Preliminary Device Performance of 4H-SiC LGAD

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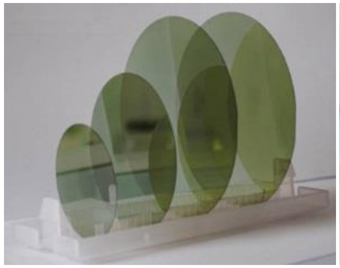
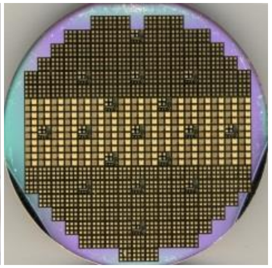
➢ Motivation

- Benefiting from the industrial investment of SiC Power electronic devices, the technology of High resistivity 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**

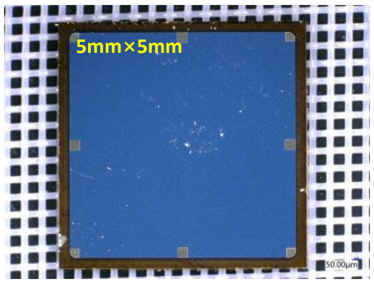
- The 4H-SiC LGAD is introduced to enhance the S/N and simultaneously acquire a high time resolution.

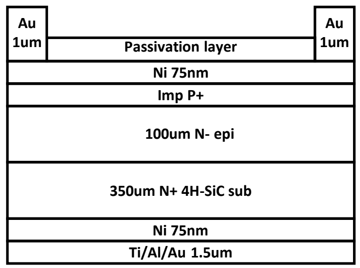
- To achieve the typical doping concentration distribution in 4H-SiC LGAD due to low doping activation rate in 4H-SiC and restricted process technology.

➢ Review time resolution of 100 μm 4H-SiC PIN

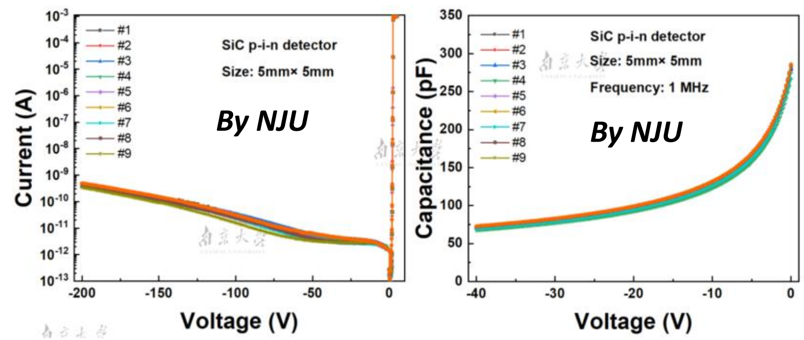
- The time resolution of 100 μm 4H-SiC PIN by Nanjing University is reported for MIPs detection. A time resolution $\boldsymbol{\sigma_T = 94\ \mathrm{ps}}$ indicates 4H-SiC sensor has potential application of fast MIPs detection. https://indico.cern.ch/event/1029124/contributions/4411189/

◆ **Device Structure**

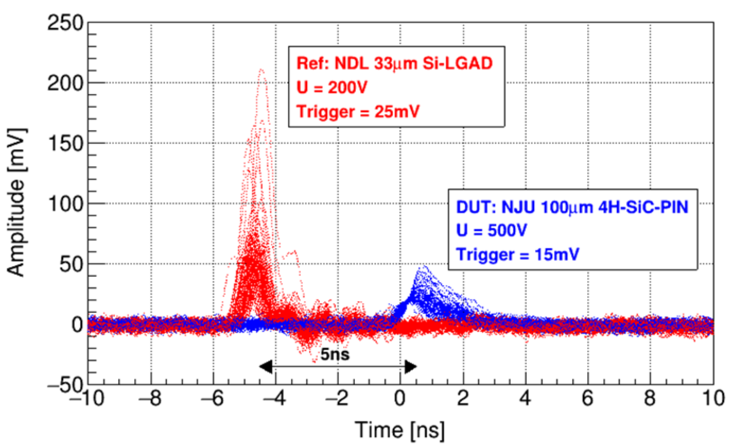




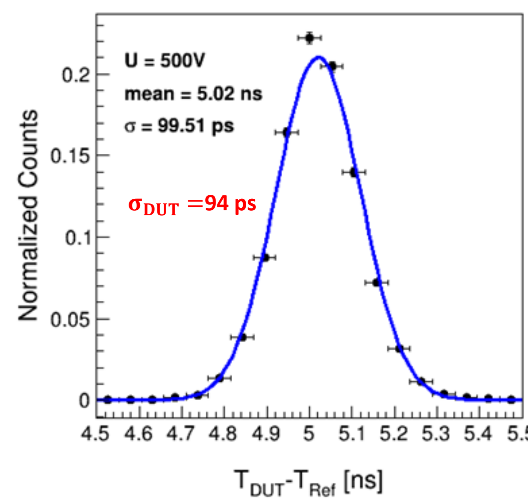
◆ **IV & CV performance**



◆ **MIPs Signal Sampling**



◆ **Time Resolution**



➢ The Challenge of fast 4H-SiC sensor

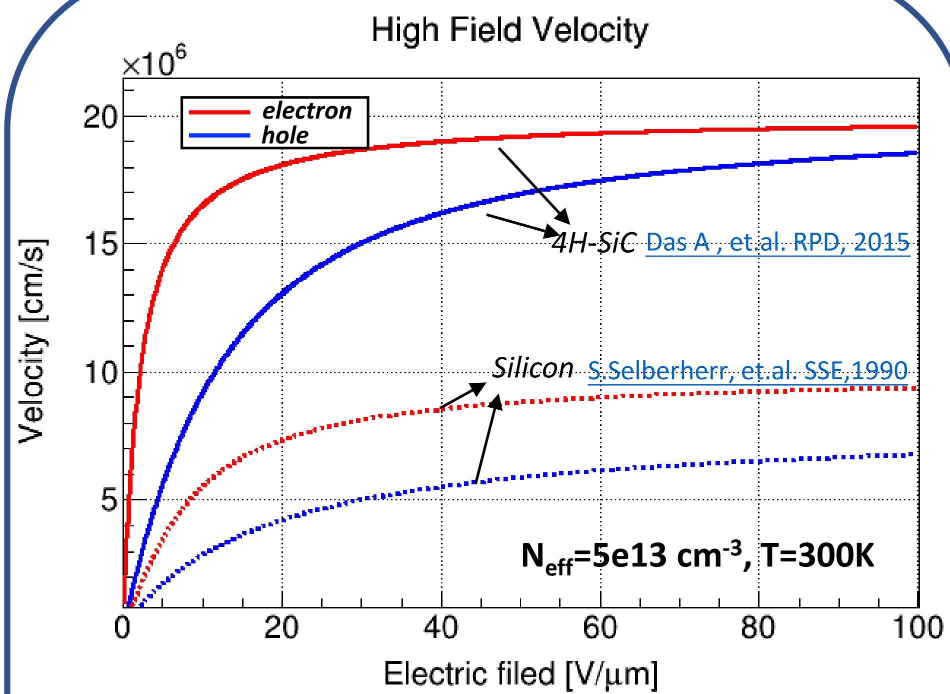
- Thicker active layer is required which is adverse to better time performance.
- To achieve the carrier velocity saturated (corresponding electric field 40-50 V/μm) and low operate voltage, the 4H-SiC sensor needs to be thin as far as possible.

- 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?

➢ Compare Silicon and 4H-SiC LGAD Design

☐ Material characteristics of 4H-SiC

Carrier velocity

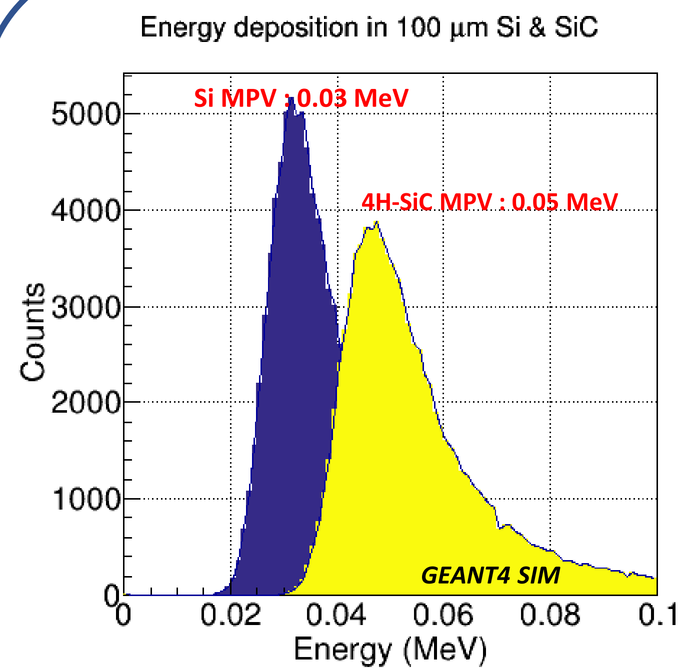


Carrier Velocity: 4H-SiC > Silicon

⇩

Fast Time Response

MIPs Energy Loss & e-h pairs generation



Silicon: **~ 80 e-h pairs / um**

(~ 3.6 eV / e-h pairs)

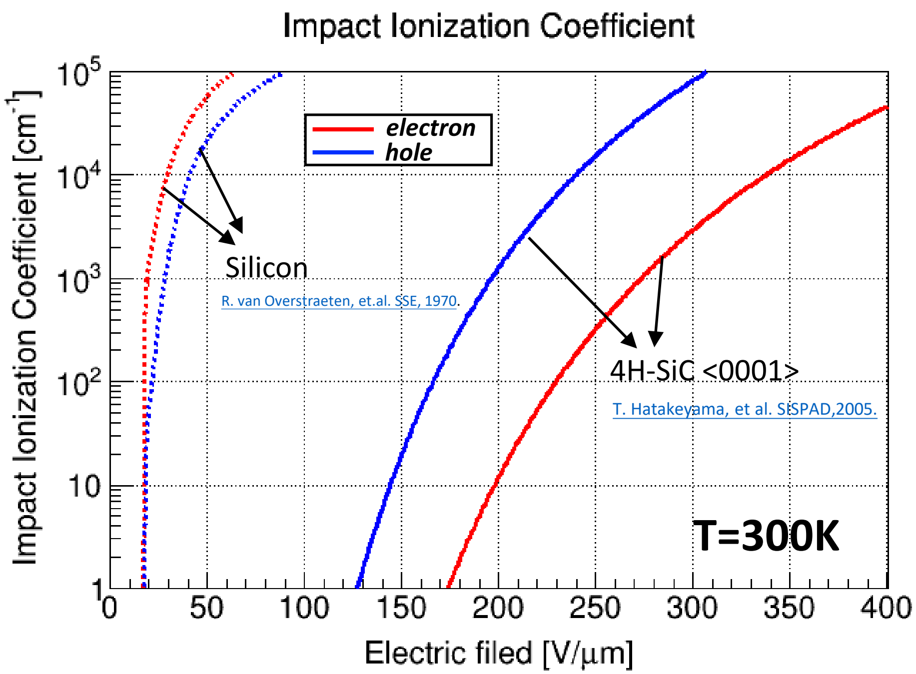
SiC: **~ 65 e-h pairs/ um**

(~ 7.8 eV / e-h pairs)

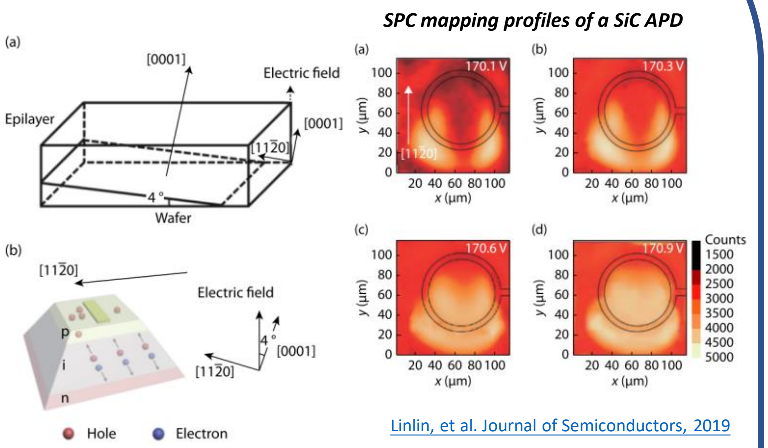
➢ Compare Silicon and 4H-SiC LGAD Design

❑ Material characteristics of 4H-SiC

Impact Ion Coefficient



Non- uniform avalanche multiplication in 4H-SiC



Linlin, et al. Journal of Semiconductors, 2019

$\alpha_{e,h}^{4H\text{-}SiC} < \alpha_{e,h}^{Silicon}$ ➡ ***Higher Electric Field***

$\alpha_{h}^{4H\text{-}SiC} > \alpha_{e}^{4H-SiC}$ ➡ ***N-type 4H-SiC Substrate***

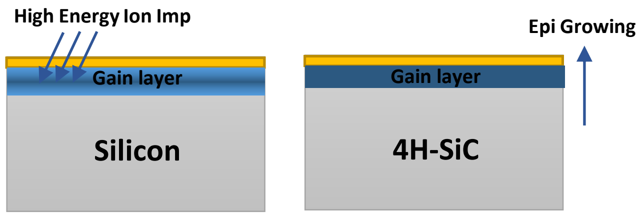
Non-uniform multiplication ➡ ***Signal Distortion***

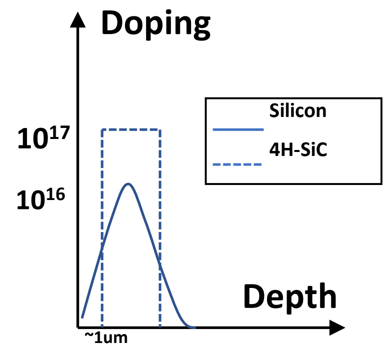
➢ Compare Silicon and 4H-SiC LGAD Design

☐ Process technology limitations of 4H-SiC LGAD

➢Process of gain layer

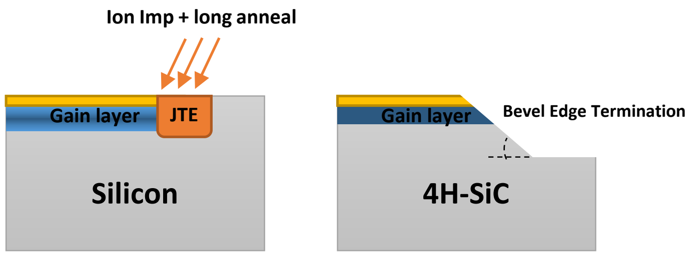
High Filed Region

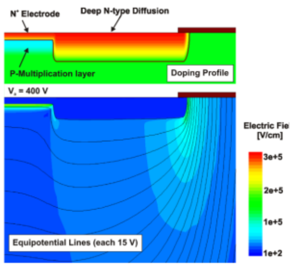




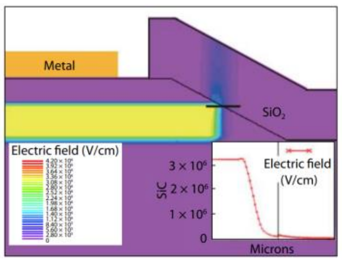
➢Process of Termination

Suppress edge pre-breakdown





Fernández M, et.al. NIMA, 2016

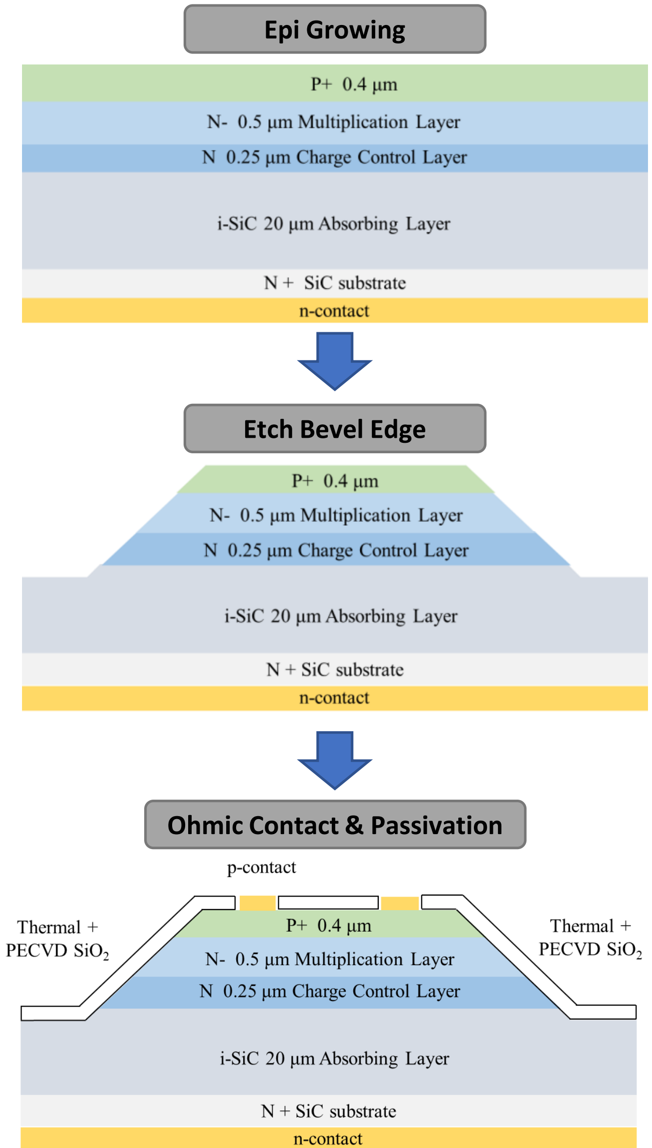


Linlin, et al. Journal of Semiconductors, 2019

***Epitaxial growing* and *Bevel Edge Termination* are adopted for 4H-SiC LGAD design.**

➢ NJU 4H-SiC LGAD prototype design

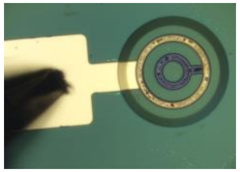
NJU 4H-SiC LGAD prototype cross section



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

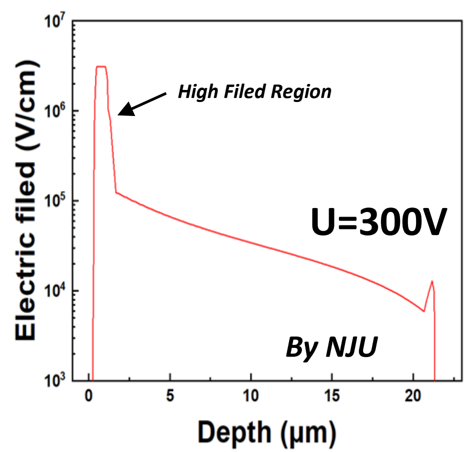
NJU 4H-SiC LGAD prototype



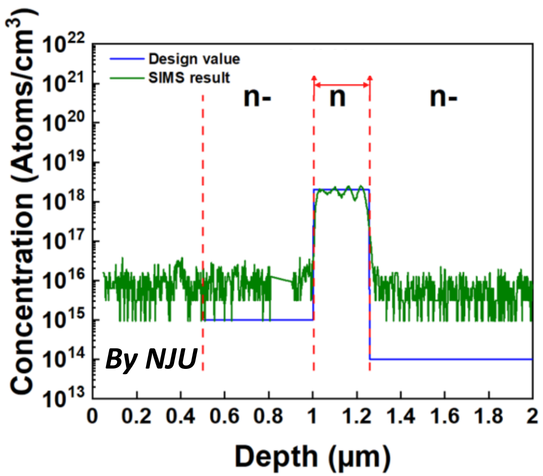
Design by Lu Hai Team, Nanjing National Laboratory of Microstructures:

https://iiiv.nju.edu.cn/10367/list.htm

Electric Field distribution

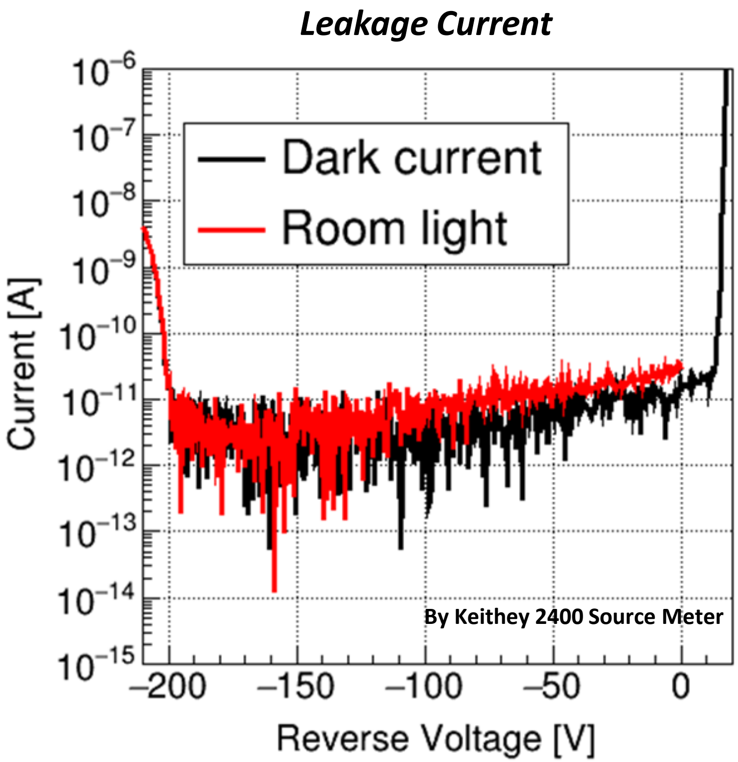


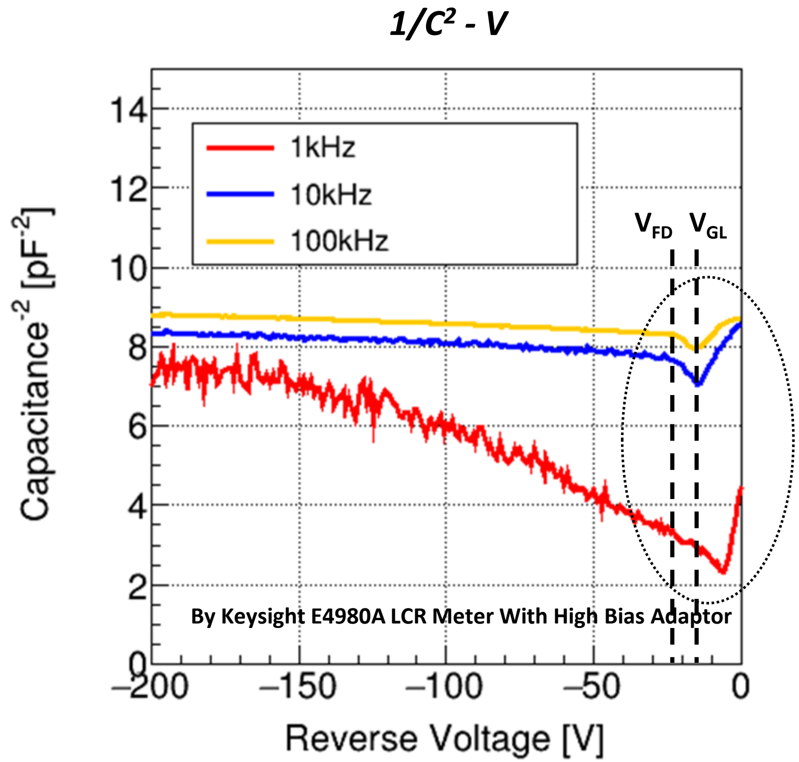
N-type Doping SIMS



- **SIMS result indicates the measured doping profile agrees with design.**

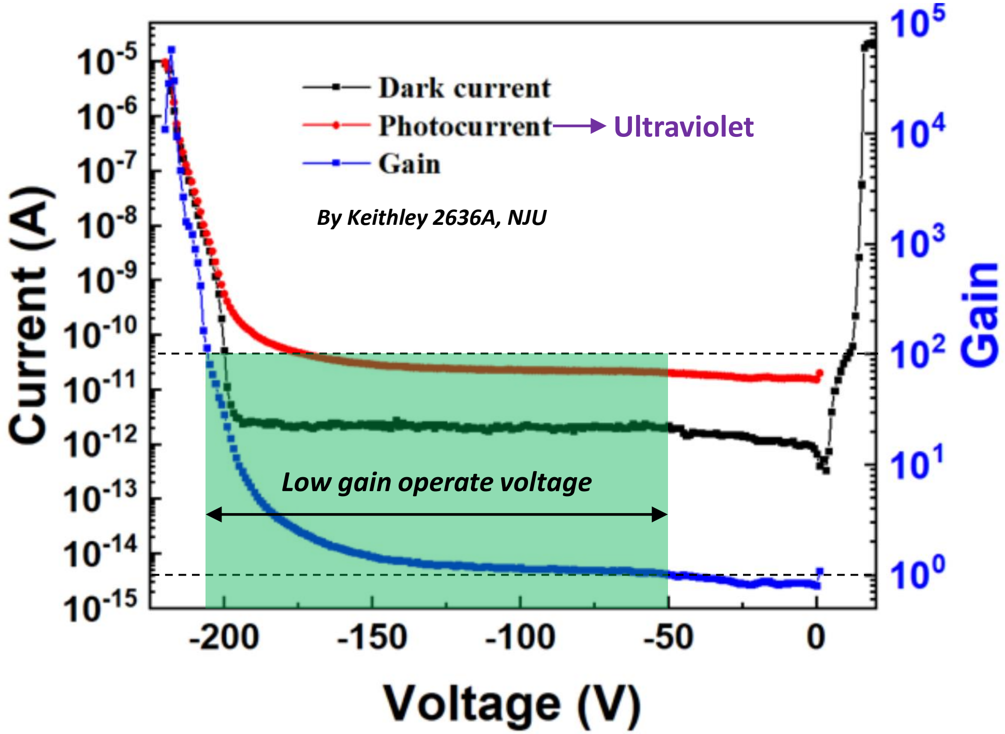
➢ IV & CV performance





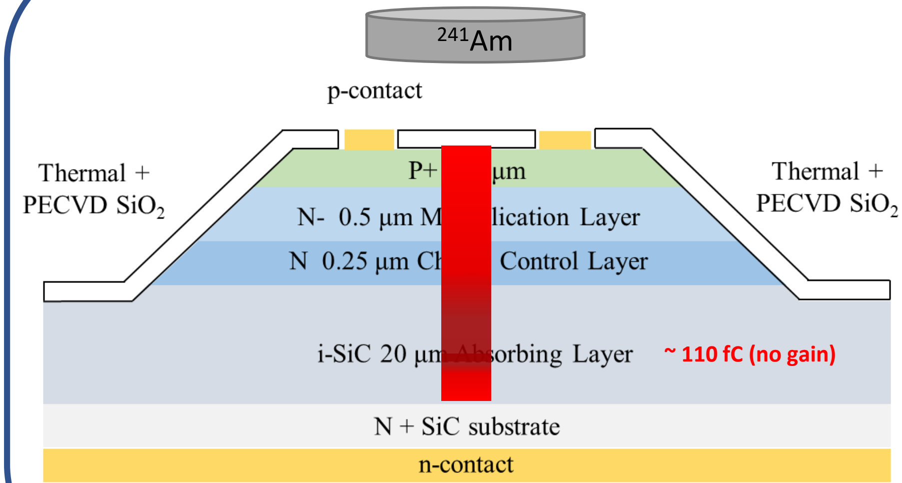
- The **unidirectional conduction** characteristic for PN is observed and the breakdown voltage is larger than 200V. The device shows the typical **solar blindness** of 4H-SiC.
- Frequency dispersion about capacitance indicates possible **traps appear in multi-epi structure**.

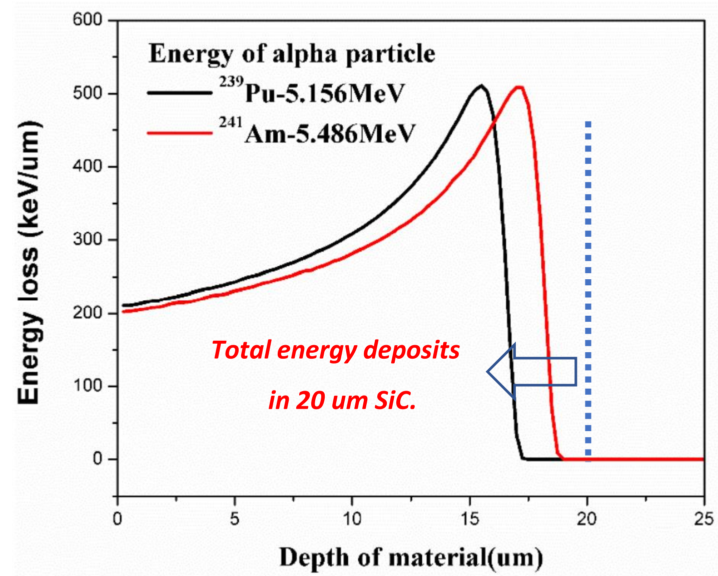
➢ Current Gain of NJU 4H-SiC LGAD prototype



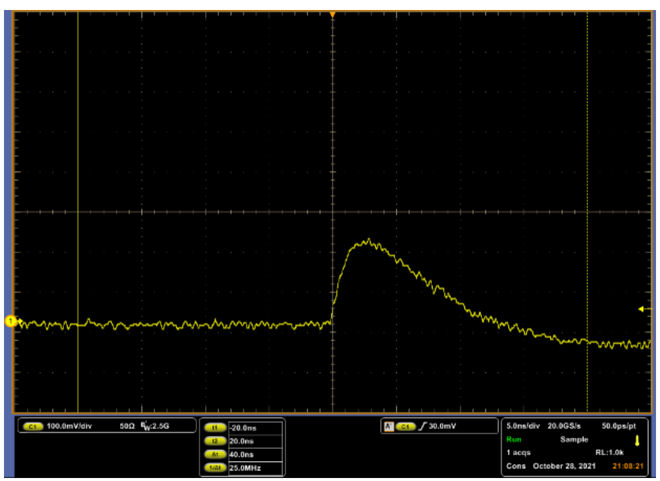
- ☐ **Between 50-200 V reverse voltage, a low photocurrent gain (1-100) and low leakage current (<10 pA) are obtained for NJU 4H-SiC LGAD prototype.**

Alpha & Beta Detection

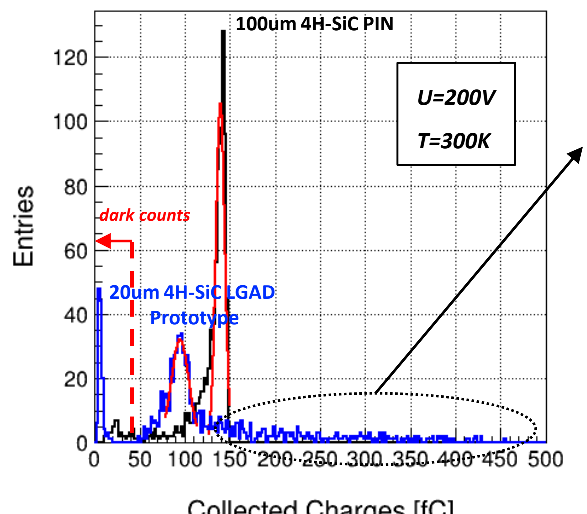




Waveform Sampling of alpha particle

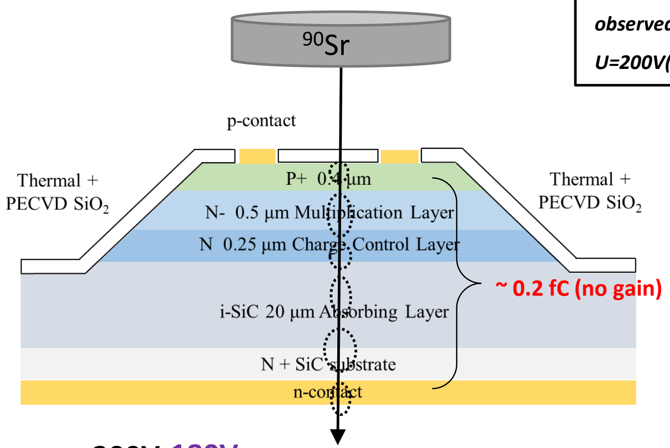


Collected Charges distribution



High gain signals are observed, but the MPV value: LGAD < PIN.

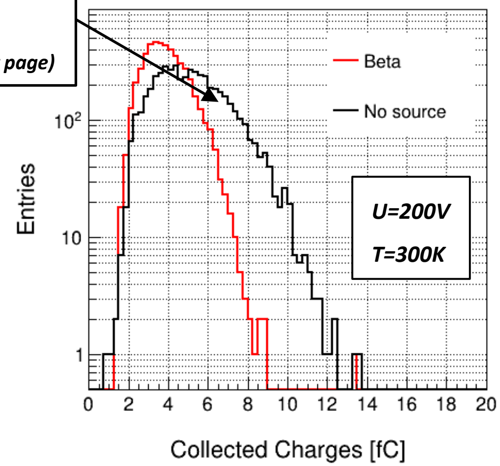
➢ Alpha & Beta Detection

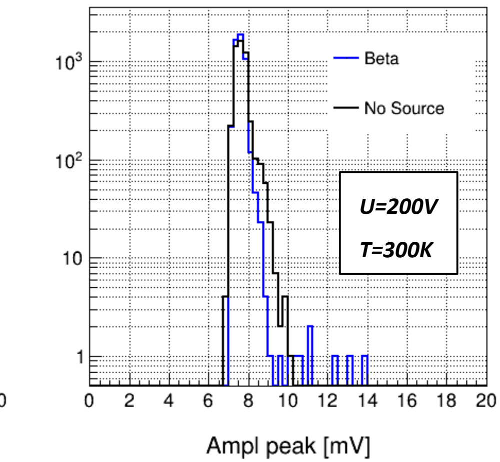


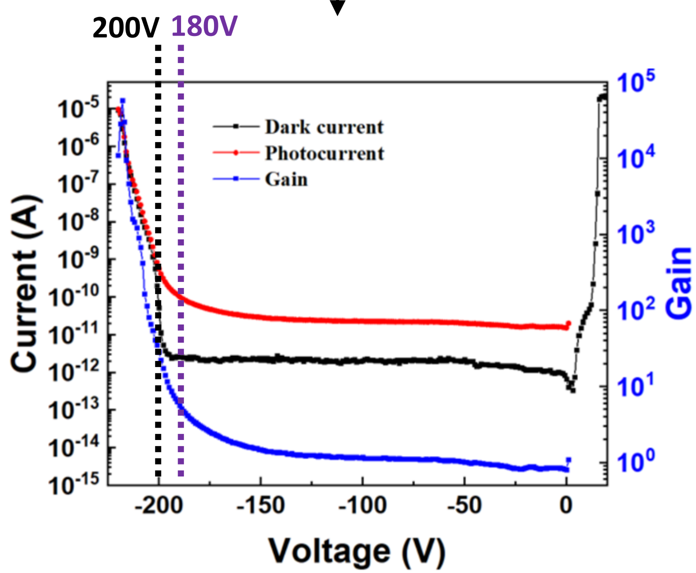
High dark counts observed near U=200V(see next page)

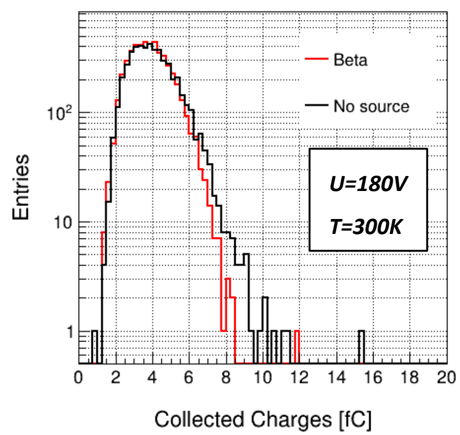
Collected Charges

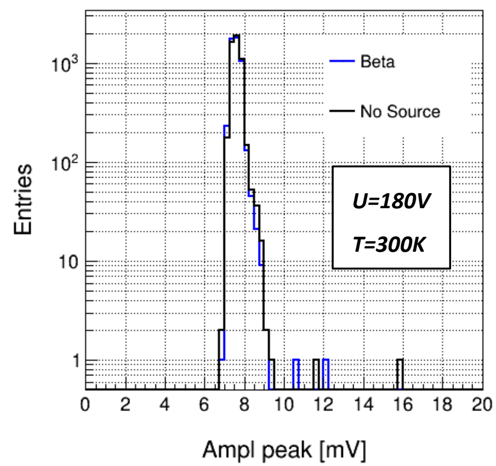
Pulse High









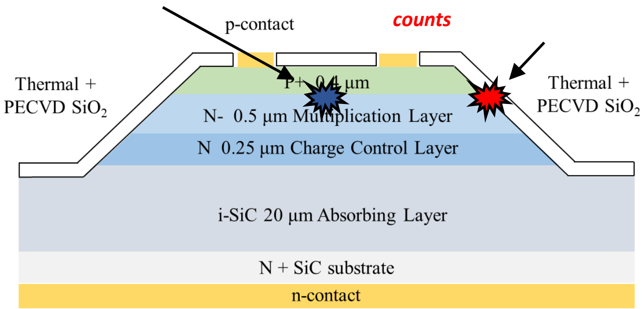


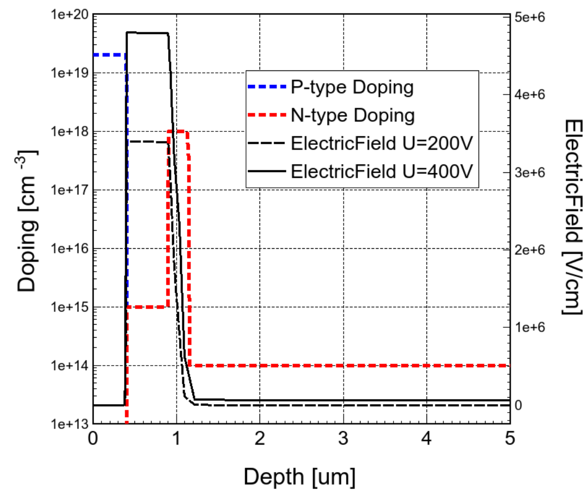
☐ **The MIPs signals are submerged in noise due to high ENC of electronics.**

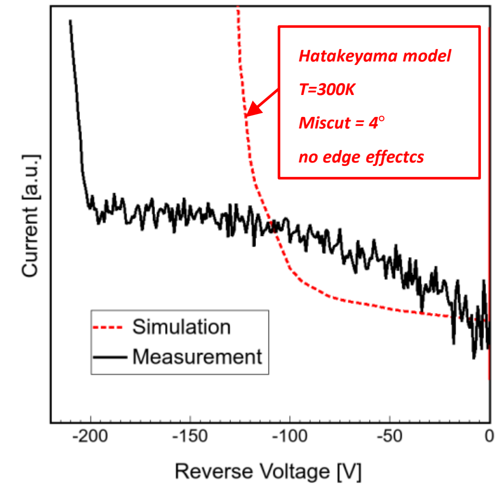
➤ Discussion of measured results

Electric field dominates charged particles detection gain

Max edge electric field dominates break down voltage and dark counts

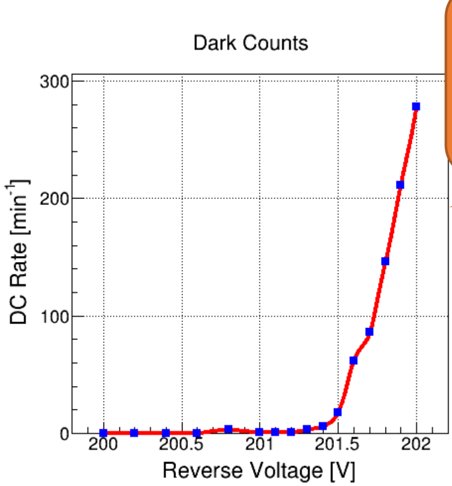






- ***Low photon current gain is observed***
- ***$V_{BD}^{mea} > V_{BD}^{sim}$ (no edge effects)***

If Hatakeyama model overestimates the impact ion coefficient for our device, the max edge electric field dominates break down.



The operate voltage could not be >201 V due to the High dark counts.

Possible solution:

- Increase the **doping concentration** or **thickness** of Multi-layer.
- Optimize the **edge termination** to **operate higher voltage**.

➢ Summary

- The material characteristics of 4H-SiC and measured time resolution of 100 μm 4H-SiC PIN show huge potential of 4H-SiC to fast MIPs detection

- A low photon current gain (1-100) and low leakage current (<10 pA) are obtained for NJU 4H-SiC LGAD prototype.

- High gain signals for alpha particles are observed, and the MIPS signals are submerged in noise under present electronics

More tests and verification of measured data are on going.

The optimization of 4H-SiC LGAD and Next production are in process.

Thanks for your attention