AUSTRIAN ACADEMY OF SCIENCES

HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

Update on the RD50-SiC-LGAD Common Project

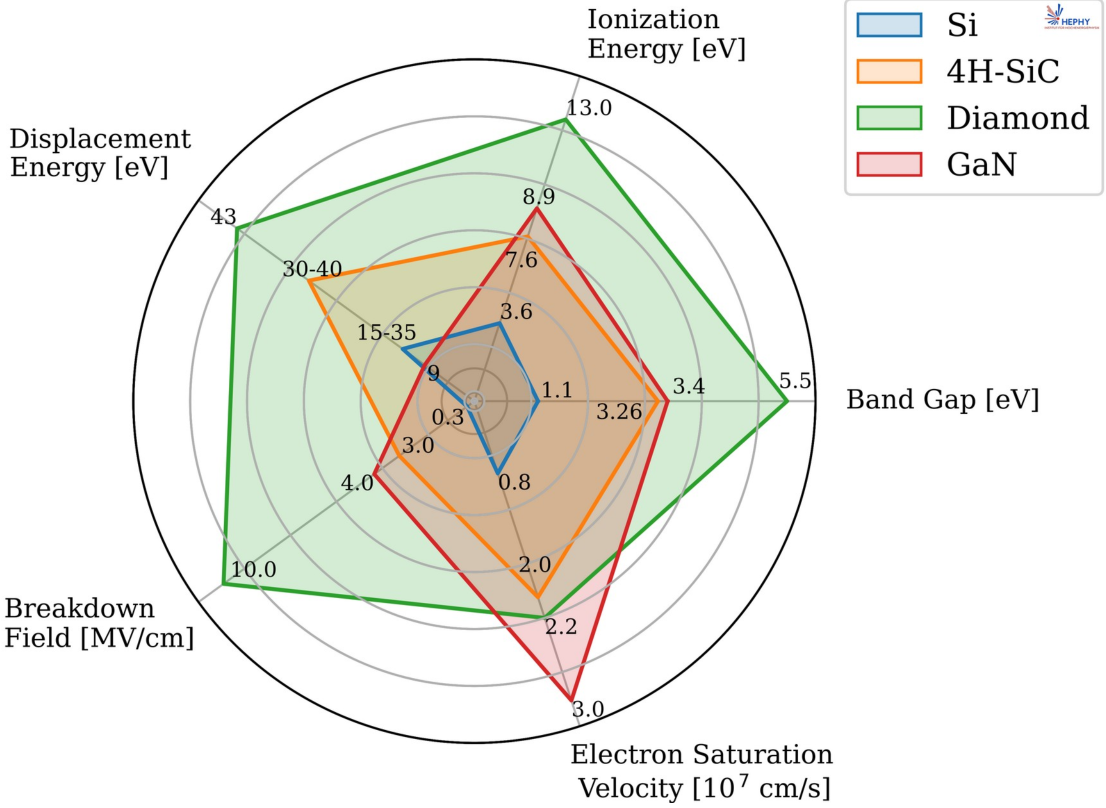
Andreas Gsponer
andreas.gsponer@oeaw.ac.at
on behalf of the HEPHY Detector Development Group

2nd DRD3 Workshop
05.12.2024

Contents

Silicon Carbide LGADs

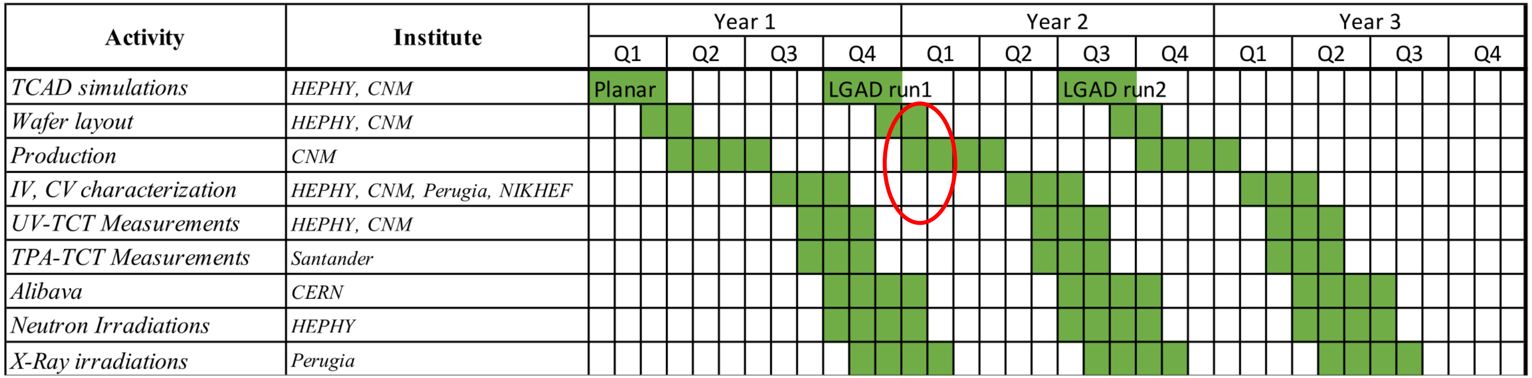
- Wide Bandgap :
  → no cooling / pA currents even after irradiation, insensitive to visible light
- High V_{BD}, high v_{sat} :
  → high voltages, fast signals → timing
- High displacement threshold:
  However, CCE rapidly decreases after 1E15 n_{eq}/cm^2
- High ε_i, low thickness → small signal
  → SiC-LGADs



RD50-SiC-LGAD Project

- Started in 2023
- Aims at producing planar devices and prototype SiC-LGADs
- Irradiation studies for PIN and LGAD

Title of project:	*SiC-LGAD*
Contact person:	*Thomas Bergauer (HEPHY Vienna)* *Nikolsdorfer Gasse 18, 1050 Wien, Vienna, Austria* *Thomas.Bergauer@oeaw.ac.at*
RD50 Institutes:	**1.** *OEAW-HEPHY, Thomas Bergauer, Thomas.Bergauer@oeaw.ac.at* **2.** *CSIC-IMB-CNM, Giulio Pellegrini, giulio.pellegrini@csic.es* **3.** *CERN, Susanne Kühn, susanne.kuehn@cern.ch* **4.** *INFN Perugia, Francesco Moscatelli, moscatelli@iom.cnr.it* **5.** *IFCA Santander, Ivan Vila ivan.vila@csic.es* **6**. *NIKHEF, Kazu Akiba kazu.akiba@nikhef.nl*
Request to RD50:	*30€*
Total project cost:	*110k€*



Activity	Institute	Year 1												Year 2												Year 3											
		Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4			Q1			Q2			Q3			Q4		
TCAD simulations	*HEPHY, CNM*	🟩 Planar	🟩	🟩							🟩 LGAD run1	🟩	🟩							🟩 LGAD run2	🟩	🟩															
Wafer layout	*HEPHY, CNM*			🟩	🟩								🟩	🟩								🟩	🟩														
Production	*CNM*				🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩											
IV, CV characterization	*HEPHY, CNM, Perugia, NIKHEF*								🟩	🟩	🟩							🟩	🟩	🟩							🟩	🟩	🟩								
UV-TCT Measurements	*HEPHY, CNM*									🟩	🟩	🟩							🟩	🟩	🟩							🟩	🟩	🟩							
TPA-TCT Measurements	*Santander*									🟩	🟩	🟩							🟩	🟩	🟩							🟩	🟩	🟩							
Alibava	*CERN*										🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩					
Neutron Irradiations	*HEPHY*										🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩					
X-Ray irradiations	*Perugia*											🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩				

Planar Run Update

- RD-50-SiC-LGAD project encompasses a planar production
- Goal : Characterize 4H-SiC and validate simulations for planar devices

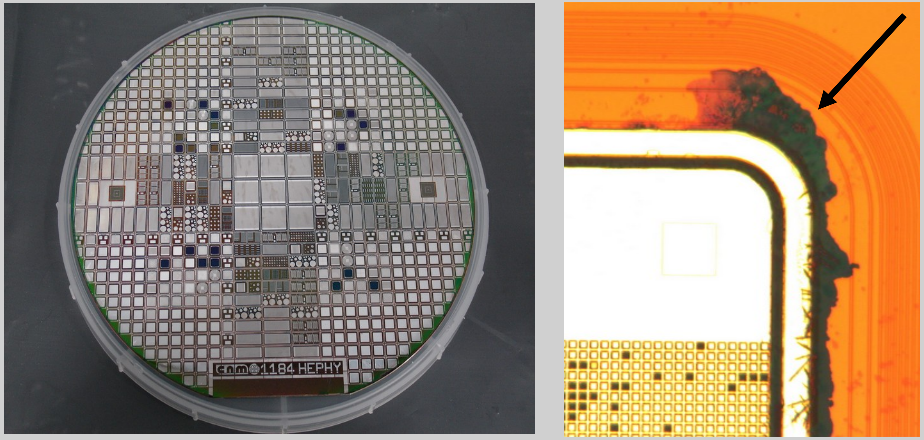
- 5 wafers in total, split into two runs
- First run : Issues with metalization (see DRD3 Talk)
- Second run: Due to finish early 2025

Run 1
March
2024

50 µm
50 µm
100 µm

Run 2
Early 2025

50 µm
100 µm



Wafer from first planar production and metalization issues

RD50-SiC-LGAD : Gain Layer Design

30 um epi thickness chosen : cost, full depletion even with gain layer

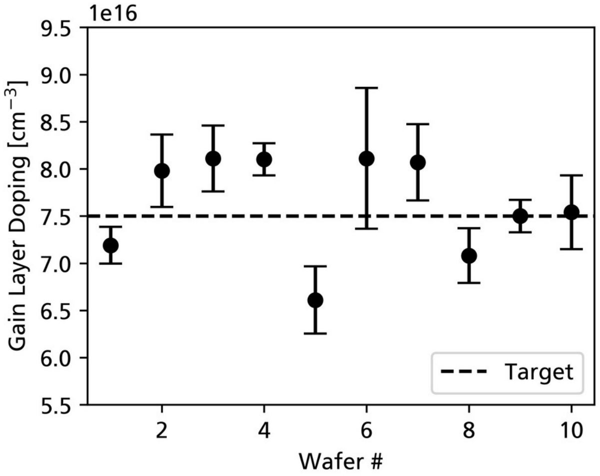
Deep implants (> 1 μm) in 4H-SiC need high energies (> 1 MeV)
→ limited implanation currents
→ use an epitaxially grown gain layer

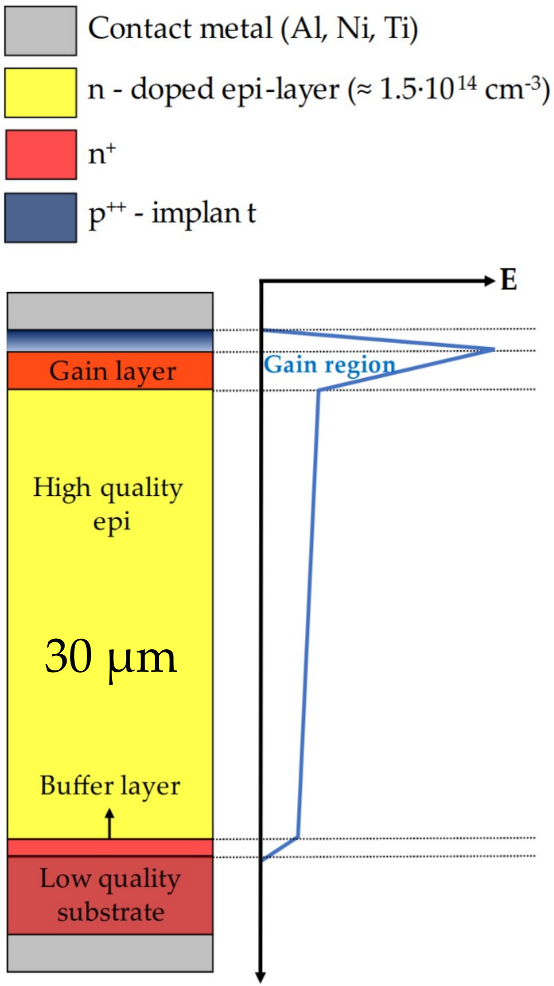
Final Design: **$7.5 \cdot 10^{16}$ cm^{-3}, 2.4 μm thick gain layer**

10x6'' wafers procured and arrived at CNM

LGAD Optimization

CnCV Measurements of Manufacturer



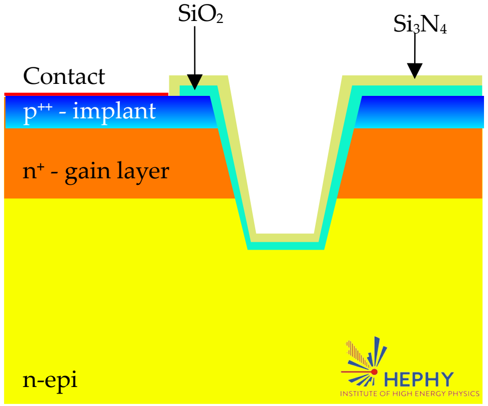


SiC-LGAD Guarding

- Epitaxial gain layer needs to be interrupted / guarded
- Electric field for charge multiplication:
  Si : ~0.3 MV/cm vs. SiC : ~3 MV/cm (x10!)
- A good gain layer termination is paramount and not easy to achieve!
  ease of production, fill factor, breakdown voltage, …

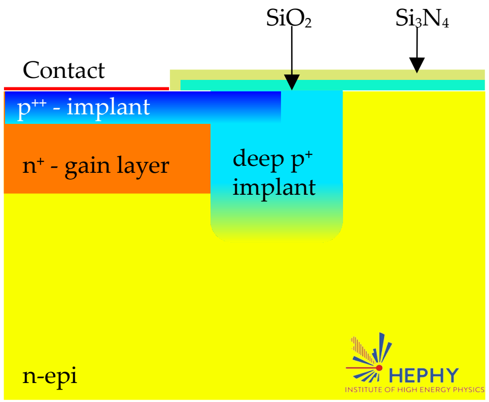
Trenches

HEPHY



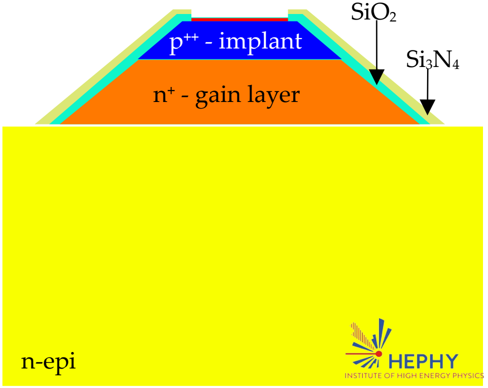
JTE

FZU/CTU/onsemi, HEPHY



Bevel-Edge

LBNL/NCSU, SICAR



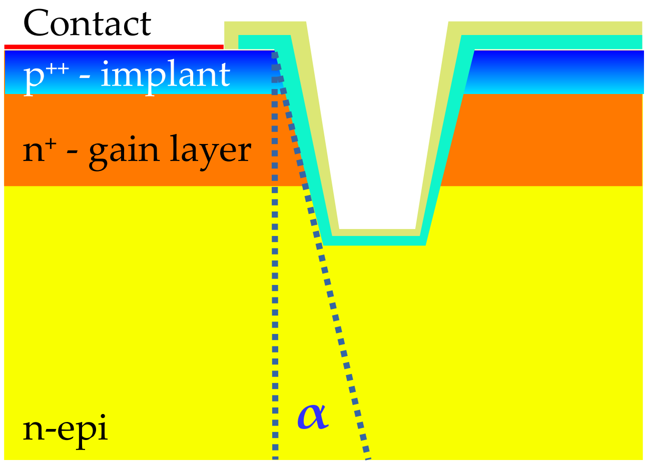
Trench Guarding

In theory trenches are ideal to interrupt the gain layer:

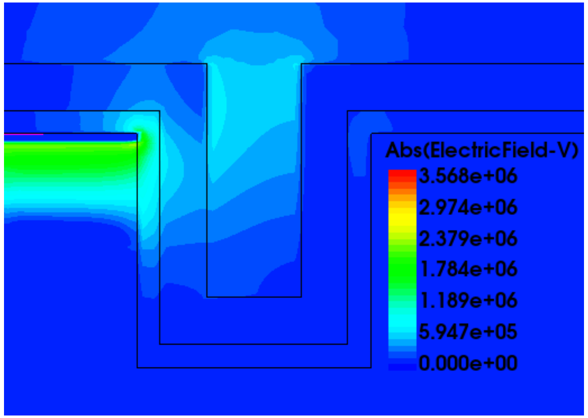
- Good fill factor, very high voltages can be achieved

However:

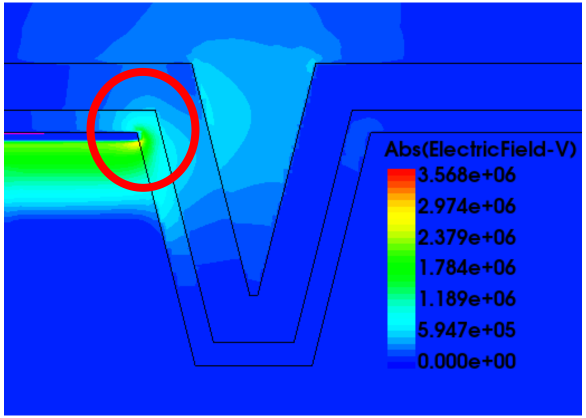
- Deep trenches (> 4 μm) are not easy to manufacture
- Aspect ratio of trench is very important, needs to be $\alpha < 5°$



Perfect trench ($\alpha = 0°$)

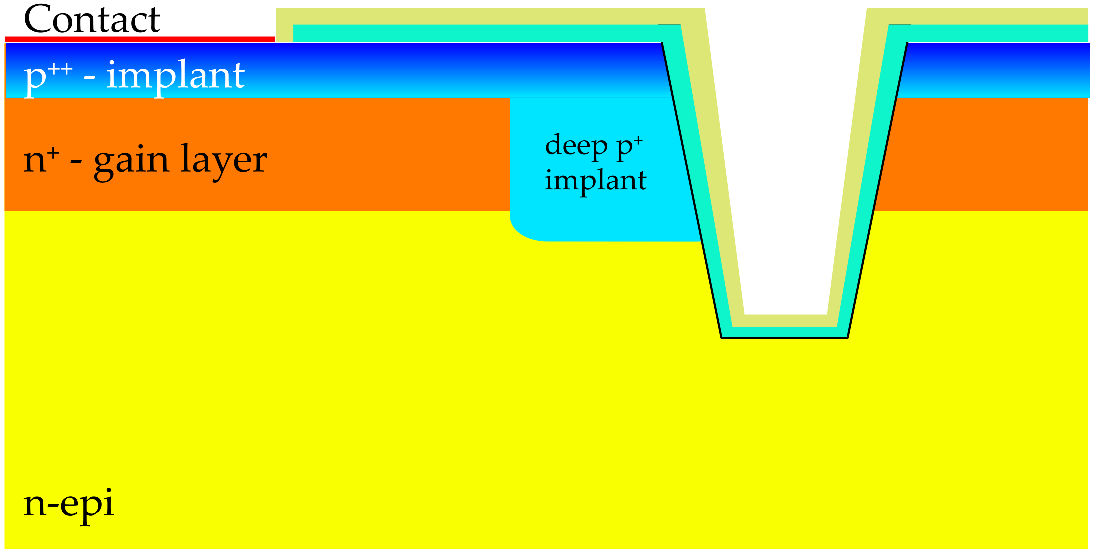


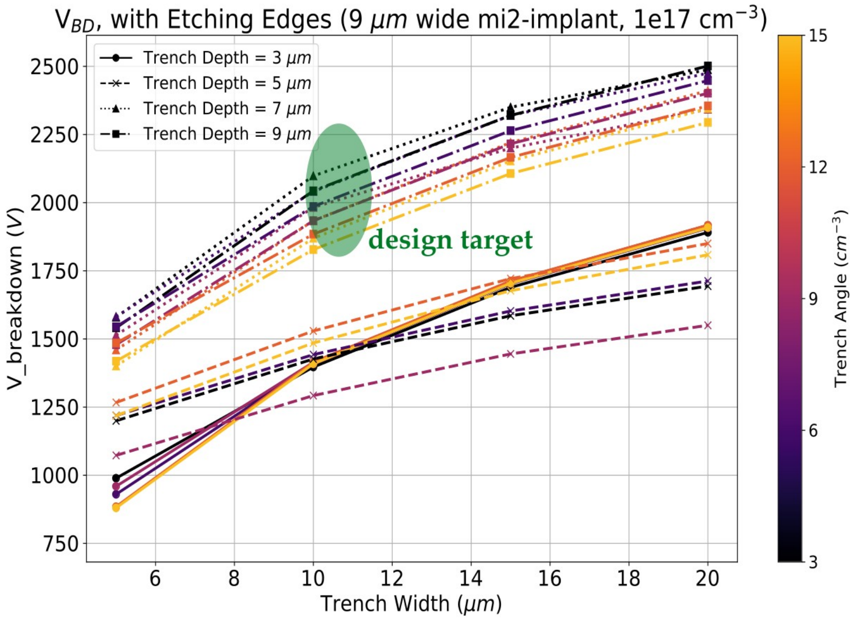
Bad trench ($\alpha = 15°$)



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 $\alpha = 12°$

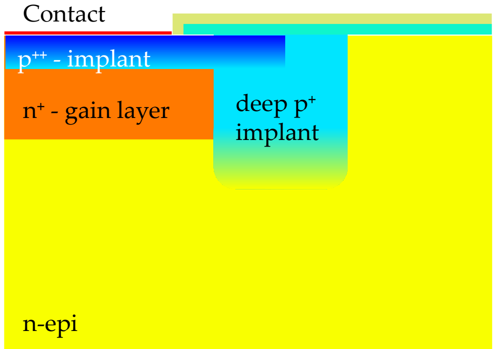




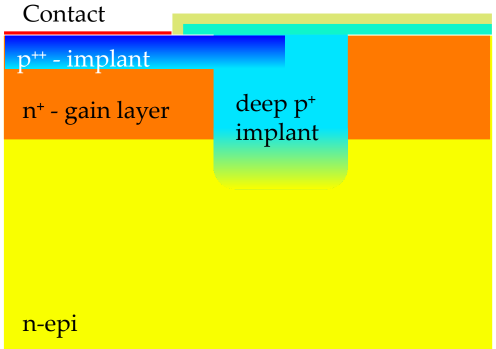
JTE Guarding

- 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

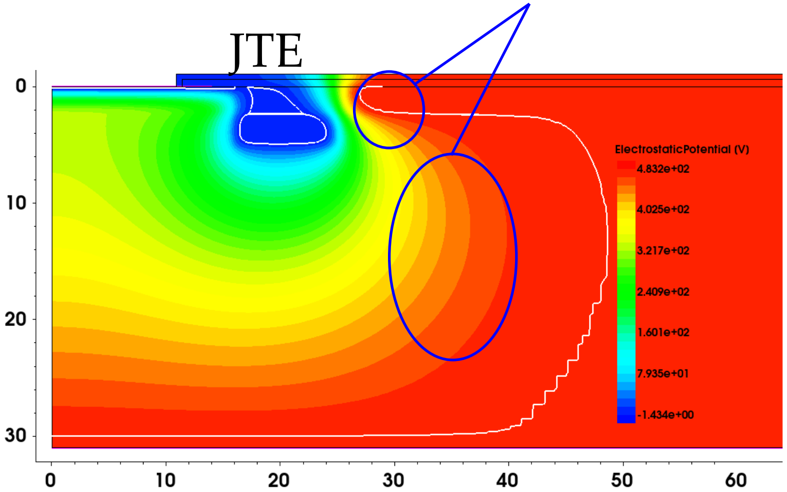
Implanted Gain Layer



Epitaxial Gain Layer

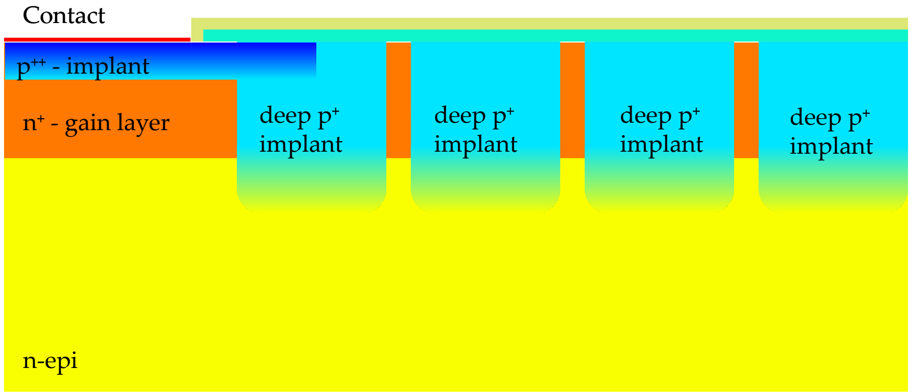


Build-up of high electric fields



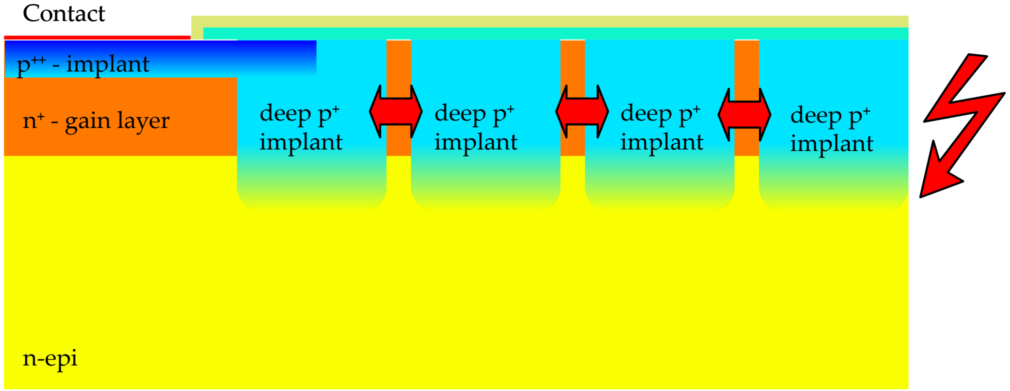
Multiple JTE Guards

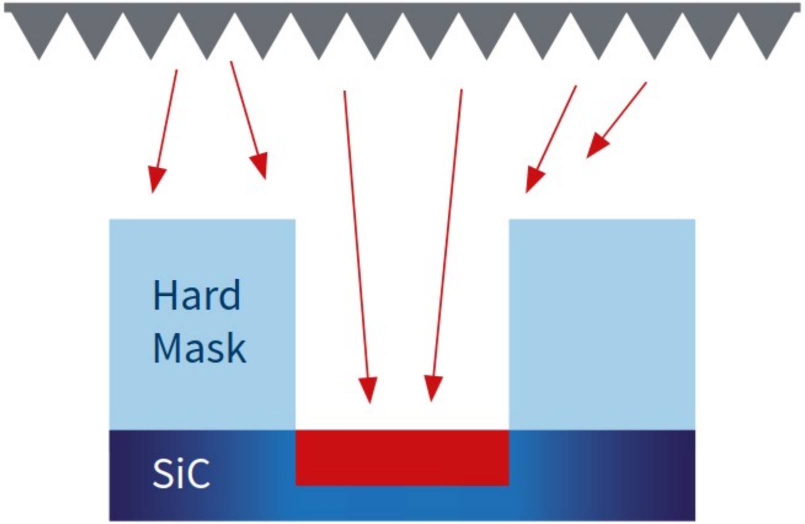
- If one JTE is not working, use multiple and slowly dissipate potential



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

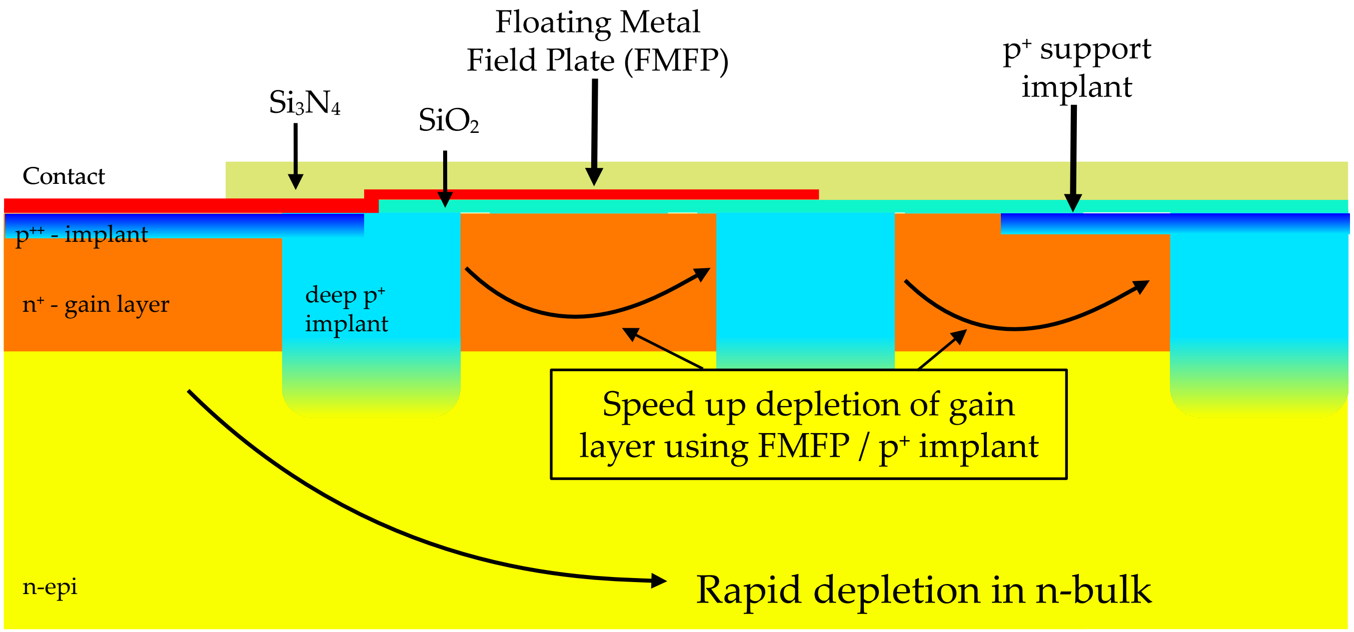


Illustration of FMFP and support implant concepts

RD50-SiC-LGAD : Layout

- Masks finished and ordered : 464 dies per wafer
- Three guarding designs (JTE and trenches), all with simulated $V_{BD} > 2$ kV
- Processing to start January 2025

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

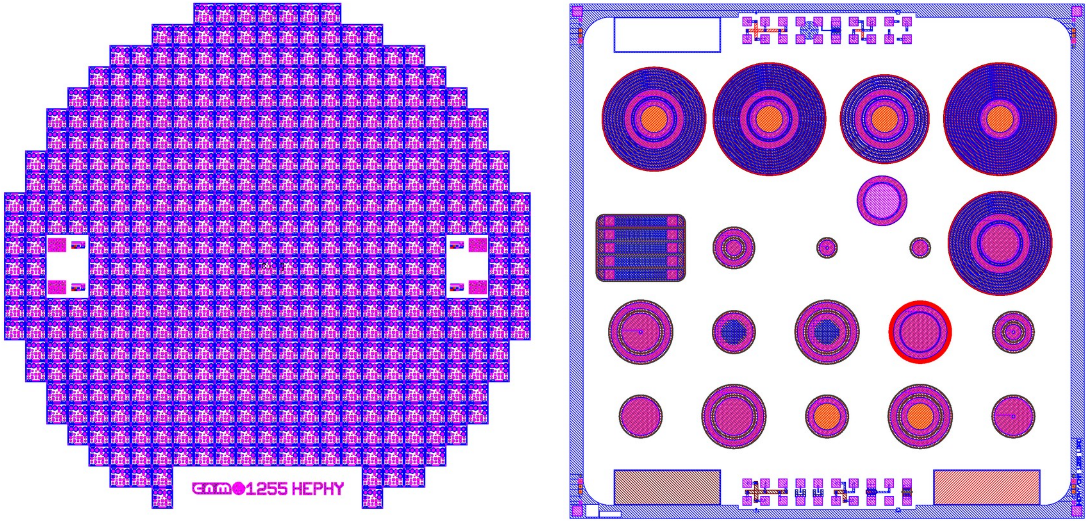
2: JTE & support-implants + FMFPs*

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

- Sensitive to deep implant widths
- Large device area

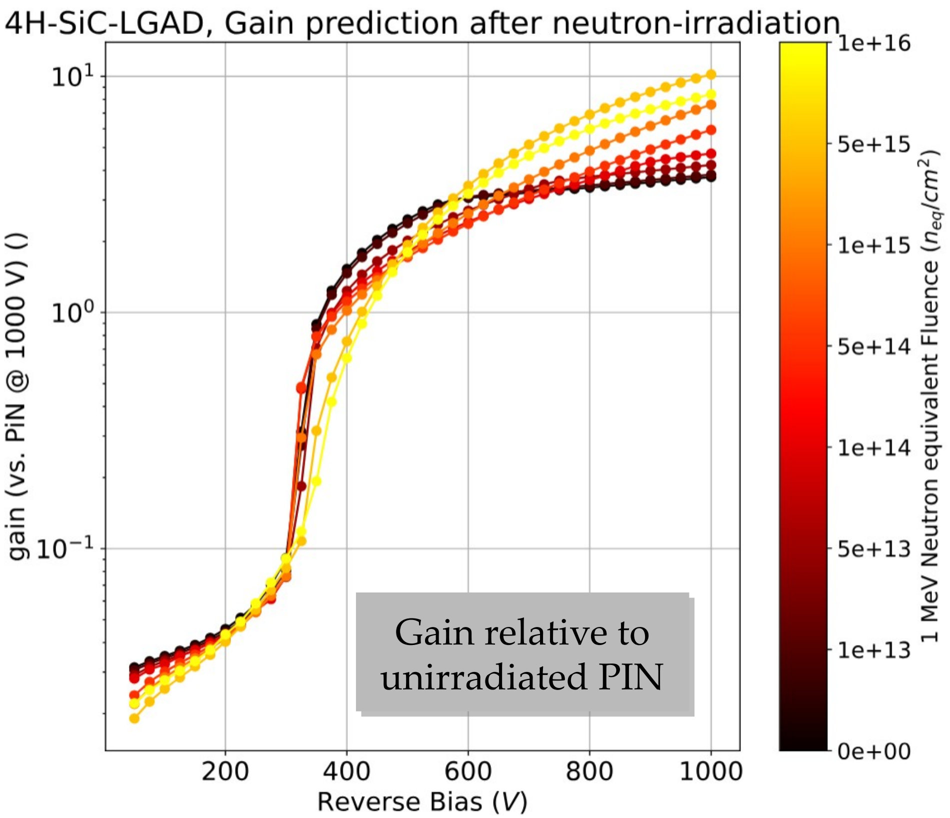
* Floating metal field plates

Finalized Mask Design for RD50-SiC-LGAD



SiC-LGAD Radiation Hardness

- Irradiation model (see 10.1016/j.nima.2024.170015 10.1109/Austrochip62761.2024.10716221, DRD3 talk) predicts that the LGAD design still shows gain (and even increases) after 1E16 n_{eq}/cm^2
- However radiation model has shortcomings:
  - Low amount of samples
  - Measurements were not sensitive to donor removal (10^{14} cm^{-3} epi already intrinsic at 1E14 n_{eq}/cm^2)
  - Study lower irradiation fluences and/or p-type epi

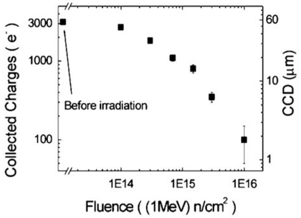


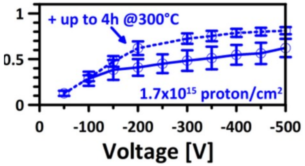
Gain relative to unirradiated PIN

Radiation Hardness of SiC in general:

- Big CCE decrease after 1E15 n_{eq}/cm^2
- Improves by annealing?
- Irradiation campaign using planar samples / LGADs

10.1109/TNS.2006.872202 (Moscatelli et. al.)





10.1109/TNS.2023.3307932 (Rafi et al)

SiC Timing Performance

Very few MIP timing studies for 4H-SiC:

MIP detection for SiC is challenging in the first place (esp. for 50 µm)

Signal : 57 eh/µm * 50 µm = 2.8 ke, for SNR = 10 → noise = 280e

What is the intrinsic timing limit for 4H-SiC?

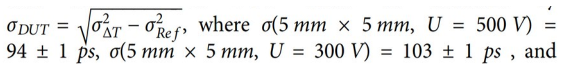
- Ionization model for Si and C, impact of increased density and ε_i ?
- How much does the increased charge carrier velocity decrease the Landau noise?
- SiC-LGAD shot noise (gain fluctuations)?

$$\sigma_t^2 = \sigma_{\text{Jitter}}^2 + \sigma_{\text{Ionization}}^2 + \dots$$

measured

Time Resolution of the 4H-SiC PIN Detector

Tao Yang[1,2], Yuhang Tan[1,2], Qing Liu[3], Suyu Xiao[1,2,4], Kai Liu[1], Jianyong Zhang[1], Ryuta Kiuchi[1], Mei Zhao[1], Xiyuan Zhang[1], Congcong Wang[1], Boyue Wu[5], Jianing Lin[6], Weimin Song[6], Hai Lu[3] and Xin Shi[1*]*



$\sigma_{DUT} = \sqrt{\sigma_{\Delta T}^2 - \sigma_{Ref}^2}$, where $\sigma(5\,mm \times 5\,mm,\ U = 500\,V) = 94 \pm 1\ ps$, $\sigma(5\,mm \times 5\,mm,\ U = 300\,V) = 103 \pm 1\ ps$, and

10.3389/fphy.2022.718071

simulated

Radiation Detection Technology and Methods (2024) 8:1140–1147
https://doi.org/10.1007/s41605-023-00431-y

ORIGINAL PAPER

Check for updates

Design and simulation of a novel 4H-SiC LGAD timing device

Keqi Wang[1,2] · Tao Yang[1,3] · Chenxi Fu[1,3,4] · Li Gong[2] · Songting Jiang[5] · Xiaoshen Kang[2] · Zaiyi Li[1,3,6] · Hangrui Shi[4] · Xin Shi[1] · Weimin Song[4] · Congcong Wang[1] · Suyu Xiao[7,8] · Zijun Xu[1] · Xiyuan Zhang[1]

The time resolution of the LGAD is (35.0 ± 0.2) ps

10.1007/s41605-023-00431-y

Bandwidth / Jitter for Planar Sensors

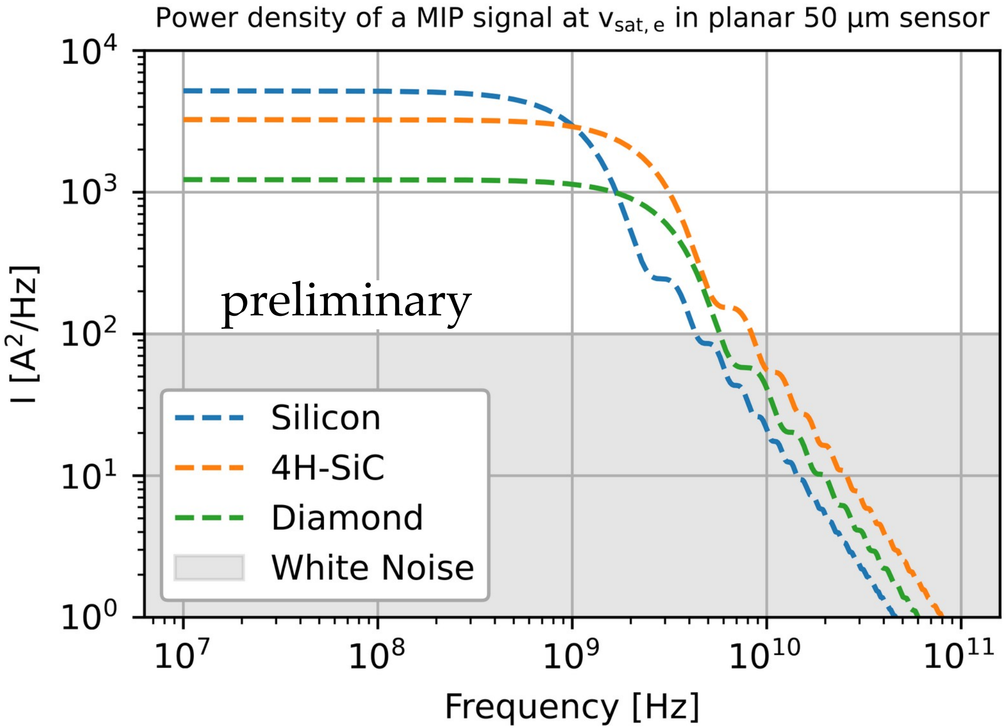
- Toy model : uniform charge deposition, charge carriers drift at $v_{sat,e}$, current from Shockley-Ramo

$$I(t) = \frac{2Q}{T} \cdot \left(1 - \frac{t}{T}\right) \qquad \int I(t)\,dt = Q$$

$$\int |I(t)|^2\,dt = \frac{4Q^2}{3} \cdot \frac{1}{T}$$

- Above ~ 1 GHz, more power density for WBG (SiC / diamond) than for Si, even though ε_i is higher

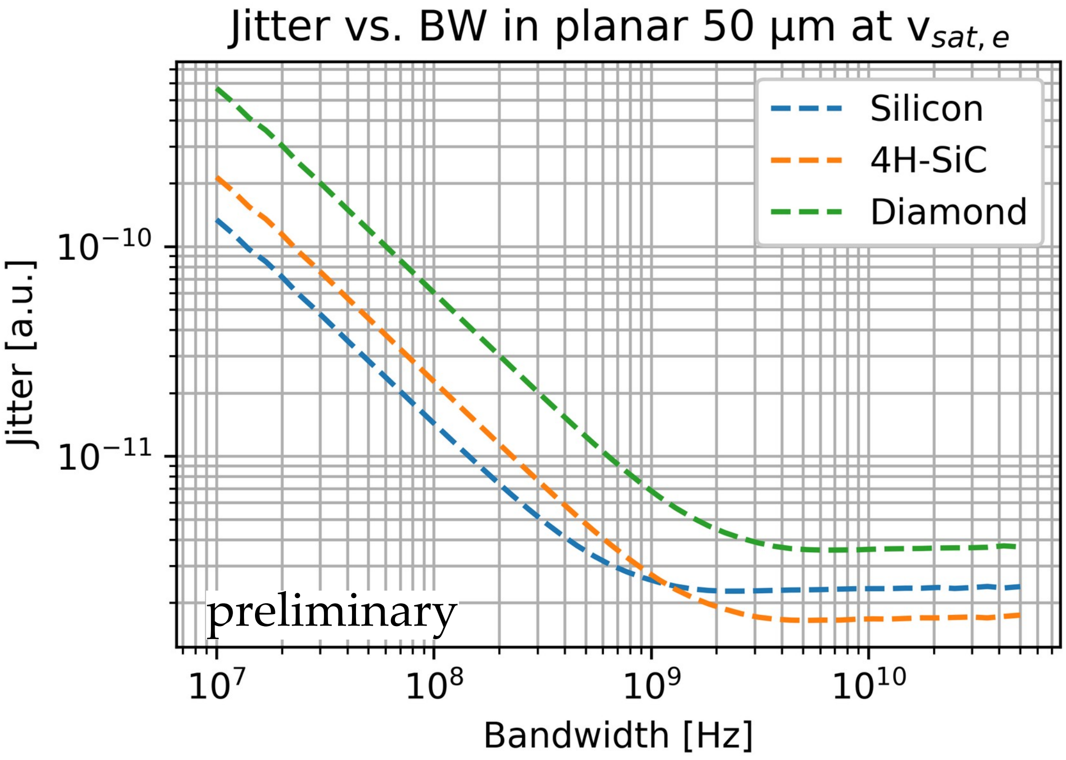
	Silicon	4H-SiC	Diamond
ρ	$2.33\,\mathrm{g/cm^3}$	$3.21\,\mathrm{g/cm^3}$	$3.5\,\mathrm{g/cm^3}$
ϵ_i	$3.62\,\mathrm{eV}$	$7.83\,\mathrm{eV}$	$13\,\mathrm{eV}$
$\mathrm{d}Q/\mathrm{d}x$	$72\,e\,\mu\mathrm{m}^{-1}$	$57\,e\,\mu\mathrm{m}^{-1}$	$35\,e\,\mu\mathrm{m}^{-1}$



Bandwidth / Jitter for Planar Sensors

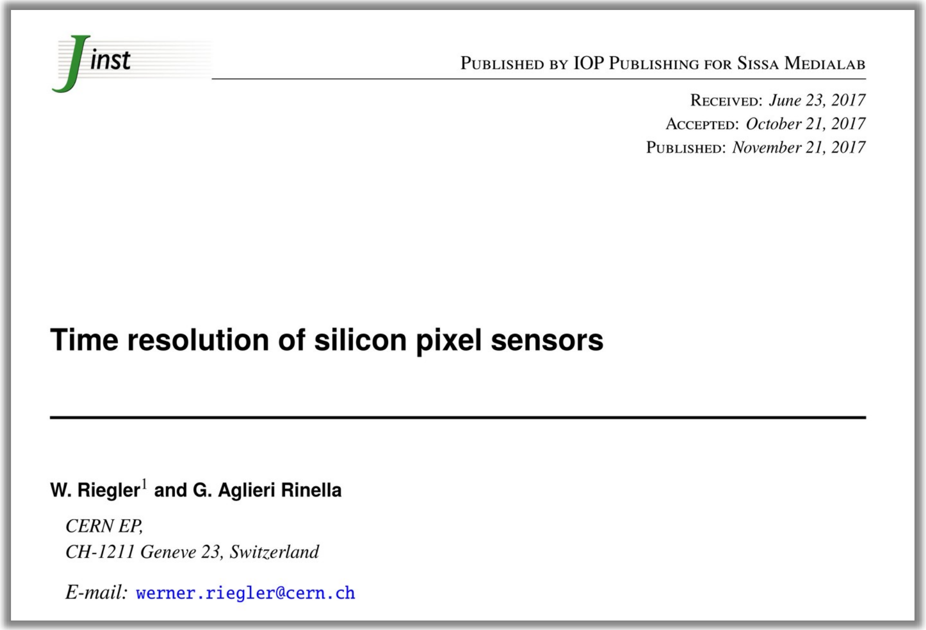
- At low frequencies:
  t_{rise} dominated by readout BW, only effect of SNR visible
- Above 1 GHz, drift velocity of 4H-SiC leads to lower jitter noise than Si
- This assumes white noise:
  (noise not increasing with BW)

$$\sigma_{jitter} = \frac{t_{rise}(f)}{SNR(f)}$$



Landau Fluctuations for Planar Sensors

- For amplifiers with $t_{peak} < t_{signal}$, we can look at variations of the signal's *center of gravity*
- Analytical treatment by Riegler et. al.
- Reproduce numerically in AllPix²



JINST

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *June 23, 2017*
ACCEPTED: *October 21, 2017*
PUBLISHED: *November 21, 2017*

Time resolution of silicon pixel sensors

W. Riegler[1] and G. Aglieri Rinella

CERN EP,
CH-1211 Geneve 23, Switzerland

E-mail: werner.riegler@cern.ch

$$\Delta_\tau = w(d)\sqrt{\frac{4}{180}\frac{d^2}{v_1^2} - \frac{7}{180}\frac{d^2}{v_1 v_2} + \frac{4}{180}\frac{d^2}{v_2^2}}$$

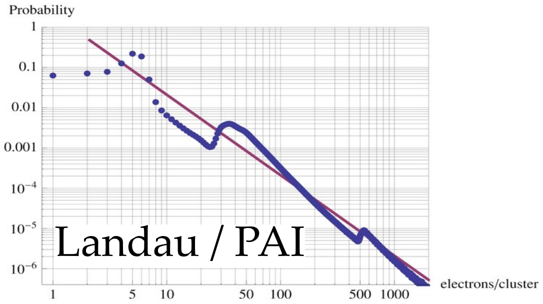
MFP λ,
thickness d

Charge carrier
velocities v_1, v_2

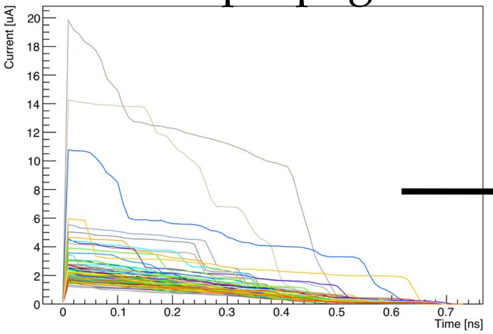
$$w(d) \approx \frac{1}{\sqrt{\ln d/\lambda}}$$

$\varrho_{Si} = 2.33\ \mathrm{g/cm^3}$
$\varrho_{SiC} = 3.21\ \mathrm{g/cm^3}$

Landau Fluctuations in AllPix²



Charge deposition and transient propagation

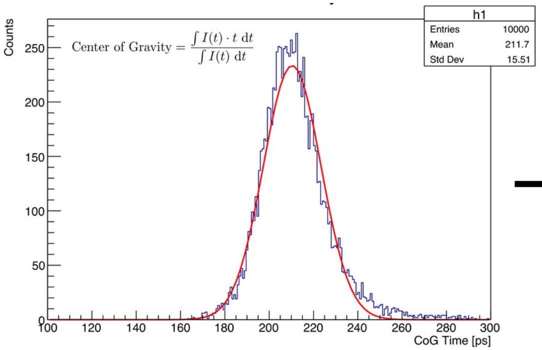


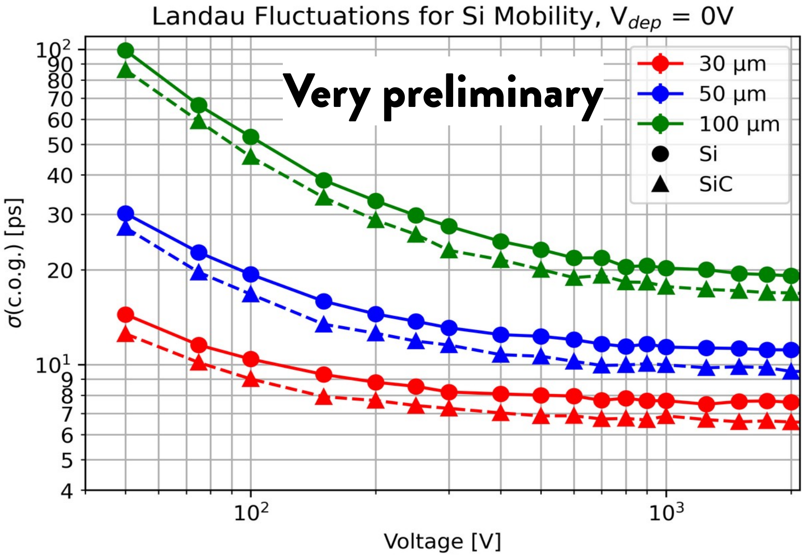
- Numerical Simulations in AllPix²
- Assuming the same mobility in Si and SiC: less Landau fluctuations in SiC due to higher density (lower MFP)

$$w(d) \approx \frac{1}{\sqrt{\ln d/\lambda}}$$

$\varrho_{Si} = 2.33\ \mathrm{g/cm^3}$
$\varrho_{SiC} = 3.21\ \mathrm{g/cm^3}$

Center of Gravity




Landau Fluctuations for Si Mobility, V_{dep} = 0V

Very preliminary

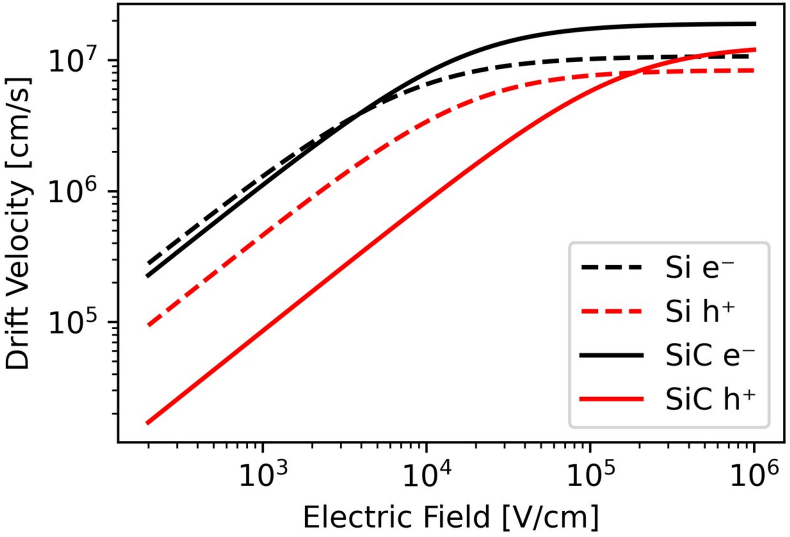
Landau Fluctuations for Planar Sensors

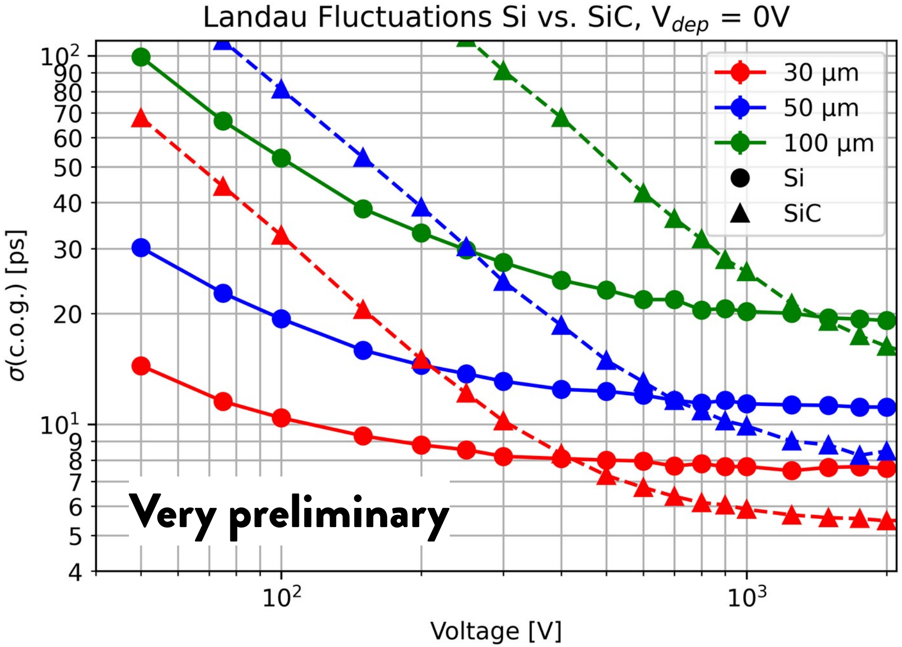
Inserting Mobility: Worse performance at low fields, but Si performance exceeded at high fields

→ Need high fields to leverage 4H-SiC saturation velocity (depletion voltage)

Next steps: SiC-LGAD in AllPix², try to investigate gain fluctuations

Mobility from Lades, Martin. "Modeling and Simulation of Wide Bandgap Semiconductor Devices: 4H/6H-SiC." (2000). [PDF]





Conclusions

- RD50-SiC-LGAD design has been finished, production is starting in 2025. Second planar run finishing soon!
- Epitaxially grown gain layers pose special challenges in terms of guarding, which have been adressed using trenches / JTEs with additional FMFP/support implants
- Radiation hardness of SiC-LGADs and donor removal needs to be studied more
- Timing performance of SiC-(LGADs) :
  Need high bandwidth and electric fields to leverage 4H-SiC material properties and enable performance superior to silicon
  More simulations (and measurements ☺) will be helpful

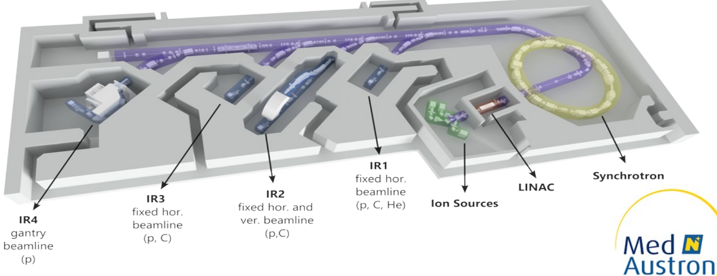
This project has received funding from the Austrian Research Promotion Agency FFG, grant number 883652.

BACKUP

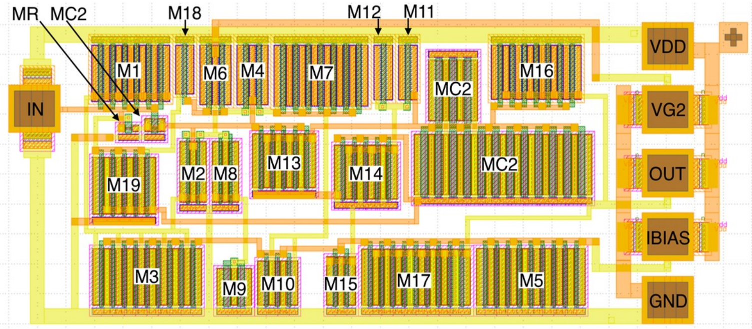
Further SiC Activities at HEPHY

- 4H-SiC material parameter literature review (10.48550/arXiv.2410.06798)
- Irradiation campaign with commercial SiC Schottky diodes (in planning)
- Theoretical estimation of the time resolution of SiC detectors (following work by Werner Riegler, 10.1088/1748-0221/12/11/P11017)
- Applications:
- Beam monitoring for ion-beam cancer therapy @ Medaustron (10.1088/1361-6560/ad5072)
- μ-dosimetry and space-dosimetry (upcoming)
- SiC-CMOS electronics design with Fraunhofer IISB (10.1109/Austrochip62761.2024.10716230)
- Si-LGADs are also investigated → comparison to SiC LGAD later on

Ion-beam cancer therapy center (close to Vienna)

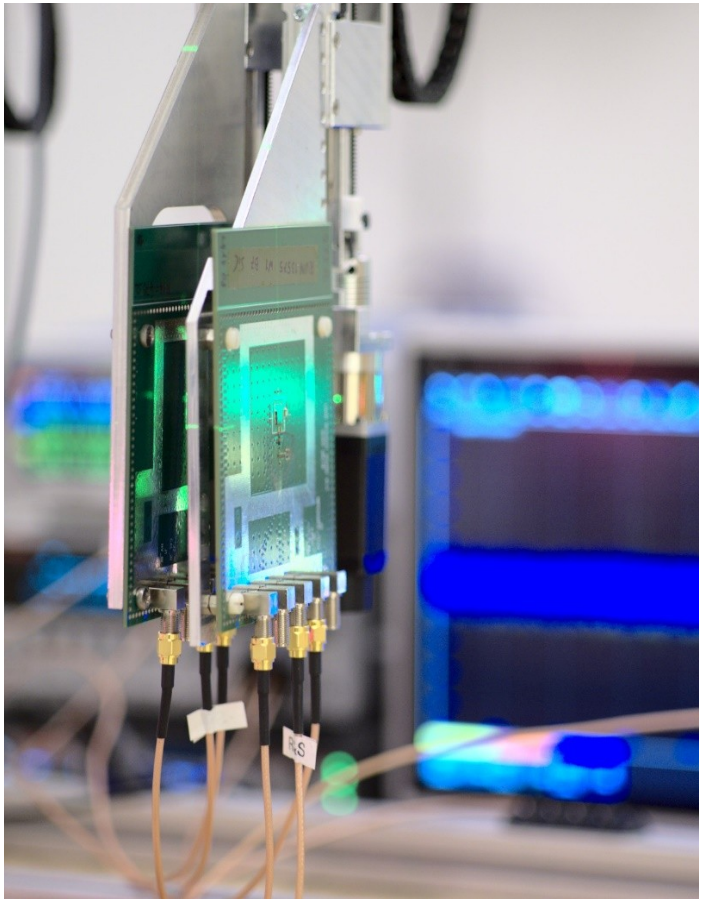


Med Austron



ASIC layout of charge sensitive amplifier in 2μm SiC-CMOS process

SiC at HEPHY Timeline



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

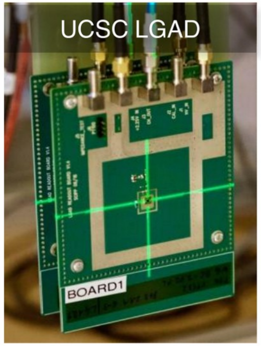
- Start of RD50 SiC-LGAD common project
- Measurement of electron-hole pair creation energy 10.1016/j.nima.2024.169412
- Planar SiC run designed and submitted

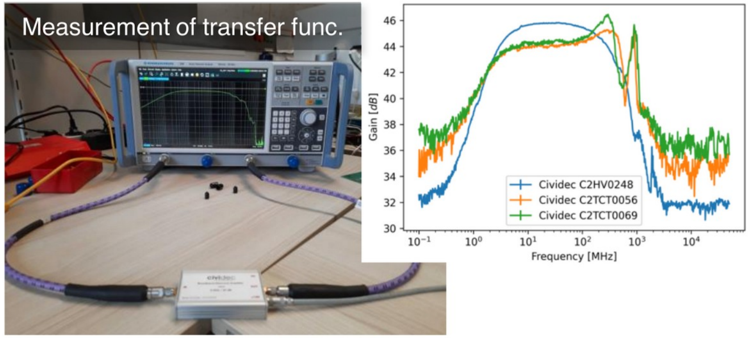
2024

- 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
- SiC TCAD parameter review arXiv:2410.06798

Readout Electronics

- For each application, ideal readout-electronics (amplifiers) exist
- Spectroscopic amplifiers (µs) to high bandwidth (ns)
- Detector pulse is < 0.5 ns

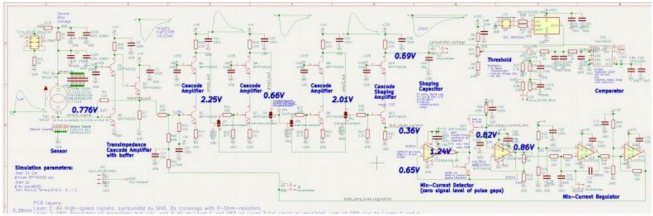

UCSC LGAD

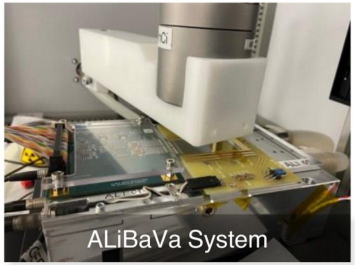

Measurement of transfer func.


Self-development

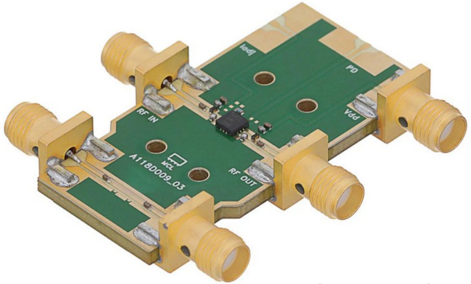

FNAL 16-ch


APVDAQ with SiC-strip




ALiBaVa System

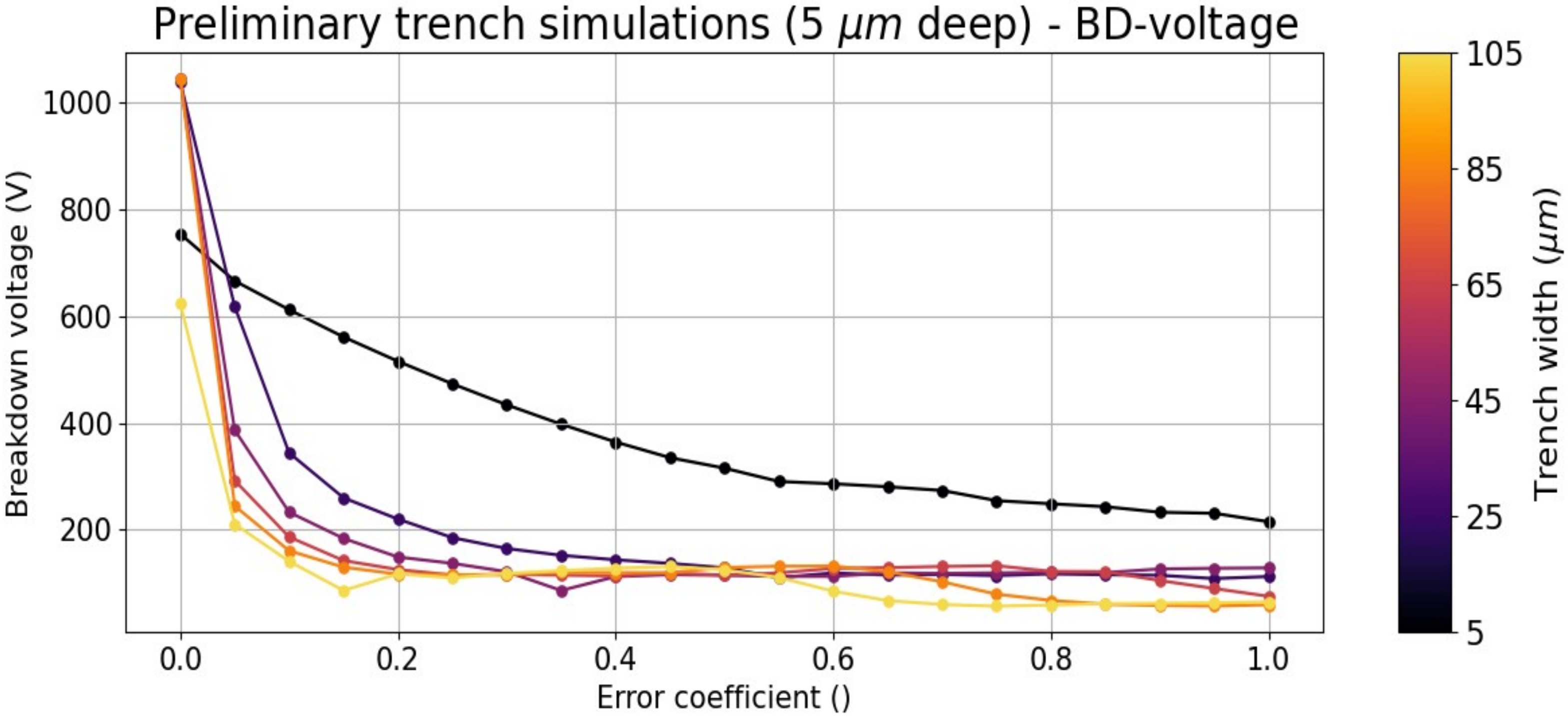
- 10 Ghz readout currently in development



10 GHz MiniCircuits Amplifer Eval Board

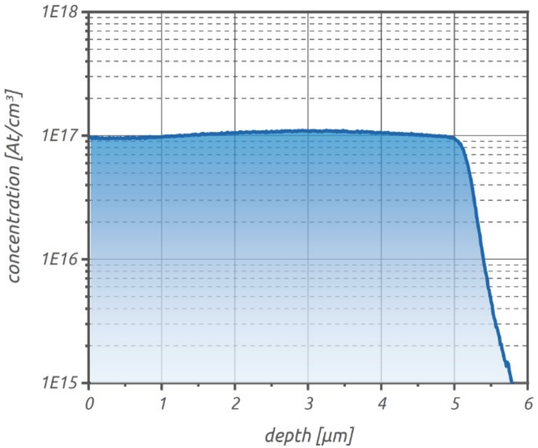
Trench Guarding : Angle

Angle needs to be very (unrealistically) good, otherwise there is a breakdown at the trench
Error coefficient : 1.0 = 45°



RD50-SiC-LGAD : Guarding

- No bevel edge process at CNM
  → trenches and/or deep-implants
- Need deep implants of sufficient doping and > 3 µm to penetrate gain layer
- 4 µm deep Al-implantation by Mi2



https://mi2-factory.com/services/#standard

Three different guarding structures on wafer:
(see backup for more detail)

1: Trench + single deep-implant

- High V_{BD}
- Mostly insensitive to process
- Small device area

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

2: Deep & support-implants + FMFPs*

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

- Sensitive to deep implant widths
- Large device area

3: Deep-implants + FMFPs*

- Less volatile processing
- Less sensitive to variation in deep implant widths

- Sensitive to oxide thickness
- Large device area

* Floating metal field plates