Silicon Carbide Detectors for Ionizing Radiation

History, state of the art and perspectives

Giuseppe Bertuccio
Politecnico di Milano
Department of Electronics, Information and Bioengineering
and
National Institute of Nuclear Physics (INFN)
Milan, Italy
Silicon Carbide

a fascinating story of

an amazing semiconductor!
SiC discovery and synthesis

Jacob Berzelius
(Chemist, Sweden, 1779-1848)
Karoliska Institute,
Royal Swedish Academy of Science

Edward Acheson
(Chemist, USA, 1856-1931)
1893: synthetic SiC
(carborundum)
U.S. Patent 492,767

Henri Moissan
(Chemist, France, 1852-1907)
International Atomic Weights Committee

1823: prepared amorphous Si hypothesis on SiC existence

1893: synthetic SiC (carborundum)

1904: Natural SiC discovery in meteor crater (moissanite)

1906 Nobel Prize in Chemistry (fluorine)
1960: a starting date for Si and SiC

1960 - Si radiation detectors

The Solid-State Ionization Chamber*

S. S. FRIEDLAND,† J. W. MAYER,‡
AND J. S. WIGGINS‡

Summary—Shallow diffused silicon p-n junction detectors have been used as room-temperature particle spectrometers for protons, alpha particles, heavy ions, and fission fragments. Both types of detectors have been investigated.

1964 - SiC radiation detectors

Silicon p-n Junction Radiation Detectors*

G. L. MILLER,† W. L. BROWN,‡ P. F. DONOVAN,§
AND I. M. MACKINTOSH‡

Summary—Silicon p-n junction particle detectors have been fabricated by diffusing phosphorus to various depths between 0.1 and 2.0 μ into high resistivity p-type silicon. Various base material resistivities have been employed, ranging from 100 Ω cm to 13,000 Ω cm. Diffusions have been carried out both by the “garrocer” and the “paint-on” electron pair. This quantity is designated ε. So far all the experimental evidence points to the fact that ε is independent of particle type. Thus any particle losing E mev of energy in the depletion layer produces N hole-electron pairs, where N is given by,

IEEE TRANSACTIONS ON NUCLEAR SCIENCE

1964 - June

HIGH TEMPERATURE NUCLEAR PARTICLE DETECTOR*

P. G. Canepa, P. Malinari, R. B. Campbell, J. Cembran
Westinghouse Research Laboratories
Pittsburgh 35, Pennsylvania

I. SUMMARY

In many applications it is necessary to use sensors which are capable of operating in regions of high temperatures. In this study, sensors have been designed, fabricated, and characterized.

II. ELECTRICAL AND COUNTING CHARACTERISTICS

The initial crystal properties such as resistivity, mobility, etc. are determined.

1965

BABCOCK: RADIATION DAMAGE IN SiC

RADIATION DAMAGE IN SiC

Richard Babcock
Westinghouse Research Laboratories
Pittsburgh, Pennsylvania

ABSTRACT

SiC has a band gap energy of about 2.8 ev; intrinsic SiC would be an excellent insulator at room temperature. In practice, the uncompensated p-n junctions are discussed they will be identified by the name of the supplying company, because there is unfortunately no more satisfactory way to indicate their composition at present.
1998-'99: SiC reconsidered

Westinghouse
Northrop Grumman (USA)

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 45, NO. 3, JUNE 1998

Development of a Silicon Carbide Radiation Detector

F.H. Ruddy¹, A.R. Duloo¹, J.G. Seidel¹, and S. Seshadri¹ and L.B. Rowland¹
¹Westinghouse Science & Technology Center, 1310 Beulah Road, Pittsburgh, Pennsylvania 15235
²Northrop Grumman Science & Technology Center, 1310 Beulah Road, Pittsburgh, Pennsylvania 15235

University of California
Bell Laboratories (USA)

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 46, NO. 4, AUGUST 1999

Development of Radiation-hard Materials for Microstrip Detectors ¹

T. Dubbs², W. Kroeger², T. Nissen², T. Pulliam², D. Roberts², W. A. Rowe², H. F.-W. Sadrozinski², A. Seiden², B. Thomas², A. Webster², G. Alers³
³SCIPP, University of California, Santa Cruz, CA 95064, USA
²Bell Laboratories, Lucent Technology, Murray Hill, NJ 07974, and USA

University of Freiburg (Germany)

Particle detectors based on semi-insulating Silicon Carbide

M. Rogalla*, K. Runge, A. Süldner-Rembold
University of Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg, Germany

University of Modena (Italy)

Epitaxial silicon carbide charge particle detectors

F. Nava*, P. Vanni*, C. Lanzieri*, C. Canali*
*Dipartimento di Fisica, Università degli Studi di Modena, Via Campi, 213/A, 41100 Modena, Italy
**Dipartimento di Fisica, Università di Milano, via Celoria 16, 20133 Milano, Italy

G. Bertuccio, Silicon Carbide Detectors for Ionizing Radiation: history, state of the art and perspectives
CPAD Instrumentation Frontier Workshop 2021, 18 - 22 March 2021, Stony Brook, NY, USA
April 2001: first commercial SiC Diode

Applications
Compact Switched Mode Power Supplies
Communications

Epitaxial Silicon Carbide for X-ray Detection

G. Bertuccio, R. Casiraghi, and F. Nava

Abstract—We present the first experimental results of X-ray detection and spectroscopy by means of Schottky junctions on epitaxial silicon carbide (SiC). The devices have a junction area of 3 mm² on an n-type 4H-SiC layer 30 µm thick with a dopant concentration of $1.8 \times 10^{18}$ cm⁻³. At 300K, the reverse current density of the best device varies between 2 pA/cm² and 18 pA/cm² as the mean electric field is increased from 40 kV/cm up to 170 kV/cm. The devices have been tested with X and γ rays from $^{241}$Am; the best measured energy resolution is 2.7 keV FWHM at room temperature.
Strength of SiC for Radiation Detection

**Wide Bandgap (> 3 eV)**
- High Schottky / pn barriers
- Low thermally generated currents
- Visible-light blindness

No cooling system required
Room and HT operation
No light shield required

**High Critical Field (2 MV/cm)**
- High bias voltage
- no soft breakdown
- no guard rings

High atom displacement energy (22-35 eV)
- Radiation hardness

High saturation carrier velocity (200 μm/ns)
- Short charge transit time
- Fast signals
- Low charge trapping probability
## SiC vs. Diamond

### Signals from radiation

<table>
<thead>
<tr>
<th></th>
<th>Silicon</th>
<th>SiC</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap (eV)</td>
<td>1.1</td>
<td>3.2</td>
<td>5.5</td>
</tr>
<tr>
<td>e-h pair creation energy (eV)</td>
<td>3.7</td>
<td>7.8</td>
<td>13</td>
</tr>
<tr>
<td>Photons/p/α: e-h pairs/keV</td>
<td>270</td>
<td>128 (Si/2.1)</td>
<td>77 (Si/3.5)</td>
</tr>
<tr>
<td>MIP: e-h pairs / μm</td>
<td>89</td>
<td>55 (Si/1.6)</td>
<td>36 (Si/2.5)</td>
</tr>
</tbody>
</table>

### SiC:

- Available in 150 mm (8’’) wafers
- Well established planar technology processing
SiC detectors

Plasma

High-Resolution Alpha-Particle Spectrometry Using 4H Silicon Carbide Semiconductor Detectors
Frank H. Ruddy, John G. Seidel, Haqian Chen, Abdul R. Dulkoo, Member, IEEE, and Sei-Hyang Ryu, Member, IEEE

Simultaneous Measurement of Neutron and Gamma-Ray Radiation Levels from a TRIGA Reactor Core Using Silicon Carbide Semiconductor Detectors
A.R. Dulkoo1, F.H. Ruddy1, J.G. Seidel1, C. Davison2, T. Finleybaugh3 and T. Daubenspeck4

Radiation tolerance of epitaxial silicon carbide detectors for electrons, protons and gamma-rays
F. Nava5, E. Vittime5, P. Vanni5, G. Verzellesi5, P.G. Fuochi5, C. Lanzieri5, M. Glaser5

Particle detectors based on semi-insulating Silicon Carbide
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University of Freiburg, Hermann-Herder-Str. 3, 79104 Freiburg, Germany

A new generation of X-ray detectors based on silicon carbide
Giuseppe Bertuccio5, Roberto Casiraghi5, Antonio Cetronio5, Claudio Lanzieri5, Filippo Nava5

Demonstration of 4H-SIC visible-blind EUV and UV detector with large detection area
X. Xin, F. Yan, T.W. Koeth, C. Joseph, J. Hu, J. Wu and J.H. Zhao

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α and β particles spectroscopy with SiC

α from Gd, Pu, Fr, At, Po


β from $^{90}$Sr

SiC detectors

Huge radiation exposure

largest signals

Plasma

Alpha

γ-ray

Electrons, protons

neutrons

MIP

X-ray

UV

SiC detectors for laser-generated plasma radiation

Giuseppe Bertuccio\textsuperscript{a,b,*}, Donatella Puglisi\textsuperscript{a,b}, Lorenzo Torrisi\textsuperscript{c,d}, Claudio Lanzieri\textsuperscript{e}

\textsuperscript{a} Department of Electronics Engineering and Information Science, Politecnico di Milano, Corso Como, Via Anzani 62, 22100 Como, Italy
\textsuperscript{b} National Institute of Nuclear Physics, INFN sez. Milano, Via Celoria 16, 20133 Milano, Italy

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\textsuperscript{a} Westinghouse Science & Technology Center, 1310 Beulah Road, Pittsburgh, Pennsylvania 15233

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X-ray Detectors

the most challenging spectroscopy….

- Low energy photons (0.1 - 20 keV)
- Generated charge: 13 - 2500 electron-hole pairs
- Detectors & electronics: ultra low-noise required
SiC Detector R&D in Italy
from Growth-Reactor to Detector characterization

Reactor Engineering and epi-SiC growth

Material Characterization

Detector/FEE design & fabrication

Detector/FEE characterization

Univ. Catania, Univ. Modena
Univ. Torino

Politecnico di Milano, Univ. Catania

Politecnico di Milano
Univ. Modena, Univ. Catania
Univ. Torino

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manufactured SiC detectors

- Pad Detectors
  - 1 mm²
  - 5 mm²
  - 0.3

- Pixel Detectors
  - 2 mm

- Microstrip Detectors
  - 3.35 mm
  - Width 25 / 50 µm
  - Pitch 100 / 55 µm
  - 40 µm
  - 200 / 400 µm

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Reverse Current in Schottky Junctions

Schottky contacts
Ni - 100 nm

undoped epitaxial layer
115 µm

n⁺ buffer - 0.5 µm

n⁺ 4H-SiC - 430 µm

Ohmic contact Ni - Ti/Pt/Au

High Barrier

Thermionic Emission

Tunneling

Thermal generation

Metal

SiC

Si

4H-SiC

Wide Bandgap

3.2 eV

1.1 eV

0.5 eV

>1 eV

4H-SiC

Si

0.5 eV

>1 eV

4H-SiC

Si
Detector current density vs. $E_{\text{field}}$

![Graph showing the comparison of detector current density at room temperature for Silicon, CdTe, CdZnTe, GaAs, and Si/Si-SDD. Key points include: Si/GaAs at 1 nA/cm$^2$, CdTe at 10$^3$, best Si-SDD at >25, and epi-SiC at <1 pA/cm$^2$ at 0.5 kV/cm and @ 80 kV/cm.]
Current density vs. $E_{\text{field}}$

- **Si / GaAs**: 1 nA/cm$^2$
- **SiC @ +127 °C**: $10^3$
- **epi-SiC**: $<1$ pA/cm$^2$ @80 kV/cm

![Graph showing current density vs. electric field for different materials](image)
SiC Microstrip leakage current

X-Ray Spectroscopy with SiC pixel

FWHM
177 eV (9.6 e⁻ rms) [+100 °C]
120 eV (6.5 e⁻ rms) [+28 °C]
Silicon Carbide opens something completely new in radiation detection...
From 1960

60 years of progress
in semiconductor detector R&D

(volume, area, energy resolution, imaging, complexity…)

What next? If any…

- Room & High temperature (SiC up to +100°C)
- Room Temperature (+20°C)
- Peltier cooled (-50 to -35°C)
- Cryogenic (-196°C)
From 1960
60 years of progress
in semiconductor detector R&D

(volume, area, energy resolution, imaging, complexity…)

Floating Temperature?

- Room & High temperature (SiC up to +100°C)
- Room Temperature (+20°C)
- Peltier cooled (-50 to -35°C)
- Cryogenic (-196°C)
SiC allows a new operation mode…

The floating temperature condition

1 h @ +30°C

ΔT_{\text{max}} 140°C

T_{\text{min}} -30°C

10 hours continuous acquisition

T_{\text{max}} +110°C

SiC microstrip detector
SiC under constant and floating-T

SiC microstrip detector

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SiC under constant and floating temperature

SiC microstrip detector

Even under Floating-T
- Low noise
- High Energy resolution
- No peak shift
- No peak distortion

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# Epitaxial vs. Bulk SiC

<table>
<thead>
<tr>
<th></th>
<th>Epitaxial SiC</th>
<th>Bulk SiC</th>
<th>Bulk SiC Semi Insulating</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wafer diameter</strong></td>
<td></td>
<td>100 - 150 mm</td>
<td></td>
</tr>
<tr>
<td><strong>Thickness</strong></td>
<td>≤ 200 μm</td>
<td>350 μm</td>
<td>500 μm</td>
</tr>
<tr>
<td><strong>Crystal politype</strong></td>
<td></td>
<td>4H</td>
<td></td>
</tr>
<tr>
<td><strong>Dopant type</strong></td>
<td>p (Al), n (N)</td>
<td>n type</td>
<td>-</td>
</tr>
<tr>
<td>**Doping concentration/</td>
<td>5x10^{13} &lt; N</td>
<td>0.02 Ωcm</td>
<td>≥ 10^6 Ωcm</td>
</tr>
<tr>
<td>resistivity**</td>
<td>&lt; 10^{19} cm^{-3}</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Defect density</strong></td>
<td>Very low</td>
<td>Relatively high</td>
<td></td>
</tr>
<tr>
<td><strong>Detector Performance</strong></td>
<td>Very High</td>
<td>Poor</td>
<td></td>
</tr>
</tbody>
</table>
Epitaxial vs. Semi-Insulating

**Epitaxial SiC**

200 μm × 200 μm, 70 μm thick

[Graph showing energy spectra for Epitaxial SiC]

- 120 eV FWHM
- +27°C

**Semi-Insulating SiC**

Ø 400 μm, 70 μm thick

[Graph showing energy spectra for Semi-Insulating SiC]

- 756 eV FWHM
- +22°C

Thicker SI-SIC detector are not spectroscopic-grade
SiC Detectors under extreme conditions!
Laser-generated Plasma Radiation

High Power Laser

\[ I = \frac{Power}{Area} \]

\[ I = \frac{1 \text{ J}/1 \text{ ps}}{1 \mu\text{m}^2} = \frac{1 \text{ TW}}{1 \mu\text{m}^2} = 10^{20} \text{ W/cm}^2 \]

very harsh environment
huge radiation doses

Plasma

Intense Radiation Beams
X-γ Rays
Electrons
Protons
Neutrons
Ions

Target

\[ E > 10^{11} \text{ V/cm} \]
\[ B > 10^5 \text{ Tesla} \]
SiC detector at PALS - Prague

SiC detector

Laser Entrance window
Time of Flight (TOF) operation

Detector

Laser light

Target

Signal

\[ \text{Time of Flight (TOF)} = \frac{L}{\text{particle velocity}} \]

\[ t=0 \text{ laser pulse} \]

\[ \text{photons} \]

\[ \text{Fast particles} \]

\[ \text{slow particles} \]

TOF + particle mass ↔ Particle Energy and identification
SiC detector at PALS
Signal from plasma radiation

- **SiC 01 Back.**
- $V_{DET} = 250 \text{ V}$
- Shot 40424

**Time of flight (ns)**

- **Signal amplitude**

- **X-ray peak**
  - $\text{H}^+ \sim 1.5 \text{ MeV}$
  - $\text{C}^+ \sim 6 \text{ MeV}$
Signal from plasma radiation

80 Volts on 50 ohm!

SiC 01 Back. 
$V_{\text{DET}} = 250 \text{ V}$
Shot 40424

Signal amplitude (V)

Time of Flight @ 94 cm (ns)
Signal from plasma radiation

- 100 Volts
- 2 Ampere
- 40 A/cm² current density

[Graph showing signal amplitude (V) and signal current (A) over time (ns).]
SiC Detector speed

Risetime: $t_R = 670$ ps

(Laser pulse: 350 ps FWHM)
I-V before and after experiment

T = 23°C

Before

After

0.3 pA/cm²

20 pA/cm²
Radiation Hardness of SiC detectors
Radiation Hardness

High atom displacement energy: 21 eV / 35 eV (Si: 13÷20 eV)

Unirradiated

After 23 MGy of $^{137}$Cs

$^{238}$Pu alpha spectra

FWHM 46 keV

FWHM 62 keV

Courtesy of F. H. Ruddy

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SiC: Radiation Hardness Overview

CCE with $\alpha$ 4.1 MeV

Gamma-ray irradiated SiC

Electron irradiated SiC

F. Nava et al., NIM A 505 (2003)
Radiation hardness

1 MeV Neutron irradiation
CCE with $\alpha$ 5.48 MeV

Proton and Neutron irradiated SiC
CCE with MIP ($^{90}$Sr)

Perspectives for Silicon Carbide
commercial SiC devices and modules

MOSFETs and Diodes
600 V – 1.2 kV, up to 150 A

High efficiency
DC/DC Converters, Inverters

MOSFETs and Diodes
600 V – 1.2 kV, up to 150 A

High efficiency
DC/DC Converters, Inverters

MOSFETs and Diodes
600 V – 1.2 kV, up to 150 A

High efficiency
DC/DC Converters, Inverters
Today: application of SiC power modules

Train/Traction

Motor Drive

Server Power Supplies

Automotive

Renewable energy

https://www.cree.com/
Summary and conclusions

- Epitaxial SiC detector already proved high performance
- Room, High, Floating temperature operation successfully demonstrated
- Microelectronic technology available for SiC
- SiC transistors and diodes are now commercial devices for power electronics and companies are investing on SiC technology and devices
- Epitaxial SiC Detector current limit:
  - thickness $T \leq 200 \ \mu m$; doping $N_d > 10^{13} \ \text{cm}^{-3}$
  - R&D needed to increase to $T \geq 300 \ \mu m$ and $N_d \leq 10^{12} \ \text{cm}^{-3}$
Acknowledgments

Thanks to all my Collegues, Collaborators and Students who partecipated to the SiC Detector R&D adventure


Thanks to companies for collaboration