Thermal Annealing of Electron, Neutron and Proton Irradiation Effects on SiC Radiation Detectors

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29th November 2023

Last (43rd) RD50 Workshop
CERN 28/11-1/12/2023
Introduction and motivation
- 4H-SiC properties
- SiC radiation detectors applications

Experimental
- Fabricated devices
- Irradiations

Radiation effects and thermal annealing
- Electrical characteristics at room temperature
- Electrical characteristics from -50°C to +200°C
- Impact of thermal annealing on electrical characteristics
- Impact of thermal annealing on α particle detection

Conclusions
Introduction and motivation
4H-SiC properties

- **Wide bandgap energy** (less affected by high T)
- **Low leakage current** (even after irradiation and room T)
- **High transparency** (not affected by visible light)
- **High breakdown voltage** (power devices and detectors)
- **High thermal conductivity** (power devices)

- **High saturation velocity** (potential for timing applications)
- **High atomic displacement threshold energy** (potential radhard)
- **Potential NEMS structures & 3D detectors** (micromechanization)
- **High quality SiC substrates available** (up to 6 or 8 inches)
  (driven by commercial applications)
Renewed interest in SiC for radiation detector applications and radiation effects (HEP, fusion, synchrotron, space, medical (real time monitoring and dosimetry), ion beams (IBIC)…)

Significant number of existing results: more primitive substrates, different polytypes, different irradiation sources, mostly Schottky diode structures but also p-n junction diodes

Scattered pioneering works already described most of the radiation-induced observed effects

Present work re-visits the potential of state-of-the-art SiC material for radiation detectors
Experimental
Fabricated devices

- IMB-CNM cleanroom
- Single diodes + 4-quadrant diodes
- n-epi 4H-SiC (no suitable high-resistivity bulk SiC)
- p-on-n process
- (+2 other substrates: HR FZ Bulk & 10 μm Si)
- MOS capacitors (interquadrant isolation)
Unbiased irradiations (terminals left floating)

- **2 MeV e-** @Takasaki-QST, Takasaki, Japan
  \[ \Phi = 1 \times 10^{14}, 1 \times 10^{15}, 1 \times 10^{16} \text{ e/cm}^2 \]
  NIEL hardness factor (Si-1MeV n) \(\sim 0.0249\)

- **Neutron** @JSI TRIGA, Ljubljana, Slovenia
  \[ \Phi = 5 \times 10^{13}, 1 \times 10^{14}, 5 \times 10^{14}, 1 \times 10^{15}, 2 \times 10^{15}, 1 \times 10^{17}, 3 \times 10^{17} \text{ n/cm}^2 \]
  NIEL hardness factor (Si-1MeV n) \(\sim 0.9\)

- **24 GeV/c p+** @PS-IRRAD CERN, Geneva, Switzerland
  \[ \Phi = 8.6 \times 10^{13}, 1.5 \times 10^{14}, 1.0 \times 10^{15}, 1.7 \times 10^{15}, 2.5 \times 10^{15} \text{ p/cm}^2 \]
  NIEL hardness factor (Si-1MeV n) \(\sim 0.56\)

Electrical characterization (except interquadrant resistance)
Radiation effects and thermal annealing
Radiation effects: I-V and C-V @Room T

- **Low $I_{\text{reverse}}$ @room T for all irradiations**: (different to Si: $I_{\text{vol,Si}} = \alpha \cdot \Phi$)

- **Radiation-induced decrease** in $I_{\text{forward}}$
  - Defects ($V_C, V_{Si}, V_C+V_{Si}...$) $\Rightarrow$ conduction resistance $\uparrow$
  - carrier removal/doping compensation $\Rightarrow$ $R_{\text{series}}$ $\uparrow$ (unipolar Schottky)
  - $\tau_{\text{recombination}}$ $\downarrow$ $\Rightarrow$ conduction modulation drift layer $\downarrow$ (bipolar p-n)

- **Electrical rectification lost** for highest fluences ($1 \times 10^{16}$ e/cm$^2$ & $>1 \times 10^{15}$ n-p/cm$^2$)

- Flat C-V

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- SIC electron irradiation
- SIC neutron irradiation
- SIC proton irradiation
Radiation effects: I-V and C-V @Room T - High V

**Electrical rectification character** is lost for the highest fluences:

- **Low currents** (reverse + direct)
- **Flat C-V characteristics** (reverse + direct)

Lightly doped epilayer **becoming intrinsic**

Geometrical capacitance

\[
C = \frac{\varepsilon_{SiC} \cdot \text{Area}}{\text{Epi thickness}} \approx 25.7 \text{ pF}
\]
I-V direct: impact of measuring T [-50°C to 200°C]

\[ I = I_0 \cdot \left( e^{\frac{q(V-I\cdot R_S)}{nKT}} - 1 \right) \]

**Non-irradiated**

- T-constant low \( R_S \)
- \( n_2 \sim [1.12-1.15] \) (quasi neutral region)
- \( n_1 \sim [1.8-2.4] \) (space charge region)

**Medium fluences**

\(~1\times10^{14} \text{ n/cm}^2\) or \(~1.5\times10^{14} \text{ p/cm}^2\)

**High fluences**

\(~2\times10^{15} \text{ n/cm}^2\) or \(~1.7\times10^{15} \text{ p/cm}^2\)

- T-dependent higher \( R_S \)
- \( T < -15°C \) defect freeze-out
I-V: impact of measuring T [-50°C to 200°C]

T-dependence $R_s$
(base/epitaxy $\rho$)

$E_{activation} [0.3-1] \text{ eV}$

Fluence $\uparrow$ ⇒ deeper $E_{act} \uparrow$
($Z_{1/2} \text{ level } 0.5 < E_a < 0.69 \text{ eV } ?$)

I-V reverse

Non-irradiated

Highest irradiation fluences
T-dependent reverse current $\uparrow$ (>100°C)

$E_{activation} \uparrow$
The figure illustrates the detection of α particles with a SiC diode. It shows the measurement of electron, neutron, and proton irradiation effects on SiC. The measurements were performed at room temperature (21 °C) and at 400 V.

- **Electron Measurement:** Non-irradiated: 3 peaks with centroids around channels 210, 230, and 250.
- **Neutron Measurement:** 5 distinct channels with the highest fluences showing a unique pattern. SRIM indicates an α range of approximately 12-15 μm < epi-SiC.
- **Proton Measurement:** Three distinct channels observed.

**Key Observations:**
- **Non-irradiated:** 3 peaks with centroids around channels 210, 230, and 250.
- **SiC spectra acquisition @ room T:** $I_{\text{reverse SiC}} < I_{\text{reverse Si}}$ (Si noise).
- **α detection still observed:** For high irradiation fluences where no electrical rectification is observed.
- **Peaks shift + broaden:** For highest neutron and proton fluences. (Defects $\Rightarrow$ recombination/charge traps $\Rightarrow$ collected charge↓, straggling↑).

The figure also highlights the use of different isotopes as α sources: $^{239}$Pu, $^{241}$Am, and $^{244}$Cm. The measurement setup includes a SiC diode with an epi-SiC layer.
α particle detection

- Non-irradiated efficiency saturation @~250 V ($W_{dep}$~12.5 μm)
- Capability for α detection is still observed for high irradiation fluences where no electrical rectification character is observed

For example: ΔCCE @400V: ~-10% @1x10^{16} e/cm², ~-50% @1x10^{15} n/cm², ~-33% @1x10^{15} p/cm²
Cumulative thermal annealing experiments

- Non-irradiated: Partial recovery of direct conduction (diode functionality) + C-V diode-like


  $T$-dependent $R_s \ (E_{activation} \sim 0.50 \text{ eV} \Rightarrow Z_{1/2} \ \text{level} \ (0.5 < E_a < 0.69 \text{ eV})) \quad \text{(No significant changes in } I_{reverse} \ \& \ R_{interquadrant})$
Some improvement in charge collection efficiency after thermal annealing

Pointing to radiation harder under high-T operation

Thermal annealing on α particle detection

- Non-irradiated
- 1x10^15 e/cm²
- 2x10^15 n/cm²
- 1.7x10^15 p/cm²
α particle detection also in forward operation

Some smaller charge collection efficiency in forward, but better energy resolution, even at low |V|

Filled radiation-induced acceptors under forward bias may decrease charge trapping
Conclusions
Conclusions

- p-n junction diodes fabricated on epitaxied SiC
- Effects of 2 MeV e-, neutron & 24 GeV/c p+ irradiation on electrical characteristics (I-V, C-V, $R_{\text{interquadrant}}$)
  - Low $I_{\text{reverse}}$ @room $T$, with loss of electrical rectification character (I-V and C-V) for highest fluences
- Impact of measuring temperature [-50$^\circ$C-200$^\circ$C]
  - Radiation-induced $T$-dependent $R_s$ in direct (Fluence $\uparrow$ $\Rightarrow$ $E_{\text{activation}}$ $\uparrow$)
  - Highest irradiation fluences $\Rightarrow$ T-dependent reverse current $\uparrow$ (>100$^\circ$C), $E_{\text{activation}}$ $\uparrow$
- Cumulative thermal annealing experiments [100$^\circ$C-400$^\circ$C]
  - e-irradiated: partial recovery of diode functionality (I-V and C-V) (annihilation of close defects, $V_s$ and $I_s$)
  - T-dependent $R_s$ in direct ($E_{\text{activation}}$ ~ 0.5 eV, in agreement with $Z_{1/2}$ level)
  - Some improvement in charge collection efficiency after thermal annealing
- $\alpha$ particle detection also in forward operation
- Studies/collaboration would be needed to get a better picture of the involved phenomena (defect characterization, annealing, simulation…)
- Some superior properties of SiC devices for radiation detectors applications: high-$T$ applications and simplify current experiments implemented with Si (no cooling needed & visible light proof)
Thank you for your attention

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This work was supported in part by the Spanish Ministry of Science, Innovation and Universities through the Nuclear and Particle Physics Program under Project PID2021-124660OB-C22, in part by the European Union’s Horizon 2020 Research and Innovation Program under Grant 654168 (AIDA-2020), in part by a collaborative research project at Nuclear Professional School, School of Engineering, The University of Tokyo, under Grant 20016, in part by The Japan Society for the Promotion of Science KAKENHI, under Grant JP19K05337 and it has made use of the Spanish ICTS Network MICRONANOFABS partially supported by MICINN. The work of Gemma Rius was supported by Spanish Ministry of Science and Innovation through Ayudas Ramón y Cajal 2016, under reference RYC-2016-21412.