Development of 4H-SiC Low-Gain Avalanche Detector

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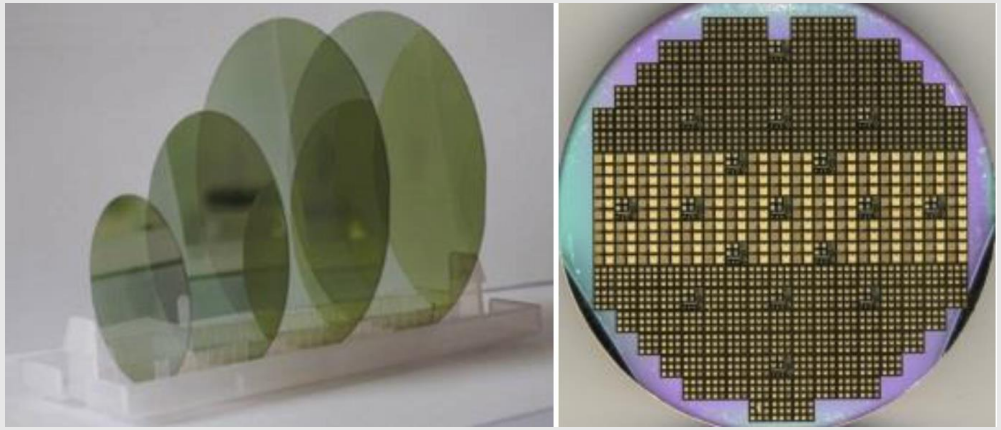
Why 4H-SiC ?

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

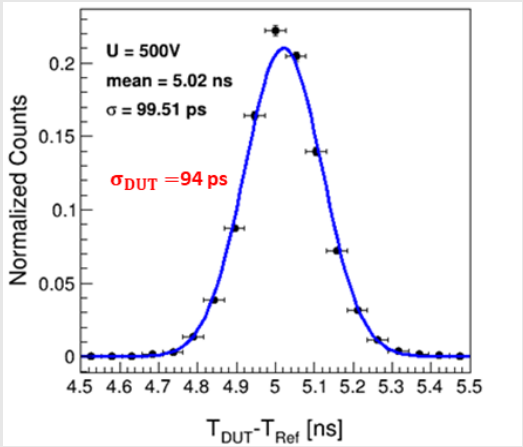


Characteristic	Si	4H-SiC
Eg (eV)	1.12	3.26
Thermal conductivity	1.5	4.9
$E_{breakdown}$ (V/cm)	0.5	3
Saturated electron velocity (cm/s)	1×10^7	2×10^7
ionization energy for e-h pair (eV)	3.64	7.8
displacement energy	13	21.8

- ✓ **High radiation hardness**
- ✓ **Low dark current**
- ✓ **high temperature resistance**
- ✓ **High saturated carrier velocity -> fast response**

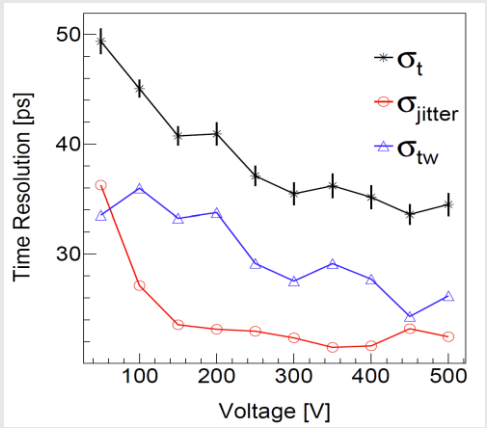
Good time resolution of 4H-SiC detector

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



https://doi.org/10.3389/fphy.2022.718071

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

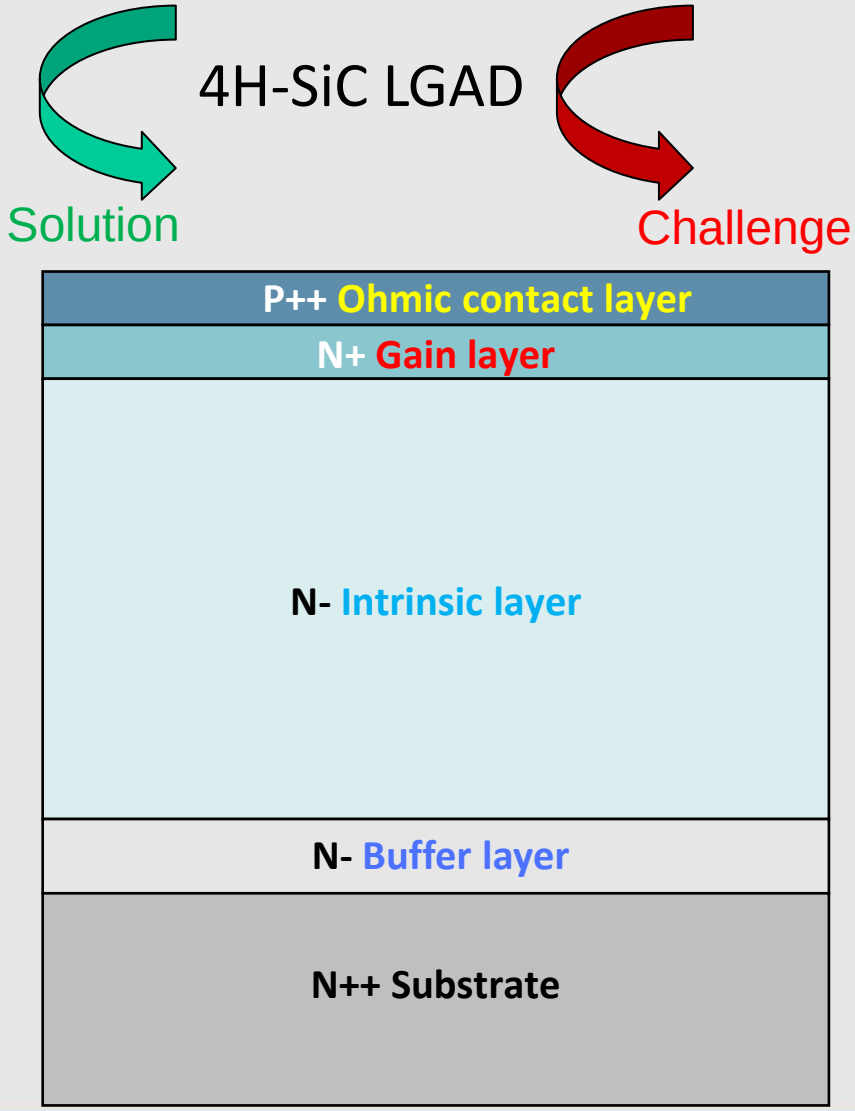


https://doi.org/10.3390/mi13010046

Challenge and solution of fast 4H-SiC detector

Goals

- Thicker active layer is required
- Achieve the carrier velocity saturated and low operate voltage

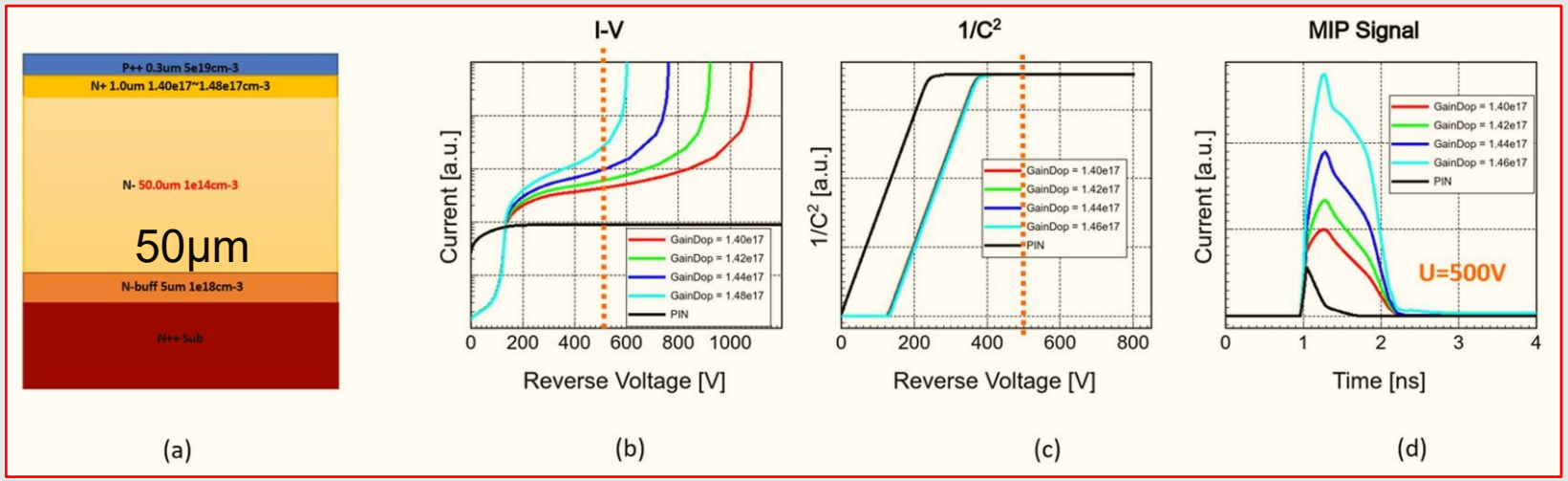


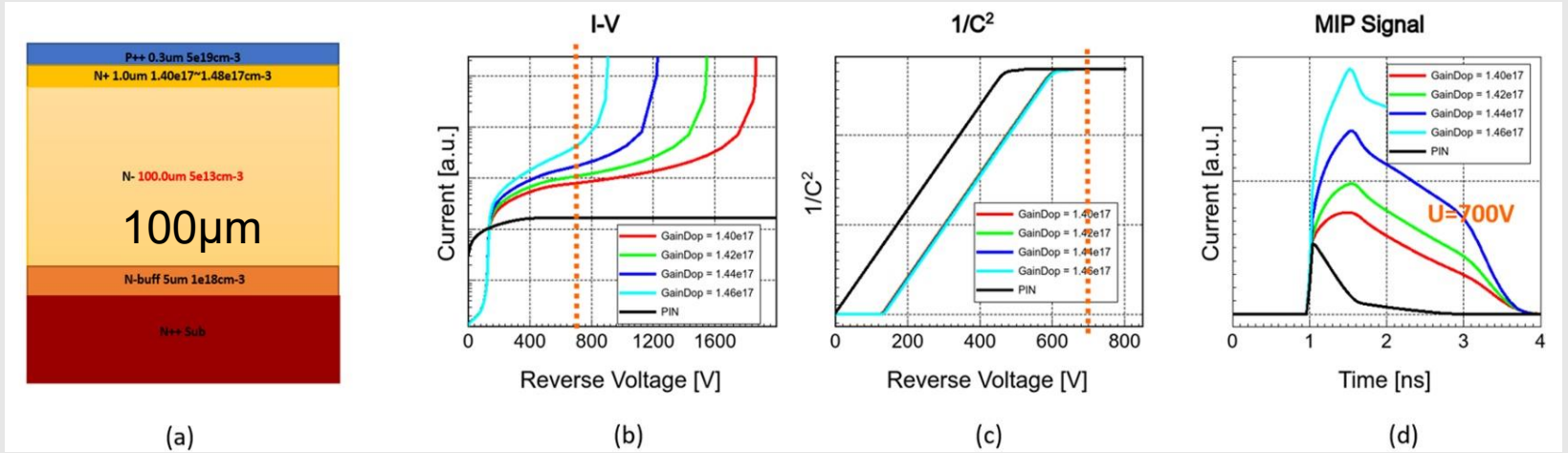
Key technologies

- Appropriate gain due to low carrier multiplication coefficient of 4H-SiC?
- Achieve the typical doping concentration distribution in 4H-SiC LGAD

Epitaxial structure simulation of 4H-SiC LGAD

Intrinsic layer





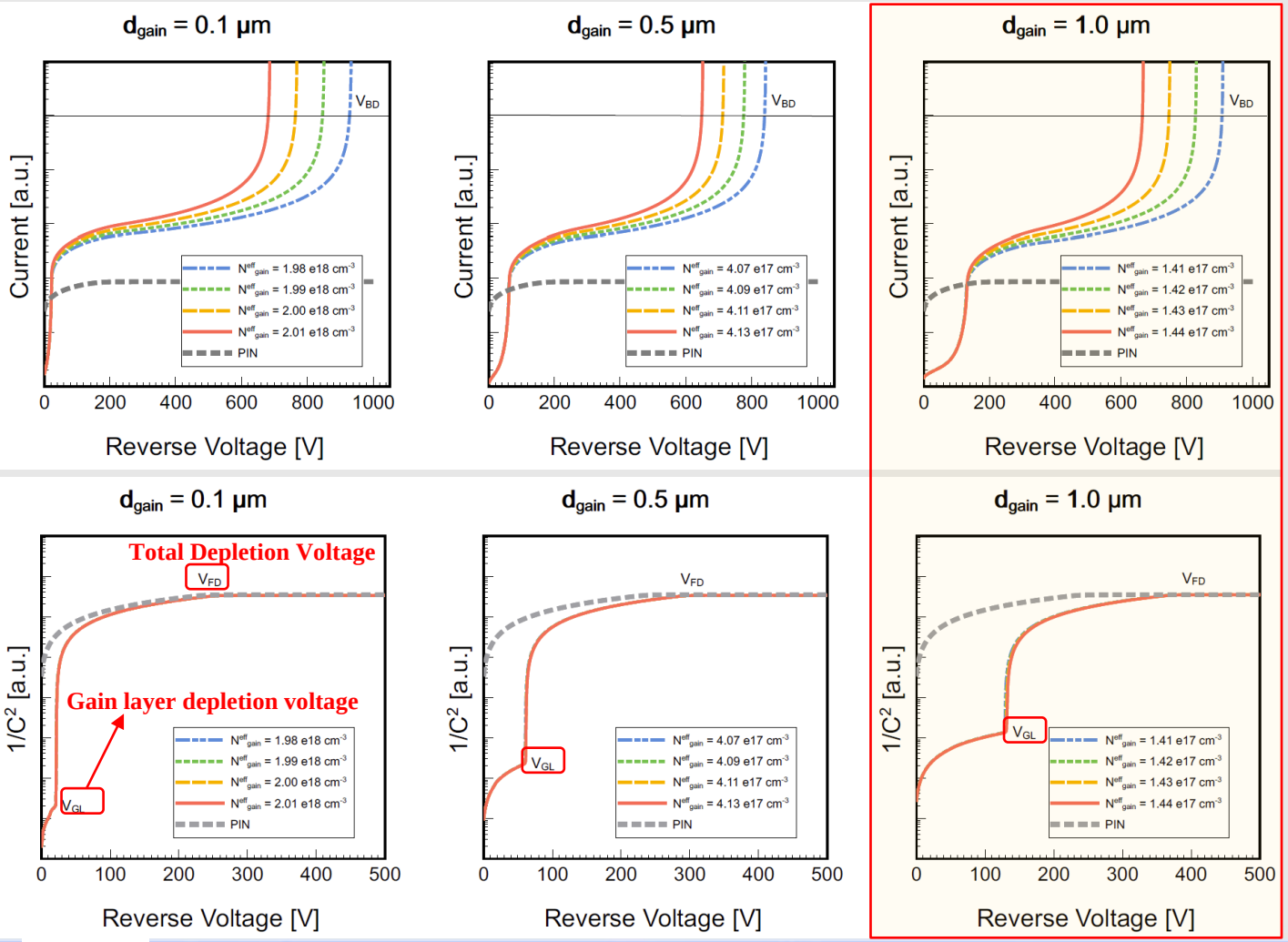
- The total depletion voltage (V_{BD}) depends on the doping concentration (N_{gain}^{eff}) and thickness.
- The doping concentration is same, intrinsic layer is 100μm, V_{BD} is higher than 700V.
- When the intrinsic layer is 50μm, the total depletion voltage is less than 500V.

https://arxiv.org/abs/2206.10191 https://arxiv.org/abs/2306.09576

Epitaxial structure simulation of 4H-SiC LGAD

Gain layer

https://arxiv.org/abs/2206.10191
https://arxiv.org/abs/2306.09576



The breakdown voltage (V_{BD}) depends on the doping concentration (N^{eff}_{gain}) and thickness.

Key technology: (V_{BD}) > (V_{FD})

N^{eff}_{gain} has little effect on gain layer depletion voltage (V_{GL}).

Designed epitaxial structure(SICAR1)

V_{GL}~ 140V

V_{FD} ~ 380V

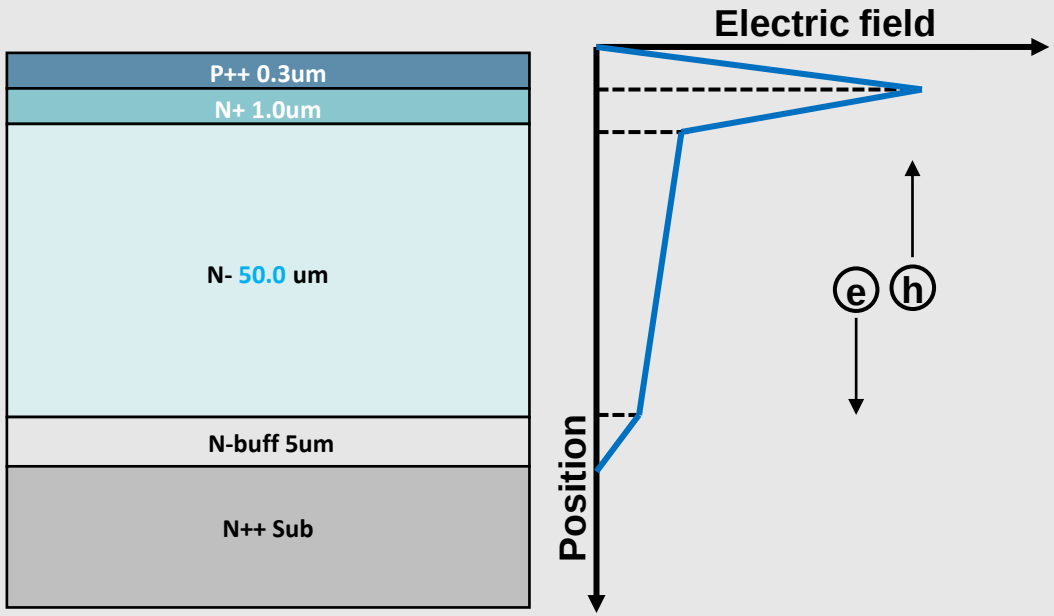
V_{BD} > 600V

Operate Voltage

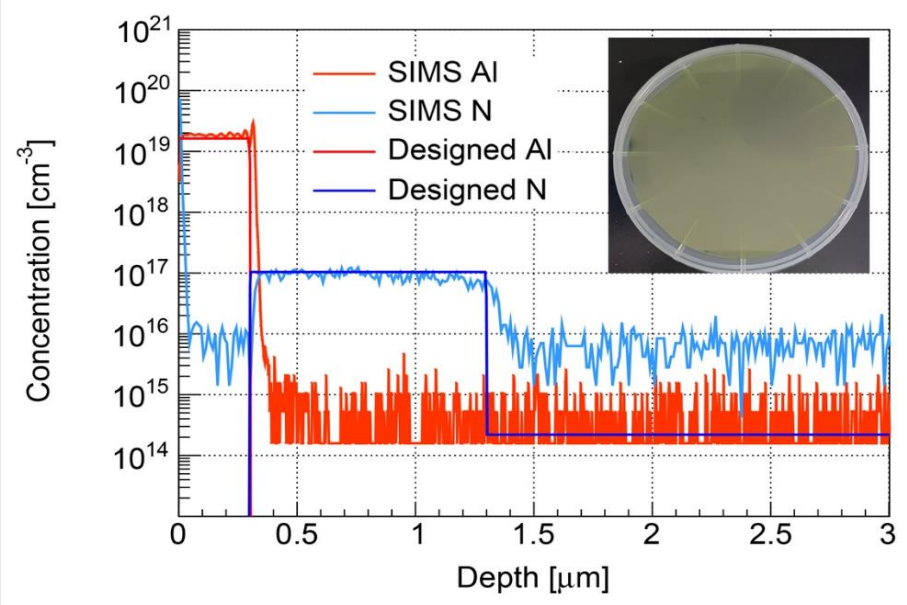
U=380V~600V

Real structure of 4H-SiC LGAD (SICAR1)

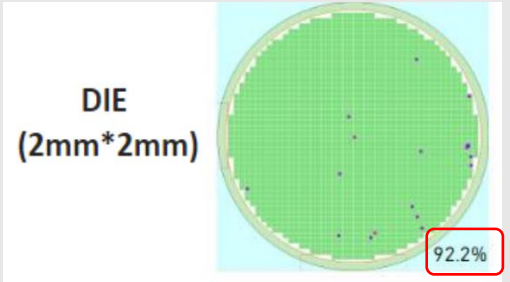
◆ **SICAR (SIlicon CARbide): 4H-SiC device for MIPs**



Epitaxial structure



Secondary ion mass spectroscopy measurement results

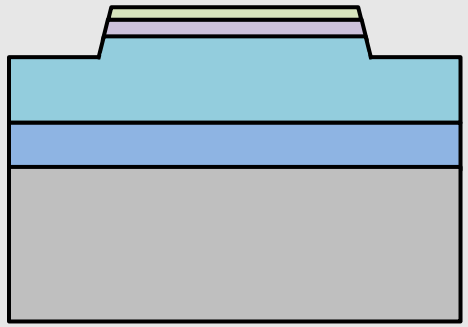


- Carrot
- Triangle

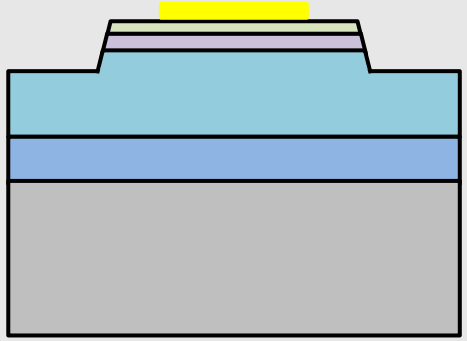
92.2%

Distribution of defects

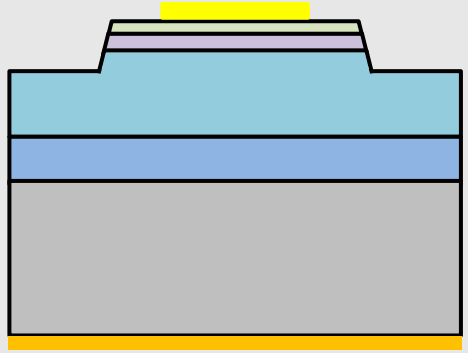
Micro machining processes



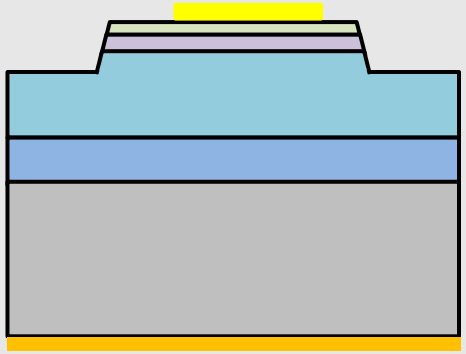
(1) Mesa Etch



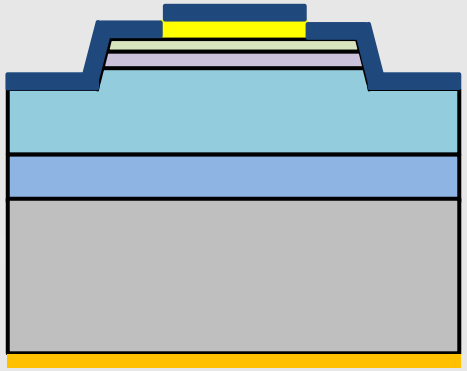
(2) Make P electrode



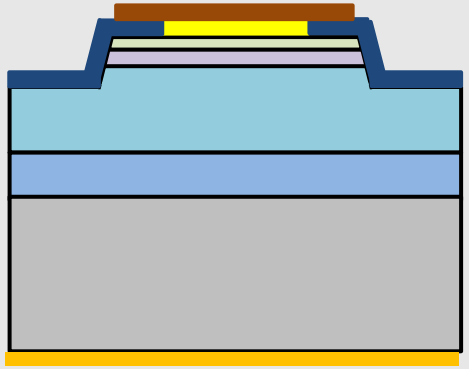
(3) Make N electrode



(4) Rapid Annealing (1000℃)



(5) Make Passivation layer

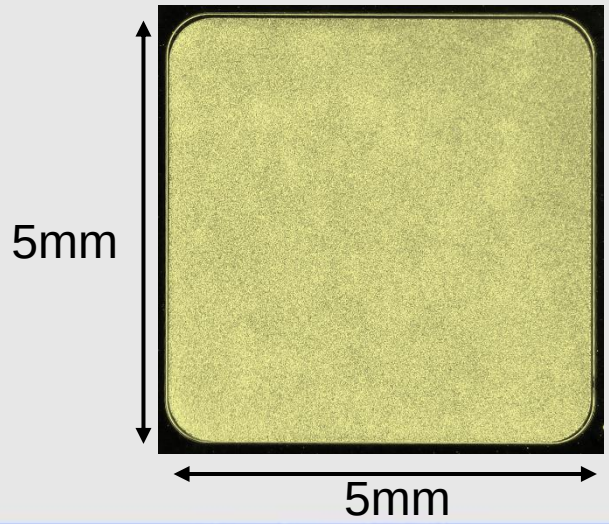


(6) Make Pad electrode

Micro machining processes

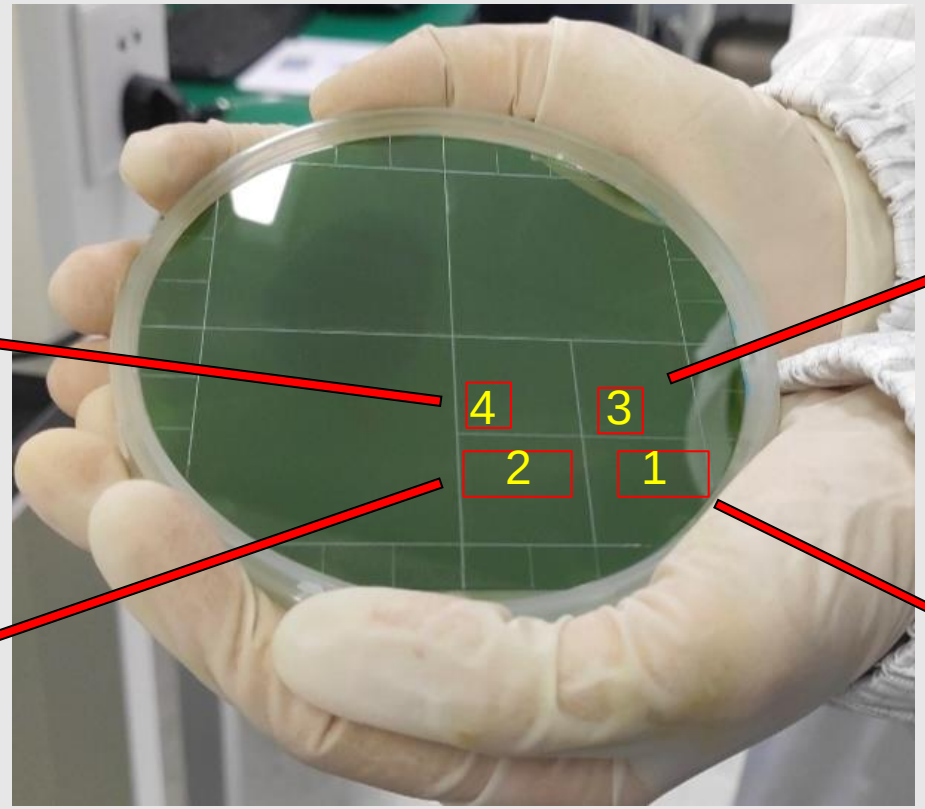
Key technologies of 4H-SiC LGAD:

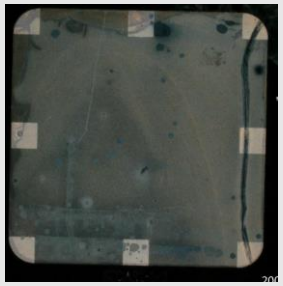
- Epitaxial structure design.
- High quality low doping 4H-SiC layer growing technology.
- N or P type ohmic contacts
- Edge Termination：Mesa Etch



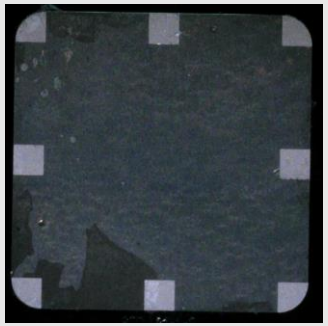
Test and analysis

- SICAR1 wafer
- 6 device under test, 5000μm×5000μm

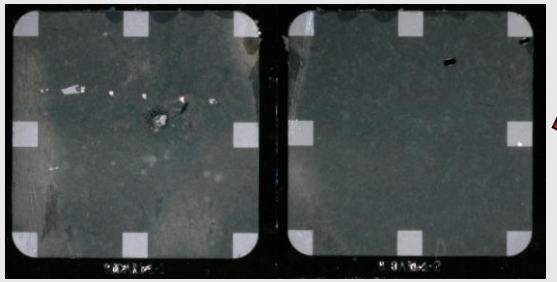




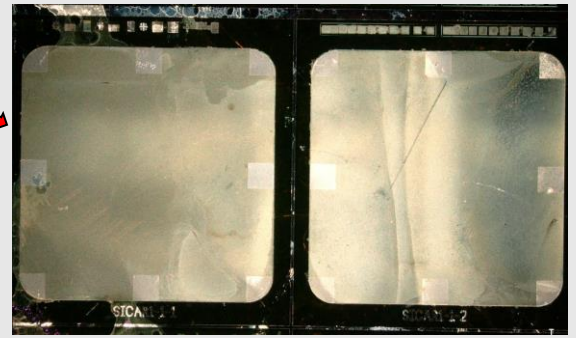
SICAR1-1-3(4)



SICAR1-1-3(3)



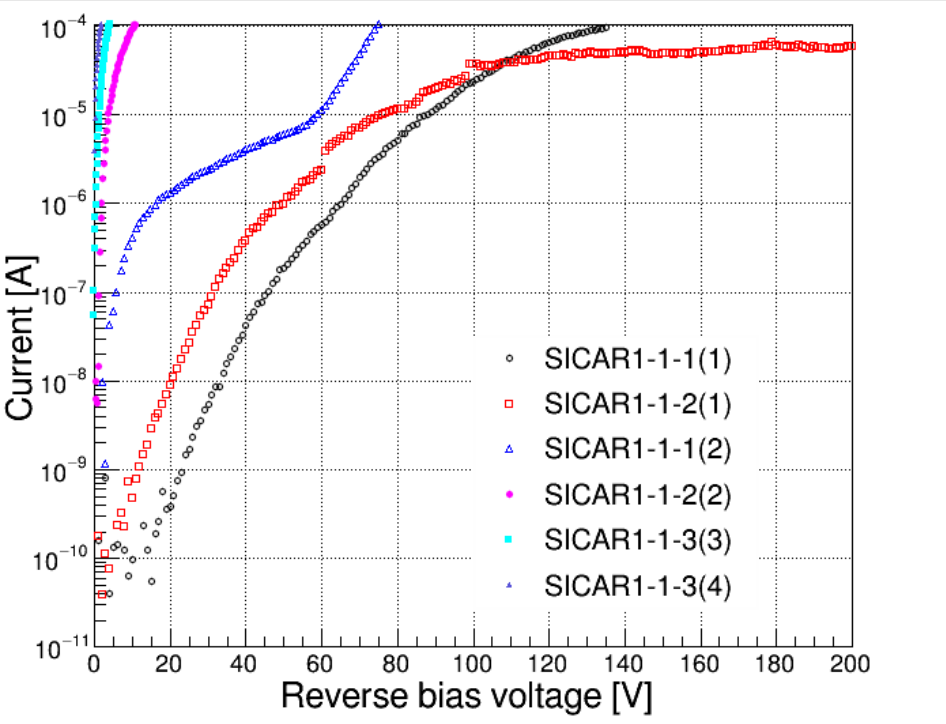
SICAR1-1-1(2) SICAR1-1-2(2)

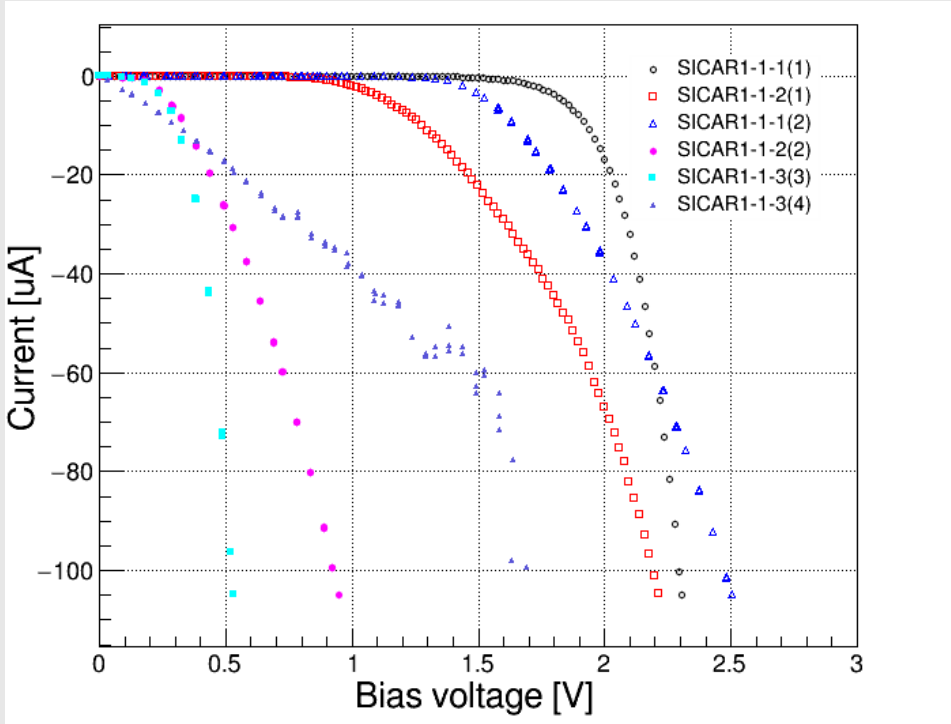


SICAR1-1-1(1) SICAR1-1-2(1)

Test and analysis

- Leakage current （Current limit: 105μA , measure at room temperature）

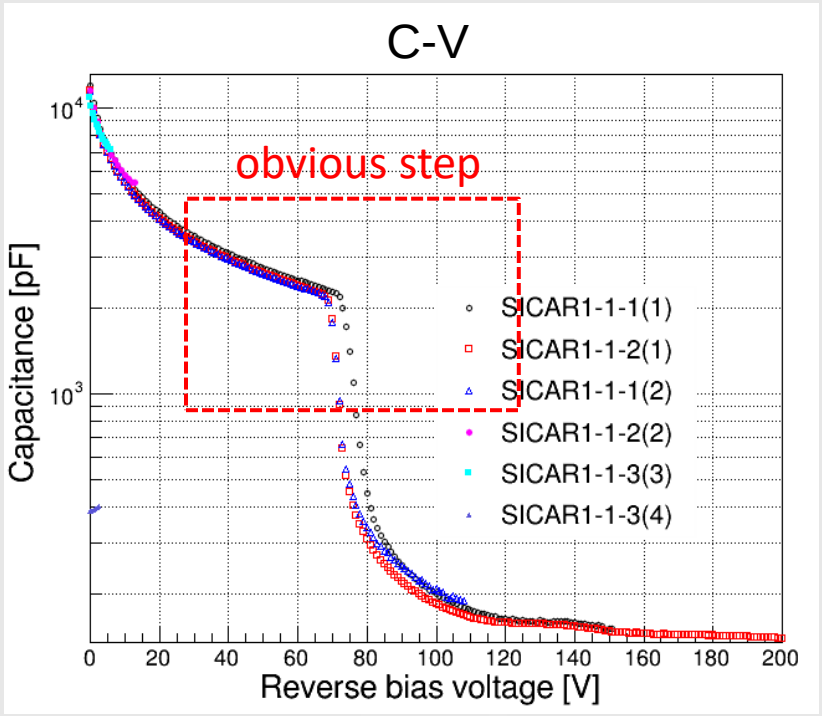


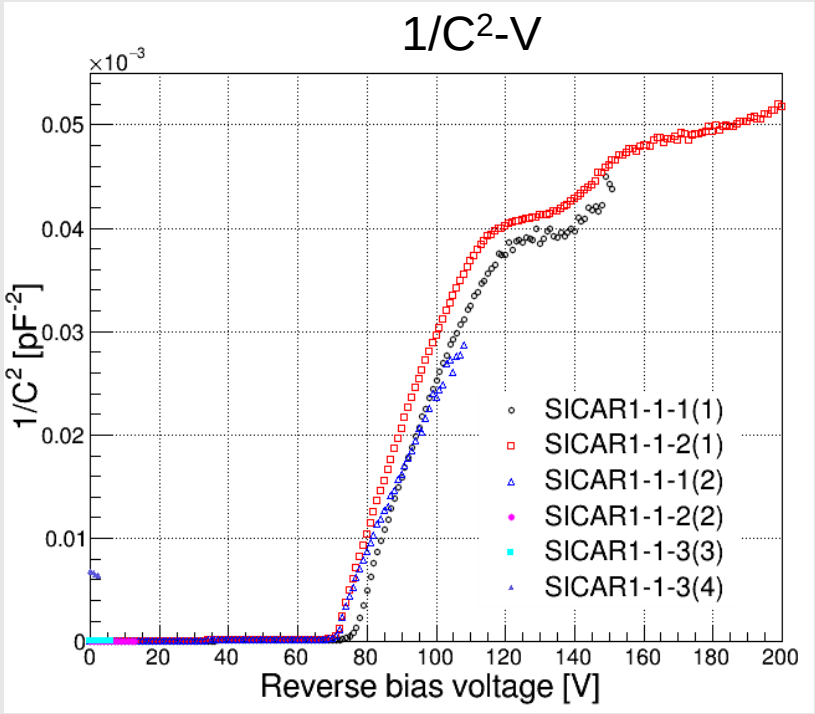


I-V characteristics of one detector is good, the leakage current is less than **50nA.** The performance of other detector needs to be optimized.

Test and analysis

- Capacitance （Current limit: 105μA , measure at room temperature）



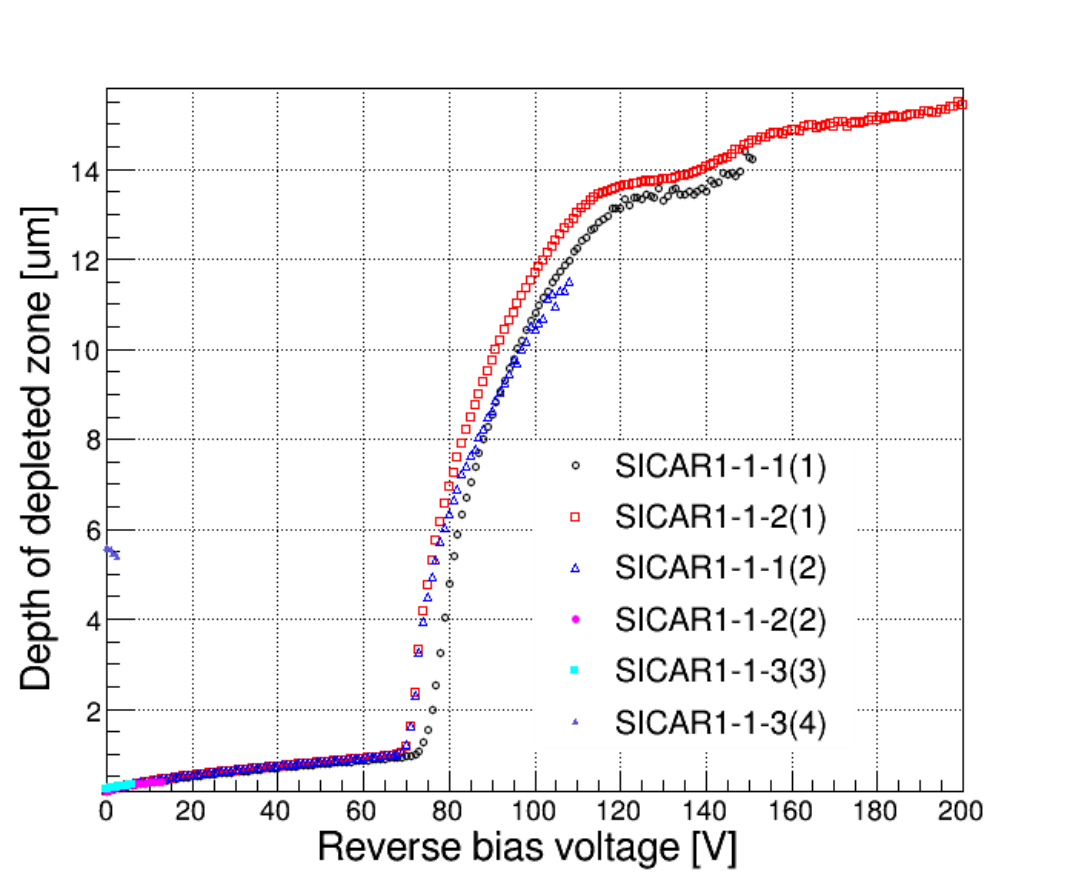


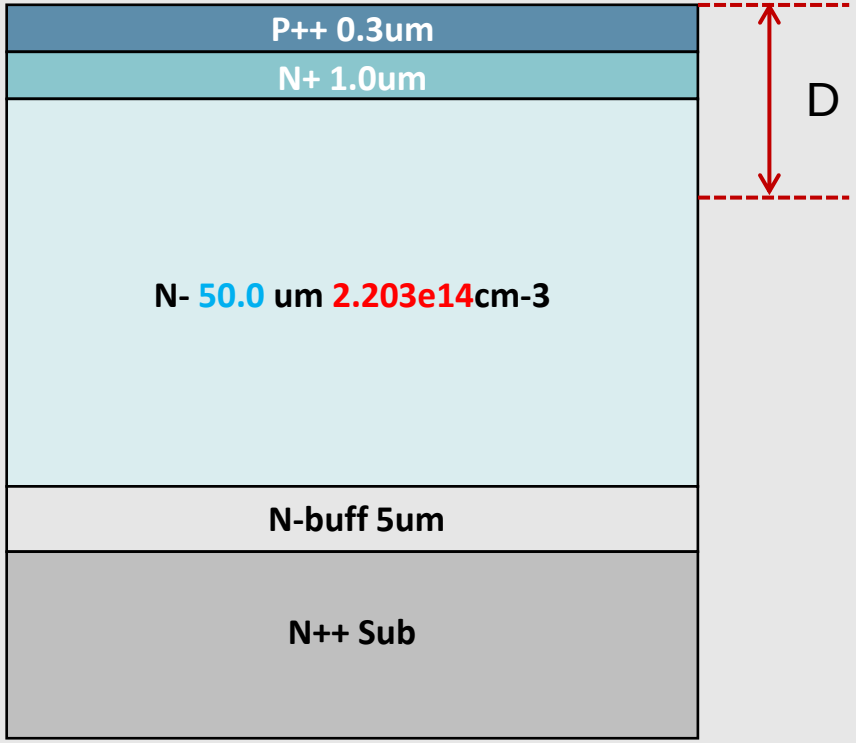
	Gain layer/cm^{-3}	Active layer/cm^{-3}	Gain layer depletion/V	Full depletion/V
SICAR1-1-1(1)	8.442±0.078 e16	2.224±0.066 e14	75	≈518
SICAR1-1-2(1)	7.689±0.065 e16	2.372±0.040 e14	70	≈553
SICAR1-1-1(2)	7.596±0.063 e16	2.495±0.626 e14	70	≈581

- There is a gain, indicating that it is a LGAD structure.
- Effective doping concentration is consistent with the actual concentration.
- Gain layer depletion voltage and full depletion voltage match the design target.

Test and analysis

- Depth of depleted zone

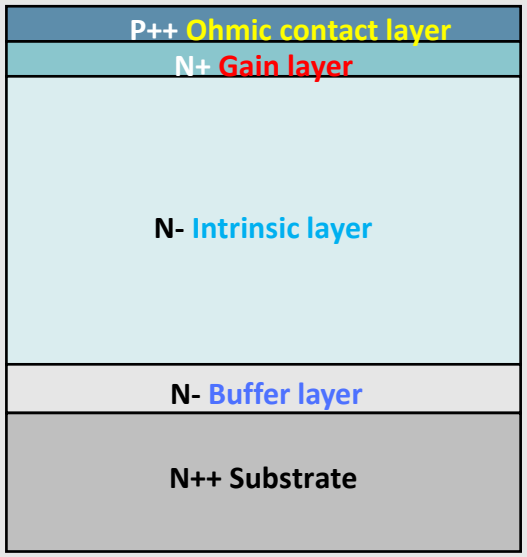


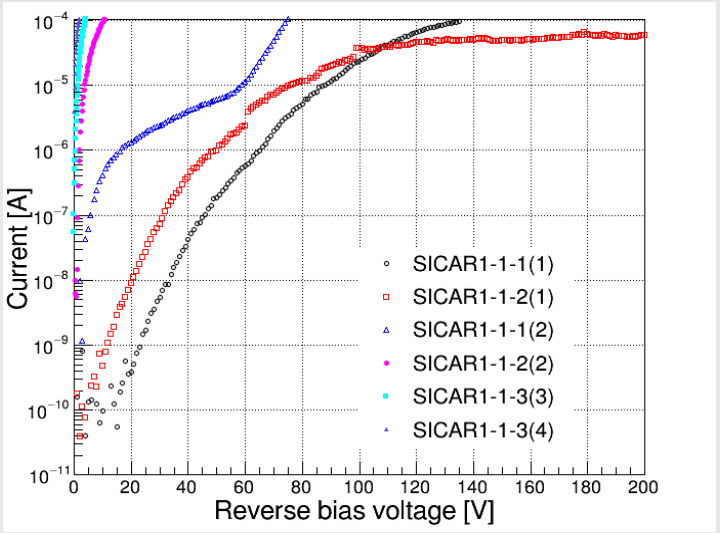


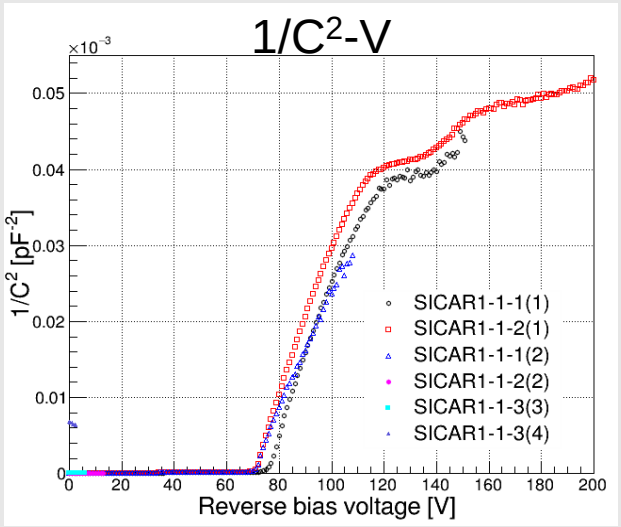
Epitaxial structure

The detector is not exhausted at 200V.

Test and analysis





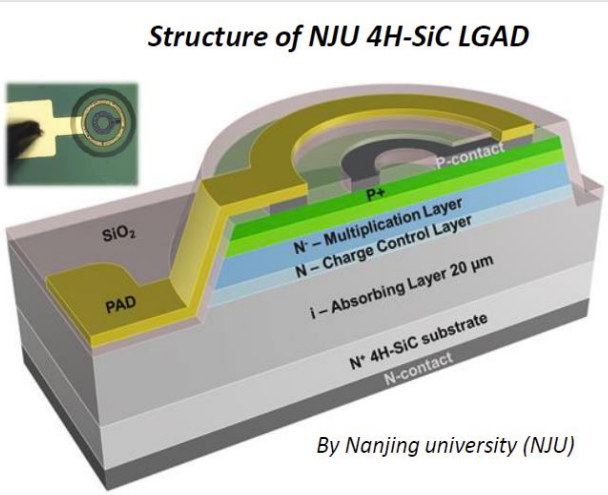


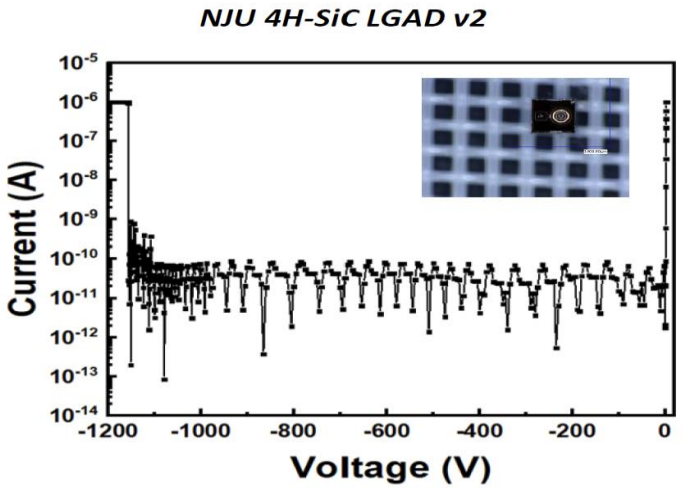
IHEP LGAD:

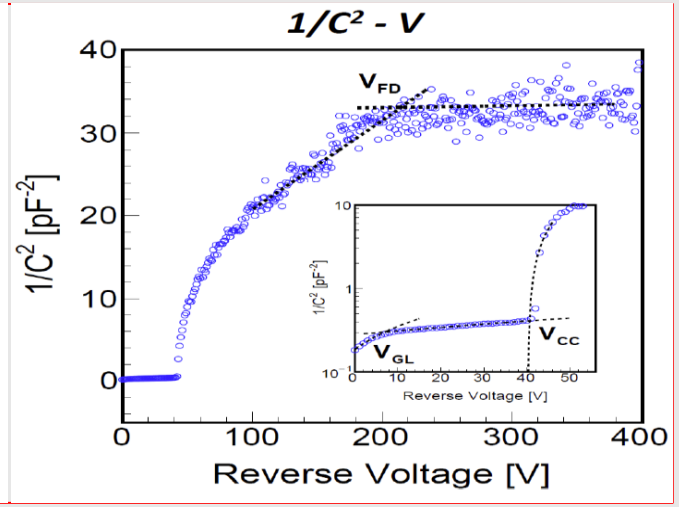
obvious gain

high breakdown voltage

IHEP 4H-SiC LGAD design







NJU LGAD:

No gain

High breakdown voltage

NJU 4H-SiC LGAD design

Summary & Plan

Summary:

1. SICAR 1 has a gain, indicating that it is a LGAD structure.
2. The gain layer depletion voltage is about 70V and the full depletion voltage is between 500V and 600V. The leakage current is less than 50nA.

3. The effective doping concentrations of the gain layer and active layer are consistent with the actual concentration.

Plan:

1. Test and analyze charge collection efficiency and time resolution.
2. Optimize the structure and chip technology, to reduce the leakage current and increase the breakdown voltage.
3. Optimize ohmic contact properties and electric field distribution using two-dimensional materials.