Operational Characteristics of SiC Diodes as Ionizing Radiation Detectors

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Introduction
Operational characteristics
Charge Collection Efficiency
Radiation damage
Conclusions

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Silicon Carbide (SiC)

Silicon Carbide is the only chemical compound of C and Si. It is composed of tetrahedra of carbon and silicon atoms with strong bonds in the crystal lattice.

Differences in the stacking of the Si-C pair generates over 200 different polytypes.

Most common polytypes are 3C-SiC, 4H-SiC and 6H-SiC.

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It is composed of tetrahedra of carbon and silicon atoms with strong bonds in the crystal lattice.

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Most common polytypes are 3C-SiC, 4H-SiC and 6H-SiC.
SiC is a semiconductor with highly suitable properties for high-power, high-frequency and high temperatures applications.

SiC sensors may soon take their place in extreme environments from volcanoes to Venus.

**SiC device business (2008)**

SiC electronics device technology:
- Schottky diodes
- MOSFET
- JFET
- BJT
- PiN diodes
- IGBT

SiC power electronics markets:
- PFC, power supplies and UPS
- Hybrid automotive
- Solar panel and wind turbine
- Industry motor control

Sensing the Extreme

SiC is a semiconductor Material for solid state radiation detectors
# Sensing the Extreme

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>4H-SiC</th>
<th>Si</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap (eV)</td>
<td>5.5</td>
<td>3.3</td>
<td>1.12</td>
<td>Low leakage current necessary for low noise operation</td>
</tr>
<tr>
<td>e-h creation energy (eV)</td>
<td>13</td>
<td>8.4</td>
<td>3.6</td>
<td>Number of pairs reasonable high to have a high signal-to-noise ratio</td>
</tr>
<tr>
<td>Breakdown field (V/cm)</td>
<td>10⁷</td>
<td>4·10⁶</td>
<td>3·10⁵</td>
<td>High bias values</td>
</tr>
<tr>
<td>Thermal conductivity (W/cmK)</td>
<td>10-20</td>
<td>9.7</td>
<td>1.5</td>
<td>Better cool down of the detector to increase its radiation hardness. Easy control of the operating temperature.</td>
</tr>
<tr>
<td>Wigner energy</td>
<td>43</td>
<td>25</td>
<td>13-20</td>
<td>Radiation resistant detector</td>
</tr>
</tbody>
</table>

Many advantages in the use of SiC for the realization of ionizing radiation detectors

**High temperatures**
**High voltages**
**High irradiation environments**

A lot of effort has gone into producing high quality SiC diodes based on Schottky diode and p-n junctions.
SiC as radiation detector: Highlights

**SILICON CARBIDE NEUTRON RESPONSE**
2.2 micrometers 6-LiF zero bias

**X-Rays**
High resolution spectroscopy above room temperature
Photon energy range covered is < 20 KeV
Main limit: the thickness of the active region is below 100 µm

**Neutrons**
Thermal neutrons using a thin $^6$LiF layer
($^6$Li(n,α)$^3$H)
SiC response linear with neutron fluence rate (0.6%)
Detection efficiency $\eta \sim 0.003$
Same efficiency up to $1.3 \cdot 10^{16}$ fast-n/cm$^2$
SiC as radiation detector: Highlights

**α particles**

- High degree of linearity
- Charge Collection Efficiency 100%
- Energy resolutions from 6.6% to 0.34%
- Collection of minority carriers diffusing from the unpolarized region

**Heavier Ions**

- 6H-SiC diodes used to detect C, O and Ni ions from 9 to 15 MeV
  - K.K. Lee et al., NIM B 210, (2003) 489

- CCE < 100% due to Auger recombination effects generated by the high charge injection of a heavy ion

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*Introduction*
Detector chips were glued on a brass foil and bonded on a board.

**Experimental setup**

### 4H-SiC Schottky diodes from ETC-Catania

<table>
<thead>
<tr>
<th>Type</th>
<th>Doping nitrogen concentration</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>$7.6 \cdot 10^{14}$ N/cm²</td>
<td>37.9 µm</td>
</tr>
<tr>
<td>b</td>
<td>$2.0 \cdot 10^{15}$ N/cm²</td>
<td>43.7 µm</td>
</tr>
<tr>
<td>c</td>
<td>$1.5 \cdot 10^{16}$ N/cm²</td>
<td>21.0 µm</td>
</tr>
</tbody>
</table>

The Schottky junction was realized by a 0.2 µm thick layer of Ni$_2$Si on the front surface.

Active area: 2x2 mm²

Detector chips were glued on a brass foil and bonded on a board.
Experimental setup

The boards were setup in a scattering chamber at the Laboratori Nazionali del Sud (LNS) in Catania.

Another board was equipped with a Si detector used as reference.

For the radiation damage measurements: $^{16}$O ions @ 35.2 MeV

The ions were accelerated by the LNS Tandem VdG.

<table>
<thead>
<tr>
<th>Incident Energy</th>
<th>Incident Energy corrected for the energy loss in the Ni$_2$Si front layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.2 MeV</td>
<td>13.7 MeV</td>
</tr>
<tr>
<td>28.1 MeV</td>
<td>27.7 MeV</td>
</tr>
<tr>
<td>37.6 MeV</td>
<td>37.3 MeV</td>
</tr>
</tbody>
</table>
The peak position moves toward higher values as the voltage increases ...

.... and finally it saturates at high bias values

\[ d \approx \sqrt{\frac{2(V + V_{\text{built-in}})\varepsilon}{eN}} \]

In type c we did not measure the energy spectra @ 37.3 MeV since already @ 27.7 MeV the signal-height does not saturate.

Saturation @ 27.7 MeV can be reached only at voltages higher than the preamplifier limit (1000 Volts)
In the signal saturation region the peak position is a measure of the $^{12}$C incident energy.

By correlating the saturated peak positions to the corresponding $^{12}$C incident energies, we calibrated the pulse-height scale.

High degree of linearity

F. Nava et al., NIM A437 (1999)354
F.H. Ruddy et al., NIM A505 (2003)159
W. Cunningham et al., NIM A 509 (2003)127

Operational characteristics
The depleted region of the diode acts as the active region for the detection of the charges produced by ionization from the incoming charged particle.

The order of magnitude of the reverse bias necessary to create in the diode the depleted region is a key parameter for nuclear physics applications.

The thickness of the depleted region is expected to depend on the dopant concentration.

\[ d \approx \sqrt{\frac{2(V + V_{\text{built-in}})e}{\epsilon N}} \]
Dopant concentration dependence of the depleted layer

\[ d \approx \sqrt{\frac{2(V + V_{built-in})e}{eN}} \]

<table>
<thead>
<tr>
<th>Doping</th>
<th>Bias to fully deplete the diodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>805 Volt</td>
</tr>
<tr>
<td>Medium</td>
<td>2322 Volt</td>
</tr>
<tr>
<td>High</td>
<td>2062 Volt</td>
</tr>
</tbody>
</table>

High values
Energy resolution

Improves by increasing the bias (type a and b)

Constant in the pulse-heigh saturation region

Large fluctuations due to random recombination of minority carriers

Energy resolution

Pulse-height saturation region

Energy Resolution Range
5.7% - 1.7% (Si < 1%)

Better resolutions (up to 0.34%) have been measured
Signal Rise-time

Operational characteristics

Drift Velocity $\alpha V_{\text{bias}}$

Depleted region $\alpha \sqrt{V_{\text{bias}}}$
Charge Collection Efficiency

\[
CCE = \frac{Q_{\text{collected}}}{Q_{\text{produced}}}
\]

- \(Q_{\text{produced}} \propto \text{Saturated Peak Position}\)
- \(Q_{\text{collected}} \propto \text{Peak Position}\)

\[
CCE = \frac{\text{Peak Position}}{\text{Saturation Value}}
\]

L. Berluti et al., NIMA 354 (1995) 364
Charge Collection Efficiency

Ionization charge collected from the depleted region where the charges drift under the influence of the electric field.

\[ CCE = \frac{1}{E_0} \int_0^d \frac{dE}{dx} \, dx \]

- \( E_0 \): Incident energy
- \( d \): Depleted layer
- \( dE/dx \): Ion energy loss per unit path

Extra collected charge
Extra collected charge: minority carriers generated in the neutral region which diffuse to the depleted region and are finally collected.

\[ CCE_{diffusion} = \frac{1}{E_0} \int_0^D \frac{dE}{dx} e^{-\frac{x-d}{L_p}} dx \]

- \( L_p \): Minority carrier diffusion length
- \( E_0 \): Incident energy
- \( D \): Active layer
- \( d \): Depleted layer
- \( dE/dx \): Ion energy loss per unit path


\( L_p = 7 \pm 1 \mu m \)
Charge Collection Efficiency

Type b

CCE_{diffusion} = \frac{1}{E_0} \int_{d}^{D} \frac{dE}{dx} e^{-\frac{x-d}{L_p}} dx

L_p = 7 \pm 1 \mu
Charge Collection Efficiency

\[ CCE_{\text{diffusion}} = \frac{1}{E_0} \int_0^D \frac{dE}{dx} e^{-\frac{x}{L_F}} \, dx \]

Type a

\[ L_p = 5 \pm 1 \mu \]
The peak position is only due to the collection of primary ionizing charges generated by the ion within the depleted region.

No minority carriers diffusion is observed.
The lack of minority carriers collection could be due to a high concentration of defects in the crystal.

They can act as trapping centers for minority carriers reducing the probability of their diffusion through the crystal.
An higher concentration of defects in SiC type c could be the result of:

- Different wafer substrate
- Different growth conditions (temperature, pressure, gas flow direction, Si/C ratio etc.)
- Higher N doping concentration

A/B: micropipes  
C: edge/screw dislocations  
D: carrot defects

Minority carriers lifetime

\[ L_p = \left( \frac{KT}{e} \mu_p \tau_p \right)^{1/2} \]

- \( \tau_p \): hole lifetime
- \( T \): temperature
- \( \mu_p \): ohmic hole mobility, \( \mu_p = 120 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \)
- \( e \): electron charge

\[ \mu_p = 120 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \]

<table>
<thead>
<tr>
<th>Type</th>
<th>( L_p )</th>
<th>( \tau_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>5±1 ( \mu \text{m} )</td>
<td>52±20 nsec</td>
</tr>
<tr>
<td>b</td>
<td>7±1( \mu \text{m} )</td>
<td>160±40 nsec</td>
</tr>
</tbody>
</table>

In Si and Ge the lifetime decreases by increasing the doping concentration.

\[ \tau = \frac{1}{(1/\tau_{SRH}) + C_p n_{dop}^2} \]

\[ \tau_R = \frac{\tau_{SRH}}{1 + n_{dop}/n_{th}} \]

- Si
- Ge

E. Gaubas et al., Physica B 401 (2007) 222
Recombination mechanisms

Shockley-Read-Hall (SRH)

Results from the thermal recombination of one electron and one hole through defect levels located in the bandgap of the material.

\[ \tau_{SRH} = \frac{1}{n_0 + p_0} \left[ \left( \sigma_n N_T v_{th} \right)^{-1} (p_0 + N_V e^{-(E_T - E_V)/kT}) + \left( \sigma_p N_T v_{th} \right)^{-1} (n_0 + N_C e^{-(E_C - E_T)/kT}) \right] \]

- \( N_T \): trap density
- \( E_T \): trap energy
- \( \sigma_n, \sigma_p \): trap cross sections for electrons and holes
- \( N_V, N_C \): density of states in the valence and conductive band
- \( E_V, E_C \): valence and conductive band energies
- \( T \): temperature
- \( n_0, p_0 \): equilibrium densities of electrons and holes
- \( v_{th} \): thermal velocity

Auger recombination

A process in which an electron and a hole recombine in a band-to-band transition.

\[ T_{Auger} = 1/(CN^2) \]

Charge Collection Efficiency

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Minority carriers lifetime

The relation can be approximated by the phenomenological $1/N$ dependence:

$$\tau = \frac{\tau_{SRH}}{1 + N/N_{thr}}$$

threshold doping density

Fluctuations due to different types and concentrations of defects in the diodes

Lifetime decrease by increasing the doping concentration

The observed $1/N$ dependence could be due the presence of dopant-related traps and trap-assisted Auger processes.

Auger lifetime

No Auger recombinatons
Radiation Damage

SiC type a and c were irradiated with $^{16}\text{O} @ 35.2 \text{ MeV}$

- **Type a**
  - Signal drops down to 50% at: $4.1 \times 10^{14}$ ions/cm$^2$

- **Type c**
  - Signal drops down to 50% at: $6.5 \times 10^{14}$ ions/cm$^2$

By increasing the $^{16}\text{O}$ fluence, the energy peak moves toward lower channels indicating an increasing incompleteness in the charge collection. After irradiation, $P_{\text{AI}} = P_{\text{Peak position}}$, and before irradiation, $P_{\text{AI}} = P_{\text{Peak position}}$.

In SiC with lower doping concentration, the radiation hardness is reduced 10 times radiation harder than normal Si detectors.
Conclusions

4H-SiC from ETC-CATANIA as light ions detectors

- Good Linearity
  - SiC with lower doping concentrations need lower bias
  - Energy resolution: 5.7%-1.7%
  - Signal risetime: 44 nsec
  - CCE: 100%
- Diffusion and collection of minority carriers
  - Minority carriers lifetime decreases by increasing the doping concentration with a 1/N dependence
  - Factor 10 harder than Si

High bias values necessary to fully deplete the diodes!

Test of diodes with very low doping concentration
Signal Inversion

<table>
<thead>
<tr>
<th>Panel</th>
<th>$^{16}$O fluence ions/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>$3.5 \times 10^{14}$</td>
</tr>
<tr>
<td>c</td>
<td>$7.0 \times 10^{14}$</td>
</tr>
<tr>
<td>d</td>
<td>$10^{15}$</td>
</tr>
</tbody>
</table>

53 MeV

35 MeV

Radiation Damage

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