Time resolution of 4H-SiC PIN and simulation of 4H-SiC LGAD

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Outline

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- Measurement of time resolution for 4H-SiC PIN
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  - ✓ Beta source system setup
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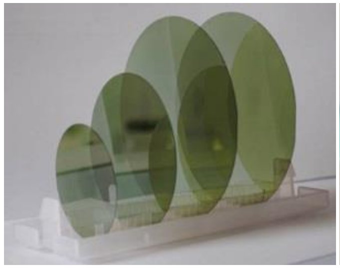
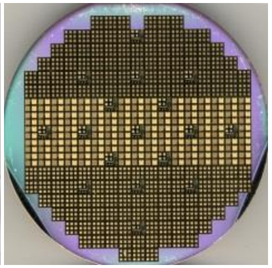
  - ✓ NJU 4H-SiC LGAD prototype design
- Summary

➢ Motivation

- Benefiting from the industrial investment of SiC Power electronic devices, the technology of SiC substrate and fabricating process develop fast.

- Silicon carbide device has huge potential to apply on future collider and nuclear fusion:

Characteristic	Si	4H-SiC
Eg (eV)	1.12	3.26
Thermal conductivity	1.5	4.9
$E_{breakdown}$ (V/cm)	0.5	3
Saturated electron velocity (cm/s)	1×10^7	2×10^7
ionization energy for e-h pair (eV)	3.64	7.8
displacement energy	13	21.8

- ✓ **High radiation hardness**
- ✓ **Low dark current**
- ✓ **Work on high temperature**
- ✓ **High saturated carrier velocity -> fast response**
- ✓ **High energy resolution**

- Much previous studies focus on charge collection efficiency and energy resolution of silicon carbide device, but lack the study of time performance for the MIPs .

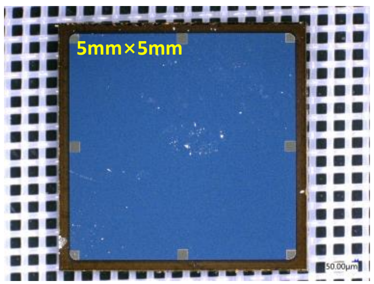
- The 4H-SiC LGAD is introduced to enhance the signal amplitude and simultaneously acquire a high time resolution.

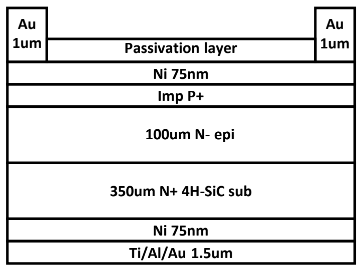
➢ NJU 4H-SiC PIN Sensor

- ✓ 100 µm active layer
- ✓ Two different size: 5mm×5mm, 1.5mm×1.5mm
- ✓ High uniformity
- ✓ Low leakage current

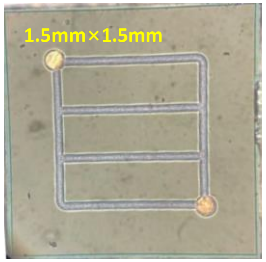
☐ Device structure

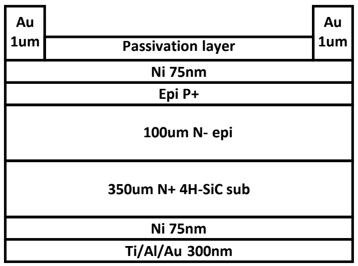
5mm×5mm





1.5mm×1.5mm

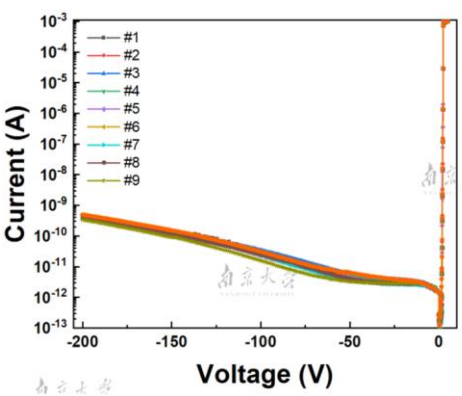




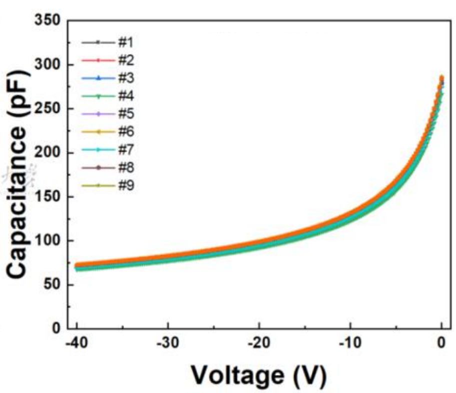
☐ Device performance

5mm×5mm

IV

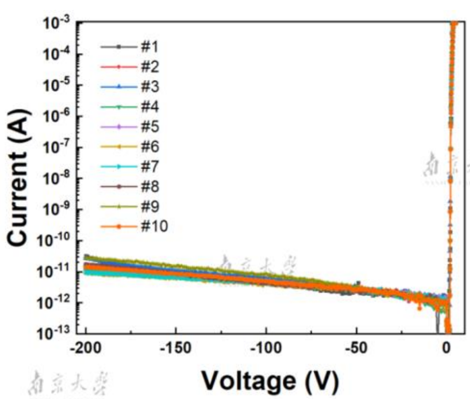


CV

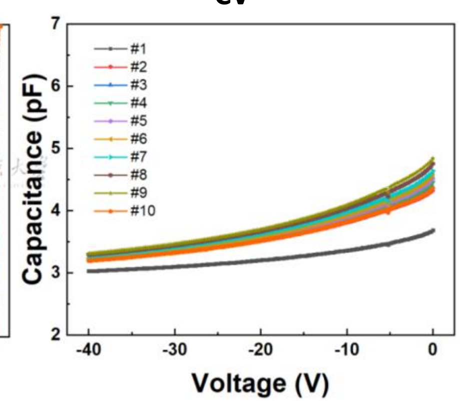


1.5mm×1.5mm

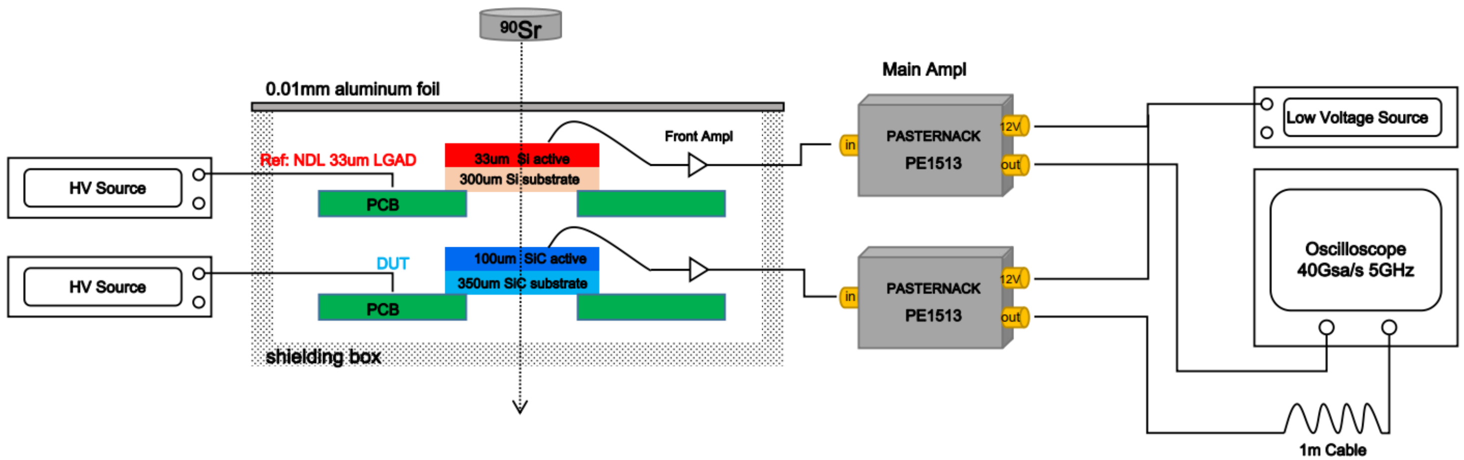
IV



CV



➢ Beta source system setup to measure time resolution



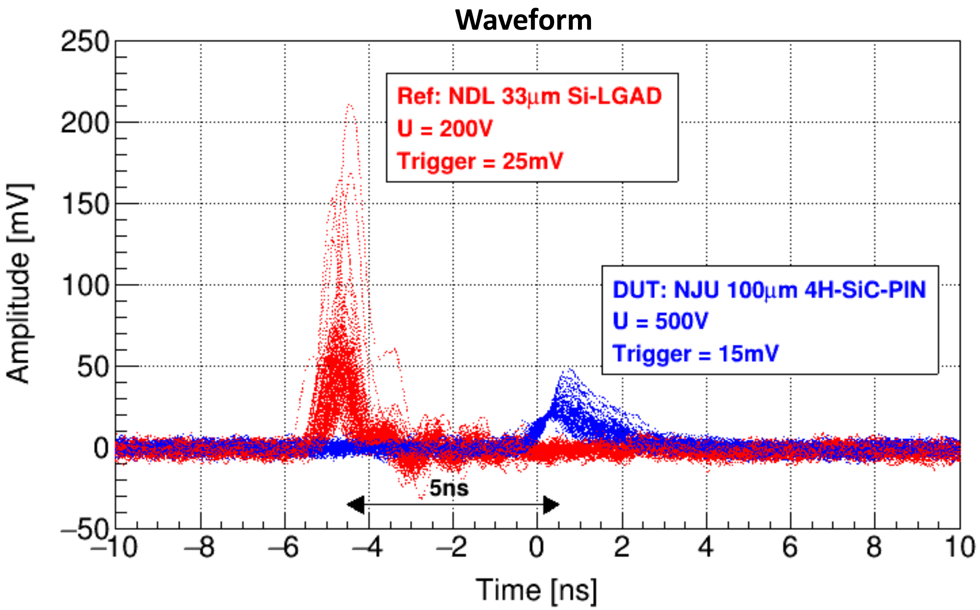
Ref: NDL 33 μm Si-LGAD $\sigma_T = 34$ ps U=200V at room temperature

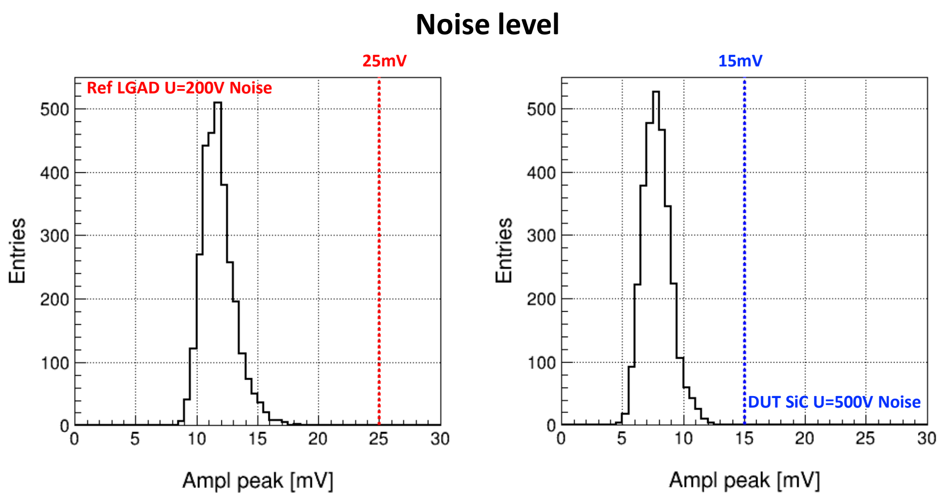
DUT: NJU 100 μm 4H-SiC-PIN 5mm×5mm, 1.5mm×1.5mm

System configuration:

- 2 channels trigger mode: $Trigger_{LGAD}$=25mV, $Trigger_{SiC}$=15mV which depend on noise level.
- DUT time delay: ~ 5 ns from 1 meter cable to enhance trigger efficiency.
- Sampling: 20 Gsa/s each channel where $\sigma_{TDC} = \frac{50\text{ps}}{\sqrt{12}} \sim 14\text{ps}$
- Timer: Constant Fraction Descriminator (CFD ratio = 50%)
- Amplifier: 100 times from (UCSC board + Broad Band Amplifier)

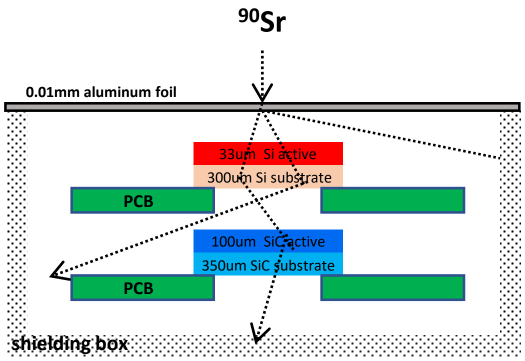
➢ Waveform sampling

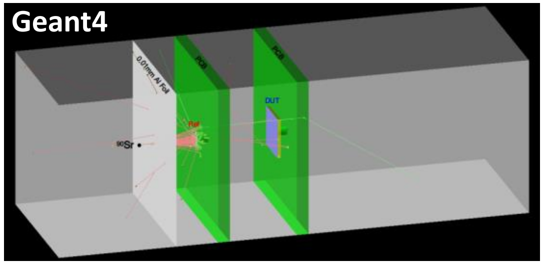




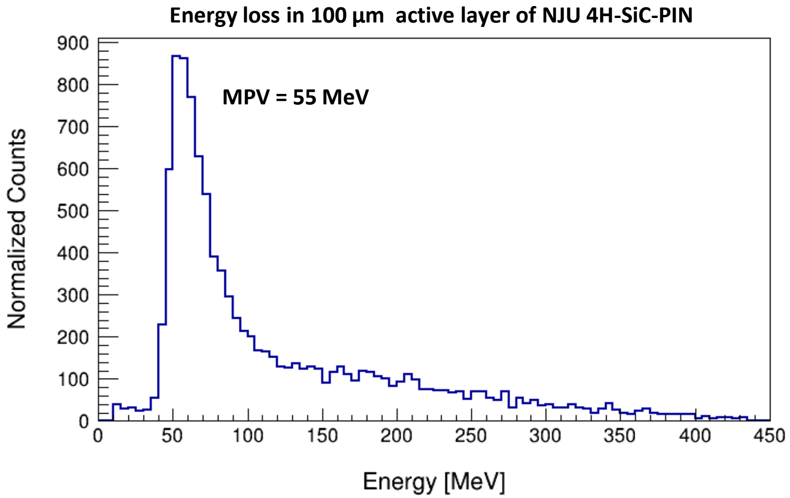
- Select the trigger level to suppress noise.
- Tow obvious pulses from Ref and DUT device by β particle.
- ~ 5ns time delay of 4H-SiC PIN signal.
- The most of signals for 4H-SiC PIN are lost due to high trigger level .

➢ Scattering and energy loss simulation by GEANT4





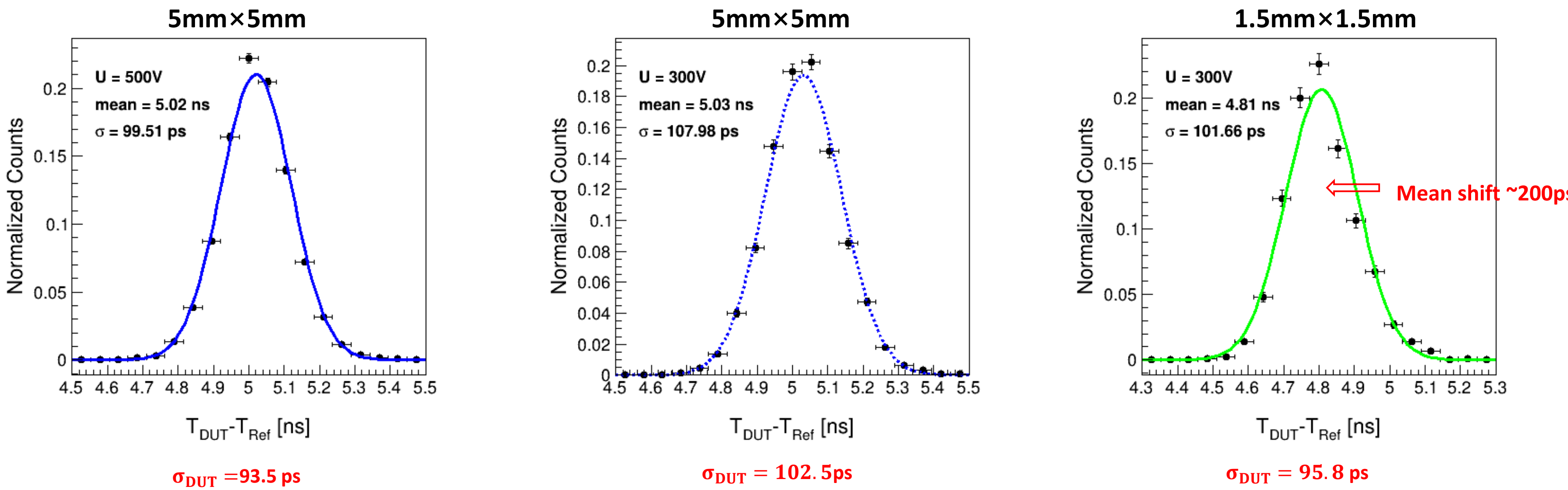
Check the influence of the scattering and verify the energy loss in 100 μm 4H-SiC:



- **The MPV of energy loss in 4H-SiC PIN active region is 55 MeV (typical experimental result ~42 MeV).**
- **The scatter by aluminum foil and Ref-LGAD would strongly decrease the hit efficiency.**
  Measured η(5mm×5mm)~5 events/min, η(1.5mm×1.5mm)~2 events/min where large size has higher trigger efficiency.

➢ Time Resolution

For large size 100 μm 4H-SiC PIN device, the measured time resolution could be smaller than 100 ps.



- ☐ Higher reverse voltage (faster carrier velocity) has better time resolution.
- ☐ Smaller size device (smaller capacitance) has better time resolution.
- ☐ The T_{DUT}-T_{Ref} mean of the 1.5mm×1.5mm device shifts around 200 ps caused by smaller rising time.

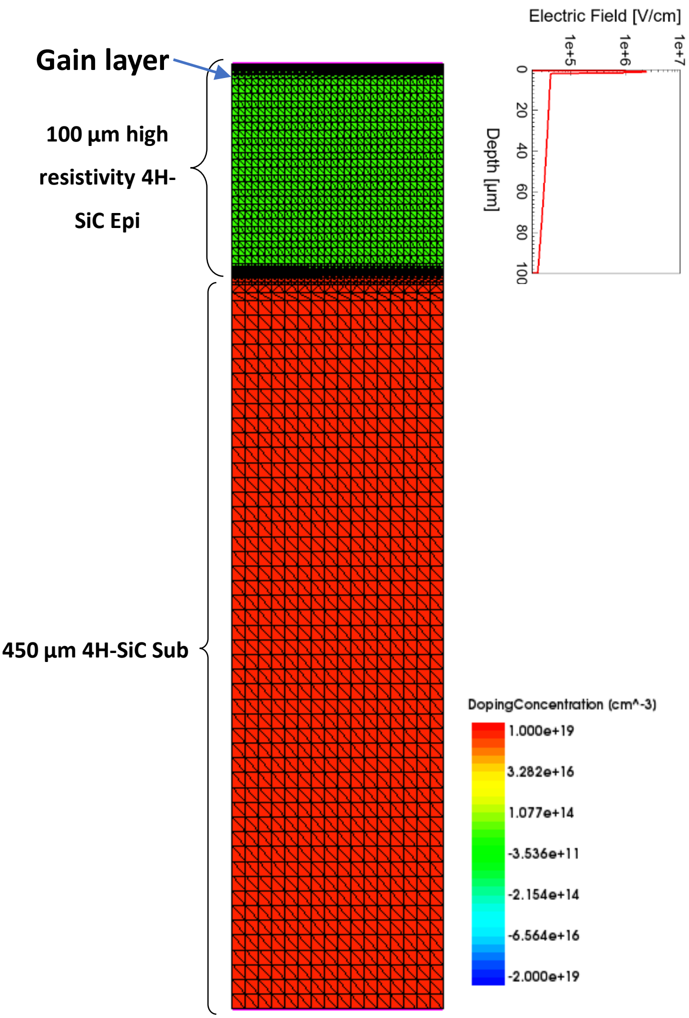
➢ The Challenge of fast 4H-SiC sensor

- ☐ Thicker active layer is required which is adverse to better time performance.
- ☐ To achieve the carrier velocity saturated (corresponding electric field 40-50 V/μm) and low operate voltage, the 4H-SiC sensor needs to be thin as far as possible.

- ☐ How to achieve appropriate gain due to low carrier multiplication coefficient of 4H-SiC?
- ☐ How to achieve the typical doping concentration distribution in 4H-SiC LGAD due to low doping activation rate in 4H-SiC and restricted process technology?

➢ TCAD simulation of 4H-SiC LGAD

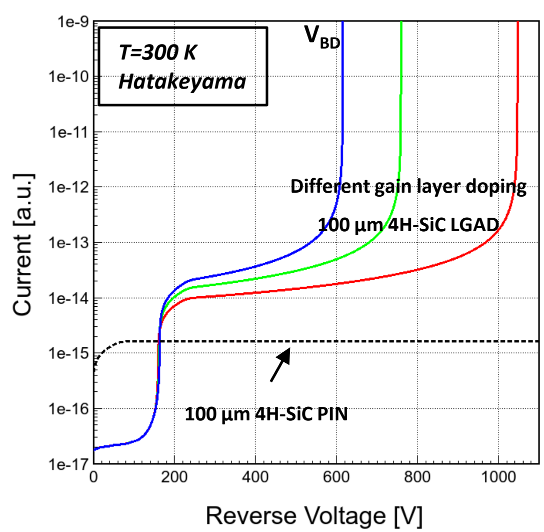
Based on NJU 100 µm 4H-SiC device process, we simulate the corresponding LGAD performance by Sentaurus TCAD.



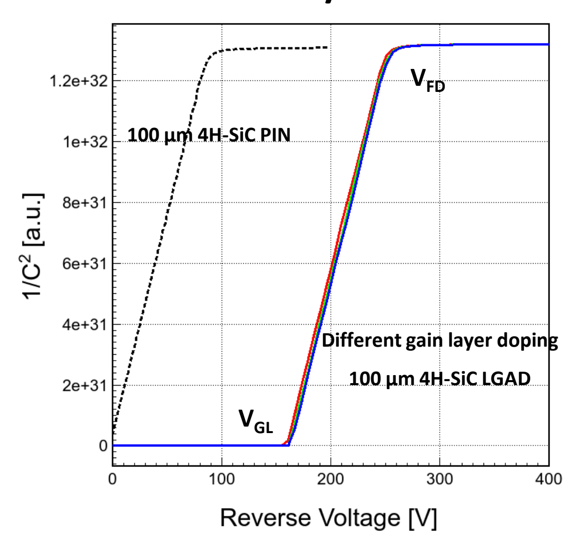
Physical model configuration:

- ➢ Material Anisotropy: physical parameters and impact ionization coefficient for 4H-SiC
- ➢ Avalanche Model: Hatakeyama
- ➢ Miscut angle: 4°

I-V



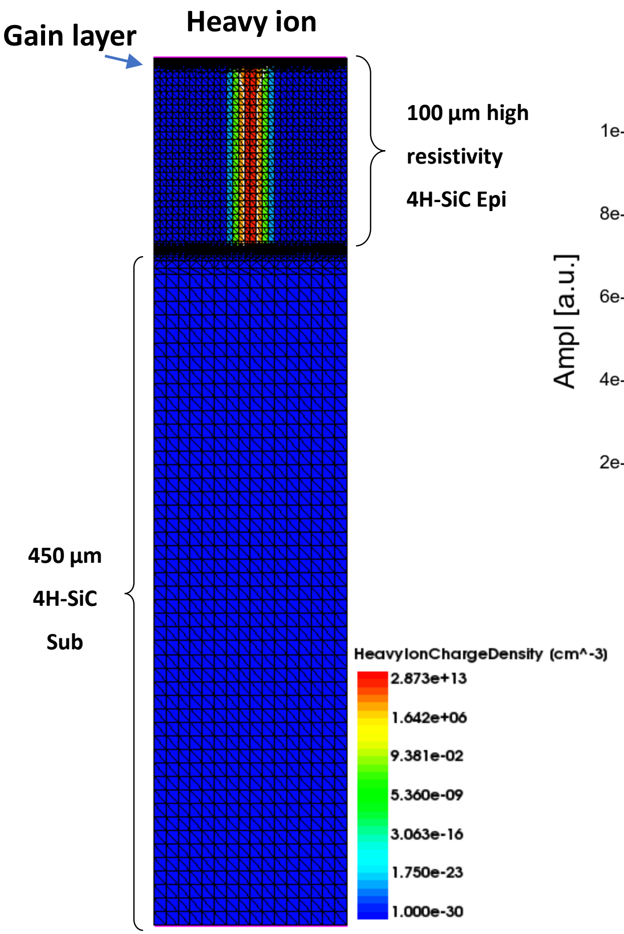
$1/C^2$-V

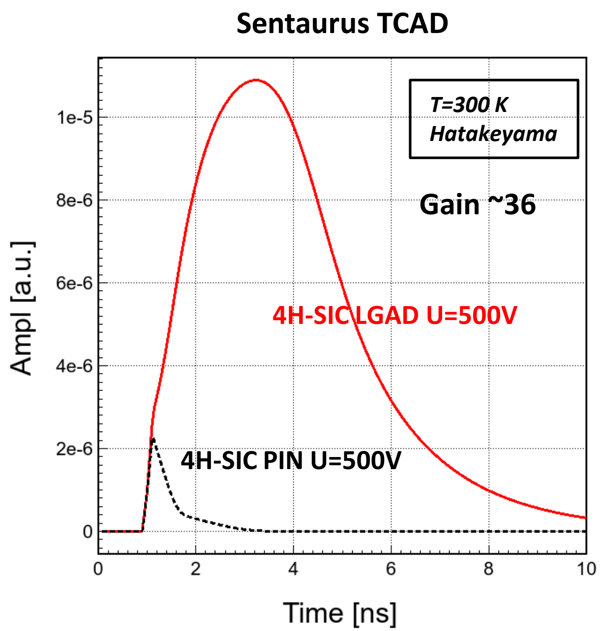


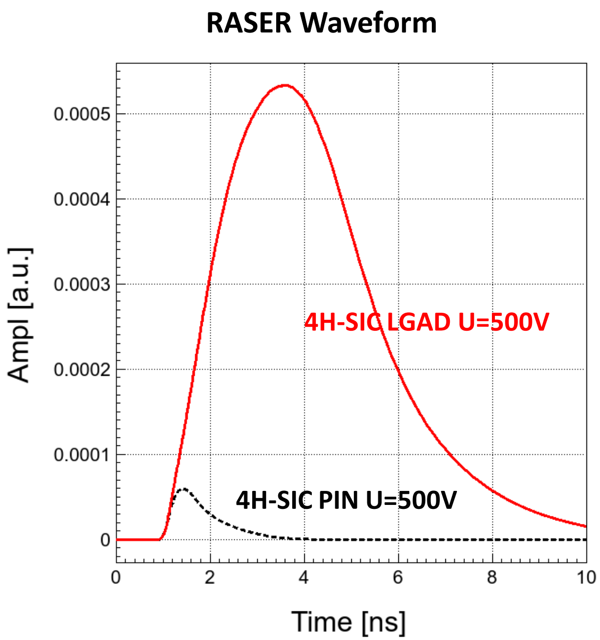
➢ TCAD simulation of 4H-SiC LGAD

MIPs signal response of the 4H-SiC LGAD could be simulated by Sentaurus TCAD and RASER.

The initial current signal is from TCAD and the waveform after electrics is from RASER*.





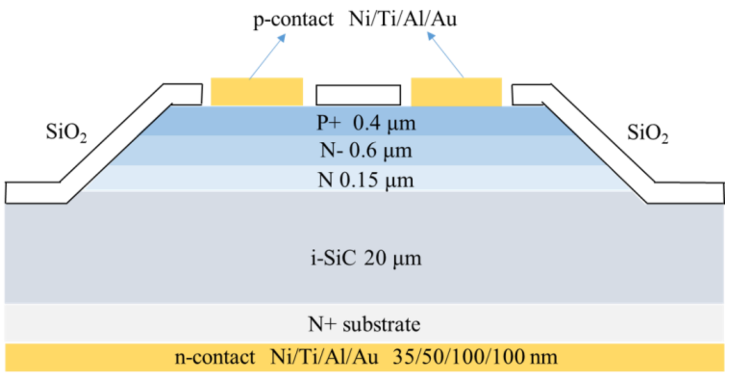


- ☐ **Prototype 4H-SiC LGAD simulation shows the gain around 36 at U=500 V.**
- ☐ **The waveform predicted by RASER shows the LGAD signal has about 2 ns rising time.**

*** RASER (RAdiation SEmiconductoR): a fast simulation tool for 4H-SiC sensor.** https://github.com/dt-np/raser/

➢ NJU 4H-SiC LGAD prototype design

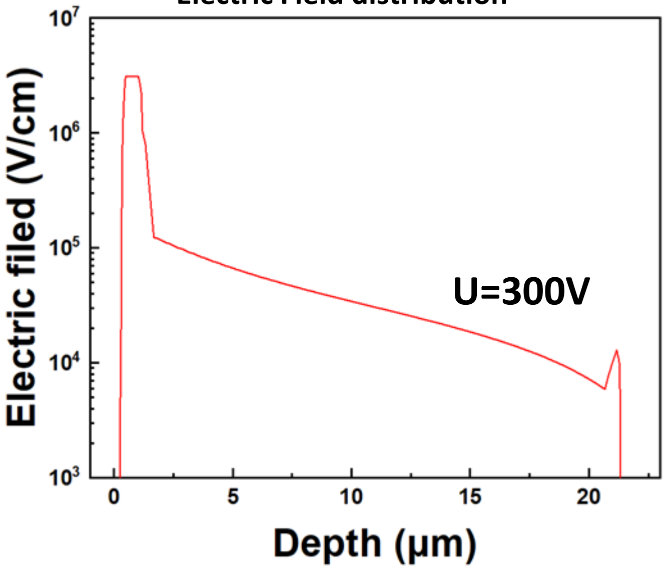
NJU 4H-SiC LGAD prototype cross section



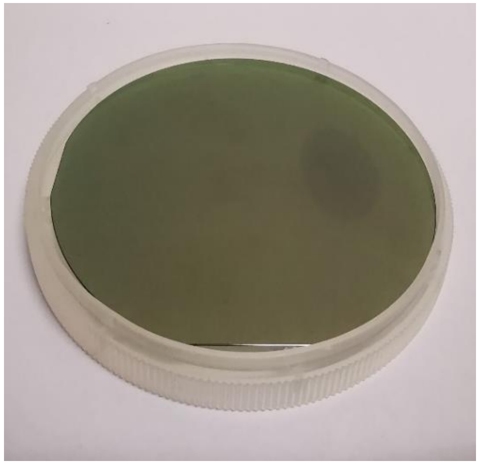
Key technologies of 4H-SiC LGAD fabricating:

- Epitaxial structure design.
- High quality low doping 4H-SiC layer growing technology.
- Bevel Edge Termination.
- High quality passivation.
- N or P type ohmic contacts

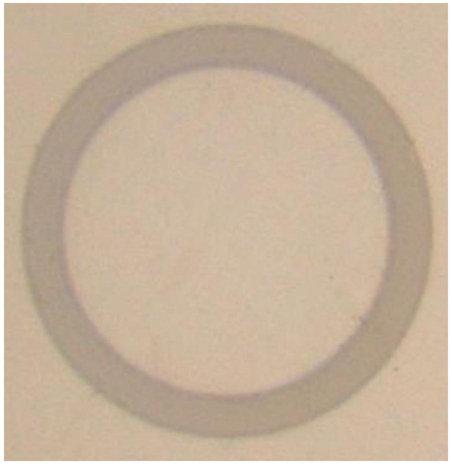
Electric Field distribution



4 inch 4H-SiC Epi Wafer



Surface of Bevel Edge Termination



➢ Summary

- ☐ **The time resolution for a 5mm×5mm 4H-SiC-PIN detector could reach 94 ± 1 ps by ^{90}Sr source.**

- ☐ **With higher reverse voltage and smaller capacitance, a better time resolution is obtained.**

- ☐ **The prototype 4H-SiC LGAD with gain ~36 is verified by Sentaurus TCAD simulation.**

- ☐ **The multi-layer epitaxy growing process for 4H-SiC LGAD is verifying by NJU.**

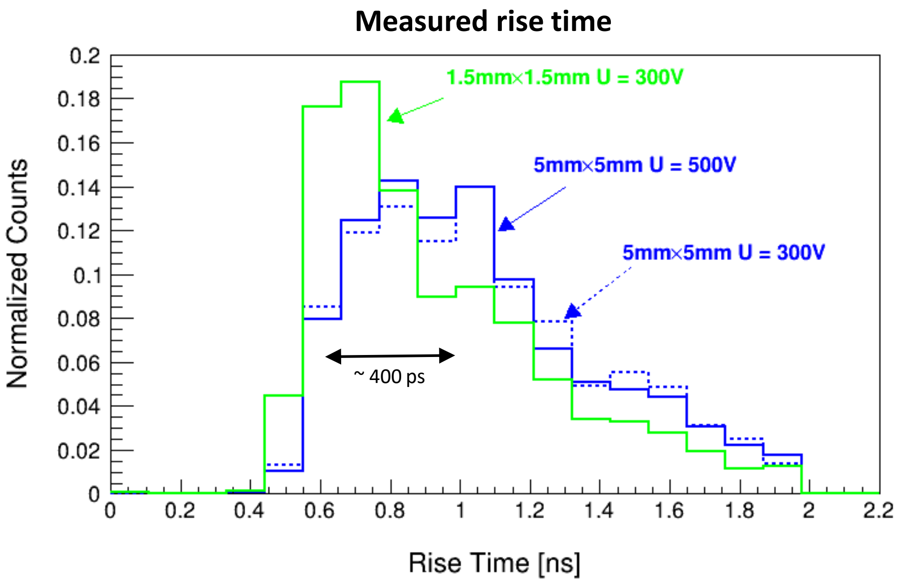
The radiation campaign and study of irradiated 4H-SiC PIN performance is on going.

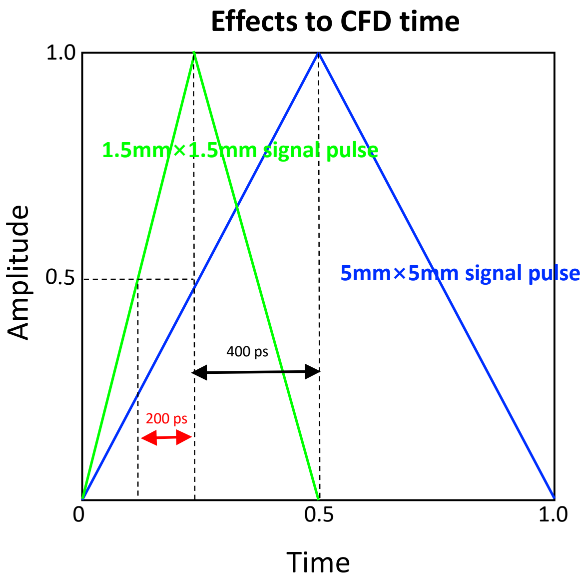
Thanks for your attention

Backup

➢ Time shift caused by rising time for different size sensors

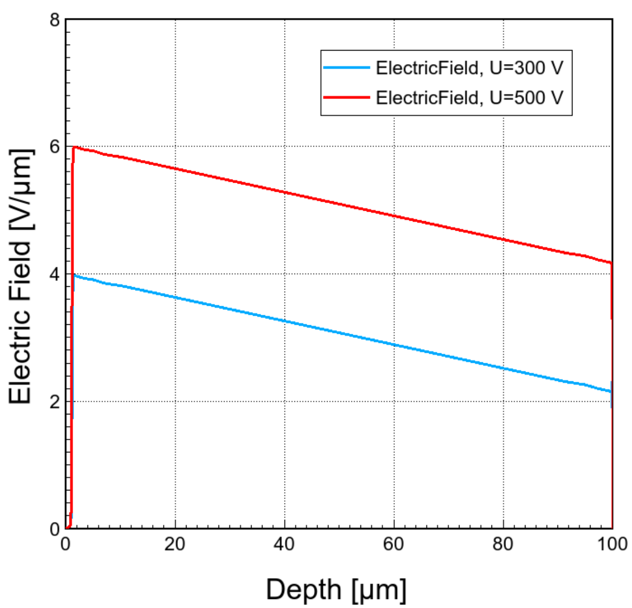
The T_{DUT}-T_{Ref} mean of the 1.5mm×1.5mm device shifts around 200ps due to faster rise time than the 5mm×5mm size device.





➢ Electric Field dependence for carrier velocity in 4H-SiC

Electric Field distribution by TCAD



Velocity distribution by TCAD