Time Resolution Simulations of 4H-SiC PiN Detectors

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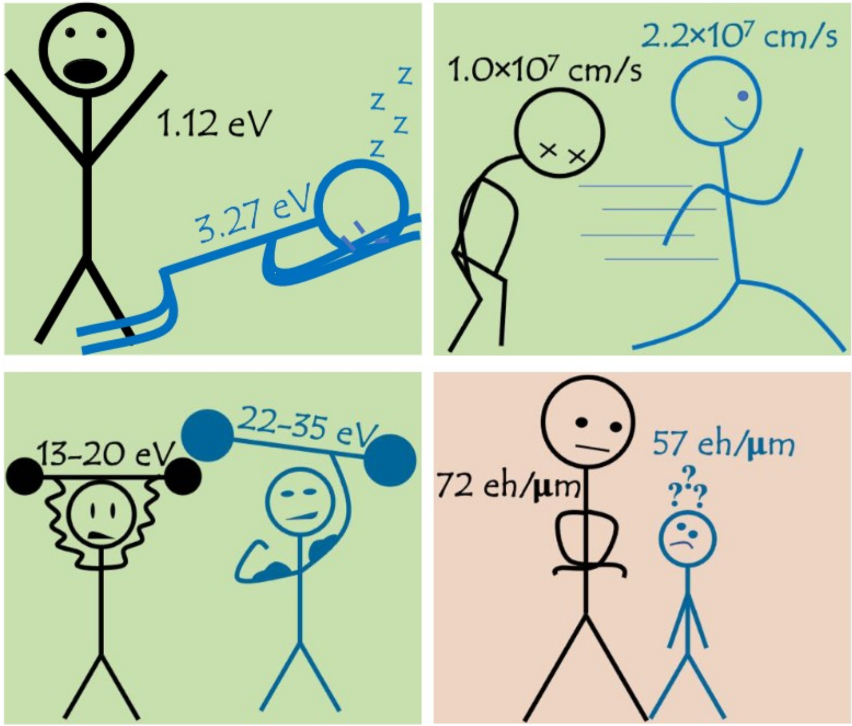
Silicon Carbide for HEP

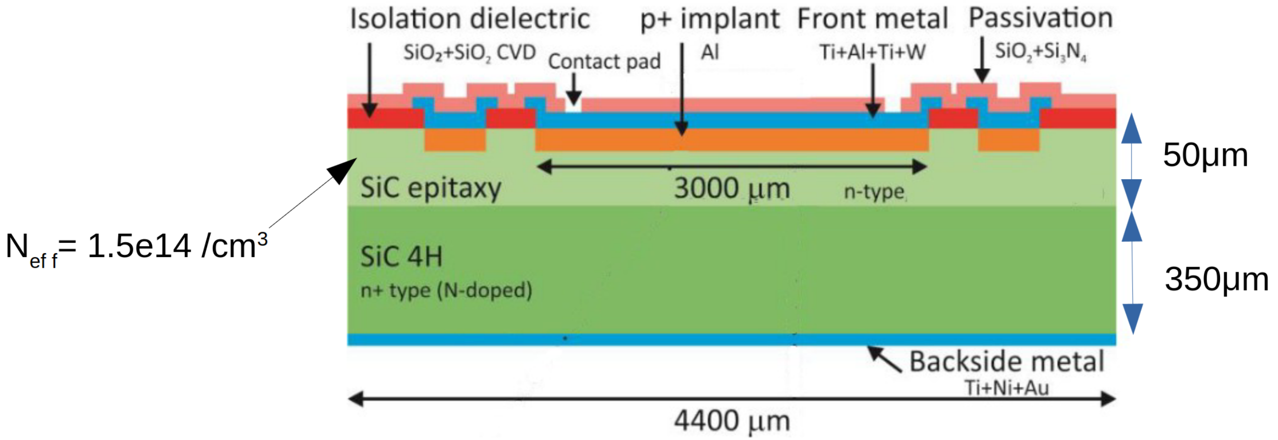
- 4H-SiC is a wide bandgap semiconductor
- Already investigated for HEP in the 2000s, renewed interest in SiC due to availability of high quality wafers from power electronics industry
- Very low leakage currents (< 1 pA), high breakdown field, insensitive to visible light
- Potentially higher radiation hardness (displacement energy)



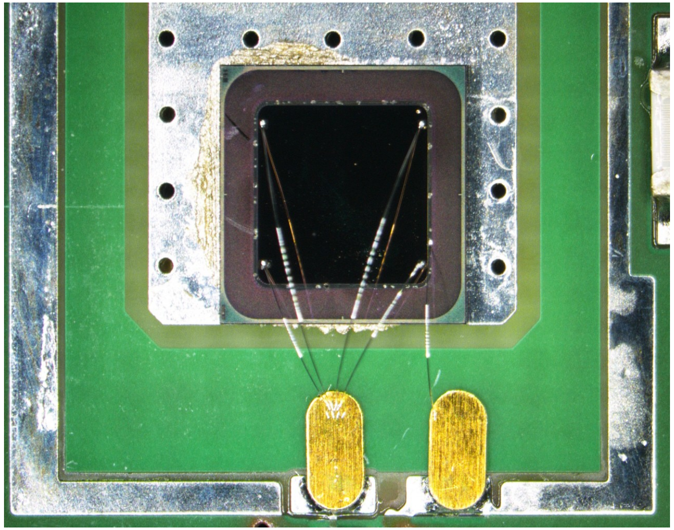
Advantages and disadvantages of 4H-SiC to Si

4H-SiC Samples

- 4H-SiC p-in-n Diodes from Run 13575 of CNM Barcelona [2]
- 3 x 3 mm² active area, 50 µm epi
- Full depletion voltage : 325V, C_{det} = 20 pF
- Ongoing characterization [3,4,5,6,7]



Cross-section of 4SiC samples from CNM's run 13575

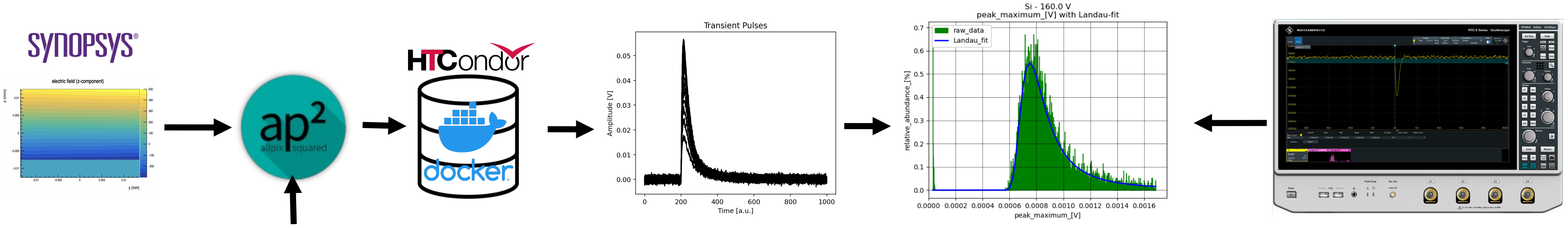


4H-SiC sample on UCSC LGAD board, with wire-bonds

Aim and Workflow

- Single particle detection, no spatial resolution at the moment
- Verify 4H-SiC parameters, combine TCAD and AllPix^2 to reproduce measurements
- With a verified model, use AllPix^2 to predict performance for testbeams

Simulation Workflow



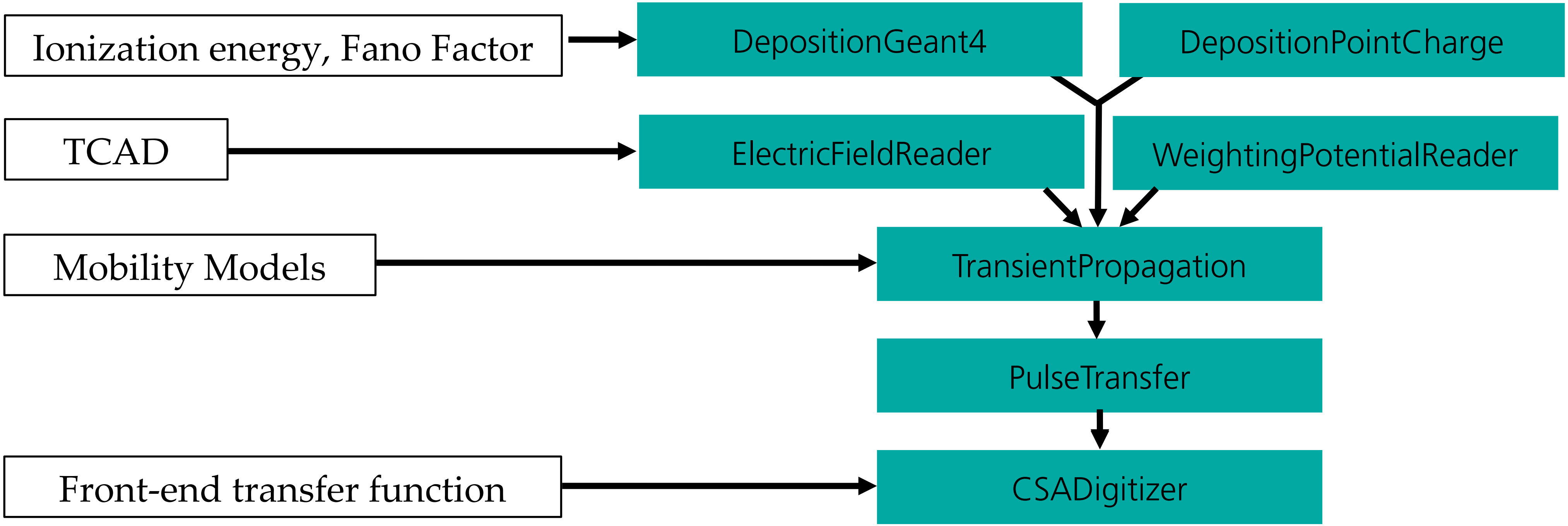
4H-SiC Material Parameters

Simulated Waveforms

Analysis Software
https://gitlab.com/dd-hephy/HiBPM/RS_DRS4_run_analysis

Measurements

AllPix² Modules and Input



Ionization energy, Fano Factor

DepositionGeant4

DepositionPointCharge

TCAD

ElectricFieldReader

WeightingPotentialReader

Mobility Models

TransientPropagation

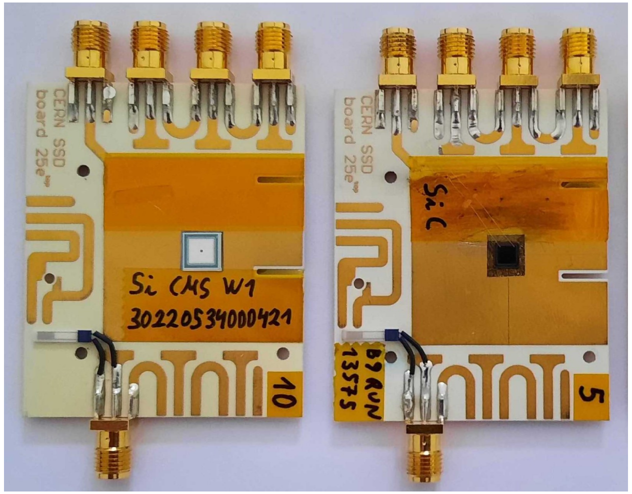
PulseTransfer

Front-end transfer function

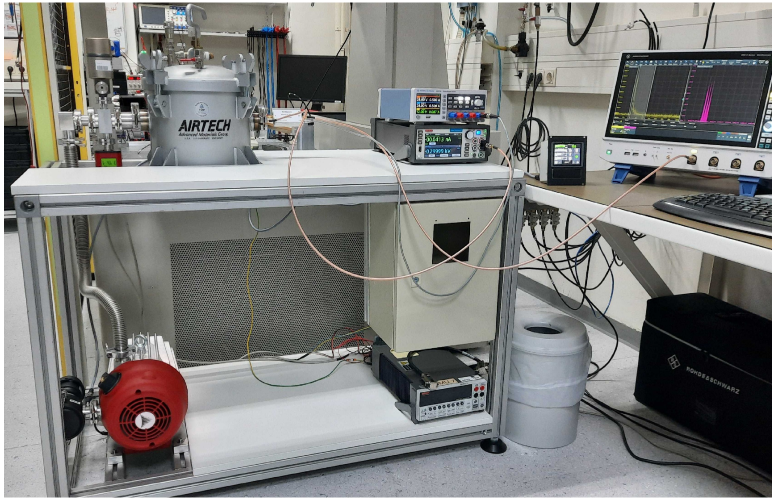
CSADigitizer

Ionization Energy + Fano Factor I

- Quite a large spread in literature values for ε_{SiC} and F_{SiC}
- Verify literature values using a comparison between Si and SiC detectors
- Tri-Alpha source (Pu^{239}, Am^{241}, Cm^{244}) in rough vacuum (10^{-1} mBar)
- Spectroscopic CSA (Cividec Cx-L, 1.2 μs shaping time)



Si (left) and SiC sensors (right) sensors



Vacuum Setup in HEPHY clean room

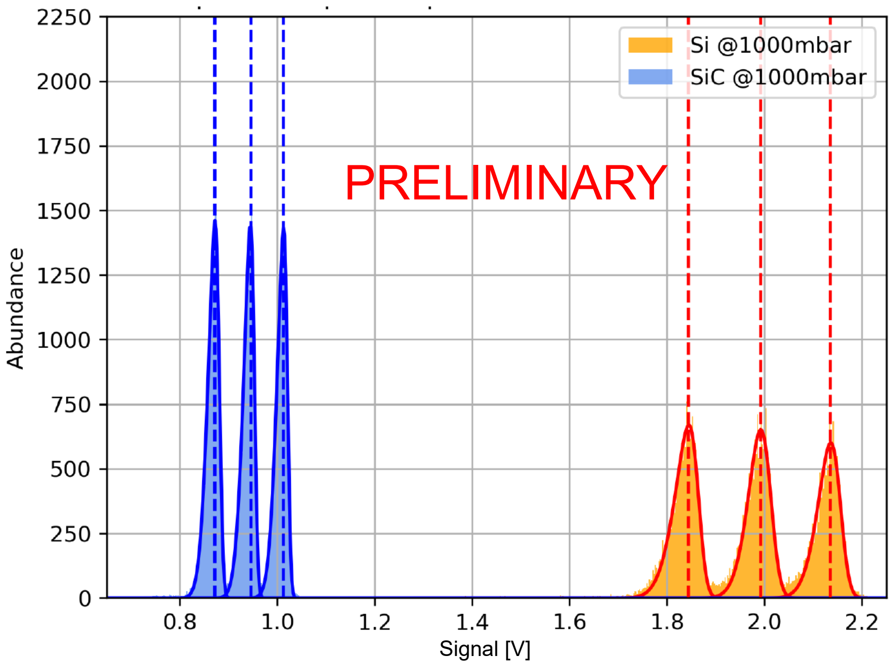
Ionization Energy + Fano Factor II

- Need to take into account ~ 1 µm of passivation and metalization on top of sensors using a Geant4 simulation
- Good agreement to recent literature values
- Results are very close to already implemented values in AllPix² (ε = 7.6 eV, F = 0.1)

$\varepsilon_{SiC} = 7.7 \pm 0.1$ eV

PRELIMINARY

$F_{SiC} = 0.10 \pm 0.01$



Comparison between Si and SiC spectra used to compute the ionization energy and Fano factor for 4H-SiC

Electric Field and Weighting Potential

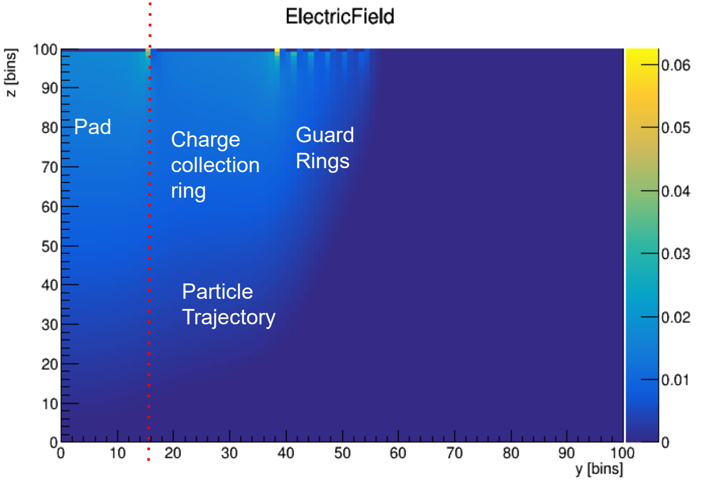
In practice, our samples are not “ideal” diodes

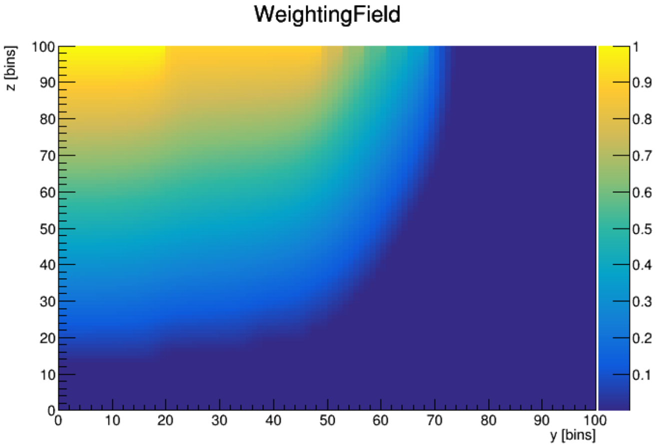
- Doping profile extracted from 1/C² measurements
- Deviation from linear electric field, need TCAD

Device simulation in Synopsys Sentaurus:

- Inadequate existing parameter files for 4H-SiC, extensive literature review was required
- Validation is still ongoing

- Export to DF-ISE, import into AllPix² using *mesh_converter*





Mobility Models

- Low Field Mobility : Masetti model [8]

$$\mu_{dop} = \mu_{min1} \cdot \exp\left(-\frac{P_C}{N_{A,0}+N_{D,0}}\right) + \frac{\mu_{const}-\mu_{min2}}{1+\left(\frac{N_{A,0}+N_{D,0}}{C_r}\right)^{\alpha}} - \frac{\mu_1}{1+\left(\frac{C_s}{N_{A,0}+N_{D,0}}\right)^{\beta}}$$

Doping profiles assumed constant in AllPix²

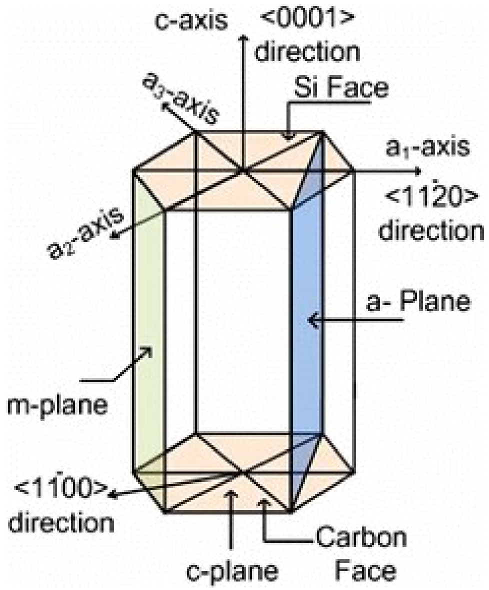
- High Field Mobility: Extended-Canali model [9, 10]

$$\mu(E) = \frac{v_m}{E_c}\frac{1}{\left(1+(E/E_c)^{\beta}\right)^{1/\beta}}$$

- Provide parameters to AllPix² after validation

- Anistropy :
  - ~20% difference per axis, not the same for e and h [11]
  - **Anisotropic parameters currently not possible in AllPix²**
  - Anisotropy can be neglected for our purposes

For our detector:
$\mu_{dop,e}$ = 991 cm²/V/s
$\mu_{dop,h}$ = 145 cm²/V/s



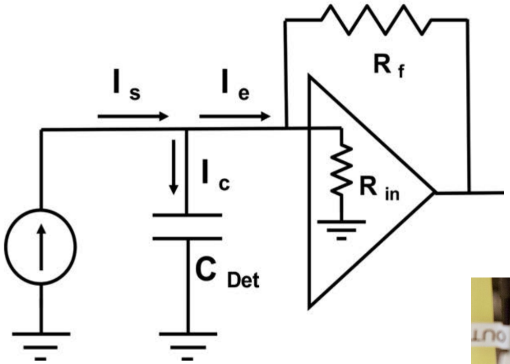
4H-SiC hexagonal crystal structure
[10.1007/s10825-016-0942-y]

Front-end Electronics

- UCSC LGAD readout board [12], high bandwidth (2 GHz) transimpedance-amplifier (TIA), transimpedance of 470 Ω
- Transimpedance amplifier : $Q = \int I \, dt$

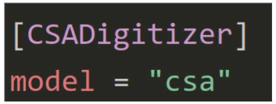
Simplified Model : Two low-pass filters

- Detector capacitance and input impedance: $\tau_{det} = C_{det} R_{in}$
- Bandwidth f_c of TIA: $\tau_{TIA} = 1 / (2\pi f_c)$



Simplifed Amplifier Model

- Analytically the same as



```
[CSADigitizer]
model = "csa"
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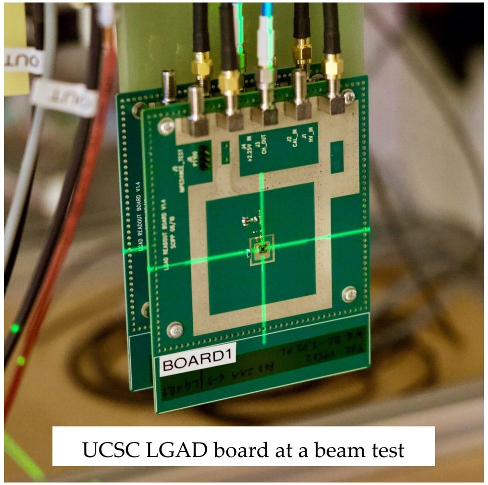


UCSC LGAD board at a beam test

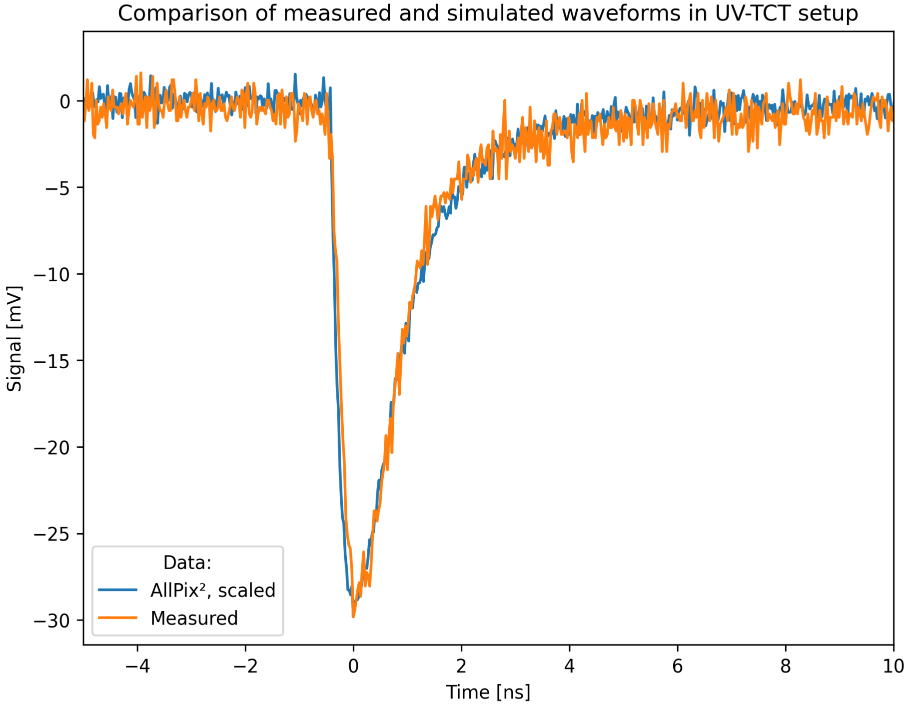
CSADigitizer Module

- Access waveforms using *PixelPulse* object (introduced in AllPix² 3.0, thanks!)

Modifications :

- Added padding before signal (some ns)
- Planned: Possibility to read impulse response from text file (more flexibility, utilize S_{21} parameters measured by a VNA)

- Shape of simulated waveforms agrees well with measurements

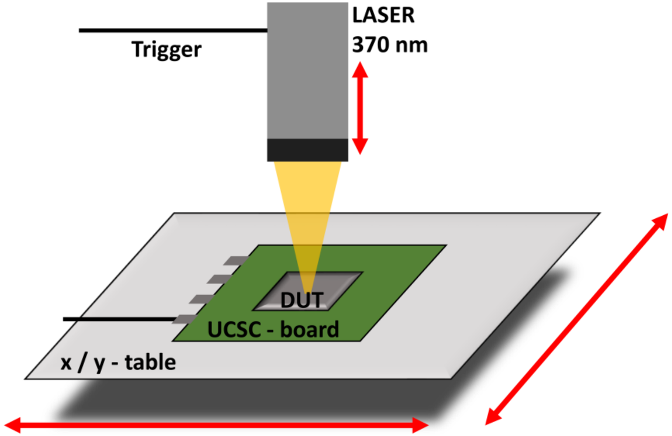


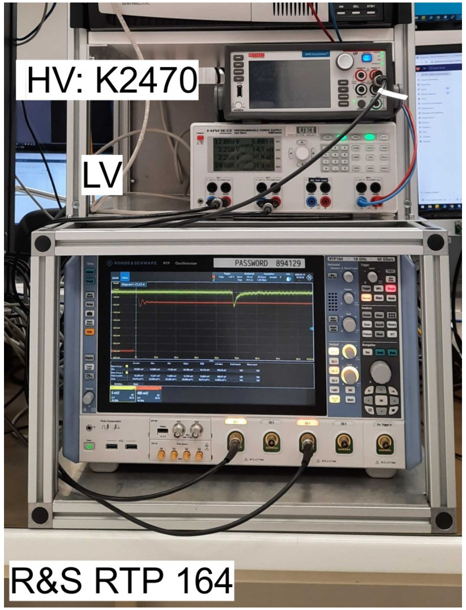
Simulation and Verification

- UV light (λ = 370 nm) needed to overcome bandgap of SiC (3.23 eV)
- Low jitter (< 3ps) electrical trigger available from laser controller [13]
- TCT allows for large signals and noise reduction by averaging
- Large signals required due to small epi thickness (MIP : 57 eh/µm · 50 µm ≈ 2.9 ke$^-$, ENC of front-end : 6.2 ke$^-$)
- See also [3]

First simulations and measurements presented here:

- **Charge collection efficiency (CCE) vs bias voltage**
- **Time Resolution**



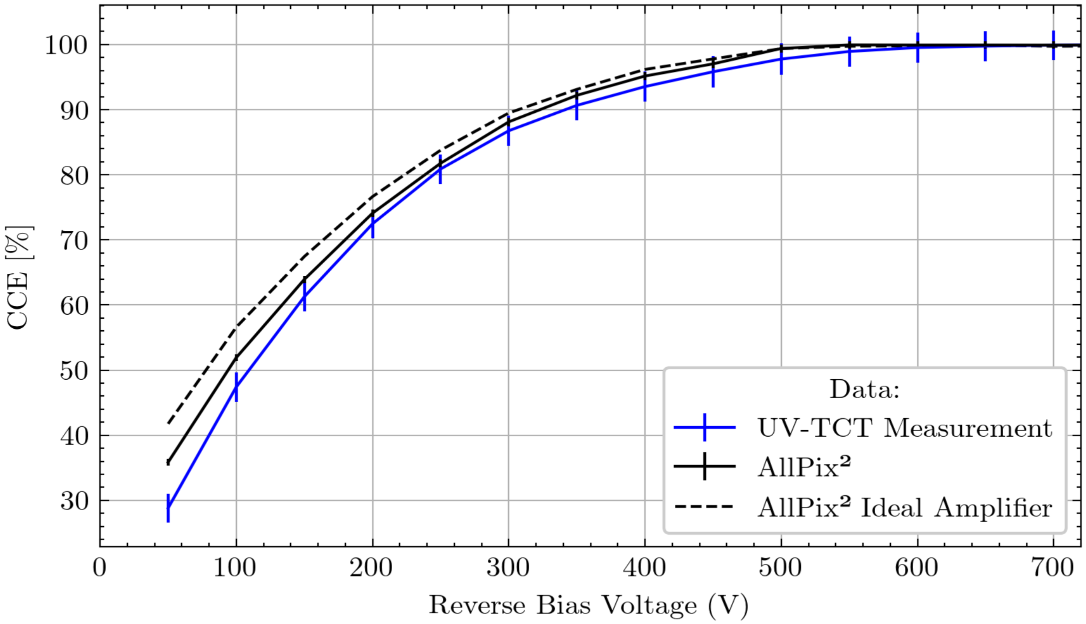


Charge Collection Efficiency CCE

- Uniform charge deposition assumed for laser in AllPix² ($\alpha \approx 42\ \text{cm}^{-1}$ [14])

- OK agreement between measured and simulated CCE (deviation < 5%)
- Increasing discrepancies at lower bias voltages

- Amplifier is non-ideal, a part of the signal is lost, esp. at low V
- Check RMS noise, add doping dependence for mobility



Time Resolution

- Large saturation velocities of SiC make it attractive for timing
- Can verify mobility models using time resolution measurements

- In general: Want to determine jitter σ_t on time stamps from detector

$$\sigma_t^2 = \sigma_{\text{Jitter}}^2 + \cancel{\sigma_{\text{Ionization}}^2} + \cancel{\sigma_{\text{Distortion}}^2} + \cancel{\sigma_{\text{TDC}}^2}$$

~~(Time walk mitigated by using CFD)~~

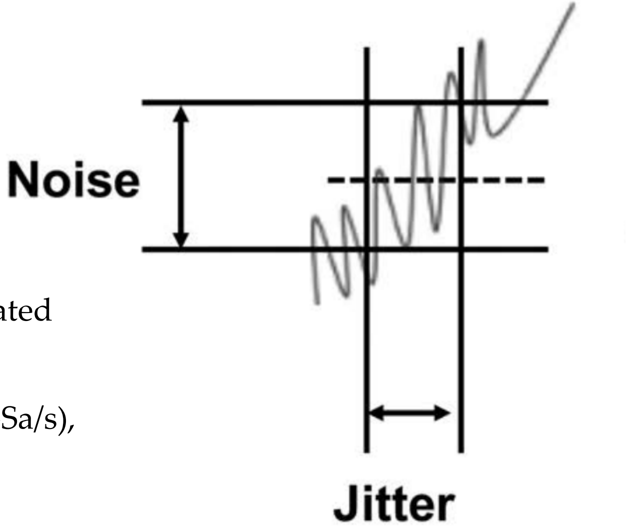
UV-TCT

Pad geometry

Fast oscilloscope (40 GSa/s), interpolation

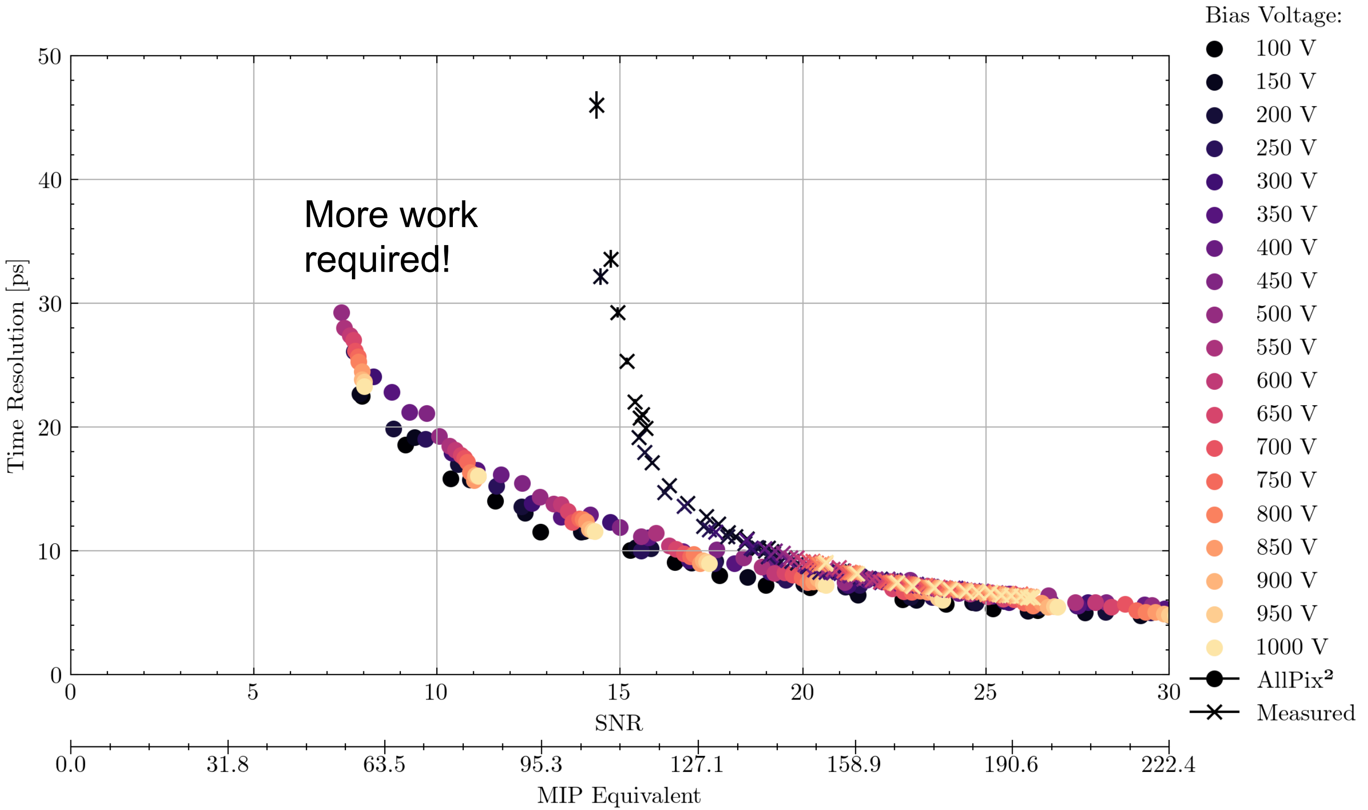
- Using TCT, only the jitter term is relevant

$$\sigma_{\text{Jitter}} \approx t_{\text{rise}} / \text{SNR}$$



Preliminary Time Resolution Results

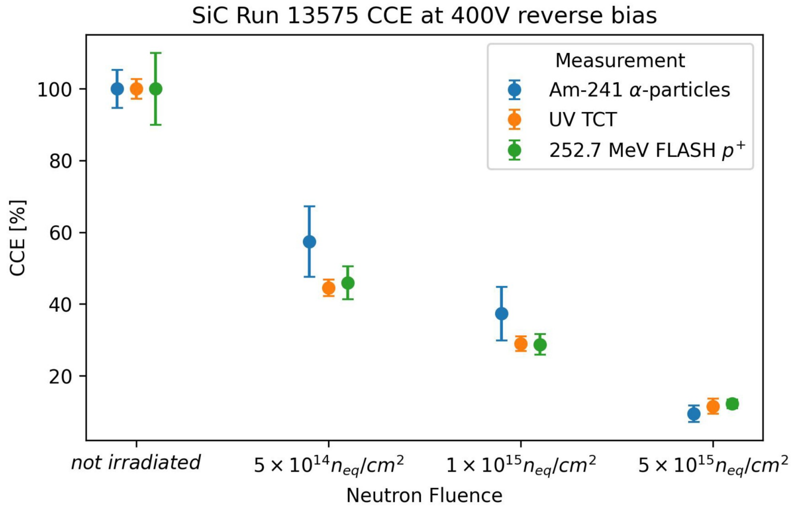
- Measurements and AllPix² follow a 1 / SNR relation
- Independent of bias voltage → t_{rise} constant → bandwidth limitation of electronics due to large sensor capacitance (20 pF)
- Disagreement at lower SNR, likely to due to issues in data analysis



Future Plans I : TCAD + Radiation Damage

- TCAD models still need to be validated
- Ongoing 4H-SiC project with an Austrian TCAD company Global TCAD solutions [14]
- Cross-check TCAD and AllPix² using *HeavyIon* simulations

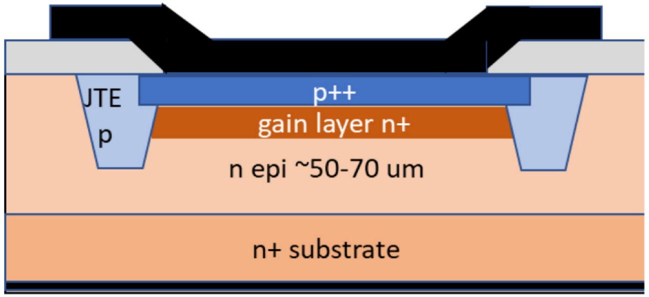
- Radiation Damage
  - Essential for future high-luminosity colliders, interesting for RD50 collaboration
  - Measured CCE for neutron-irradiated samples [3,4,5]
  - **Try to reproduce CCE results in AllPix²**



Future Plans II : LGADs

- SiC suffers from limitations on epi thickness and resistivity
  → Use internal charge multiplication, Low Gain Avalanche Didoes (LGAD)

- Attractive properties of SiC:
  - Multiplication of holes ($\alpha_e < \alpha_h$) instead of electrons ($\alpha_e > \alpha_h$ for Si)
  - Higher saturation velocity, especially interesting for timing



Idealized SiC LGAD structure [16]

- Work on SiC LGADs is ongoing, see [17] and [6]
- Need to compare and verify TCAD and AllPix² impact ionization models
- Use AllPix² as a simulation tool to predict perfomance

References

[1] : M. De Napoli, “SiC detectors: A review on the use of silicon carbide as radiation detection material,” Front. Phys., vol. 10, p. 898833, Oct. 2022, doi: 10.3389/fphy.2022.898833.

[2] : Rafí et al. Electron, Neutron, and Proton Irradiation Effects on SiC Radiation Detectors. IEEE TRANSACTIONS ON NUCLEAR SCIENCE 67, 9 (2020).

[3] : Gaggl et al.,, Charge collection efficiency study on neutron-irradiated planar silicon carbide diodes via UV-TCT, 10.1016/j.nima.2022.167218

[4] : Gaggl et al., Performance of neutron-irradiated 4H-silicon carbide diodes subjected to alpha radiation, J. Inst.18, C01042 (2023)

[5] : Gsponer et al., Measurements and Simulations of High Rate 4H-SiC Particle Detectors, 40th RD50 Workshop on Radiation Hard Semiconductor, Geneva (2022)

[6] : T. Bergauer, Silicon Carbide LGAD RD50 common project, 41st RD50 Workshop on Radiation Hard Semiconductor, Sevilla (2022)

[7] : Christanell et al., 4H-silicon carbide as particle detector for high-intensity ion beams. J. Inst. 17, C01060 (2022).

[8] : Stefanakis, et al.. Tcad models of the temperature and doping dependence of the bandgap and low field carrier mobility in 4h-sic. Microelectronic engineering, 116:65–71, 2014. ISSN 0167-9317.

[9] : Kimoto, et. al.. Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices and Applications. Wiley – IEEE. Wiley, New York, 1 edition, 2014. ISBN 9781118313527.

[10] : I.A Khan and J.A Cooper. Measurement of high-field electron transport in silicon carbide. IEEE transactions on electron devices, 47(2):269–273, 2000

[11] : Nilsson et al. Monte carlo simulation of electron transport in 4h-sic using a two-band model with multiple minima. Journal of applied physics, 80(6):3365–3369, 1996.

[12] : https://twiki.cern.ch/twiki/bin/view/Main/UcscSingleChannel

[13] : https://www.nktphotonics.com/products/pulsed-diode-lasers/pilas/

[14] : Sridhara, S. G. et al.,Absorption coefficient of 4H silicon carbide from 3900 to 3250 Å. Journal of Applied Physics 84, 2963–2964 (1998).

[15] : https://www.globaltcad.com/

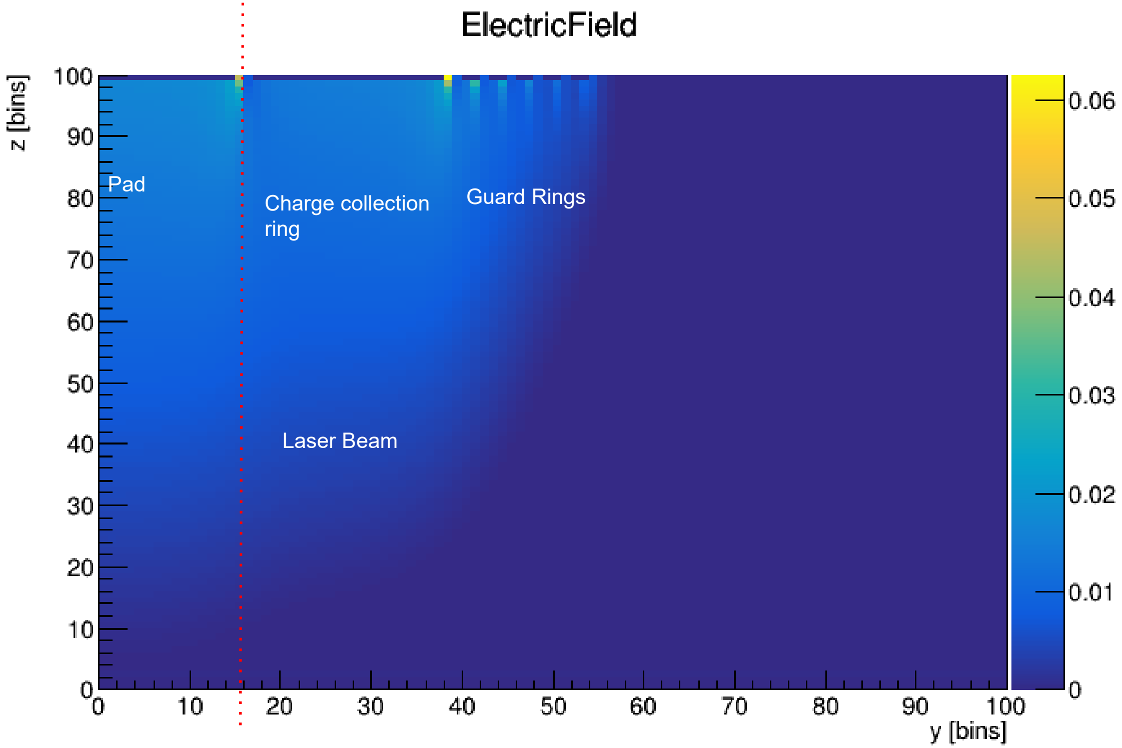
[16] : Barletta et al., Fast Timing With Silicon Carbide Low Gain Avalanche Detectors, Snowmass 2021, arXiv:2203.08554

[17] : Yang et al., Simulation of the 4H-SiC Low Gain Avalanche Diode, arXiv:2206.10191

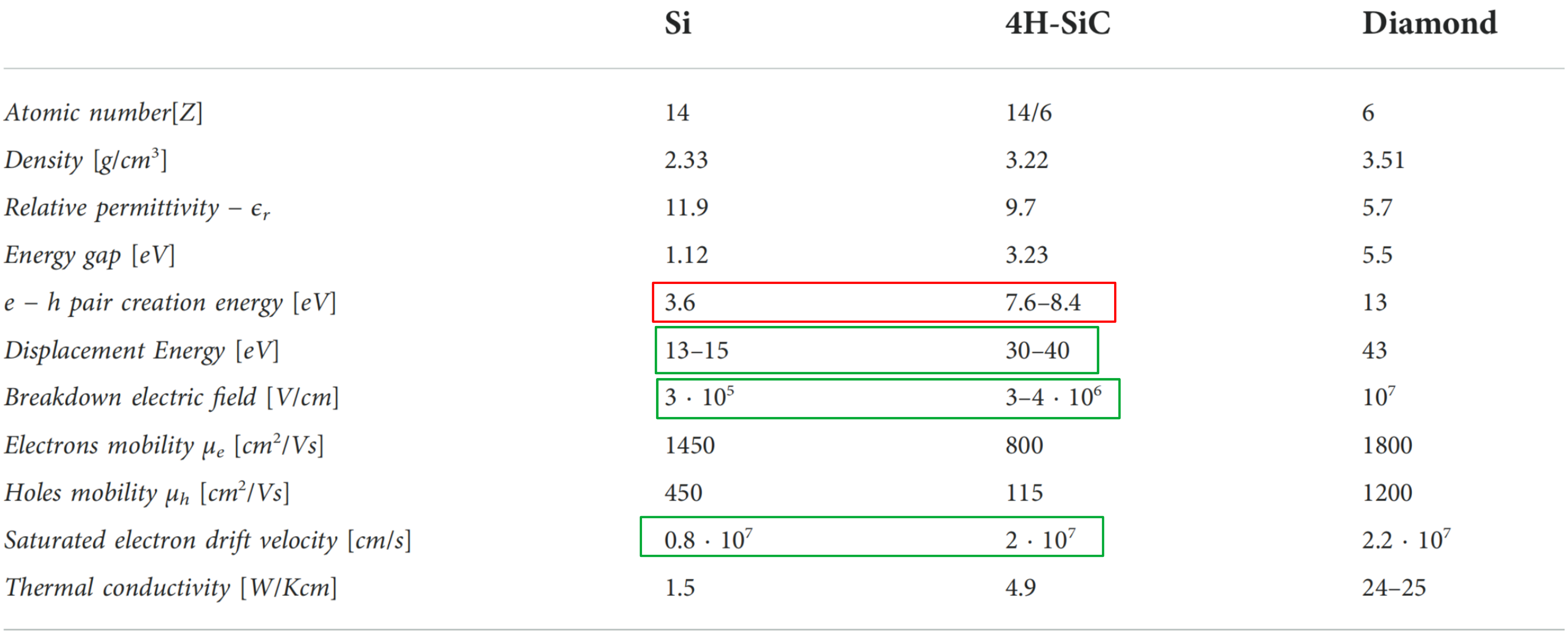
BACKUP

TCT Geometry

- Due to metalization on top of sample, we can only inject at edge of pad (5 µm gap)



Material Parameters

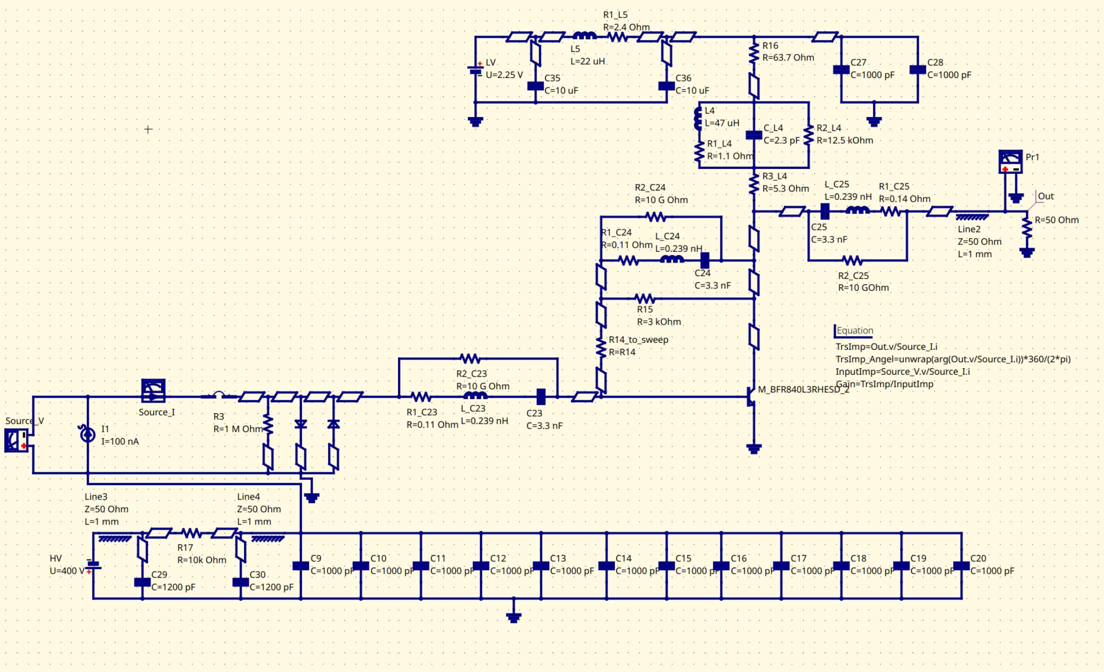


	Si	4H-SiC	Diamond
Atomic number[*Z*]	14	14/6	6
Density [*g*/*cm*^{3}]	2.33	3.22	3.51
Relative permittivity $- \epsilon_r$	11.9	9.7	5.7
Energy gap [*eV*]	1.12	3.23	5.5
e − *h pair creation energy* [*eV*]	3.6	7.6–8.4	13
Displacement Energy [*eV*]	13–15	30–40	43
Breakdown electric field [*V*/*cm*]	$3 \cdot 10^5$	$3\text{–}4 \cdot 10^6$	10^7
Electrons mobility μ_e [*cm*^{2}/*Vs*]	1450	800	1800
Holes mobility μ_h [*cm*^{2}/*Vs*]	450	115	1200
Saturated electron drift velocity [*cm*/*s*]	$0.8 \cdot 10^7$	$2 \cdot 10^7$	$2.2 \cdot 10^7$
Thermal conductivity [*W*/*Kcm*]	1.5	4.9	24–25

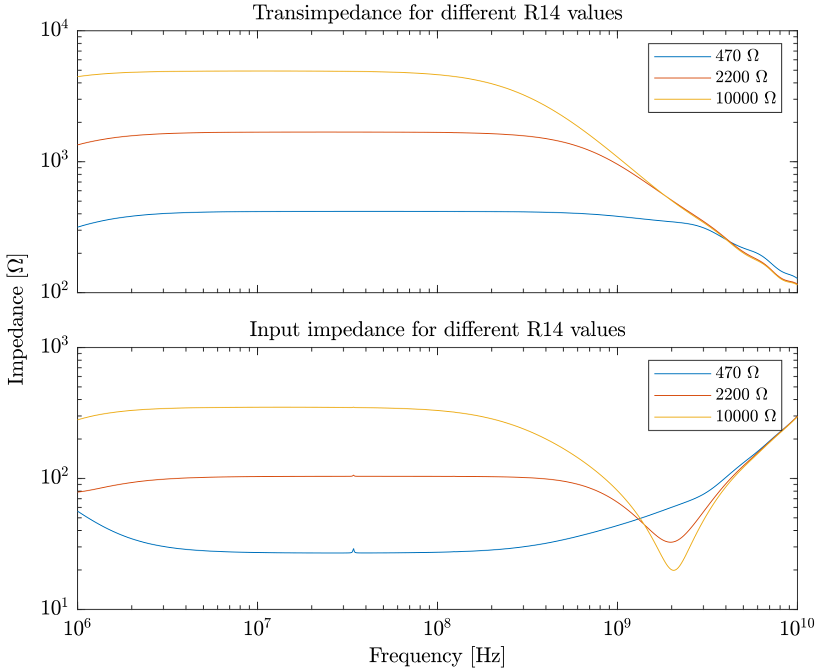
Comparison of material properties between silicon, silicon carbide and diamond [1]

Electronics Transfer Function : Simulation

- Spice simulations using QUCS
- HF simulations not trivial (non-ideal components, wire-bonds, PCB transmission lines)



```
TrsImp=Out.v/Source_I.i
TrsImp_Angel=unwrap(arg(Out.v/Source_I.i))*360/(2*pi)
InputImp=Source_V.v/Source_I.i
Gain=TrsImp/InputImp
```



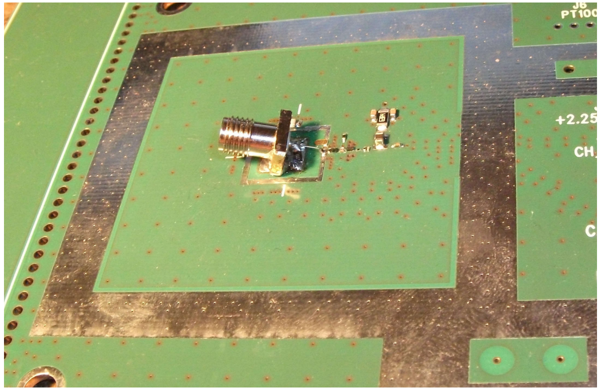
Electronics Transfer Function : Measurement

Different Measurement methods:

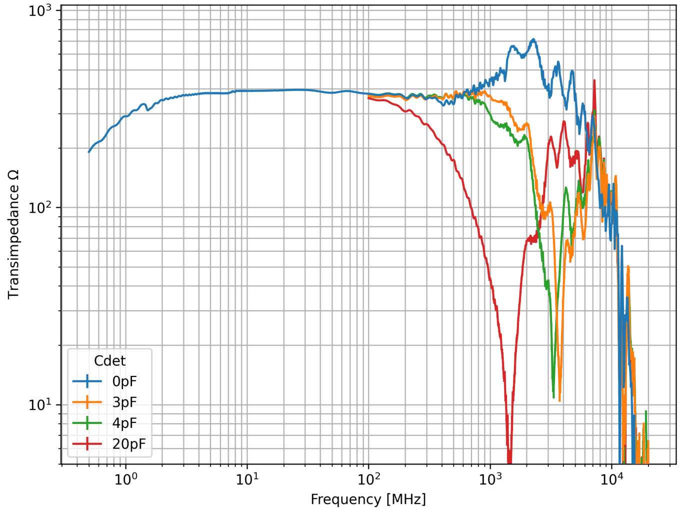
- Vector Network Analyzer (VNA) (sine sweep)
- Step response using R&S RTP-B7 Pulse Source (22 ps rise time)

Need to take into account detector capacitance (~2-3 pF to 20 pF)

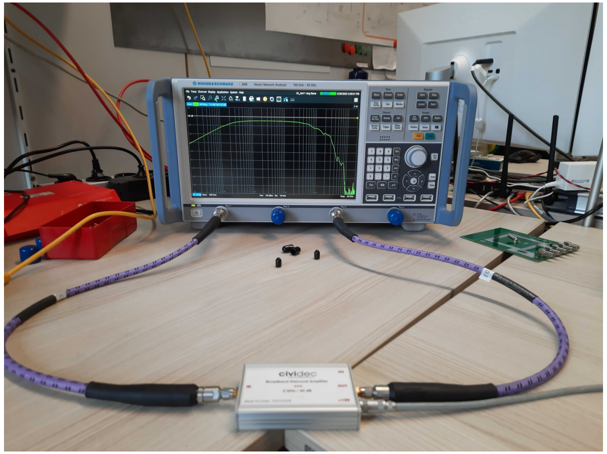
- Large SiC detector capacitance of 20 pF reduces bandwidth



“Detector Dummy” using SMA Connector



Measured AC gain vs. different simulated detector capacitances



S_{21} measurement using VNA