Development of 4H-SiC Low Gain Avalanche Diode

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The 40th CERN RD50 workshop

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Why develop 4H-SiC Low gain Avalanche Diode?

Silicon & 4H-SiC

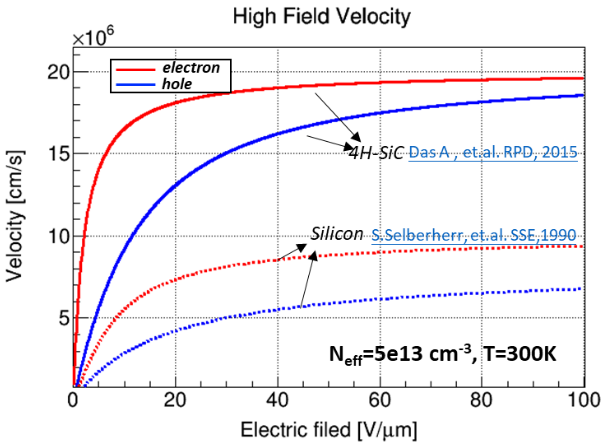
Characteristic	Si	4H-SiC
Eg (eV)	1.12	3.26
Thermal conductivity	1.5	4.9
$E_{breakdown}$ (V/cm)	0.5	3
Saturated electron velocity (cm/s)	1×10^7	2×10^7
ionization energy for e-h pair (eV)	3.64	7.8
displacement energy	13	21.8

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

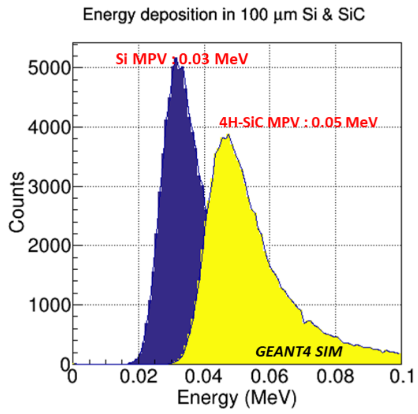
Previous RD50 workshop reports about 4H-SiC LGAD:

https://indico.cern.ch/event/1029124/contributions/4411189/
https://indico.cern.ch/event/1074989/contributions/4601968/

Potential application for fast MIPs detection



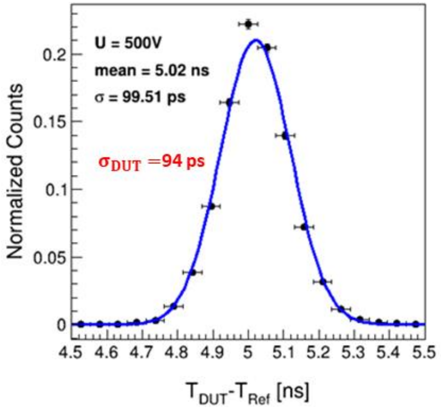
Saturated Carrier Velocity: 4H-SiC > Silicon



~ 55 e-h pairs/ um for MIPs in SiC

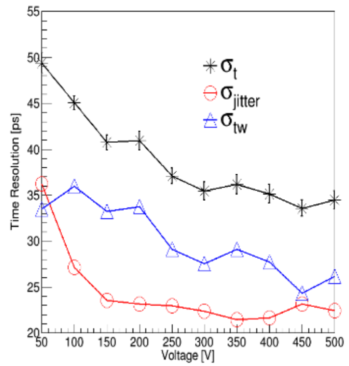
Good time resolution of 4H-SiC detector

100 µm 4H-SiC PIN for MIPs (measurement)



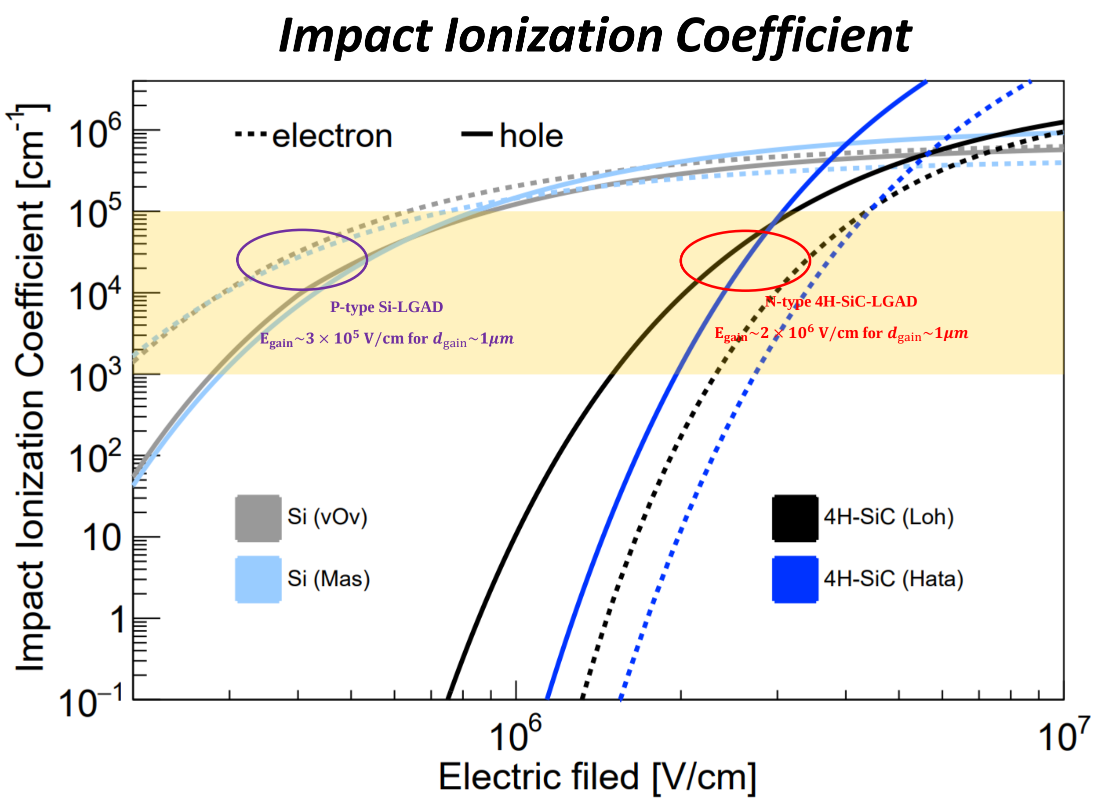
doi: 10.3389/fphy.2022.718071

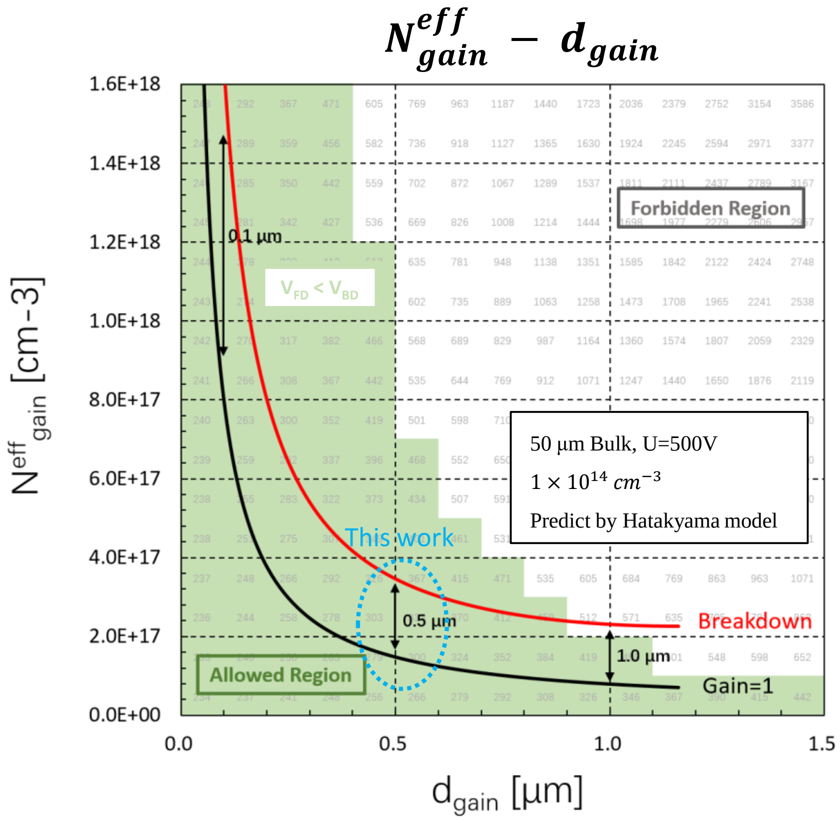
3D 4H-SiC Detector for MIPs (simulation)



doi: 10.3390/mi13010046

Design of 4H-SiC Low gain Avalanche Diode





- ➢ Impact ionization coefficient for 4H-SiC : $\alpha_{hole} > \alpha_{electron}$
- ➢ Fluctuation of 4H-SiC epitaxial growing: $N_{gain}^{eff} \pm 20\%, d_{gain} \pm 0.1\mu m$
- ➢ Limitation for the doping of 4H-SiC bulk layer : $\sim 1\times10^{14}\ cm^{-3}$
- ➢ LGAD operating condition: $V_{FD} < U < V_{BD}$

N-type 4H-SiC LGAD

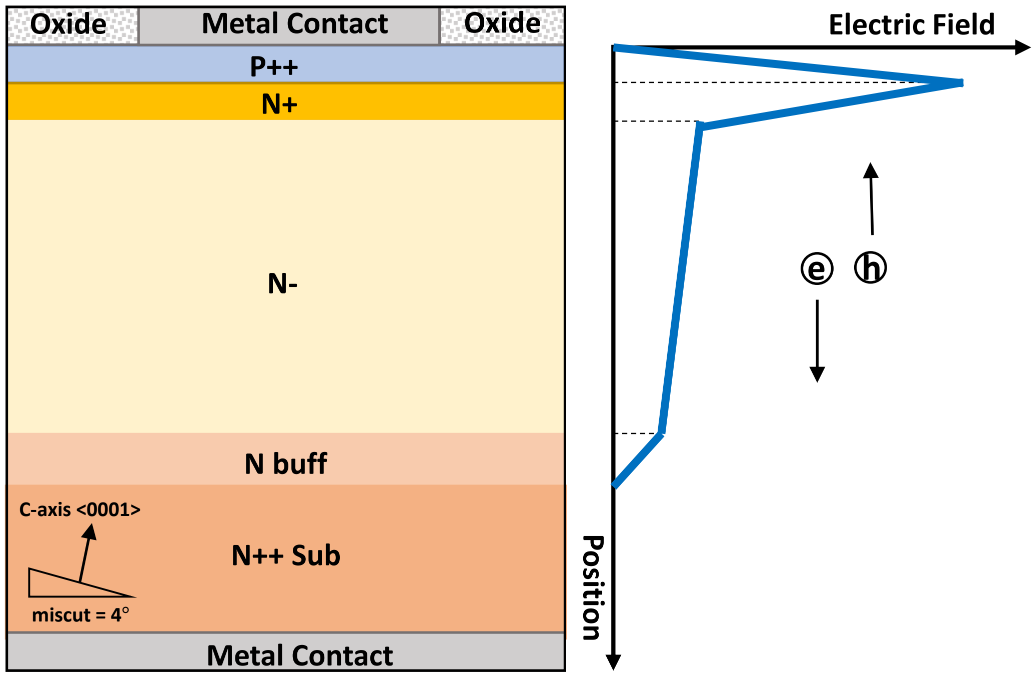
$d_{gain}: 0.4\sim0.6\ \mu m$

$E_{gain}:\ 2\times10^6\ V/cm\sim3\times10^6\ V/cm$

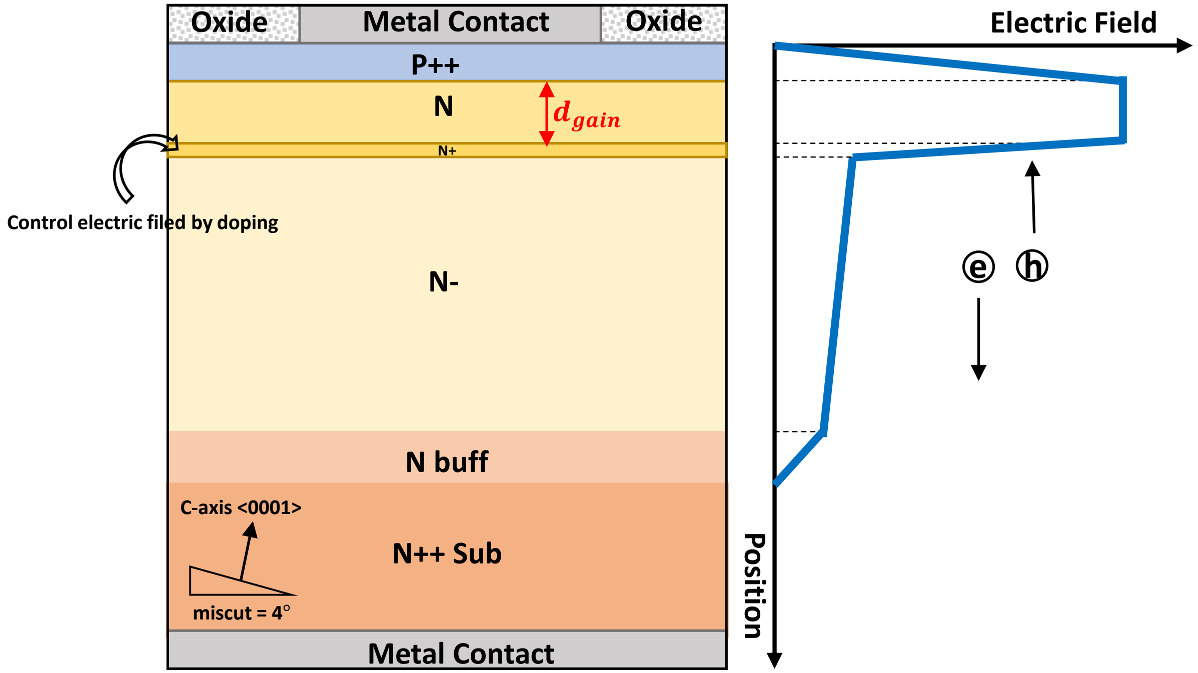
Gain 10 - 100

Design of longitudinal 4H-SiC epitaxial growing

“Triangle” Electric Field



“Trapezoid” Electric Field



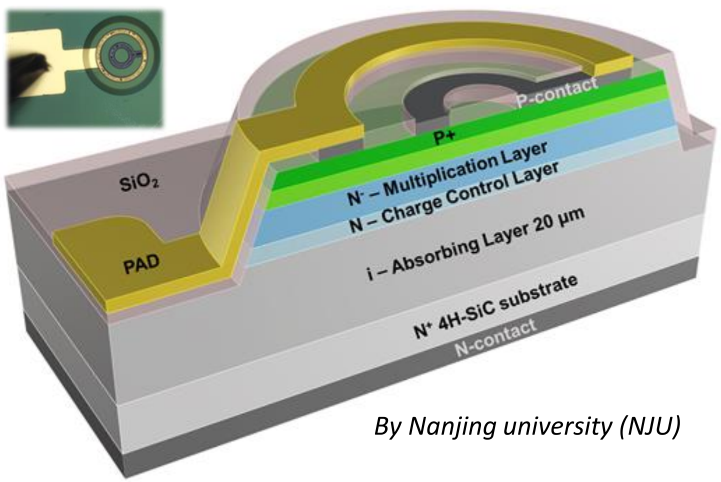
- ***Triangle-Type*** *has higher efficiency of gain obtaining but premature breakdown easily.*
- ***Trapezoid-Type*** *has more stability meanwhile it has medium efficiency of gain obtaining.*

Design in this work

arXiv: https://arxiv.org/abs/2206.10191

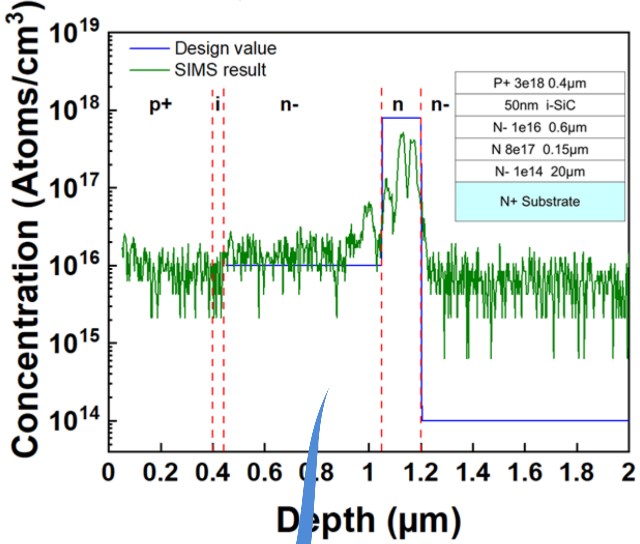
Introduction of NJU 4H-SiC LGAD Program

Structure of NJU 4H-SiC LGAD

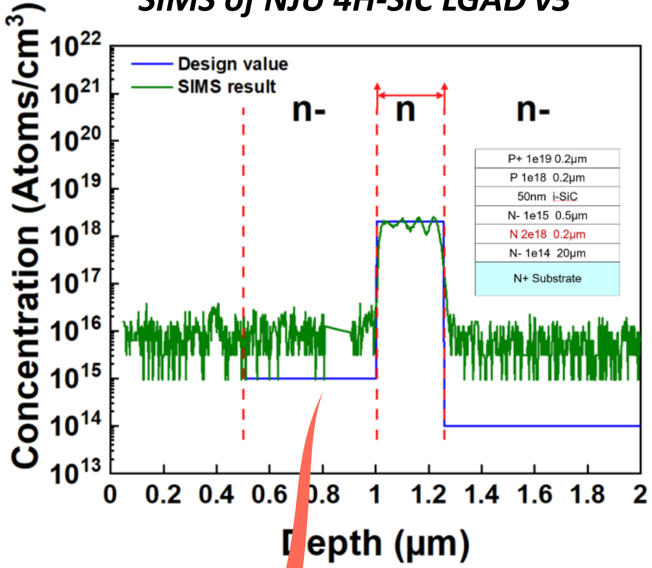


By Nanjing university (NJU)

SIMS of NJU 4H-SiC LGAD v2

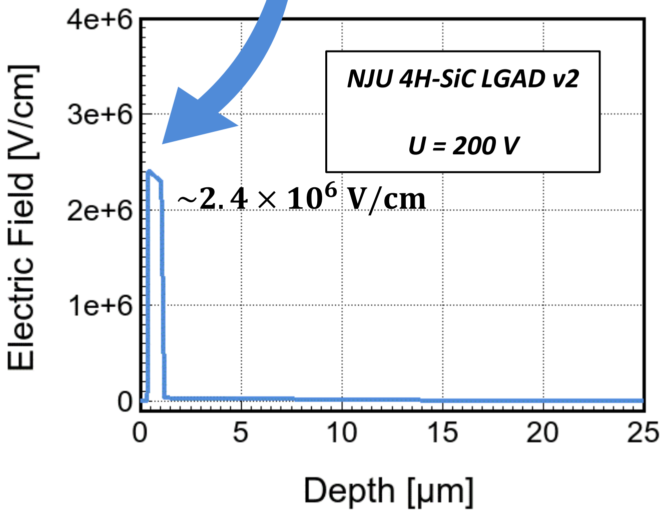


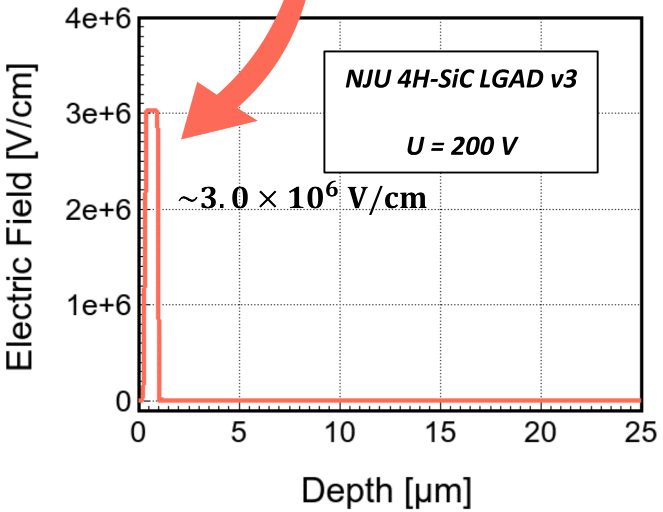
SIMS of NJU 4H-SiC LGAD v3



Motivation: Searching for the electric field value in ~0.5 μm 4H-SiC layer to achieve low gain.

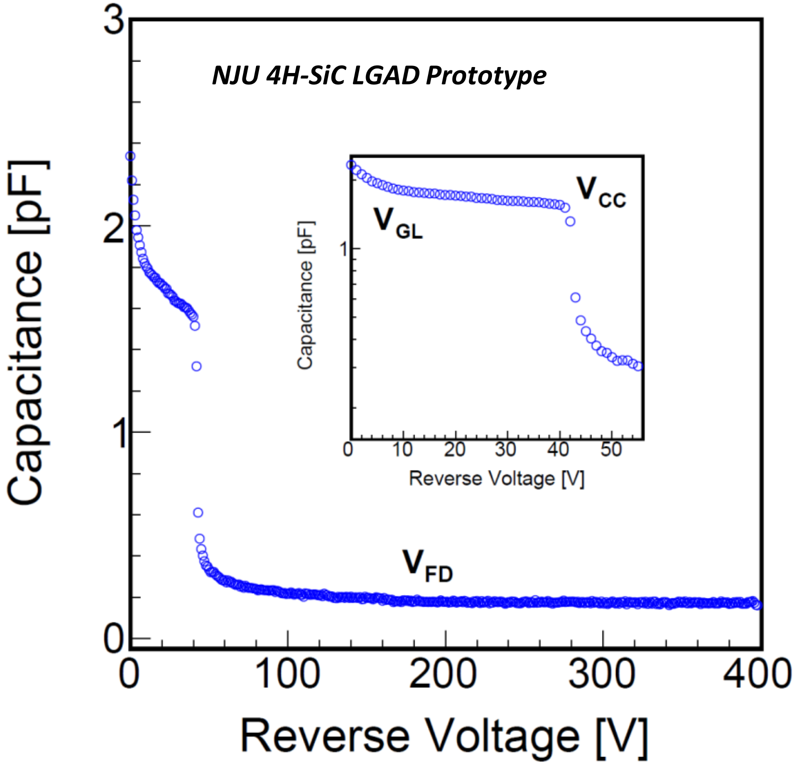
- v2 : low E_{gain} with low doping level of charge control layer.
- v3 : high E_{gain} with high doping level of charge control layer.



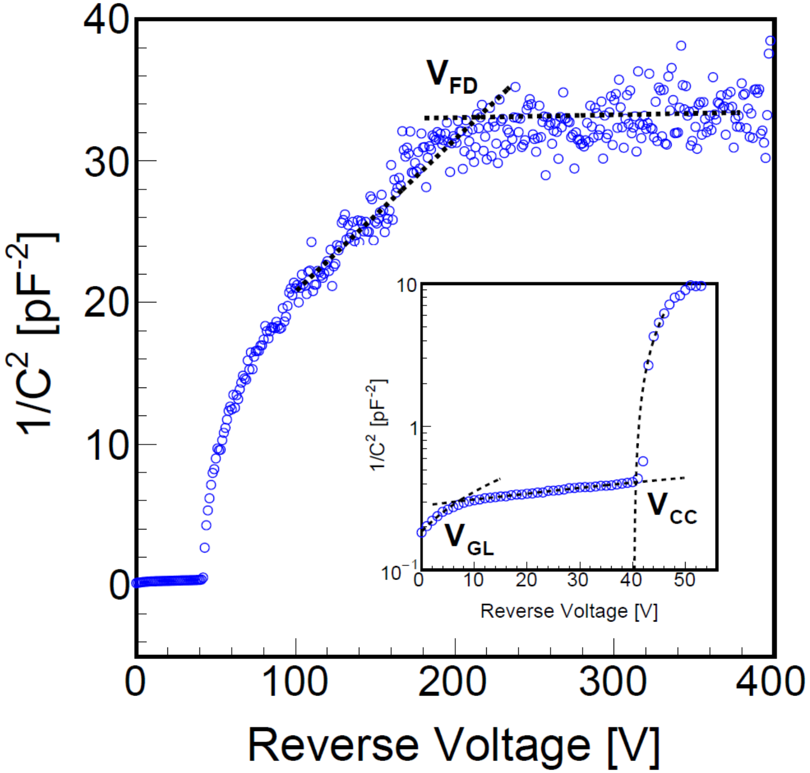


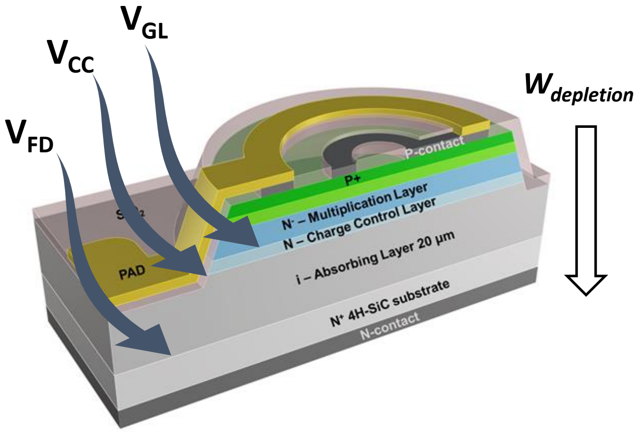
Capacitance measurement for NJU 4H-SiC LGAD v2

C - V



1/C² - V





V_{GL}: Gain Layer depletion voltage

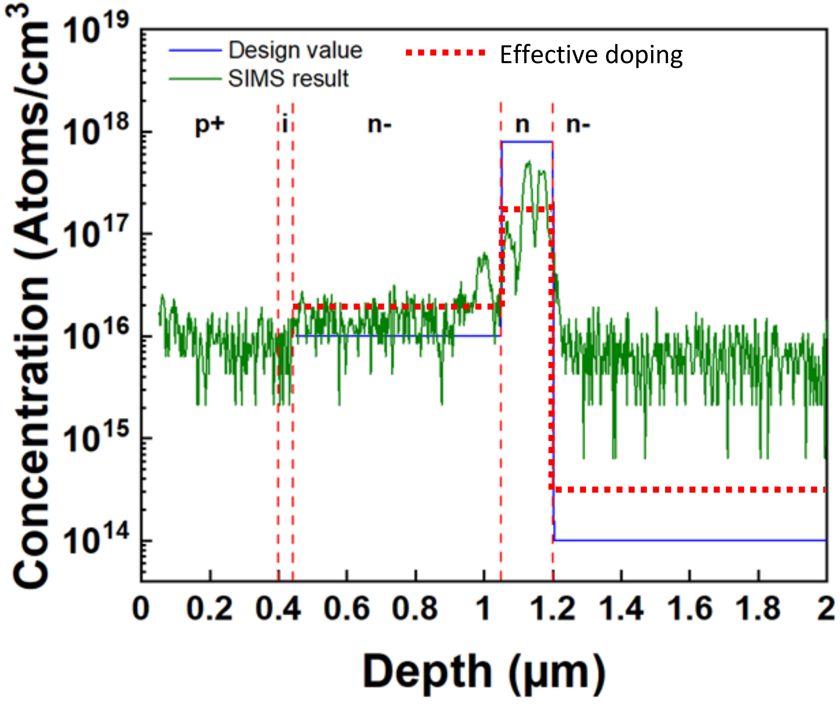
V_{CC}: Charge Control Layer depletion voltage

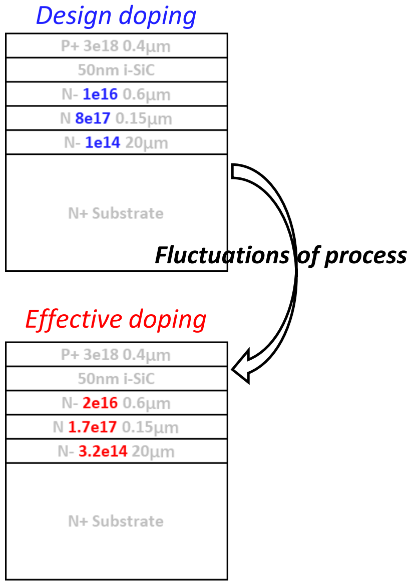
V_{FD}: Full Depletion voltage

- Three turning-voltages **V_{GL}, V_{CC}, V_{FD}** are corresponding to the three different doping layers.
- The NJU 4H-SiC LGAD v2 could be fully depleted when **U > 200 V**.

Effective doping concentration for NJU 4H-SiC LGAD v2

SIMS of NJU 4H-SiC LGAD v2





Design doping

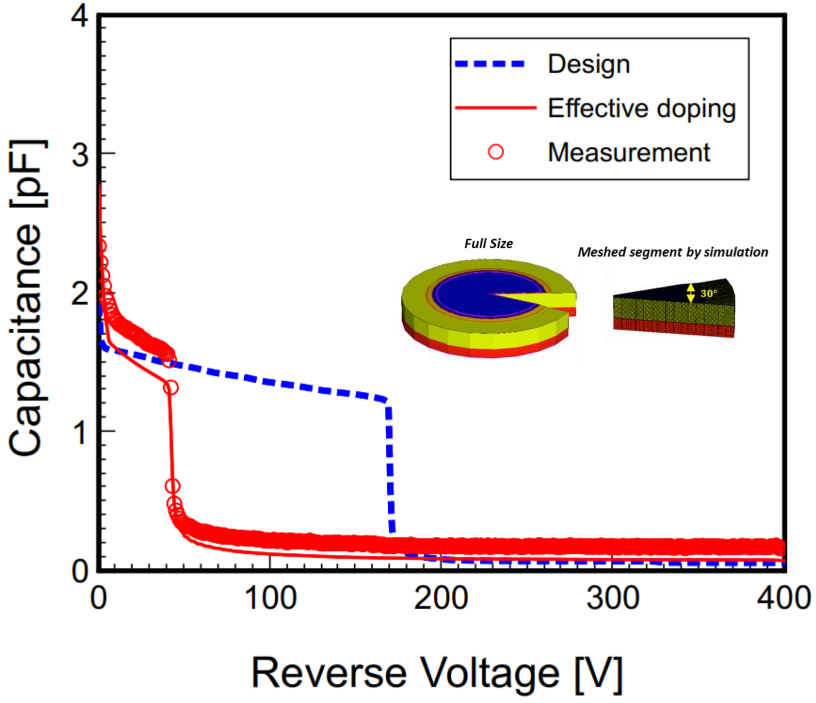
P+ 3e18 0.4μm
50nm i-SiC
N- **1e16** 0.6μm
N **8e17** 0.15μm
N- **1e14** 20μm
N+ Substrate

Fluctuations of process

Effective doping

P+ 3e18 0.4μm
50nm i-SiC
N- **2e16** 0.6μm
N **1.7e17** 0.15μm
N- **3.2e14** 20μm
N+ Substrate

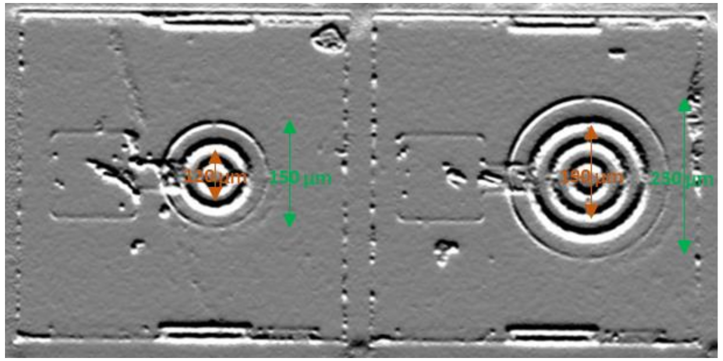
Simulated C-V

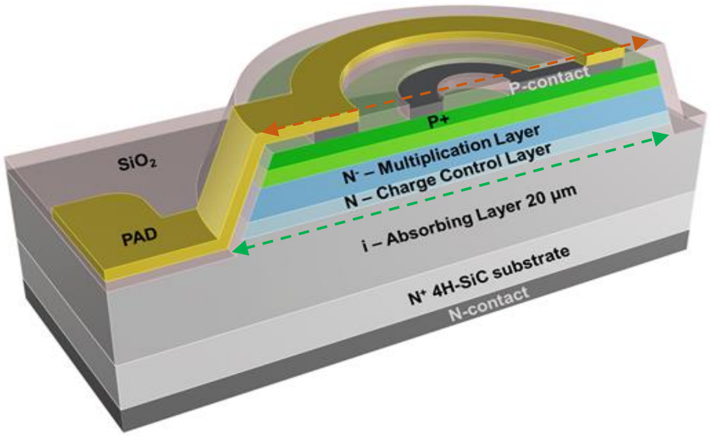


- ➢ The effective doping profile could reproduce the ***C-V*** well.
- ➢ The decrease of doping level (8e17 -> 1.7e17) of charge control layer : lower electric filed E_{gain}.

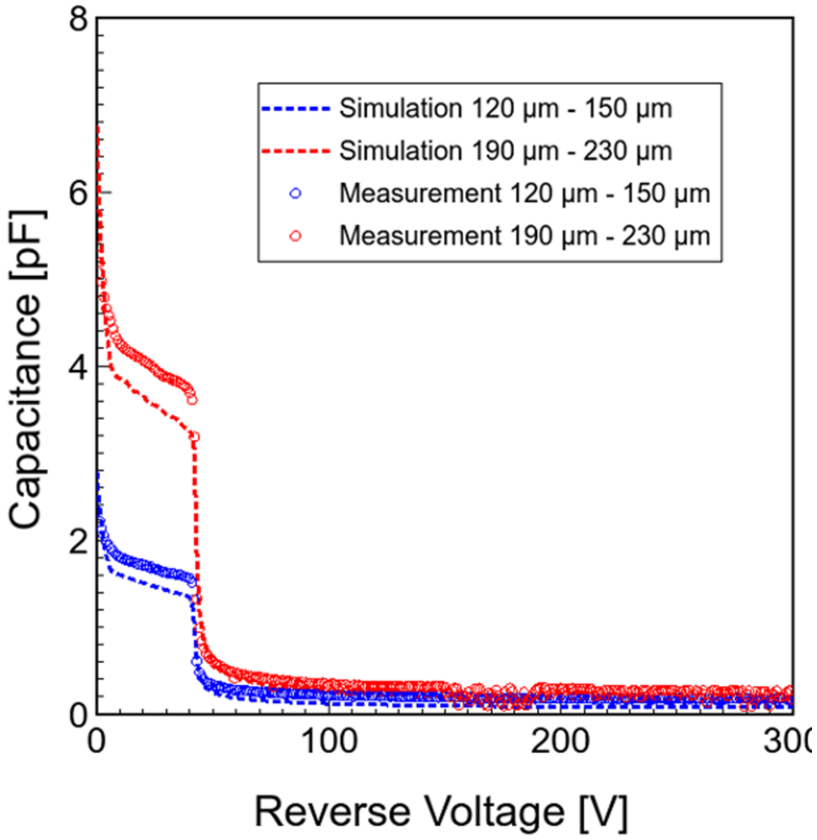
Different bevel terminations for NJU 4H-SiC LGAD v2

microscopic structure of different size





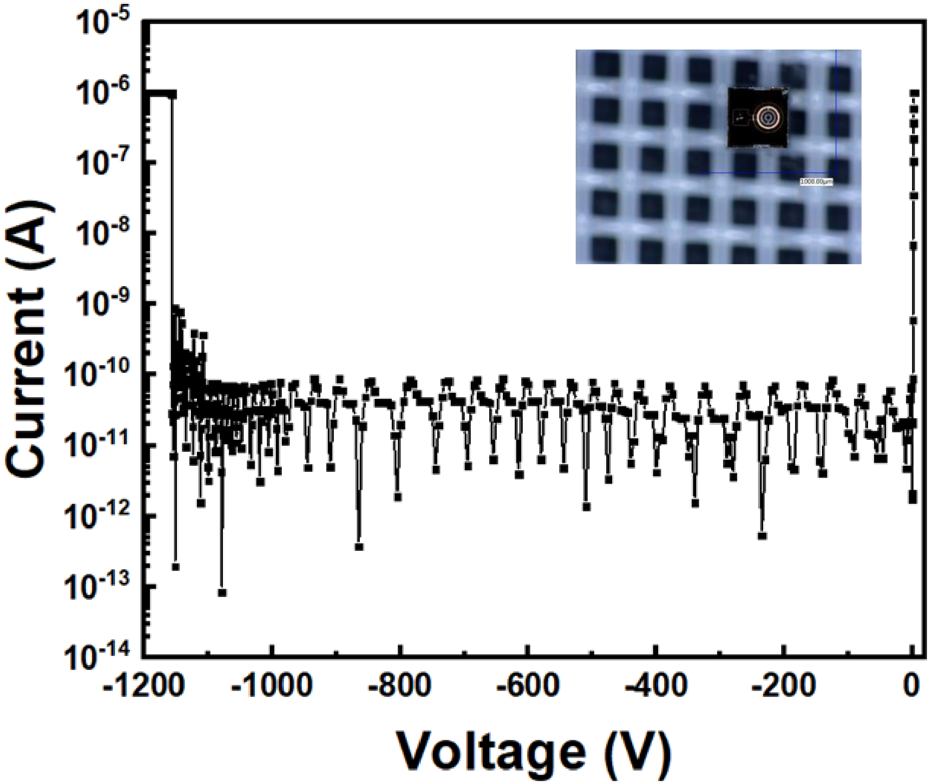
Simulated C-V for different bevel terminations



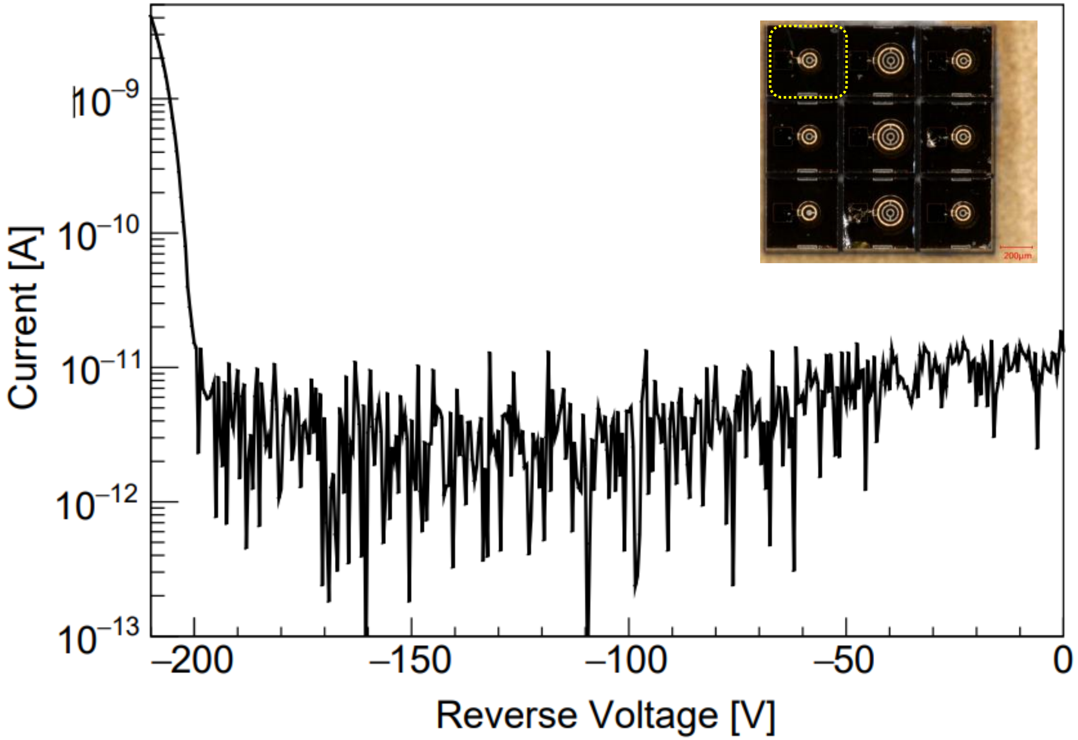
- ➢ Good agreement between measurement and simulation of effective doping profile.

Measurement of leakage current

NJU 4H-SiC LGAD v2

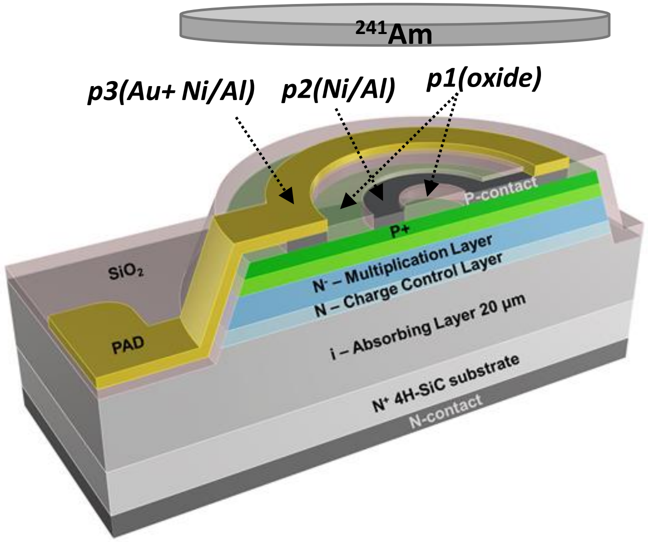


NJU 4H-SiC LGAD v3

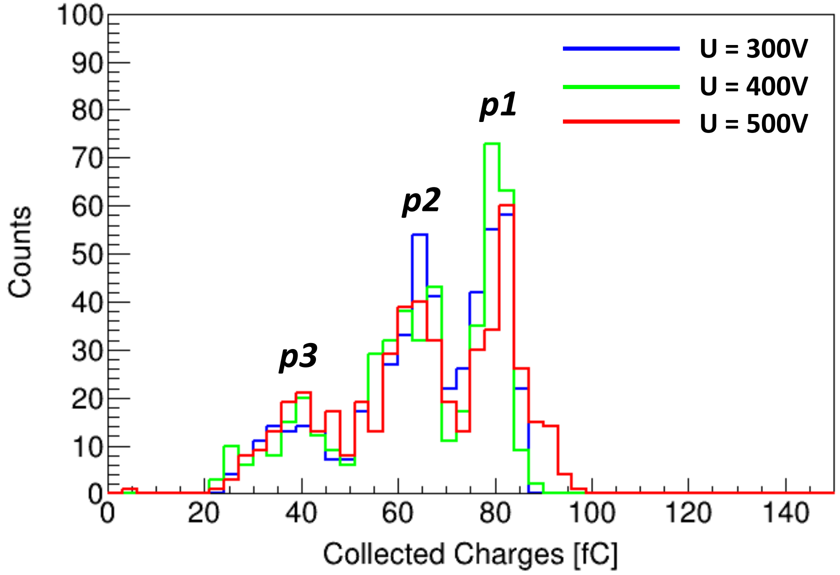


- v2 : low E_{gain} with high breakdown voltage which $V_{BD} > 1100V$ and $V_{BD} > V_{FD}$.
- v3 : high E_{gain} with low breakdown voltage which $V_{BD} > 200V$ and $V_{BD} < V_{FD}$ (premature breakdown).

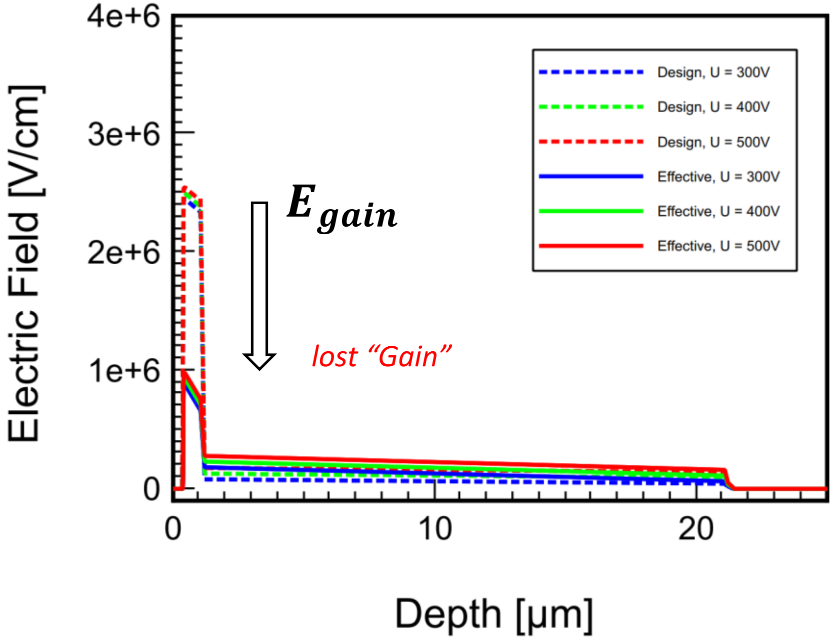
α particles detection of NJU 4H-SiC LGAD v2



Collected charges spectrum for v2



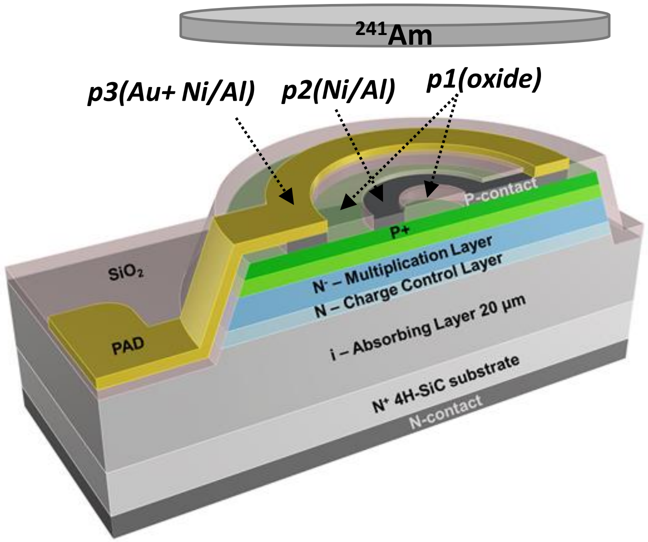
Simulated electric field for v2



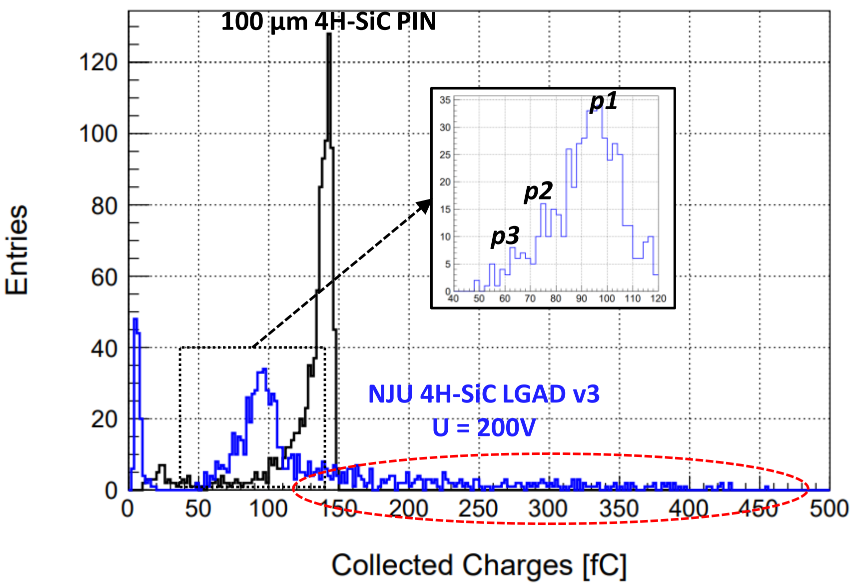
- No collected charges increasing by increase of voltage. -> No gain observed in v2 that agrees with the simulation by effective doping.
- Three peaks in collected charges spectrum are caused by different energy loss of α particle in various coverings.

α particles detection of NJU 4H-SiC LGAD v3

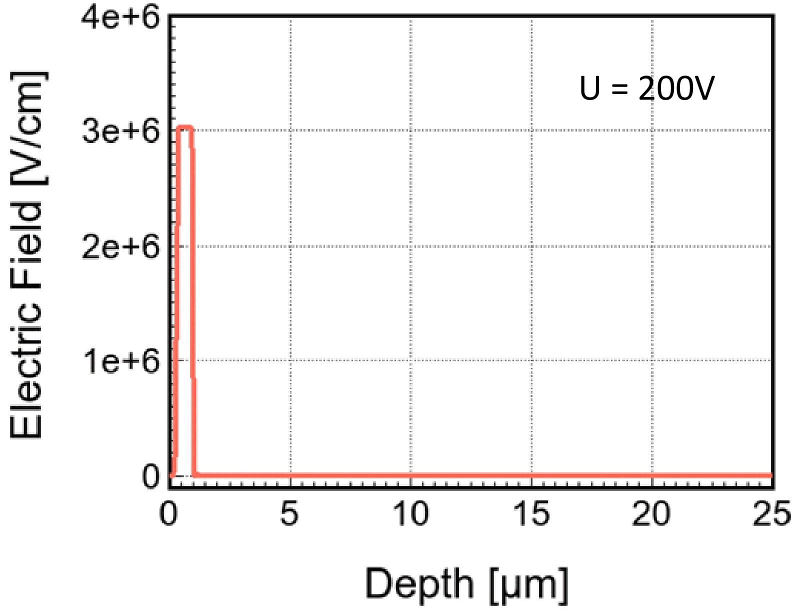
v3 enhances the electric field by changing the doping profile



Collected charges spectrum for v3

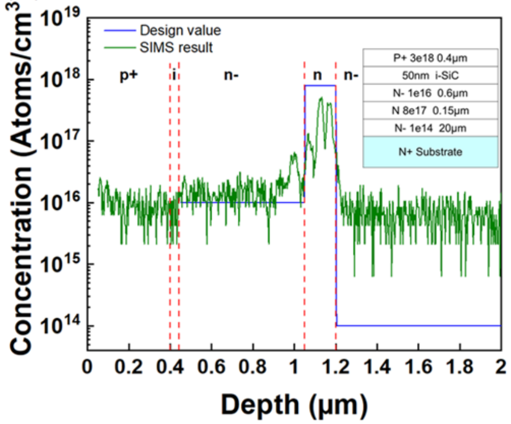


Simulated electric field for v3

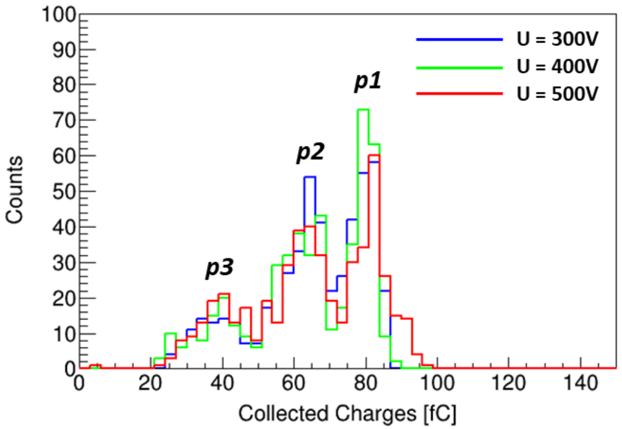


- ➢ Charges spectrum: three peaks are observed in v3 (same with v2).
- ➢ High gain signals are observed, but the distributing of high gain signals are dispersed.
- ➢ The maximum gain < 5 when U=200V due to premature breakdown.

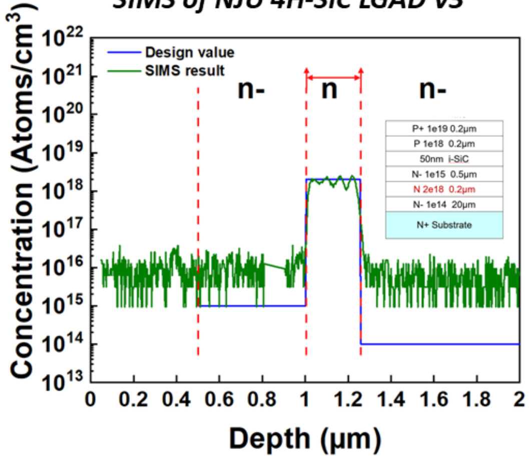
Summary & Plan



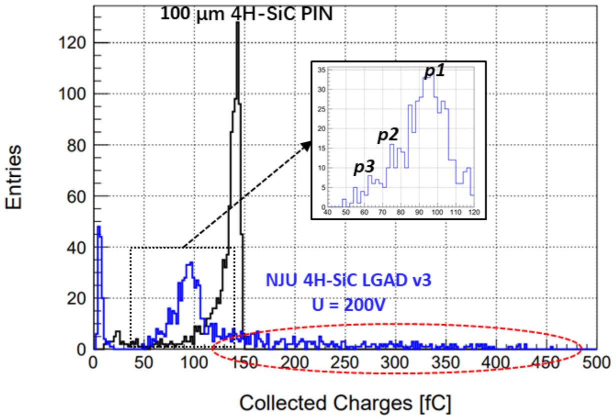
SIMS of NJU 4H-SiC LGAD v2



Collected charges spectrum for v2



SIMS of NJU 4H-SiC LGAD v3



Collected charges spectrum for v3

Design

- ☐ The design of 4H-SiC LGAD with “trapezoid” electric field is adopted.
- ☐ The thickness of gain layer should < 1.0 μ m accord with the analytical analysis. 0.5 μ m is studied in this work.

Measurement

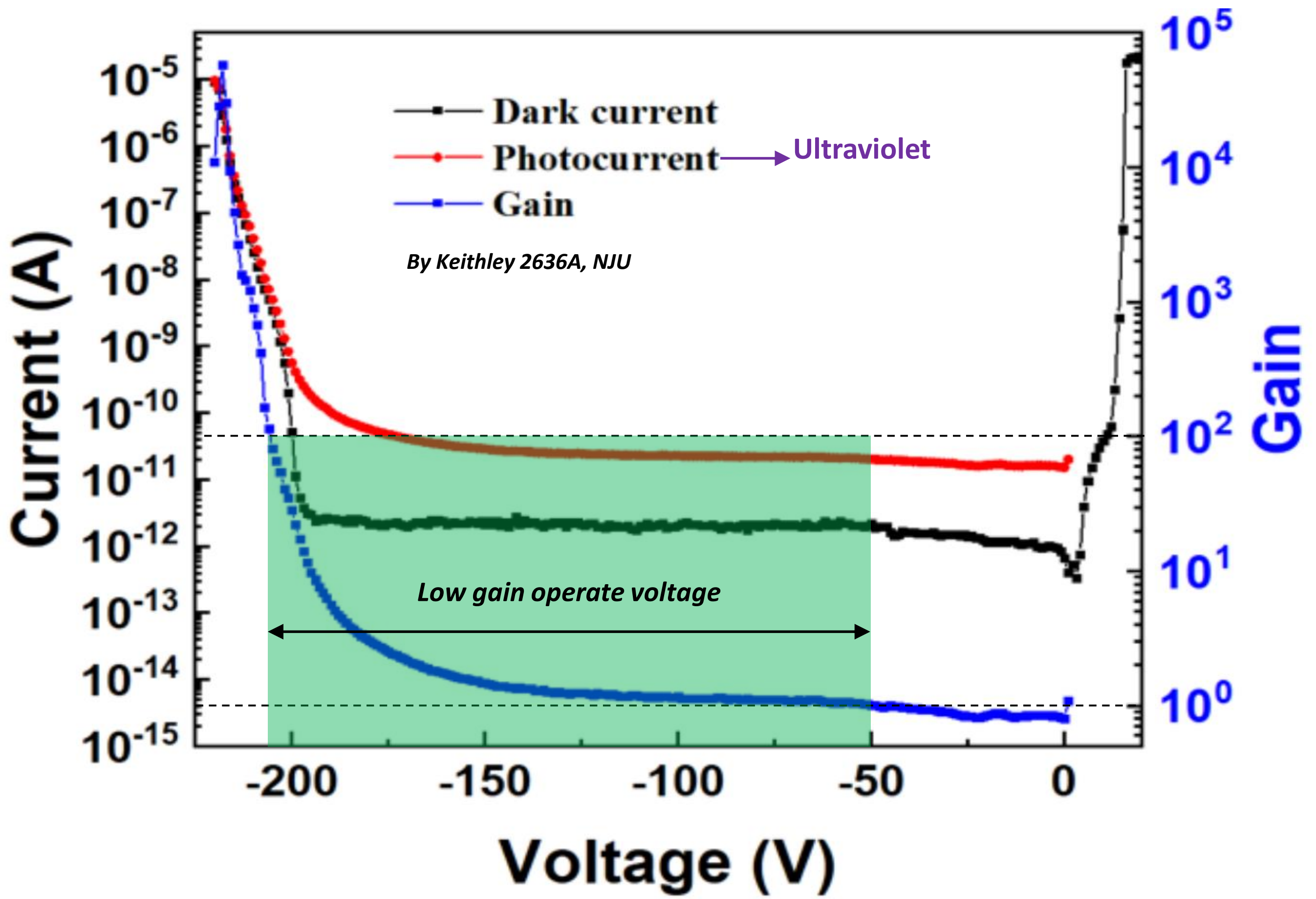
- ☐ v2: verify the process for 4H-SiC LGAD, but no high gain signals are observed. There is discrepancy between designed doping and effective doping.
- ☐ v3: high gain signals are observed but the high gain signals are dispersed. The measured gain is still small (<5) due to premature breakdown.
- ☐ v4 optimizes the doping level that targets to acquire gain>20 for MIPs detection, the production by NJU is in progress...

Thanks for your attention

Backup

Current Gain of NJU 4H-SiC LGAD prototype

NJU 4H-SiC LGAD v3



- 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.