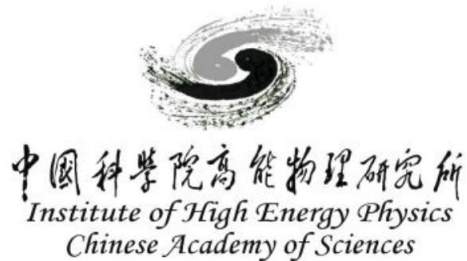


Recent Progress in 4H-SiC Detectors for Extreme Environments: From PIN to LGAD

Congcong Wang

Institute of High Energy Physics, CAS



Why Silicon Carbide Detectors?

Physical Properties	Si	4H-SiC
Band gap energy(eV)	1.12	3.26
Thermal conductivity(W/(m·K))	150	490
Breakdown Electric field (V/cm)	0.5	3
Saturated electron velocity (cm/s)	1×10^7	2×10^7
displacement threshold	13-15	21.8

Compared with silicon, silicon carbide has the following physical properties:

- Wide band gap → Low leakage current
- High thermal conductivity → Stable high-temperature performance
- Large breakdown electric field → High voltage tolerance
- High saturated electron velocity → Fast response
- High threshold → High radiation hardness

Silicon carbide detector has potential applications in high-energy physics and nuclear facility monitoring.

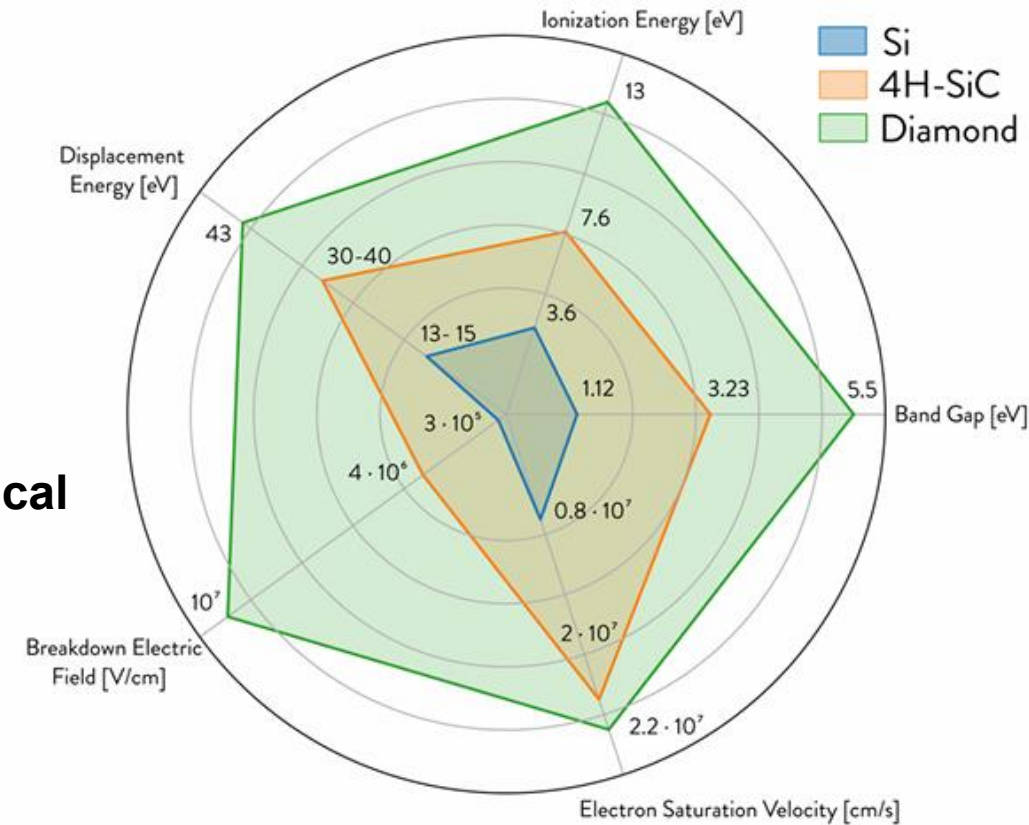


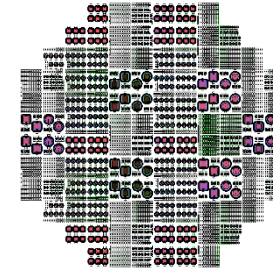
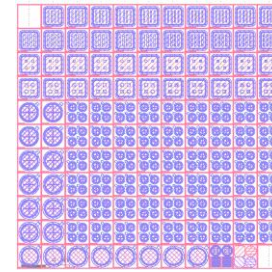
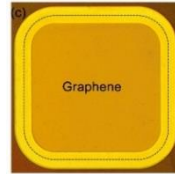
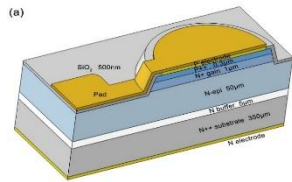
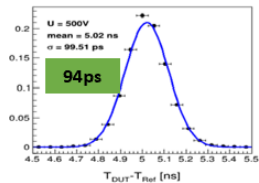
Fig.1 Physical properties of Si, 4H-SiC and diamond

Research Progress and Roadmap of Silicon Carbide Detectors

Goal: High sensitivity Bipolar Junction Transistor (BJT) alpha-particle detector ;

Fast time resolution detector (PIN and LGAD);

High spatial resolution (Multi-pixel LGAD detector).



In 2022

SiC-PIN

Time resolution: 94ps

In 2024

SiC-LGAD (SICAR 1)

Gain factor:3

In 2025

Graphene/SiC PIN

Time resolution: 58ps

In 2026

SiC LGAD

Gain Factor > 10

In 2027

BJT alpha-particle detector

Gain Factor > 300

In 2028-2030

Multi-pixel LGAD

aim to achieve

has been achieved

1. Silicon Carbide Detectors (In 2022)

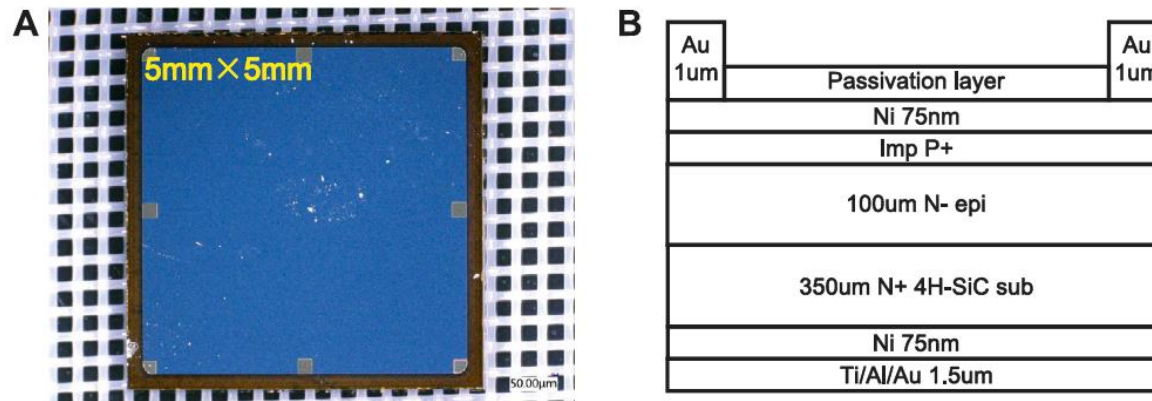
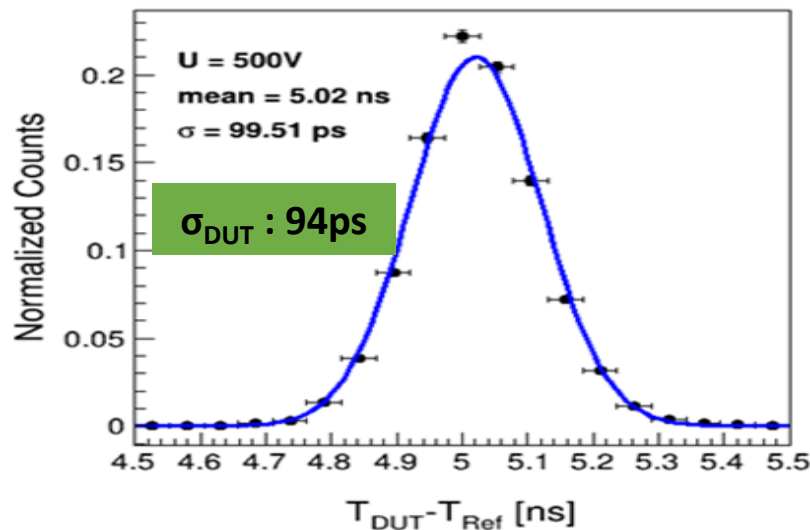
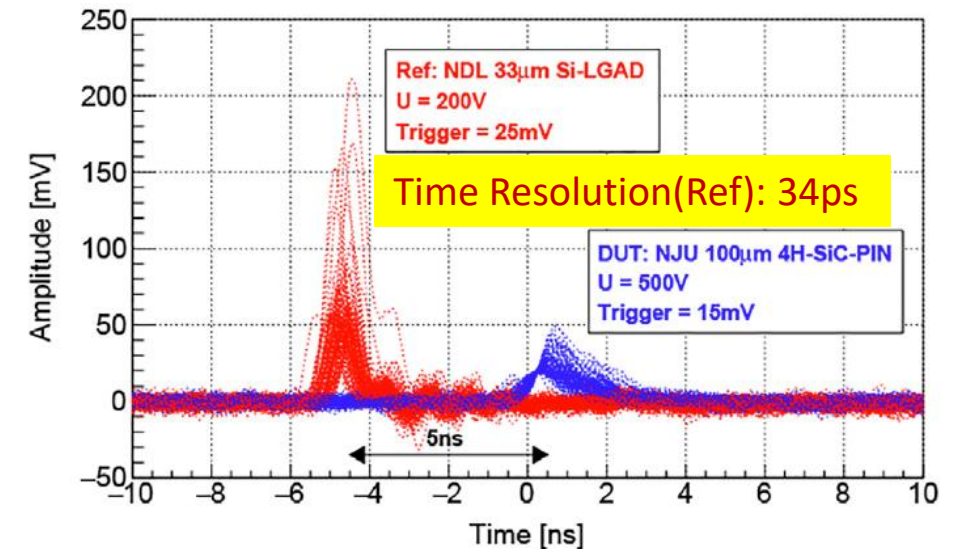


Fig 1: 5 × 5 mm 4H-SiC detector sample (A) Photography and (B) cross section.



Time resolution of silicon carbide detector measured for the first time.

- Detector under test: SiC detector with a 100-μm intrinsic layer
- Reference detector: Si LGAD (a known time resolution of 34 ps)
- Source: β particles (^{90}Sr)
- Result: Time resolution (SiC detector) = 94 ps

Detailed results are presented in *Frontiers in Physics*

<https://www.frontiersin.org/journals/physics/articles/10.3389/fphy.2022.718071>

2. Silicon Carbide Detectors (In 2023-2024)

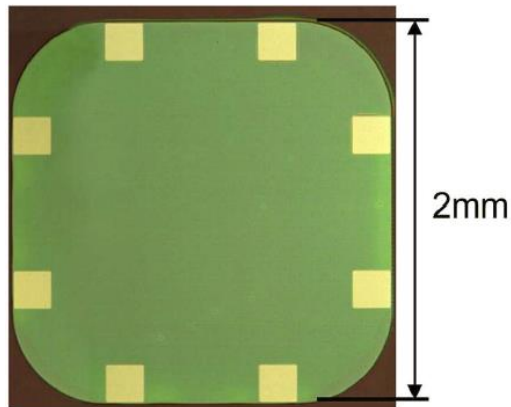


Fig 1: 2 × 2 mm 4H-SiC detector

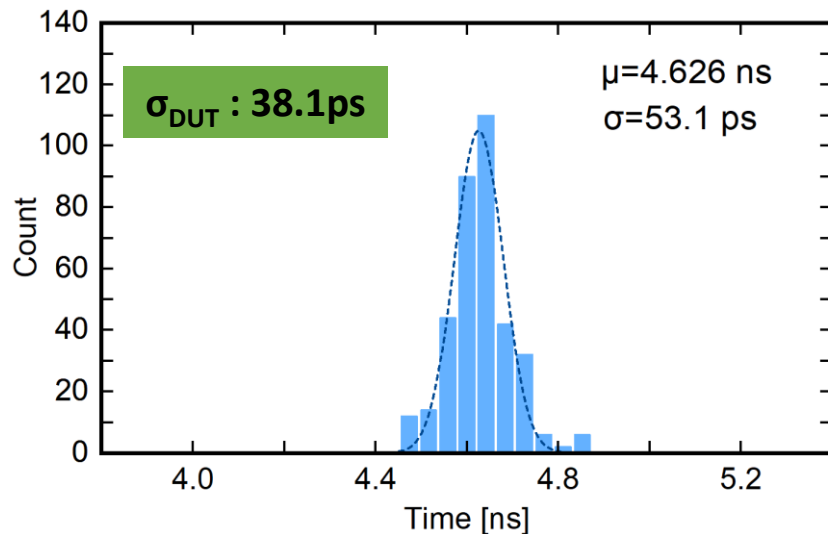


Fig 2: Coincidence time resolution

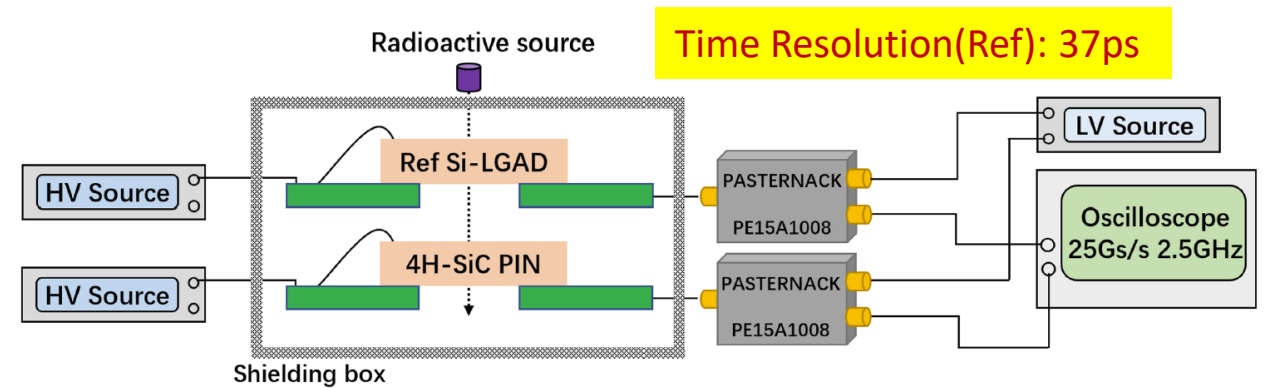


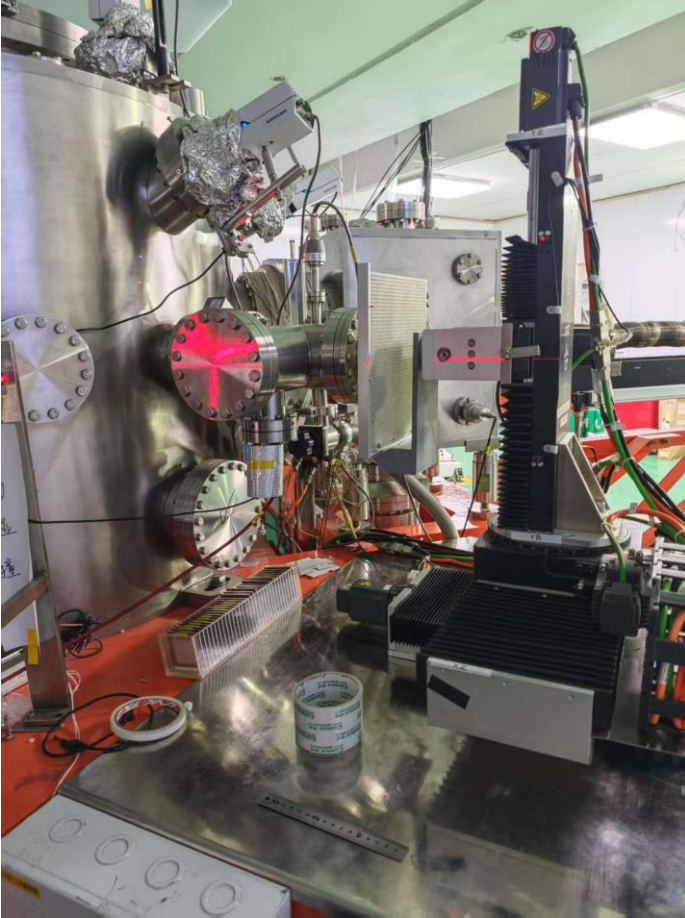
Fig. 3: Experimental setup for time resolution of a ^{90}Sr source.

After chip structure optimization, investigated time resolution of silicon carbide detector (Process Optimization)

- Detector under test: SiC detector with a 50- μm intrinsic layer)
- Reference detector: Si LGAD (a known time resolution of 37 ps)
- Source: β particles (^{90}Sr)
- Result: Time resolution (SiC detector) =38.1 ps

Detailed results are presented in IEEE TRANSACTIONS ON NUCLEAR SCIENCE
<https://ieeexplore.ieee.org/document/11616607>

3. Silicon Carbide Detectors After 16 MeV/u Ta Heavy-Ion Irradiation (In 2025)



Motivation

- Heavy ions present in high-energy physics, space radiation environments
- Silicon carbide detector performance studied under heavy-ion irradiation

Irradiation conditions:

Ion fluences: $1 \times 10^9 \text{ cm}^{-2}$

$5 \times 10^{11} \text{ cm}^{-2}$

$1 \times 10^{12} \text{ cm}^{-2}$

Total energy of tantalum (Ta) ions: 2.896 GeV

The irradiation was performed at the Institute of Modern Physics, Chinese Academy of Sciences.

3. Silicon Carbide Detectors After 16 MeV/u Ta Heavy-Ion Irradiation (In 2025)

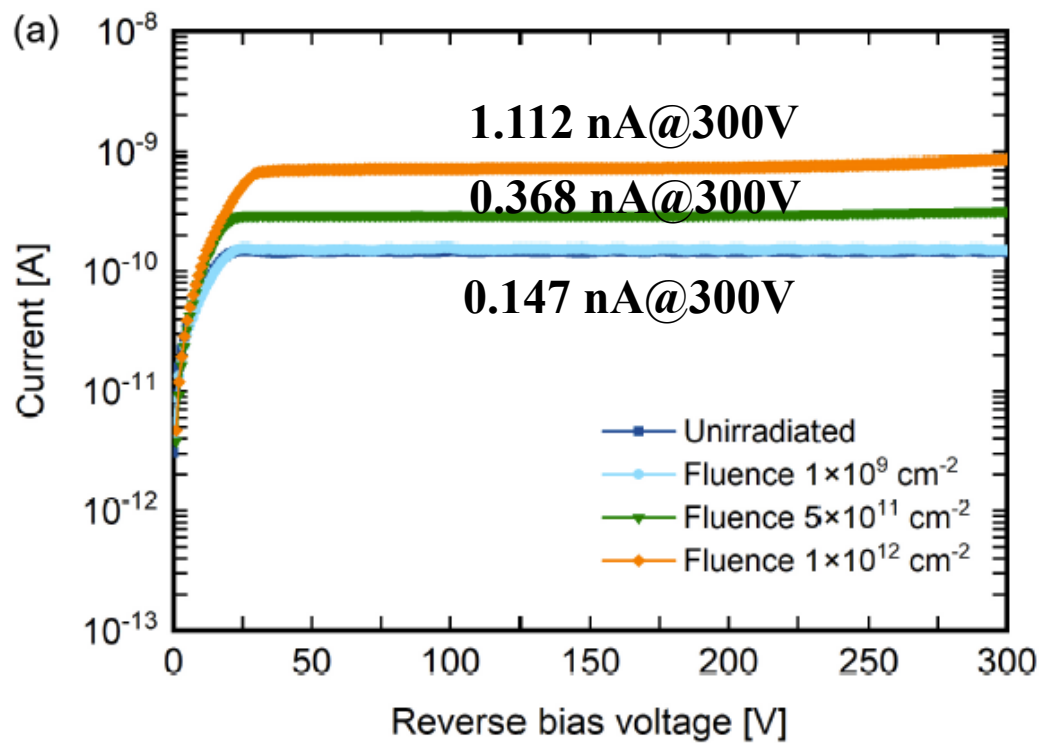
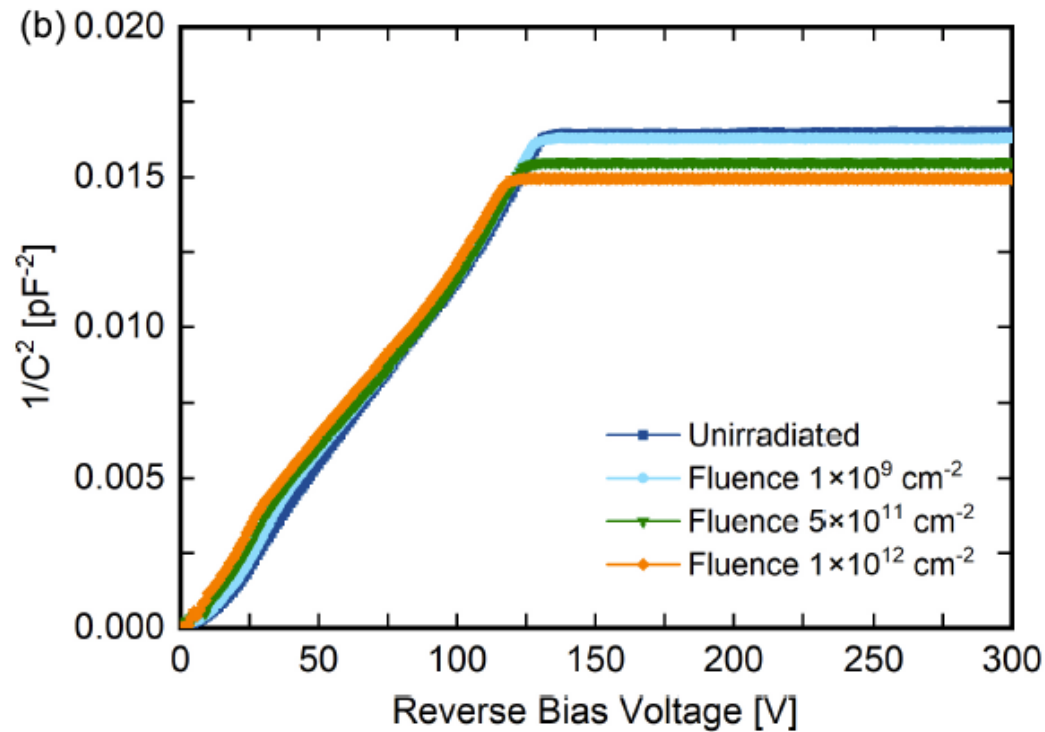


Fig. (a) I-V characteristics of 4H-SiC PIN detectors.



(b) $1/C^2$ -V characteristics of 4H-SiC PIN detectors.

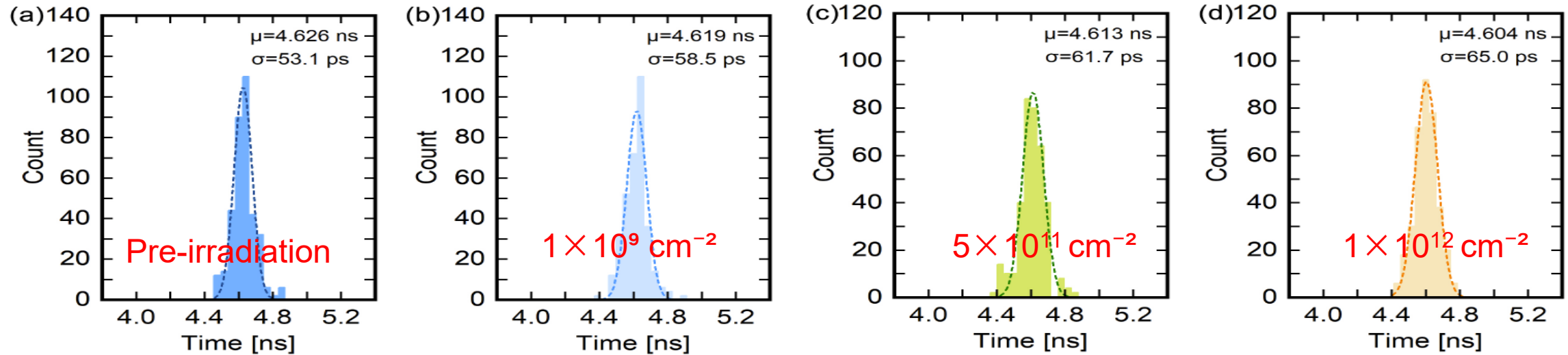
TABLE I
DOPING CONCENTRATIONS AND DEPLETION DEPTHS

4H-SiC PIN	Doping concentrations	Depletion depths
Unirradiated	$6.21 \times 10^{13} \text{ cm}^{-3}$	$43.13 \text{ } \mu\text{m}$
Fluence 1×10^9	$6.13 \times 10^{13} \text{ cm}^{-3}$	$43.54 \text{ } \mu\text{m}$
Fluence 5×10^{11}	$5.77 \times 10^{13} \text{ cm}^{-3}$	$44.02 \text{ } \mu\text{m}$
Fluence 1×10^{12}	$5.34 \times 10^{13} \text{ cm}^{-3}$	$44.18 \text{ } \mu\text{m}$

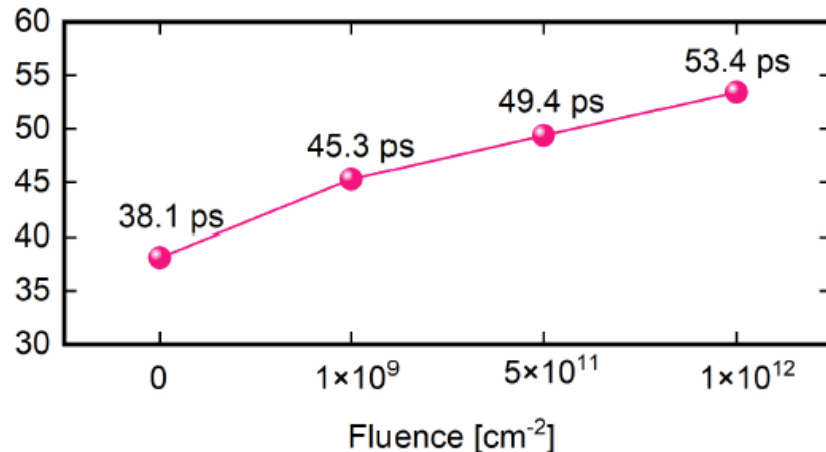
1. Lowest fluence: leakage current showed almost no change
2. Increasing fluence: carbon vacancy defects and recombination centers $\rightarrow$ slight increase in leakage current, slight decrease in effective doping concentration

3. Silicon Carbide Detectors After 16 MeV/u Ta Heavy-Ion Irradiation (In 2025)

Coincidence time resolutions



Time Resolution vs. Fluence



Time Resolution performance studied before and after Irradiation:

Before irradiation: time resolution = 38.1 ps

With increasing fluence: time resolution increased, reaching 53.4 ps at maximum fluence

Mechanism: Hole capture–release at carbon vacancy defects → additional time fluctuation

Detailed results are presented in IEEE TRANSACTIONS ON NUCLEAR SCIENCE
<https://ieeexplore.ieee.org/document/11616607>

4. Graphene-Enhanced Silicon Carbide Detector

Metal electrodes on the surface affect SiC detector applications in:

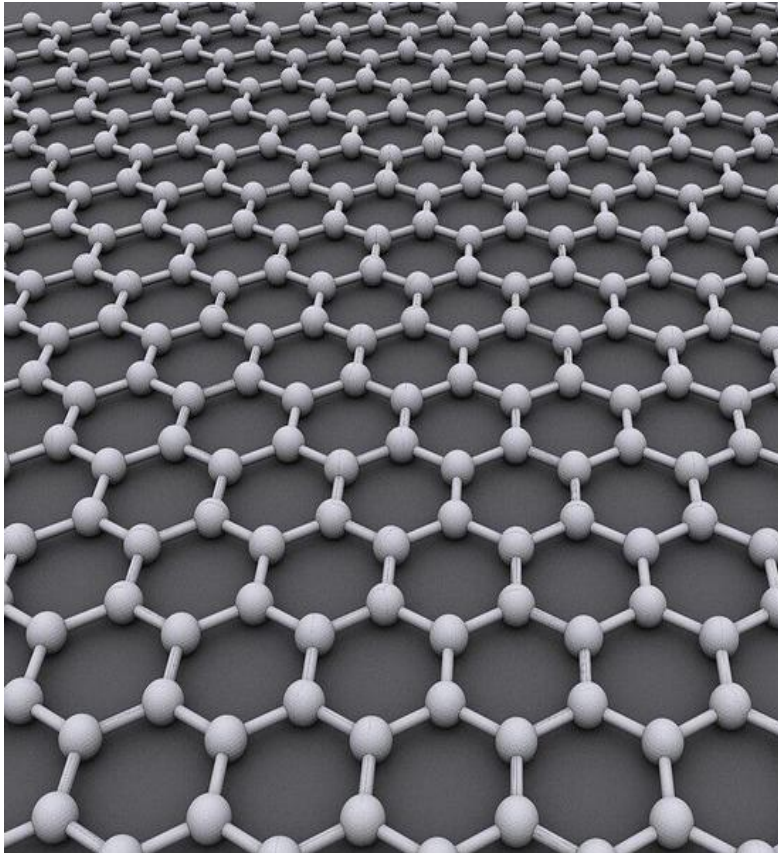
- **Low-penetration particle detector**
- **Low-energy soft X-ray**
- **Ultraviolet (UV) light**
- **Transient current technique(TCT) detection**

The traditional solution is to open a window in the electrode.

But the open-window structure causes problems:

- **Increased dead zone**
- **Non-uniform electric field**
- **Unstable signal**
- **Poor time resolution**

4. Graphene-Enhanced Silicon Carbide Detector



Single-layer graphene

Graphene has two key properties:

- High thermal conductivity ($5300 \text{ W}/(\text{m} \cdot \text{K})$)
- High carrier mobility ($15000 \text{ cm}^2/(\text{V} \cdot \text{s})$)

Graphene-Enhanced SiC Detector

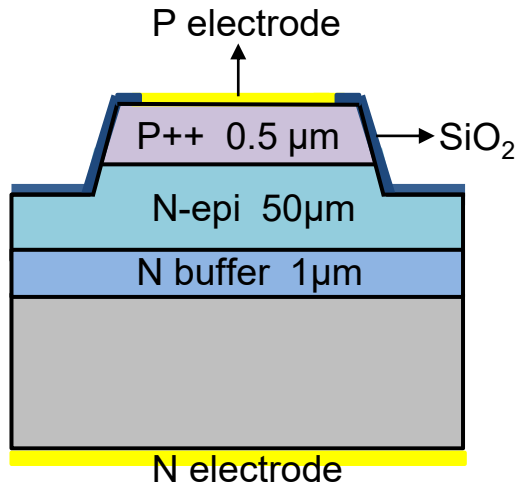
Use graphene to enhance silicon carbide detector

Our goal is:

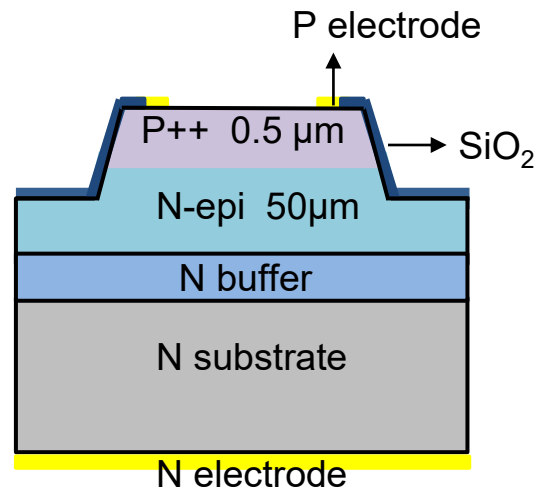
Enhanced signal stability

Improved uniformity of time resolution

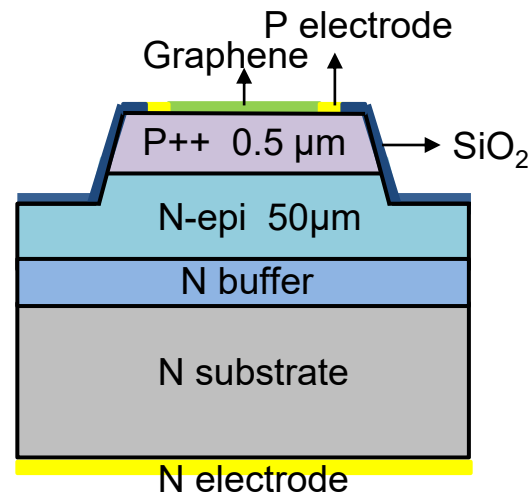
4. Graphene-Enhanced Silicon Carbide Detector



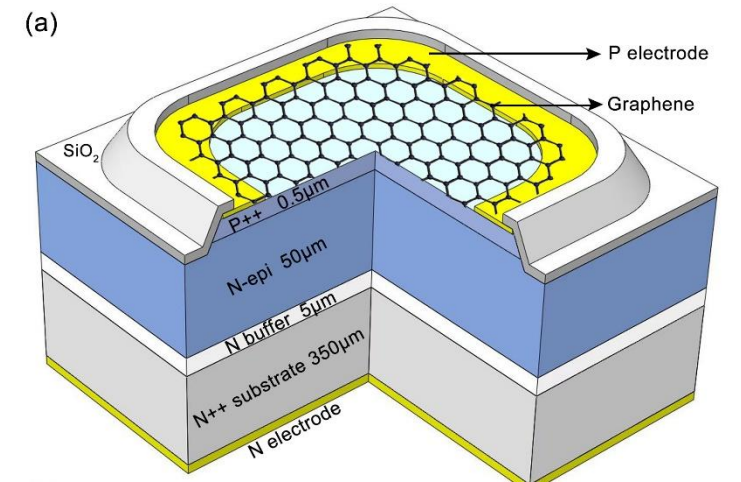
SE detector
(surface metal electrode)



RE detector
(ring metal electrode)



Graphene-Enhanced detector (G/RE)
(ring metal + graphene electrode)



3D view of the G/RE detector structure

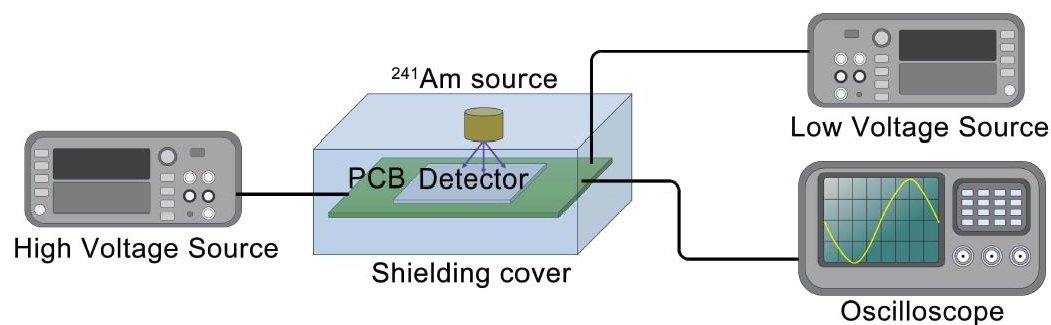
To compare device performance, fabricated three detector structures:

SE Detector: With a full-surface metal electrode.

RE Detector: Metal electrode is only a ring at the edge, leaving the center open as a window.

G/RE Detector: Metal ring at the edge, and the center window is covered by a graphene layer.

4.1 Charge Collection Performance



Detector	Mean Rise Time
RE (ring metal)	443 ps
SE (surface metal)	335 ps
G/RE (ring metal + graphene)	336 ps

Fig.1: Setup for testing charge collection performance using an α source

G/RE detector shows a fast rise time matches SE detector— much better than RE detector. Graphene effectively improves signal rise time.

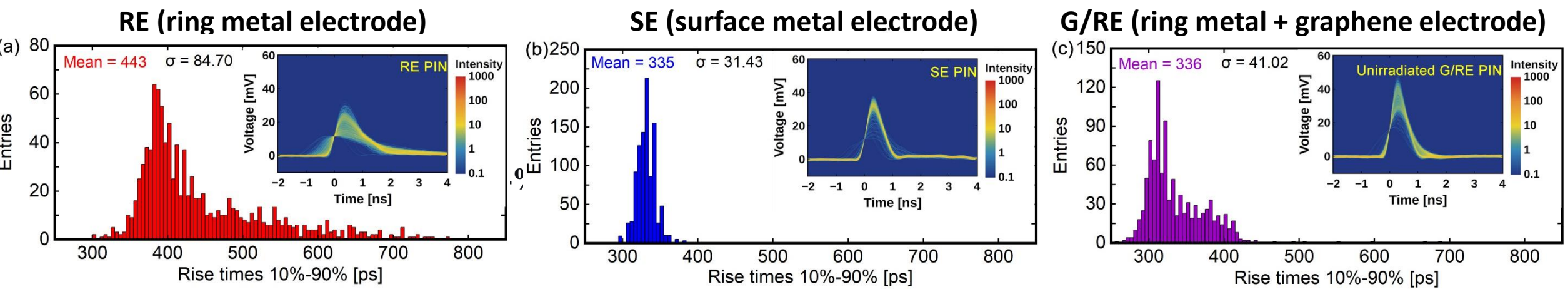
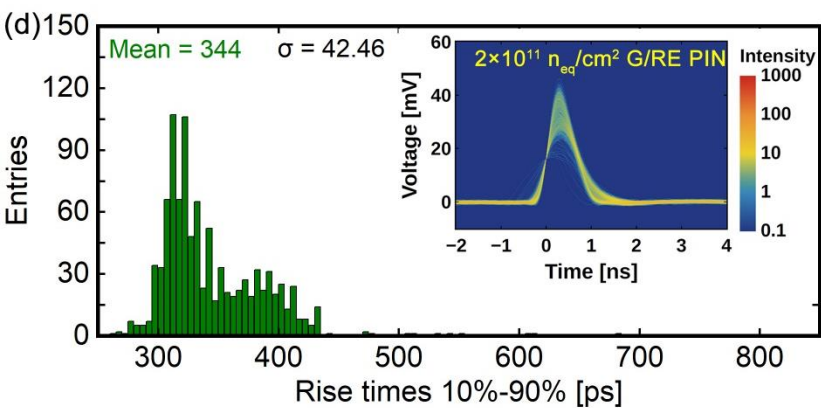


Fig. 2: Signal waveforms and rise time distributions

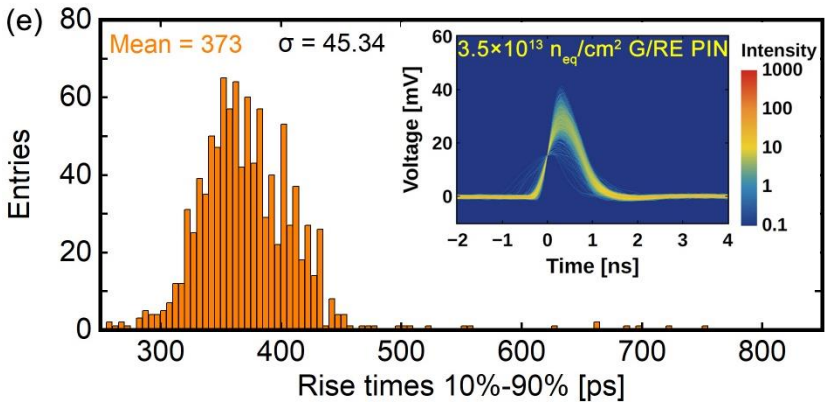
Detailed results are presented in IEEE Transactions on Electron Devices
<https://ieeexplore.ieee.org/document/11372937>

4.2 Charge Collection Performance Under Proton Irradiation

G/RE detector (ring metal + graphene electrode)



proton irradiation: $2.1 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$



proton irradiation: $3.5 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$

Fig 1: Signal waveforms and rise time distributions

Detector	Mean Rise Time
G/RE (ring metal + graphene)	336 ps
$2.1 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$ G/RE	344ps
$3.5 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ G/RE	373ps

Detailed results are presented in IEEE Transactions on Electron Devices
<https://ieeexplore.ieee.org/document/11372937>

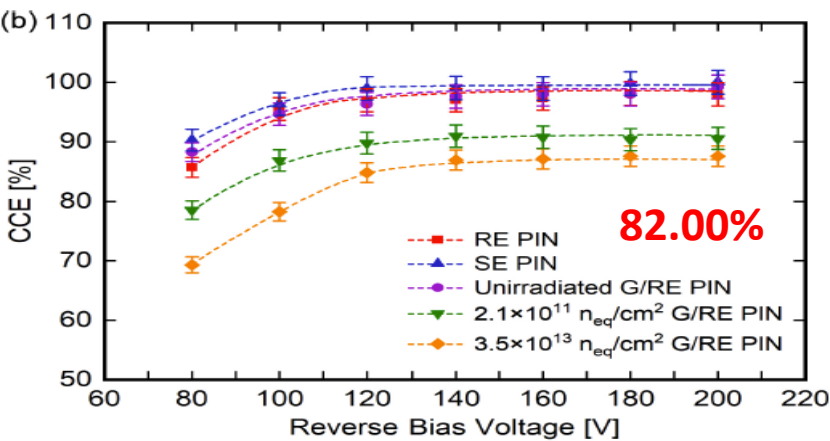


Fig. 2 Charge collection efficiencies

Proton irradiation: 80 MeV

Equivalent neutron fluences:

$$2.1 \times 10^{11} \text{ n}_{\text{eq}}/\text{cm}^2$$

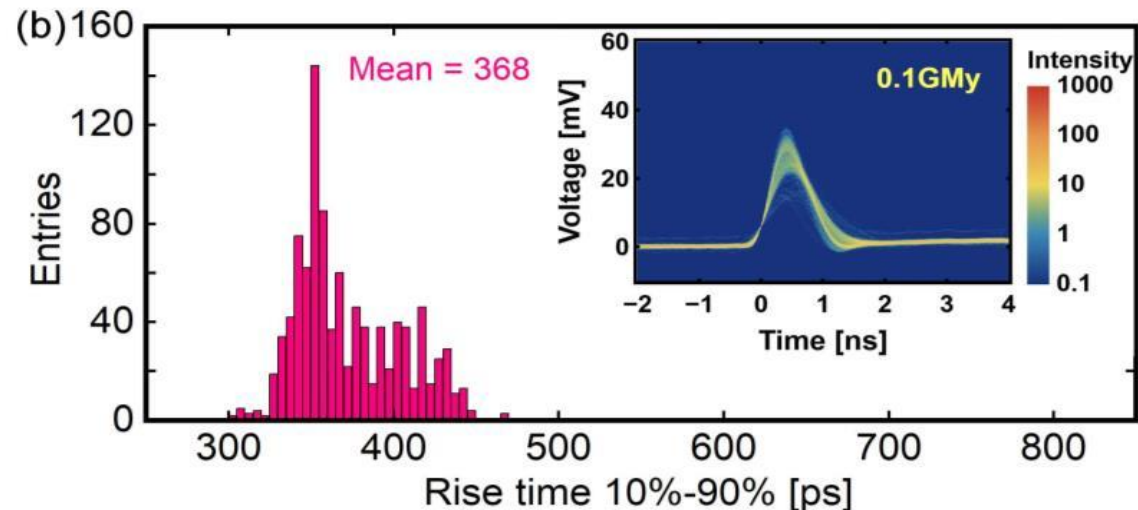
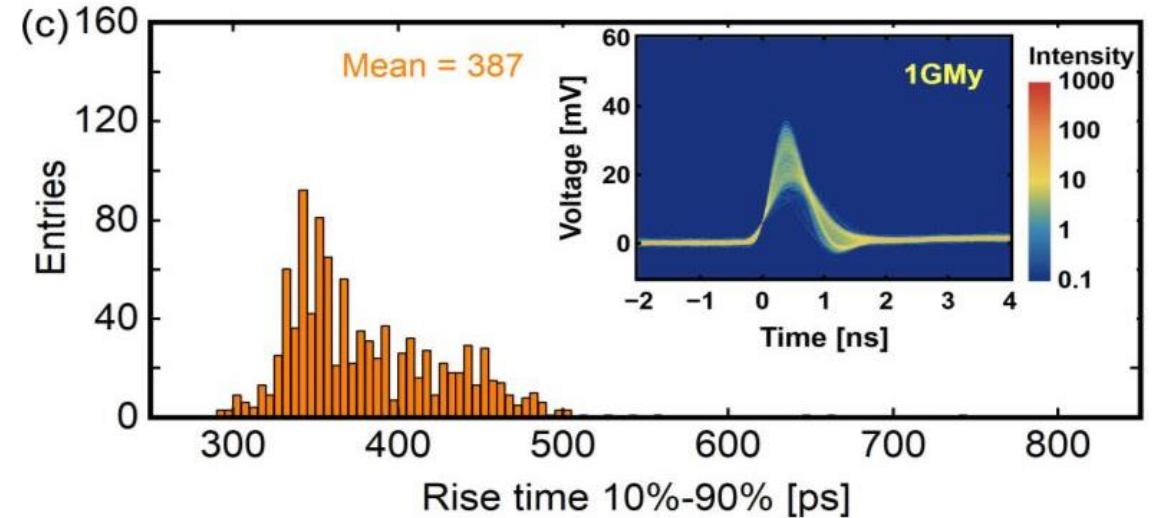
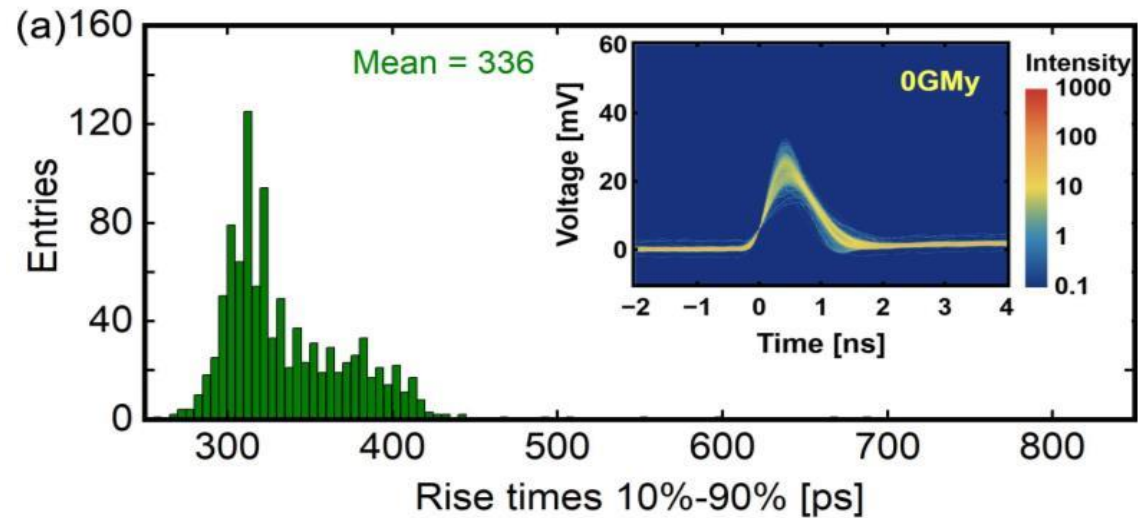
$$3.5 \times 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$$

After irradiation: signal rise time increased slightly; CCE showed a small decrease

Even at maximum fluence: CCE still reached 82%, consistent with the expected target

4.3 Charge Collection Performance Under X-ray Irradiation

Signal waveforms and rise time distributions at 200 V for α particles X-ray irradiation.



X-ray Irradiation Conditions:

- Energy: 160 keV
- Doses: 0.1 MGy, 1 MGy (SiO_2)

Rise time increases from 336 ps to 387 ps after 1 MGy X-ray irradiation due to graphene oxidation and trap states. X-ray irradiation will result in a slight increase in the rise time.

4.3 Charge Collection Performance Under X-ray Irradiation

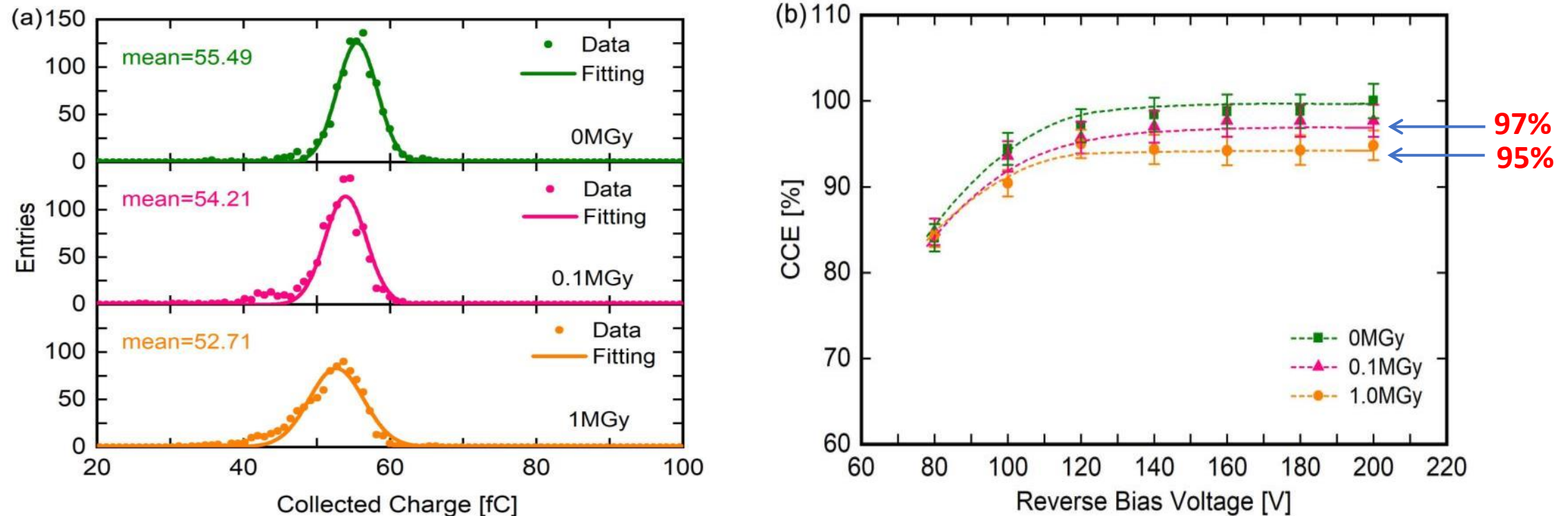


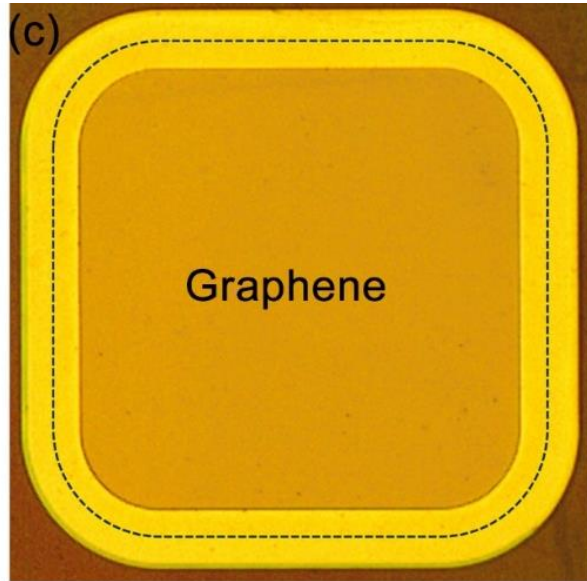
Fig. 1: Charge collection performance at 200 V for α particles: (a) Gaussian fit of the collected charge spectrum (b) CCE versus reverse bias for the 0 MGy, 0.1 MGy and 1 MGy X-ray irradiated G/RE 4H-SiC PIN.

CCE remains high at 97% and 95% after 0.1 and 1 MGy X-ray irradiation. Charge loss arises from carrier trapping at graphene/SiC interface, not SiC bulk damage.

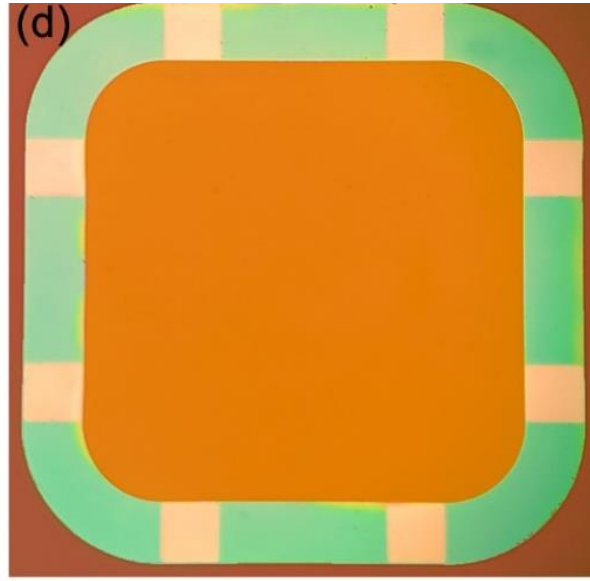
Detailed results are presented in IEEE TRANSACTIONS ON NUCLEAR SCIENCE

<https://ieeexplore.ieee.org/document/11667112>

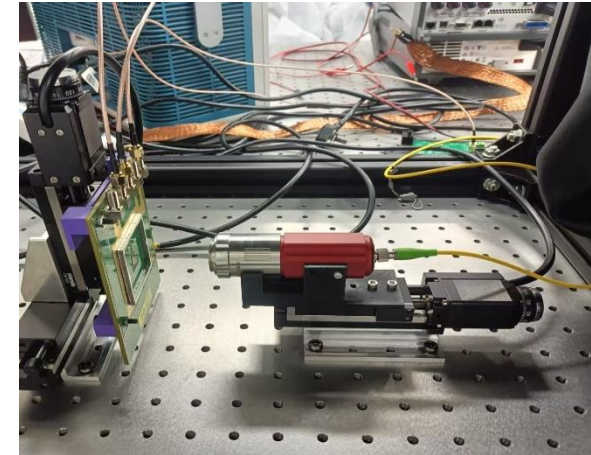
4.4 Time Resolution



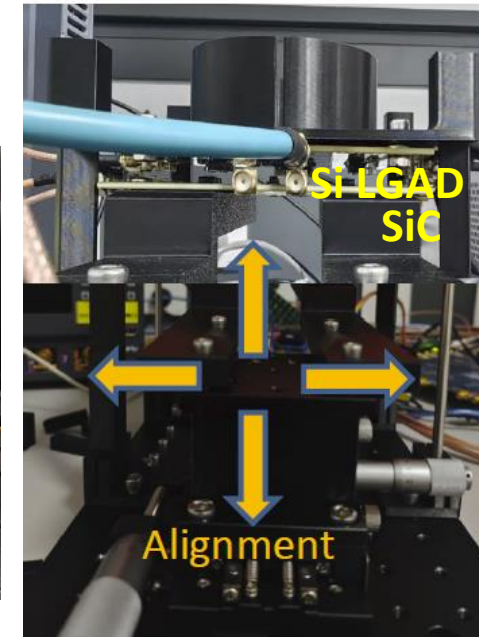
Graphene-Enhanced SiC detector (G/RE)
(ring metal + graphene electrode)



RE SiC detector
(ring metal electrode)



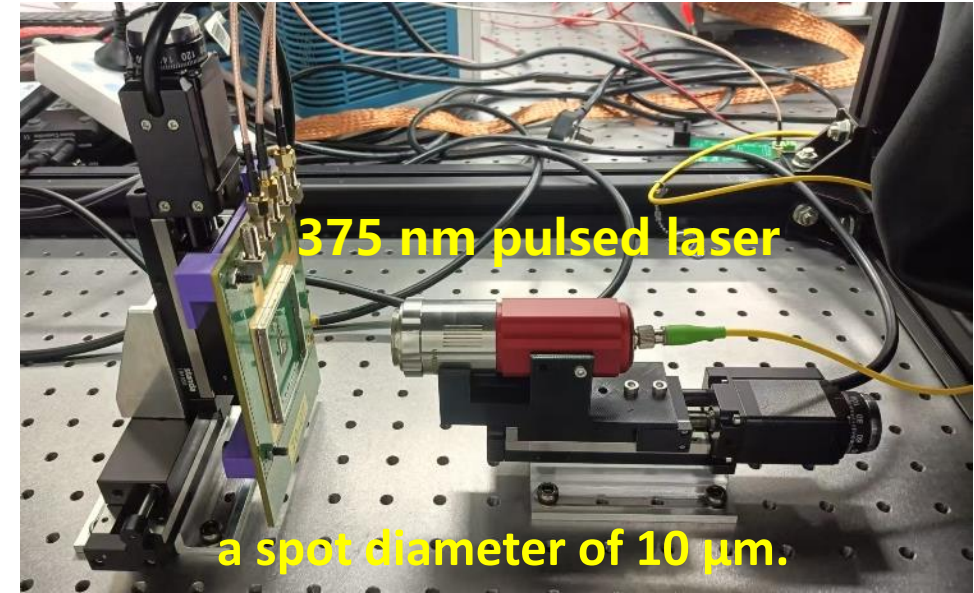
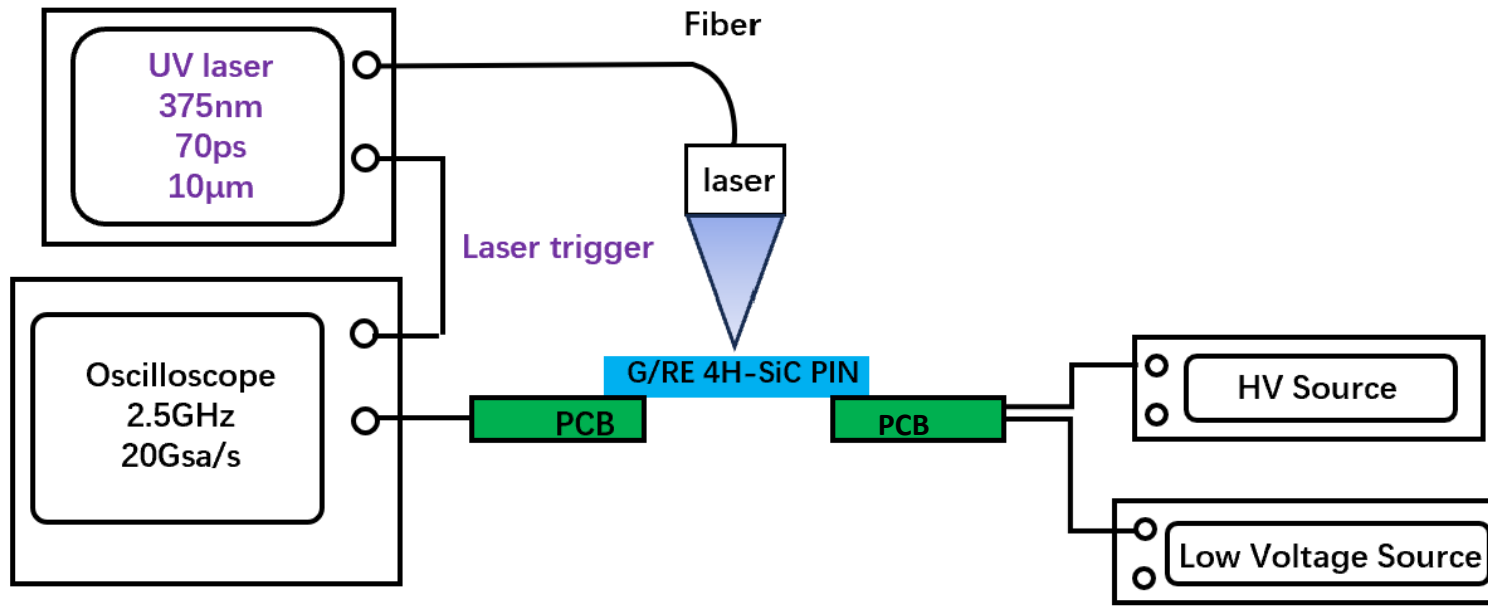
TCT Experimental Setup



Time resolution measurement using a ^{90}Sr source

Time resolution performances of graphene-enhanced SiC detector and RE SiC detectors were compared via laser and radioactive source measurements.

4.4.1 Time Resolution (TCT)



Photograph of the TCT experimental setup

- UV laser: wavelength 375 nm, pulse width below 70 ps, spot diameter 10 μm
- Detector under test (DUT): G/RE 4H-SiC detector
- Low-voltage source and high-voltage (HV) source
- Oscilloscope: bandwidth 2.5 GHz, sampling rate 20 GSa/s

4.4.1 Time Resolution (TCT)

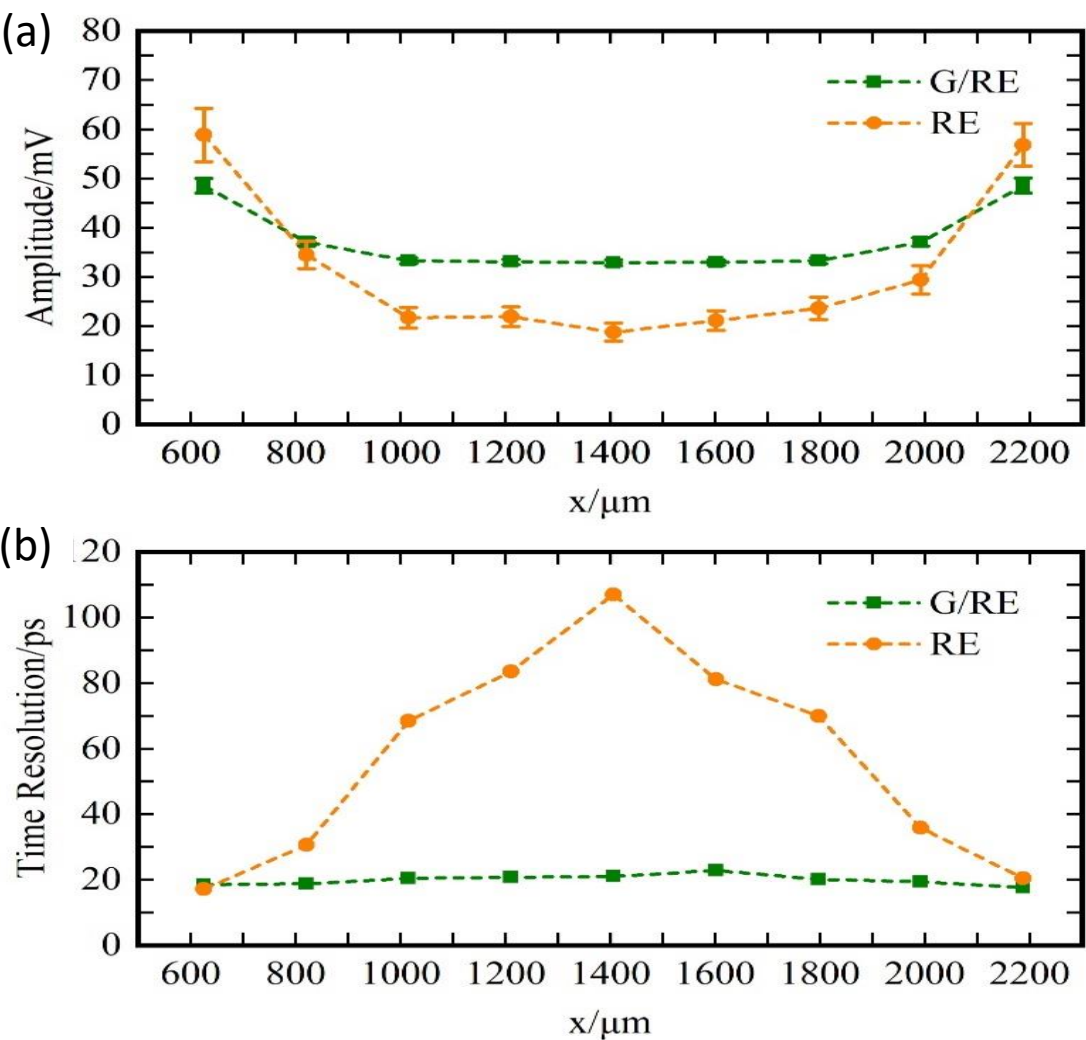
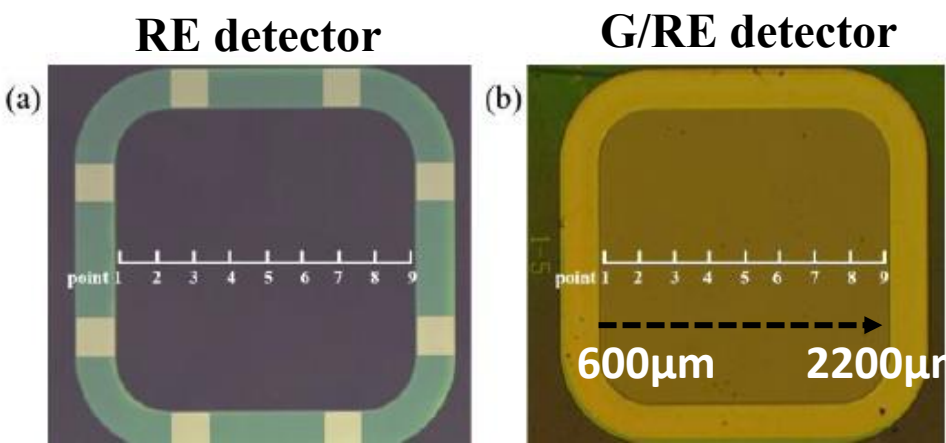


Fig. 1 (a) Signal amplitude and (b) Time resolution

Detailed results are presented in IEEE TRANSACTIONS ON NUCLEAR SCIENCE
<https://ieeexplore.ieee.org/document/1160384>



Parameter	RE detector	G/RE detector
Time resolution	17 ps $\rightarrow$ >107 ps	$\sim$ 20 ps
Signal amplitude	60 mV $\rightarrow$ 20 mV	50 mV $\rightarrow$ 35 mV

Moving from the active-area edge to center:

For RE detector:

- ❑ Signal amplitude decreased from 60 mV to 20 mV
- ❑ Time resolution degraded from 17 ps to 107 ps

For G/RE detector: time resolution remained at around 20 ps.

Graphene enhances the stability of the signal amplitude and time resolution across the entire detector region.

4.4.2 Time Resolution Under X-ray Irradiation

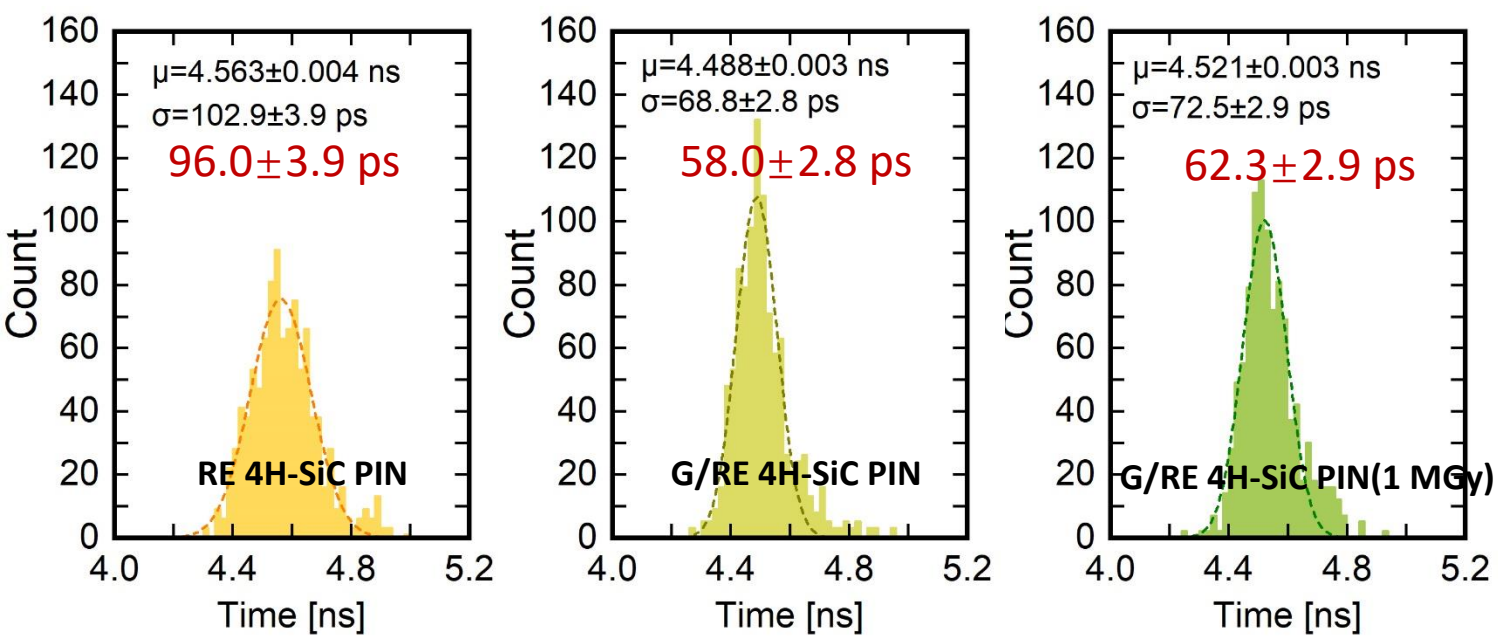


Fig. 1: Coincidence time resolutions

X-ray Irradiation Conditions:

- Energy: 160 keV
- Doses: 1 MGy (SiO₂)

Detector	Time Resolution	
RE SiC PIN	96.0±3.9 ps	
G/RE SiC PIN	58.0±2.8 ps	↓ 39.6% (RE SiC PIN)
1 MGy X-ray Irradiation G/RE SiC PIN	62.3±2.9 ps	

Time resolution: RE detector at 96.0 ps, graphene-enhanced detector improved to 58.0 ps (39.6% enhancement). After 1 MGy X-ray irradiation, the G/RE detector slightly degrades to 62.3 ps, showing good timing performance and radiation tolerance.

Detailed results are presented in IEEE Transactions on Electron Devices
<https://ieeexplore.ieee.org/document/11703811>

5. Silicon Carbide LGAD Detector Under 80-MeV Proton Irradiation (SICAR 1)

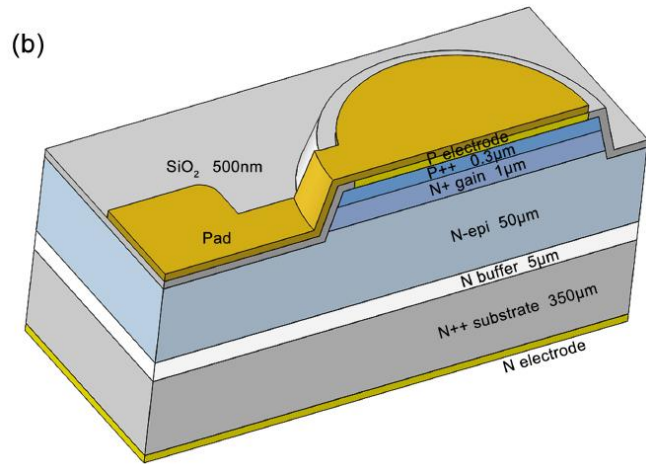


Fig. 1 3D schematic of 4H-SiC LGAD

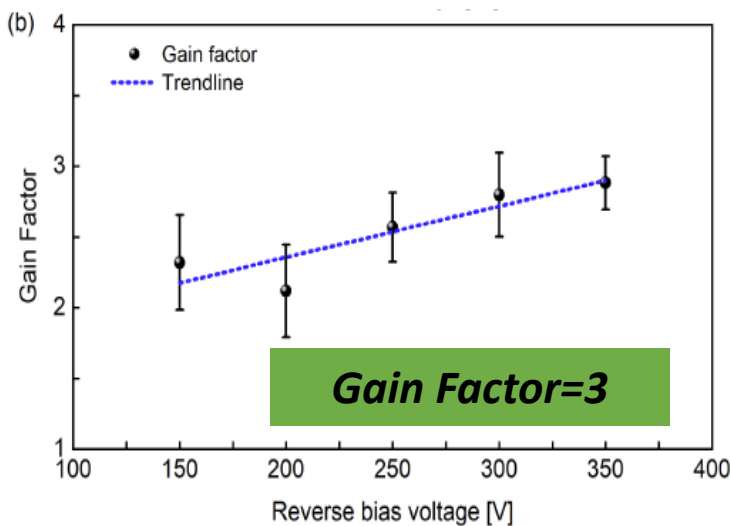


Fig. 2 Gain factor of 4H-SiC LGAD

Proton Irradiation Conditions:

Energy: 80 MeV

Doses:

$$1.4 \times 10^{11} \text{ p/cm}^2$$

$$2.5 \times 10^{13} \text{ p/cm}^2$$

$$7.0 \times 10^{13} \text{ p/cm}^2$$

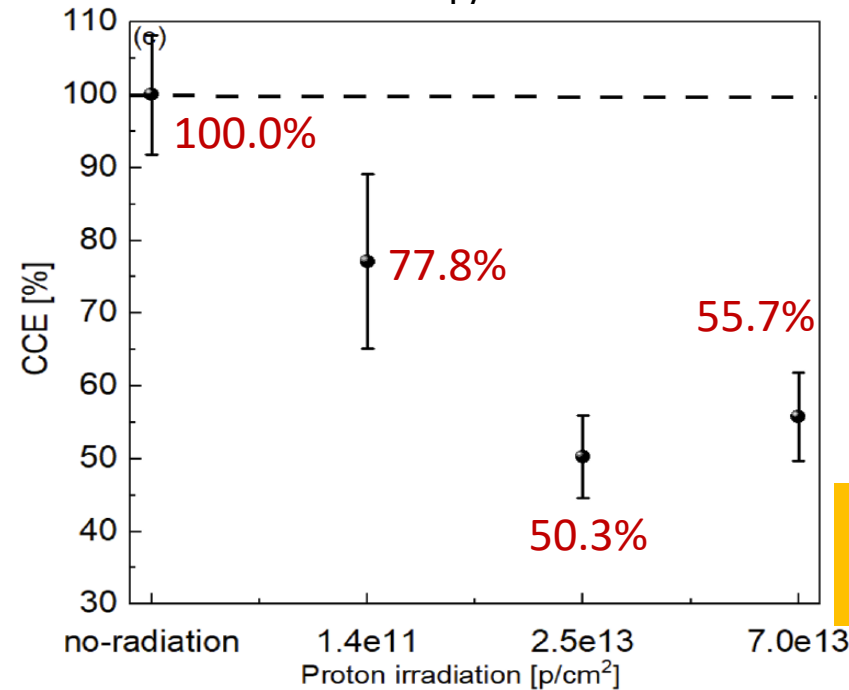


Fig. 3 Charge Collection Efficiency of LGAD

Our team fabricated 4H-SiC LGAD with gain factor of 3.

Charge Collection Efficiency of LGAD Under Proton Irradiation studies:

- CCE shows a decreasing trend with increasing irradiation dose
- Minimum charge collection efficiency: 50.3%

Detailed results are in IEEE TNS

<https://ieeexplore.ieee.org/document/10701498>

<https://ieeexplore.ieee.org/document/11261898>

Next step: optimize process

→ improve radiation tolerance

Summary

1. 4H-SiC detector

Time resolution of 4H-SiC detector degrades slightly from **38.1 ps** to **53.4 ps** under heavy-ion irradiation.

2. Graphene-Enhanced 4H-SiC PIN detector

^{241}Am : After 1 MGy X-ray irradiation, CCE remains 95.00%.

^{90}Sr : Graphene electrode improves time resolution by 39.6% vs. ring electrode.

TCT: Graphene-enhanced SiC detector maintains 20 ps across the entire active area.

3. The fabricated 4H-SiC LGAD achieved a gain factor of 3.

Based on these performance advantages, 4H-SiC detectors are planned to be used in the CEPC luminosity monitor (Xiyuan Zhang's report) and the CSNS beam monitoring system.

Summary and plan

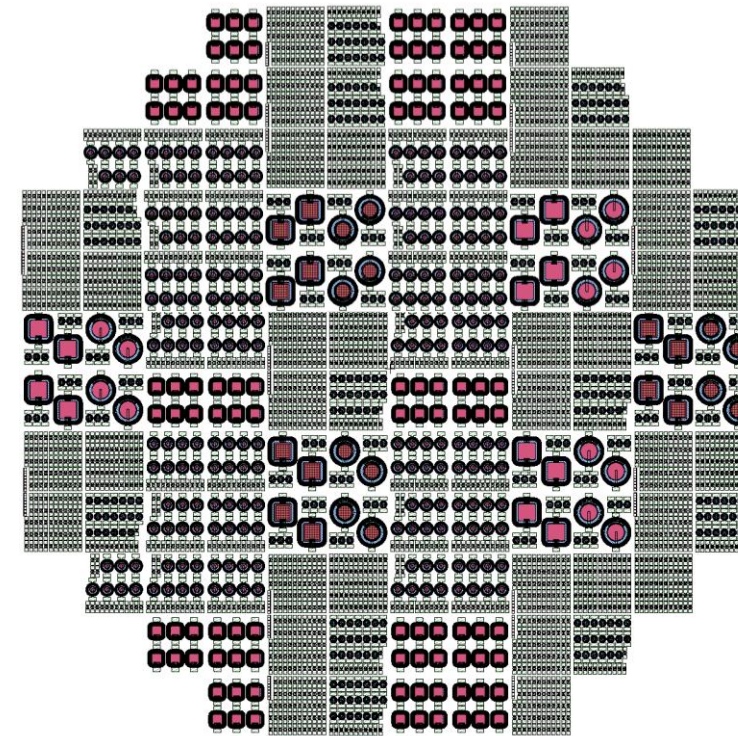
Plan

■ 4H-SiC BJT Detector (*Gain Factor* > 200)

Epitaxial wafer

N-type Emitter
P-type Base
N-type Collector
N-type buff 1um $1 \times 10^{18} \text{ cm}^{-3}$
N-type sub 20um $1 \times 10^{19} \text{ cm}^{-3}$

Mask layout (6 inch)

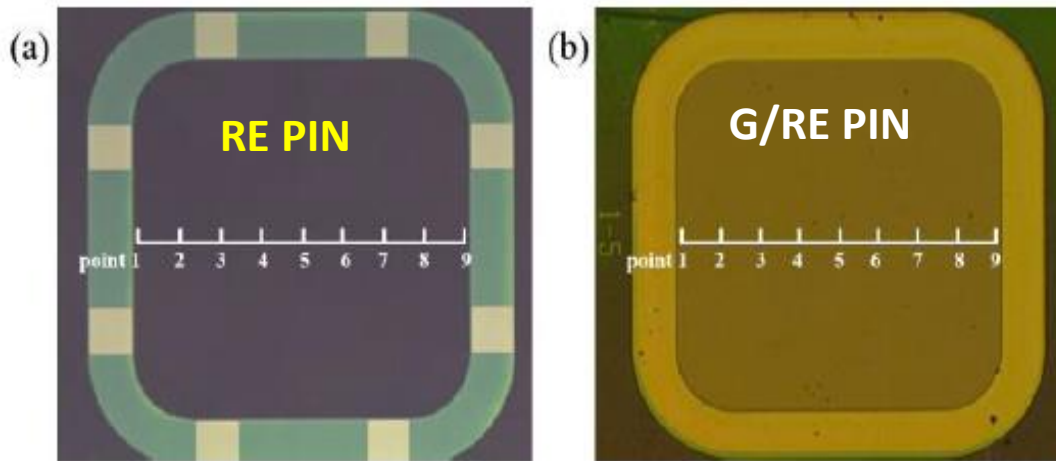


We will develop a 4H-SiC BJT detector for small-signal (alpha-particle, X-ray, etc.) detection.

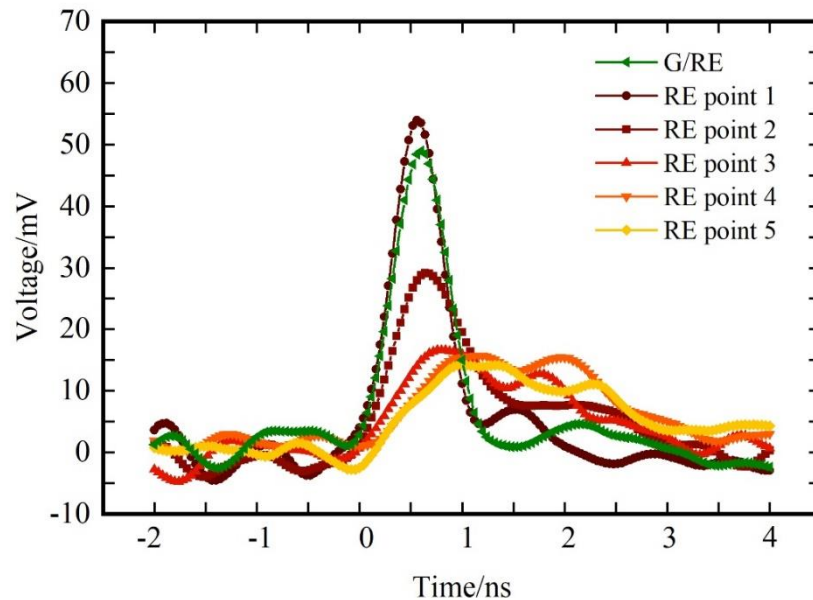
Thank You!

Back Up

Time Resolution (TCT)



Waveforms of the RE detector and the G/RE



RE detector (points 1→5)

- ✗ Signal reduction
- ✗ Waveform broadening
- Root cause:
 - P^{++} layer sheet resistance
 - Increased transmission delay
 - RC time constant $\uparrow$

G/RE detector (points 1→5)

- ✓ Stable signal response
- Improvement mechanism:
 - The graphene layer provides a lateral conduction path
 - Reduced transmission delay
 - Reduced RC

Graphene enhances the signal stability in the active region of the detector.