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

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Why Silicon Carbide Detectors?

Physical Propertis	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**

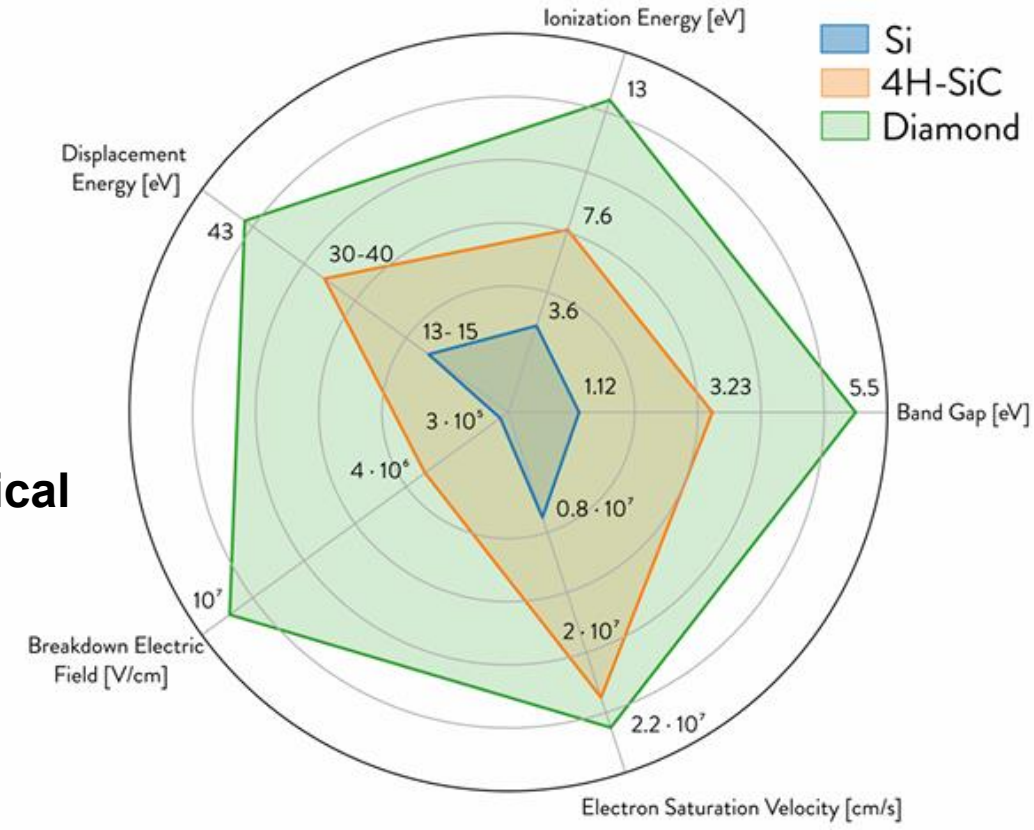


Fig.1 Physical properties of Si, 4H-SiC and diamond

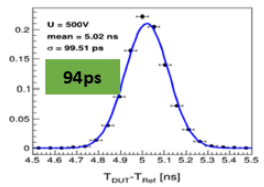
Silicon carbide detector has potential applications in CEPC luminosity monitor and nuclear facility monitor.

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);

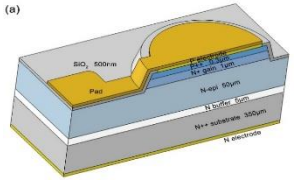
High spatial resolution (Multi-pixel LGAD detector).



In 2022

SiC-PIN

Time resolution:94ps



In 2024

SiC-LGAD (SICAR 1)

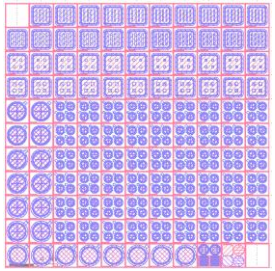
Gain factor:3



In 2025

Graphene/SiC PIN

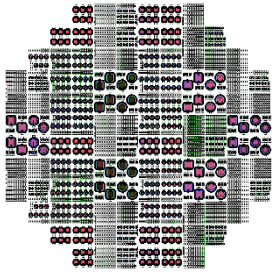
Time resolution:58ps



In 2026

SiC LGAD

Gain Factor＞10



In 2027

BJT alpha-particle detector

Gain Factor＞300

In 2028-2030

Multi-pixel LGAD

has been achieved

aim to achieve

1. Silicon Carbide Detectors (In 2022)

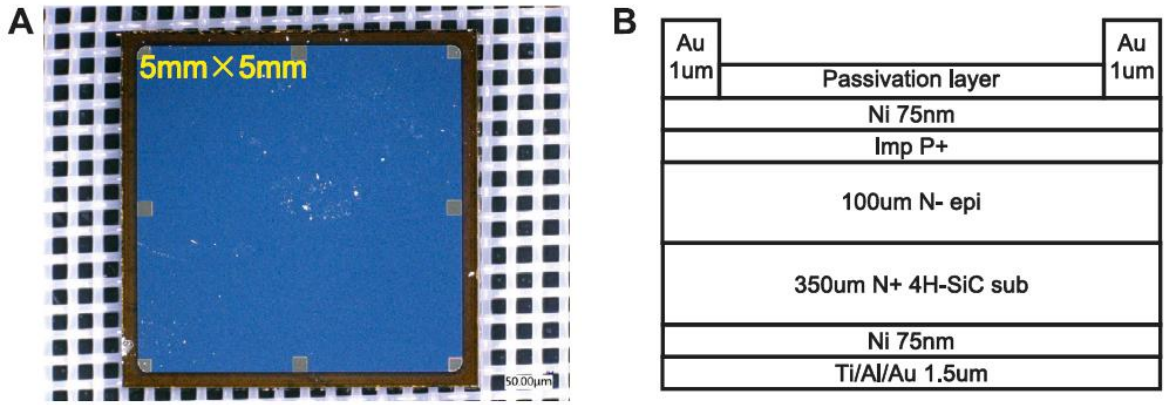
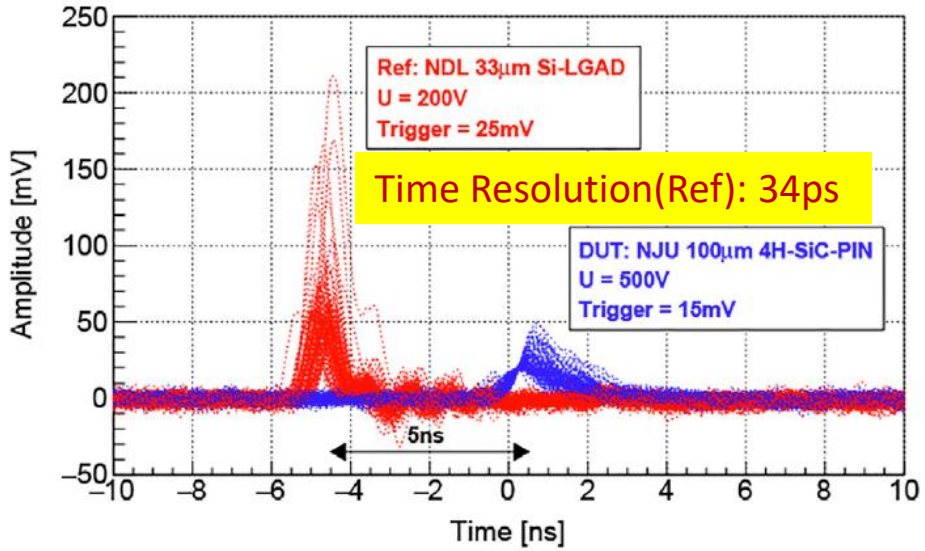
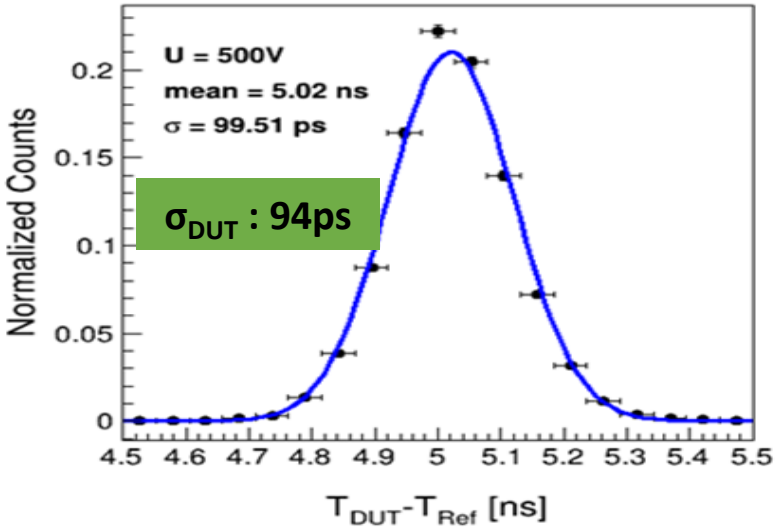


Fig 1: 5 × 5 mm 4H-SiC detector sample (A) Photography and (B) cross section.





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**

2. Silicon Carbide Detectors (In 2023-2024)

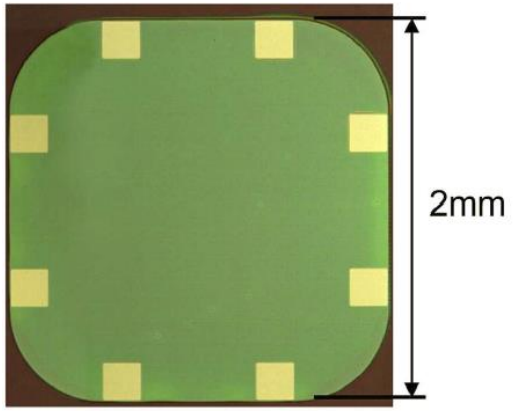


Fig 1: 2 × 2 mm 4H-SiC detector

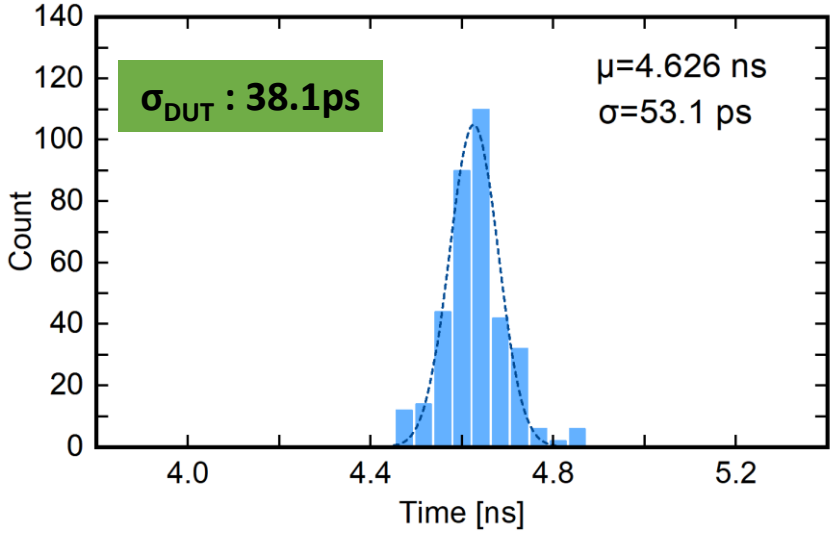


Fig 2: Coincidence time resolution

Time Resolution(Ref): 37ps

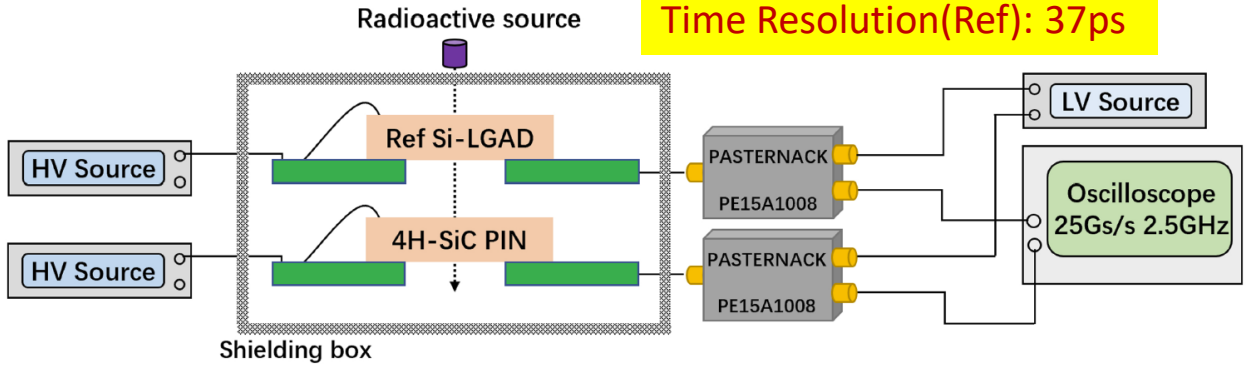
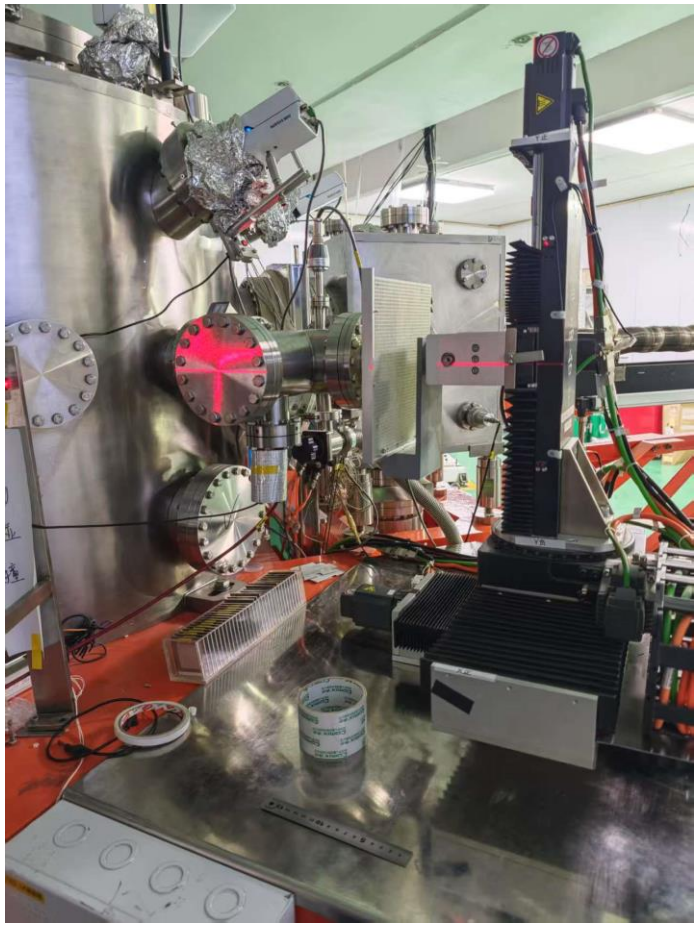


Fig. 3: Experimental setup for time resolution of a ^{90}Sr source.

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**

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



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

Motivation

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

Irradiation conditions:

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

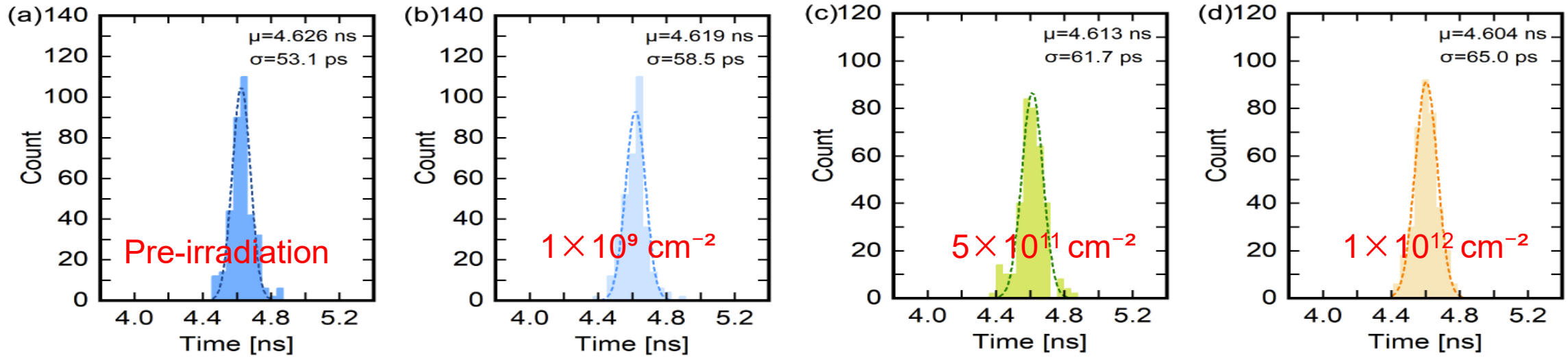
$5 \times 10^{11}\ cm^{-2}$

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

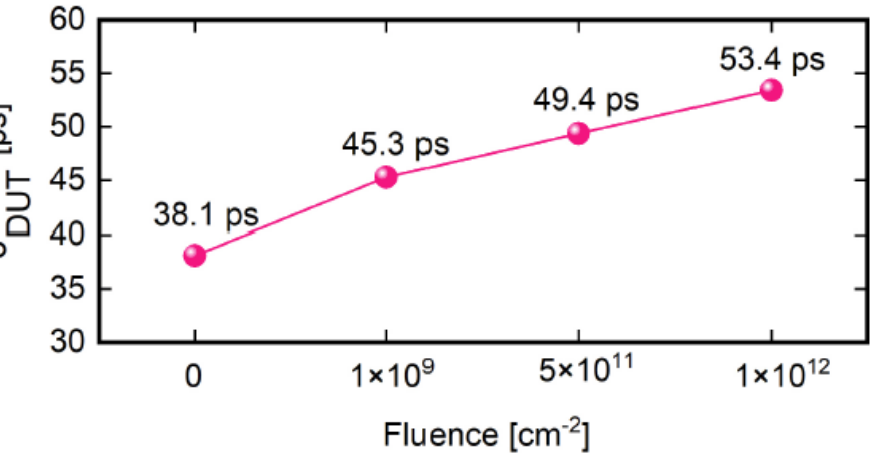
Total energy of tantalum (Ta) ions: 2.896 GeV

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

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

4. Graphene-Enhanced Silicon Carbide Detector

Metal electrodes on the surface affect SiC detector applications in:

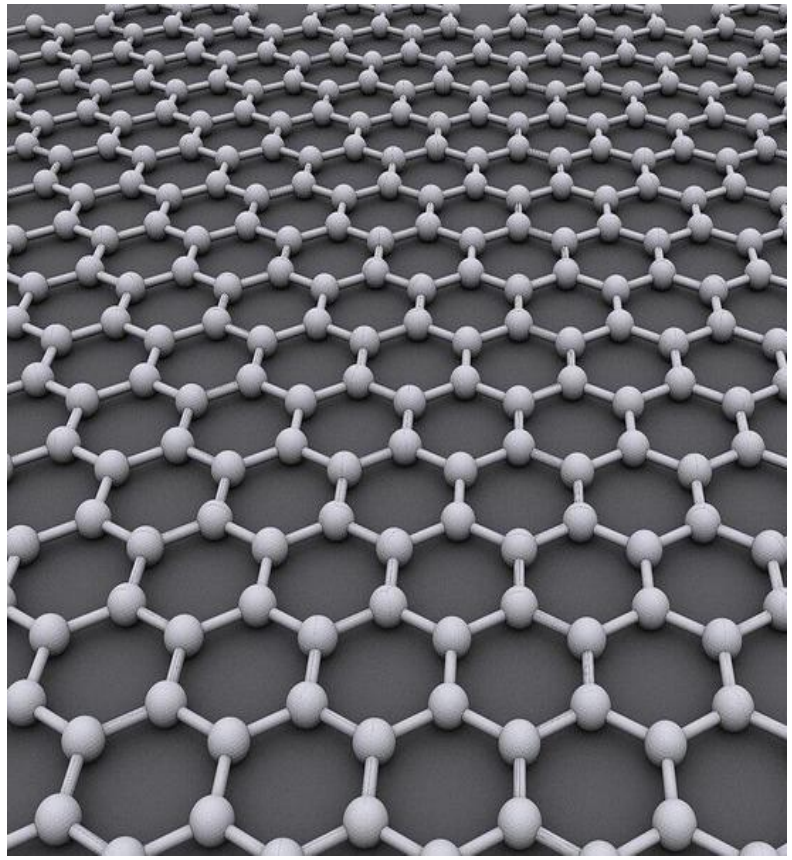
- **Low-penetration particle detector**
- **Low-energy soft X-ray**
- **Ultraviolet (UV) light**
- **Transient current technique(TCT) detection**

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 (5300W/(m·K))
- High carrier mobility (15000 $cm^2/(V \cdot s)$)

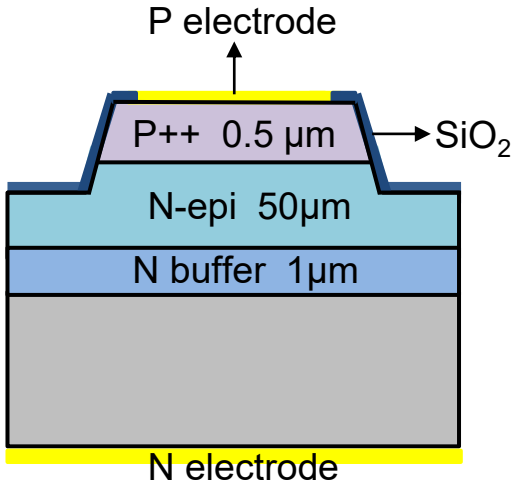
Graphene-Enhanced SiC Detector

Use graphene to enhance silicon carbide detector

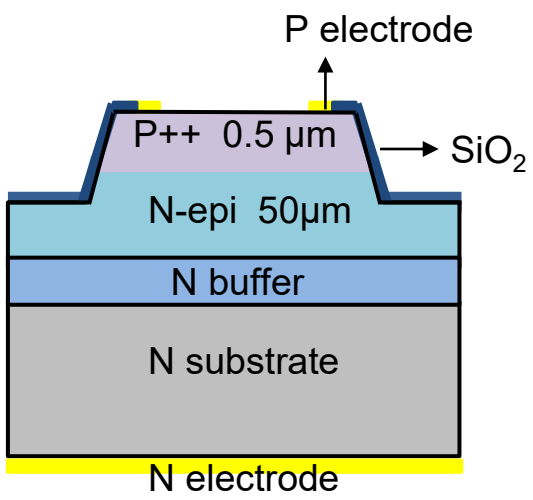
Our goal is:

- Enhanced signal stability
- Improved uniformity of time resolution

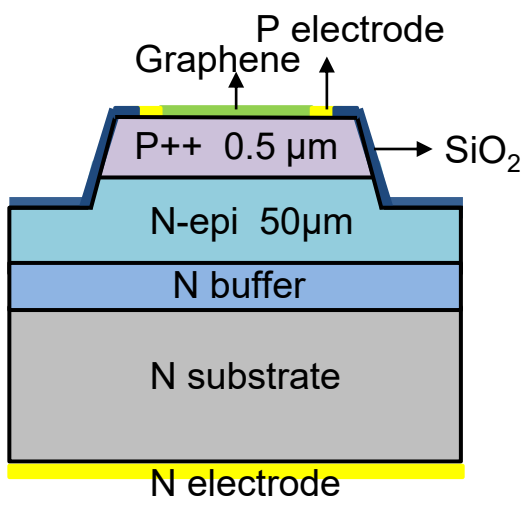
4. Graphene-Enhanced Silicon Carbide Detector



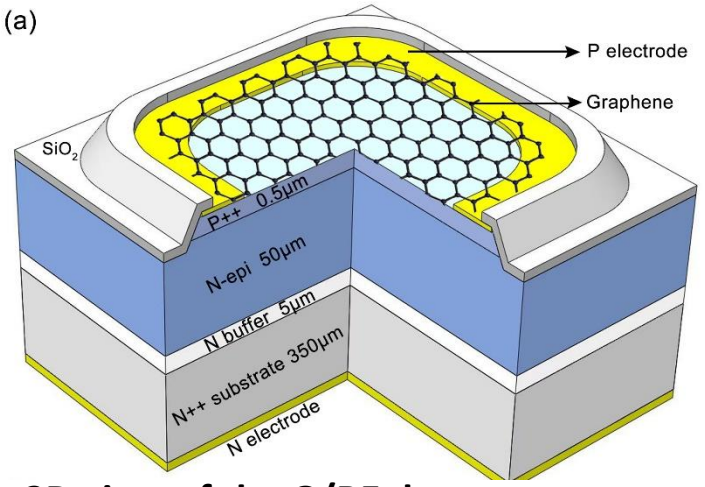
SE detector
(surface metal electrode)



RE detector
(ring metal electrode)



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



3D view of the G/RE detector structure

To compare performance, fabricated three type detectors:

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

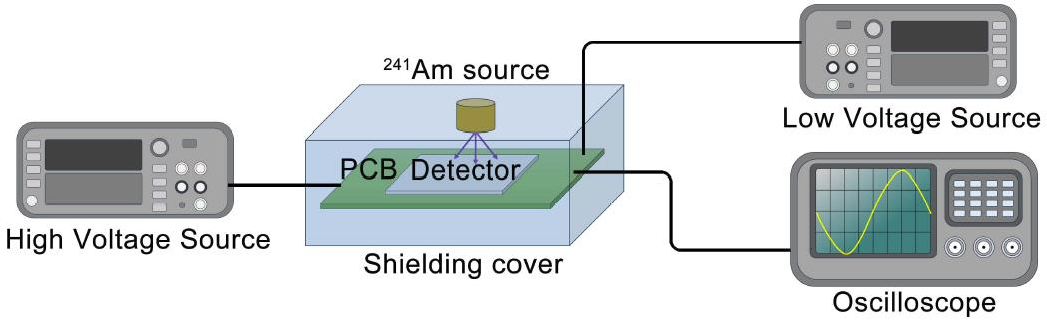


Fig.1: Setup for testing charge collection performance using an α source

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

G/RE detector shows a fast rise time (336 ps) matches SE detector(335 ps)—better than RE detector(443 ps). Graphene effectively improves signal rise time.

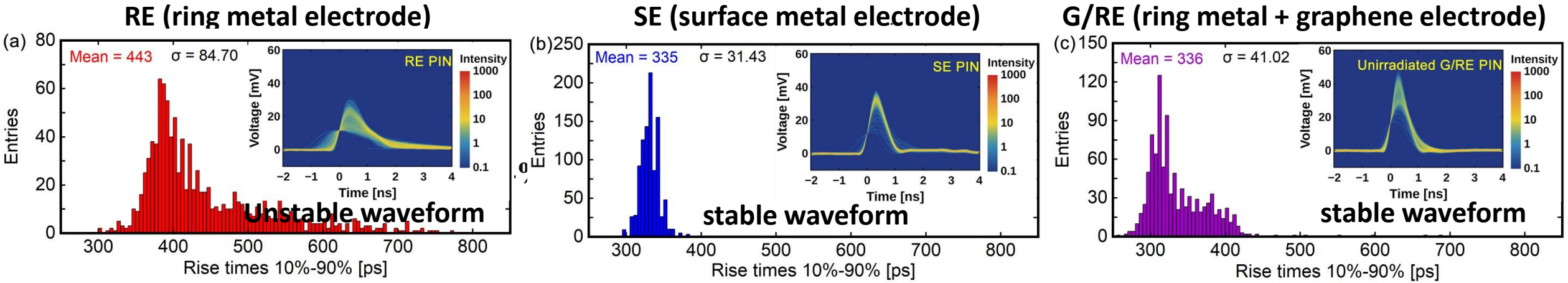
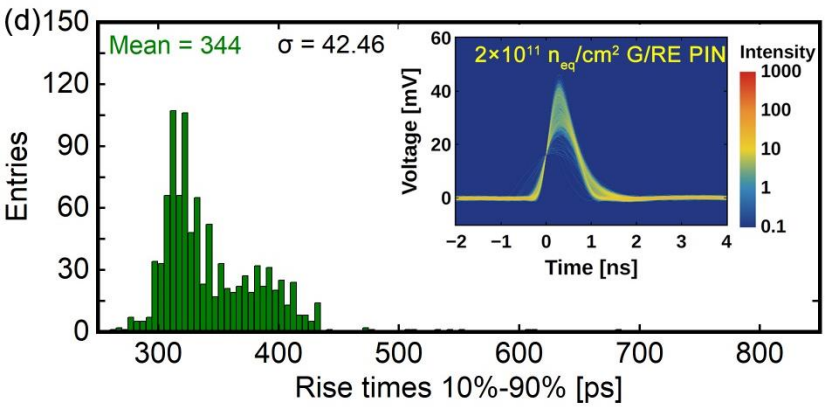


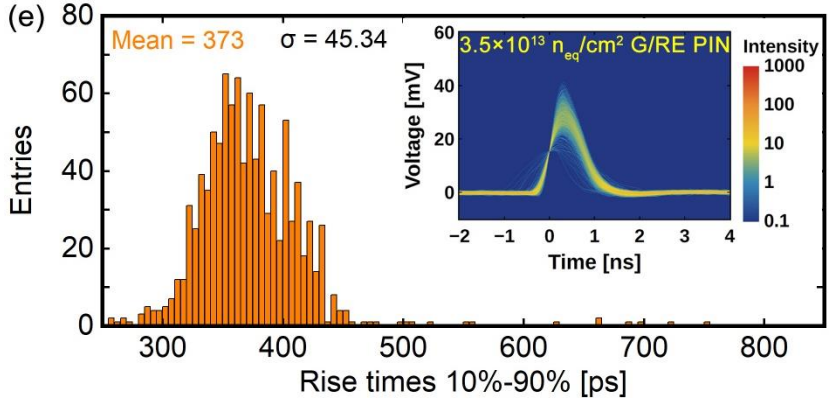
Fig. 2: Signal waveforms and rise time distributions

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 × 10^{11} n_{eq}/cm^2 **proton irradiation: 3.5 × 10^{13} n_{eq}/cm^2**

Fig 1: Signal waveforms and rise time distributions

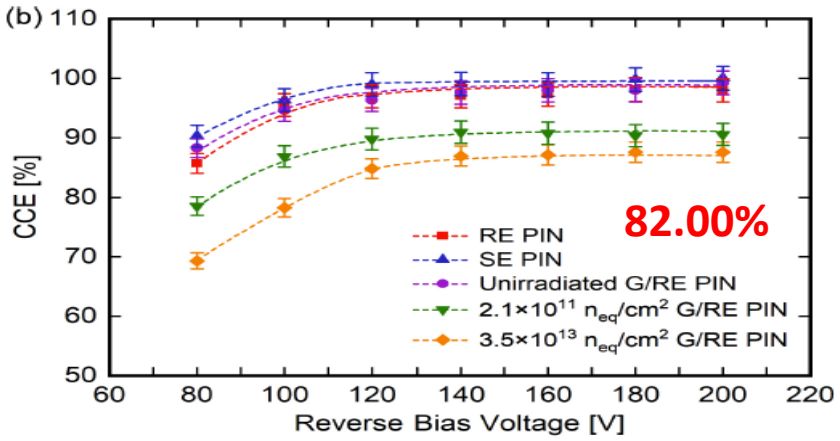


Fig. 2 Charge collection efficiencies

Detector	Mean Rise Time
G/RE (ring metal + graphene)	336 ps
2.1 × 10^{11} n_{eq}/cm^2 G/RE	344ps
3.5× 10^{13} n_{eq}/cm^2 G/RE	373ps

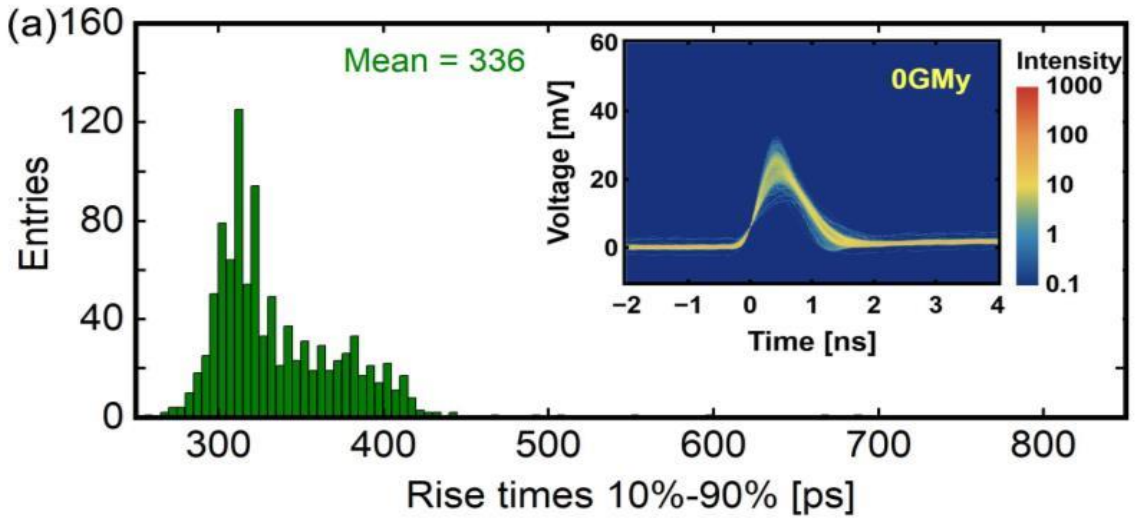
Detailed results are presented in IEEE Transactions on Electron Devices
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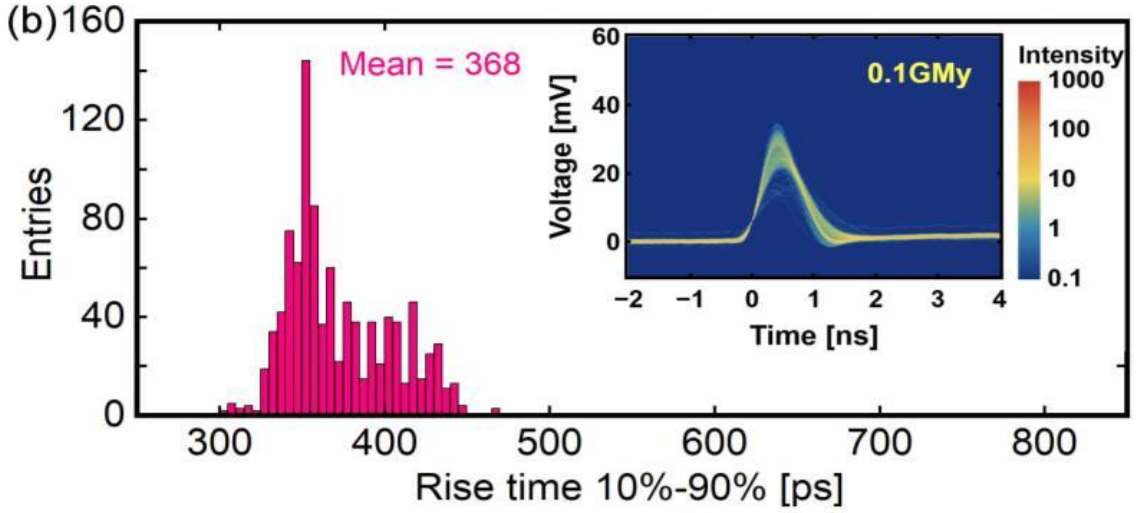
Proton irradiation: 80 MeV
Equivalent neutron fluences:
2.1 × 10^{11} n_{eq}/cm^2
3.5 × 10^{13} n_{eq}/cm^2

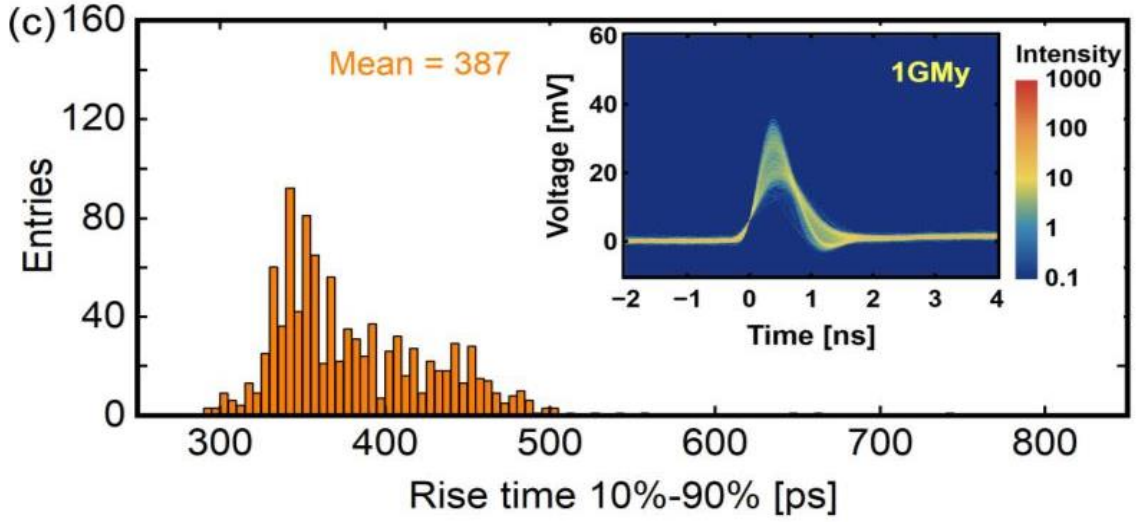
After irradiation: signal rise time increased slightly; CCE showed a small decrease
At maximum fluence: CCE still reached 82%, consistent with the expected target

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

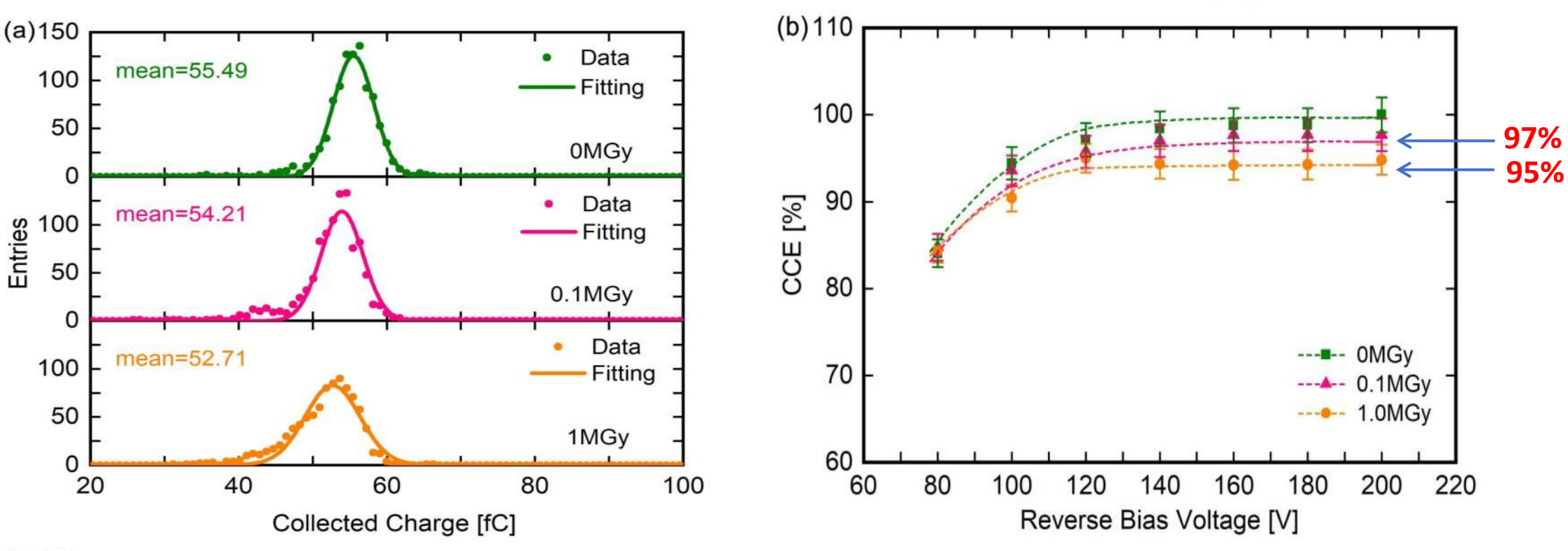


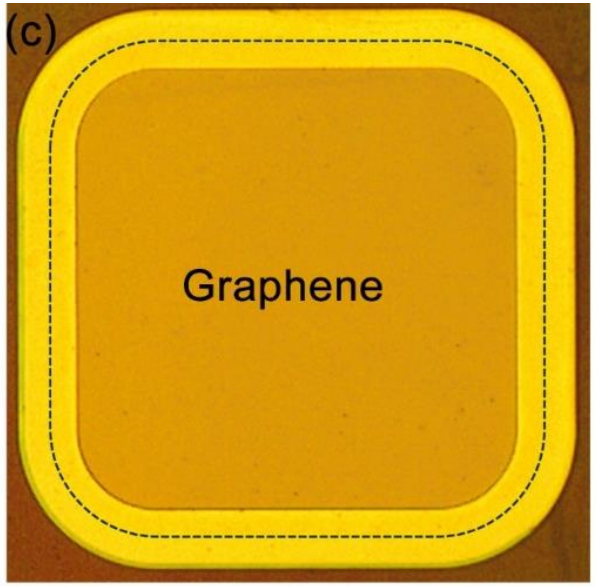
Fig. 1: Charge collection performance at 200 V for α particles:(a) Gaussian fit of the collected charge spectrum (b) CCE versus reverse bias for the 0 MGy, 0.1 MGy and 1 MGy X-ray irradiated G/RE 4H-SiC PIN.

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.

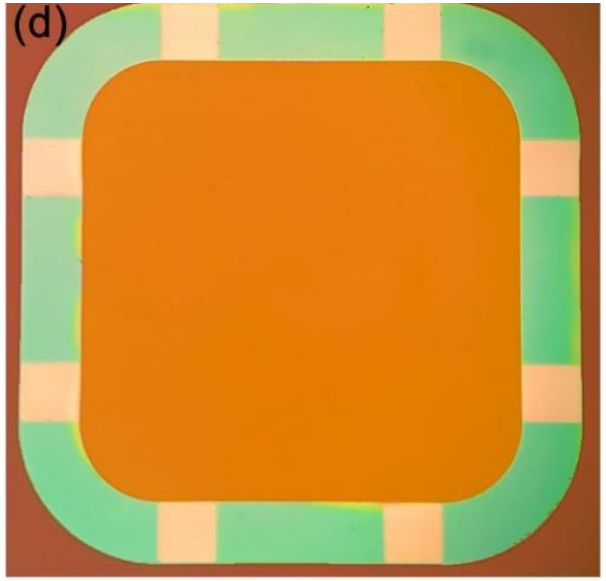
Detailed results are presented in IEEE TRANSACTIONS ON NUCLEAR SCIENCE

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

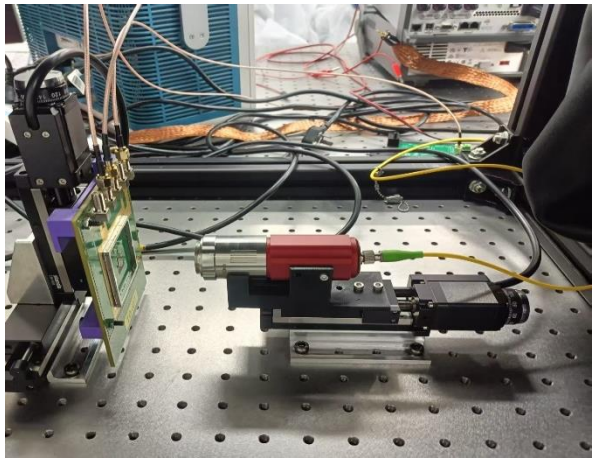
4.4 Time Resolution



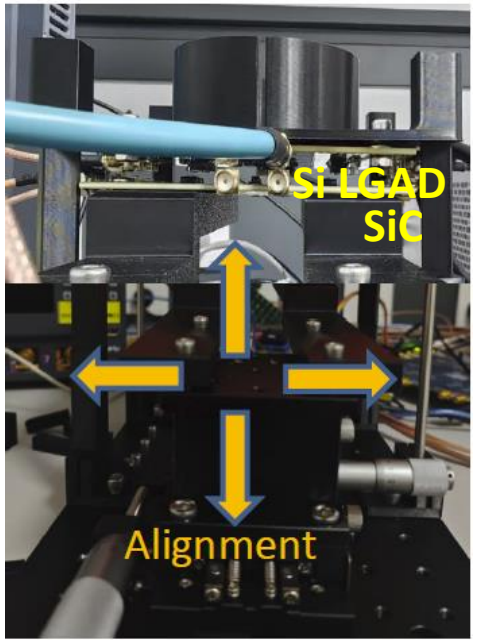
Graphene-Enhanced SiC detector (G/RE)
(ring metal + graphene electrode)



RE SiC detector
(ring metal electrode)



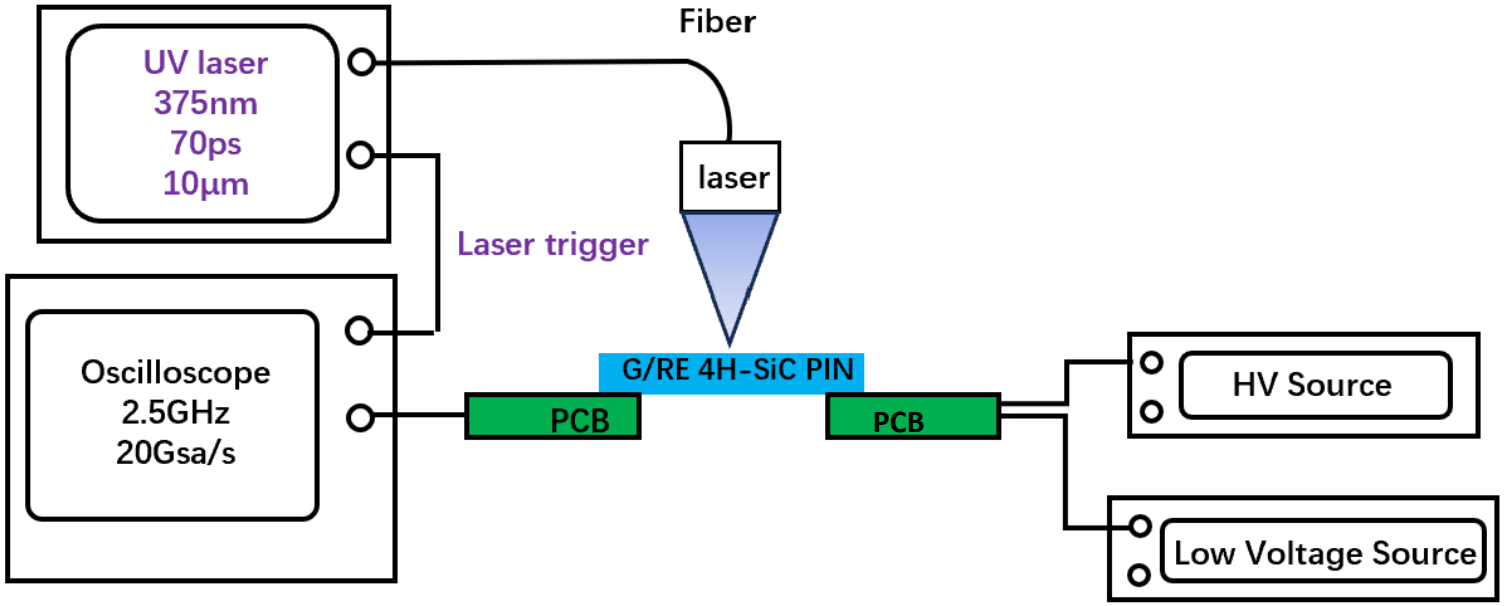
TCT Experimental Setup

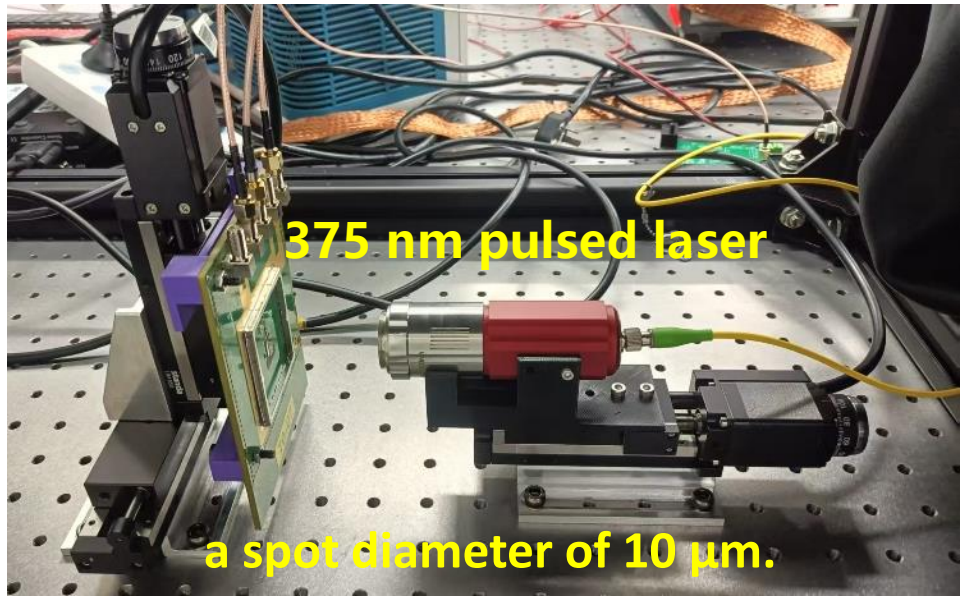


Time resolution measurement using a ^{90}Sr source

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
(Shandong Institute of Advanced Technology)

- 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)

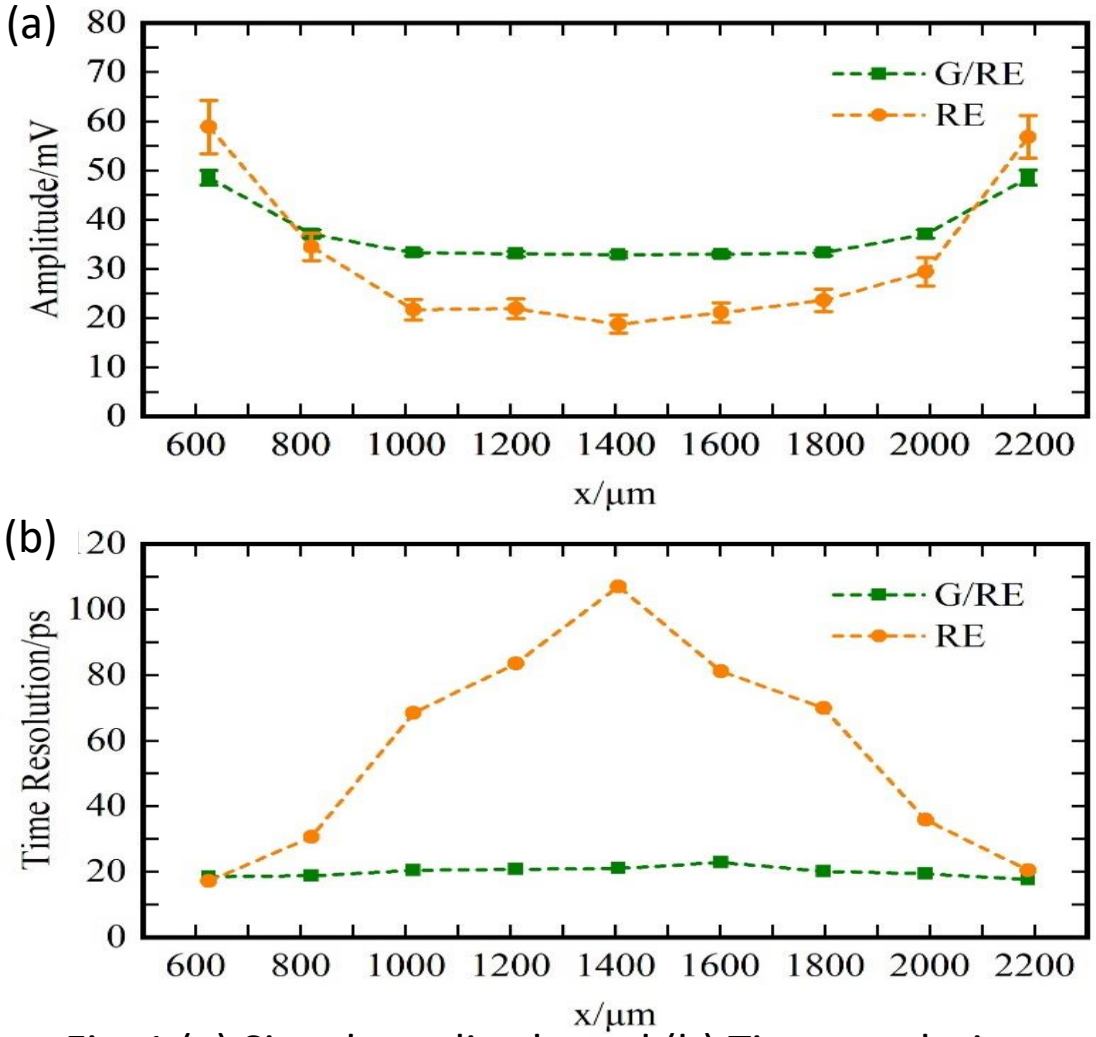
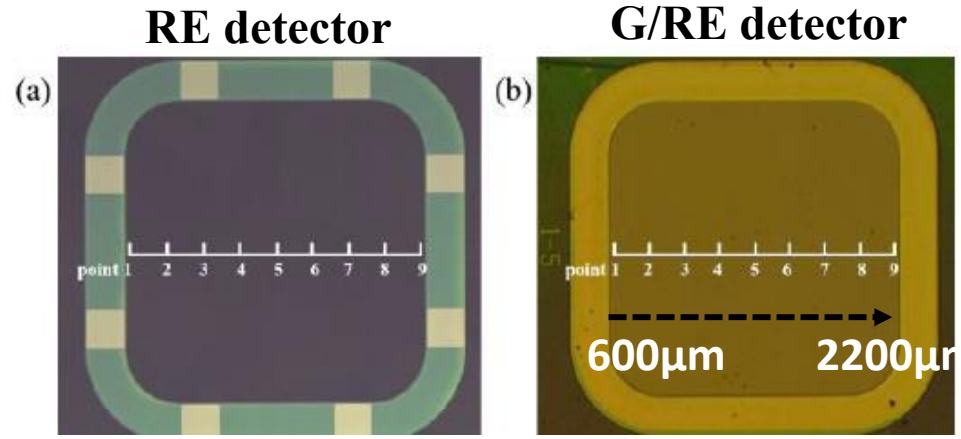


Fig. 1 (a) Signal amplitude and (b) Time resolution

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 → >107 ps	~20 ps
Signal amplitude	60 mV → 20 mV	50 mV → 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

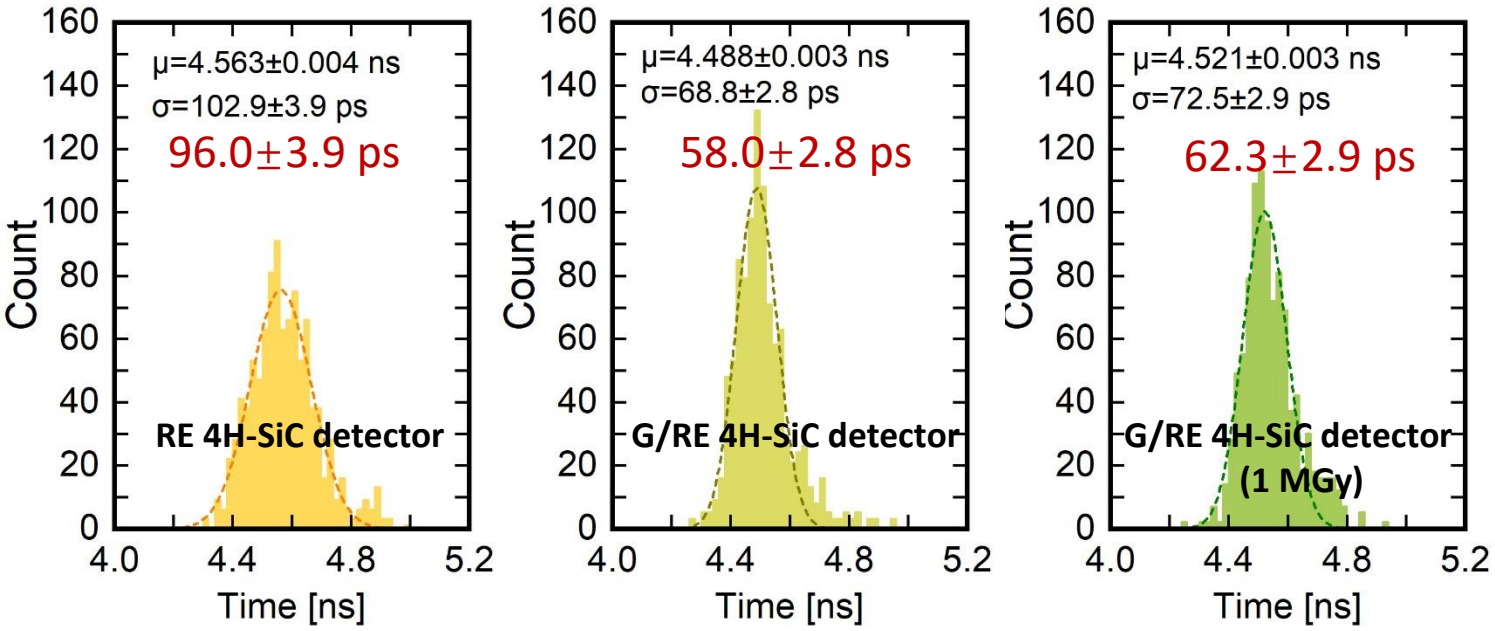


Fig. 1: Coincidence time resolutions

X-ray Irradiation Conditions:

- **Energy: 160 keV**
- **Doses: 1 MGy (SiO_2)**

Detector	Time Resolution
RE SiC detector	96.0±3.9 ps
G/RE SiC detector	58.0±2.8 ps
1 MGy X-ray Irradiation G/RE SiC detector	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.

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

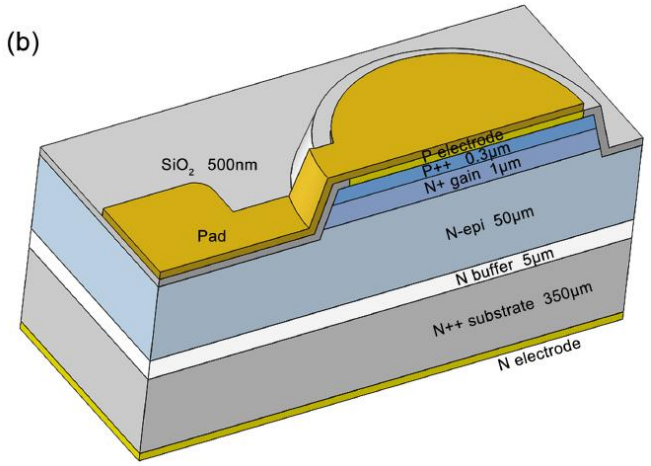


Fig. 1 3D schematic of 4H-SiC LGAD

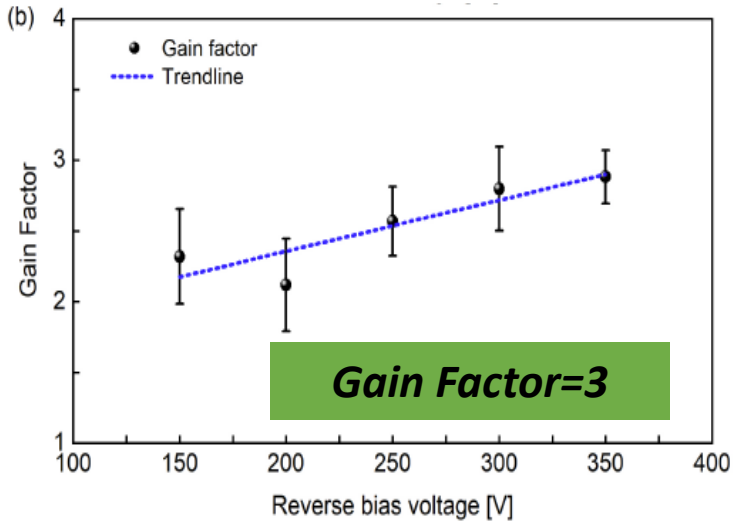


Fig. 2 Gain factor of 4H-SiC LGAD

Proton Irradiation Conditions:

Energy: 80 MeV

Doses:

1.4×10^{11} p/cm^2

2.5×10^{13} p/cm^2

7.0×10^{13} p/cm^2

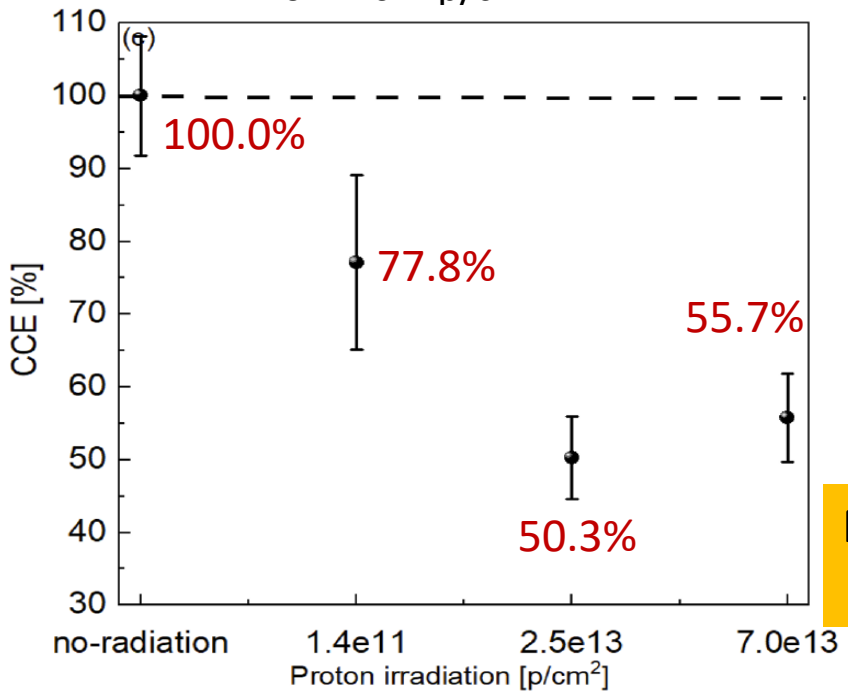


Fig. 3 Charge Collection Efficiency of LGAD

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

Charge Collection Efficiency of LGAD Under Proton Irradiation studies:

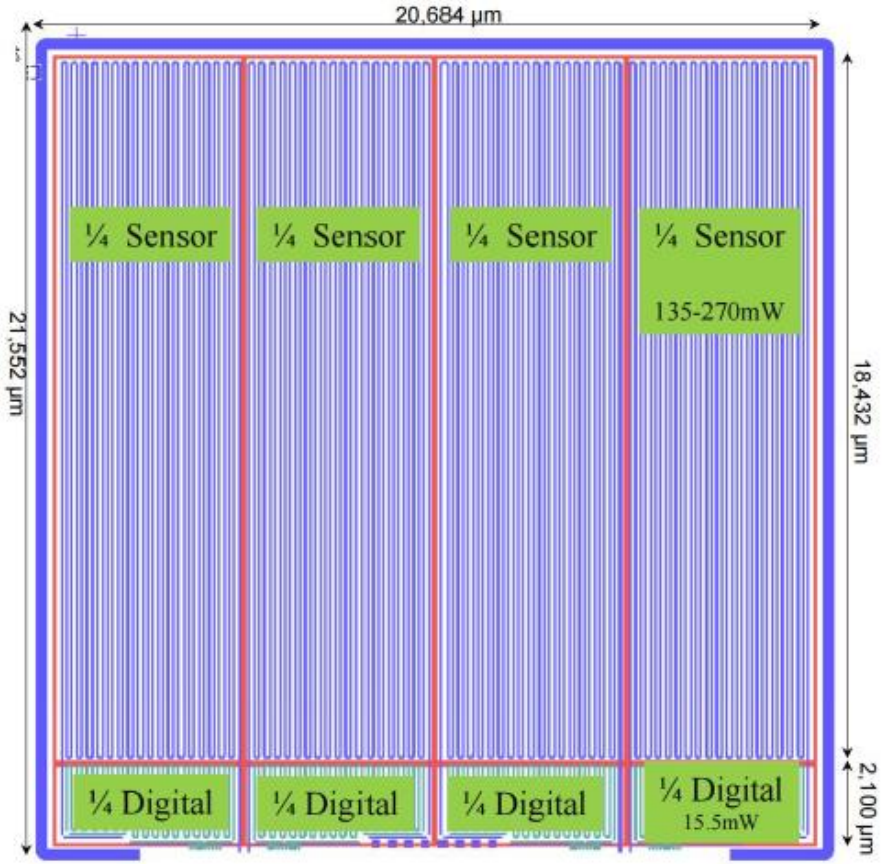
- CCE shows a decreasing trend with increasing irradiation dose
- Minimum charge collection efficiency: 50.3%

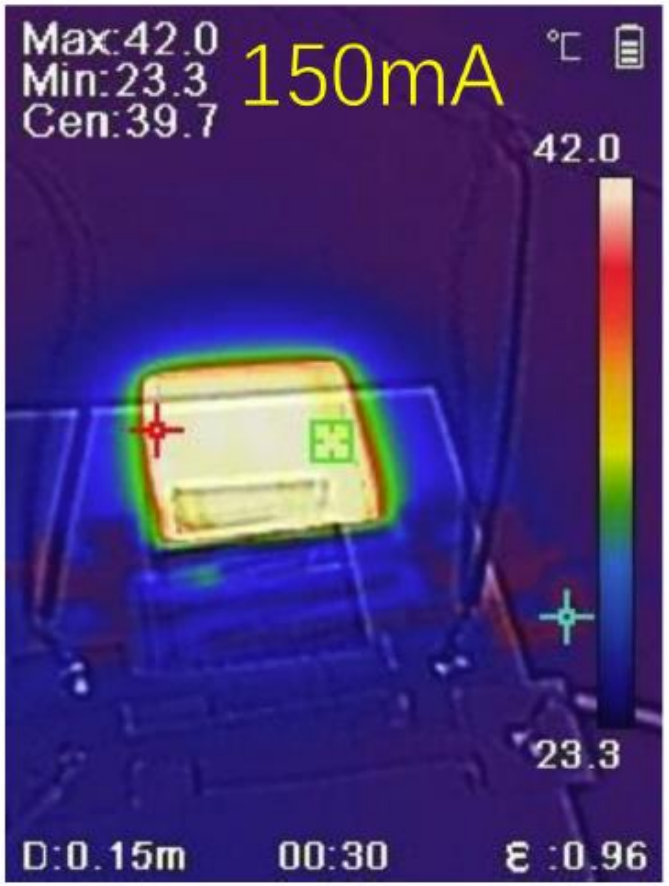
Detailed results are in IEEE TNS
https://ieeexplore.ieee.org/document/10701498
https://ieeexplore.ieee.org/document/11261898

Next step: optimize process
→ improve radiation tolerance

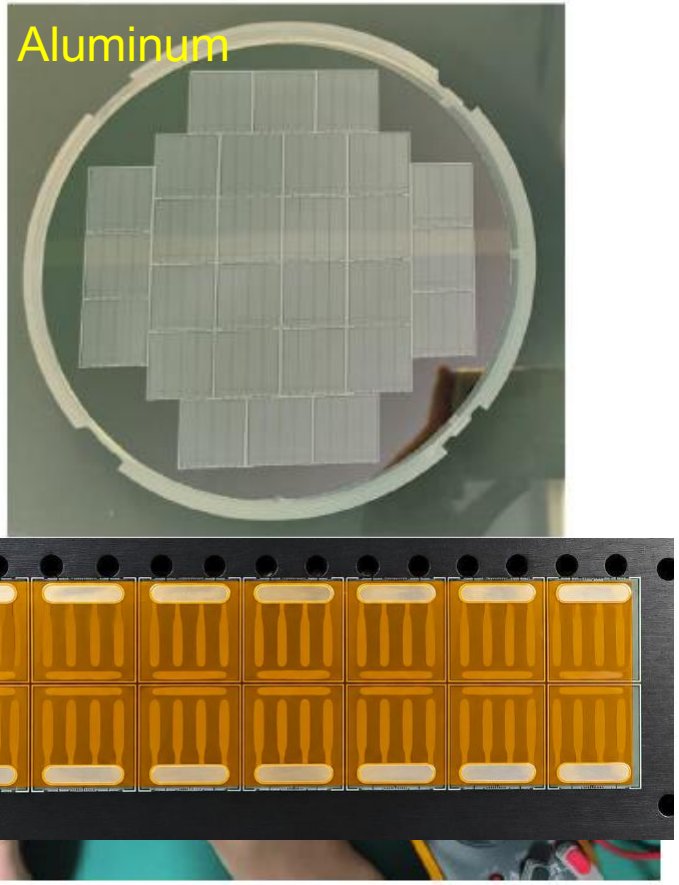
6. Modules assemble

Module Prototyping for the CEPC/AGORA Inner Tracker





6-inch wafer (Si Substrate)



Designed heating dummy sensor (close to real sensor in dimensions, materials, and heat) for assemble— matching real chips to advance CEPC ITK R&D, with experience transfer to SiC sensor modules

Summary and plan

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 detector

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

^{90}Sr: Compared with the detector without graphene, the graphene-enhanced detector achieves a 39.6% improvement in time resolution.

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

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

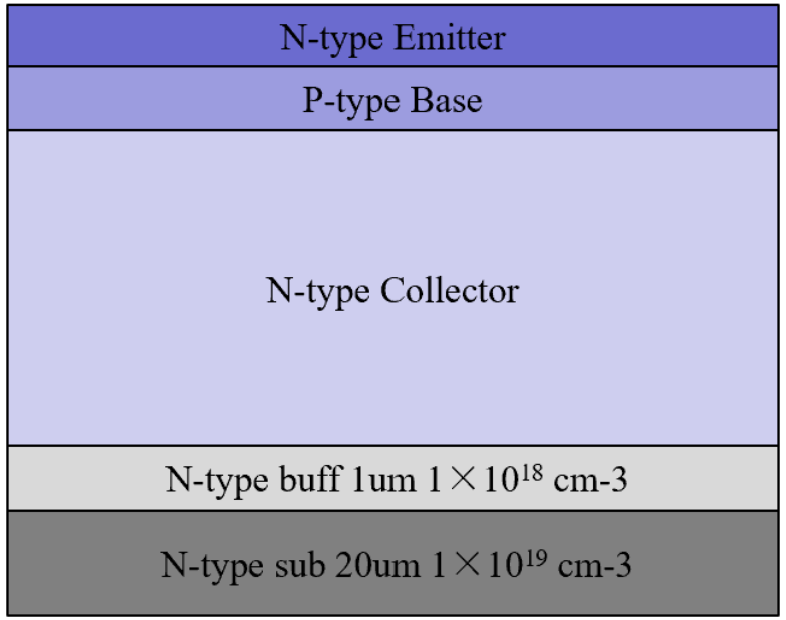
Based on these performance advantages, 4H-SiC detectors are used in the CEPC luminosity monitor (Xiyuan Zhang's report**) and fusion detection on Xuanlong-50U (**Suyu Xiao's report**).**

Summary and plan

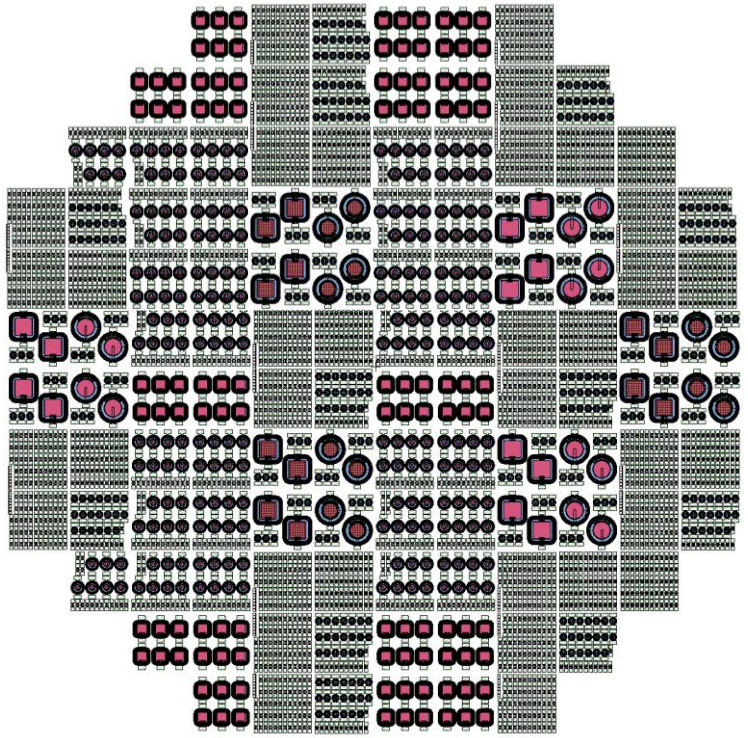
Plan

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

Epitaxial wafer



Mask layout (6 inch)



- **No external pre-amplifier, avoiding the introduction of external noise**
- **The internal gain amplifies the signal.**

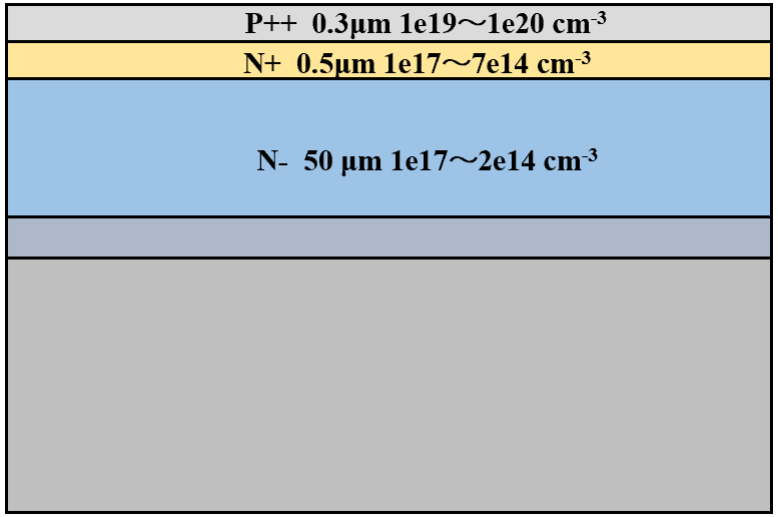
We will develop a 4H-SiC BJT detector for small-signal (alpha-particle, X-ray, etc.) detection.

Summary and plan

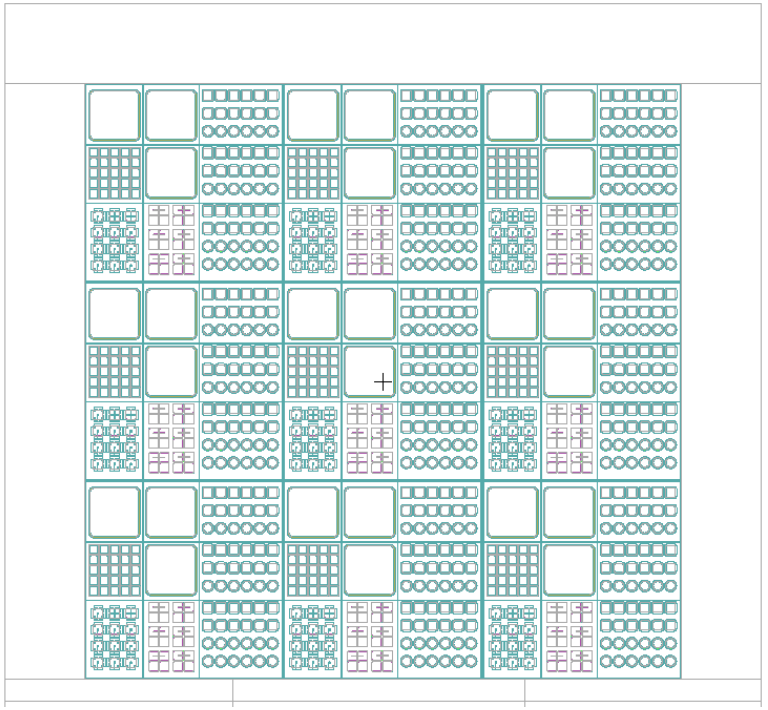
Plan

2. 4H-SiC LGAD (SICAR 2: *Gain Factor＞10, Time resolution: 30ps*)

Epitaxial wafer



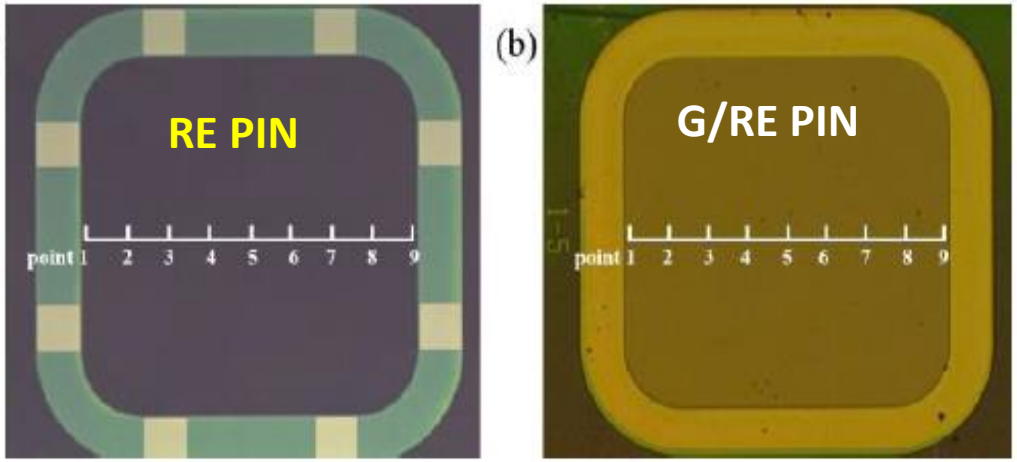
Mask layout



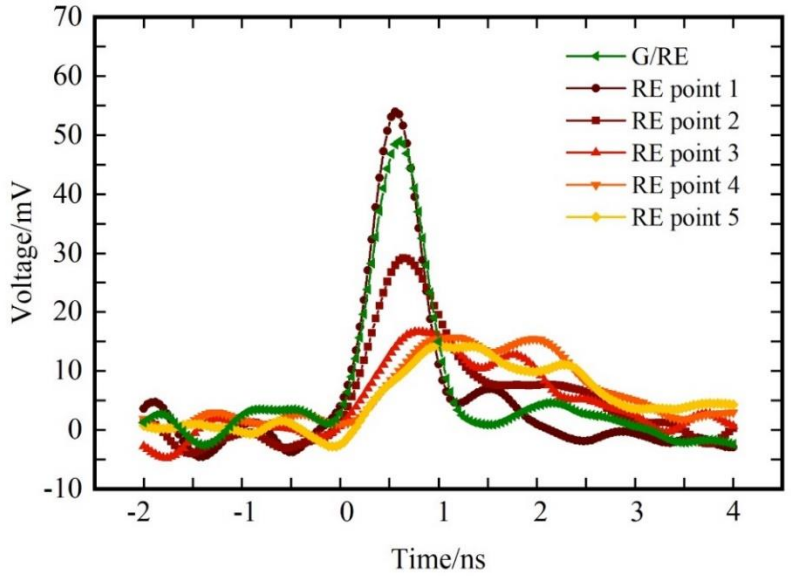
Thank You!

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 ↑

G/RE detector (points 1→5)

- ✅ Stable signal response
- 🟢 Improvement mechanism:

The graphene layer provides a lateral conduction path

Reduced transmission delay

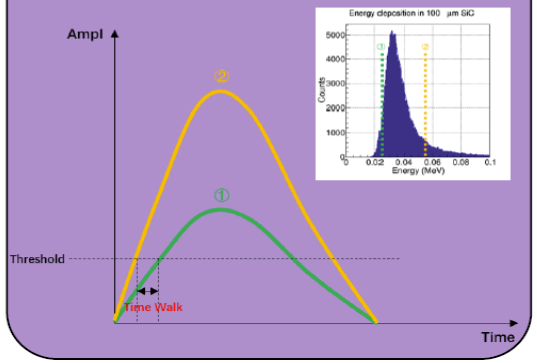
Reduced RC

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

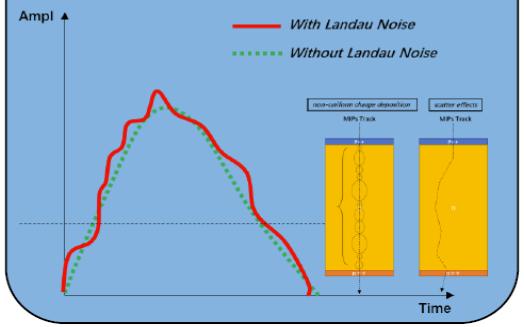
Key factors influencing time resolution

$$\sigma_t^2 = \sigma_{Time\ Walk}^2 + \sigma_{Landau\ Noise}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$

- Signal amplitude variation caused by the uncertainty of particle energy loss in the detector.

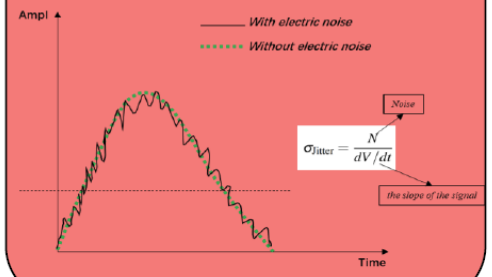


- Signal jitter caused by the non-uniformity of particle energy loss in the detector.



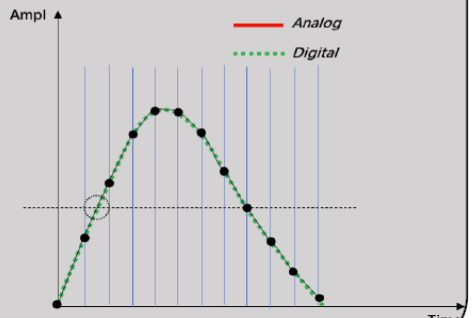
- Signal jitter caused by noise superimposed on the signal.

$$\sigma_{\text{Jitter}} = \frac{N}{dV/dt} = \frac{N}{S/t_{rise}} = t_{rise}/(S/N)$$



- Error induced by A/D conversion

$$\frac{\Delta T}{\sqrt{12}}$$



Laser testing yields better time resolution than beta-source testing because it eliminates Landau fluctuations and time walk. Radioactive sources involve random emission and energy deposition, thus being closer to real particle environments.