Advances in SiC Detectors for HEP and Medicine

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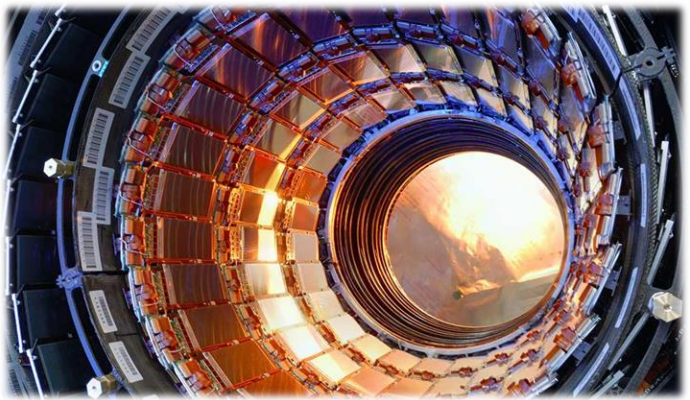
HEPHY SiC Research

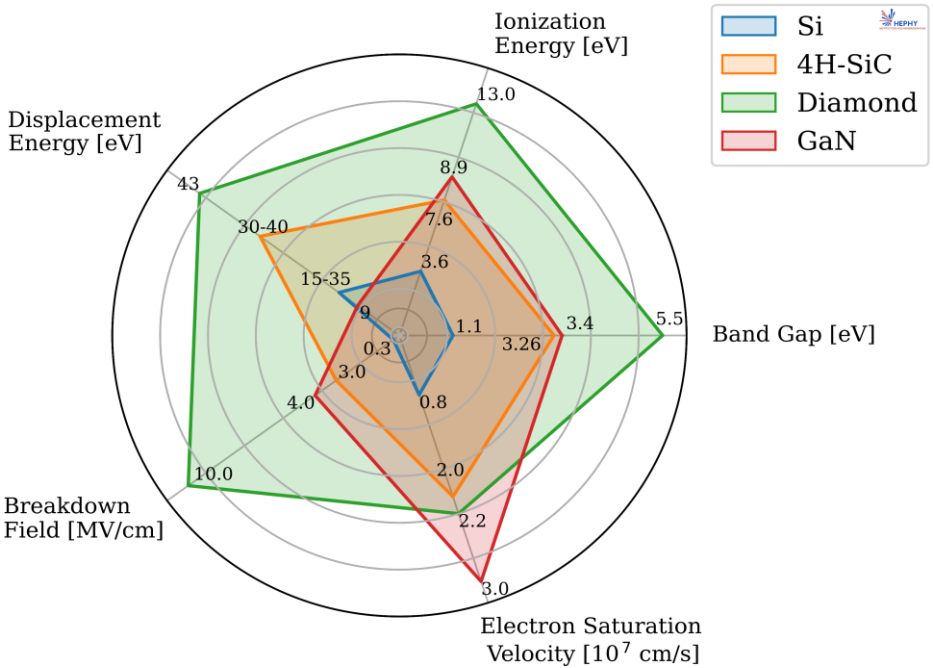
High Energy Physics
Timing, Radiation Hardness



Medical Applications
Beam Monitoring, Dosimetry

4H-SiC for Particle Detectors

- Investigated as detector material already 20 years ago [1], [2]
- Recently got attention due to applications in the power electronics and automotive industry
  ⇒ Increased availability and lower costs
- Wide bandgap
  ⇒ no cooling / pA dark currents even after irradiation
  ⇒ insensitive to visible light
- High V_{BD} & high v_{sat}:
  ⇒ high voltages, fast signals ⇒ timing



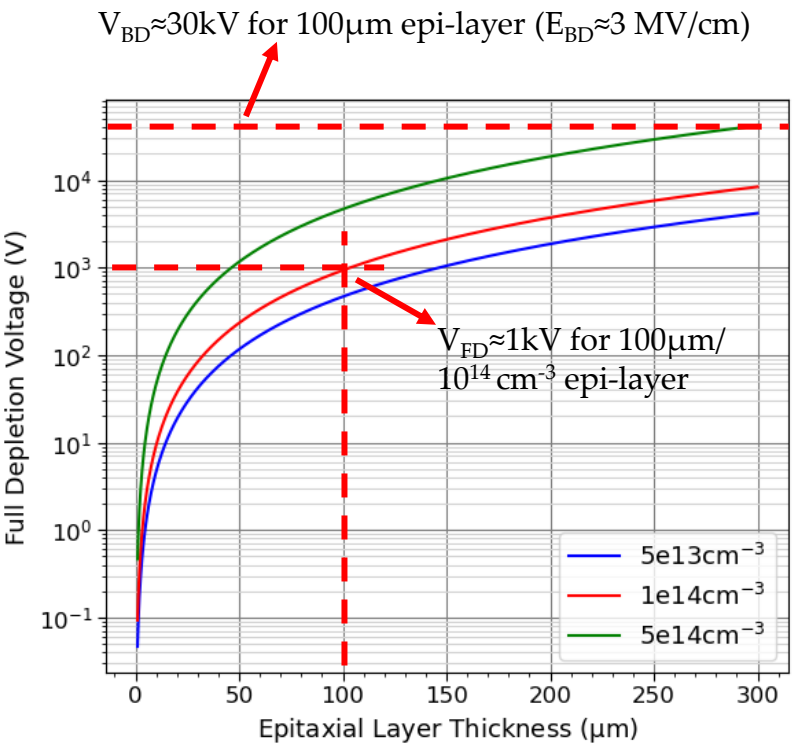
[1] Pintilie, I., et. al. (2010). Analysis of electron traps at the 4H–SiC/SiO2 interface; influence by nitrogen implantation prior to wet oxidation. Journal of Applied Physics, 108(2).
[2] Moscatelli, F., et. al. (2005). Measurements and simulations of charge collection efficiency of p+/n junction SiC detectors. Nuclear Instruments and Methods in Physics Research Section a Accelerators Spectrometers Detectors and Associated Equipment, 546(1–2), 218–221.

4H-SiC for Particle Detectors: Limitations

- Epi doping ≥10^{14} cm^{-3} by standard
  ⇒ ~1kV needed for fully depleting 100µm
  ⇒ HV stability becomes a challenge for thick sensors due to arcing, insufficient guarding or isolation (but not due to the material, E_{BD} = 3 MV/cm)

- High ionization energy (57 e/h-pairs per µm by MIP [3]) & epi thickness limited to ~100µm
  ⇒ small signals ⇒ not sufficient for MIP detection

  ⇒ Improve SNR with **SiC LGAD** (Low Gain Avalanche Diode) with internal signal amplification

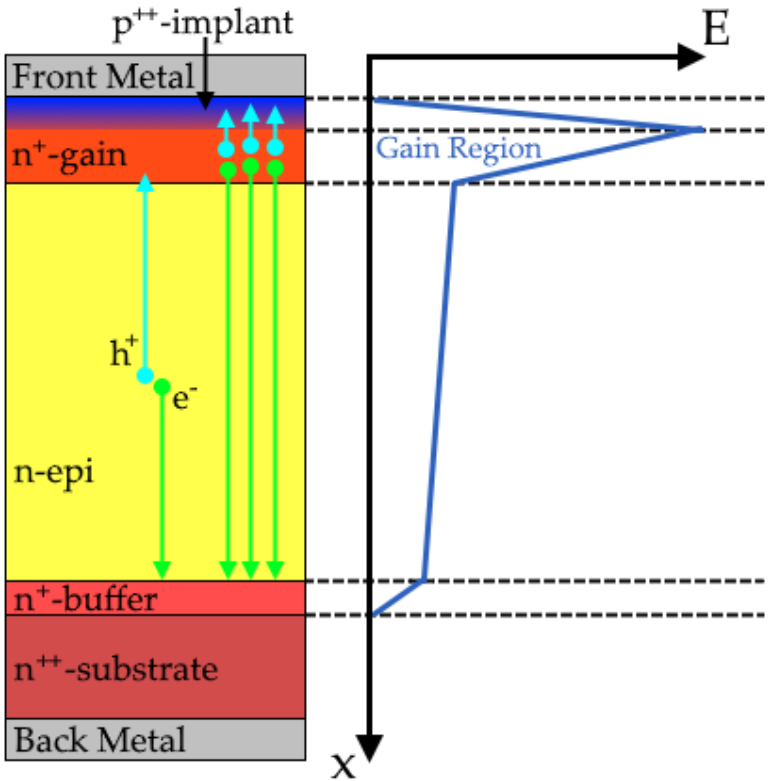


[3] Christanell, M., Tomaschek, M., & Bergauer, T. (2022). 4H-silicon carbide as particle detector for high-intensity ion beams. *Journal of Instrumentation*, *17*(01), C01060. https://doi.org/10.1088/1748-0221/17/01/c01060

SiC-LGAD

	Si-LGAD	4H-SiC-LGAD
Structure	n-in-p	**p-in-n**
Impact Ionization	$\alpha_e > \alpha_h$ electrons multiply	**$\alpha_h > \alpha_e$ holes multiply**
E_{BD}	300 kV/cm	**3 MV/cm**
$v_{sat,e}$	$1.0 \cdot 10^7$ cm/s	**$1.9 \cdot 10^7$ cm/s**
$v_{sat,h}$	$0.8 \cdot 10^7$ cm/s	**$1.3 \cdot 10^7$ cm/s**

- Si LGAD lose gain with increasing irradiation
  ⇒ SiC LGAD more radiation hard? (donor removal in SiC?)

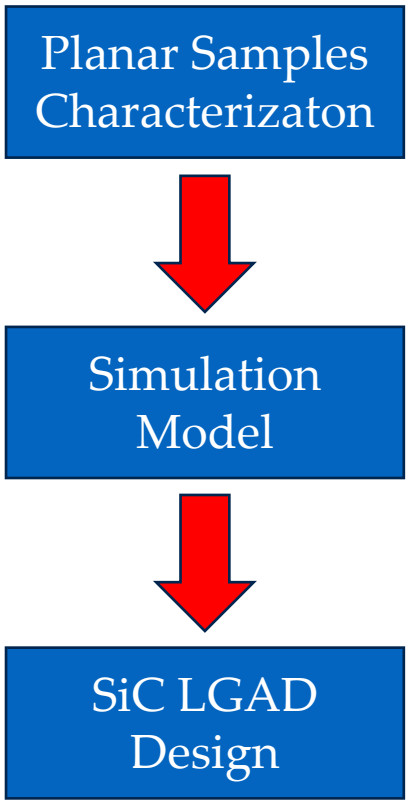


4H-SiC Sensor Design Workflow

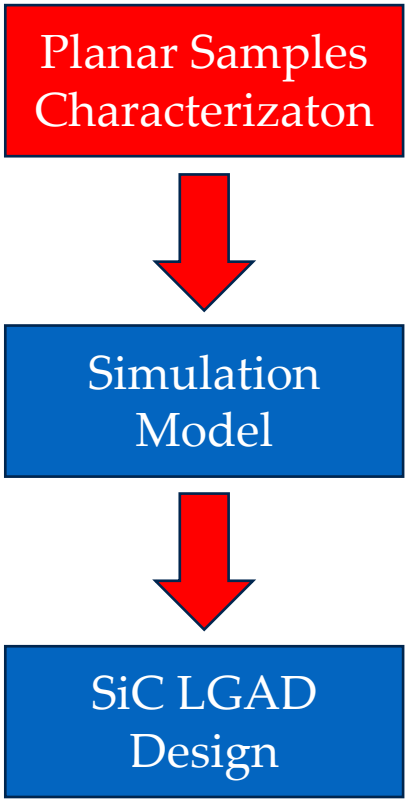
1. Characterize 4H-SiC planar samples (without internal amplification) pre-/post irradiation

2. Simulation of (un)irradiated 4H-SiC sensors
   - Modelling of I-V, C-V and CCE characteristics based on measurements
   - Literature review of material parameters
   - Radiation damage modelling

3. SiC Low Gain Avalance Diodes (LGAD)
   - Design of SiC LGAD architecture in simulation
   - Production (i.e. waiting until samples arrive) ← We are here
   - Testing timing performance and radiation hardness



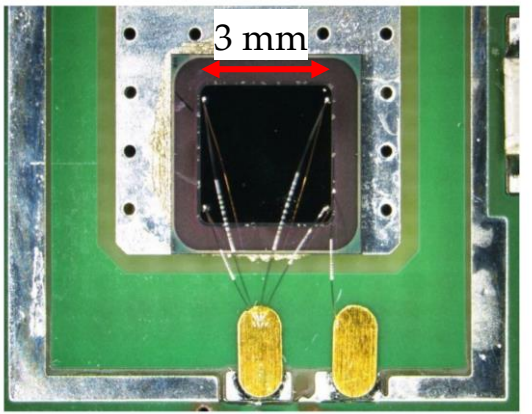
Characterization of Planar Samples



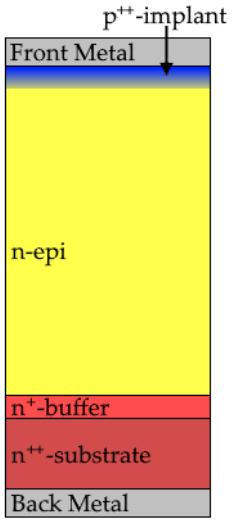
Characterization of Planar Samples

- 3x3mm² planar 4H-SiC sensor diodes by CNM

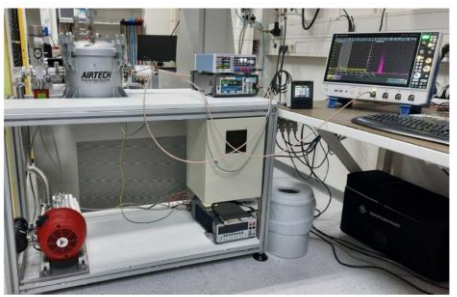
- Neutron irradiation for radiation hardness studies
  - Up to 10^{16} n_{eq}/cm^2 at Atominstitut in Vienna
  - Recently also 10^{18} n_{eq}/cm^2 at JSI in Ljubljana
  - Only small sample size per fluence
- Pre- and post irradiation characterization using:
  - I-V and C-V measurements
  - Charge collection efficiency (CCE) using UV-laser, alphas and protons



4H-SiC pad diode on readout board



https://doi.org/10.1088/1748-0221/18/11/c11027

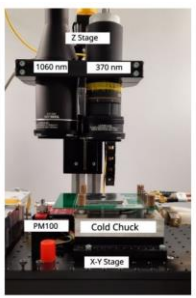


Tri-Alpha in Vacuum (^{239}Pu, ^{241}Am, ^{244}Cm)

https://doi.org/10.1088/1748-0221/18/11/c11027

62.4 MeV p⁺ at MedAustron (AT)

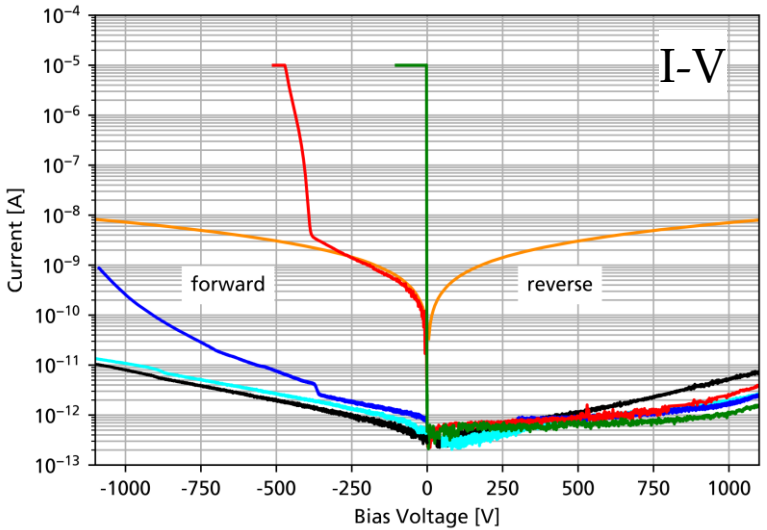
https://doi.org/10.1016/j.nima.2022.167218

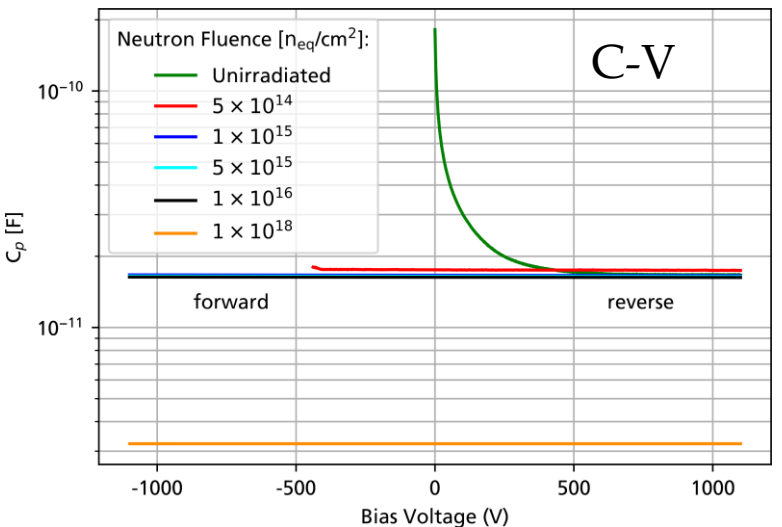


UV-LASER (370nm)
< 100 ps pulse length

Planar Diodes: I-V and C-V pre/post Irradiation

- Up to 10^{16} n_{eq}/cm^2:
  - Negligible increase of reverse current (10 pA)
  - Forward current reduced due to increased charge carrier trapping
  - C-V flatlines: epi n-doping compensated by deep-level traps ($Z_{1,2}$, EH_4)
- For 10^{18} n_{eq}/cm^2:
  - Forward/reverse current is identical and increased (>1 nA)
  - Traps also compensate buffer layer and substrate
    ⇒ full die thickness contributes to capacitance ⇒ significant decrease in capacitance

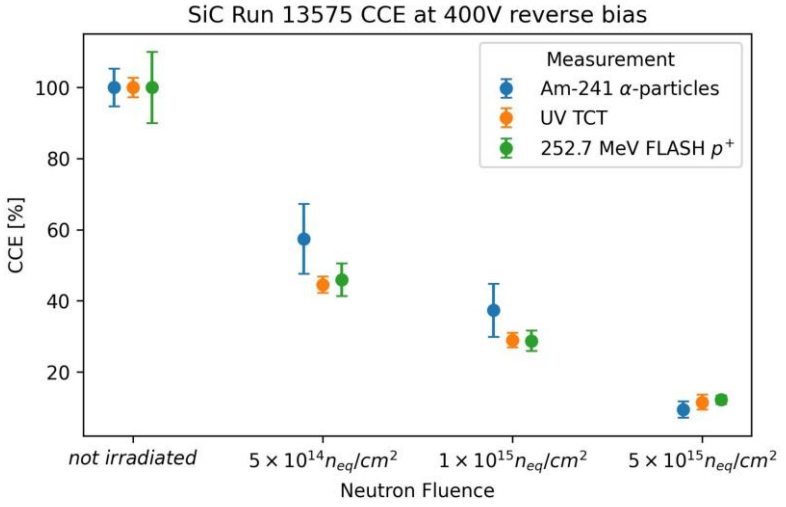




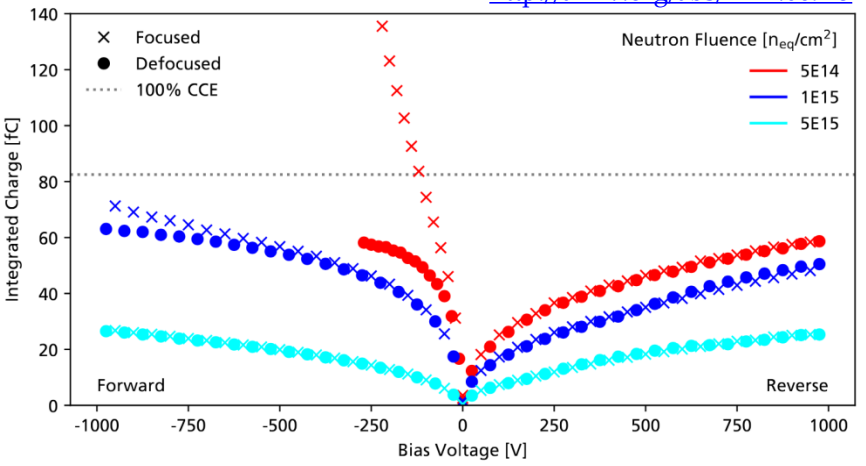
Planar Diodes: CCE pre/post Irradiation

- ~25% CCE after 10^{15} n_{eq}/cm^2
  - Trapping
  - Beneficial annealing at elevated temperatures (> 200°C) [4], [5]?
- Charge collection also possible in forward direction
- For UV-TCT in forward bias and low fluence: CCE can surpass 100%!
  - Traps are filled ⇒ carrier lifetimes increase ⇒ conduction is restored
  - Only for sufficient injected charge density ⇒ high laser power and tiny focus needed ⇒ not for MIPs

[4] J. M. Rafi et al., (2023). Low Temperature Annealing of Electron, Neutron and Proton Irradiation Effects on SiC Radiation. Detectors IEEE Trans. Nucl. Sci., pp. 1–1.
[5] E. Medina et al., (2023). Radiation Hardness Study of Silicon Carbide Sensors under High-Temperature Proton Beam Irradiations. Micromachines, vol. 14, no. 1, p. 166.

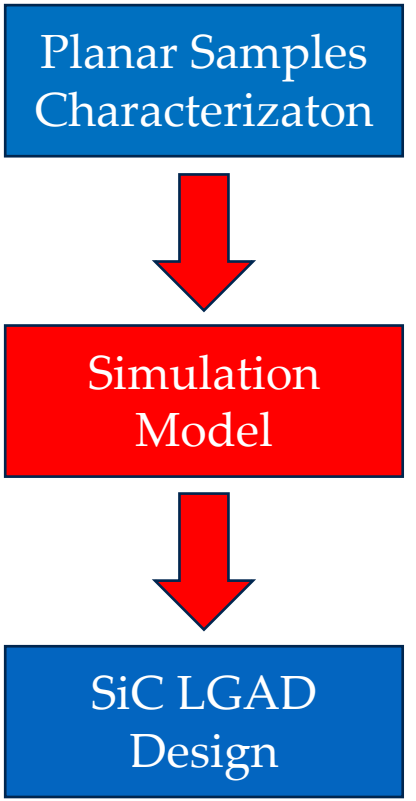


http://arxiv.org/abs/2412.06973



Signal for defocused / focused UV-laser

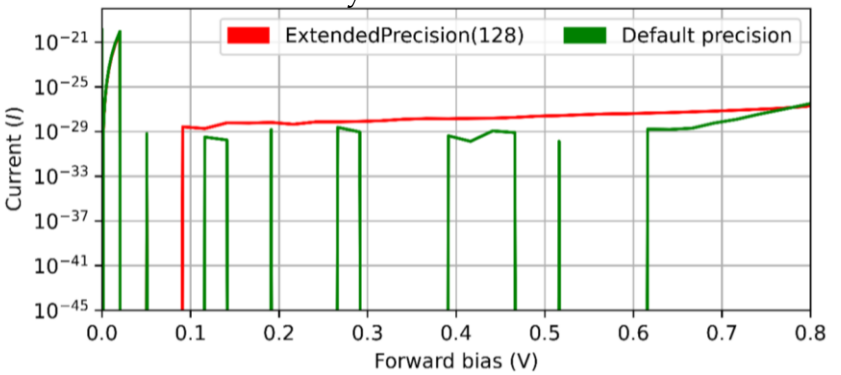
Simulation of 4H-SiC Devices



Simulating 4H-SiC Devices

- Device simulation using Synopsys Sentaurus [6], Global TCAD Solutions [7] and AllPix² [8]
- Convergence issues in Synopsys TCAD:
  - Wide bandgap of 4H-SiC leads to very low intrinsic charge carrier densities
    ⇒ Numerical errors using default floating-point precision
    ⇒ Extended floating-point precision needed
  - Finer mesh needed
    ⇒ Increase in computation time
- Material parameters:
  - Deviate across literature
  - Si or 6H-SiC parameters often misused for 4H-SiC
- ⇒ Extensive literature review to understand origin of commonly used material parameter values

Numerical instability in forward-IV TCAD simulation



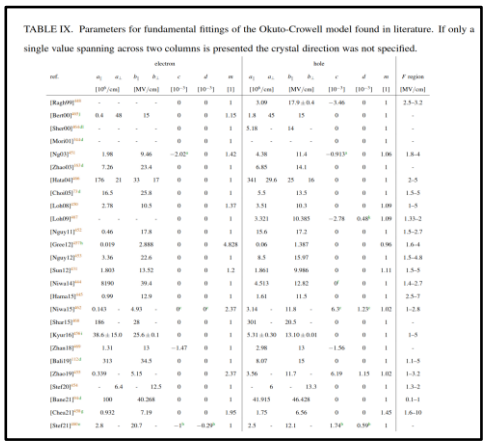


TABLE IX. Parameters for fundamental fittings of the Okuto-Crowell model found in literature. If only a single value spanning across two columns is presented the crystal direction was not specified.

Literature Review of 4H-SiC model parameters
https://arxiv.org/abs/2410.06798
(>180 pages, >800 references)

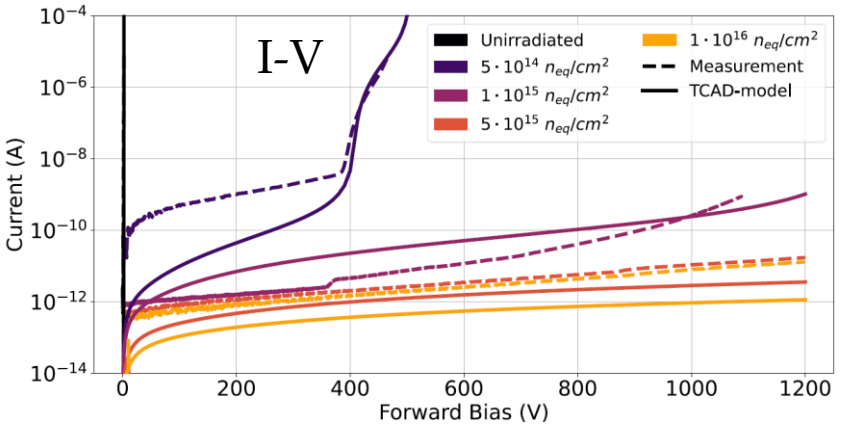
[6] Synopsys Sentaurus TCAD Framework. URL: https://www.synopsys.com/manufacturing/tcad/framework.html.
[7] GTS Framework. URL: https://www.globaltcad.com/products/gts-framework/.
[8] S. Spannagel et al. (2018). Allpix²: A modular simulation framework for silicon detectors. Nucl. Instr. Meth. A 901 (2018) 164 – 172.

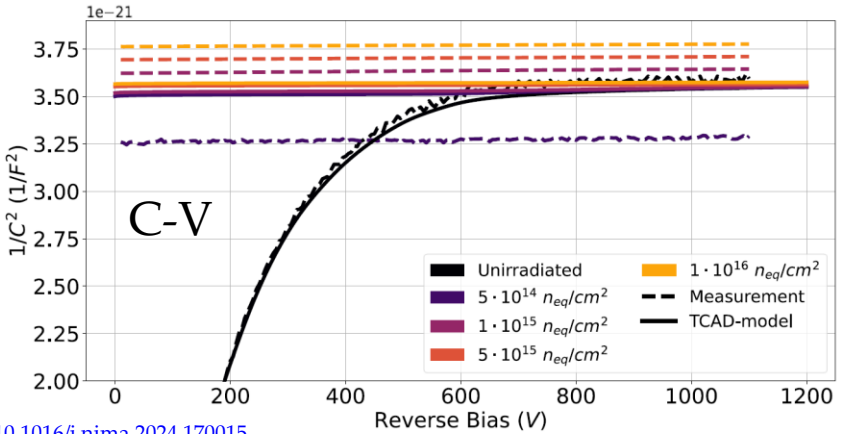
Radiation Damage Model

- Radiation damage model (preliminary) via radiation induced traps for simulation in TCAD [9], [10]
- Material and defect parameters deviate across literature:
  - Initial guesses from literature
  - Optimized by fitting simulation results to measurement
- Reasonable agreement

Defect	Type	Energy	g_{int} [cm^{-1}]	σ_e [cm^2]	σ_h [cm^2]
$Z_{1,2}$	Acceptor	$E_C - 0.67\,eV$	5.0	2e−14	3.5e−14
$EH_{6,7}$	Donor	$E_C - 1.6\,eV$	1.6	9e−12	3.8e−14
EH_4	Acceptor	$E_C - 1.03\,eV$	2.4	5e−13	5.0e−14

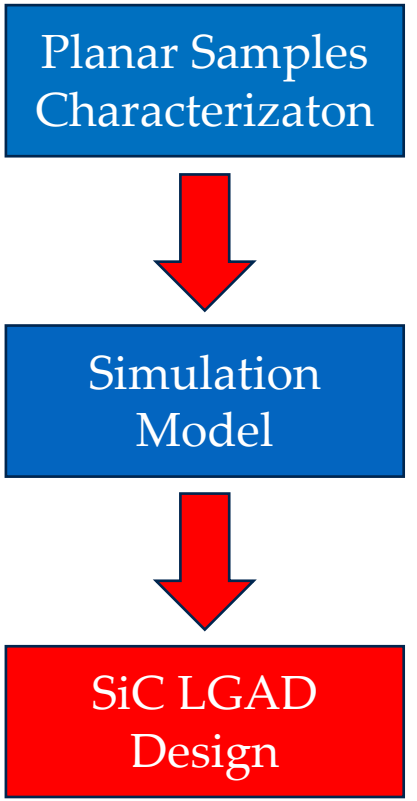
(most significant trap levels)





[9] P. Gaggl, et. al. (2024). TCAD modeling of radiation-induced defects in 4H-SiC diodes. *NIM A*, 170015. https://doi.org/10.1016/j.nima.2024.170015
[10] J. Burin, et.al. (2024). TCAD Simulations of Radiation Damage in 4H-SiC. Austrochip 2024. https://doi.org/10.1109/Austrochip62761.2024.10716221.

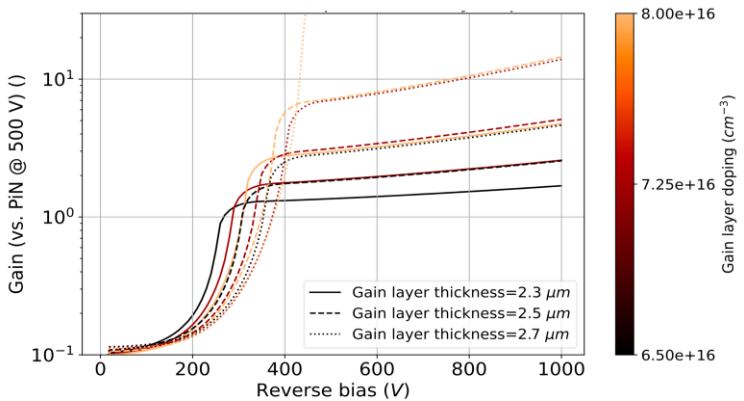
SiC LGAD Design



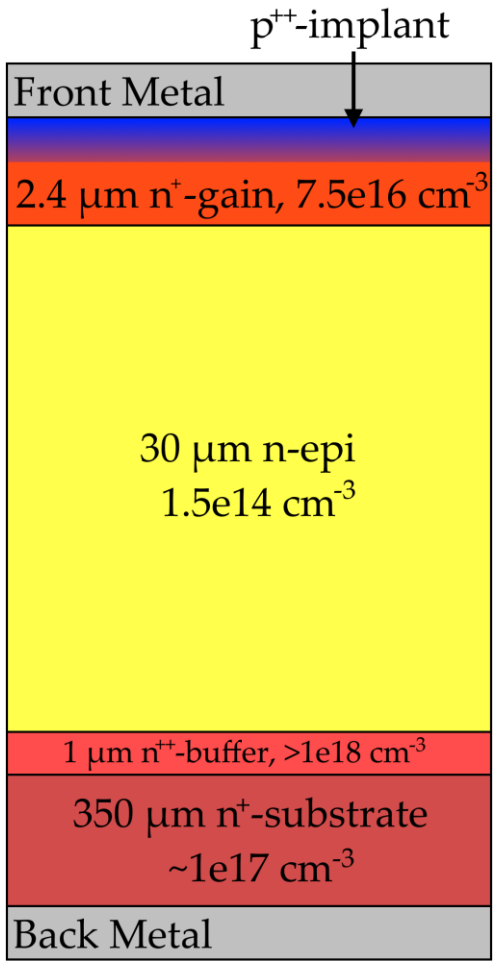
SiC-LGAD Design I

- RD50 SiC LGAD Common Project* (+ planar run → back up)
- Designed by HEPHY, produced by CNM
- Gain layer is non-trivial to manufacture:
  - Dopant diffusion is extremely low in SiC
  - Deep implants (> 1 µm) need high energies (> 1 MeV)
- ⇒ Epitaxially grown gain layer on 30 µm epi, V_{FD} < 600V
- Gain of 1-10 within error margin of gain layer thickness / doping, $V_{FD} < V_{BD}$

*Contributing institutes:
HEPHY, CNM, CERN, INFN Perugia, ICFA Santander, NIKHEF

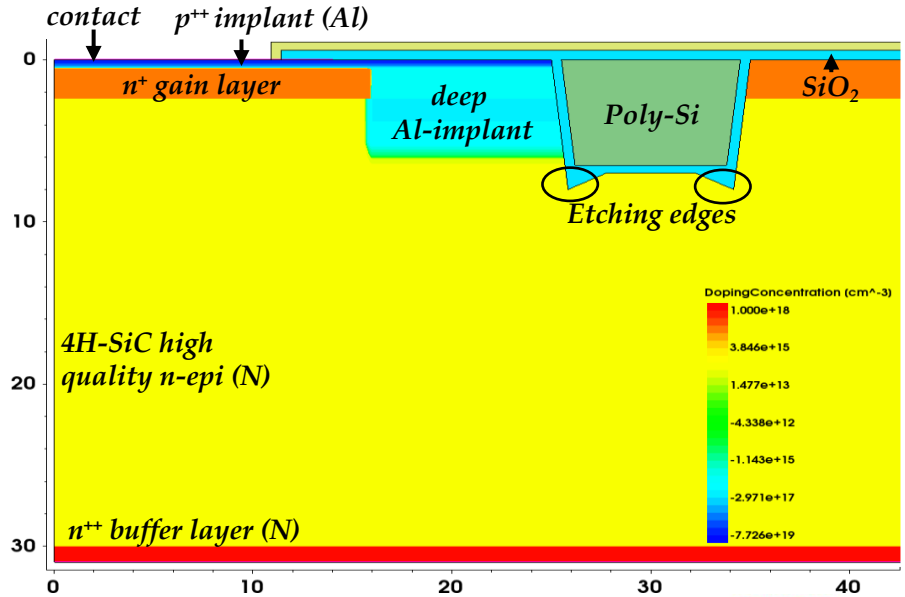


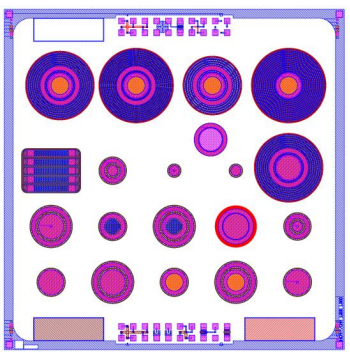
Design parameter	Target	Error
Sensor thickness	30 µm	-
Gain layer thickness	2.4 µm	0.2 µm
Gain layer doping	$7.5 \cdot 10^{16}$ cm^{-3}	10 %

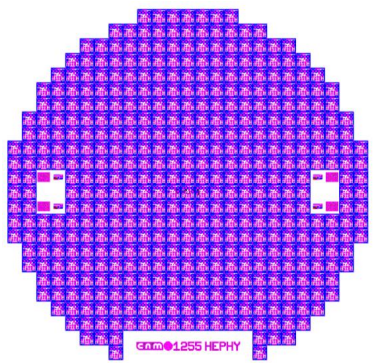


SiC-LGAD Design II

- Gain layer epitaxially grown homogeneously across whole wafer
  ⇒ no guarding with shallow implants
- 3 guard structure variants utilizing combinations of
  - etched trenches
  - deep JTE implants (4 µm)
  - floating metal field plates (FMFPS)
- TCAD simulations suggest V_{BD} > 2kV for all combinations
- Mask design is finalized and submitted for production



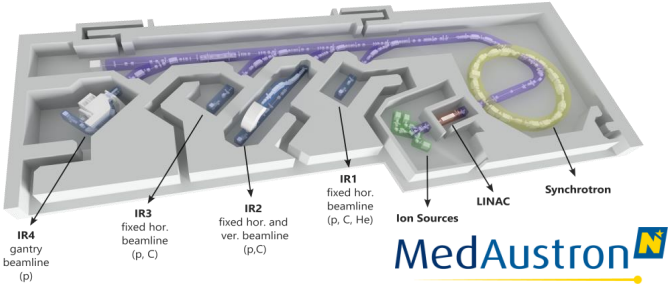


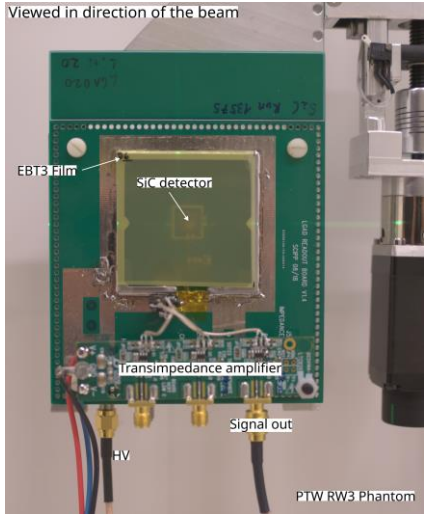


Mask Layout of
SiC LGAD design

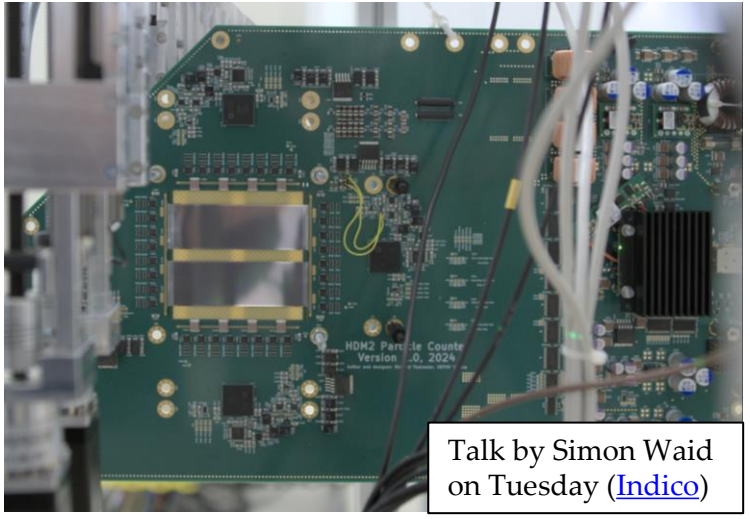
Medical Applications: Beam Monitor & Dosimetry

- Collaboration Partner: ion beam radiotherapy center MedAustron
- Low leakage currents, after irradiation and at room-temperature
  ⇒ DC readout
- Insensitive to visible light, better tissue equivalence
- Beam monitoring for clinical therapy beams (p^+ and ^{12}C)
- Microdosimetry: single particle dose deposition on length scale of cells (<10µm) ⇒ thin sensors



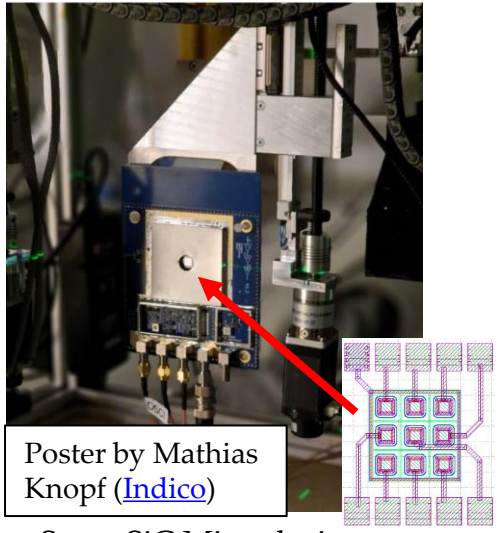


[UHDR beam monitor](#) prototype (planar SiC sensor)



Talk by Simon Waid on Tuesday (Indico)

[New SiC-based beam monitor](#) for a wide dynamic beam intensity range and FLASH-like beams in the future

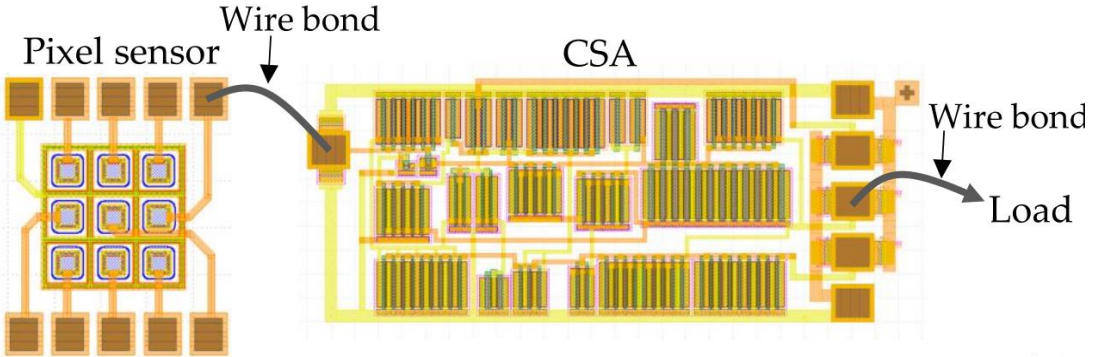


Poster by Mathias Knopf (Indico)

Soon: SiC Microdosimeter (50µm x 50µm pitch, 10µm epi)

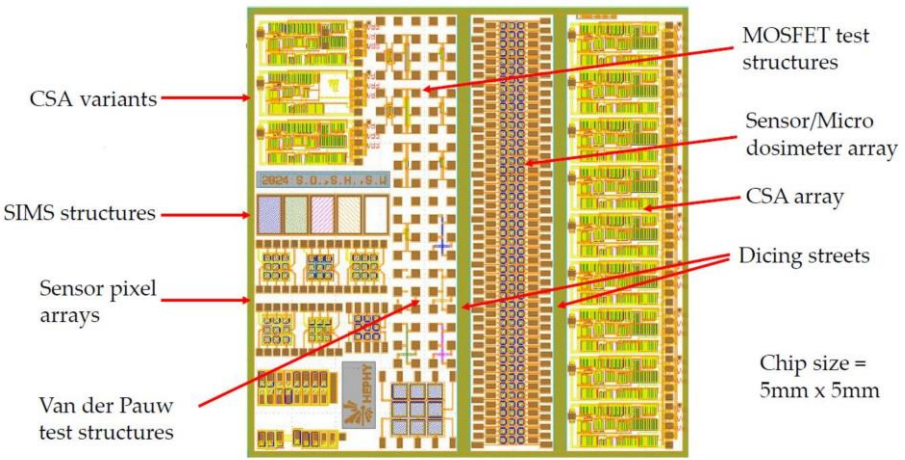
SiC-CMOS Development

- Fraunhofer IISB 2µm SiC-CMOS PDK via Europractice (Integrated NMOS/PMOS, resistors, capacitors working up to 500°C) [11]
- First submission last year: **charge sensitive amplifier (CSA)** [12], pixels, test structures for radiation hardness and more. Samples expected to arrive in mid 2025.
- Long-term goal: DMAPS (depleted monolithic active pixel sensors) in SiC



(not true to scale)

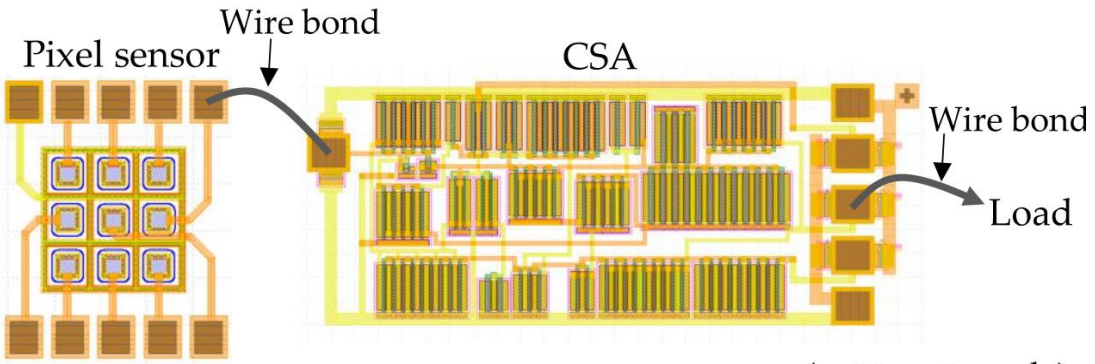
ENC: 118 e^- (C_{det} = 1 pF)
ENC: 205 e^- (C_{det} = 4.5 pF)
Bandwidth of 31kHz



[11] May, A., et. al. (2024). A 4H-SiC CMOS Technology enabling Smart Sensor Integration and Circuit Operation above 500 °C (pp. 1–5). https://doi.org/10.1109/ssi63222.2024.10740550
[12] Onder, S., et. al. (2024). Towards silicon carbide monolithic active pixel radiation sensors. Austrochip 2024. https://doi.org/10.1109/austrochip62761.2024.10716230.

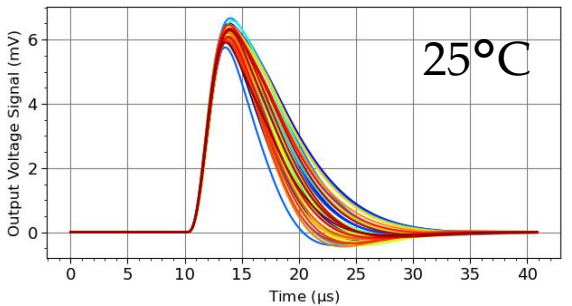
SiC-CMOS Development

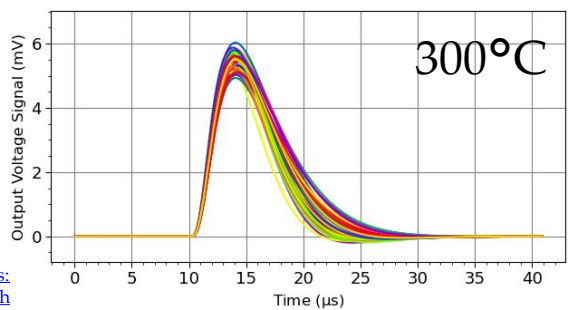
- Fraunhofer IISB 2µm SiC-CMOS PDK via Europractice (Integrated NMOS/PMOS, resistors, capacitors working up to 500°C) [11]
- First submission last year: **charge sensitive amplifier (CSA)** [12], pixels, test structures for radiation hardness and more. Samples expected to arrive in mid 2025.
- Long-term goal: DMAPS (depleted monolithic active pixel sensors) in SiC



(not true to scale)

ENC: 118 e^- (C_{det} = 1 pF)
ENC: 205 e^- (C_{det} = 4.5 pF)
Bandwidth of 31kHz





CSA Output for 2750e signal charge (MIP in 50µm thick SiC sensor)

[11] May, A., et. al. (2024). A 4H-SiC CMOS Technology enabling Smart Sensor Integration and Circuit Operation above 500 °C (pp. 1–5). https:
[12] Onder, S., et. al. (2024). Towards silicon carbide monolithic active pixel radiation sensors. Austrochip 2024. https://doi.org/10.1109/austroch

Outlook

- Radiation hardness of SiC → it's complicated
  - Leakage current <10pA at fluence of 10^{16} n_{eq}/cm^2 and room temperature ⇒ no cooling needed
  - CCE significantly reduced at high fluences
  - Based on small sample size without prior annealing
- Properties up for investigation:
  - SiC LGAD gain loss with increasing irradiation (donor removal)
  - Timing capabilites
- Several SiC devices in production: planar/LGAD sensors, CMOS electronics
- Large interest from the community
  - SiC LGAD productions from FNSPE/FZU/onsemi (CZ) (Talk on Thursday, Indico), LBNL/NCSU [13], SICAR [14]
  - DRD3 SiC LGAD project with 27 participating institutes (including HEPHY)
- Stay tuned!

[13] Yang, T., et.al. (2024, August 22). *Characterization of 4H-SIC Low Gain Avalanche Detectors (LGADS)*. https://arxiv.org/abs/2408.12744.
[14] Zhao, S., et.al. Electrical properties and gain performance of 4H-SIC LGAD (SICAR). *IEEE Transactions on Nuclear Science*, *71*(11), 2417–2421. https://doi.org/10.1109/tns.2024.3471863.

Thank you!

This work was supported by the Austrian research promotion agency FFG, project number 883652.

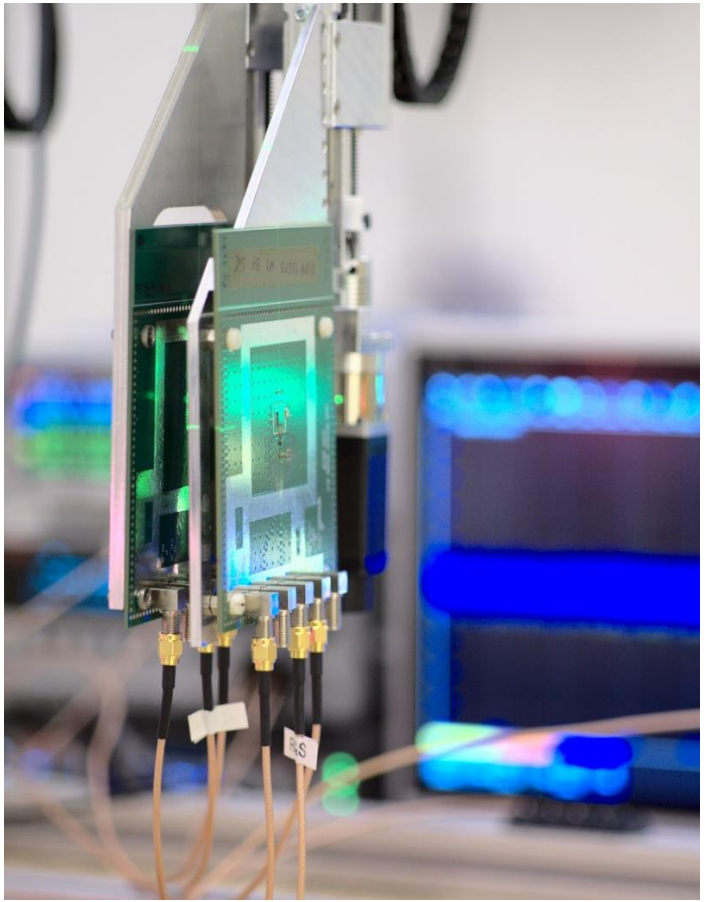
The financial support of the Austrian Ministry of Education, Science and Research is gratefully acknowledged for providing beam time and research infrastructure at MedAustron.

Production and development of the 4H-SiC samples was supported by the Spanish State Research Agency (AEI) and the European Regional Development Fund (ERDF), ref. RTC-2017-6369-3.
The production of the planar 6''-SiC samples has been supported in part by the RD50 collaboration (RD50-SiC-LGAD common project)

We thank our colleagues at the irradiation facilities of JSI, Ljublijana for the irradiation of SiC samples to 1E18 neq/cm2

Back Up

SiC References



2021

- First SiC Samples from CNM run 13575
  2 Master Theses, Strip Sensor Measurements: 10.1088/1748-0221/17/01/C01060
- Start of FFG funded Project "HiBPM"
  2 PhDs and 1 Postdoc full-time on SiC

2022

- Neutron irradiation at ATI Vienna, CCE Characterization with UV-TCT / Alphas
  10.1016/j.nima.2022.167218, 10.1088/1748-0221/18/01/C01042, 10.1088/1748-0221/18/11/C11027
- Medical applications (ion therapy): Beam monitoring / FLASH dosimetry
  10.1088/1748-0221/19/04/C04055, 10.1088/1748-0221/19/04/C04055, 10.1007/s00502-023-01201-w
- TCAD simulations for unirradiated sensors

2023

- Start of RD50 SiC-LGAD common project
- Measurement of electron-hole pair creation energy 10.1016/j.nima.2024.169412
- Planar SiC run designed and submitted

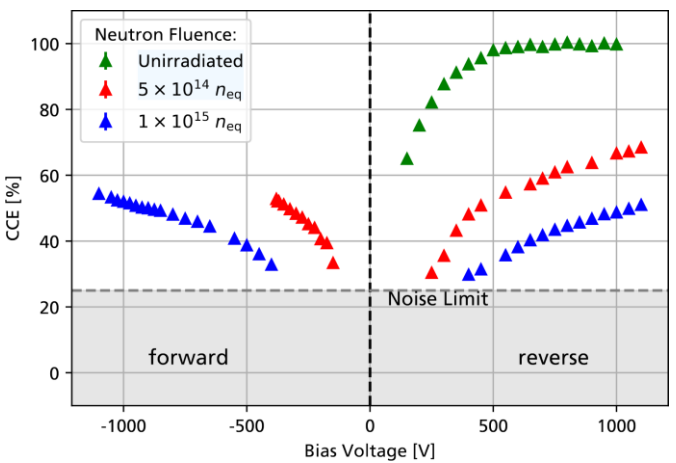
2024

- Characterization of first planar run (CNM 16886 and 17407) DRD3
- TCAD model describing radiation damage in 4H-SiC arXiv:2407.11776, arXiv:2407.16710
- SiC-LGAD design and layout finished

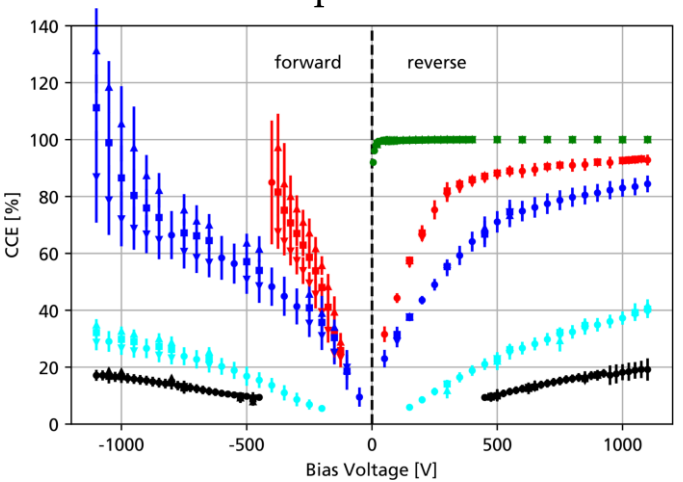
CCE after Irradiation

- Reduced forward current allows operation of detector in forward and reverse bias
- Higher CCE in forward direction (electron collection)
- For α particles and UV-TCT : CCE surpasses 100%!

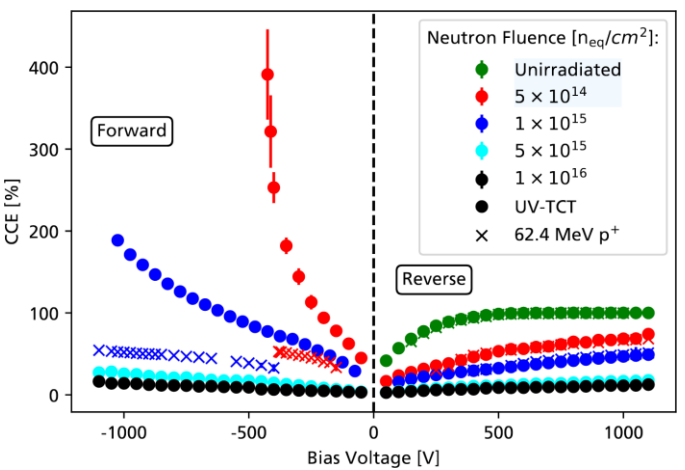
62.4 MeV protons



α particles

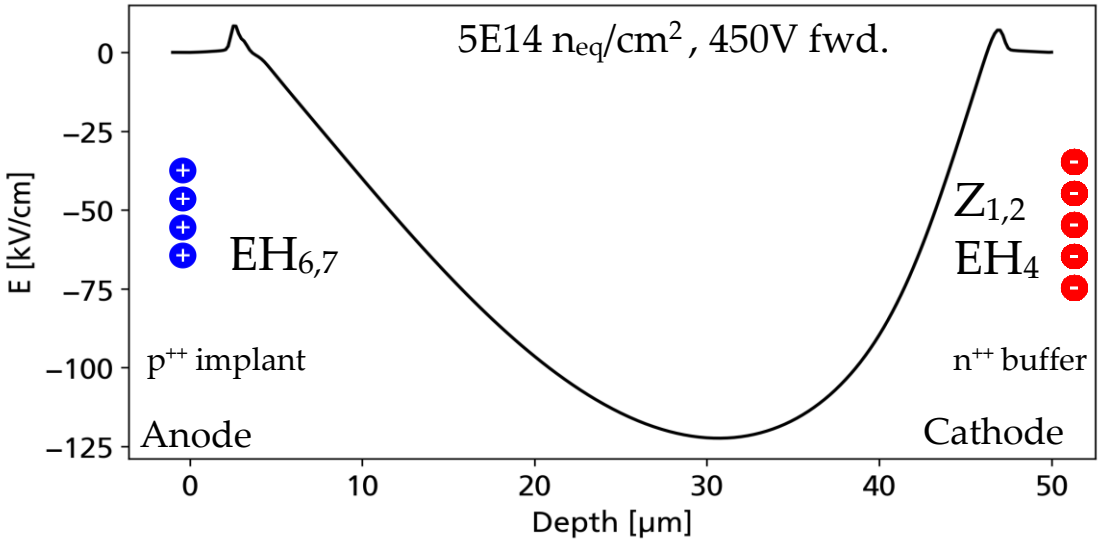


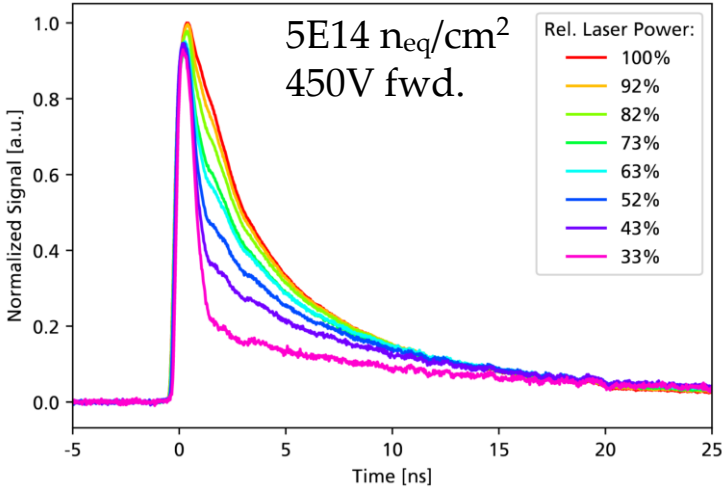
SPA-UV-TCT



Bipolar Operation of irradiated SiC

- Trapped space charge near anode and cathode decrease charge carrier lifetime and decrease conductance
- For high bias voltages (or charge injection), traps are fully filled and charge carrier life time significantly increases → conduction is restored (until de-trapping occurs)
- EH_4 levels (at backside) are filled first and responsible for start of conduction

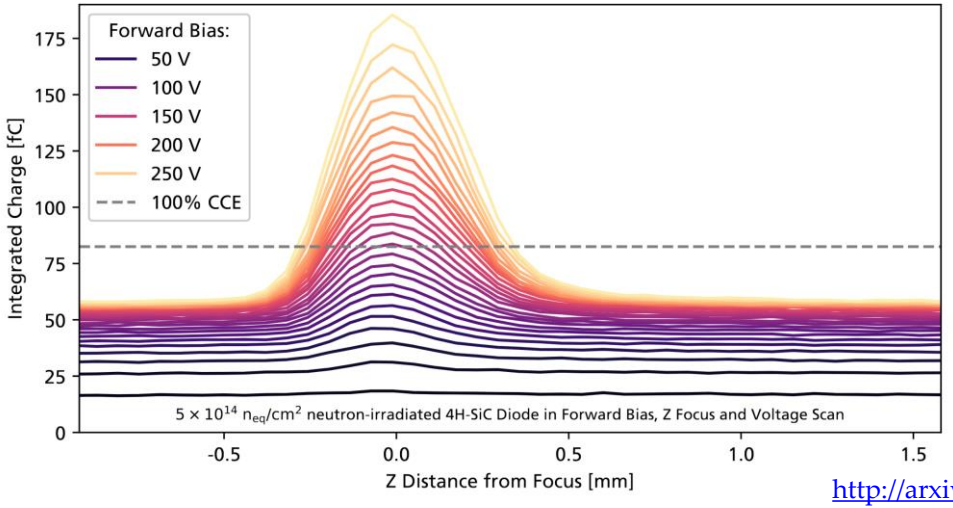




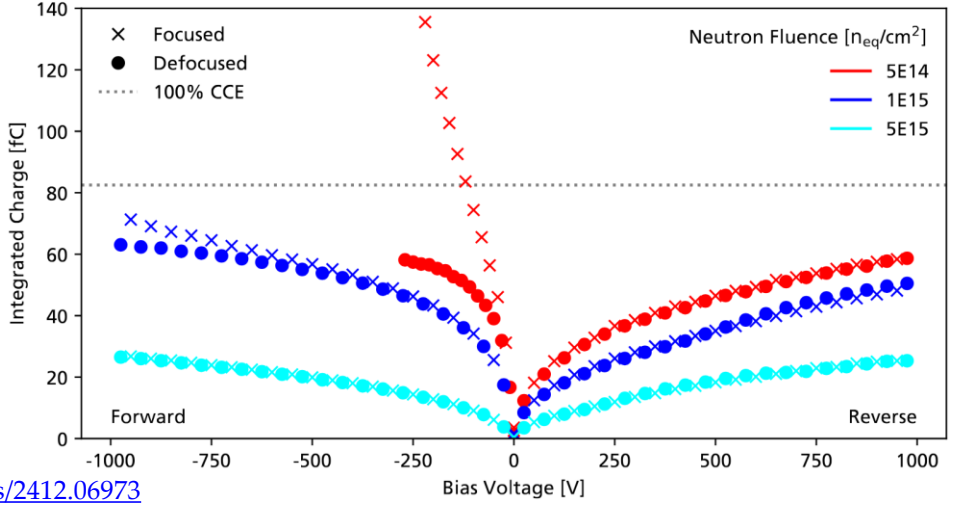
UV-TCT transient waveforms in forward bias as a function of the injected charge

Charge Enhancement in Forward Bias

- Charge enhancement depends directly on injected charge density
  - In UV-TCT : High power, tiny focus → >100% CCE
- For lower charge density (de-focused laser spot), this effect does not happen!
  → Can not be leveraged to get larger signals in MIP detection



Signal vs. laser focus



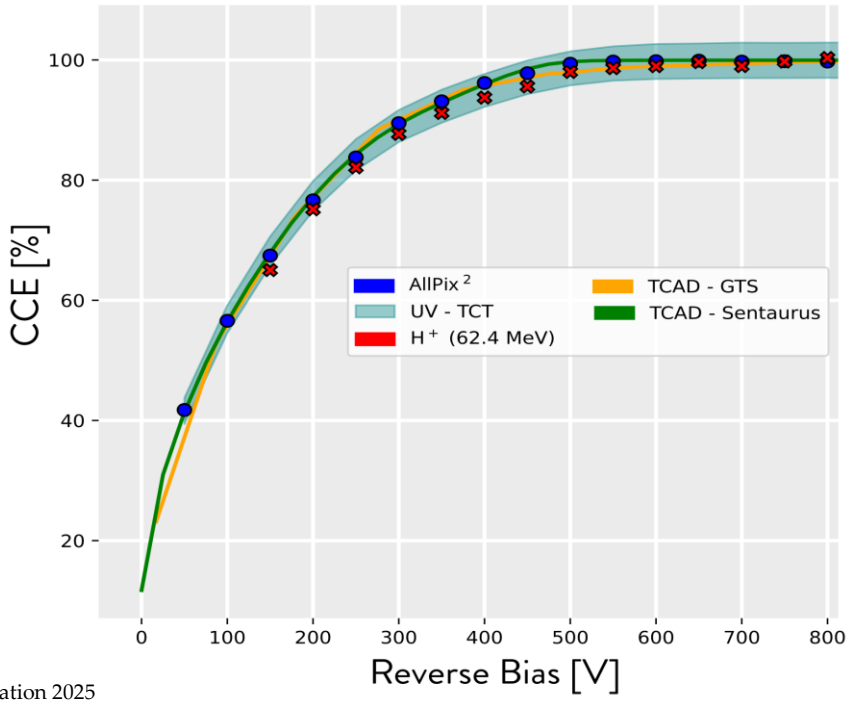
http://arxiv.org/abs/2412.06973

Signal for defocused / focused laser

Simulations of 4H-SiC Devices II

- Material parameters deviate across literature
  ⇒ optimization by fitting simulation to measurement
- Additional input: Doping profile extracted from C-V measurements (bulk + buffer layer)

- Device simulation using Synopsys Sentaurus [4], Global TCAD Solutions [5] and AllPix² [6]
- Very good agreement for CCE curves



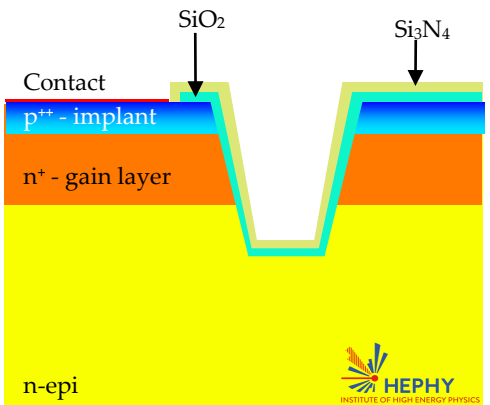
SiC-LGAD Comparison

- Several other groups have designed, produced and characterized SiC-LGADs
- Different sensor architectures and guarding concepts

	HEPHY/CNM/RD50	FNSPE/FZU/onsemi (CZ)	LBNL/NCSU (USA)	SICAR (China)
Guard Structure	Trenches, JTE	JTE	Bevel Edge	Bevel Edge
Gain	-	15-20	~10	2-3
Time resolution	-	100ps (Sr-90)	<35ps (Sr-90)	-

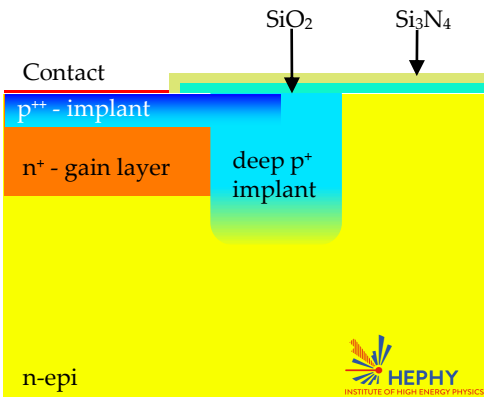
Trenches

HEPHY



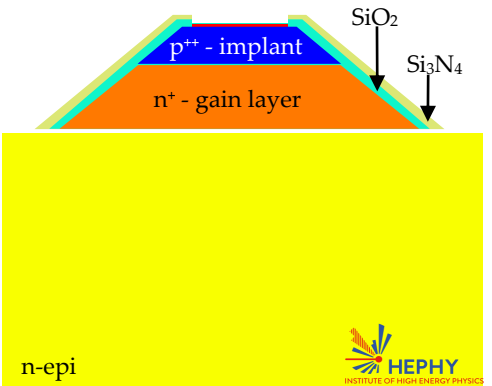
JTE

FNSPE/FZU/onsemi,
HEPHY



Bevel-Edge

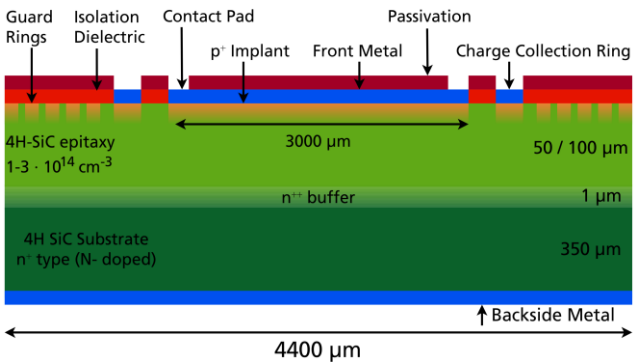
LBL (USA), SICAR (China)



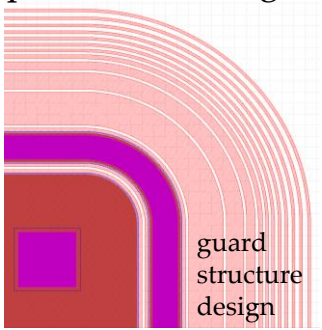
RD50 SiC-LGAD Common Project*

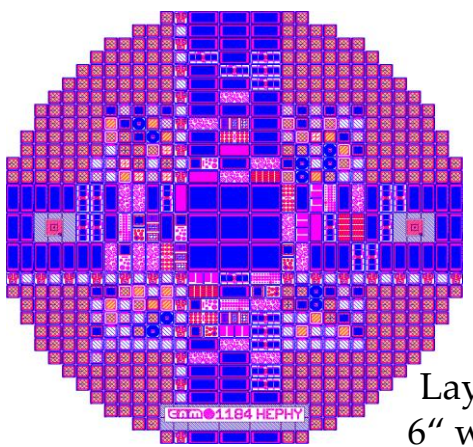
*Contributing institutes:
HEPHY, CNM, CERN, INFN Perugia, ICFA Santander, NIKHEF

- LGAD run + additional planar run
- Design by HEPHY via TCAD
- Production at CNM (first time 6”)
- Planar run:
  - More statistics for material/irradiation study
  - 5 wafers (3x50µm, 2x100µm epi thickness)
  - 2x50µm and 1x100µm have been processed and received (yield <50% due to production error)
  - Remaining 2 wafers finished by early to mid 2025
- LGAD run:
  - Production starting this spring
  - Mask design has been finalized



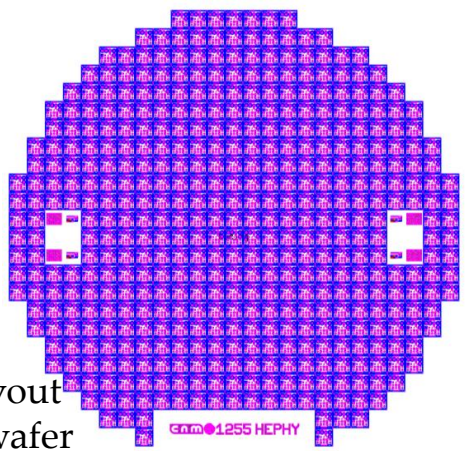
planar run design





planar run

Layout 6“ wafer

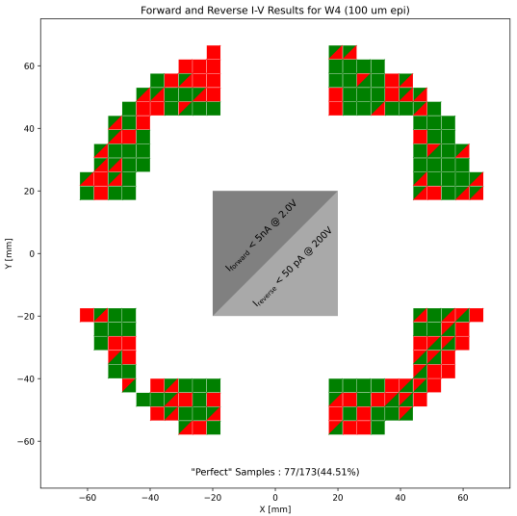


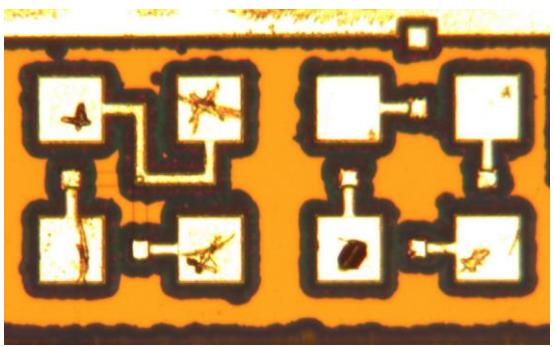
LGAD run

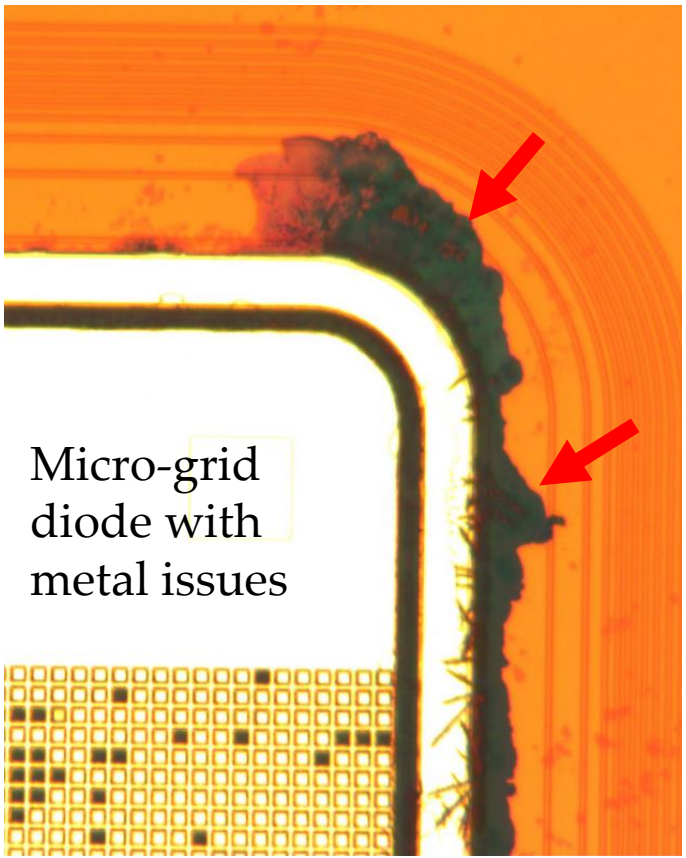
Planar Run Issues

- Contact metal is not allowed to be on oxide (instead of forming a silicide, metal will spill out from mask)
- Shorted a lot of structures
- Adressed by splitting metal masks into high-temperature contact metal and low-temperature metal

Wafer	Epi [um]	Yield
2	50	57/173 [33%]
3	50	7/173 [4%]
4	100	77/173 [44%]

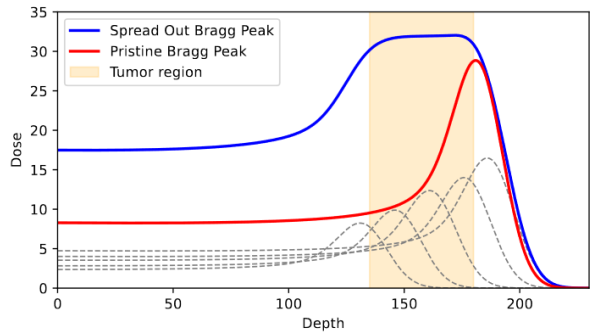


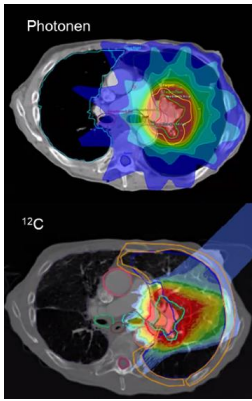


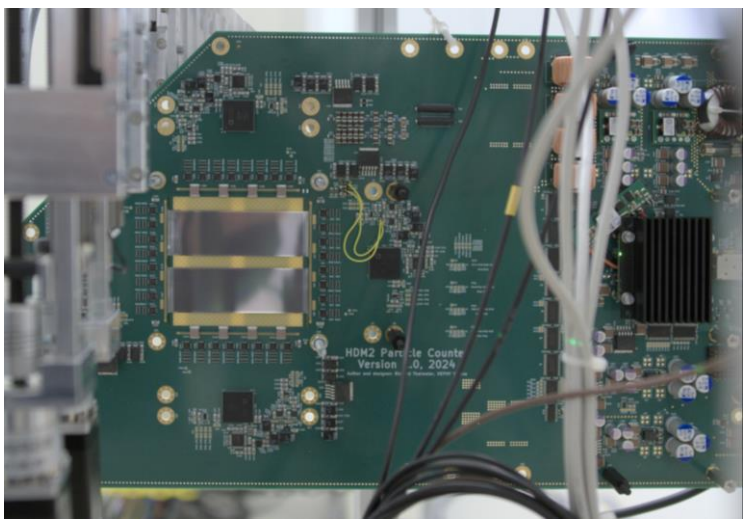


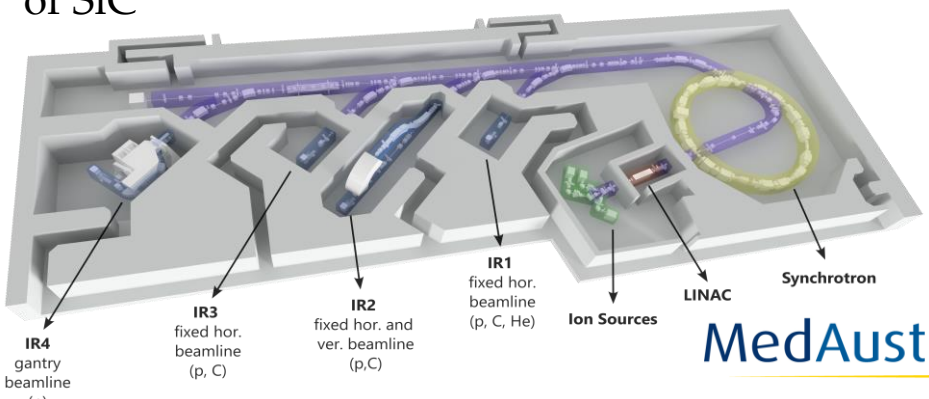
Medical Applications: Beam Monitor & Dosimeter

- Ion radiation allows effective cancer therapy by placing Bragg peak in tumor tissue
  ⇒ precise knowledge about beam characteristics needed
- Advantages of SiC for therapy beam monitoring and dosimetry:
  - Low leakage currents (DC readout)
  - Insensitive to light
- Development of a SiC based beam monitor (use at MedAustron): Single particles to clinical intensities (GHz/cm²), talk by Simon Waid on Tuesday (Indico)
- Microdosimetry and UHDR (FLASH) applications of SiC









MedAustron

New SiC-based beam monitor for a wide dynamic beam intensity range and FLASH-like beams in the future

Ultra High Dose Rate Therapy: Beam Monitoring

- FLASH effect at ultra high dose rates: Same tumor control but with improved survival of healthy cells
  ⇒ wider treatment window and higher treatment speed
- SiC-based beam monitor prototype with DC-coupled 20 MHz TIA
  - Fast response due to TIA
  - Linear with dose rate (up to 10 kGy/s inst., 100 Gy/s avg.)
  - No saturation observed

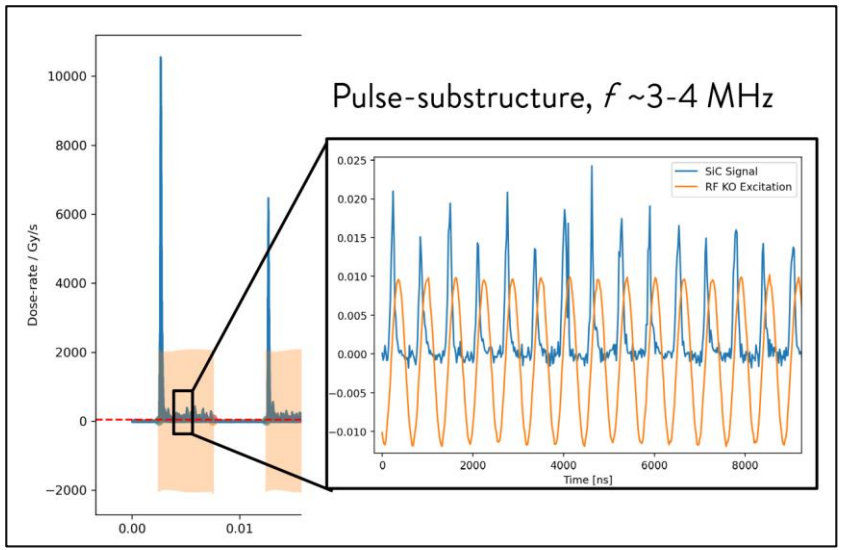
CONVENTIONAL RADIOTHERAPY

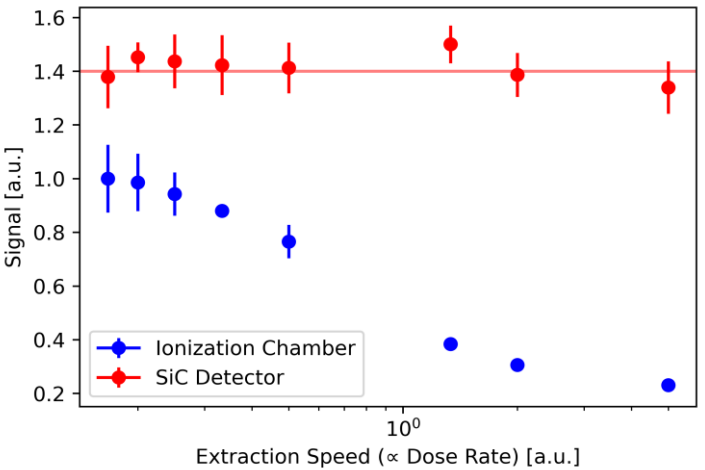
Dose: ~2 Gy/fract. (x 30 fractions)
Dose Rate: ~ Gy/min
Irradiation Time: few minutes

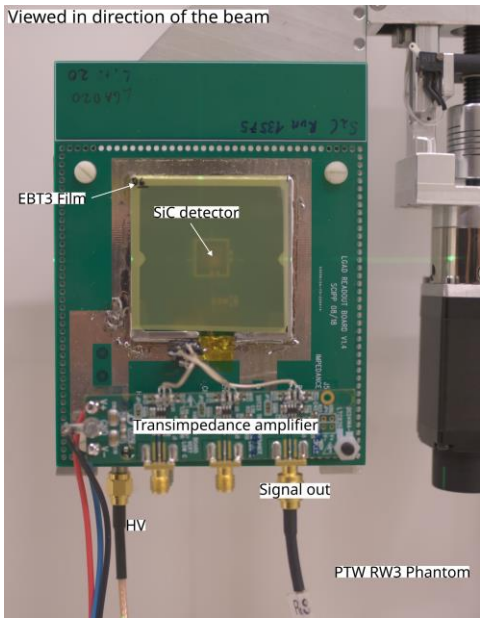
FLASH RADIOTHERAPY

Dose: > 8 Gy (x 1 fraction?)
Dose Rate: > 40 Gy/s
Irradiation Time: <200 ms

Taken from "Instrumentation for FLASH Radiotherapy"
Francesco Romano, iWoRiD 2023

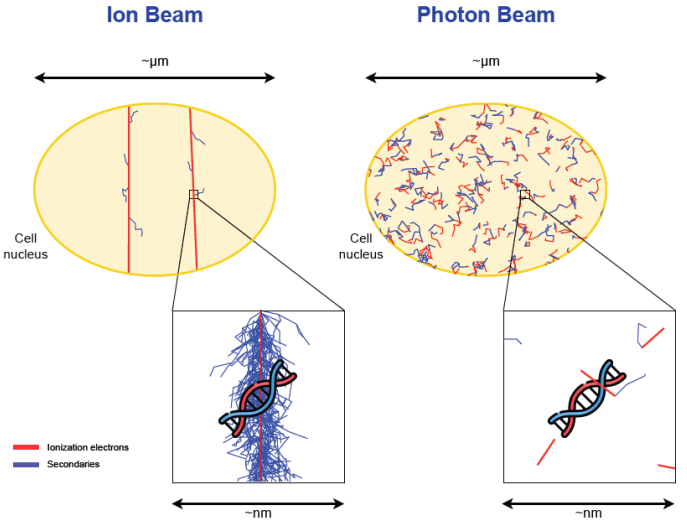


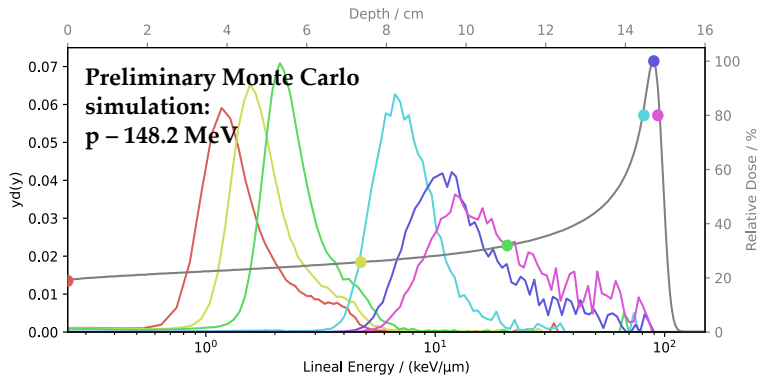


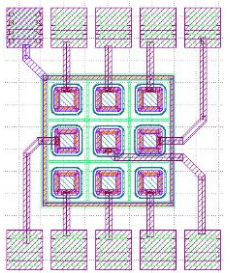


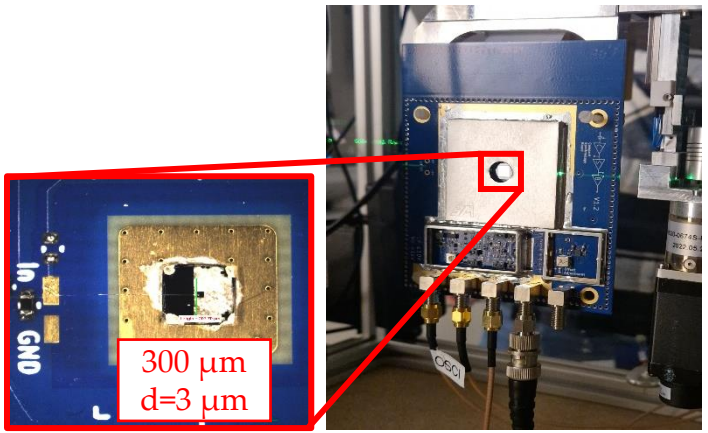
Micro-Dosimetry

- Study of biological effects of radiation on cellular level:
  - Dose deposition of single particles spatially resolved in µm scale needed
  - Different particle types have different microscopic dose distribution
- Challenges for detectors:
  - Need thin sensors (<10µm) ⇒ small signal ⇒ high SNR readout
  - Clinical particle rates up to 10^{10}/s ⇒ fast electronics, pileup (poster about pile up rejection by Matthias Knopf, Indico)
- HEPHY is developing new SiC-based microdosimeters
  - First prototypes expected soon
  - Additional development of new readout system









Fast Readout

https://indico.cern.ch/event/1506319/#2-high-bw-readout-electronics

- Based on a 10 GHZ LNA MMIC
- UV-TCT laser (370 nm)
- Risetime : 55 ps (~ 6.4 GHz BW)
- Partially limited by laser pulse (45 ps FWHM)
- (Almost) no reflections!

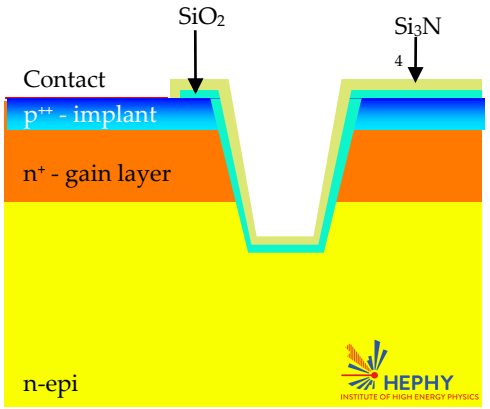
SiC LGAD Backup

SiC-LGAD Guarding

- Because deep implantation (> 1 µm) in 4H-SiC requires very high energies (> 1 MeV), we used a LGAD wafer with an epitaxially grown gain layer (homogenous over the wafer area)
- Creates challenges in guarding / inter-strip isolation!
- Dielectric breakdown (SiO_2) has to be avoided

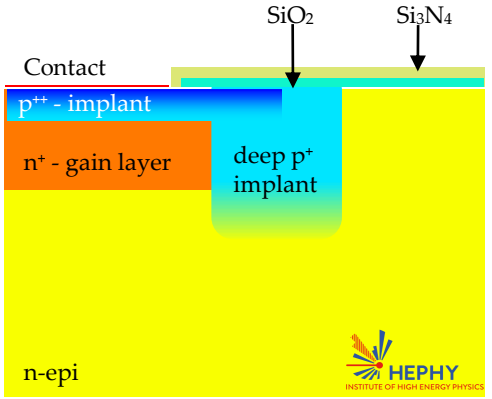
Trenches

HEPHY



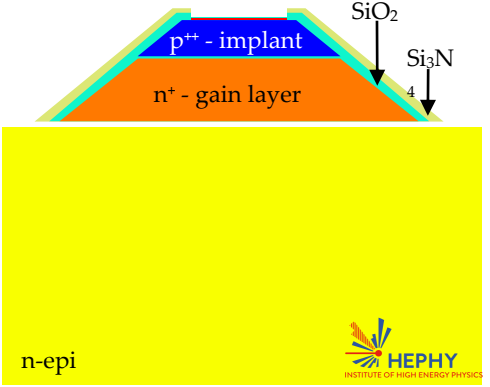
JTE

FNSPE/FZU/onsemi,
HEPHY



Bevel-Edge

LBL (USA), SICAR (China)



For more info see backup

RD50-SiC-LGAD Wafer Layout

- 464 dies per wafer, 10 wafers available. PIN diodes using wafers without gain layer
- Three guarding designs (JTE and trenches), all with simulated V_{BD} > 2 kV
- Processing to start this spring

1: Trench + single deep-implant

+ High V_{BD}
+ Smallest process uncertainties
+ Small device area

- Potential problems with trench-etching process
- Charge trapping in Poly-Si

3: JTE + FMFPs*

+ Less processing uncertainties
+ Less sensitive to variation in deep implant widths

- Sensitive to oxide thickness
- Large device area

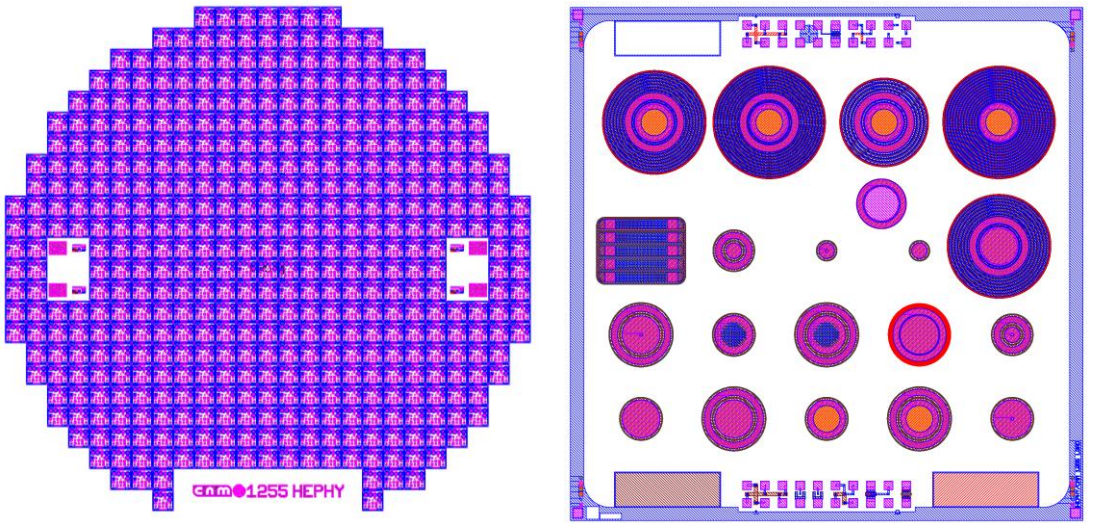
2: JTE & support-implants + FMFPs*

+ High V_{BD}
+ Less sensitive to oxide thickness

- Sensitive to deep implant widths
- Large device area

* Floating metal field plates

Finalized Mask Design for RD50-SiC-LGAD



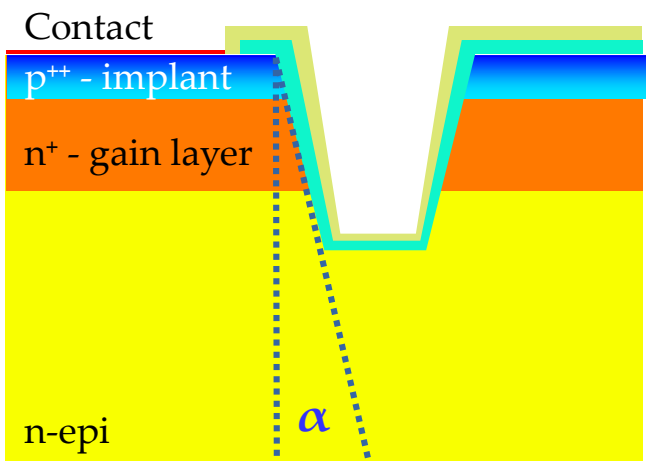
Trench Guarding

In theory trenches are ideal to interrupt the gain layer:

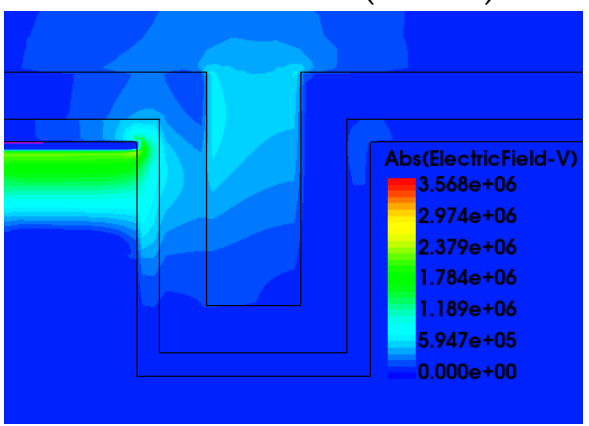
- Good fill factor, very high voltages can be achieved

However:

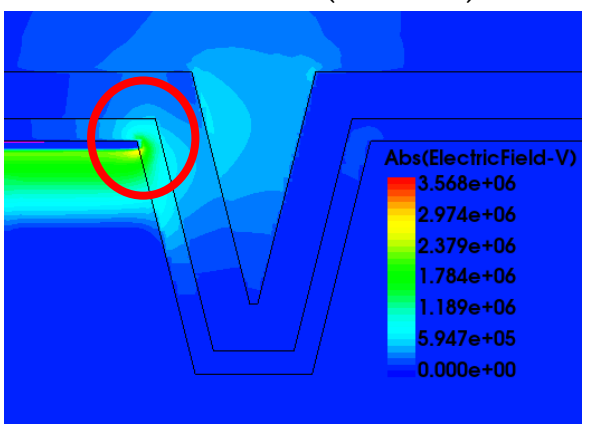
- Deep trenches (> 4 µm) are not easy to manufacture
- Aspect ratio of trench is very important, needs to be $\alpha < 5°$



Perfect trench ($\alpha = 0°$)

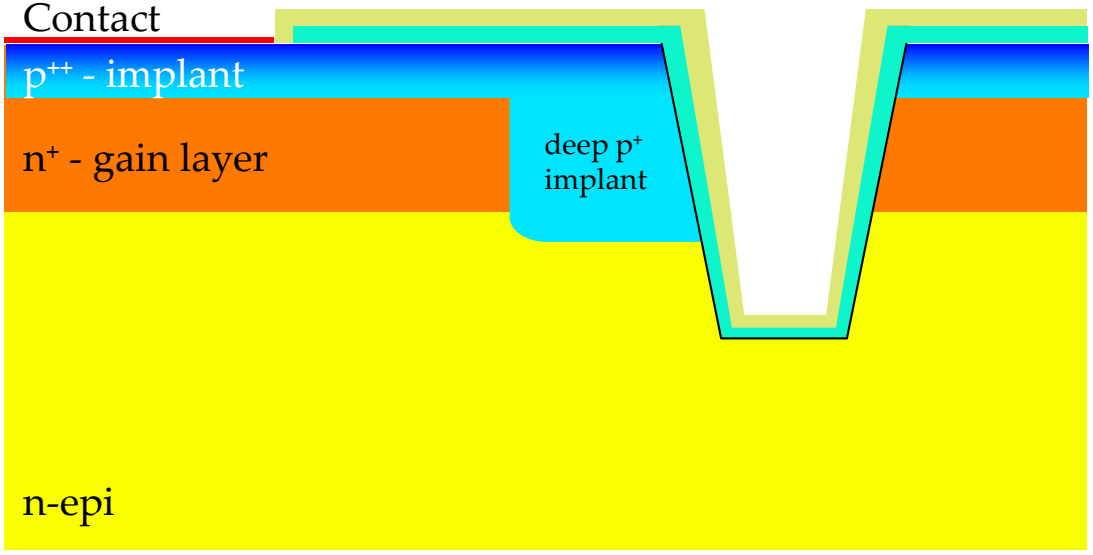


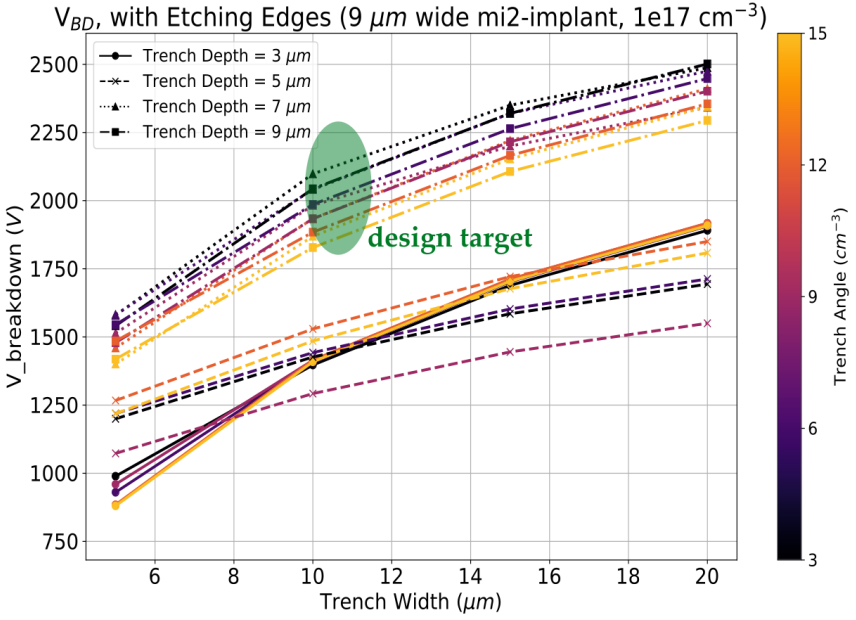
Bad trench ($\alpha = 15°$)



Trench + Deep Implant

- JTE in front of trench can be used to pull down field lines and spread out high field areas
- JTE does not necessarily need to be deep enough to cut gain layer
- Very good results independent of trench angle, V_{BD} ~ 2 kV even for $\alpha = 12°$

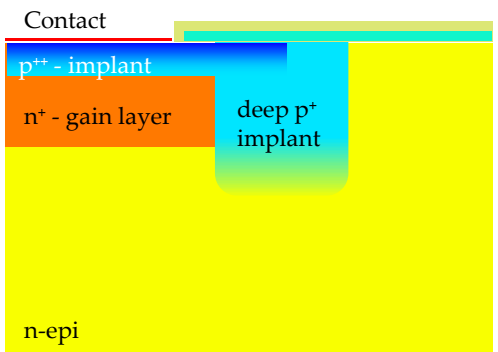




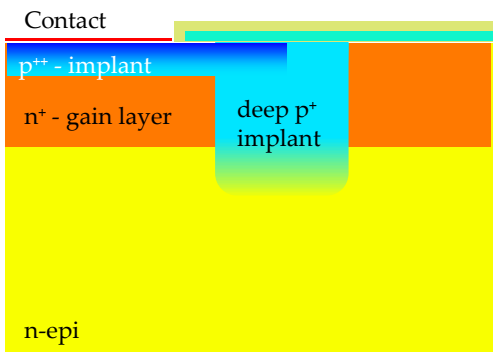
JTE Guarding

- Gain layer in 4H-SiC is much easier to grow than to implant it
  (need high energies of several MeV, thick masks, large implantation currents)
- JTE guarding design complementary to trench design
- For epitaxial gain layers, a simple JTE is not sufficient

Implanted Gain Layer

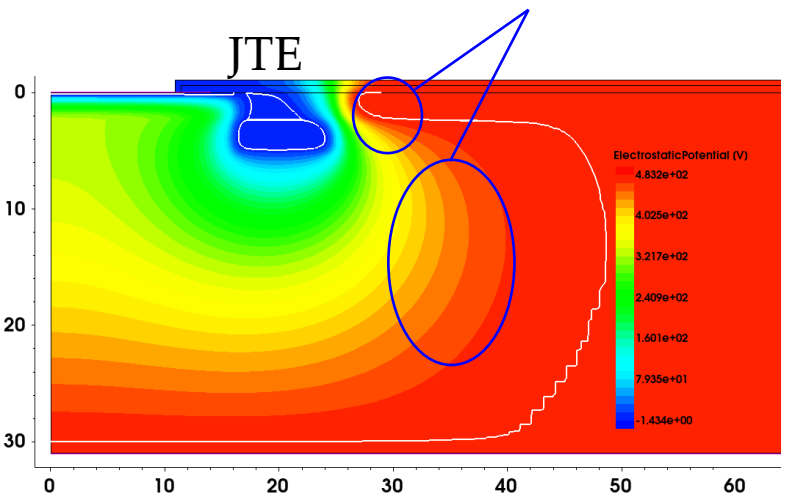


Epitaxial Gain Layer



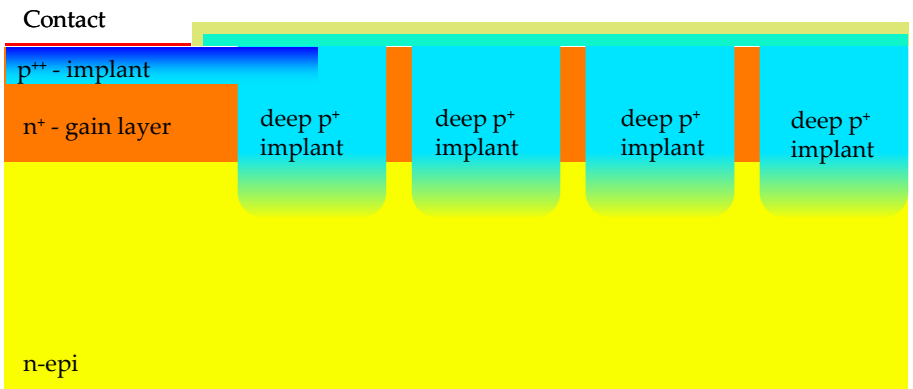
Build-up of high electric fields

JTE



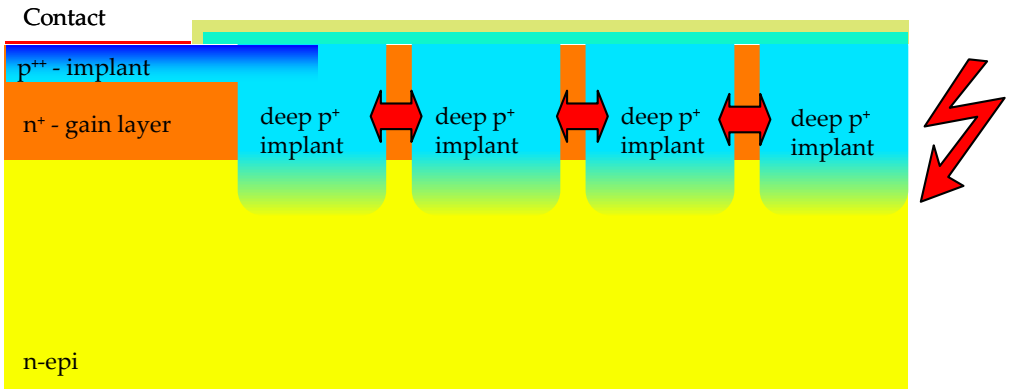
Multiple JTE Guards

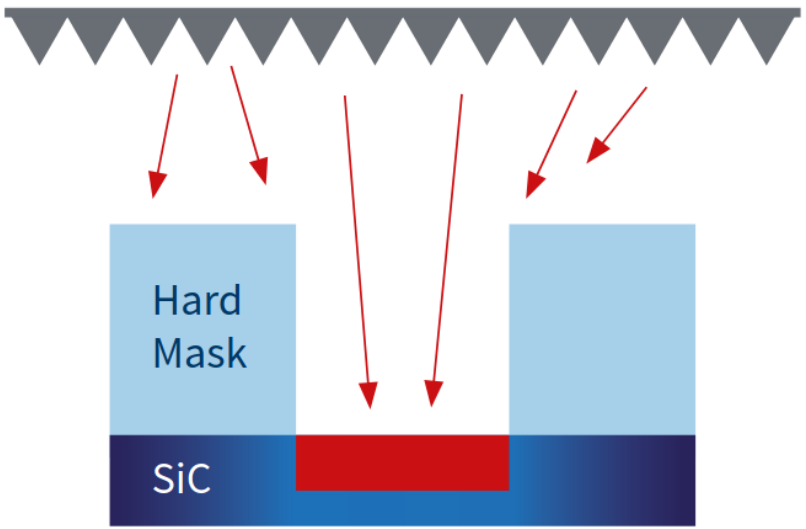
- If one JTE is not working, use multiple and slowly dissipate potential



Multiple JTE Guards

- If one JTE is not working, use multiple and slowly dissipate potential
- However, implant-implant distance is limited to >10 µm because of thick masks required to stop the high energy ions in implanation





[mi2-factory hard masks]

Multiple JTE Guards

- Can use floating metal field plates (FMFPs) or support implants to enhance the spreading of electric potential between the guards
- FMFPs are sensitive on the oxide thickness
- Support implants are sensitive on mask alignment to deep implants

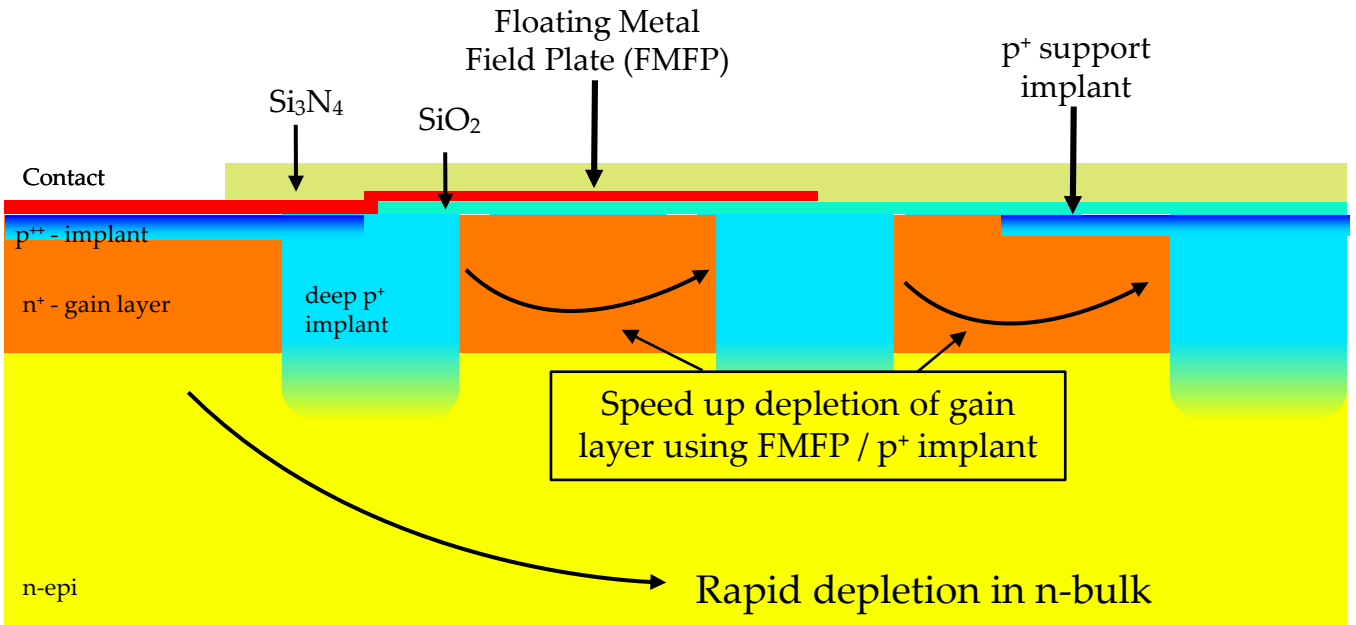


Illustration of FMFP and support implant concepts