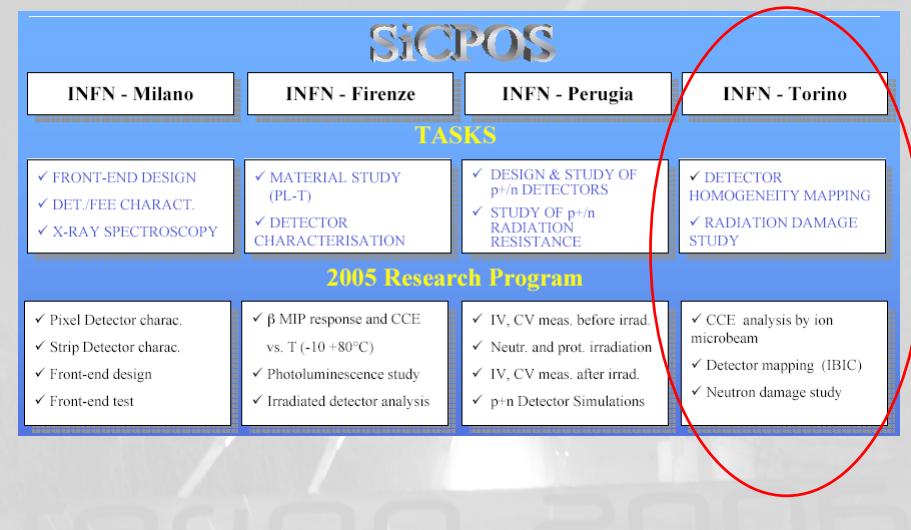
MIUR-COFIN: “Silicon Carbide Radiation Detectors for Room and High Temperature Spectrometry”. Coordinator: G.Bertuccio, Politecnico di Milano.

Principal Investigators: A.Cavallini: (Univ. Bologna), F.Nava (Univ. Modena), E.Vittone, (Univ. Torino); in collaboration with: CNR-LAMEL, Univ. Milano Bicocca, Alenia Marconi System

INFN-GAMMANEU: “SiC neutron detectors”. ... l'esperimento e' volto alla progettazione, simulazione e caratterizzazione di un nuovo rivelatore a semiconduttore per neutroni, basato sul carburo di silicio.... Coordinator: C.Manfredotti, University of Torino

INFN-SICPOS: “Realization of SiC detectors able to work at high temperature and in high radiation environments”. Coordinator: F. Nava (Univ. Di Modena) / G. Bertuccio (INFN Milano)

Progetti inerenti rivelatori a base di SiC con coinvolgimento del gruppo di Torino



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Progetti inerenti rivelatori a base di SiC con coinvolgimento del gruppo di Torino

RD50 Scientific Organization of RD50

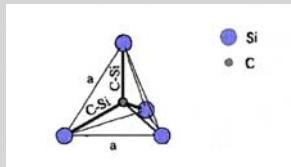


Michael Moll - December 05

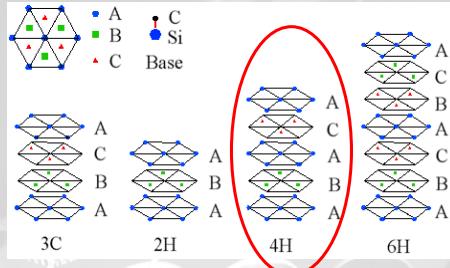
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Proprietà del SiC



Il SiC cristallizza in strutture che pur mantenendo la stessa composizione chimica differiscono nell'ordine di impilamento dei tetraedri di Si e C.



Numero: indica la periodicità cioè dopo quanti piani Si-C la struttura si ripete
Lettura: indica il tipo di cella elementare (C=cubica, H=esagonale, R=romboedrica).

Il politipo dalle proprietà più interessanti è il 4H-SiC.

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	8.4	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	No
Minimum energy for defect creation (eV)	12.8	9	25	43

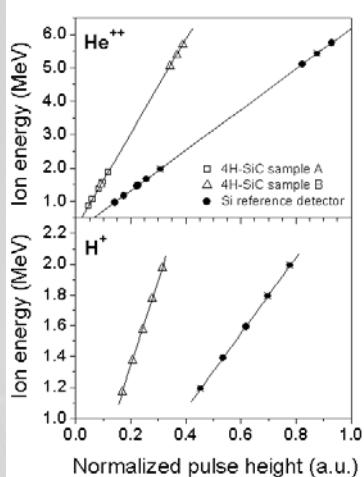


(2003)

- Wide band gap → High temperature operation
- High saturation velocity → High frequency/speed devices
- High thermal conductivity → High power devices
- High critical field → High voltage devices
- High resistance to radiation damage

Problems and drawbacks
 defects at the interface of epilayers
 contacts technology and surface treatments
 thin depletion layer widths
 pair creation energy not well known

Misura dell'energia di creazione di coppia nel SiC



$$\varepsilon_{\text{SiC}}^{\alpha} = (7.78 \pm 0.05) \text{ eV}$$

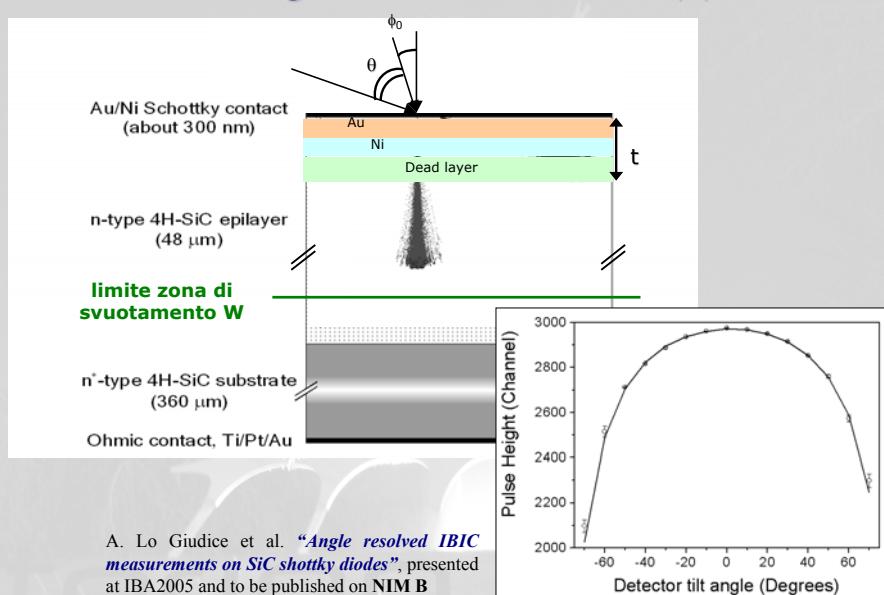
$$\varepsilon_{\text{SiC}}^p = (7.79 \pm 0.09) \text{ eV}$$

Because of the uncertainty indicated, it is not possible to observe a trend in energy deposition with particle nature.

The values we obtained have to be considered upper limits.

A. Lo Giudice et al. "Average energy dissipated by MeV hydrogen and helium ions per electron-hole pair generation in 4H-SiC", Applied Physics Letters 87 (2005)

Misura dell'energia di creazione di coppia nel SiC



A. Lo Giudice et al. "Angle resolved IBIC measurements on SiC shottky diodes", presented at IBA2005 and to be published on NIM B

Misura dell'energia di creazione di coppia nel SiC

Measured values of ε_{SiC} .

Reference	Year	Material	ε_{SiC} (eV)	Radiation
Quoted by Klein ¹	1968	6H-SiC	9.0 ± 0.7	e ⁻
Bertuccio et al. ²	2003	Epitaxial n-type 4H-SiC Schottky diode	7.8	x-ray
Quoted by Rogalla et al. ³	1999	Semi-insulating 4H-SiC	8.4	α
Ivanov et al. ⁴	2004	Epitaxial n-type 4H-SiC Schottky diode	7.71	α
Lebedev et al. ⁵	2004	Epitaxial n-type 4H-SiC Schottky diode	8.6	α
Lo Giudice et al. ⁶	2005	Epitaxial n-type 4H-SiC Schottky diode	7.78 ± 0.05	α
		Epitaxial n-type 4H-SiC Schottky diode	7.79 ± 0.09	protons

¹ C.A. Klein, Journal of Applied Physics 39, 2029 (1968).

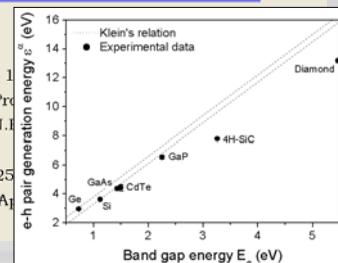
² G.Bertuccio, R.Casiraghi, IEEE Trans. on Nuclear Science 50, 1.

³ M.Rogalla, K.Runge, A.Söldner-Rembold, Nuclear Physics B (Proc. Suppl.) 69, 103 (1999).

⁴ A.M.Ivanov, E.V.Kalinina, A.O.Konstantinov, G.A.Onushkin, N.I.Tikhonov, V.P.Zhuravlev, Technical Physics Letters 30, 575 (2004).

⁵ A.A.Lebedev, A.M.Ivanov, N.B.Strokan, Semiconductors 38, 125 (2004).

⁶ A. Lo Giudice, F. Fizzotti, C. Manfredotti, E. Vittone, F. Nava, A. Sartori, A. Tassan-Got, AIP Conference Proceedings 222105 NOV 28 2005



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GOOD
BAD

(2005)

Wide band gap → High temperature operation

High saturation velocity → High frequency/speed devices

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High resistance to radiation damage

Problems and drawbacks

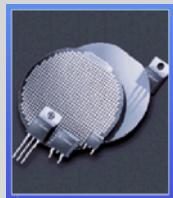
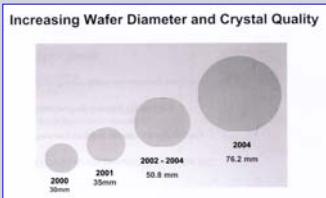
defects at the interface of epilayers

contacts technology and surface treatments

thin depletion layer widths

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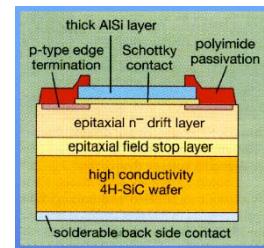
Tecnologia a base di SiC



2001: first commercial SiC diode
(600 Volt – 4 Ampere)

Rockwell International
High Power X-Band MESFET

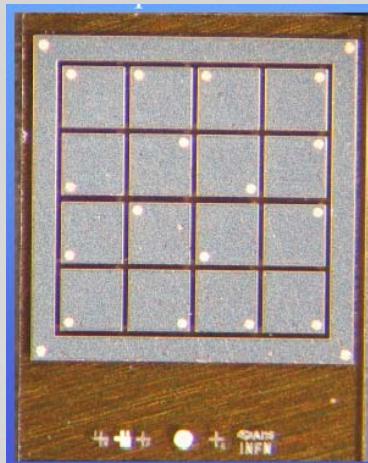
$f_T = 14.5 \text{ GHz}$, $f_{MAX} = 38 \text{ GHz}$
 $I_{Dmax} = 400 \text{ mA}$, $V_{DSmax} = 150\text{V}$
Gain: 16 dB @ 2 GHz



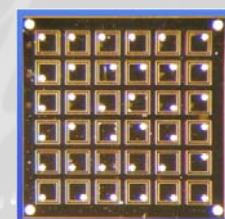
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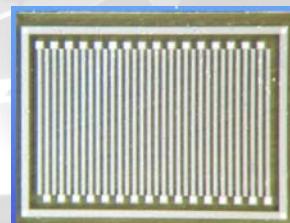
Rivelatori di SiC in ambito INFN



4x4 matrix,
Pixel size 400 $\mu\text{m} \times 400 \mu\text{m}$



32 strips, 2 mm long, 100 μm pitch

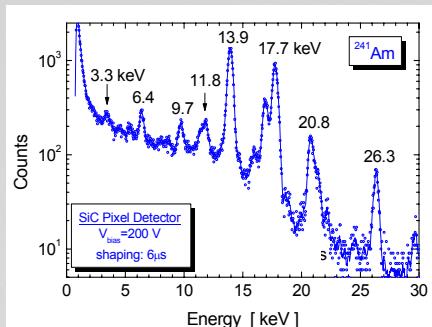


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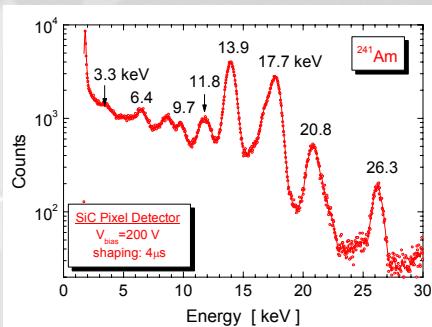
Spettroscopia a raggi x

27 ° C



Energy Resolution: FWHM = 315 eV

100 ° C



Energy Resolution: FWHM = 797 eV

G. Bertuccio et al., "Silicon carbide for high resolution X-ray detectors operating up to 100°C", Nucl. Instr. Meth. in Physics Res. A 522 (2004) 413

GAMMANEU Samples

Starting Material: 360 μm n-type 4H-SiC by [CREE \(USA\)](#)

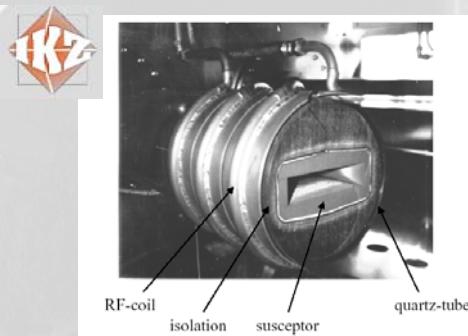


We processed two 2.0 inches wafers

1st wafer: SMP quality: 16-30 micropipes/cm²

2nd wafer: LMP quality: ≤ 15 micropipes/cm²

Epilayer by [G. Wagner](#), Institute of Crystal Growth (IKZ), Berlin, Germany



Pre-treatment:

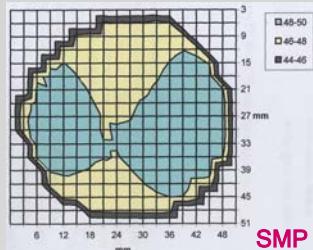
etching by hydrogen/propane gas for 4 minutes, in order to remove the damage layer (about 40 nm).

Growth conditions:

- hot-wall CVD reactor
- temperature: 1550 °C
- total pressure: 150 mbar
- C/Si ratio: 1.5
- growth rate: 9.5 μm/h
- nitrogen partial pressure: 2 × 10⁻⁴ mbar

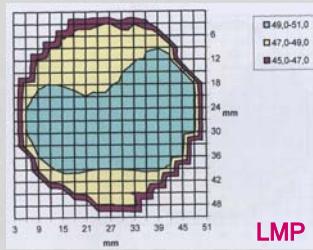
Samples

Epilayer by [G. Wagner, Institute of Crystal Growth \(IKZ\), Berlin, Germany](#)



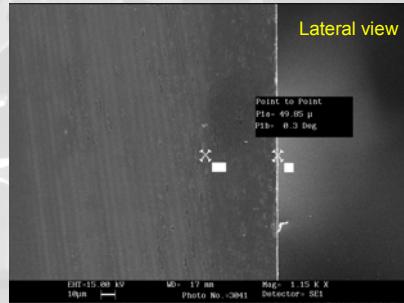
SMP wafer

Epilayer thickness: $48.0 \pm 0.6 \mu\text{m}$



LMP wafer

Epilayer thickness: $48.9 \pm 0.8 \mu\text{m}$



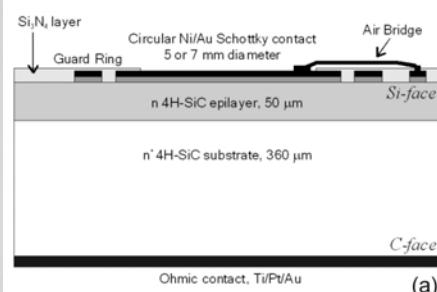
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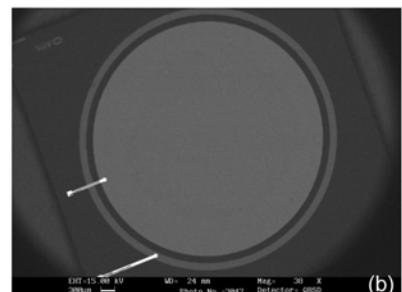
Samples

Devices by [C. Lanzieri, Alenia Marconi System JV \(AMSJV\), Rome, Italy](#)

Using a mask designed for our purposes, Alenia produced "small" (3 mm diameter) and large (5 mm diameter) Schottky SiC diodes. Up to now only 1.5 mm.



(a)



(b)

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I-V and C-V characterization

Our set-up (University of Torino)



Voltage Source Keithley 617: -2 / +100 Volt
Stanford PS350: +30 / +350 Volt

Picoamperometer Keithley 617

Capacimeter Bontoob BD52

When possible, to standardize measurements we used recommendation for Si diode measurements by A. Chilingarov.

"Measurements should be made between the backside and the central electrode with the guard ring kept at the same potential as the central part part (usually grounded)".

Guard ring at ground, polarization on the backside

"Wherever possible measurements should be performed at a temperature around either 20°C or 0°C".

Temperature: 19.1 - 21.6 °C

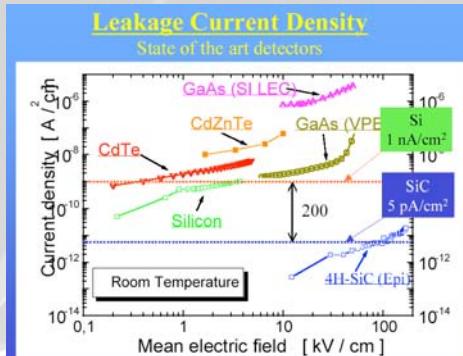
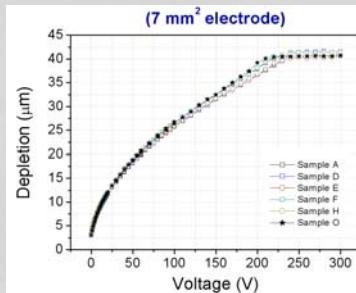
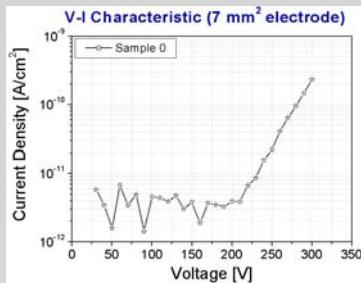
The IV and CV measurements between minimum and maximum bias values should be made both for increasing and decreasing voltages.

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Best results

I-V and CV characterization



Doping ≈ 1.5 10¹⁴ cm⁻³

About 15 pF (50 pF) at full depletion voltages for 3 mm (5 mm) diodes.

Full depletion at about 200 V - 220 V

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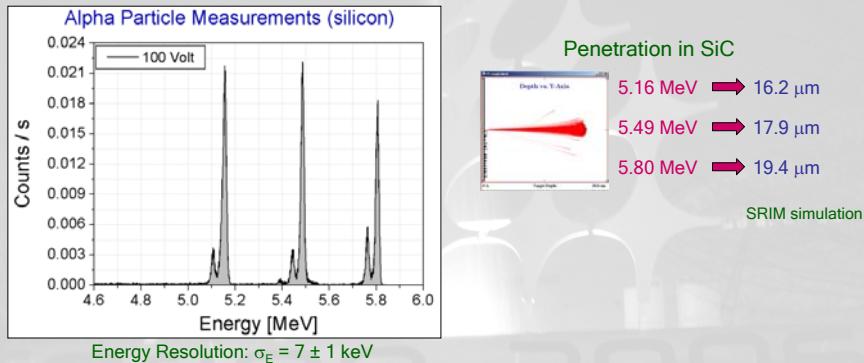
Alessandro Lo Giudice 18

Alpha particle measurements

To perform alpha particle measurements we used a triple ultra-thin window Alpha Source.

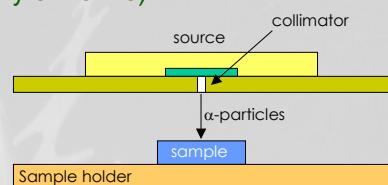
Plutonium (^{239}Pu): Peaks: 5.16 MeV (73.1 %); 5.14 MeV (15.0%); 5.10 MeV (11.8 %); others
Americium (^{241}Am): Peaks: 5.49 MeV (85.2 %); 5.44 MeV (12.8 %); 5.39 MeV (1.4 %); others
Curium (^{244}Cm): Peaks: 5.80 MeV (77.4 %); 5.76 MeV (23.0 %); others

Spectrum obtained using a 25 mm² Si detector and our electronic set-up.



Alpha particle measurements

Our set-up (University of Torino)



Preamplifier: Amptek A250

Amplifier & Multichannel: Eagle/Classic (APTEC-NRC)

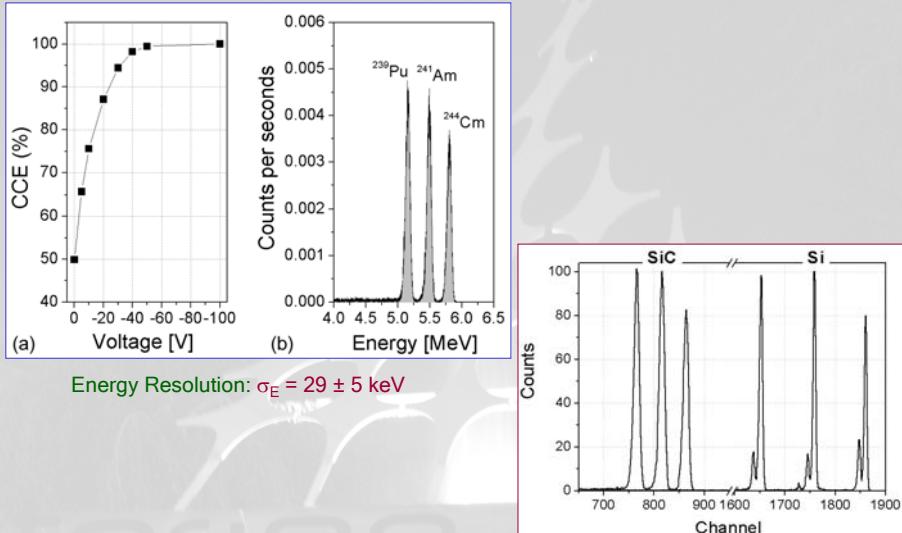
Voltage Source: Keithley 617: 0 / +100 Volt
Stanford PS350: +30 / +350 Volt



The source-sample-preamplifier box was placed in vacuum.

Alpha particle measurements

(alpha source)



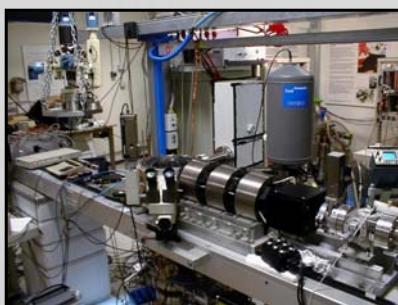
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Ion Beam Analysis

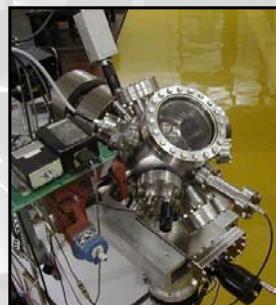
AN2000 microbeam facility @
INFN National Laboratories (Legnaro, I)
Dr. Valentino Rigato

2.5 MV Van de Graaff accelerator
available ions: H, He
micrometric spot size
PIXE, IBICC and IBIL measurements
recently developed cryogenic apparatus



Nuclear microprobe facility @
Ruđer Bošković Institute (Zagreb, Croatia)
Dr. Milko Jaksic

6 MV Tandem accelerator
available ions: H, C, Li, O, ...
micrometric spot size
PIXE, IBICC measurements



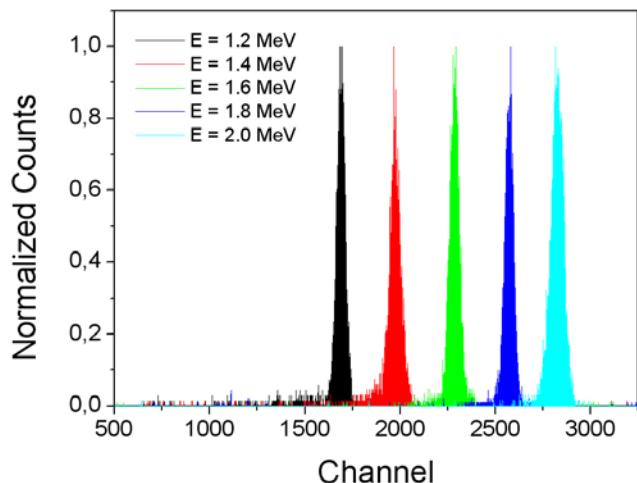
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Particle detection measurements

(Ion Beam at Legnaro)

Proton Spectra (SiC detector)

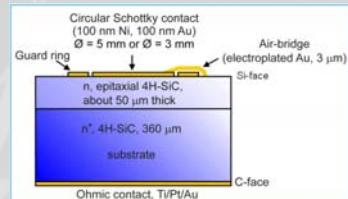
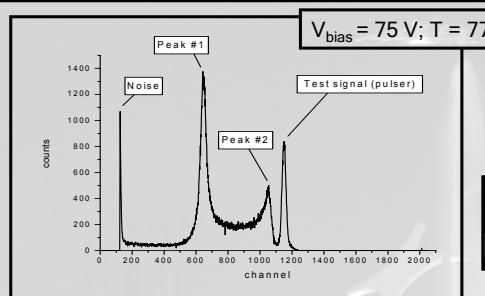


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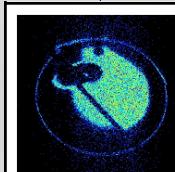
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Ion Beam Analysis

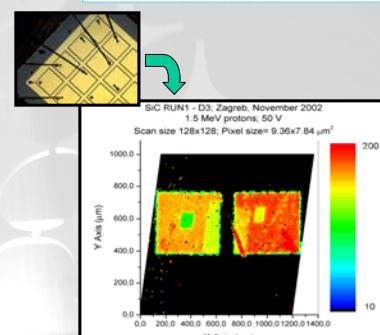
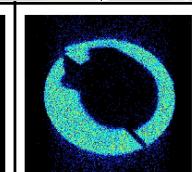
4H-SiC IKZ sample; 1.5 MeV protons (Legnaro 2003)



Peak #1 map



Peak #2 map



Vittone et al., 2003

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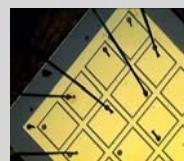
Alessandro Lo Giudice 24

X-ray Beam Analysis

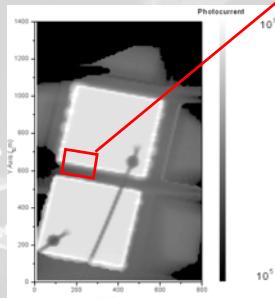
SXM (X-ray Scanning Microscopy) @ ESRF in Grenoble (France), ID21
Dr. R. Barrett

3 keV x-ray energy

About 10^8 photons/s
micrometric spot size

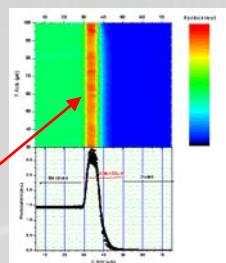


Optical microscope image

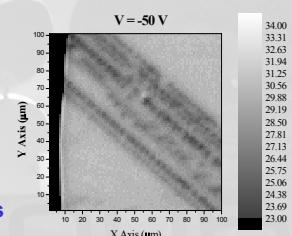


XBIC map of two electrodes

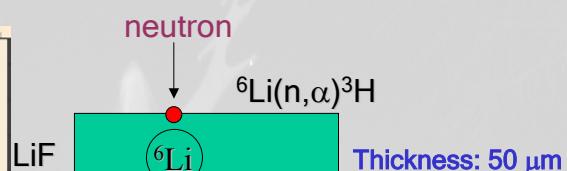
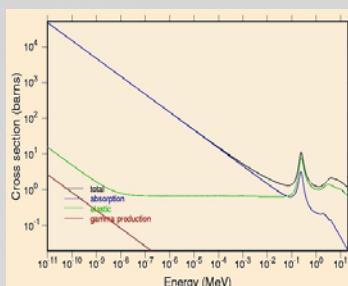
XBIC map of two electrodes



XBIC profile



Neutron detectors

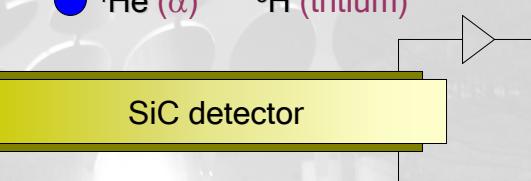


Thickness: 50 μm



Detector
Depletion layer > 30 μm

SiC detector



Neutron detectors

Conversion reaction: ${}^6\text{Li}(\text{n},\alpha){}^3\text{H}$

Q-value = 4.78 MeV

For a neutron spectrometer:

mean free path of reaction products within the active volume of the detector

		Neutron Energy [MeV]	
		2.5 10^{-8} MeV	10 MeV
Alpha	Ion Energy	2.05 MeV	10.86 MeV
	Penetration in SiC	4.8 μm	53.0 μm
Tritium	Ion Energy	2.73 MeV	3.92 MeV
	Penetration in SiC	27.4 μm	48.2 μm

Due to the low deposited energy, gamma background signals can be effectively distinguished from neutron signals, by choosing an appropriate cut-off.

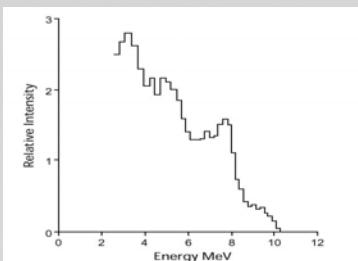
Possible applications of SiC: intense neutron fields (included the case of mixed radiation fields):

1. Fast neutron fields (fusion reactors)
2. Epithermal neutron fields (BNCT facilities) $10^9\text{-}10^{13}\text{ n cm}^{-2}\text{ s}^{-1}$

where a small obstruction, a great radiation hardness and a continuous radiation monitoring are required.

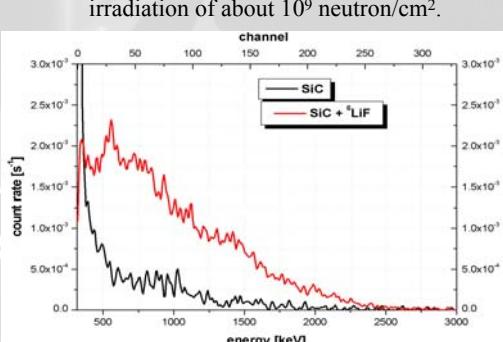
Preliminary neutrons detection measurements

AmBe Neutron Source @ JRC Ispra



Activity: 574 GBq

$3.4 \cdot 10^7$ neutrons/s



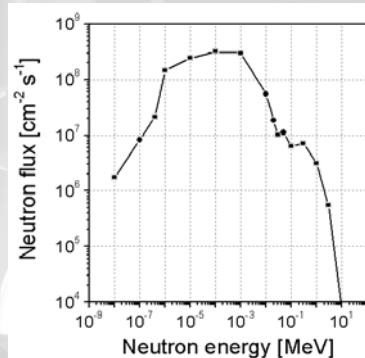
(2003)

Neutron detection measurements

TAPIRO reactor

TAPIRO: reactor located at ENEA Casaccia Research Centre, Roma. Epithermal column designed and realized in view of BNCT (Boron Neutron Capture Therapy) treatments.

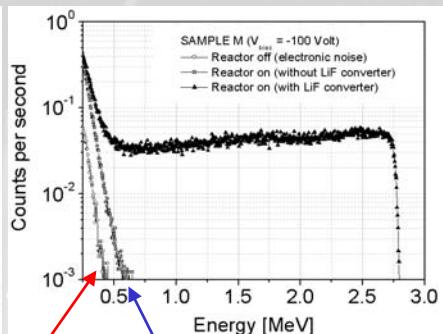
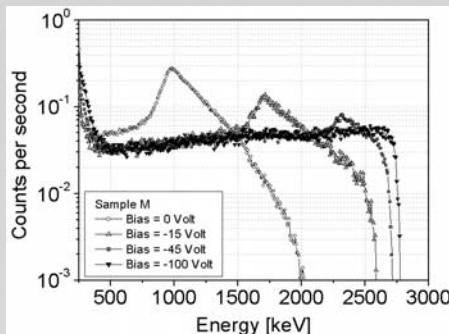
Total neutron flux @ maximum reactor power (5 kW): $1.15 \cdot 10^9 \text{ cm}^2 \text{ s}^{-1}$.



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Neutrons detection measurements



Total flux @ 1 Watt reactor power:

$$\Phi = 2.3 \cdot 10^5 \frac{\text{neutrons}}{\text{s} \cdot \text{cm}^2}$$

$$\eta \cong 0.003$$

SiC detector counts above 500 keV:

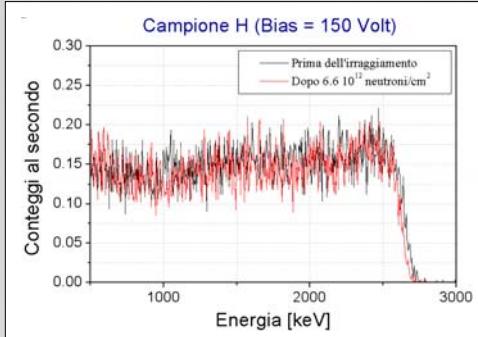
$$\Phi = 630 \frac{\text{counts}}{\text{s} \cdot \text{cm}^2}$$

C. Manfredotti, A. Lo Giudice, F. Fasolo, E. Vittone, C. Paolini, F. Fizzotti, A. Zanini, G. Wagner, C. Lanzieri, ["SiC detectors for neutron monitoring"](#), Nuclear Instruments and Methods in Physics Research A 552 (2005) 131-137

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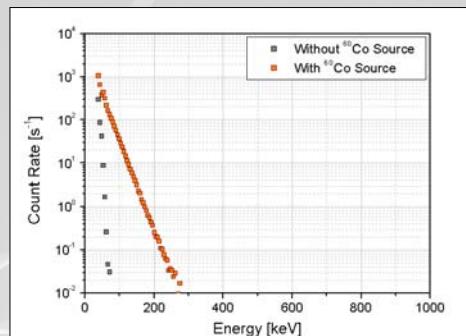
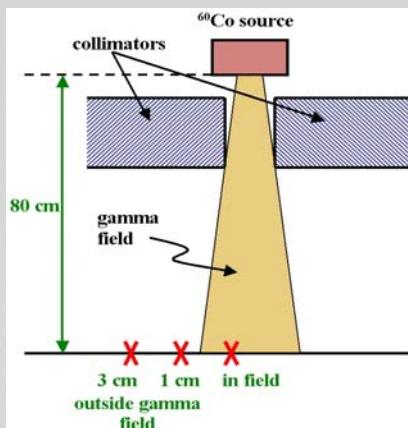
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Neutrons detection measurements



No significative change in count rate after about $6.6 \cdot 10^{12}$ neutrons/cm².

Preliminary neutrons detection measurements ^{60}Co source (S. Giovanni Hospital)



In order to verify the capability of discriminating different types of radiation, some samples have been exposed to an intense gamma source (^{60}Co source, a facility of S. Giovanni Hospital in Torino). It has been demonstrated that discrimination can be easily performed by simply setting the lower threshold (LLD) at 300 KeV (Fig. 6).

Conclusioni

- Sono stati prodotti diodi Schottky a base di carburo di silicio (4H) di dimensione elevata (3 e 5 mm di diametro).
- I dispositivi sono stati caratterizzati elettricamente per mezzo di misure I-V e C-V. I campioni migliori hanno mostrato una corrente di buio inferiore a 10^{-11} A/cm² (ovvero inferiore a 0.1 pA sui dispositivi da 3 mm di diametro), una capacità di 15/50 pF (per i dispositivi da 3 mm/5 mm), una regione di svuotamento massima di circa 40 μ m (completamente svuotata a circa 200 Volt) e un drogaggio di circa $2 \cdot 10^{14}$ cm⁻³.
- Misure con particelle alfa da sorgente (Torino) e alfa/protoni da microfascio (Legnaro), hanno mostrato un'efficienza di $\eta=100\%$ ed una risoluzione energetica di $\sigma_E = 29 \pm 5$ keV (bassa a causa delle dimensioni dell'elettrodo e della presenza di oro sul contatto).
- I dispositivi sono stati testati come rivelatori di neutroni per mezzo della sorgente di neutroni di ispra e del reattore della Casaccia. L'efficienza del rivelatore è circa $\eta=0.003$ e non sono state riscontrate differenze significative nel count rate (< 2%) per una dose fino a circa 10^{13} n/cm².
- Ulteriori misure saranno effettuate per studiare l'effettiva resistenza al danneggiamento da parte dei dispositivi a base di SiC.
- Test su nuovi campioni di materiale semi-isolante.