Development of 2D GaN and 3D SiC detectors

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Outline

- Motivation
- 2D GaN partical detector
- 3D SiC radiation detector
- Prospect

Advantages of semiconductor radiation detectors

Narrow band gap semiconductor detector
w~3eV

Fano factor (~0.1)

- ✓ Energy resolution
- ✓ Detection efficiency
- ✓ Pulse rise time
- ✓ Energy linear range
- ✓ Integrated
- × Small size
- × Radiation damage
- × High temperature
- × Protect from light

VS

Gas detector
w~30eV

Fano factor (0.2~0.5)

- ✓ Energy resolution
- × Detection efficiency

Scintillator detector
w~300eV

Fano factor (~1)

- ✓ Detection efficiency
- × Energy resolution
- × Carrier collection

Wide bandgap semiconductor based detector can met the demand

Table 1: Basic physical parameters of semiconductor materials

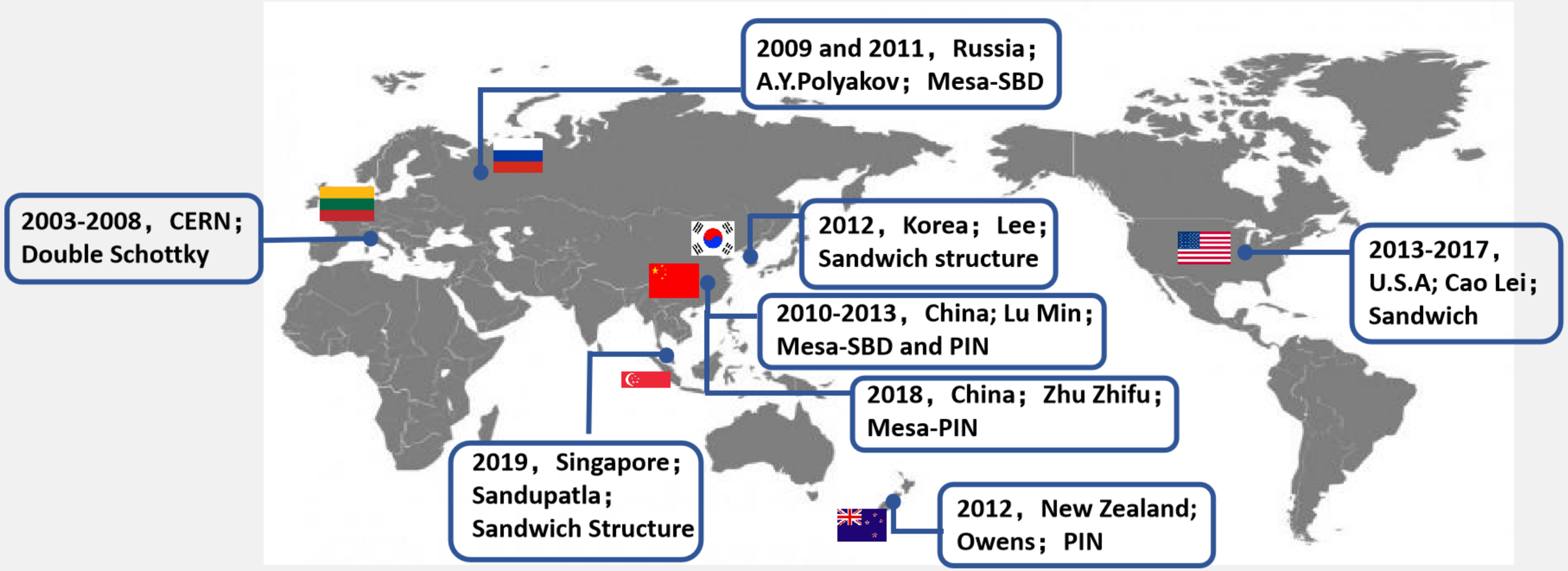
Material	Si	4H-SiC	Diamond	GaN
E_g (eV)	1.12	3.27	5.5	3.39
Displacement energy (eV)	13-20	20-35	43	10-20
Density (g/cm^3)	2.33	3.22	3.52	6.15
e-h energy (eV)	3.6	7.8-9	13	8-10

Motivation for the development of 2D(planer) GaN radiation detector

1. The band gap of GaN is 3.4 eV, suggesting excellent high temperature resistance
2. High breakdown field strength, suggesting better carrier collection efficiency
3. Mature process technology, suggesting large-scale integration
4. Industrialized epitaxial growth, suggesting low device cost

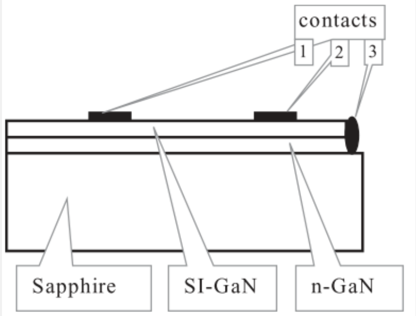
High temperature resistance and radiation resistance

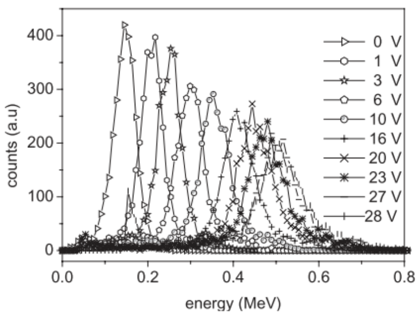
Main research units of GaN-based α particle detectors:



GaN α particle detector structure:

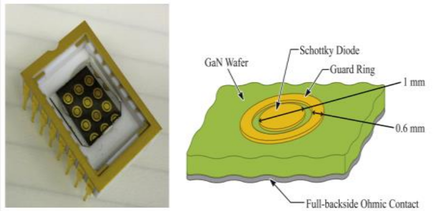
(a) Double-Schottky contact structure：

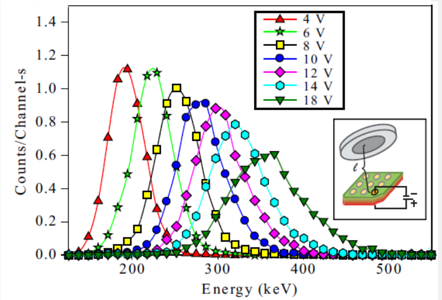


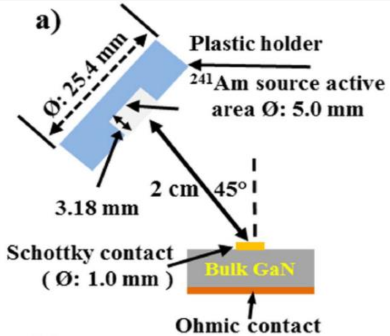


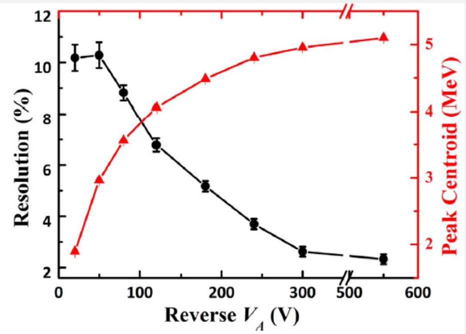
J. Vaitkus, W. Cunningham, E. Gaubas, M. Rahman, S. Sakai, K. M. Smith, and T. Wang, Nucl. Instrum. Methods Phys. Res., Sect. A 509(1–3), 60–64 (2003).

(b) Sandwich Structure (schottky structure)：





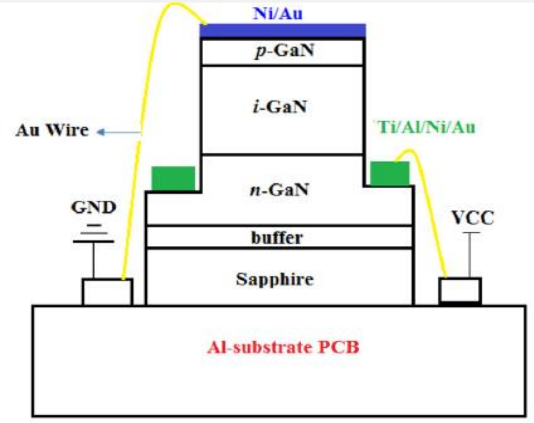


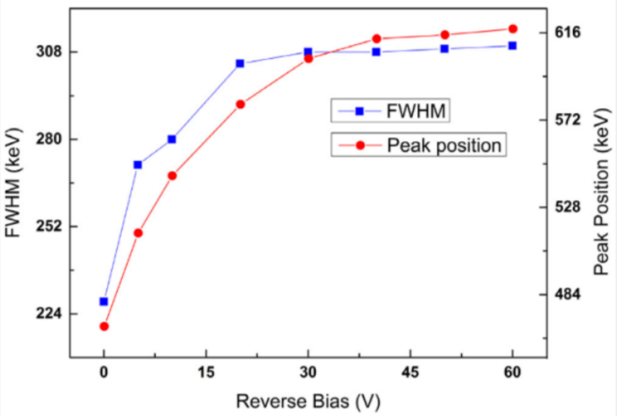


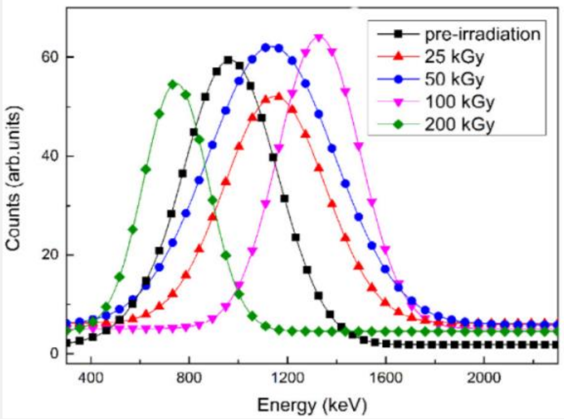
Q. Xu, P. Mulligan, J. H. Wang, W. Chuirazzi, and L. Cao, "Bulk GaN alpha-particle detector with large depletion region and improved energy resolution," *Nucl. Instrum. Methods Phys. Res. A*, vol. 849, pp. 11-15, Dec. 2016.

P. Mulligan, J. H. Wang, and L. Cao, "Evaluation of freestanding GaN as an alpha and neutron detector," *Nucl. Instrum. Methods Phys. Res. A*, vol. 719, pp. 13-16, Apr. 2013.

(c) p-i-n structure



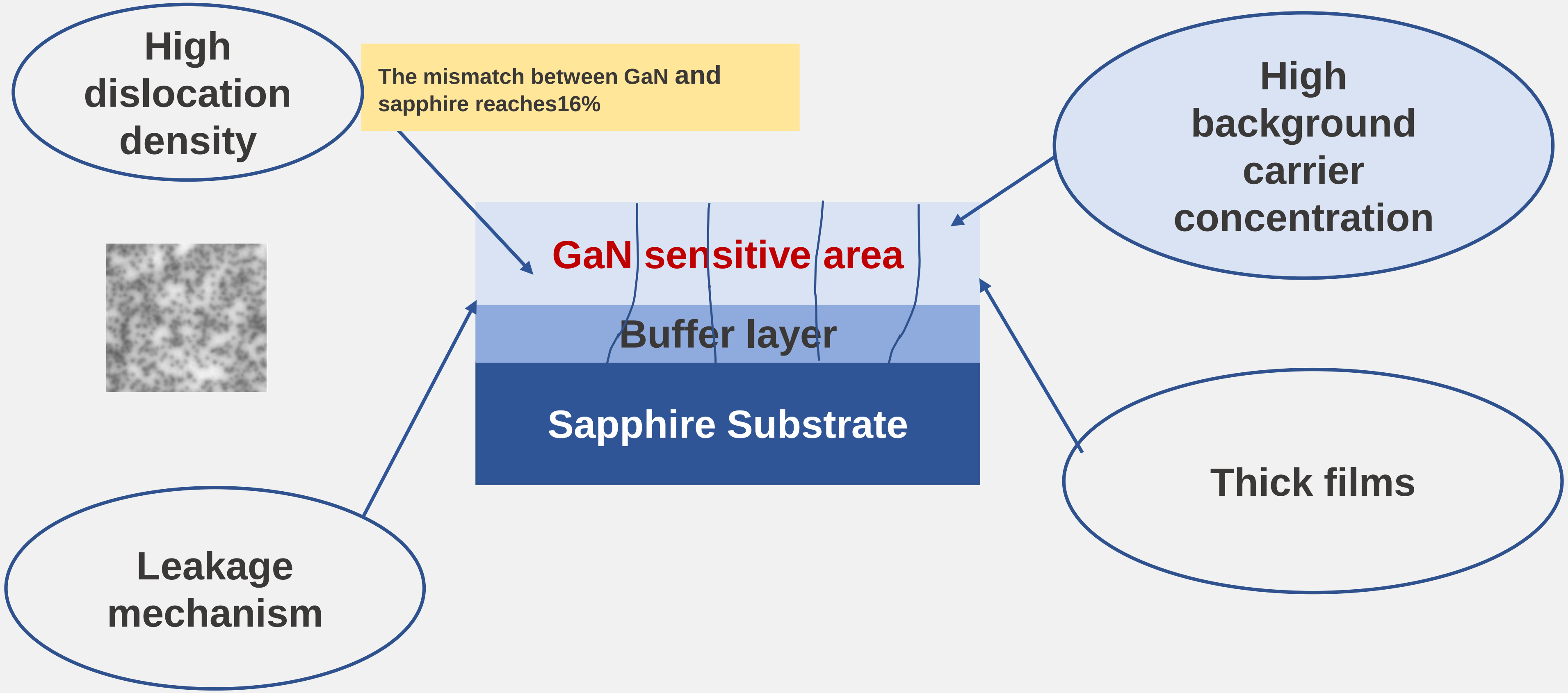




Lower leakage current noise

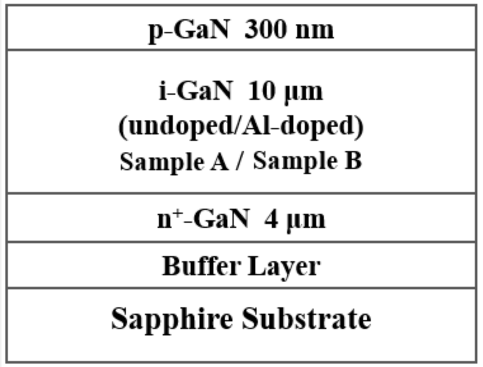
Z. F. Zhu, H. Q. Zhang, H. W. Liang, B. Tang, X. C. Peng, and J. X. Liu *et al*., "High-temperature performance of gallium-nitride-based pin alpha-particle detectors grown on sapphire substrates," *Nucl. Instrum. Methods Phys. Res. A*, vol. 893, pp. 39–42, Mar. 2018.

The main problems in the development of Mesa pin detectors

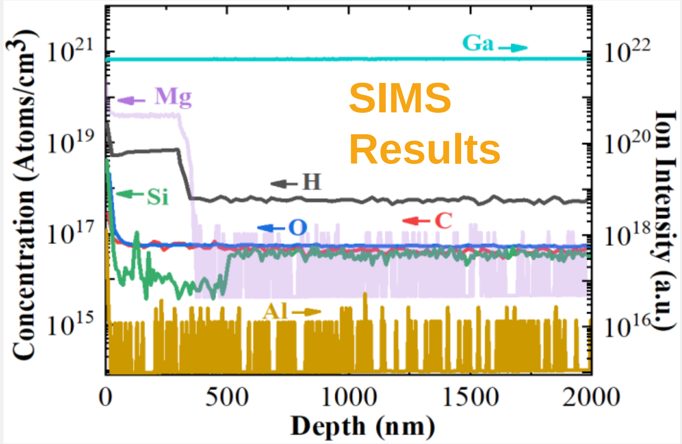


Our solution: Aluminum Isoelectronic doping technique

Epitaxial layer structure



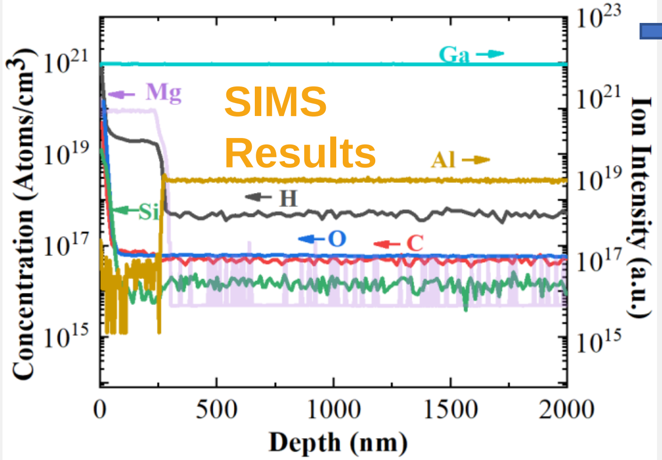
Sample A: undoped i-GaN



[Si]≈[C], N_d=[Si]+[O]-[C]

≈10^{16} cm^{-3}

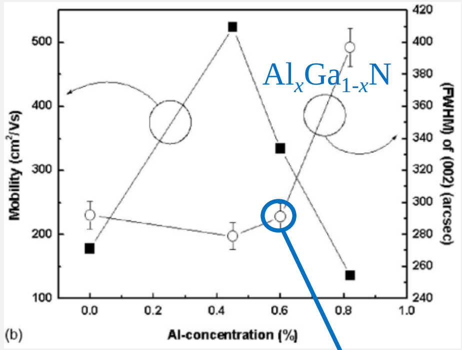
Sample B: Al-doped i-GaN



[Si]<[C], N_d≠[Si]+[O]-[C]

<[Si] or [C], 10^{14} cm^{-3}

Al concentration：0.214%



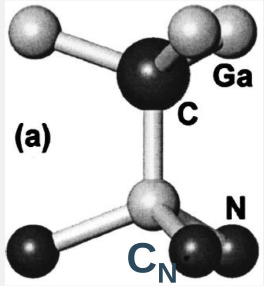
J. H. Lee, and J. H. Lee, *J. Appl. Phys.*, vol. 105, p. 064508, Mar. 2009.

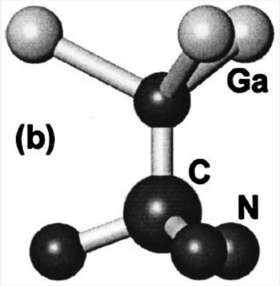
$Al_xGa_{1-x}N$ tends to grow

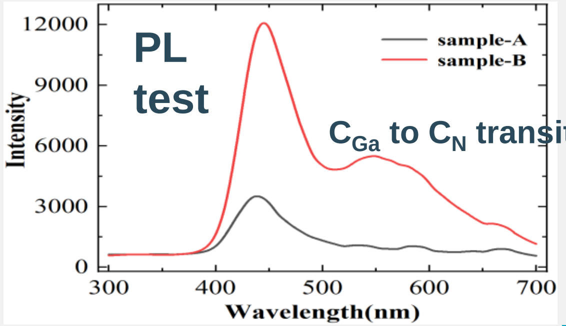
C_N → C_N and C_{Ga} Self-compensation → **Decrease in electron concentration**

The role of Si, O, C impurities in different positions in the GaN lattice：

	Si	O	C
Ga	✓ (12-17 meV) donor	✓ (30-33 meV) donor	✓ (200 meV) donor
N	——	——	✓ (900 meV) acceptor

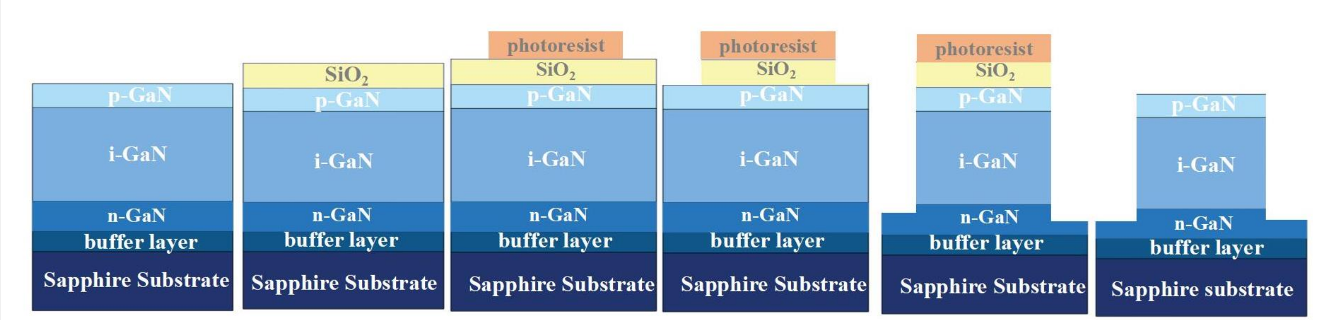


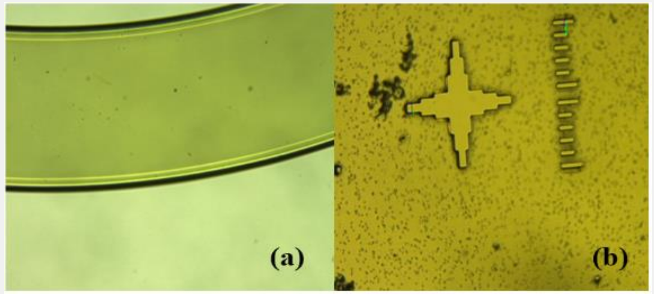


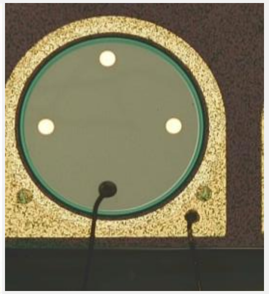


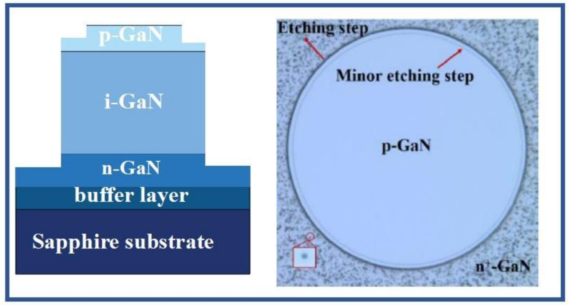
Process flow

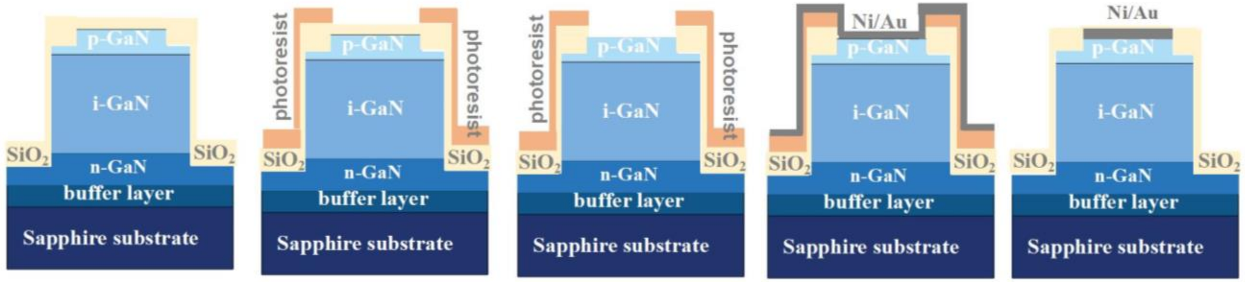
Clean | Deposition SiO_2 | Photolithography | Etch SiO_2 | ICP | Lift off | Etch steps | TMAH

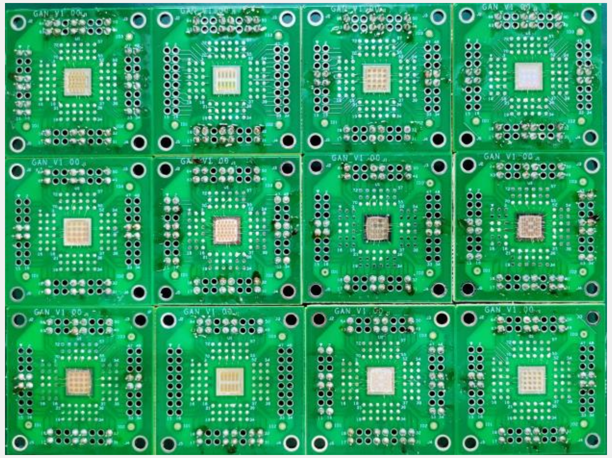


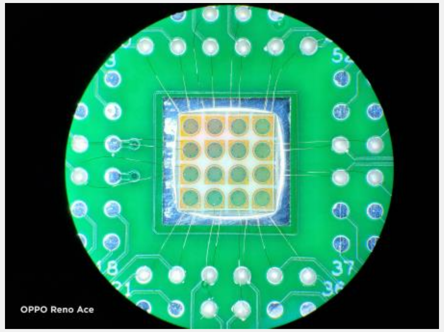


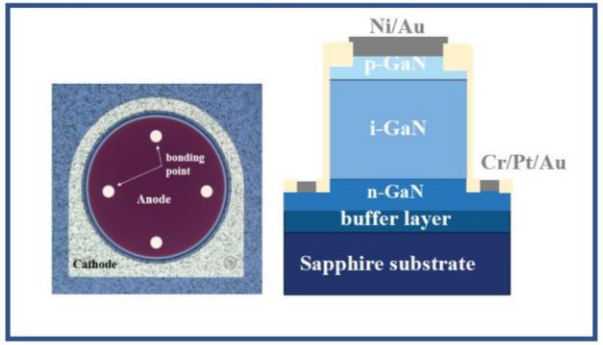






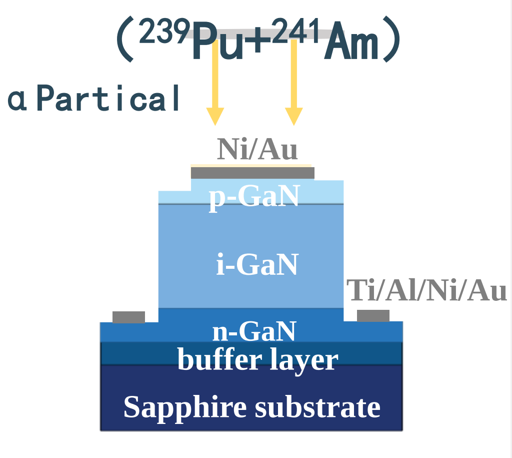


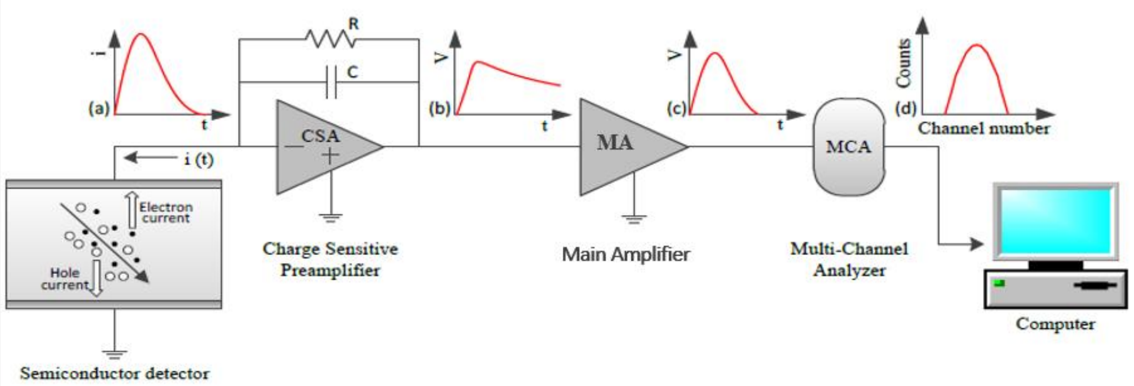




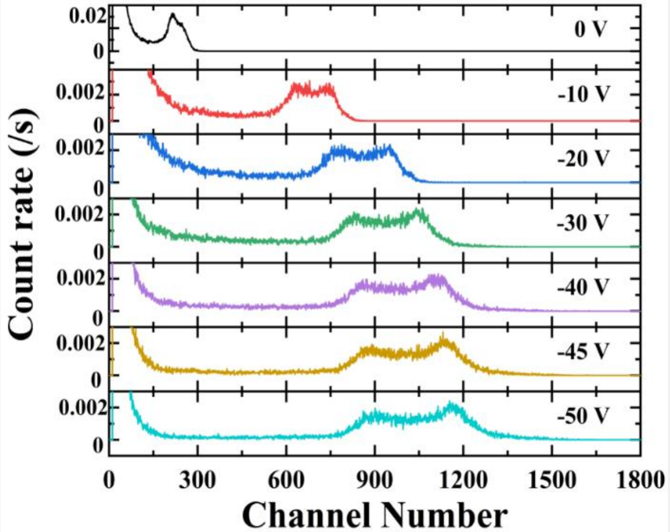
Deposition SiO_2 | Photolithography | Etch | Metal deposition | Lift off | Annealing

Schematic diagram of particle irradiation detection system

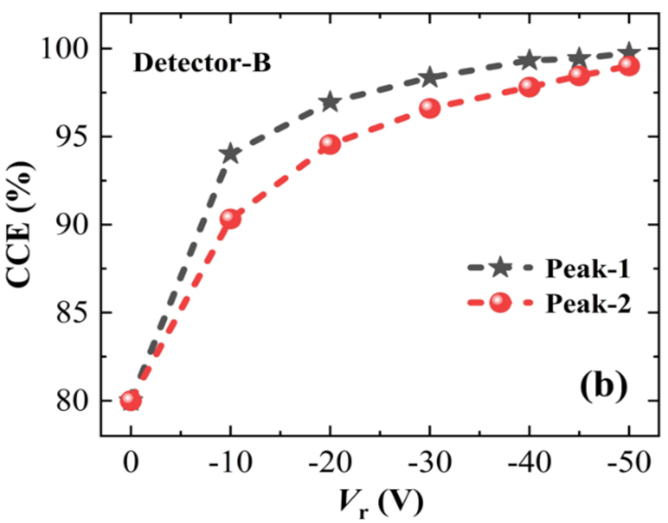




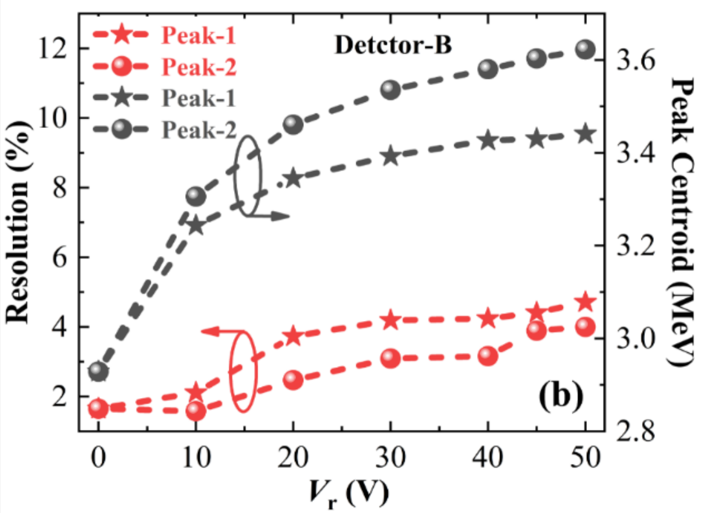
Dead zone includes: 1mm Air、Ni/Au electrode and p-GaN



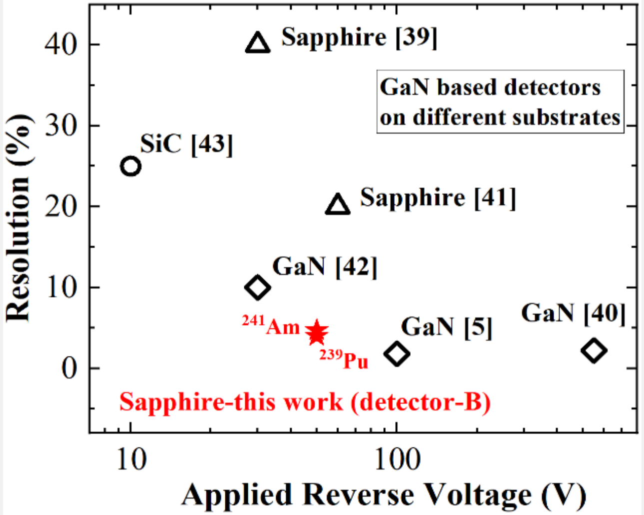
Spectra acquired by detector at varied Vr from 0 to -50 V



CCE datas of detector under different Vr.



FWHM and peak centroid datas for detector with the varied Vr



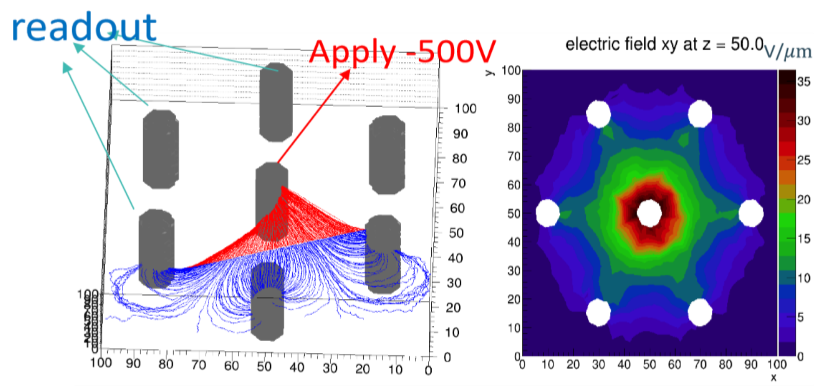
Resolution comparisons with GaN alpha-particle detectors

Motivation for the development of 3D SiC radiation detector

1. Wide band gap (3.2 eV), High breakdown field strength, Mature process technology
2. Narrow electrode spacing – good time resolution and charge collection
3. Good singlecrystal quality – Thick thickness – larger charge collection and signal
4. More radiation resistant than 2D SiC

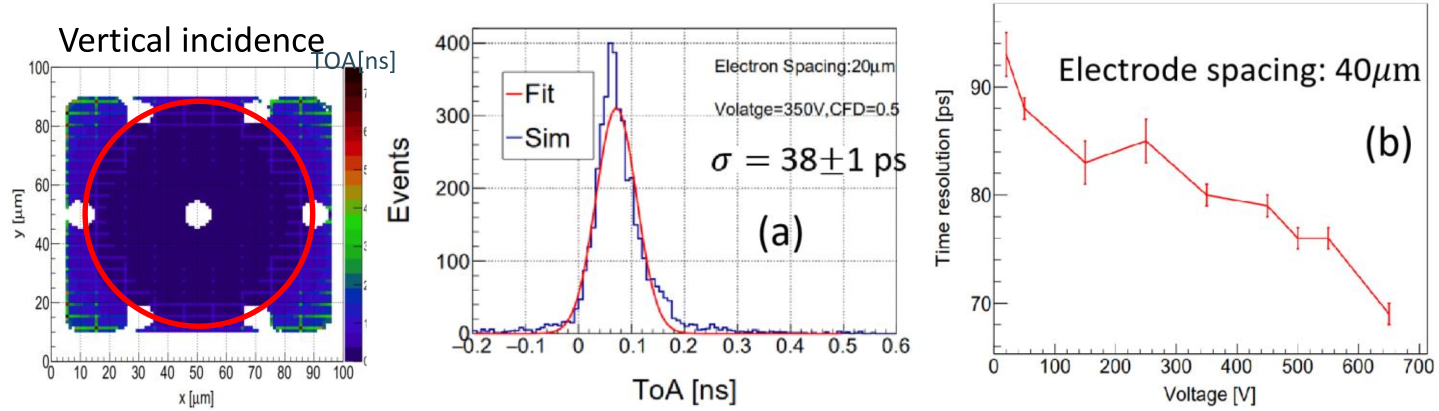
3D-SiC simulation – time resolution：

Device structure



- SiC structure. Electrode radius 5μm, electrode spacing 40μm and 100μm thick
- Drift path: blue electrons and red holes in Fig.a
- Electric field xy plane at z=50 μm in Fig.b

Device performance



- Detector scan: 10000 events. Step: 1μmX1μm
- Fig.a: Time resolution is 38 ps at 350V with electrode spacing 20μm
- Fig.b: Time resolution vs voltage

Method of making 3D structure

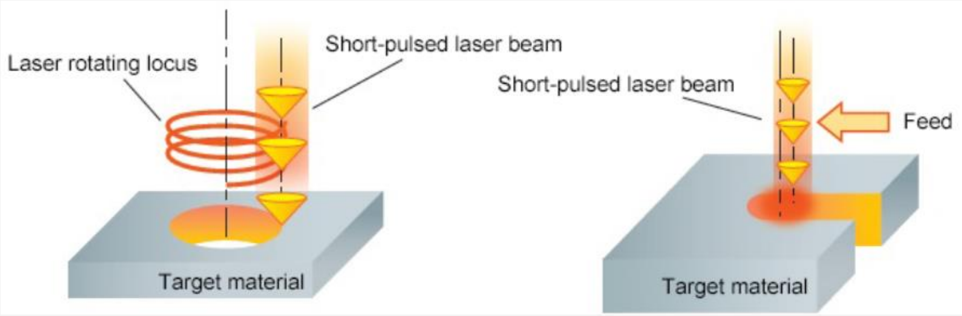
1. ICP etching (Inductive Coupled Plasma Emission Spectrometer Etch)

2. Chemical or electrochemical etching

3. Laser drilling

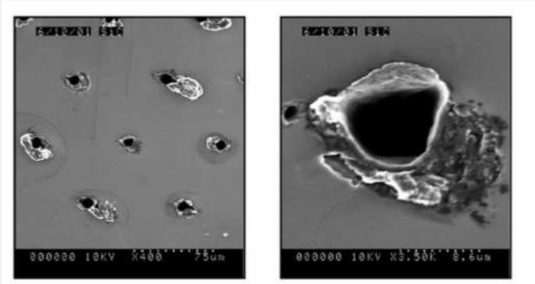
Auger drilling

Pulse drilling



Advantage of laser drilling technology

1. Suitable for a variety of materials
2. Few steps and parameters
3. Short process time



(g) (h)

Giulio Pellegrini and P. Roy *et al.*, “Technology development of 3D detectors for high-energy physics and imaging” Nuclear Instruments and Methods in Physics Research A 487 (2002) 19–26.

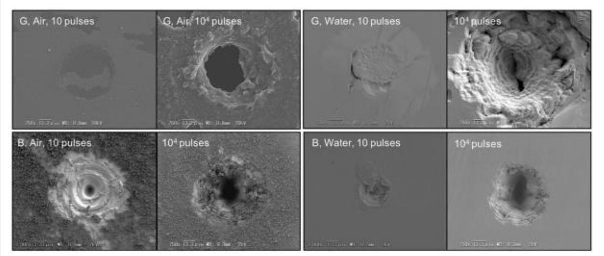
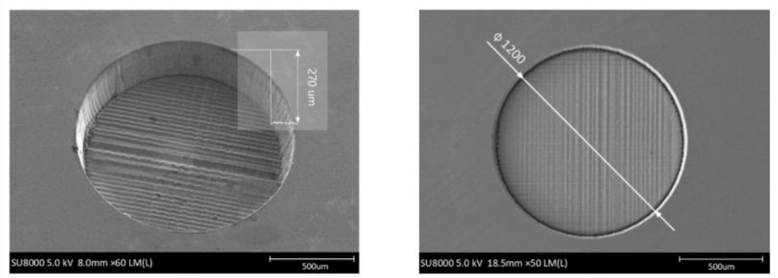


Fig. 2 SEM images of top view of drilled craters with $F = 60$ J/cm^2 of 1064 nm irradiance. In each figure, characters “*G*” and “*B*” stand for Gaussian and Bessel beams, respectively. In the case of Bessel beam irradiation, entrance of the hole enlarged with increasing pulse numbers affected by side lobes heating. Gaussian irradiation under water environment led to formation of cracks

Byunggi Kim and Ryoichi Iida *et al.*, “Mechanism of nanosecond laser drilling process of 4H-SiC for through substrate vias” Appl. Phys. A (2017) 123:392.

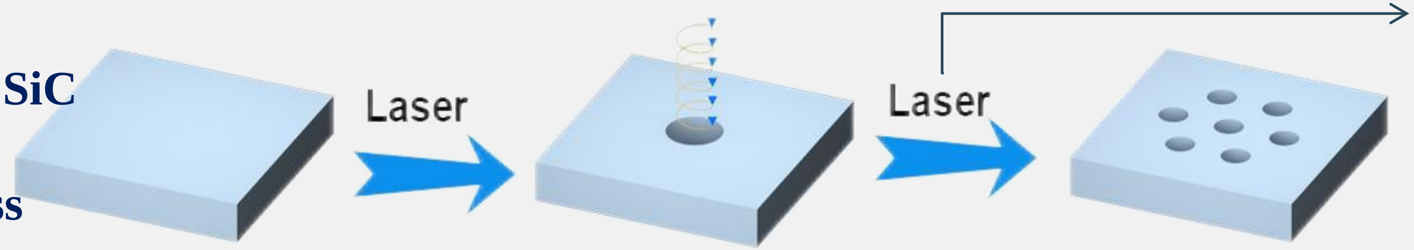


(a) (b)

Lukang Wang and You Zhao *et al.*, “Design and Fabrication of Bulk Micromachined 4H-SiC Piezoresistive Pressure Chips Based on Femtosecond Laser Technology” Micromachines 2021, 12, 56.

Process flow of making 3D SiC structure

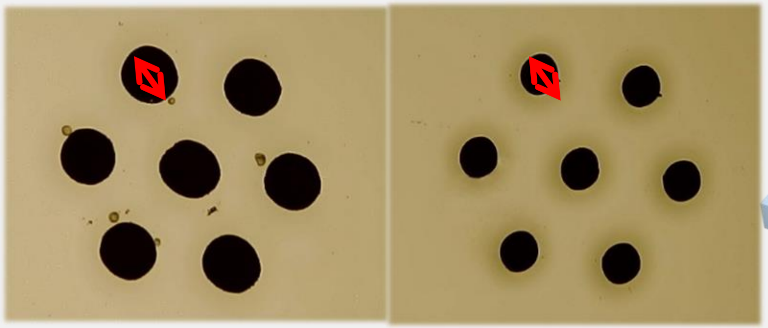
Semi-insulating SiC single crystal
350 μm thickness

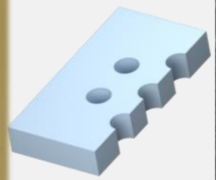


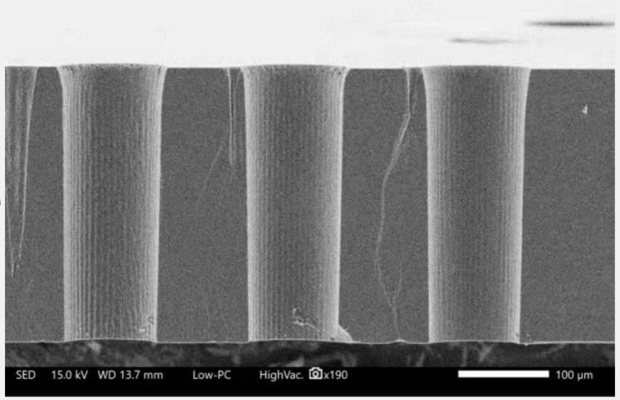
Device model	FM-UVPM3A
Laser wavelength	355nm
Processing power	3W
Pulse Width	12ps
Processing speed	100mm/s
Processing time	30min/pcs

Diameter of the cylinder at the top and bottom of the sample

Hole	Diameter（μm）
Entrance	103
Exit	81

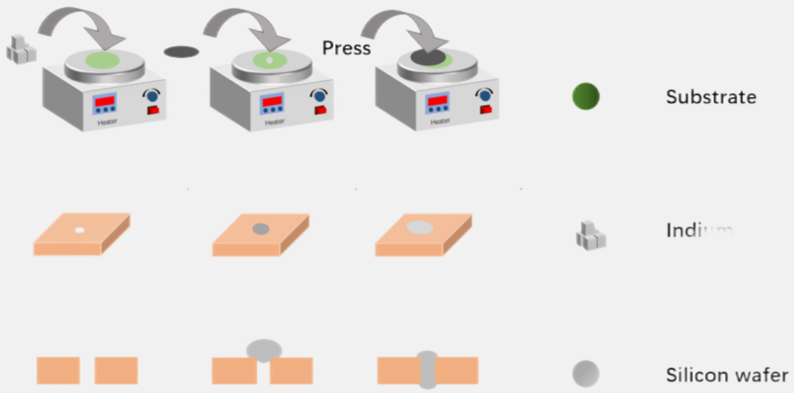


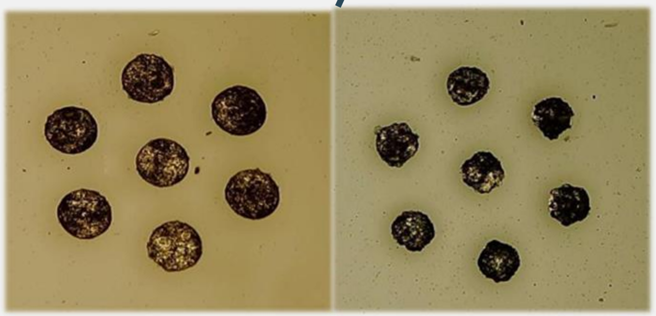


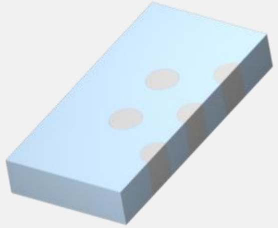


Entrance hole / *Exit hole*

SEM image







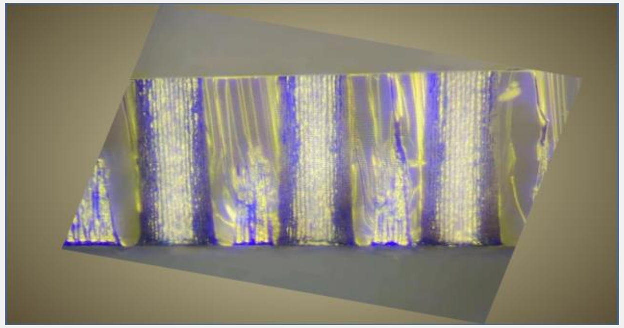
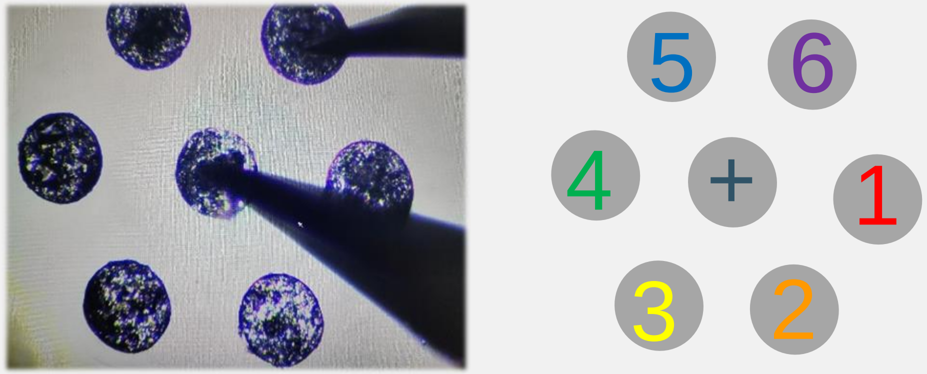


Image of the filled metal indium electrode

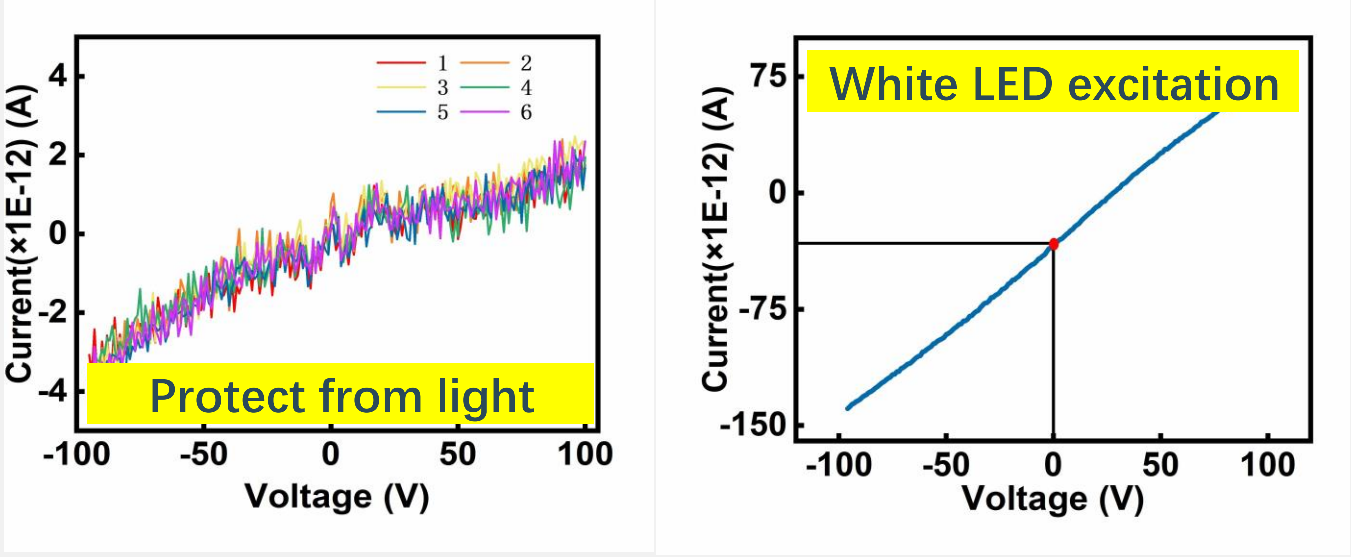
Cross-sectional image

Electrical characteristics of 3D SiC structure

Label the electrode



The test process diagram and electrode number



I-V curve of the 3D SiC device under dark and light status

Parameters extracted from the IV test

	Voltage(V)	Current(pA)	I_{Light}/I_{Dark}
Light	-100	139	32.55
Dark	-100	4.27	

The device exhibits light response characteristics, indicating that radiation detection is possible!

Prospect

- Study the damage caused by laser drilling.
- Investigate the effect of contact type on device performance.
- Making terminal protection structuure.
- Package the device to improve the reliability of the device.
- Study radiation detection performance.
- Carry out multi-device integration research

Thanks!