Measurements and Simulations of High Rate 4H-SiC Particle Detectors

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Silicon Carbide (SiC)

- Recently has become more available due to interest in power electronics industry
- Insensitive to optical light and can be operated without any cooling
- Currently only thin (< 100 μm) epi layers possible (limited by defect density).
- For MIP particles and typical detectors:
  - SiC: 50 μm * 57 e/μm ~ 2.8 ke
  - Si: 300 μm* 72 e/μm ~ 21ke

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>4H-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap energy E_g [eV]</td>
<td>1.12</td>
<td>3.27</td>
</tr>
<tr>
<td>Ionization energy E_i [eV]</td>
<td>3.64</td>
<td>5-8 [2,3]</td>
</tr>
<tr>
<td>e/h pairs per μm for MIPs (MPV)</td>
<td>~ 72</td>
<td>~57 [2]</td>
</tr>
<tr>
<td>Atomic displacement threshold [eV]</td>
<td>13-20</td>
<td>22-35</td>
</tr>
<tr>
<td>Breakdown field [MV/cm]</td>
<td>0.3</td>
<td>⊥: 4.0;</td>
</tr>
<tr>
<td>Saturated electron velocity v [10⁷ cm/s]</td>
<td>1</td>
<td>2.2</td>
</tr>
<tr>
<td>Electron mobility [cm²/V/s] (at 300K)</td>
<td>1300</td>
<td>800-1000 [3]</td>
</tr>
<tr>
<td>Hole mobility [cm²/V/s] (at 300K)</td>
<td>460</td>
<td>115</td>
</tr>
<tr>
<td>Impact ionization coefficient</td>
<td>α_e &gt; α_h [3]</td>
<td>α_e &lt; α_h [3]</td>
</tr>
</tbody>
</table>

Data taken from [1] if not noted otherwise.

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SiC Samples

- p on n diode, 3 x 3 mm² active area, 50 μm nominal thickness
- Planar and strip (64 strips, 50 μm pitch) diodes
- Samples from Run 13575 of IMB-CNMCNM-CSIC Barcelona
- $V_{depl} = 300$ V, Leakage Current < 10 pA for $V_{bias} < 600$ V and planar sensor

Geometry of SiC samples (without segmentation) [4]

SiC strip (top) and planar sensor (bottom) samples [5]
Readout Electronics

- UCSC “LGAD” board for planar diodes and APV25 ASIC [6] for strip detectors

- Waveform digitization using R&S RTP164 oscilloscope or DRS4 evaluation board

~ 200 k€
40 Gs/s, 16 GHz

~1 k€
5 Gs/s, 700 MHz

UCSC “LGAD” readout board with planar SiC sample (left) and APV25 ASIC with SiC strip detector (right) [5]
Pulse Analysis Software

- Import data from oscilloscopes or simulations (AllPix², WeightField2, ...)
- Fixed threshold or constant fraction discrimination (CFD) analysis
- Calculation of pulse area, maximum and time-over-threshold as well as SNR.
- Landau/Gauss fits and voltage ramp evaluation

[Graphs showing pulse analysis results with annotations]

https://gitlab.com/dd-hephy/HiBPM/RS_DRS4_run_analysis
Proton Beam Measurements: Energy Scan

- Measurements performed at the MedAustron (Wiener Neustadt) ion beam therapy center [9]
  - 60 – 800 MeV protons
  - Using special low flux (~5·10^6 protons/s) settings [10].
  - Beam extracted in spills of 5-10 s
- Beam telescope using a SiC strip detector and two DSSD + trigger scintillators [2].

Experimental Setup [5]

Overview of the MedAustron accelerator. Proton beams, as well as carbon and (soon) helium beams are available [10]
Proton Beam Measurements: Energy Scan

- Small SiC Signals $\rightarrow$ Landau distributed energy loss overlaps with Gaussian noise
- Employ cuts on samples-over-threshold and use tracks to separate signal and noise peaks.

- Measured $E_i = 5.85$ eV via calibration with a Silicon detector
- Extrapolated charge carrier creation to ~2’800 e/h pairs for a MIP particle in 50 μm SiC
- $57 \pm 4$ eh-pairs/μm for a MIP particle (in 45 μm thickness), matching with literature [1]

Left: Fitted Landau distribution for 800 MeV protons after applying cuts.
Right: ADC counts as a function of the incident beam energy [5]
Irradiation Studies

- Irradiation of planar samples using MeV neutrons at the TRIGA Mark-II reactor in Vienna [10].

- Investigated equivalent fluences between $5 \cdot 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$ and $1 \cdot 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ with UV-TCT and proton beam measurements.

Leakage current (with UCSC board) for different fluences [12]. Even for very high fluences, the leakage current is not a limiting factor.
UV TCT

- UV- Top Transient Current Technique (UV has enough energy to overcome SiC bandgap)
- PILAS DX PiL037-FC Laser, $\lambda = 370$ nm ($\sim 3.35$ eV), pulse width $<70$ ps [13], custom UV beam optics, spot size $<10$ $\mu$m.
- Absorption coefficient in 4H-SiC: $\alpha \approx 42.2$ cm$^{-1}$ [14] → uniform charge deposition in detector
- Large, Gaussian distributed signals (around $4 \cdot 10^6$ e/h pairs per pulse)
**Irradiated Samples: UV-TCT**

- No saturation reached in collected charge for irradiated samples (the voltage range in this measurement was limited by the SMU)
- Signals become smaller and shorter for higher fluences
- Charge collection efficiency CCE (normalized to non-irradiated sample) compares well to other measurements (using a $\alpha$-source) [15]
- No Signals from detector with $1 \cdot 10^{16}$ $n_{eq}/cm^2$ irradiation
As seen in the proton beam energy scan, SiC signals are very challenging to measure for our samples because of the low amount of produced charge carriers.

For irradiated samples with a lower CCE, this problem will be even worse → Need to somehow increase the deposited charge.

Can not use same tracking setup as for the energy scan because only planar sensors were irradiated.

Idea: “Simulate” thicker sensor by varying the incidence angle of the beam.
Proton Beam Angle Scan

- For lower incidence angles only the Landau tail is observable, as the SiC signal overlaps with the Gaussian noise peak.
- For higher incidence angles (= longer track length in detector), the entire peak (now Gaussian) can be measured.
- Conclusion: Use an incidence angle of 90° (similar to edge TCT) for irradiated samples.

![Chart showing Planar SiC non-irradiated, Angle Scan](chart.png)

- **p⁺ beam**: 252.7 MeV

Setup at the MedAustron accelerator with green alignment lasers [12]

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Proton Beam Measurements: Irradiated Samples

- CCE unfortunately not available due to electrical issues during the measurement of the non-irradiated sample.
- Collected charge (proportional to signal area) increases with bias voltage, except for most heavily irradiated sample.
- Charge collected for sample with fluence $1 \cdot 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ (cyan) hard to discriminate from noise.
- Time-over-threshold is very short (< 1 ns) for highly irradiated samples.

Signal area vs. reverse bias voltage (left) and time-over-threshold (right) for irradiated samples in 90° orientation and 252.7 MeV protons.

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High Proton Beam Rates

- Very large interest in ultra high dose rate (UHD) radio therapy [16,17].
- FLASH effect: Preliminary evidence for better normal tissue sparing at high dose rates (> 40 Gy/s)[17].
- Challenges in UHD dosimetry because of dose rate dependencies
- Silicon (relative) dosimeters show non-negligible dose rate dependencies, especially after irradiation. [18]
- SiC could be an interesting candidate for UHD dosimetry [19]
- Can achieve higher dose rates at MedAustron by decreasing the synchrotron extraction time (nominal 5-10s)

Tumor control vs. normal tissue complication probabilities for conventional and FLASH radiotherapy [16]
High Proton Beam Rates

- Measure particle flux via leakage current through planar SiC detector:

- Flux \( [\text{cm}^{-2} \text{s}^{-1}] \approx \frac{I_{\text{SMU}}}{(5.6 \text{ keV}) / (3 \text{ mm} \times 3 \text{ mm})} \)

- For medical beam rates (5s extraction of \(~10^{10}\) protons), we measure a flux of \(~2 \cdot 10^7\) p/cm\(^2\)/s

![Experimental Setup](image.png)
High Proton Beam Rates

• Tested extraction times from 1 s down to 7 ms using “Constant Optics Slow Extraction” COSE [20].

• Fast sampling (2.8 kHz) using the Keithley 2470 SMU

• No saturation observed up to a leakage current of 300 μA, corresponding to a flux of

$$\sim 3 \cdot 10^{12} \text{ protons} / \text{cm}^2 / \text{s}$$

• Because of the experimental accelerator settings, the beam is likely lost after the first half of the extraction.
AllPix\(^2\) Simulation of SiC Sensors

- Materials other than Si are not always supported by solid state detector frameworks.
- For frameworks that support SiC, the material parameters are not always correct (WeightField2) or numerical issues exist (convergence issues in Synopsys TCAD).
- AllPix\(^2\) [8] is a modular framework, where each submodule can be modified and adapted to SiC.
- Often used for testbeam setups (integration with Corryvreckan) but simulating single detectors is also possible.
- Physics models (for ex. e/h mobility model) can be defined using a macro language → no need to recompile.
- Energy deposition using Geant4.
- Electric/Weighting fields can be imported from TCAD / COMSOL.
Our Simulation Workflow

- **Geant4**: A simulation toolkit
- **HEPHY Fork**: https://gitlab.cern.ch/allpix-squared/allpix-squared/-/merge_requests/759
- **HTCondor**: Transient Pulses
- **Electric Field Weighting Field**: Analysis Software

Benchmarks with planar Si detectors ongoing, SiC as a next step

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Next Steps

- New run with CNM aiming at planar SiC detectors with a thickness of 100 μm
- Work towards SiC LGADs
- Simulate SiC planar sensors and LGADs in AllPix²
- Ongoing development of a high rate / integrating ASIC, first prototypes expected to arrive in Autumn
- Further investigate SiC detectors at very high dose rates (higher time resolution, dosimetric comparisons)
References + Acknowledgments

We thank IMB-CNM-CSIC for the SiC samples.
This work was supported by the Austrian research promotion agency FFG, project number 883652

References:

[9] https://www.medaustron.at/
[12] Markus Göbel, Studies on Irradiated 4H-SiC Diodes as Semiconductor Particle Detectors, Master’s Thesis
[20] Prokopovich, D. A. et al. INVESTIGATION OF CONSTANT OPTICS SLOW EXTRACTION (COSE) AT MEDAUSTRON.
BACKUP SLIDES
Microscope Image of Planar SiC sample
Electrical Characterization of planar SiC samples

Electrical Characterization of SiC samples [5]

V_{depl} = 296 V
C @ 400V = ~20 pF
SiC LGAD production

<table>
<thead>
<tr>
<th>Challenge: Low doping activation rate of SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inefficient implantation of doping layers</td>
</tr>
<tr>
<td>Use epitaxial growing</td>
</tr>
</tbody>
</table>

- High energy ion implantation
- Epitaxial growing
- Ion implantation + long annealing
- Bevel edge termination

Challenges in SiC LGAD production [7]
Planar SiC Am-241 (α) Measurements

Comparison of signals induced by α-particles in SiC (above) and Si (below) [5]
Planar SiC Sr-90 ($\beta$) Measurements

For a Sr-90 source, the induced signals in our SiC sample are too small to be distinguished from noise.
Irradiated Samples: UV-TCT

Pulse maximum and ToT as a function of the bias voltage
Proton Beam Angle Scan

- At normal incidence, each particle “sees” the same detector thickness
- Because our detector is not infinitely large, some tracks will be cut off and “see” a lower thickness
  → Overlap of Landau distributions for different detector thickness
- At a “critical angle” $\alpha_{\text{crit}}$, all track lengths between the diagonal through the detector and zero are equally likely
Proton Beam Angle Scan

GEANT4 simulation of deposited charge in 320 μm Si for different incidence angles

- Landau distribution for normal incidence
- Gaussian Peak
- Contributions from smaller track lengths

0 deg = 320 μm
85.5 deg ~ 4000 μm
Proton Beam Angle Scan

Planar SiC non-irradiated, Angle Scan

- Angle: 0.0°, eqv. Thickness: 45.0μm
- Angle: 76.5°, eqv. Thickness: 193.0μm
- Angle: 81.0°, eqv. Thickness: 288.0μm
- Angle: 82.8°, eqv. Thickness: 359.0μm
- Angle: 84.6°, eqv. Thickness: 478.0μm

Charge (Signal Area) [Vs]

Normalized Probability

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ASIC for High Rate Beam Monitor

Manufactured using the free, open-source SKY130 process

Preliminary architecture of the readout ASIC under development. The ASIC has two signal pathes. The first signal path (shown in blue) is used for counting individual particles, the second is used to measure the bulk particle flux (green).
AllPix²: Transient Signals

- Current at readout electrode is calculated using Ramo’s theorem during each propagation step
- Convolution of current with amplifier response function yields signal

Electron and Hole current for a MIP in a planar Si sensor with 320 μm thickness

Amplifier response function

+ Gaussian noise

Amplifier signal with added noise in pixel (0-0)

“PixelPulse” object, see https://gitlab.cern.ch/allpix-squared/allpix-squared/-/merge_requests/759
FLASH offers a larger therapeutic index ( = TC/NTC), which means that tumors can be irradiated with higher doses, increasing TC.

The actual mechanism of the FLASH effect (normal tissue sparing) is still unknown. One leading theory is oxygen depletion [17].
High Proton Beam Rates

- Constant optics slow extraction (COSE) should result in a Gaussian extraction of the stored beam as a function of time.

- Gaussian fits matches well to measurements

Measured SMU current (blue) together with a Gaussian fit (black) for different extraction times.
SiC Simulation Challenges : TCAD

From [7]:

- SiC poorly implemented in most material databases
- Insufficient adaption for drift diffusion and impact ionization
- Convergence issues for due to low current densities
  → Floating point precision is essential
- Active cooperation with Global TCAD Solutions (GTS) to improve software regarding SiC simulation
SiC Simulation Challenges : WeightField2 (v5.2)

- For the “MIP Landau” particle type, WF2 uses either a deposited energy spectrum for Si or Diamond (“Silicon_Vin” or “Diamond_Vin” in Geant_Vin.root. For SiC no distribution is available and the Si one is used.
- For “MIP Landau” the pair creation energy of Si (3.6 eV) is used instead of the one for SiC (5-8 eV).
- In order to handle different detector thicknesses, WF2 rescales the Landau distributions according to measurements and fits for Si [21]. This is incorrect for Diamond and SiC.
- The dielectric constant for SiC is also incorrect, at $\varepsilon_r = 11.9$ (taken from Si) instead of $\varepsilon_r \sim 9.6$ for SiC.