

# 4H-SiC Low Gain Avalanche Detectors

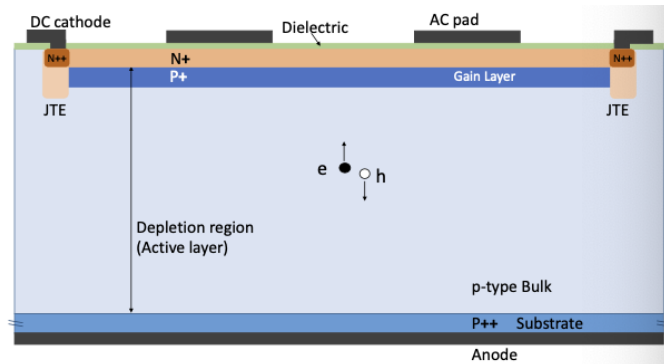
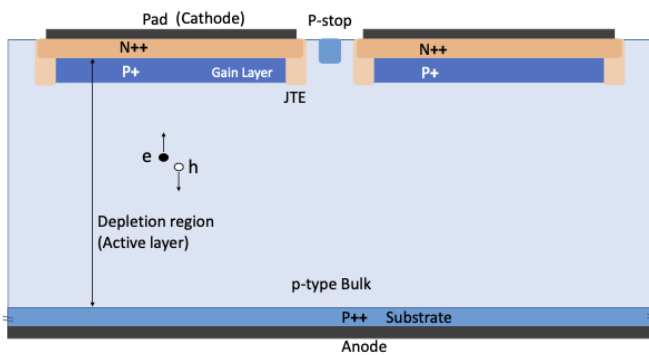
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**Qingdao, 2026.4.23**

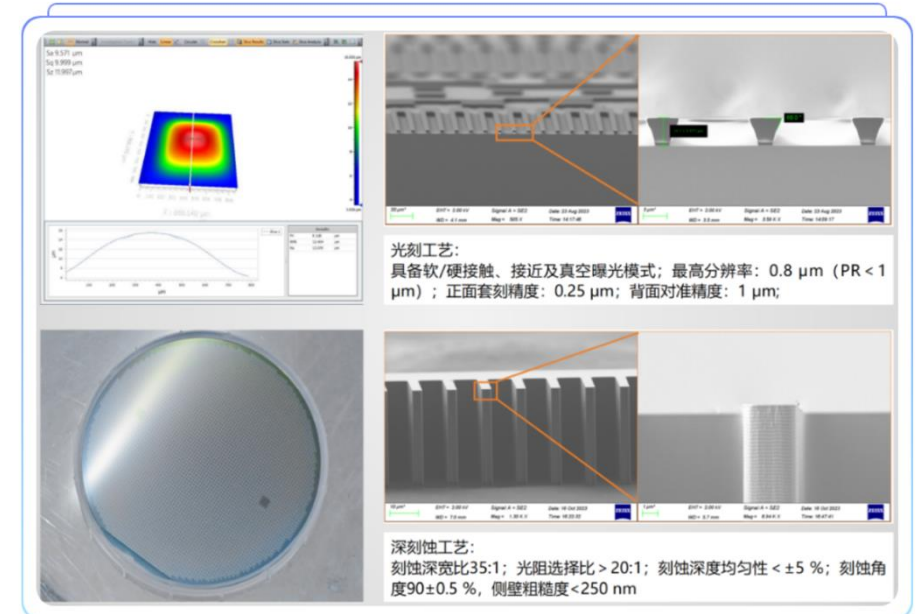
# Silicon LGADs

- Silicon LGADs have demonstrated excellent timing resolution ( $< 50\text{ps}$ )
  - Designated for use in ATLAS and CMS
  - Planned for future use in EIC
- From DC-LGADs to AC-LGADs
  - DC-LGADs have limitations in spatial resolution due to pixel size constraints and dead zones induced by JTE and P-stop between pixels
  - AC-LGADs deliver both high-precision timing and spatial measurements with  $\sim 100\%$  fill factor



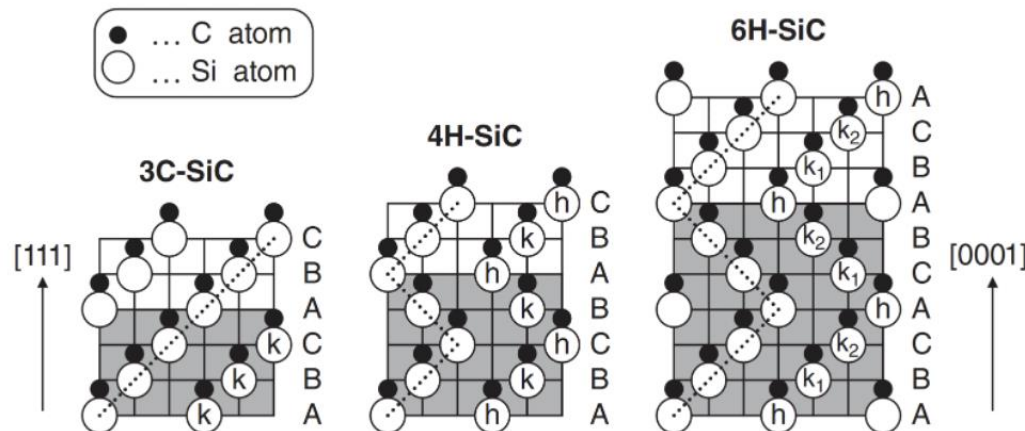
- Foreseen AC-LGAD fabrication at Shandong Institutes of Industrial Technology

平台工艺能力展示



# Silicon → Silicon Carbide

- Irradiated Si LGADs exhibit increased leakage current and gain degradation
- Si detectors cooled to  $-30^{\circ}\text{C}$  in real operation, to address radiation damage effects → Operational costs and material budget
- To consider Silicon Carbide (a wide bandgap semiconductor) as another material for radiation detector
  - SiC potential as a radiation detector has been demonstrated in as early as the 1960s
  - A long history, but the adoption of SiC detectors limited by process technologies
  - Recent flourish with high-quality and low doped epitaxial layers, promoted by the use of SiC to fabricate power devices
  - SiC polytypes are classified by lattice symmetry as cubic (C), hexagonal (H), and rhombohedral (R)

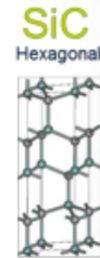


- 4H-SiC most commonly used in commercial application

# Potential of SiC material for radiation detectors

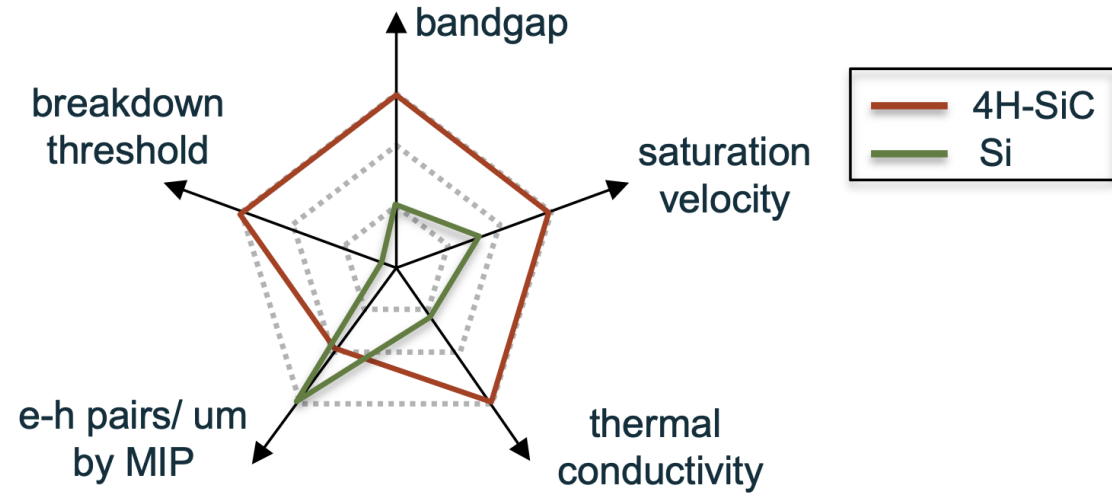
- Wide bandgap (x3) results in **low leakage current and operation at high T even after irradiation**
  - High atomic displacement threshold energy (x1.7) makes it more **radiation hard** (21.8/13eV for SiC/Si)
  - **NO cooling required** due to high thermal conductivity (x3)
  - High breakdown voltage (x15) allows for operation at high E-fields & High saturation drift velocity (x2)
    - charge carriers move faster with lower probability getting trapped by the defects in the lattice
    - enables **enhanced timing performance and effective charge collection**
- **4H-SiC detectors have the potential to outperform Si for fast charged particles detection.**

Property	SiC advantage	Material	Value	Relative Performance
$E_g$ (eV) - band gap	x3	Si	1.1	Short pink bar
		SiC	3.3	Long green bar
$v_{sn}$ (cm/s) – electron saturation velocity	x2	Si	$1 \times 10^7$	Short pink bar
		SiC	$2 \times 10^7$	Medium green bar
$\mu_n$ (cm <sup>2</sup> /Vs) – electron mobility	~	Si	1350	Short pink bar
		SiC	950	Short green bar
$\epsilon_r$ - dielectric constant	~	Si	11.8	Short pink bar
		SiC	9.7	Short green bar
$E_c$ (V/cm) - critical electric field	x15	Si	$2 \times 10^5$	Very short pink bar
		SiC	$3 \times 10^6$	Long green bar
$k$ (W/cm K) - thermal conductivity	x3	Si	1.5	Short pink bar
		SiC	5	Long green bar



# 4H-SiC LGADs

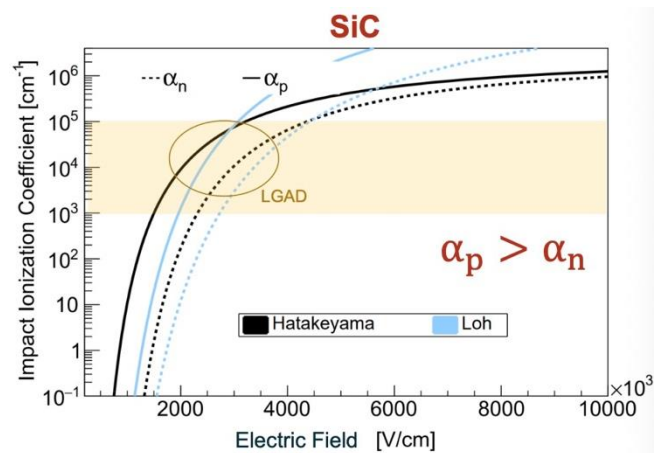
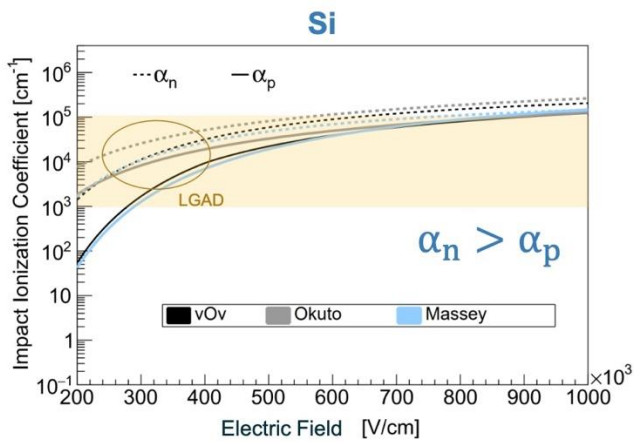
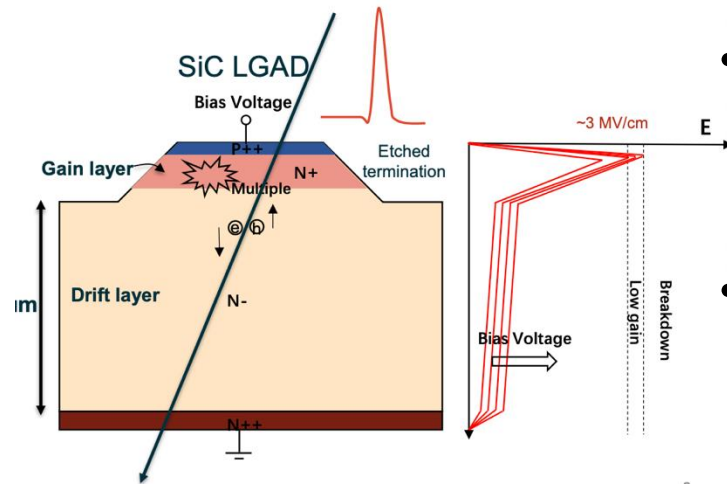
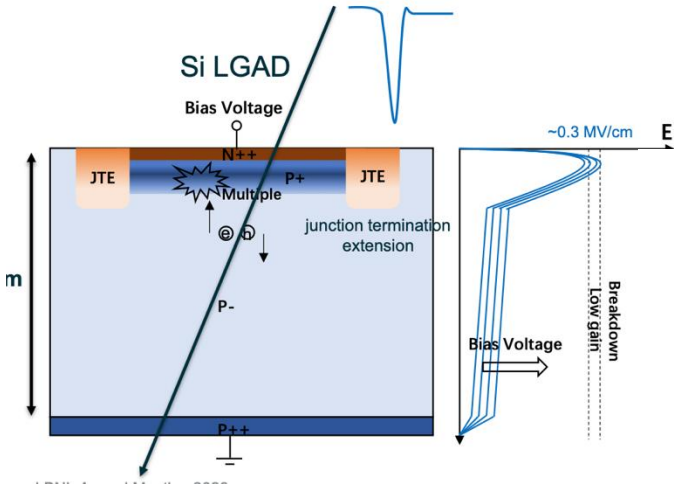
- 4H-SiC Advantages: Higher electric breakdown strength, higher charge carrier mobilities, no cooling required (especially after irradiation)
- 4H-SiC Disadvantages:
  - Larger mean ionization energy of MIPs (7.8/3.6eV for SiC/Si) → smaller signal for the same amount of deposited energy
  - Limited epitaxial thickness and quality → **<100 $\mu\text{m}$  sensitive volume**



## A promising solution is to develop 4H-SiC LGADs

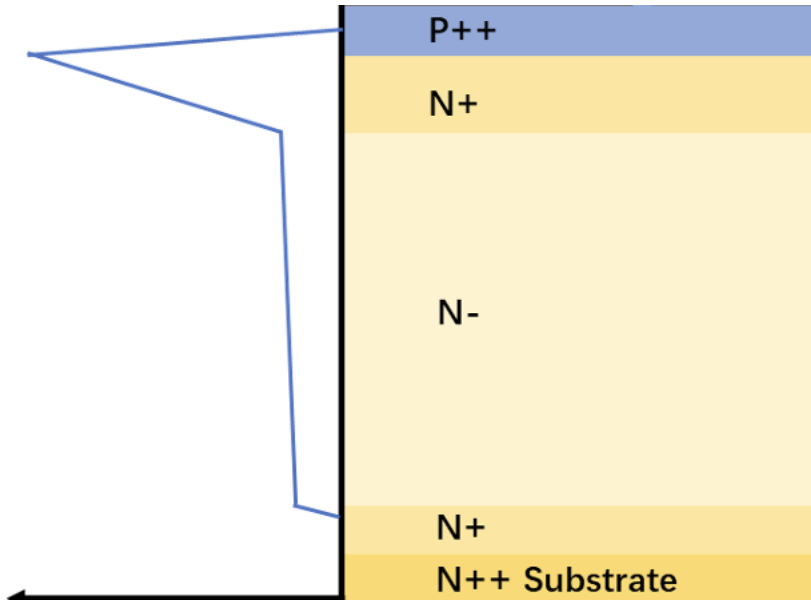
- provide enhanced signal charges through gain layer, and inherit the intrinsic material advantages of 4H-SiC
- operate effectively in **high-radiation environments while providing precise time measurements**

# 4H-SiC LGADs



- Impact ionization coefficients of holes ( $\alpha_p$ ) / electrons ( $\alpha_n$ ) smaller in SiC  $\rightarrow$  **Higher E-field**
- $\alpha_p > \alpha_n$  in SiC & saturation velocity of electrons in SiC is over twice that of holes in Si  $\rightarrow$  **N-type drift and gain layers**
- Higher mobility of electrons drifting back across an N-type epitaxial layer  $\rightarrow$  **Faster signal**
- High quality N-type SiC substrates and drift layers easier to grow

# 4H-SiC LGADs — Epitaxial Layers



Method: Chemical Vapor Deposition (CVD)

## Drift layer

- Nitrogen(N)-doped
- Doping concentration as low as possible to decrease the depletion voltage ( $\sim 10^{14} \text{ cm}^{-3}$ )

## Gain layer

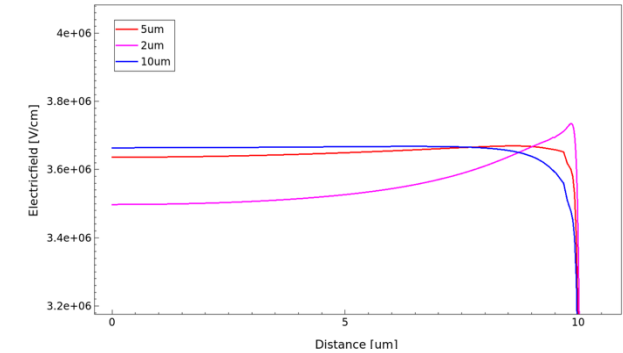
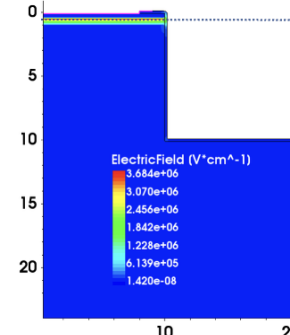
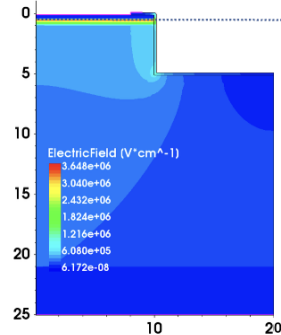
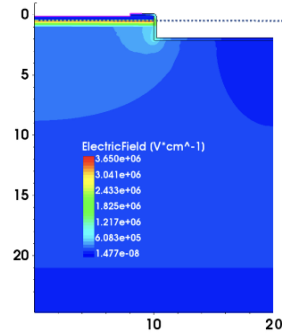
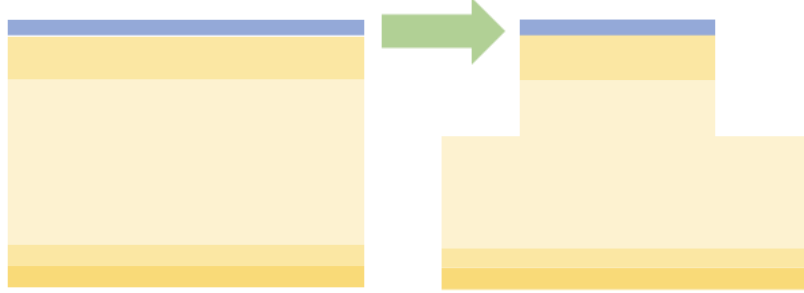
- Highly N-doped gain layer ( $\sim 10^{17} \text{ cm}^{-3}$ ) and p-type layer to create a large E-field at the p-n junction to induce avalanching

## P-type contact layer

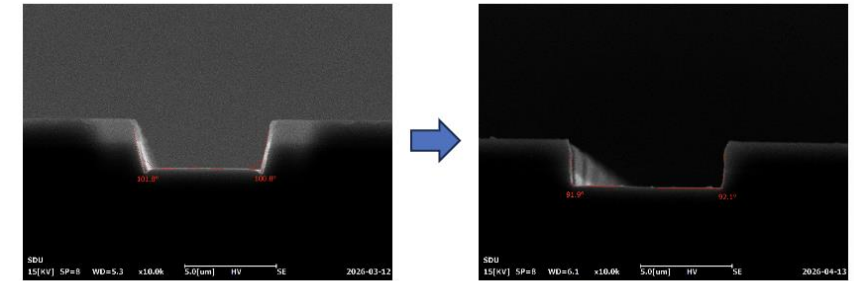
- Aluminum doped ( $\sim 10^{20} \text{ cm}^{-3}$ )

# 4H-SiC LGADs – Vertical Mesa Termination

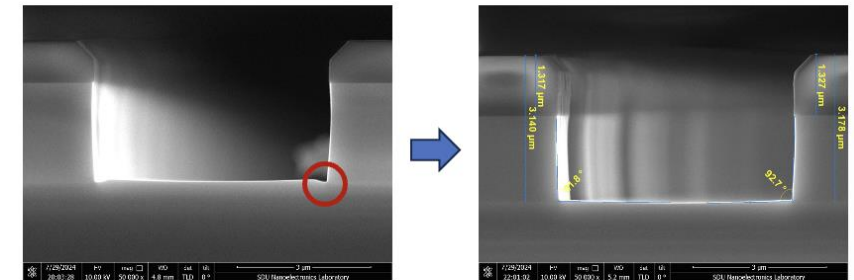
ICP



- **Vertical mesa structures** fabricated via etching to realize a **high breakdown voltage**
- A mesa terminations **deeper than 2μm** to etch through the contact and gain layers and isolate the devices
- Inductively Coupled Plasma-Reactive Ion Etching (ICP-RIE)
- Etching process refined to achieve
  - **Vertical and smooth sidewalls**
  - **Rounded bottom corners**



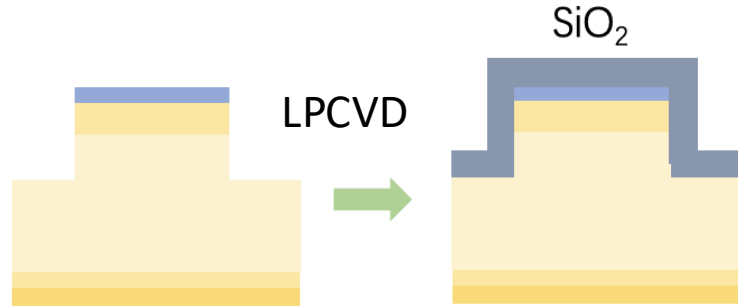
Optimize etching angle



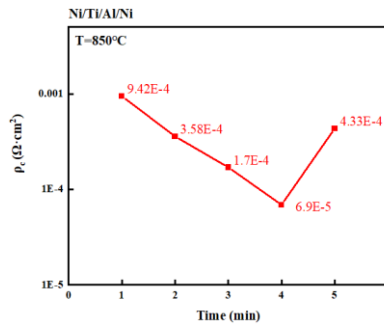
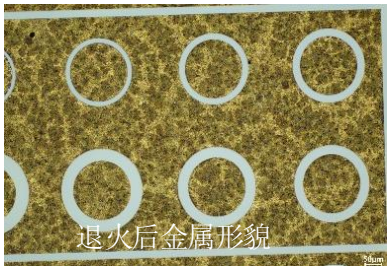
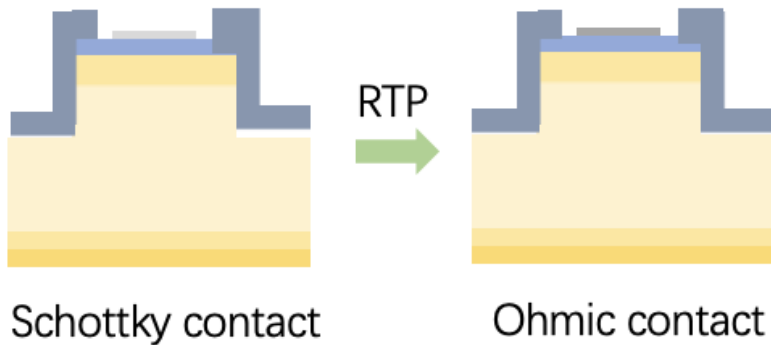
Eliminate the micro-trenching effect

# 4H-SiC LGADs — Passivation and Metal Contacts

## Low Pressure Chemical Vapor Deposition

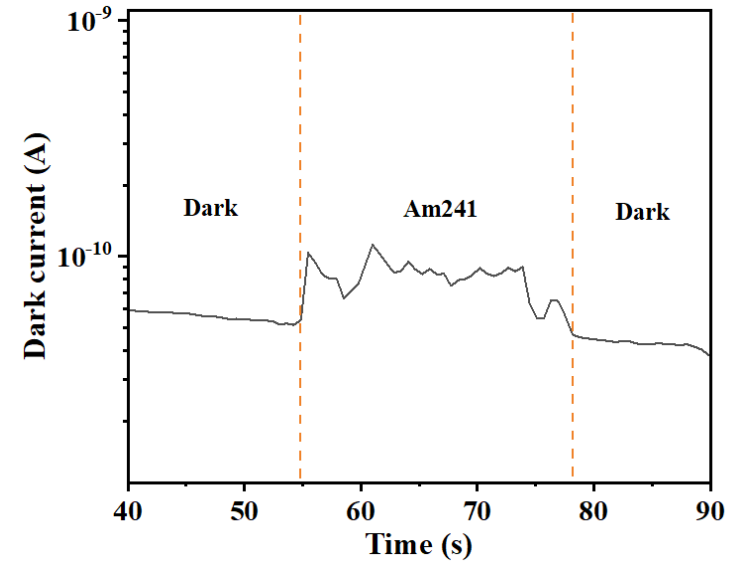
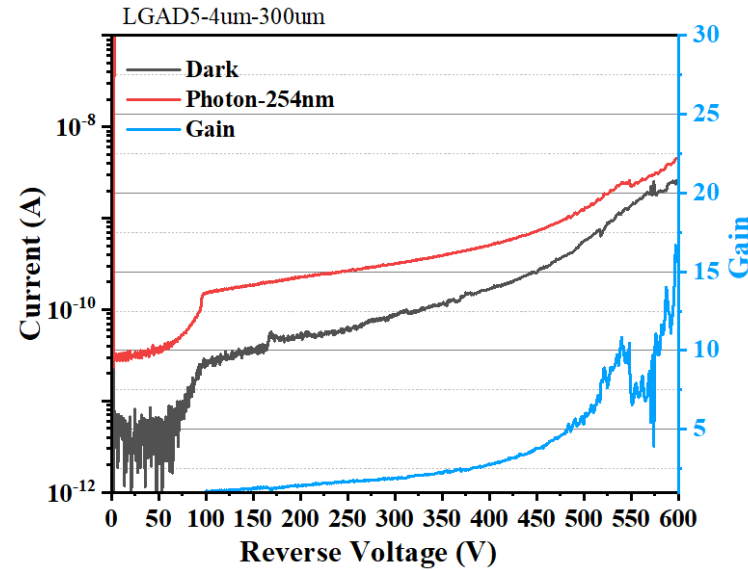
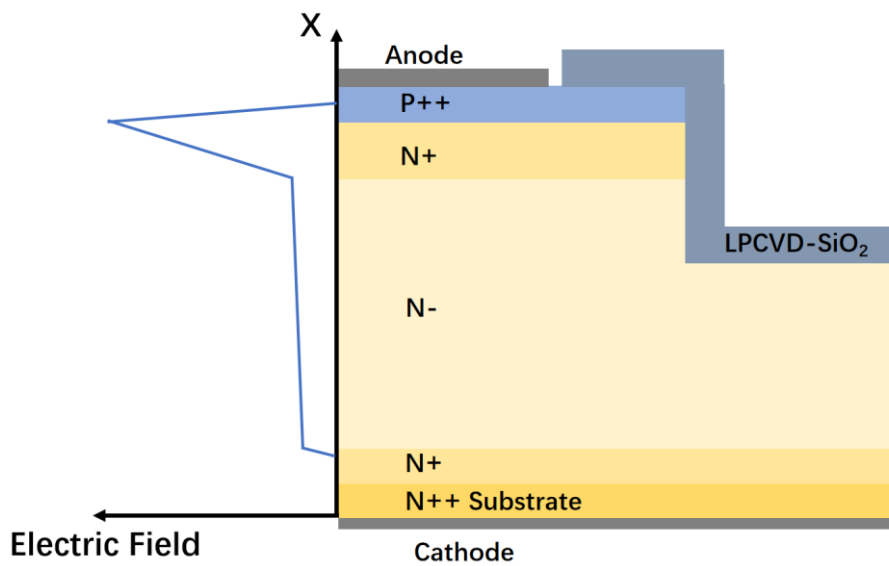


## Rapid Thermal Processing

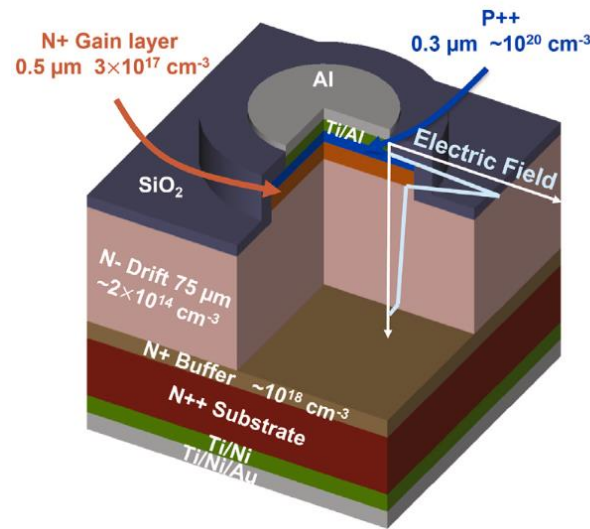


- **Device passivation to minimize surface traps**
- **DC coupling** in current design: selectively exposing the top of the mesa by Reactive Ion Etching (RIE) of the passivation layer
- After metal contacts deposition, **rapid annealing** of the device induces an interfacial reaction between the metal and SiC, **reducing the contact resistance**.
- Various metals and annealing schemes tried. A p-SiC ohmic contact scheme with a specific contact resistivity of  $6.9 \times 10^{-5} \Omega \cdot \text{cm}^2$ , featuring good morphology and uniform resistivity.
- Ni/Ti/Al/Ni is deposited as the anode and Ti as the cathode.

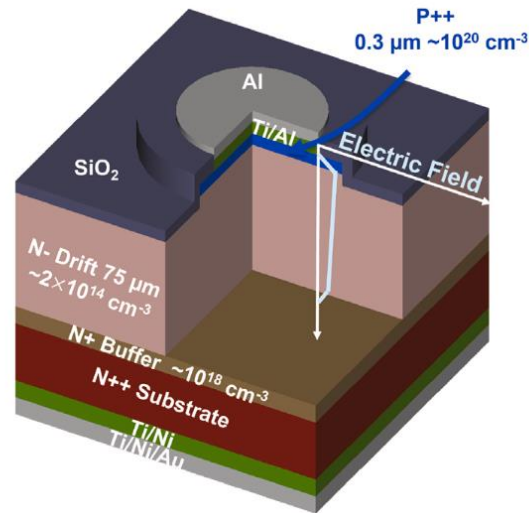
# 4H-SiC LGADs — Device Fabricated at SDU



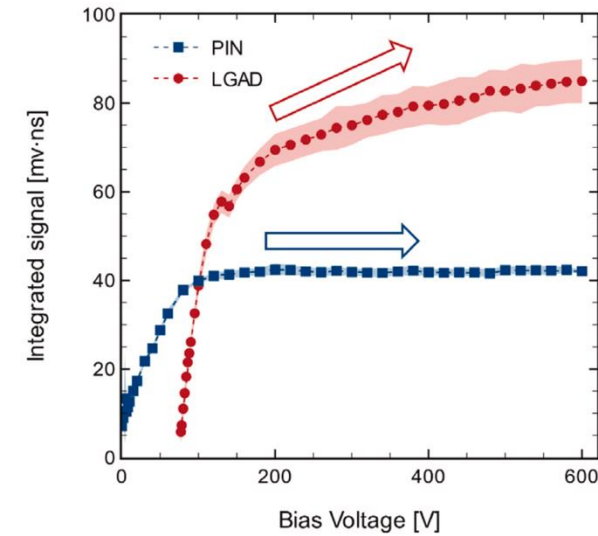
- **A very preliminary prototype device** ( $10\mu\text{m}$  drift layer) fabricated by Institute of Novel Semiconductors to **validate the fabrication process**
- Quick check
  - Using a 254nm LED as the signal source, the device gain was tested up to 600V, achieving a maximum gain of  $>10$ .
  - Under 200V bias, a measurable response to  $\alpha$  particles emitted from an Am-241 source.
- More tests on-going



4H-SiC LGAD



4H-SiC PiN diode

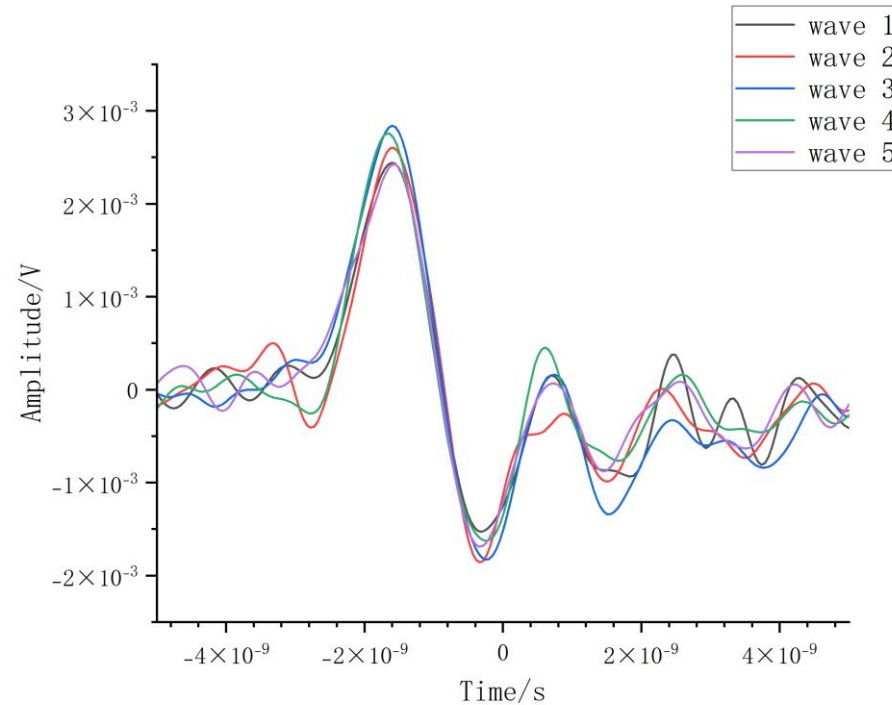


- PIN diode w/o gain layer for comparison
- Amount of charge collected from  $\alpha$ -particle ionization in the LGAD higher than that in PiN diode  
→ low-gain multiplication of charge carriers in LGAD
- A new paper is coming out soon: an upgraded device with gain factor  $\sim 80$ , better timing resolution, and verified radiation hardness → **4H-SiC LGAD confirmed as a high-performance timing detector**

Experience accumulated in testing silicon AC-LGADs developed by IHEP, is directly transferable to the testing of SiC LGADs.

This section is handled by Kun HU.

# Characteristics of AC-LGAD signal



## Characteristics of AC-LGAD output signal

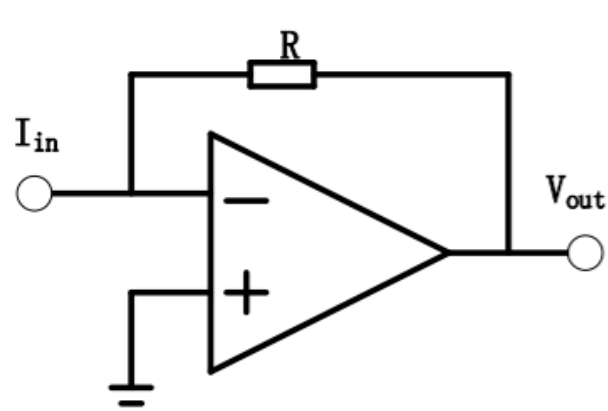
- Short pulse ( $\sim 2$  ns)
- Fast rise time ( $\sim 500$  ps)
- Small amplitude ( $< 10$  mV)



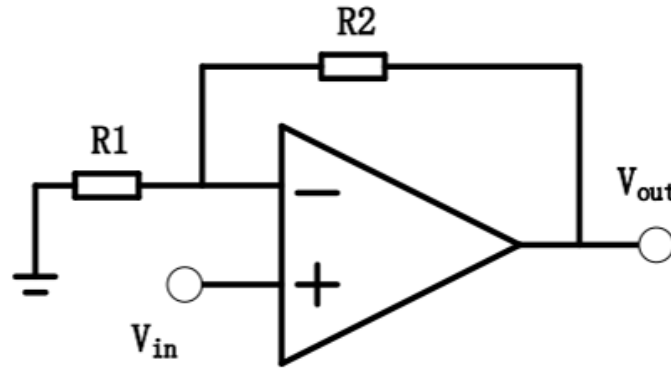
## Characteristics of Front-End Electronics (FEE)

- **Fast response**
- **High bandwidth** of the FE amplifier
- **Large gain** of the FE amplifier

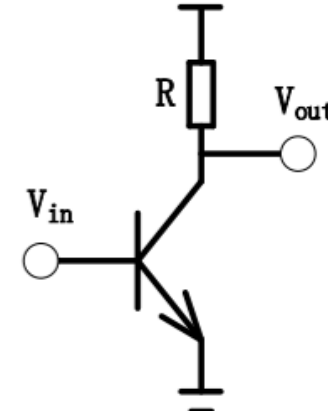
# Front-End Readout electronics



(a)



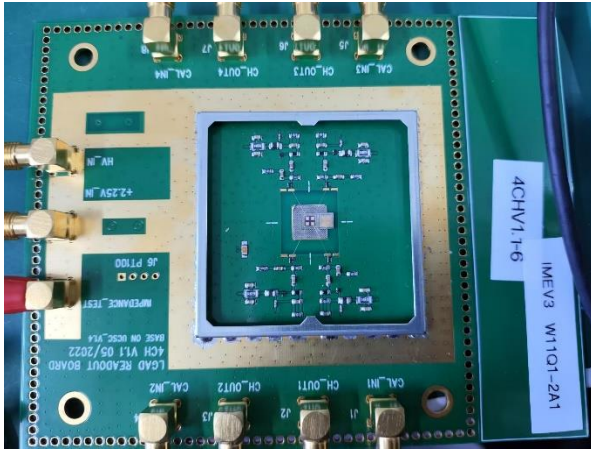
(b)



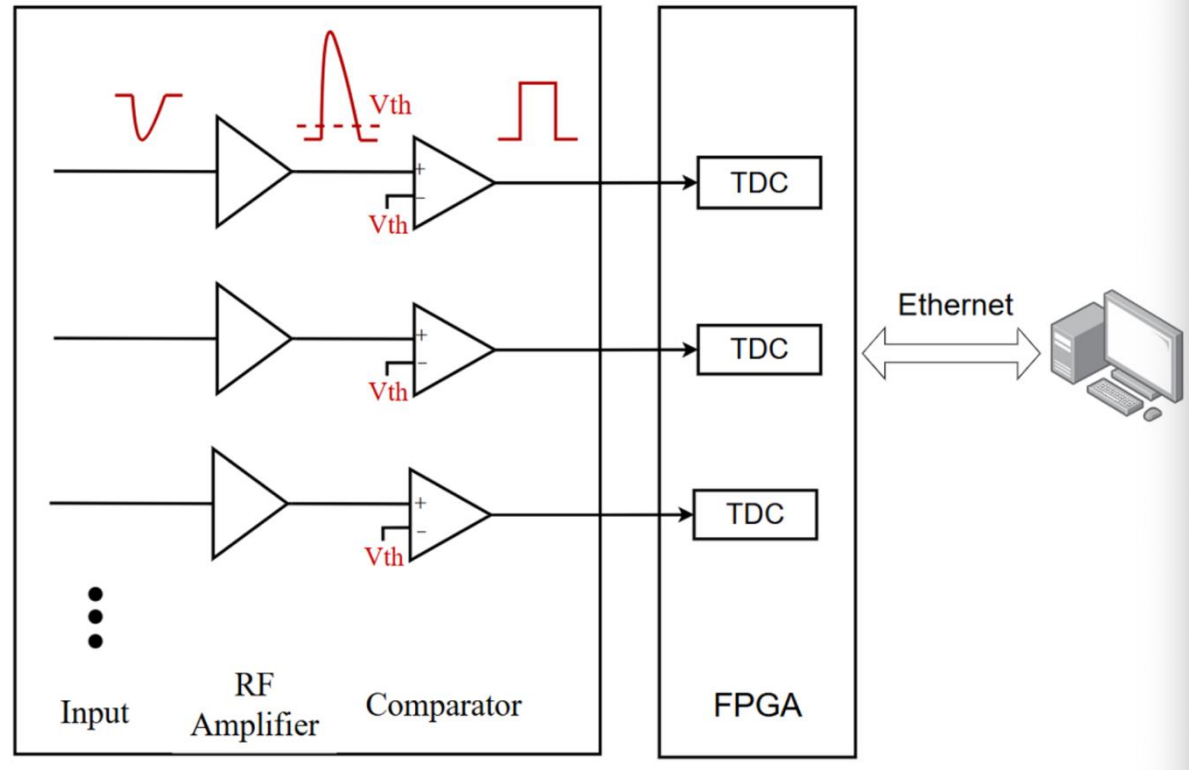
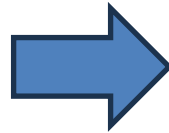
(c)

- Charge sensitive amplifier (CSA) not feasible for a very fast leading edge, due to the integration process
- **Amplifiers for the fast signals**
  - a) Transimpedance Amplifier (**TIA**):  $V_{out} = I_{in} * R$ , bandwidth sensitive to the feedback resistor
  - b) Voltage Amplifier (**VA**):  $V_{out} = (1 + R_2/R_1)V_{in}$ , bandwidth limited by the voltage gain
  - c) **Wideband Radio-Frequency Amplifier (RF): fixed gain, bandwidth is more than 1GHz**

# Framework of the FEE



LGAD detector & adapter board



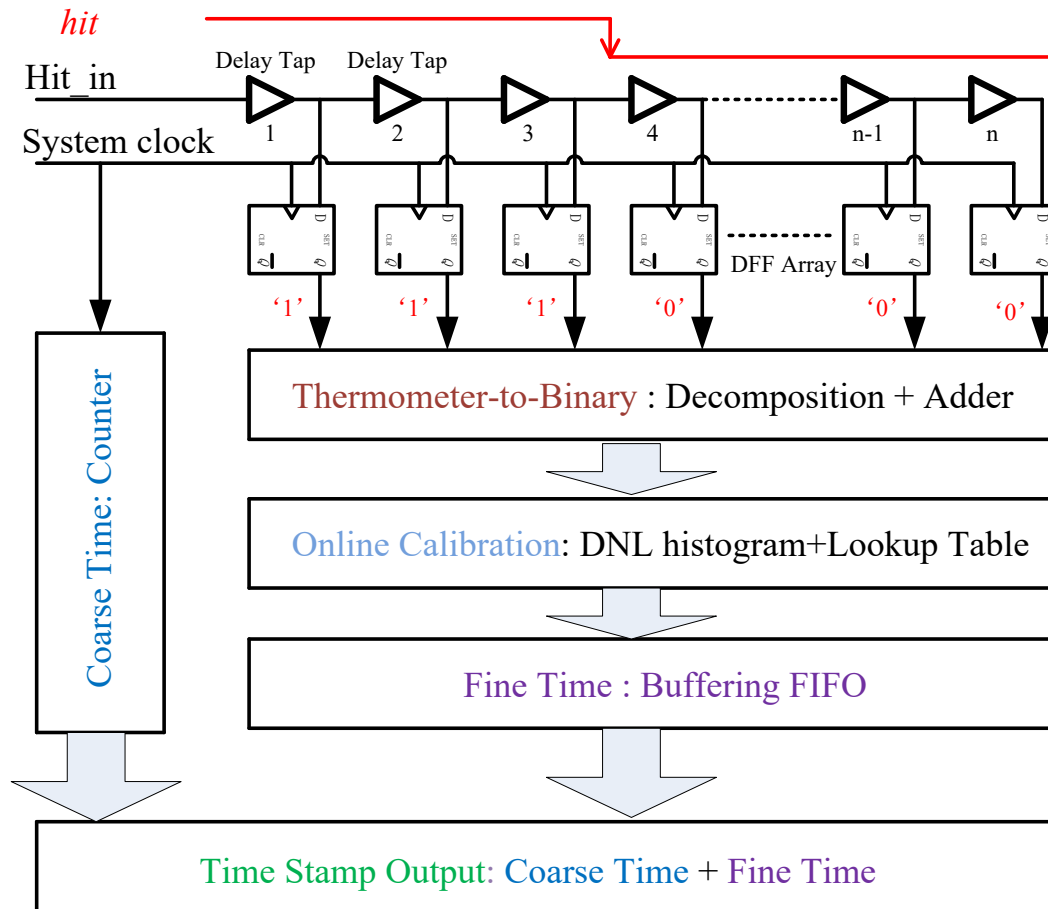
LGAD front-end electronics (FEE)

PC

## We designed a framework of FPGA based readout electronics

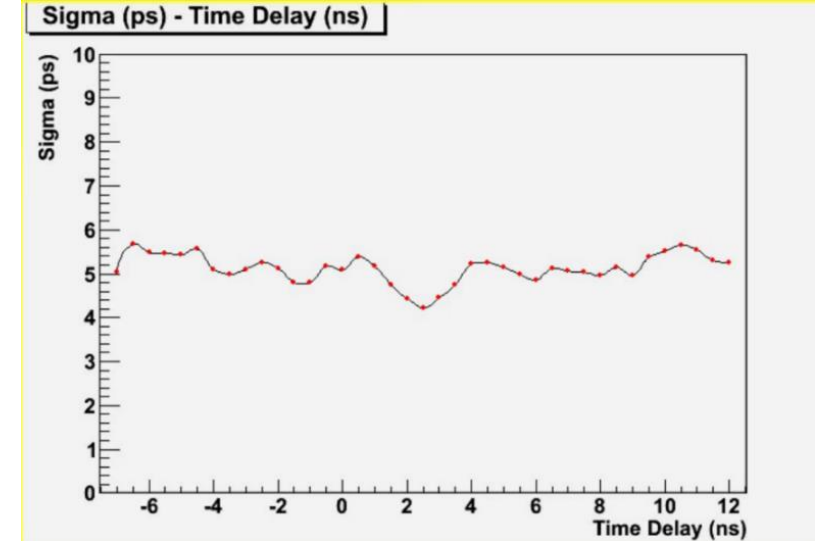
- LGAD detectors are wire bonded to a FE adapter board on which the signals undergo the first-stage amplification.
- The amplified signals are discriminated using fast discriminator
- The discriminated digital signals are sent to FPGA for ToA and ToT measurement.

# FPGA-based TDL-TDC



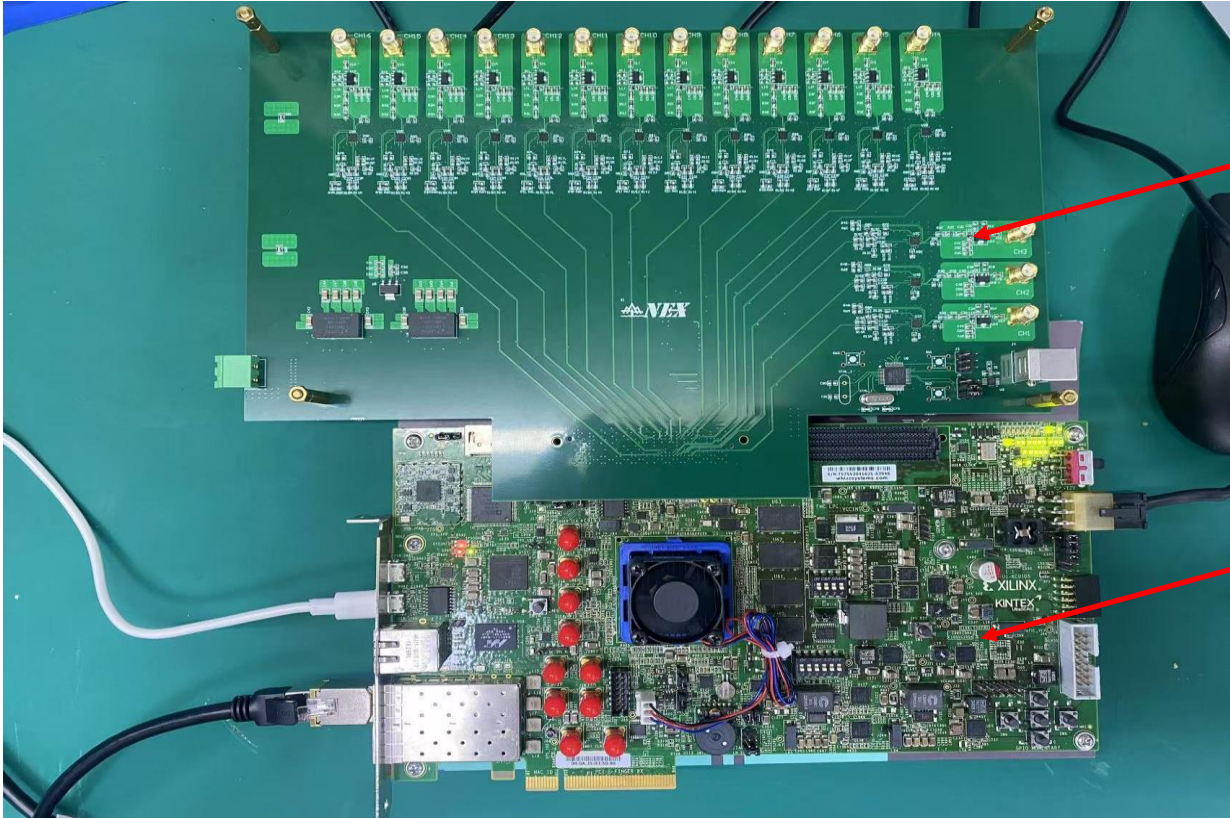
## FPGA-based Tapped Delay Line (TDL) TDC

- Coarse time: 16-bit counter
- Fine time: Tapped delay line, implemented with dedicated carry chains (CARRY8)



- Pulses from generator input to TDL-TDC in Kintex Ultrascale family → Timing resolution  $\sim 4$  ps

# 16-ch FEE Prototype



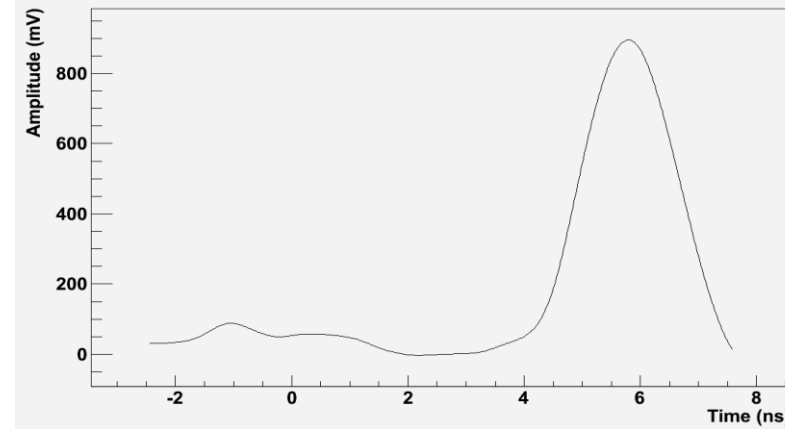
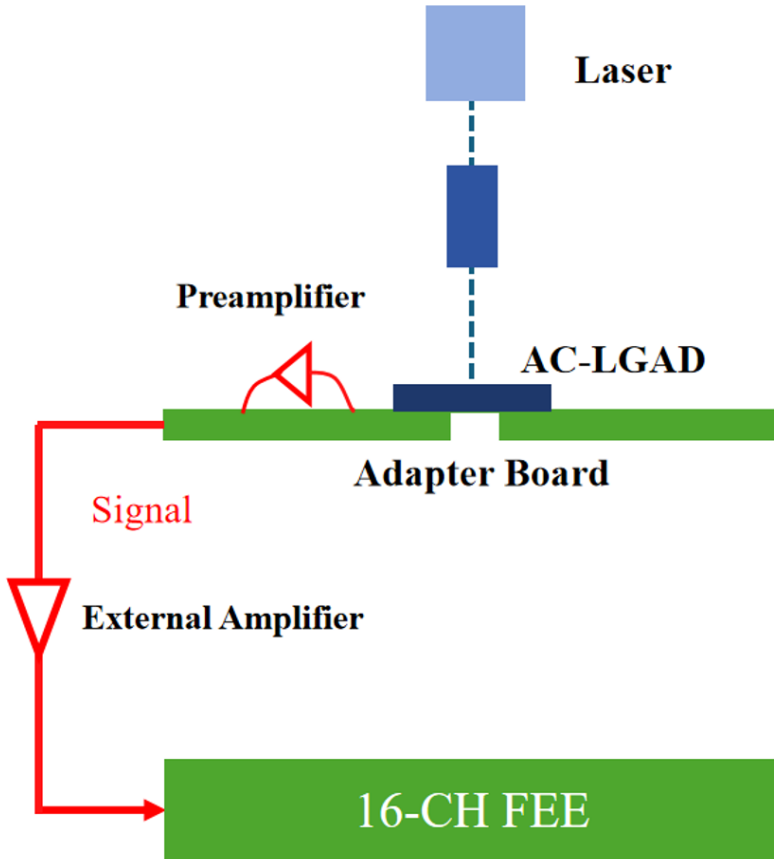
## 16-ch front-end board

- **RF amplifier:** ADL5545, 6 GHz with integrated bias control circuit
- **Discriminator:** ADCMP572 with differential output

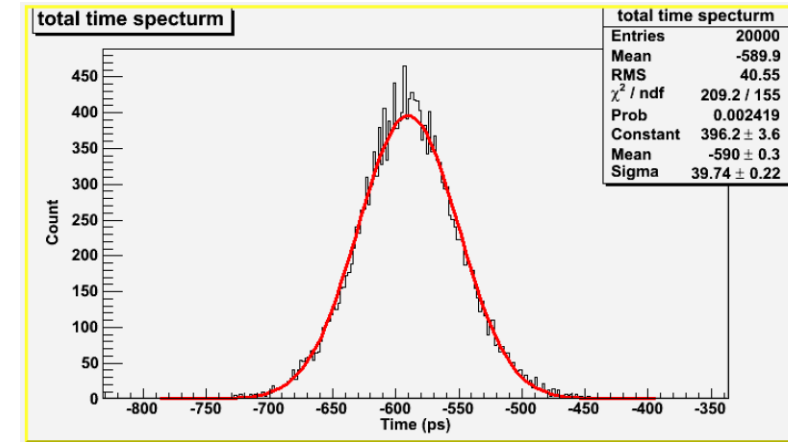
## KCU116 development board

- **FPGA-based TDC:** ToA & ToT measurement

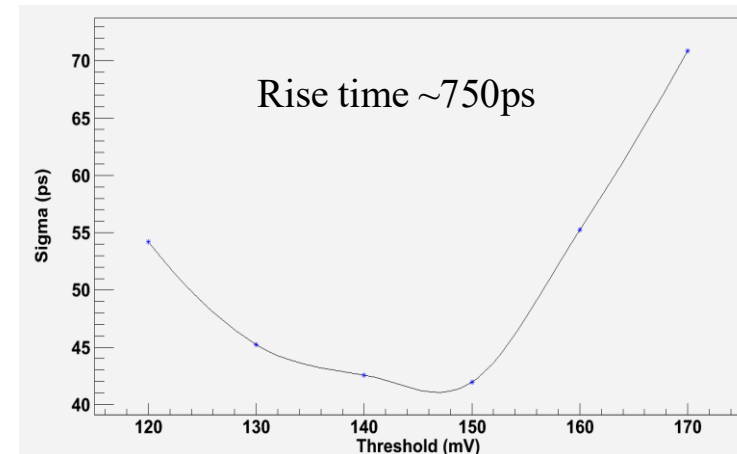
# Detector Test with 16-ch FEE prototype



AC-LGAD signal after three-stage amplifiers (~900mV), pulse width ~3ns



~28 ps at threshold of 145mV



Resolution vs Threshold

- Low threshold: Timing resolution limited by the amplified noise
- At high threshold: The rising edge of the signal pulse becomes less steep

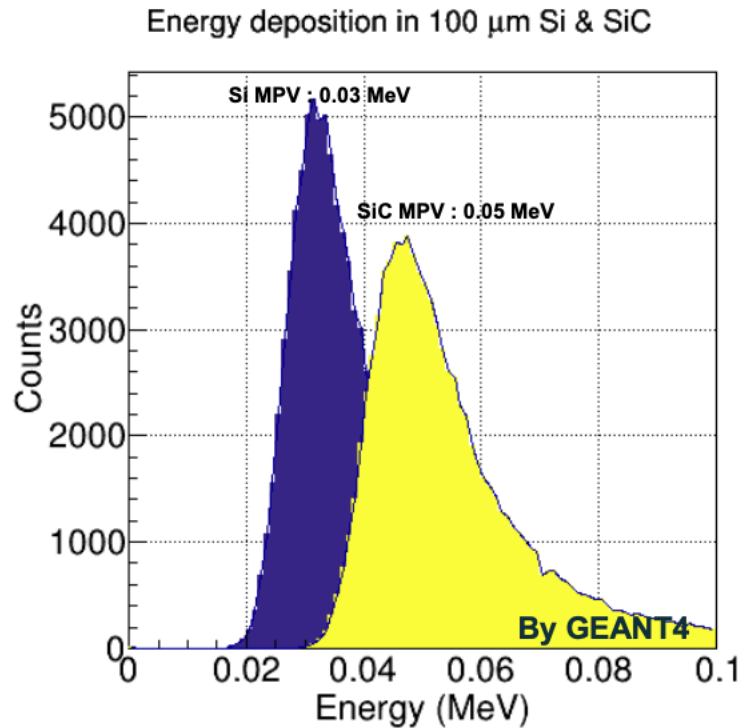
# Summary

- **4H-SiC detectors have the potential to outperform Si for fast charged particle detection.**
- A preliminary prototype device was fabricated and validated the fabrication process.
- After the initial proof-of-design/fabrication, we proceed to fabricate **more prototype devices** for comprehensive characterization.
- For electric testing , **16-ch FEE prototype was developed.**
  - **ToA measurement achieved.** Preliminary test results of AC-LGAD detector shows a good timing resolution, it could be improved after the ToT calibration in the future.
  - To achieve ToT measurement
  - Try other types of amplifiers with high bandwidth



backup

# Minimum Ionizing Particle (MIP) Detection



- In the Si and SiC detectors with same thickness, the signal generated by the MIP in the SiC is smaller than that in the Si.

Silicon:  $\sim 78$  e-h pairs /  $\mu\text{m}$   
( $\sim 3.6$  eV / e-h pairs)

SiC:  $\sim 55$  e-h pairs /  $\mu\text{m}$   
( $\sim 7.8$  eV / e-h pairs)

50  $\mu\text{m}$  Si LGAD

$\sim 75$   $\mu\text{m}$  SiC LGAD

# RF Amplifier test in IHEP

**PGA-103+** : BandWidth 4GHz, rise time 600ps-800ps;

**BGA420** : BandWidth 3GHz, rise time 500-600ps;

**BGA427** : BandWidth 3GHz, rise time 400-500ps;

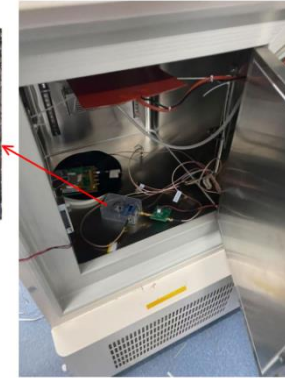
**PHA-23LN+** : BandWidth 2GHz, rise time 600ps;

**ADL 5536** : BandWidth 1GHz, rise time 700ps-900ps;

**MAR-6+/ADL5545** : BandWidth 6GHz, rise time **550ps**, pulse width < **2ns**.



AC-LGAD 探测器



AC-LGAD 测试箱



AC-LGAD 前置放大电路测试结果

Experimental setup in IHEP

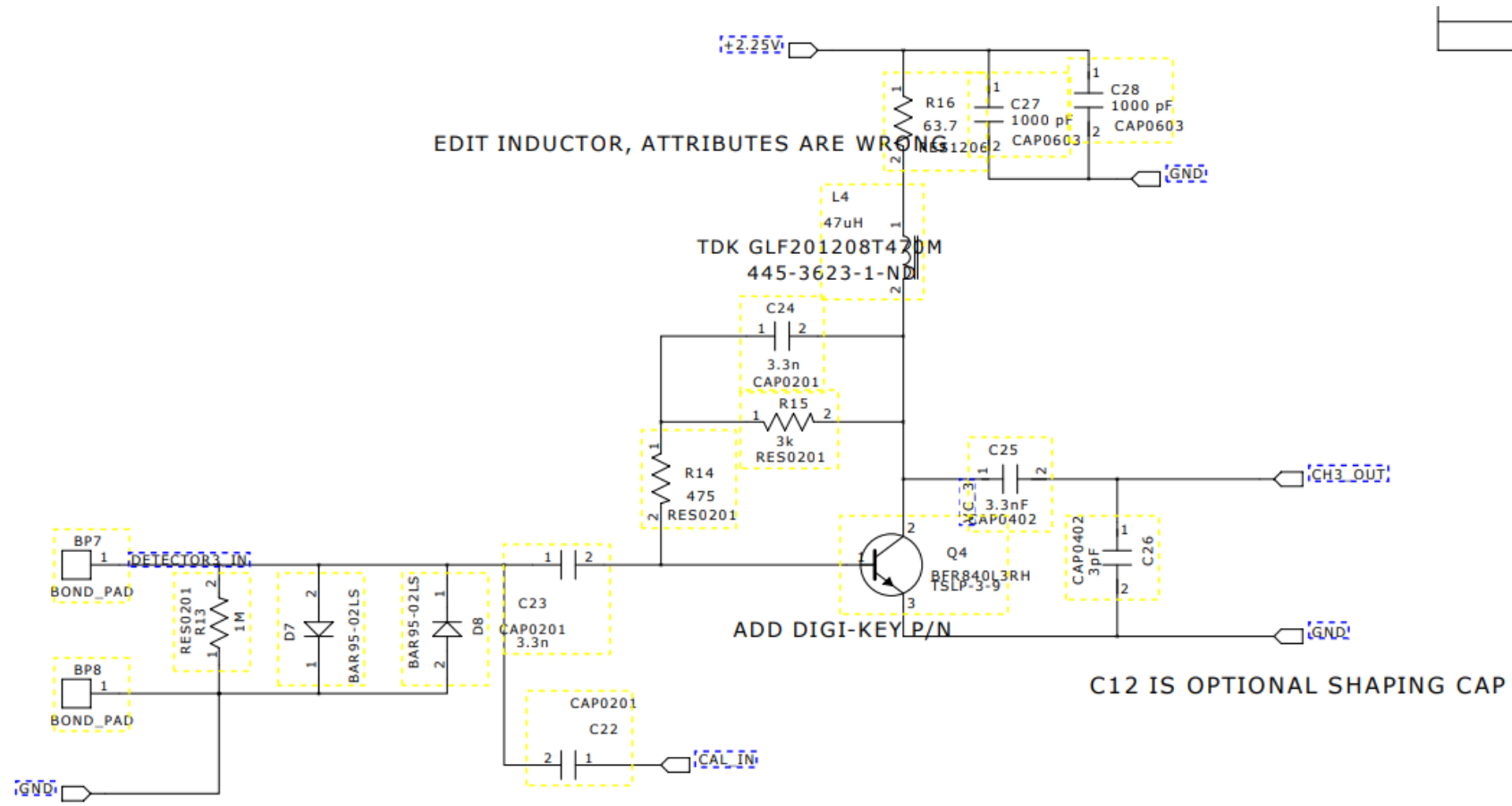


More than 100 mV after two-stage RF Amp.

# Adapter board



LGAD detector & adapter board



One-stage or two-stage emitter amplifiers