The Development of Silicon Carbide Low Gain Avalanche Detector

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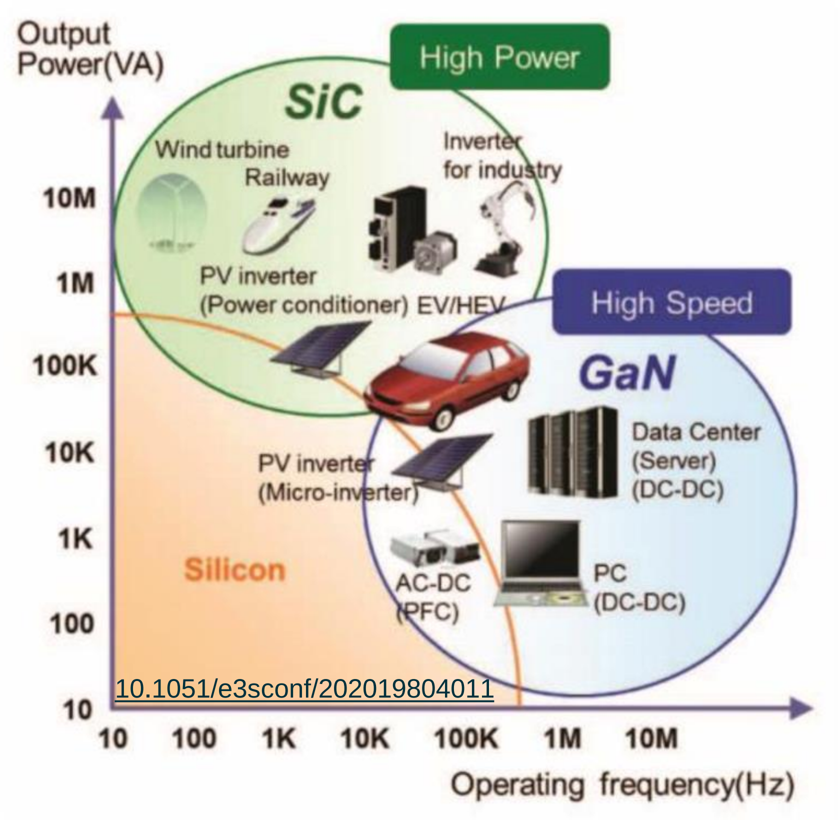
Introduction of Silicon Carbide

Third generation (Wide Bandgap) Semiconductors

- **First generation semiconductors (indirect bandgap & narrow bandgap)** : Since 1950, semiconductor materials represented by silicon (Si) have replaced electron tubes, which is suitable for low-voltage, low-frequency, and medium-power integrated circuits.
- **Second-generation semiconductors (direct bandgap & narrow bandgap)** : Since 1990, such as gallium arsenide (GaAs), indium phosphide (InP). They are suitable for making high-speed, high-frequency, high-power and light-emitting electronic devices.
- **Third generation semiconductors (direct bandgap & wide bandgap)** : long history but limited by process technologies. In recent years, materials represented by gallium nitride (GaN) and silicon carbide (SiC) have attracted much attention with the development of process technologies, which are suitable for making high temperature, high frequency and high power devices.



10.1051/e3sconf/202019804011

1st generation
- **Materials:** Si, Ge
- **Properties:** low-voltage, low-frequency, and medium-power
- **Applications:** electronics, new energy, and photovoltaic industry

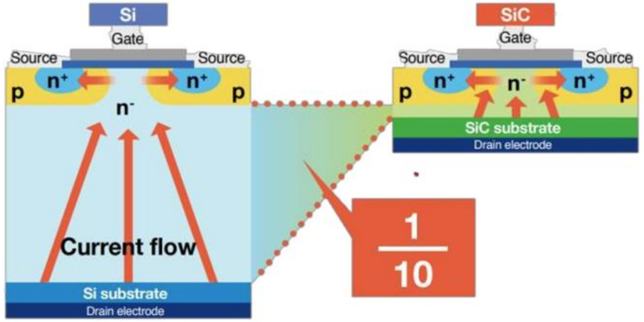
2nd generation
- **Materials:** GaAs, InP
- **Properties:** high-frequency and low-noise
- **Applications:** wireless communications, optical communications

3rd generation
- **Materials:** GaN, SiC, Diamond and ZnO
- **Properties:** wide bandgap
- **Applications:** new energy vehicles, photovoltaic energy storage

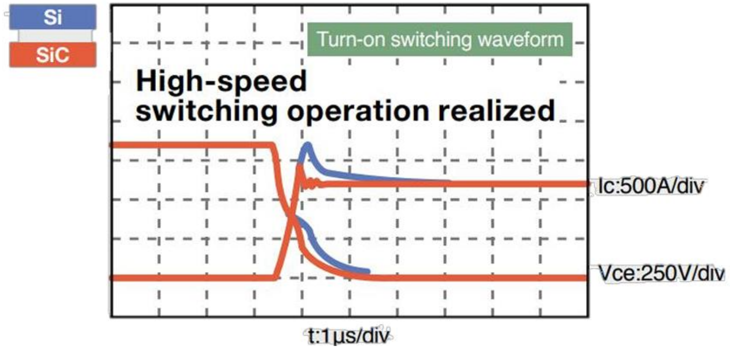
Silicon Carbide(SiC) for Integrated Circuit

Silicon Carbide is useful for power devices and high-speed switching.

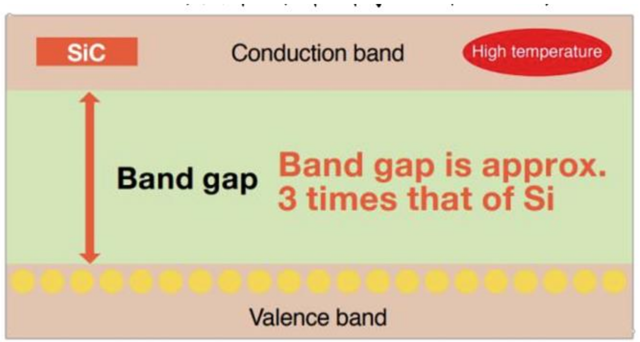
- **Low power consumption**: On-resistance of SiC device is only 1/10 of that of Si



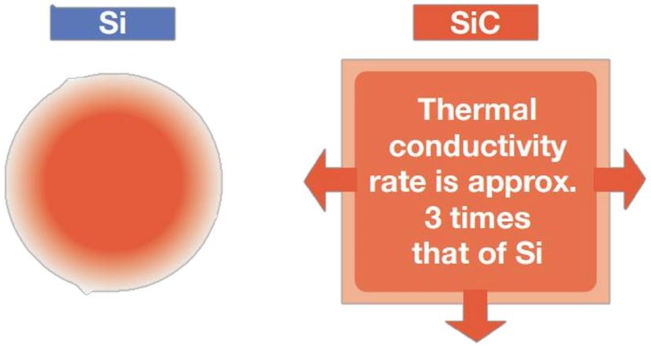
- **High-speed switching:** high drift velocity and small transit time



- **High temperature resistance**: SiC's bandgap is three times that of Si, preventing leakage current flow and allowing operation at high temperatures.



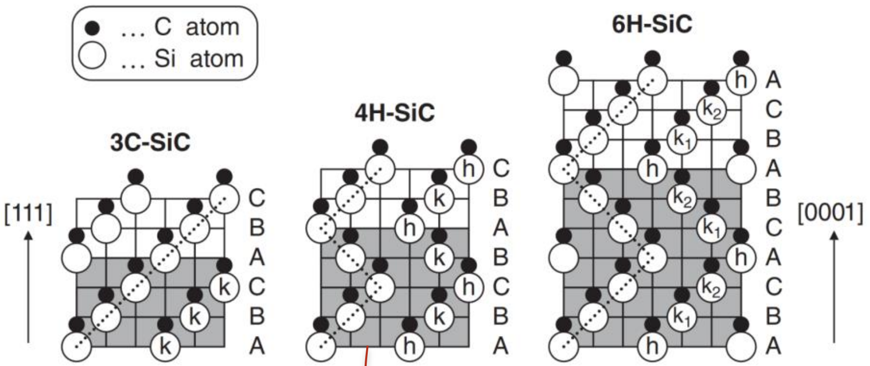
- **Heat dissipation:** the thermal conductivity of SiC is about 3 times that of Si, which dissipates heat quickly.



Silicon Carbide for Charged Particle Detection

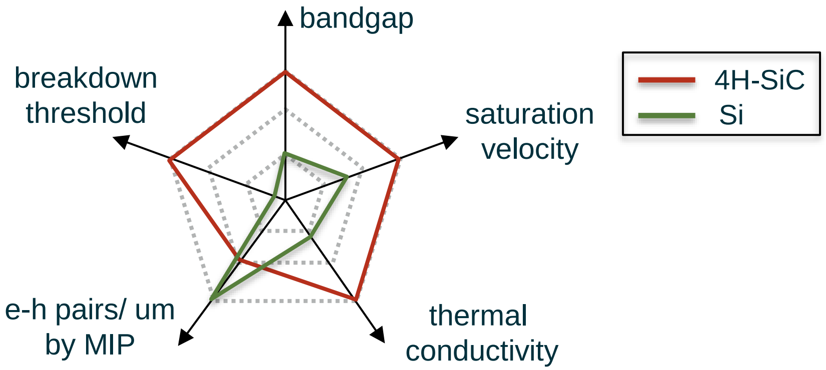
As a wide-band semiconductor material, among many silicon carbide (SiC) polymorphs, 4H-SiC has potential applications in radiation detection, especially fast time detection and high temperature environment.

Schematic structures of popular SiC polytypes: 3C, 4H and 6H



Kimoto, Tsunenobu. Fundamentals of Silicon Carbide Technology,2014

Highest mobility
Most widely used



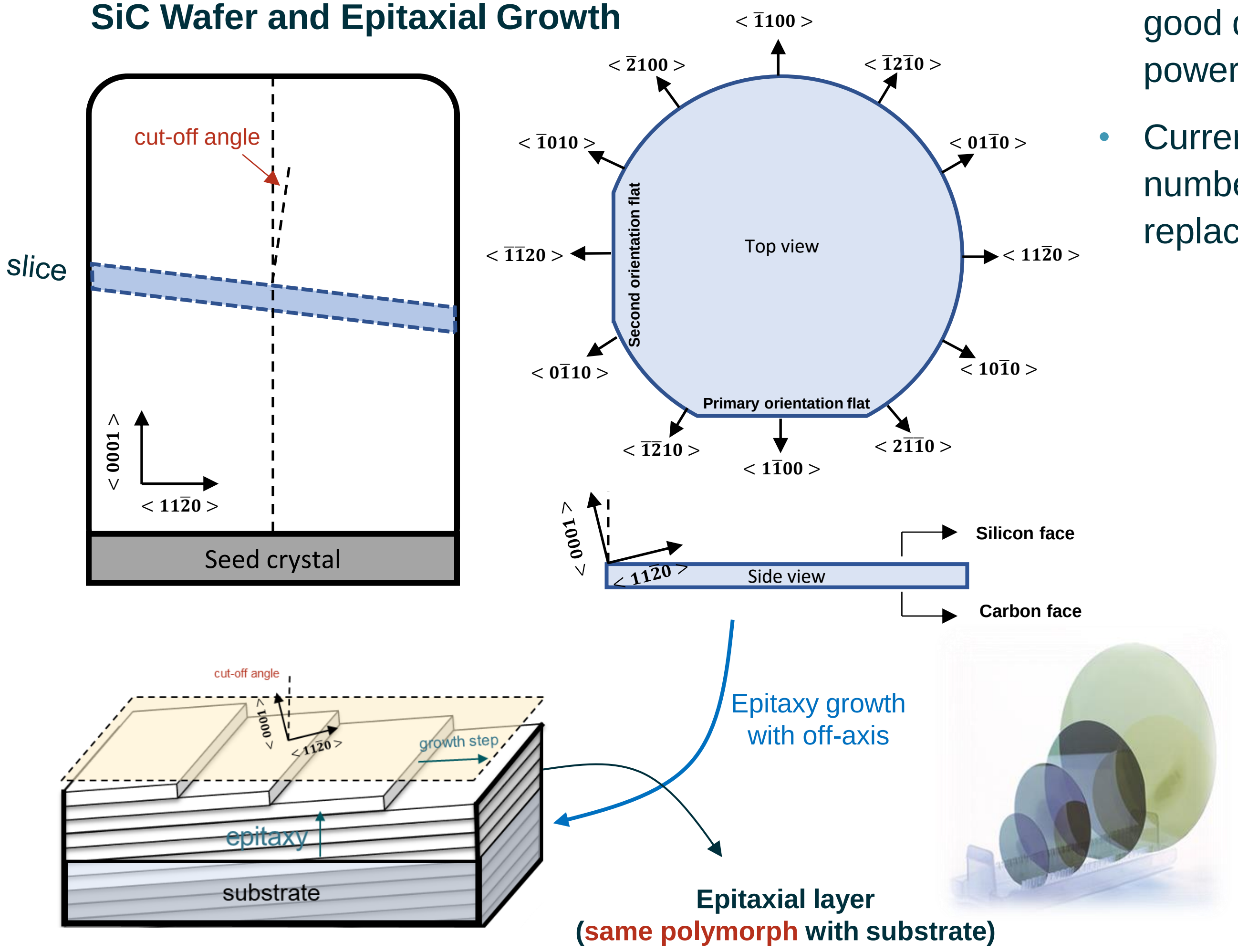
The parameters of Si and 4H-SiC

Parameters	Si	4H-SiC
Band gap[eV]	1.12	3.26
Relative permittivity	11.7	9.76
Thermal conductivity[W/K·cm]	1.5	4.9
Average ionization energy [eV/e-h pair]	3.6	5-9
Average e-h pairs for MIP [μm^{-1}]	~78	~55
Breakdown Threshold [MV/cm]	~0.3	~2.0
Atom displacement energy [eV]	13-15	30-40
Funno factor	0.11-0.13	0.04-0.12
Electron mobility [cm2/Vs]	1450	800
Hole mobility [cm2/Vs]	450	115
Electron saturation velocity [cm/s]	1×10^7	2×10^7
Hole saturation velocity[cm/s]	0.6×10^7	1.8×10^7

Epitaxial Growth of Silicon Carbide

Silicon Carbide has had a long history, but for many years was limited by crystal quality including micropipes and basal plane defects. Schottky Barrier Diodes were first made widely available in the early 2000's followed by the commercialization of high voltage MOSFETS around 2011.

SiC Wafer and Epitaxial Growth



- Benefiting from off-axis epitaxial growth technology, which provides high purity, good doping control and uniformity, SiC became the preferred choice for power device fabrication in the mid-1990s.
- Currently there are several vendors offering SiC epitaxy and wafers, with the number of wafers produced per year growing rapidly as SiC is adopted to replace silicon in power electronics.
  - **wafer size: 3 / 4 / 6 / 8 inch**
  - **epi thickness：< 200 µm**
  - **epi doping range: 1e14 ~ 2e19 cm^{-3}**

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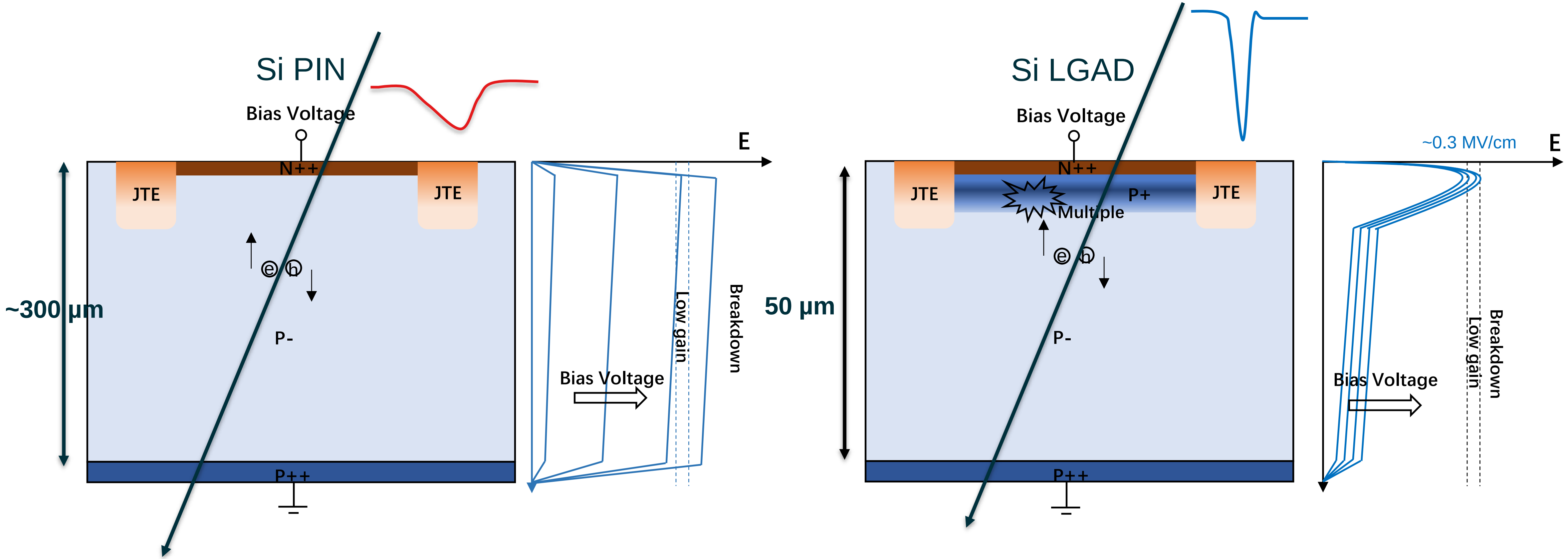
Silicon Carbide LGAD

Silicon Low Gain Avalanche Detector

PIN and LGAD

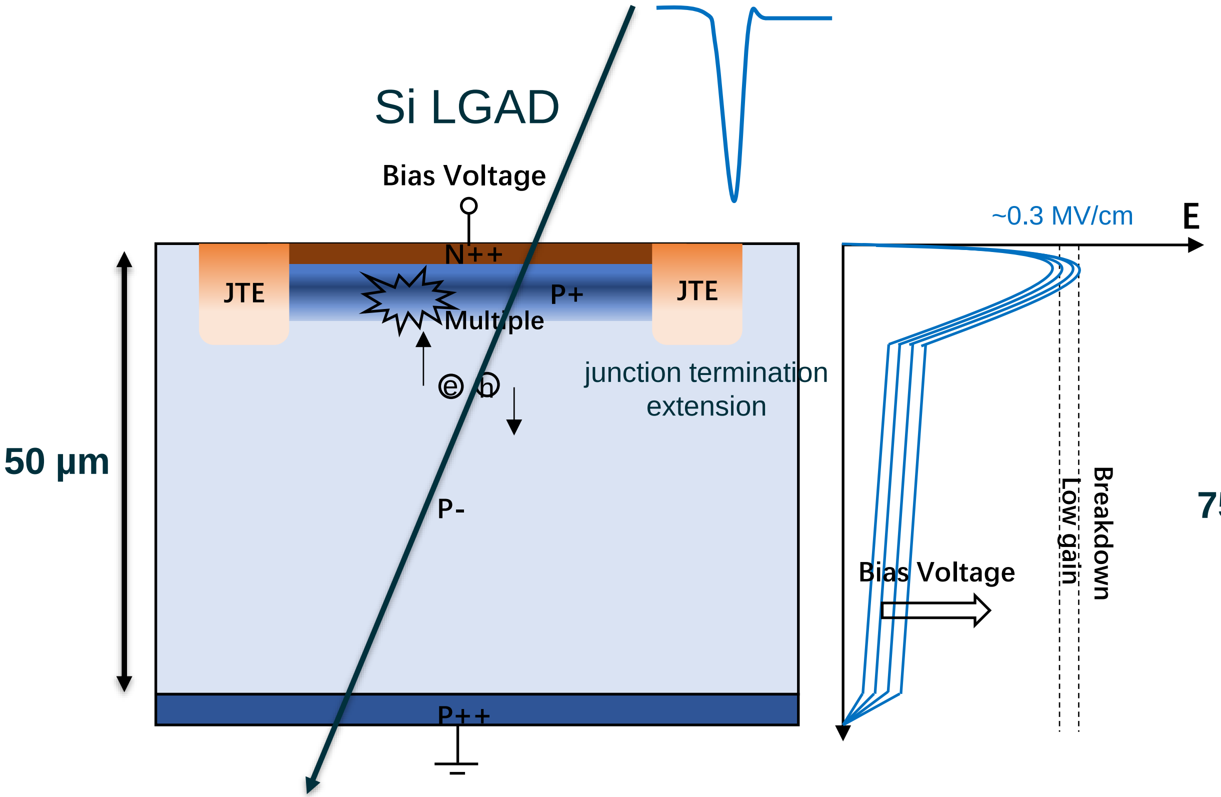
- LGAD has long operating voltage range with low gain 10~100.
- The electric field in the gain layer could make carries multiplication but don't reach the breakdown threshold.
- Si LGAD has been characterized by an excellent timing resolution < 50 ps benefited its great S/N.

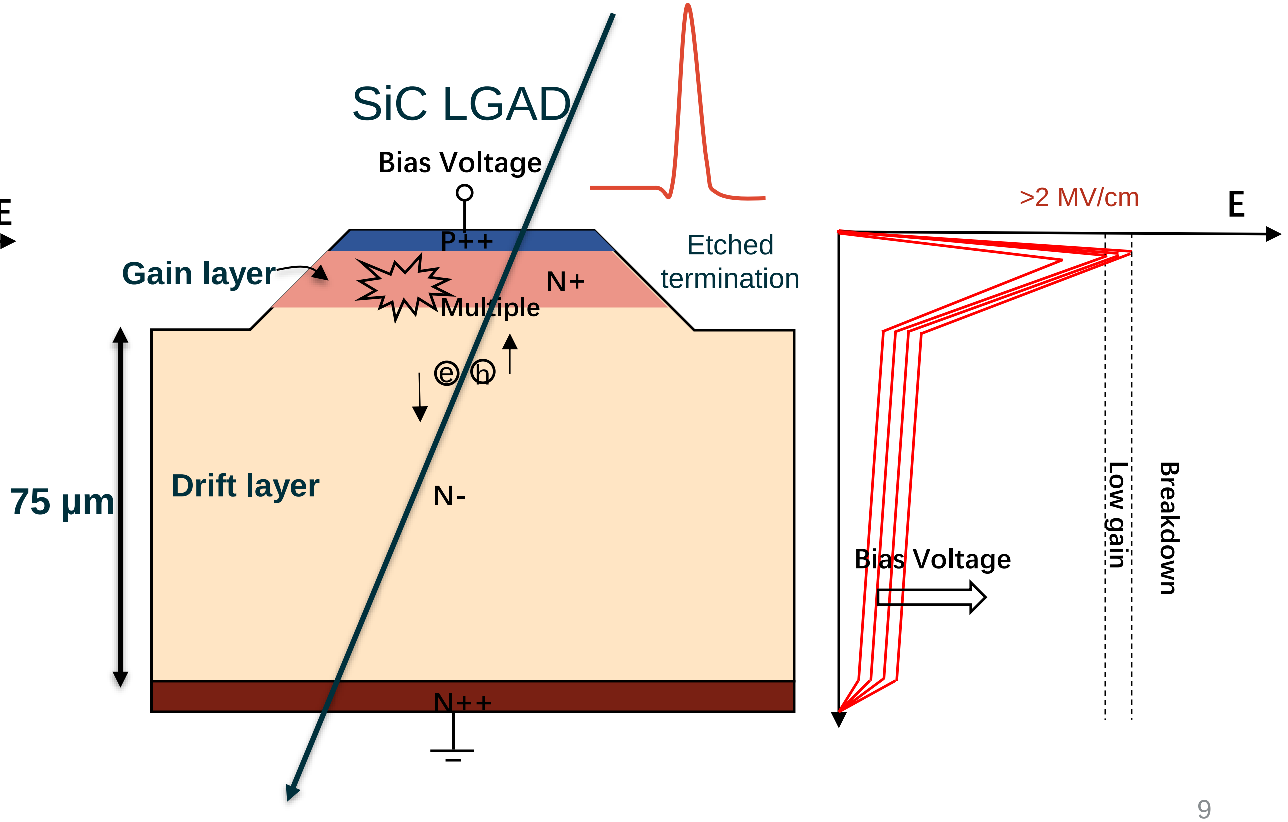


Silicon Carbide Low Gain Avalanche Detector (SiC LGAD)

- 50 µm P-type (~1e13 cm^{-3}) drift layer
- Primary electrons multiplication.
- Ion implantation for gain layer and JTE
- Electric field: ~0.3 MV/cm
- Gain layer doping: ~1e16 cm^{-3}

- 75 µm N-type drift layer(~2e14 cm^{-3})
- Primary holes multiplication.
- Epitaxial stack with etched termination (or ion implantation)
- Electric field: ~ 3 MV/cm
- Gain layer doping: > 2e17 cm^{-3}





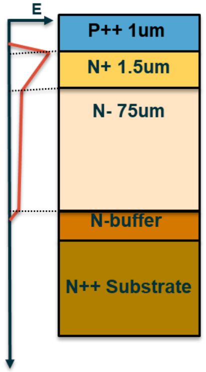
The Development of SiC LGAD by LBNL and NCSU

The simulation and design by LBNL and the fabrication by NCSU.

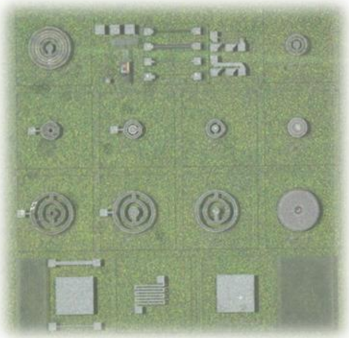
1st Generation SiC LGAD Prototype (2023)

- Based on 6-inch wafers from two vendors.
- 2 wafers with same LGAD epitaxial stacks.

Epitaxial stack

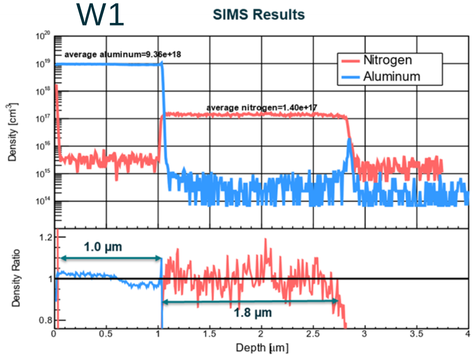


Fabricated devices

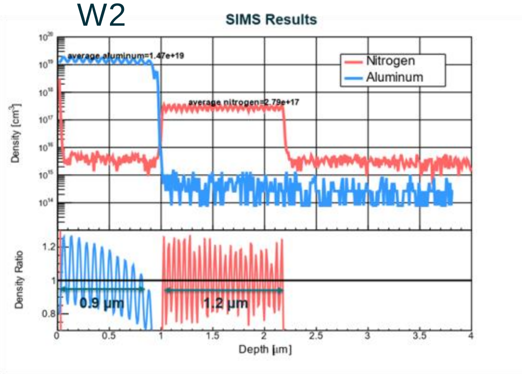


- LGAD
- Resistor
- MOS capacitor
- …

W1



W2

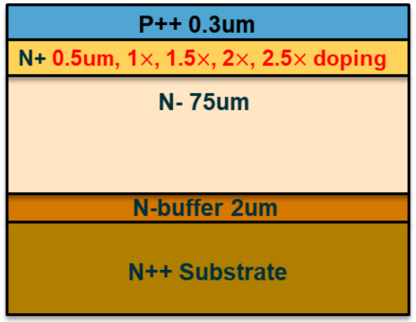


The thickness and doping of both wafers deviated from the expected values.

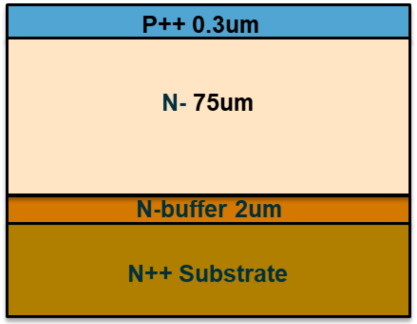
2nd Generation SiC LGAD Prototype (2024)

- Based on 6-inch wafers from one vendor, and the doping calibration is required for the epitaxy growth by vendor.
- 4 wafers with LGAD epitaxial stacks and one wafer with PIN epitaxial stacks.

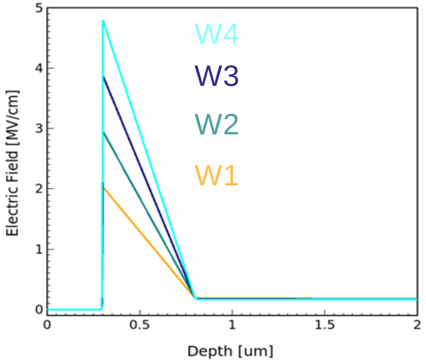
W1~W4 (LGAD)



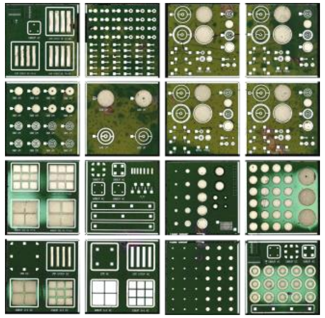
W5 (PIN)



Simulated Electric Field @500V



Fabricated devices



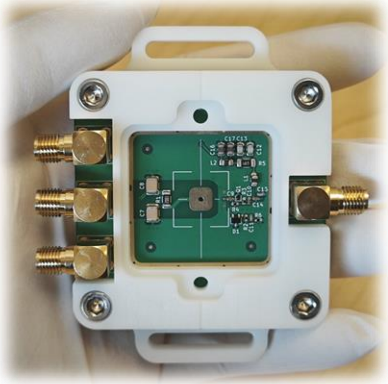
- DC-LGAD
- AC-LGAD
- Pixel-LGAD
- Strip-LGAD
- Resistor
- MOS capacitor
- …

Criteria necessary to demonstrate a 4H-SiC LGAD :

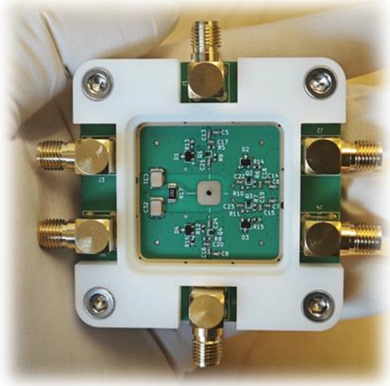
- LGAD requirement : $V_{GL} < V_{FD} < V_{BD}$.
  - The ultra-high voltage (0~2 kV) and low leakage(< 100 fA) IV/CV test.
- Demonstrate charge gain (PIN and LGAD with same thickness of drift layer and same process technology)
  - Response to α particle (large amount of charge generation).
  - Response to β particle (less amount of charge generation): landau distribution of collected charges
  - UV-TCT: gain uniformity, gain suppression and anisotropic effect.
- Time resolution for the β particle detection.
- Gain vs voltage dependent as per expectations from increasing field.
- SIMS measurement of doping and layer profile.
- Leakage current due to SiC LGAD itself and not parasitic etc.
- At least 2 devices from the same wafer with similar performance.
- A device from another wafer with higher doping shows expected performance. (Such as W3 and W4 of 2nd generation prototypes)
- (optional) Comparison of measured and predicted gain - either from simulation or analytic calculation.

Test Setup

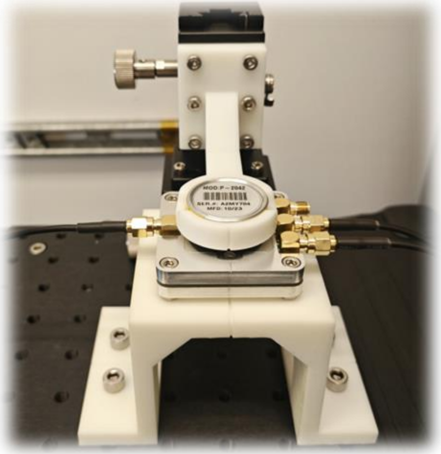
- **Single channel TIA board**



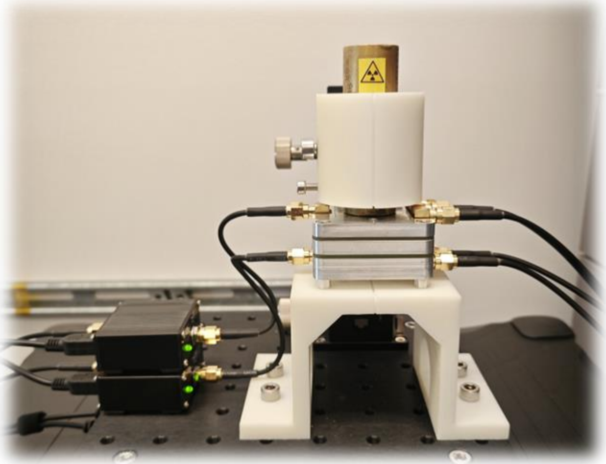
- **4-channels TIA board**



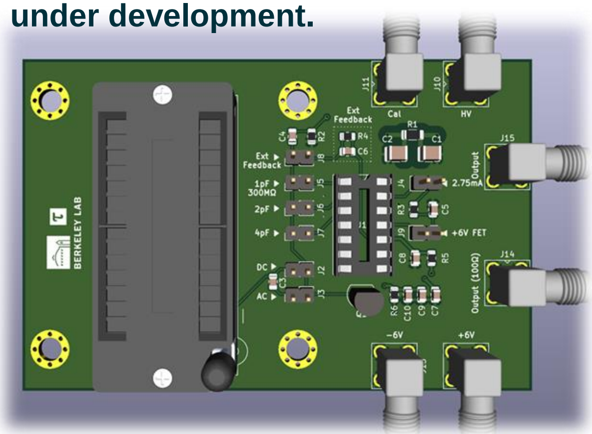
- **α source test setup**



- **β source test setup**

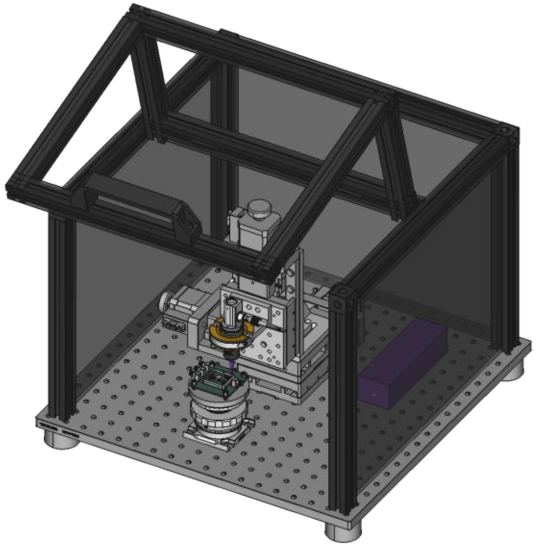


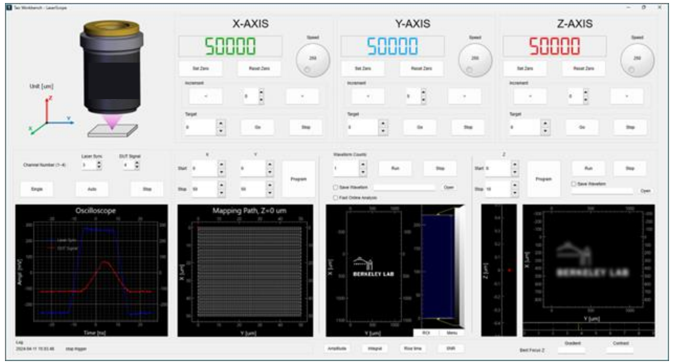
- **Low noise charge sensitive preamplifier under development.**



- **Pulse shaped module**

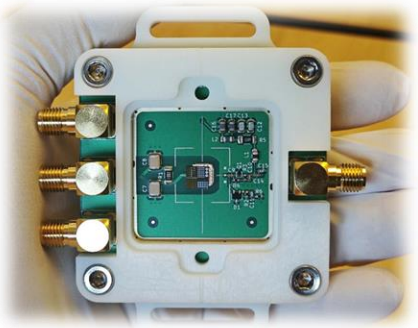
- **UV-TCT system (Under construction)**:
  - 375 nm +- 10 nm
  - 30 ps pulse width
  - 1 µm laser spot size
  - 0.625 µm increment distance of XYZ stage
  - control interface with online analysis functions





- **The ultra-high voltage (0~2 kV) and low leakage(< 100 fA) IV/CV test setup are working by NCSU and BNL…**

Measurements of 1st Generation SiC LGAD Prototype (2023)

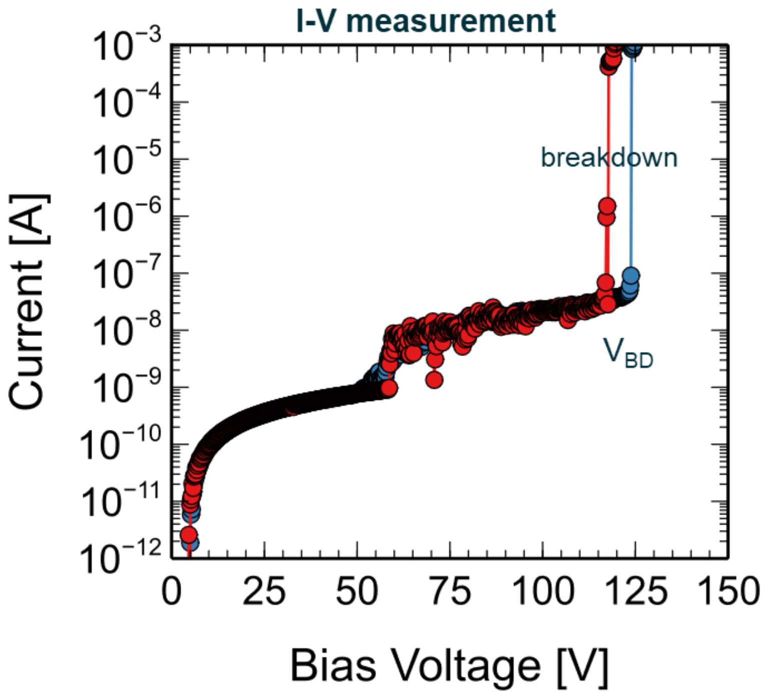


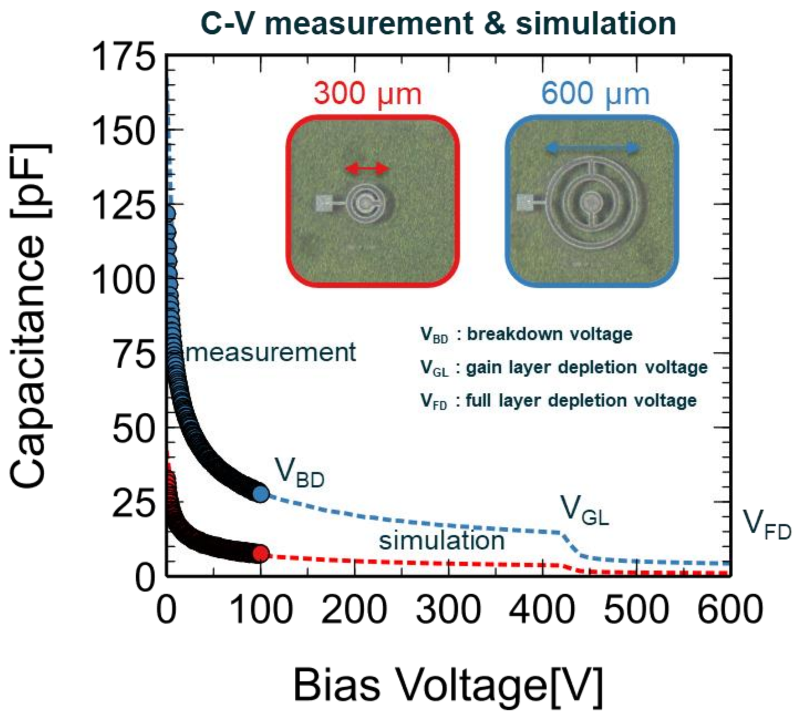
Fabricated on July, 2023

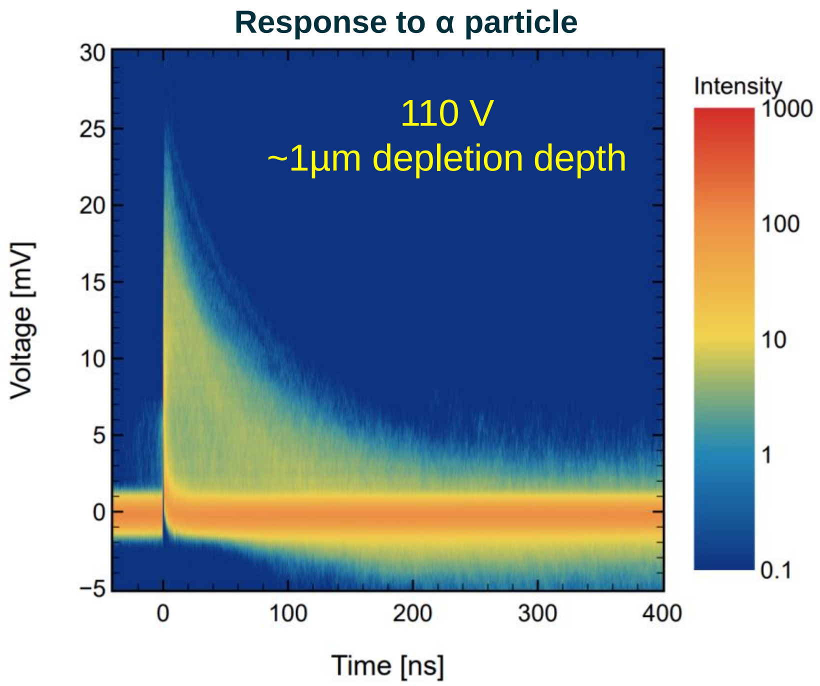
- Early breakdown where $V_{BD} < V_{GL} < V_{FD}$

LGAD requirement : $V_{GL} < V_{FD} < V_{BD}$

- The electric field in the gain layer is too high, and it works on Geiger-mode rather than LGAD.





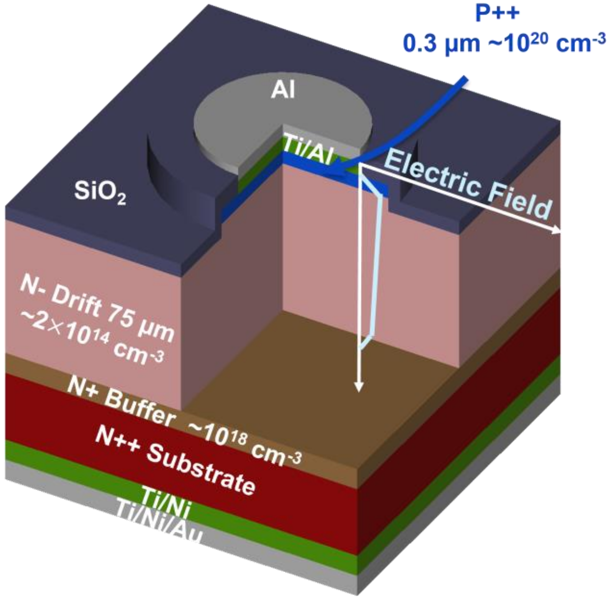


Preliminary Measurements of 2nd Generation SiC LGAD Prototype (2024)

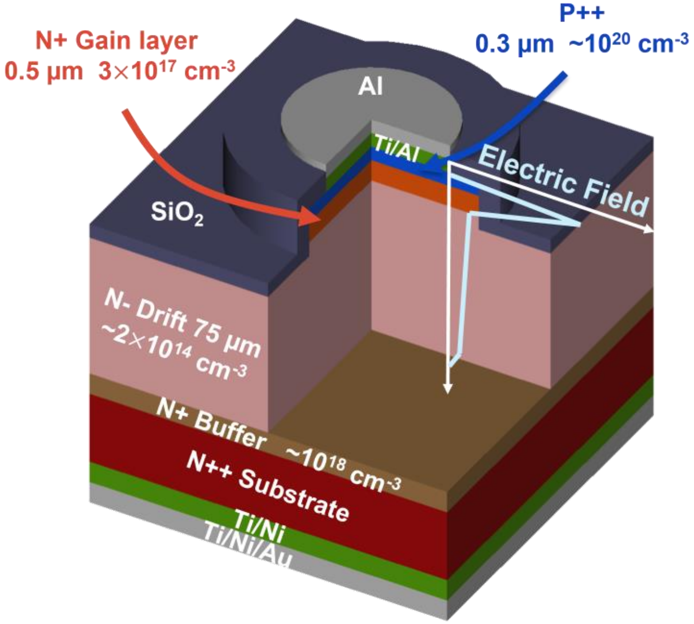
Fabricated on May, 2024 (W2, W5)

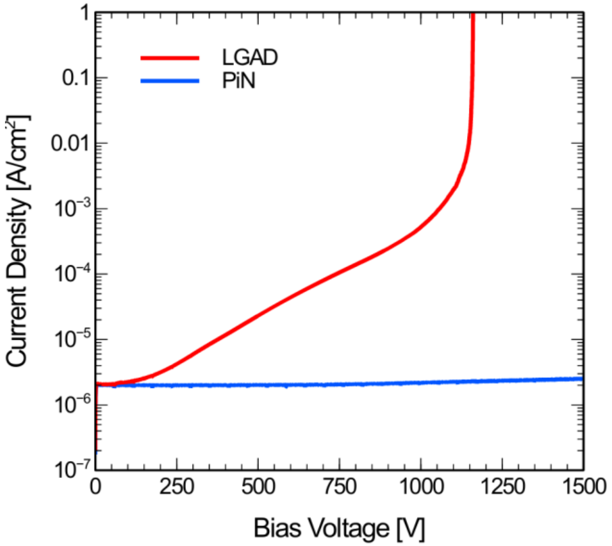
- The wafer (W2) with 4H-SiC epitaxial stacks having specific doping concentrations, which exhibit the typical electric field distribution of LGADs.
- For comparison, we removed the gain layer in another wafer (W5), resulting in a typical PIN electric field distribution.
- The measurements:
  - Both LGAD and PIN have high breakdown voltages.
  - Lower breakdown voltage and higher leakage current of LGAD are observed comparing PIN.

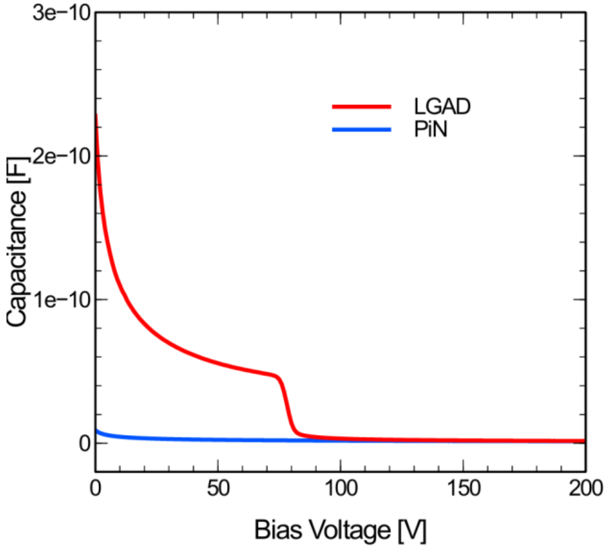
4H-SiC PIN



4H-SiC LGAD

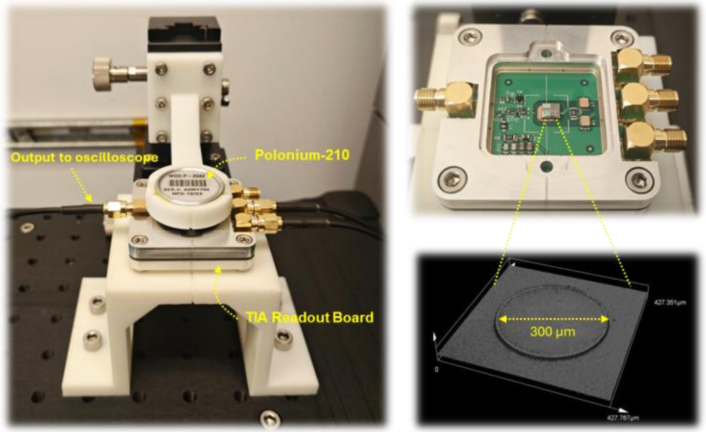


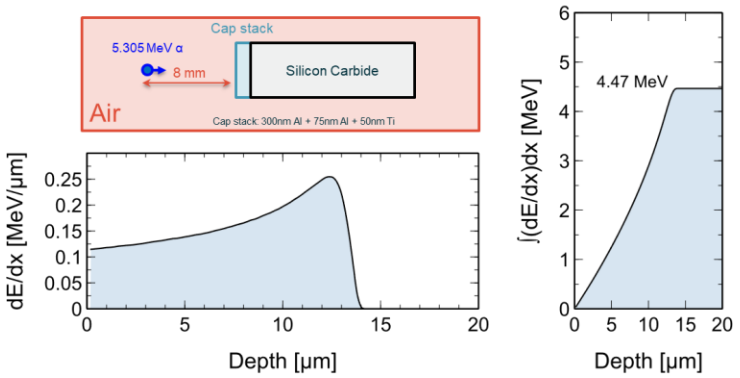




Response of α particles from 210Po Source

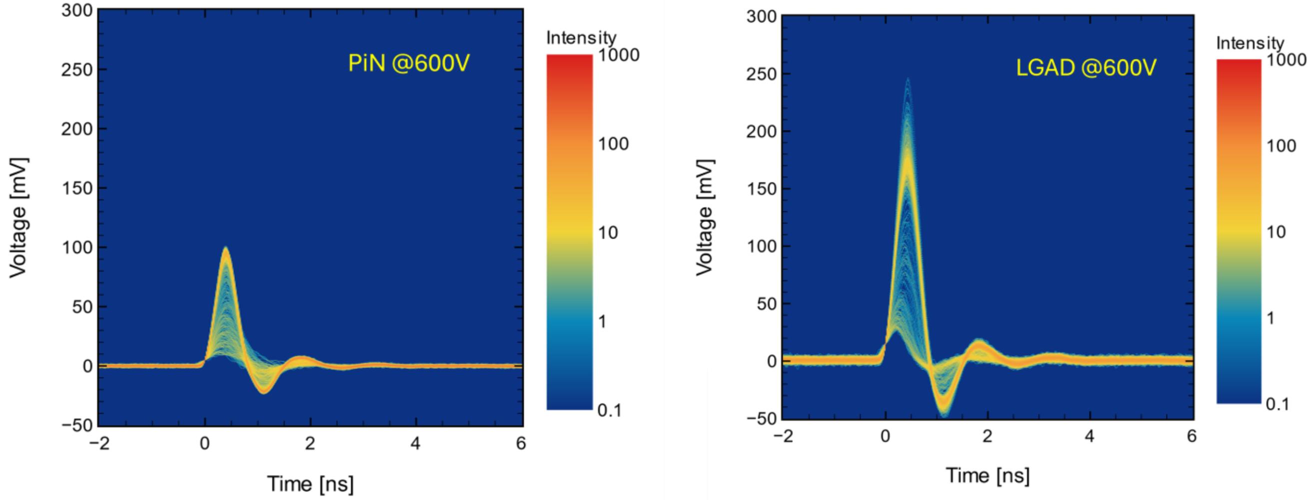
✓ Evidence of the low gain carrier multiplication

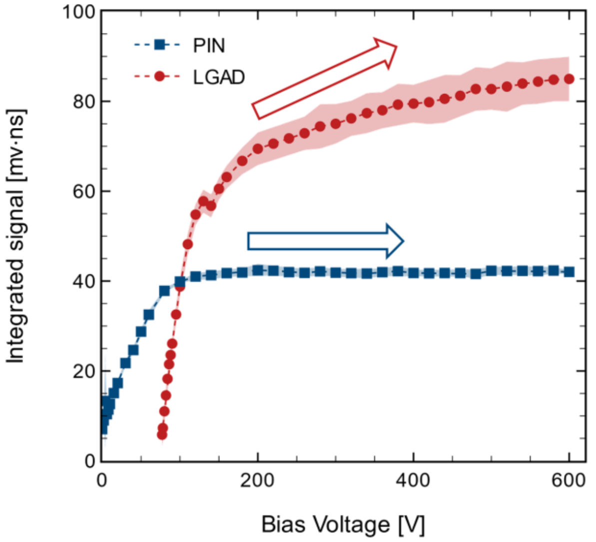


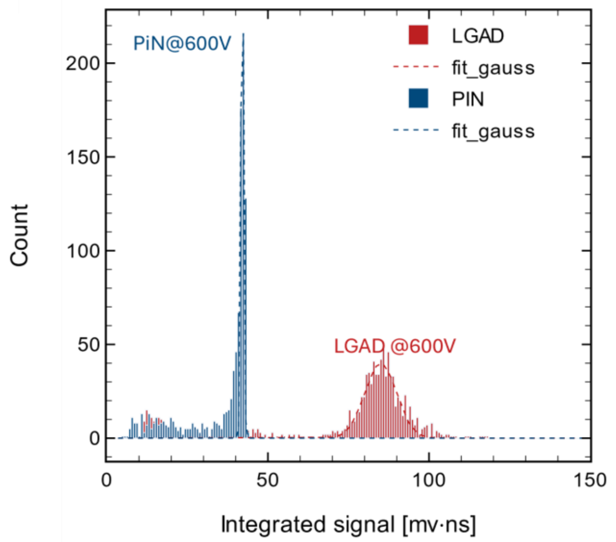


The gain is observed!

Response to α particle



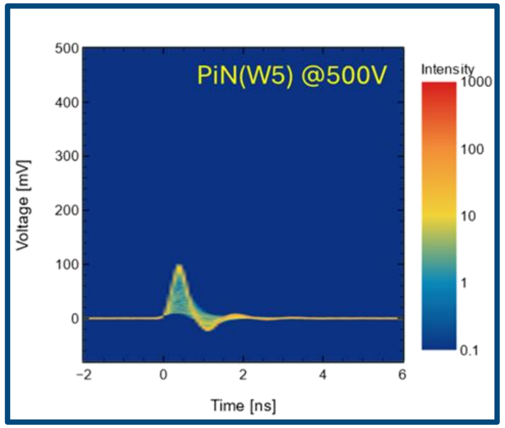


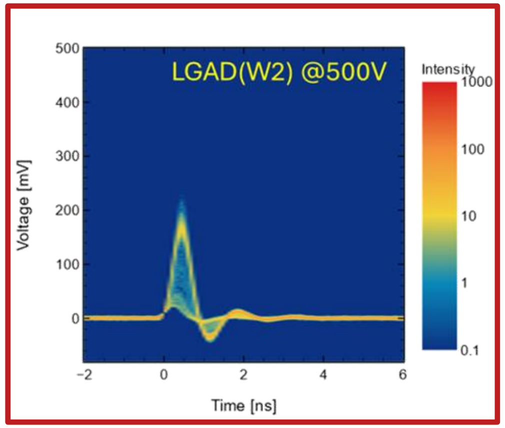


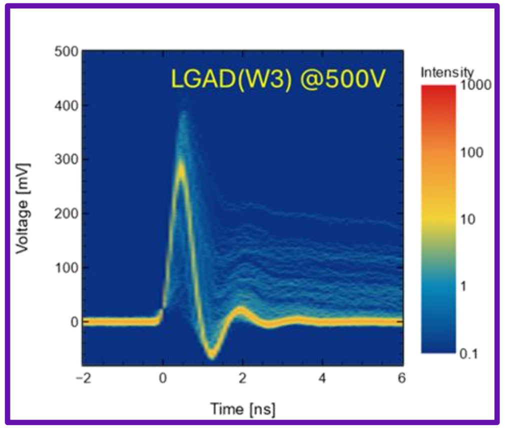
Response of α particles from ^{210}Po Source

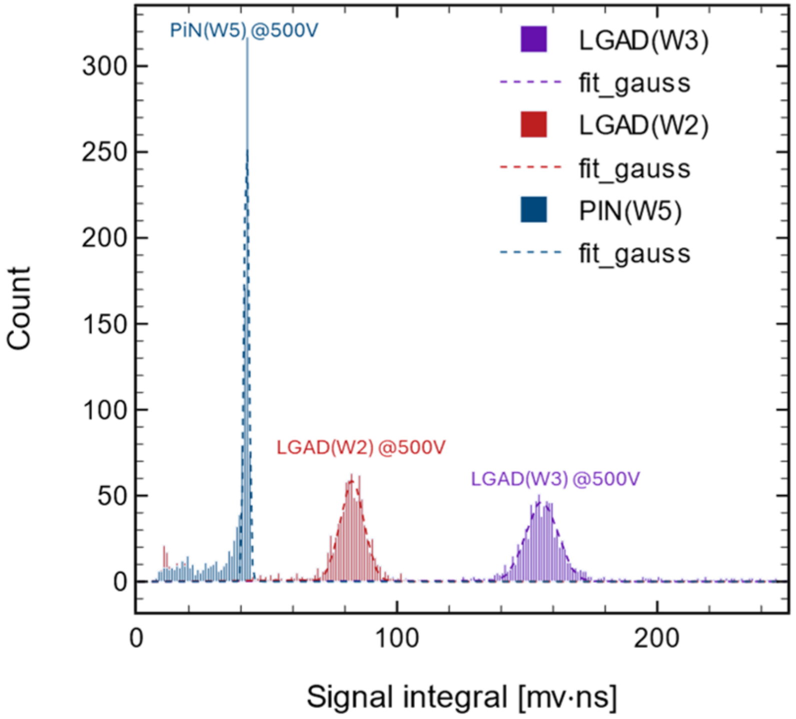
Fabricated on July, 2024 (W3)

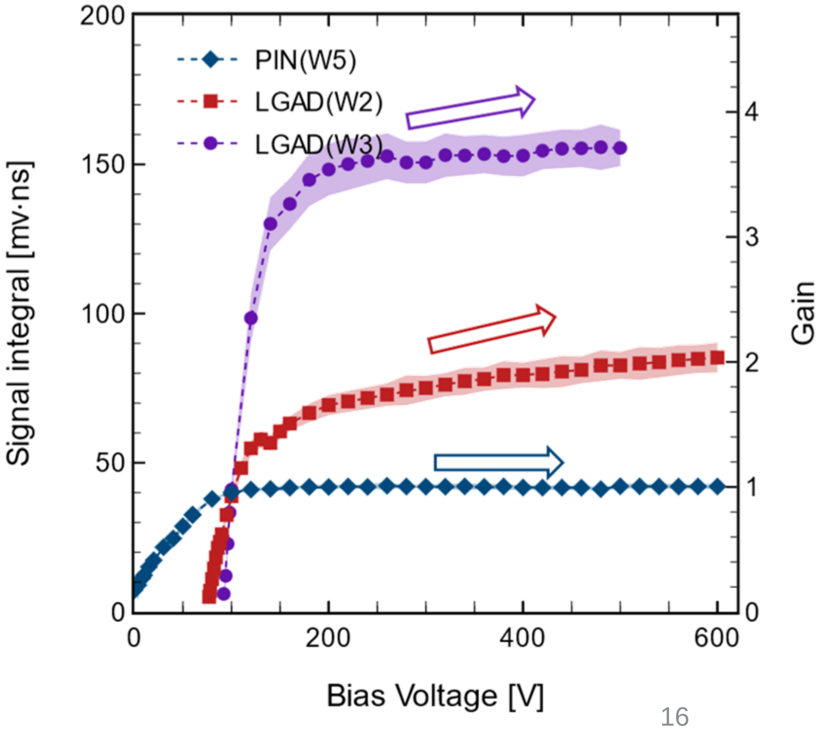
- As expected, a higher doping concentration of the gain layer has a larger gain at the same voltage.
- The collected charge of the LGAD increases with voltage, but not very fast. In the high gain W3, the gain changes slowly with increasing voltage.
- The larger the gain, the wider the half-height width of the charge collection distribution. (homogeneity or multiplication uncertainty?)
- When the bias voltage of W3 is 600V, the long tail of signal starts to appear.
  Similar pulse shape of G1 SiC-LGAD











Criteria necessary to demonstrate a 4H-SiC LGAD :

Done | In progress | In the coming months

- LGAD requirement : $V_{GL} < V_{FD} < V_{BD}$.
  - The ultra-high voltage (0~2 kV) and low leakage(< 100 fA) IV/CV test.
- Demonstrate charge gain (PIN and LGAD with same thickness of drift layer and same process technology)
  - Response to α particle (large amount of charge generation).
  - Response to β particle (less amount of charge generation): landau distribution of collected charges
  - UV-TCT: gain uniformity, gain suppression and anisotropic effect.
- Time resolution for the β particle detection.
- Gain vs voltage dependent as per expectations from increasing field.
- SIMS measurement of doping and layer profile.
- Leakage current due to SiC LGAD itself and not parasitic etc.
- At least 2 devices from the same wafer with similar performance.
- A device from another wafer with higher doping shows expected performance. (Such as W3 and W4 of 2^{nd} generation prototypes)
- (optional) Comparison of measured and predicted gain - either from simulation or analytic calculation.

Summary & Plan

- By comparing the α particle response of 4H-SiC LGAD and 4H-SiC PIN, we achieved low-gain carrier multiplication in the 4H-SiC LGAD prototype. First 4H-SiC LGAD!
- The collected charges in the 4H-SiC LGAD significantly increased with higher bias voltage, indicating that the gain factor increases with the electric field in the gain layer.
- Observe larger gain at the same voltage with a higher doping concentration of the gain layer.

Ongoing work:

- Irradiation campaign at BNL, 2.5 GeV proton
- Beam test at SLAC, 70 MeV electron

…

Thanks for your attention

Backup

Impact ionization coefficient $\alpha_{Si} > \alpha_{SiC}$

- In silicon carbide, it has smaller impact ionization coefficient than silicon at the same electric field. And the holes has larger impact ionization coefficient. Thus, the SiC LGAD should be designed with N-type drift layer and higher electric field (Si: ~0.3 MV/cm ; SiC: ~ 3MV/cm).