中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Research of Low Gain Avalanche Detectors for High-Precision 4D Tracking in Future Collider Experiments

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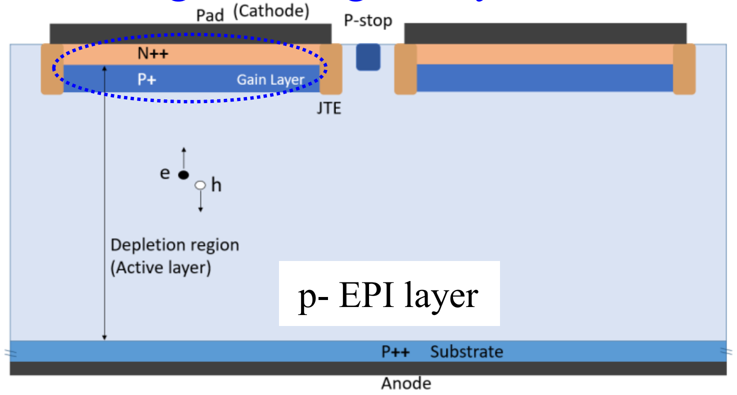
On behalf of IHEP LGAD group & CEPC Silicon Tracker Group

2025-11-19

DC-LGAD and AC-LGAD

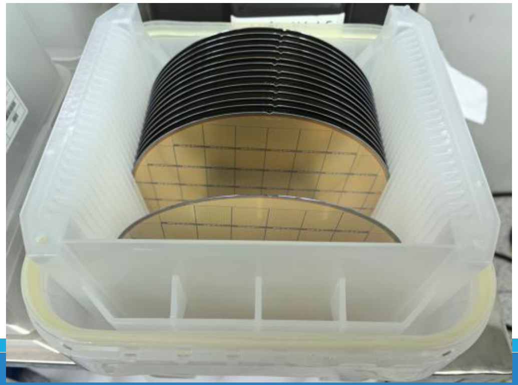
DC-LGAD (Low-Gain Avalanche Diode)

Segmented gain layer



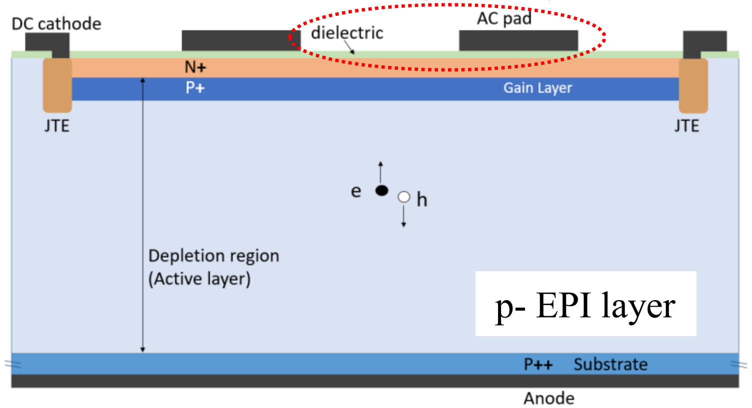
- P+ Gain layer, with Gain:10-50
- The read-out electrode is placed and connected to the N++ layer.
- Large pixel size and dead zone between pixels(JTE, Pstop)

- **IHEP design LGAD contribute 90% sensors of ATLAS HGTD project, production ongoing, ~300 wafers been fabricated.**
- **Fabricated by IME**



AC-LGAD (AC-coupled LGAD)

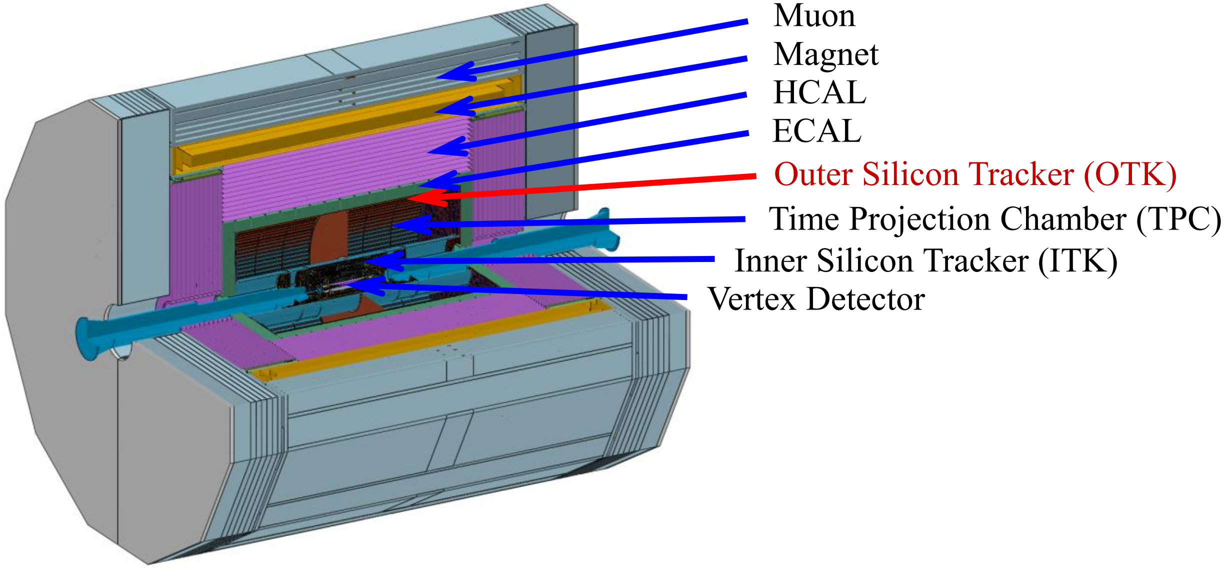
Continuous gain layer

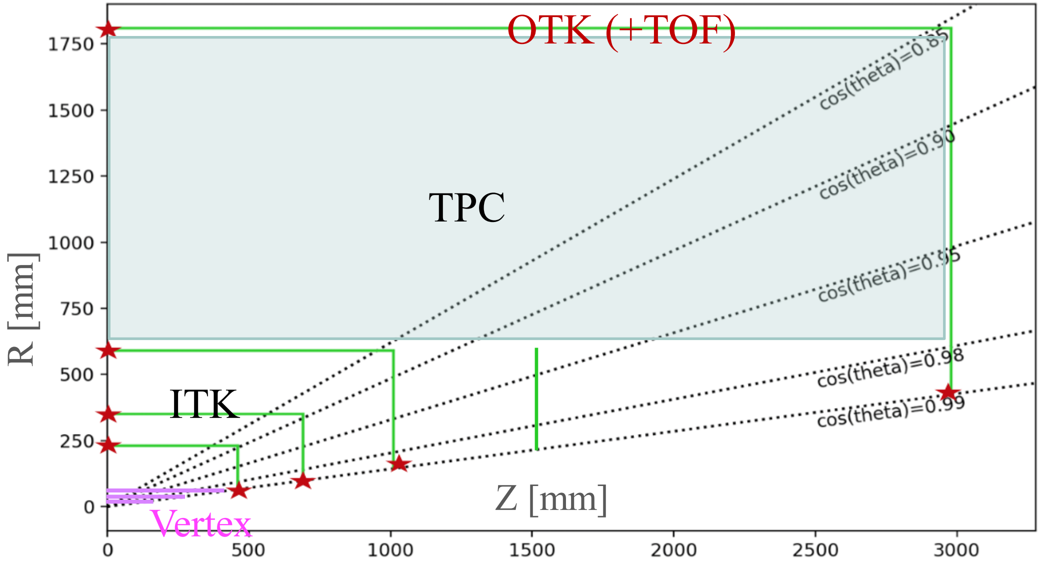


- Metal AC readout electrode and a thin dielectric layer (Si_3N_4, SiO_2) above the N+ layer
- Position information is determined by charge shared between pads.

- Less dead area and better position resolution

CEPC OTK&TOF





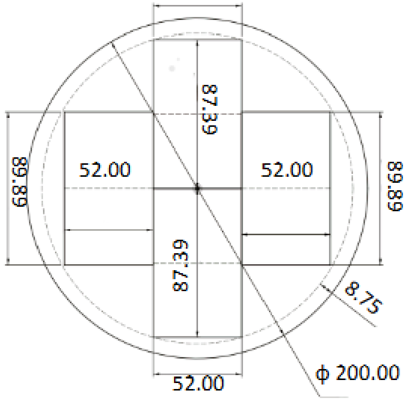
- **CEPC**-- measurement potential for precision tests of SM: Higgs, electroweak physics, flavor physics, QCD/Top
- Produce 10^{12} Z boson at Z pole: Rich flavor physics program
- **The LGAD based OTK (+TOF) detector** will be placed between TPC and ECAL
- Timing detector is complementary to gas detector for PID:
  to improve the separation ability: 0-4 GeV for K/pi separation, 0-8 GeV for K/p separation
- **Barrel : ~65 m^2 , Endcap 20 m^2**

CEPC Technical Design Report -- Reference Detector:
https://arxiv.org/abs/2510.05260

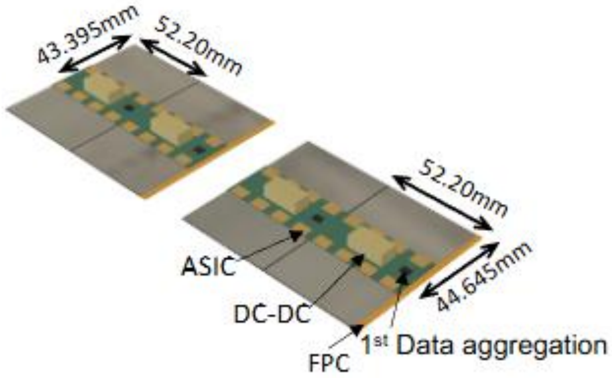
CEPC OTK Barrel Design (AC-LGAD Strips)

- **AC-LGAD strip sensor is the choice for CEPC OTK baseline since it can provide both high-precision spatial resolution for momentum measurement and high-precision timing for particle identification.**

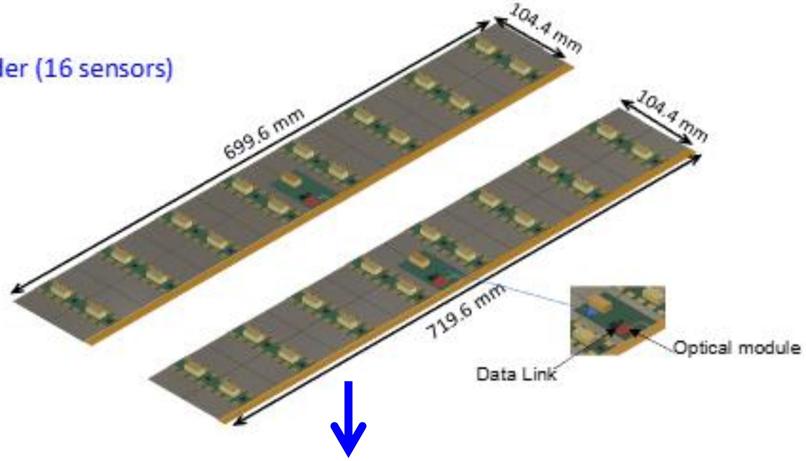
8-inch wafer



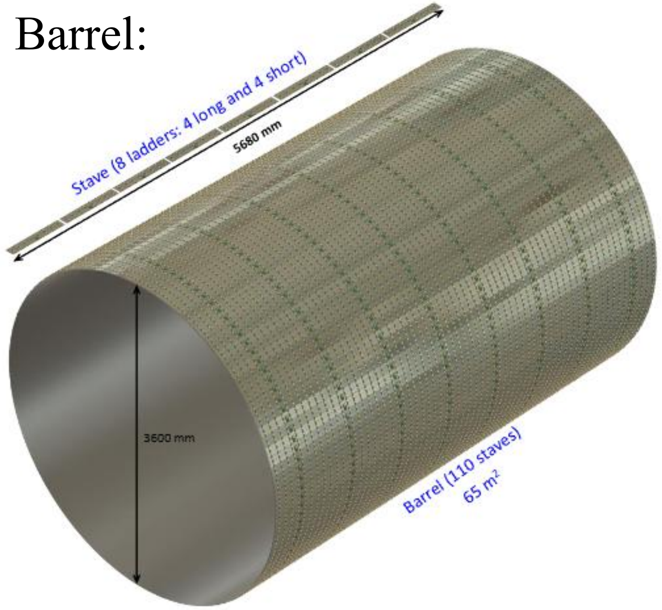
Module (2×2 sensors)



Ladder (16 sensors)



Barrel:



- **CEPC outer silicon tracker (OTK) utilizes AC-LGAD:**
  - For barrel: Sensor size: 4.34 cm × 5.22 cm
    4.46 cm × 5.22 cm
    Large size
  - Strip number per sensor: 512
  - Strip pitch size: 100 µm
  - **Spatial resolution: 10 µm**
  - **Time resolution: 50 ps**
    4D detector
  - Power consumption: ~300 mW/cm^2

Towards tracking application in CEPC

Scaling AC-LGAD to centimeter-scale strip lengths-essential for large-area tracking systems-introduces challenges:

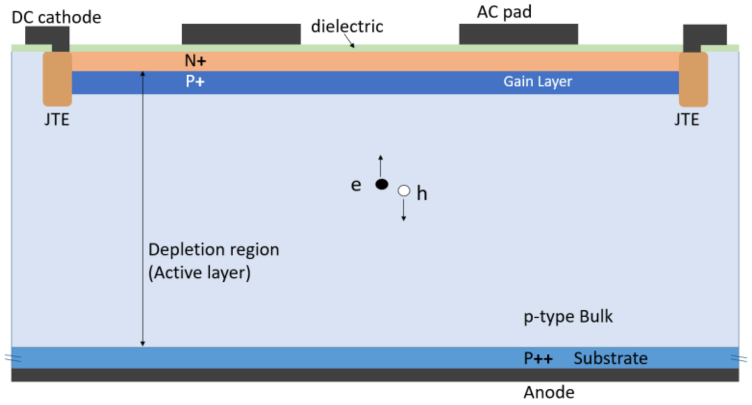
- **Increased strip capacitance:**

  increase noise and power consumption, worse timing performance

  $S/N \propto (1/\text{Capacitance})$, $\sigma_{jitter} \propto t_{rise}/(S/N) \longrightarrow \sigma_{jitter} \propto \text{Capacitance}$

- **Decreased signal performance**

- Conduct structural and process simulations to design AC-LGAD that are suitable for use in tracking systems:
  - Process parameter: n+ doping concentration, Dielectric material and thickness
  - Structure parameter: metal pad-pitch size
  - Isolation structures



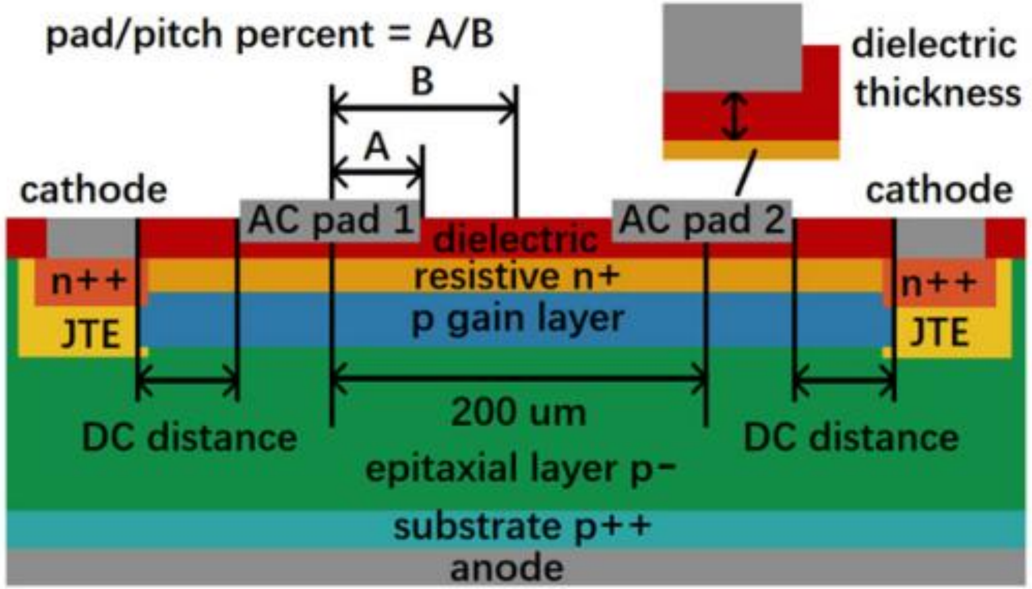
- Fabricate and test of AC-LGAD prototype
  - Sensors with different n+ doping concentration, metal pad-pitch size
  - Timing and spatial resolution
  - Radiation performance

AC-LGAD simulation

◆AC-LGAD sensor simulation： Optimization of process and structure parameters

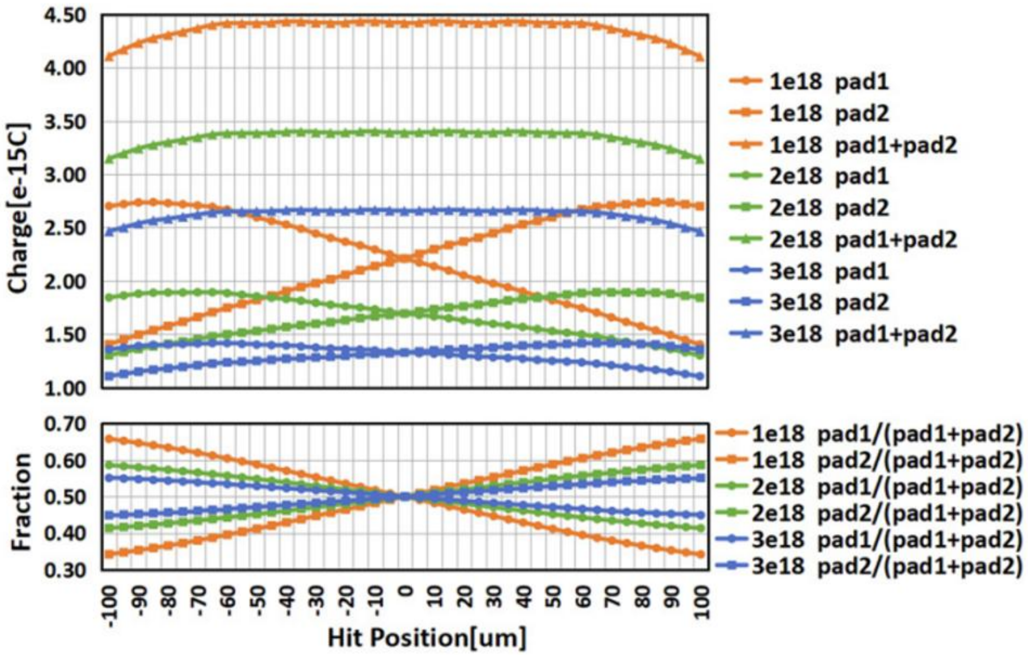
Process parameter: n+ layer dose, AC dielectric material and thickness

Structure parameter: Metal pad-pitch size



TCAD model of AC-LGAD for simulation

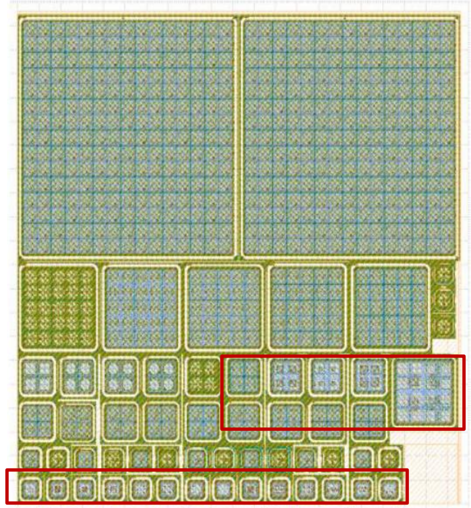
Design of AC-coupled low gain avalanche diodes (AC-LGADs): a 2D TCAD simulation study, JINST, 2022.9, DOI:10.1088/1748-0221/17/09/C09014



Lower n+ dose→ Large resistivity →good spatial resolution

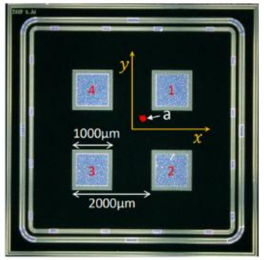
Less n+ dose(large resistivity), Large signal from begin and drop fast as changing position.
This means spatial resolution will be better as decreasing the n+ dose

AC-LGAD R&D



In 2021

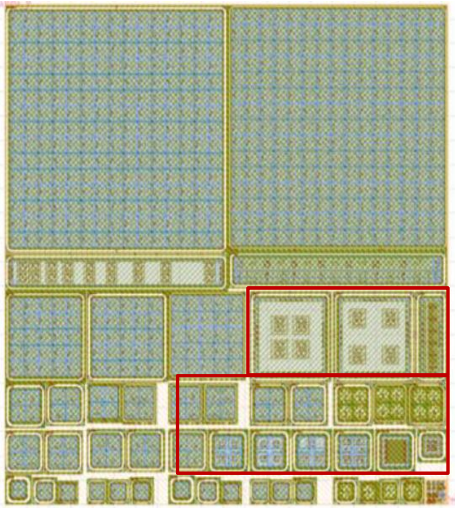
- ➢ Pixelated AC-LGAD
- With different pad-pitch size
  1000-2000um
  100-500um
  100-200um
  50-100um

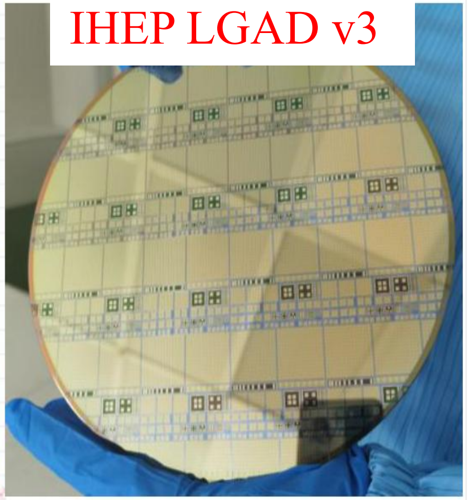


- EPI thickness:50um
- Wafer: with different n+ dose: 10P to 0.2P

Process parameters(n+ dose) be studied.

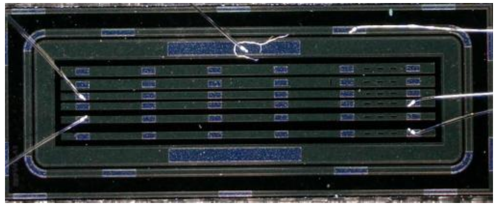
The performance of large-pitch AC-LGAD with different N+ dose， Trans. Nucl. Sci.， 2023.6





In 2022

- ➢ Pixelated and strip AC-LGAD
- With different pad-pitch size
  1000-2000um pixel
  100-250um strip
  100-150um strip
  50-100um strip



- EPI thickness:50um
- Wafer: with different n+ dose:0.2P to 0.01P
- **Strip sensor with different pad-pitch size be studied**

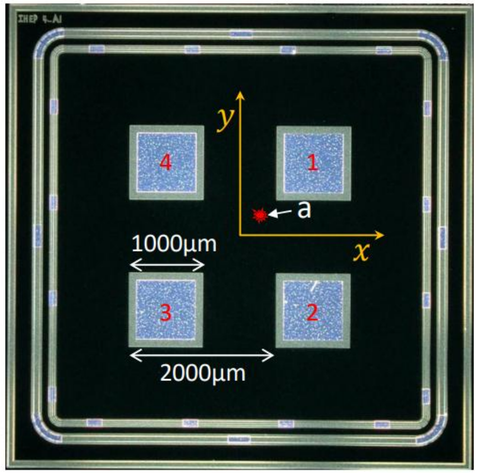
The performance of AC-coupled Strip LGAD developed by IHEP, NIMA, Volume 1062, May 2024, 169203

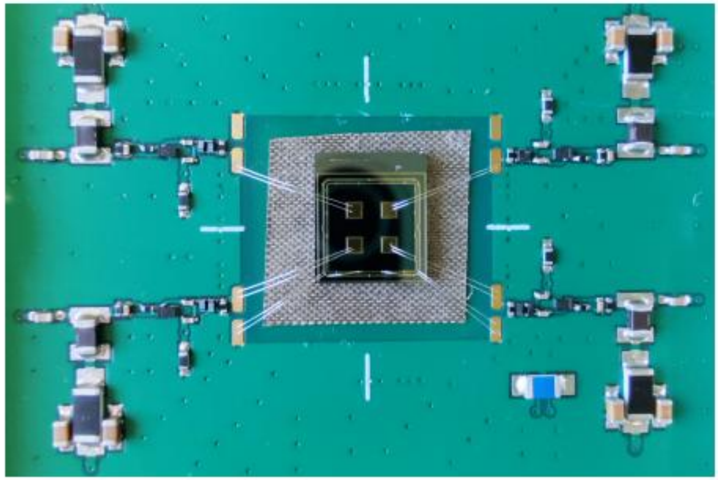
Pixelated AC-LGAD test results

- **AC-LGAD R&Dv1: pixelated AC-LGAD**

  Large pad-pitch size: 1mm-2mm

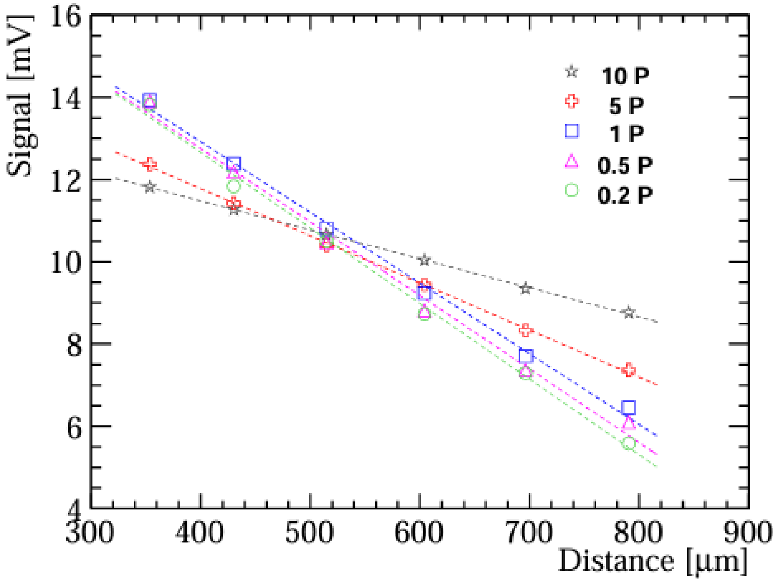
  To study the process parameter

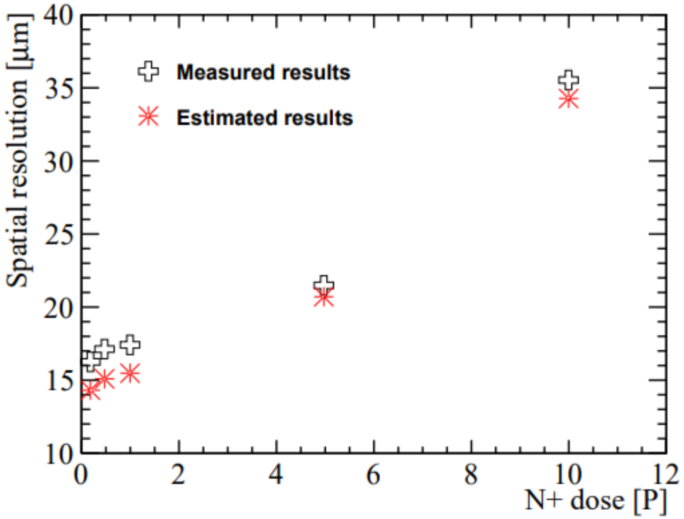




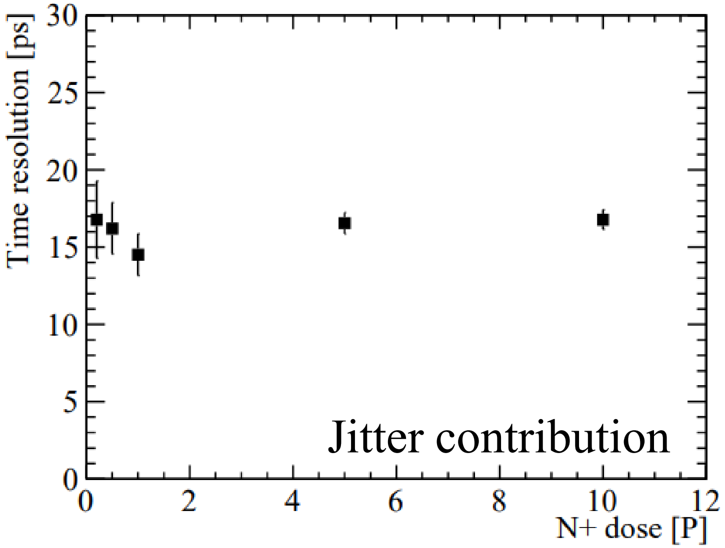
- Spatial resolution be better

  as decreasing the n+ dose(10P to 0.2P)





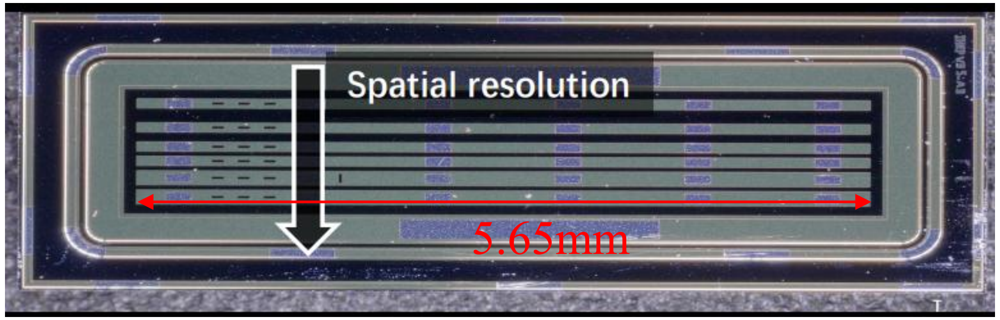
Spatial resolution: 15um



Timing resolution: 15-17ps

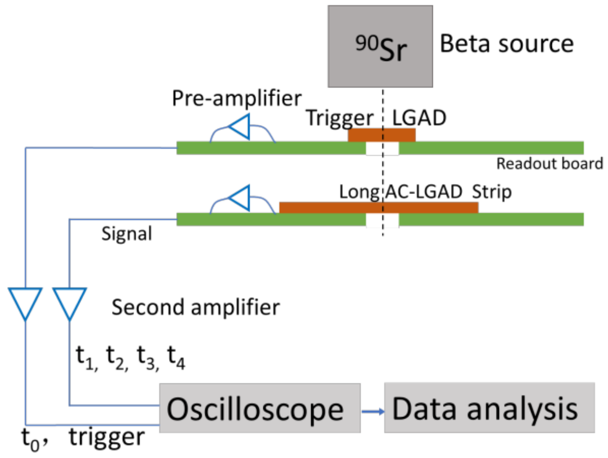
Strip AC-LGAD test

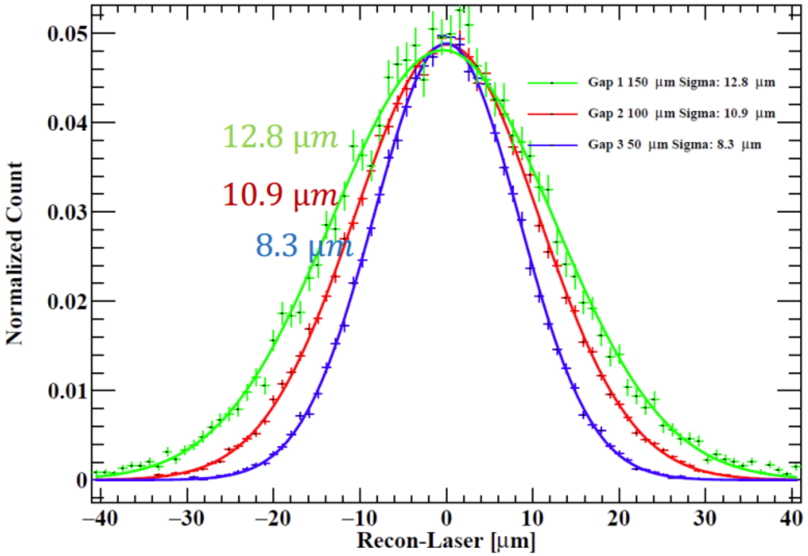
Spatial resolution: Laser testing
Timing resolution: Beta source test

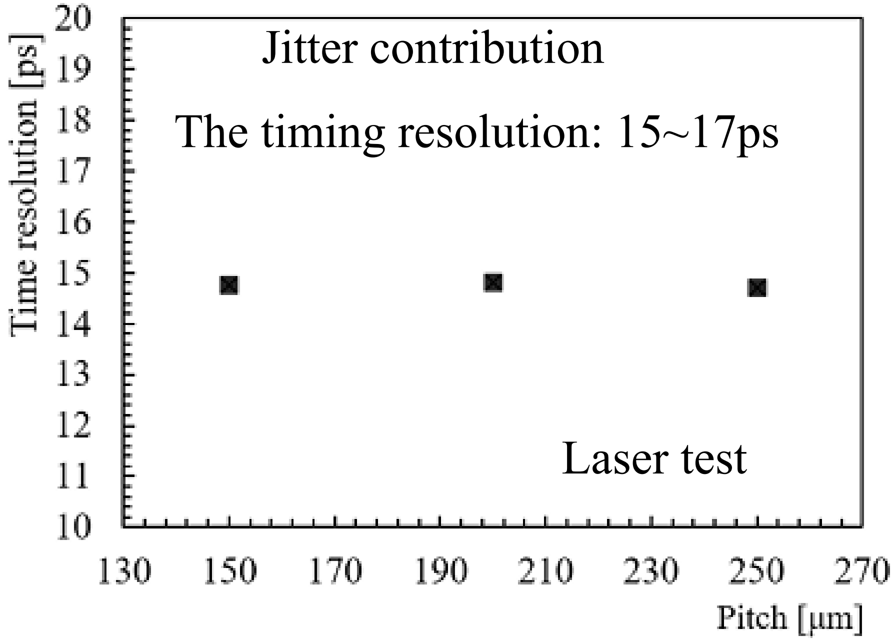


- Strip length 5.65mm
- pad-pitch size:
  100-250 um
  100-200 um
  100-150 um

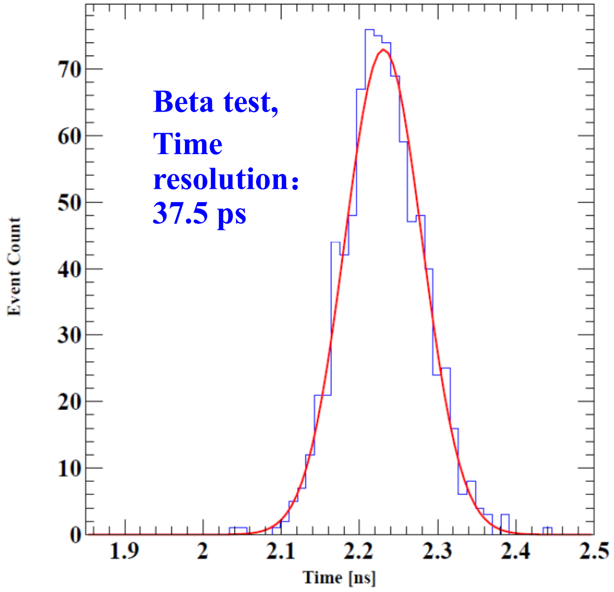
^{90}Sr test setup







Landau and jitter contribution



AC-LGAD with pitch size as 150um:
Best spatial resolution~8um (laser test)

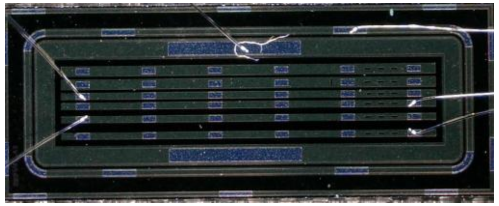
The performance of AC-coupled Strip LGAD developed by IHEP, NIMA, Volume 1062, May 2024, 169203

Strip AC-LGAD test: TID

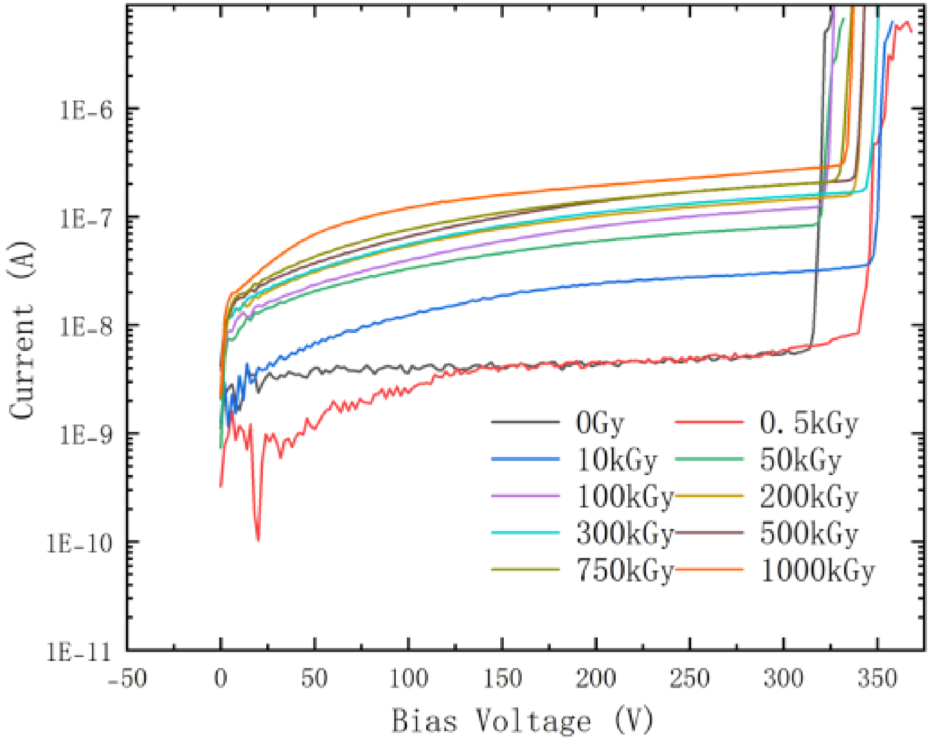
TID Impact on IHEP AC-LGAD Strip Sensors:

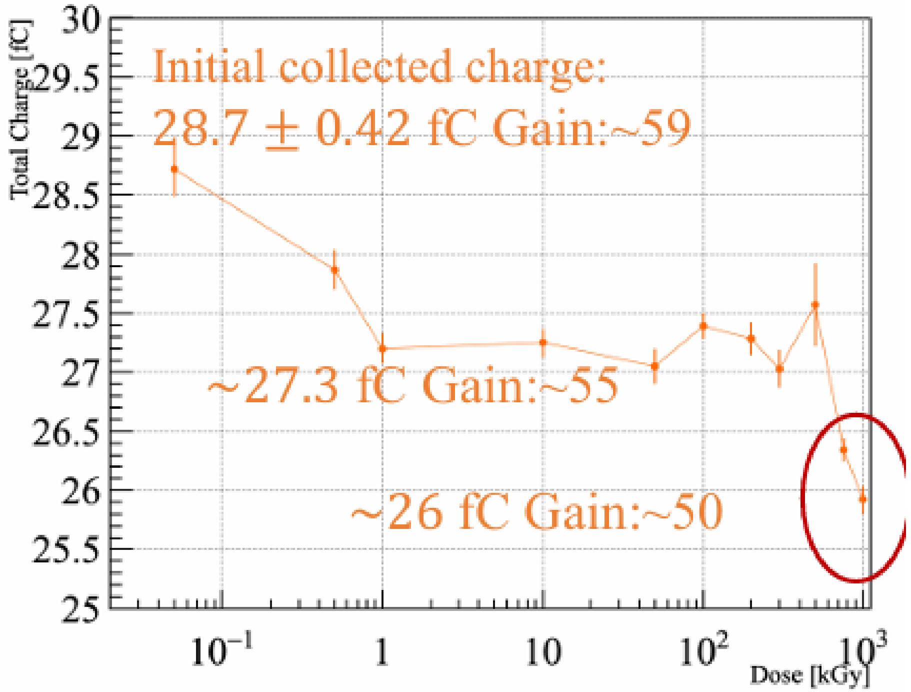
Irradiation: Multi-Rad 160 X-ray@40keV, up to 1MGy

Done by Weiyi Sun from IHEP, more details in his poster #57 this meeting



- Strip length 5.65mm
- pad-pitch size:
  100-250 um
  100-200 um
  100-150 um





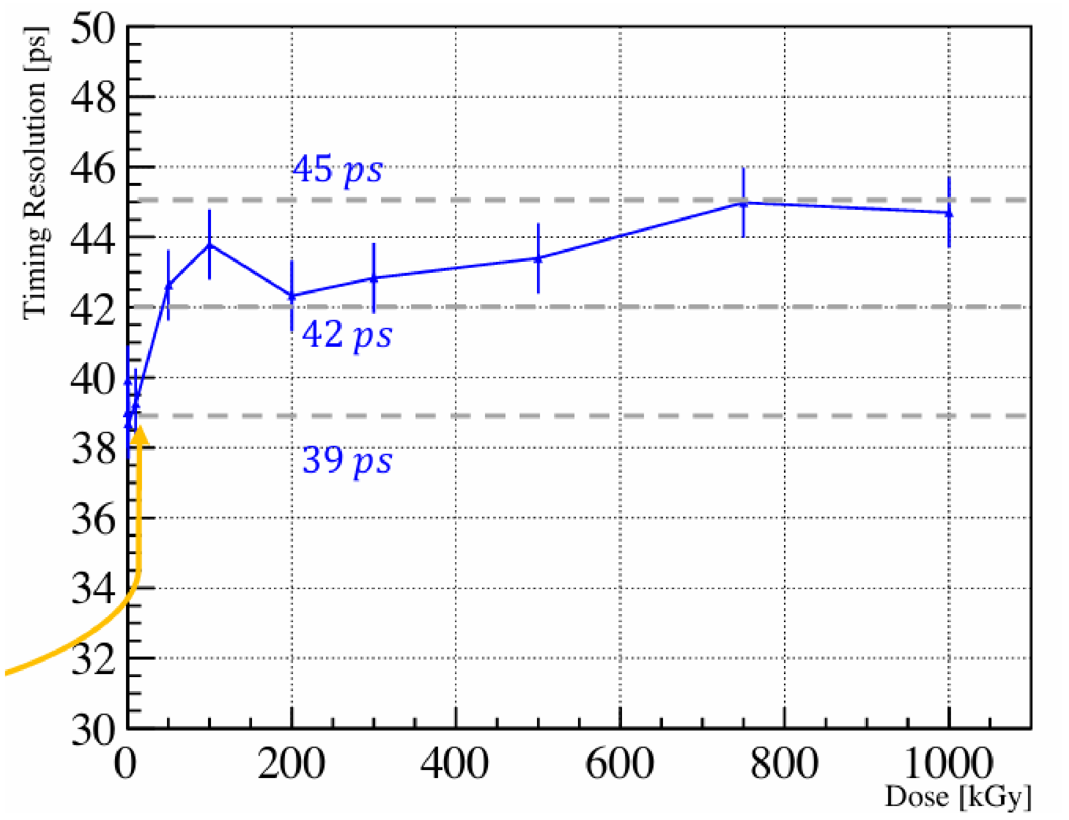
➢ Leakage current increases by one order for sensors with TID dose as 1MGy

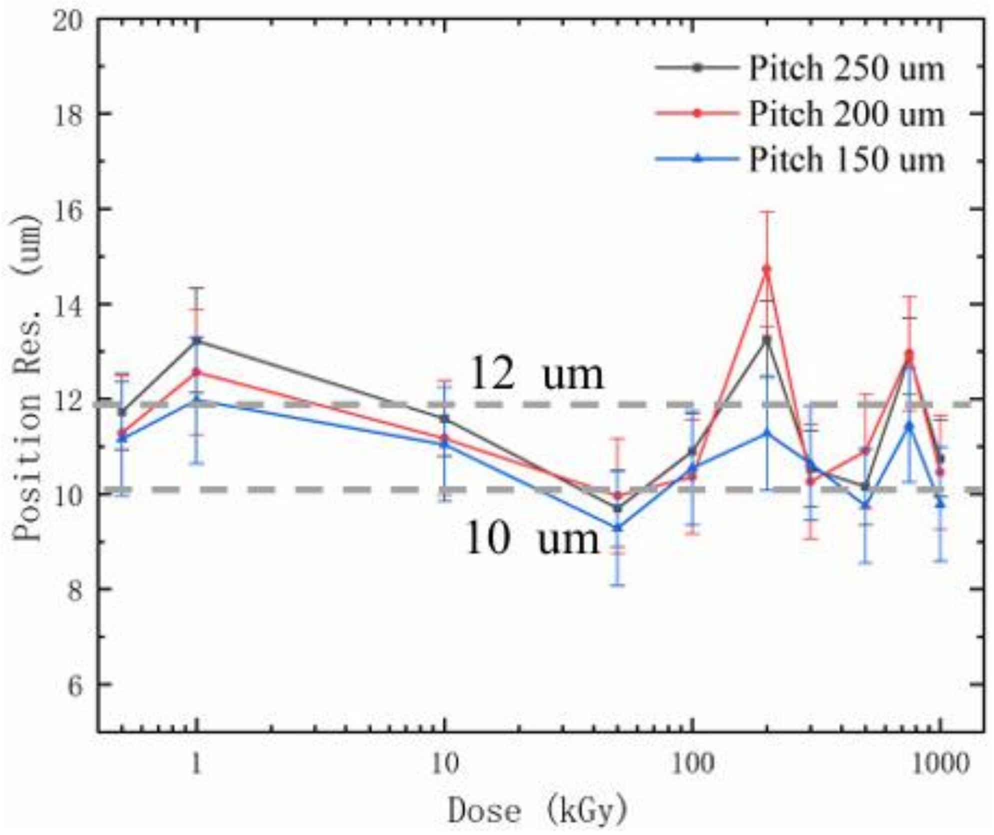
➢ Collected charge reduces, but very less up to 1MGy.

Strip AC-LGAD test: TID

TID Impact on IHEP AC-LGAD Strip Sensors performance:

Done by Weiyi Sun from IHEP





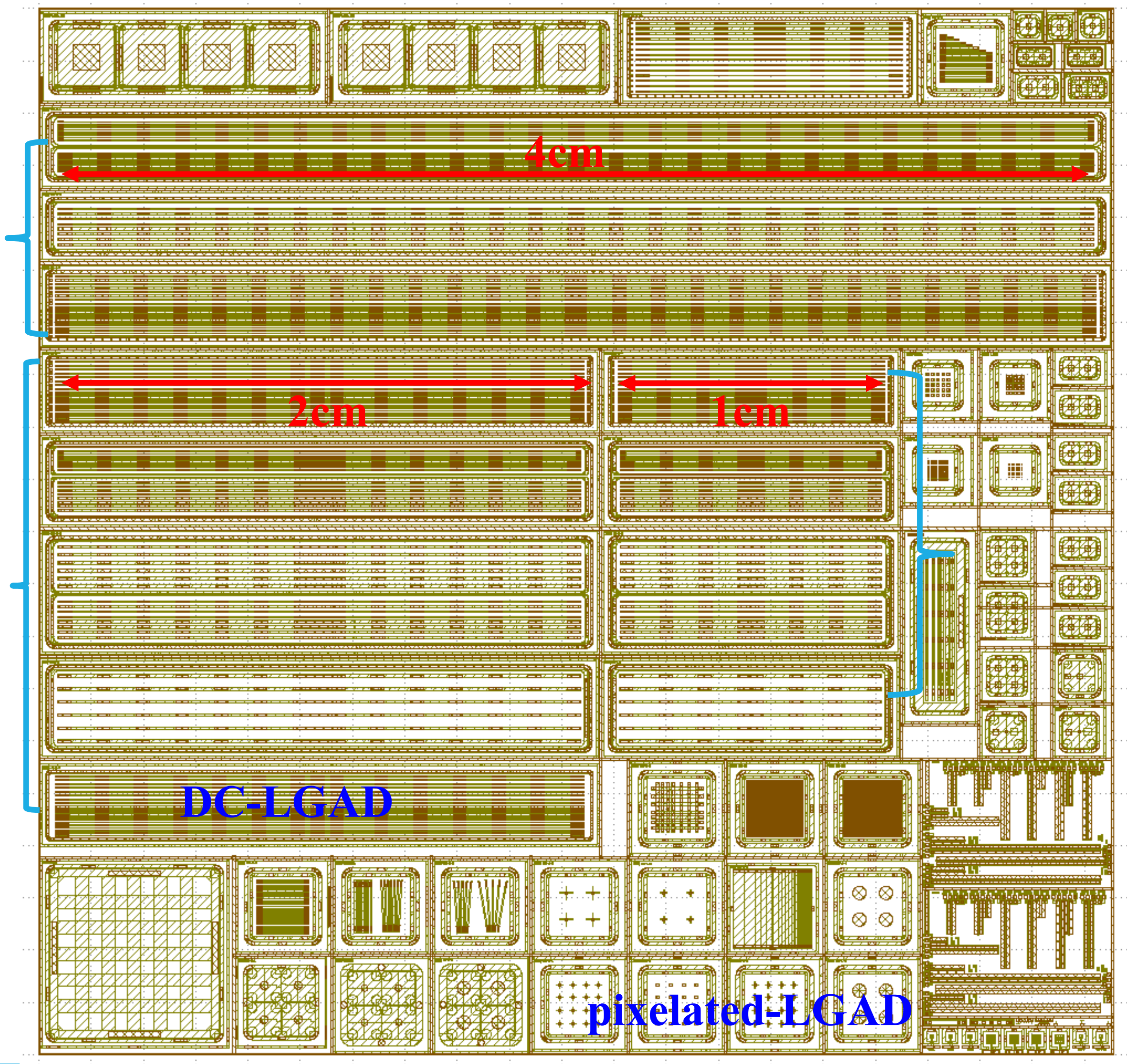
- Time resolution degrades from 38ps to 42ps.
- Spatial resolution maintained in 10-12 μm up to 1 MGy

AC-LGAD with long strip

◆AC-LGAD and DC-LGAD with long strip been submitted for fabrication in April 2025

- Strip lengths: 1 cm, 2 cm, and 4 cm
- Strip pitch sizes: 100 μm, 200 μm, and 500 μm
- Electrode widths: 25 μm, 50 μm, and 100 μm
- Isolated structure design and EPI thickness(50 μm, 80 μm) to reduce sensor capacitance
- Process design optimization: n+ doping concentration

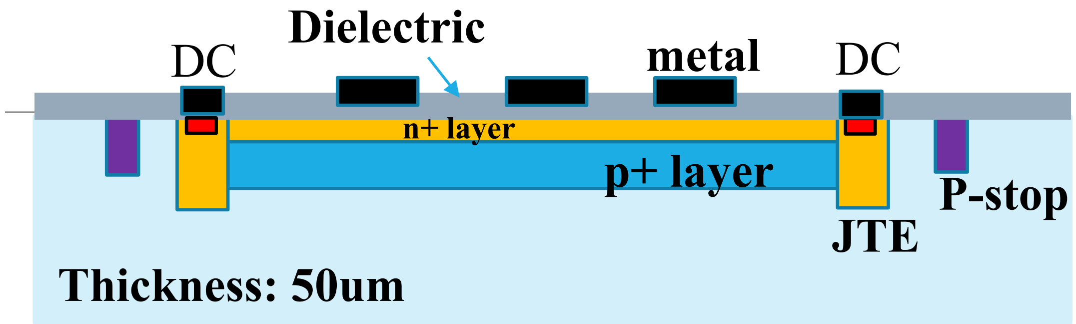
◆Sensors will be delivered in December



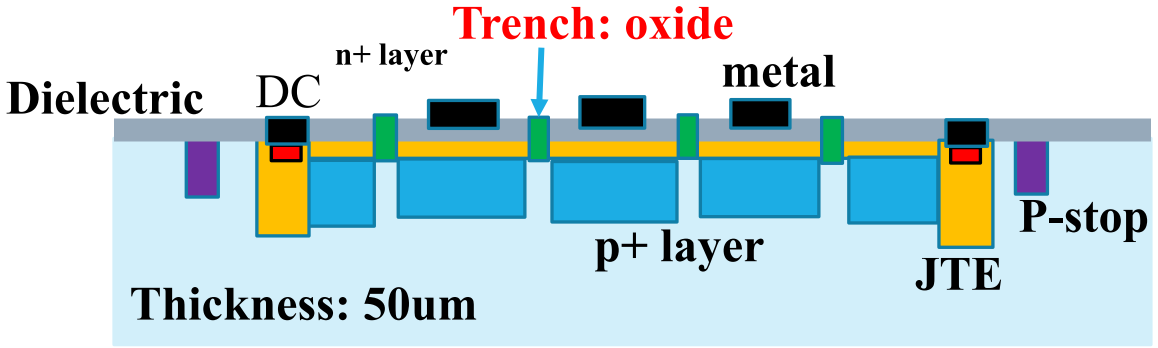
Isolated AC-LGAD simulation and design

- Trench isolation structure be added to reduce the bulk and inner-strip capacitance, critical for power consumption.
- Sensors with 3 types of structures be simulated using TCAD tools.
- Sensor performance been simulated:

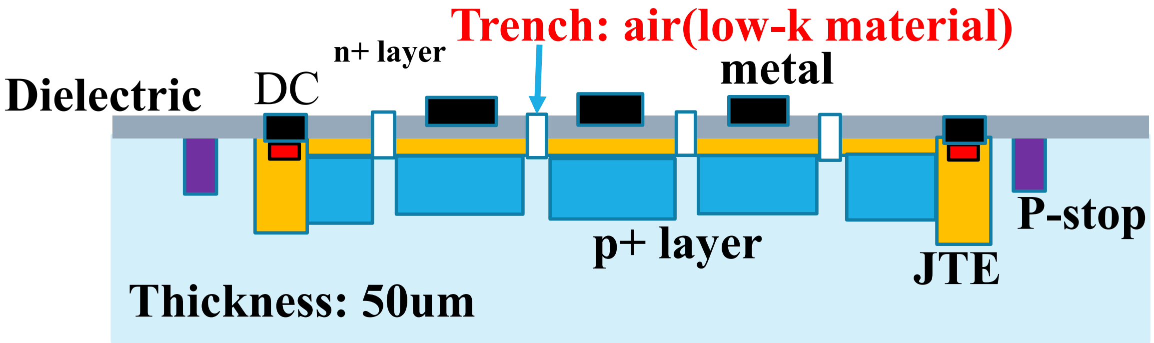
  I-V; C-V: bulk capacitance, coupling capacitance, inter-strip capacitance;



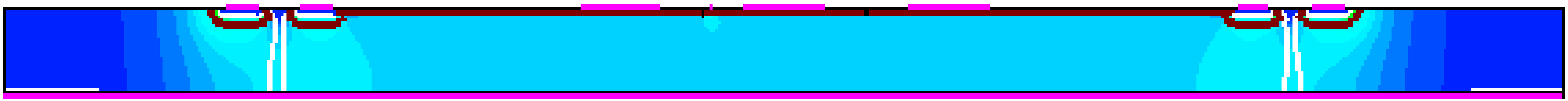
Type 1



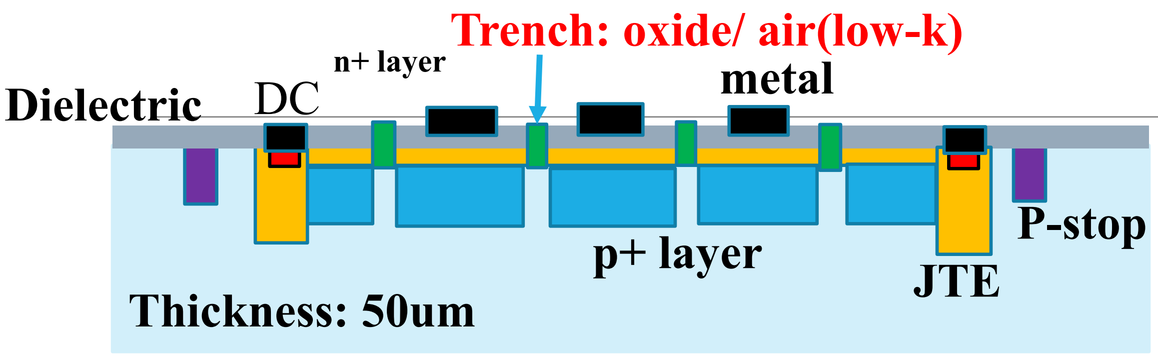
Type 2



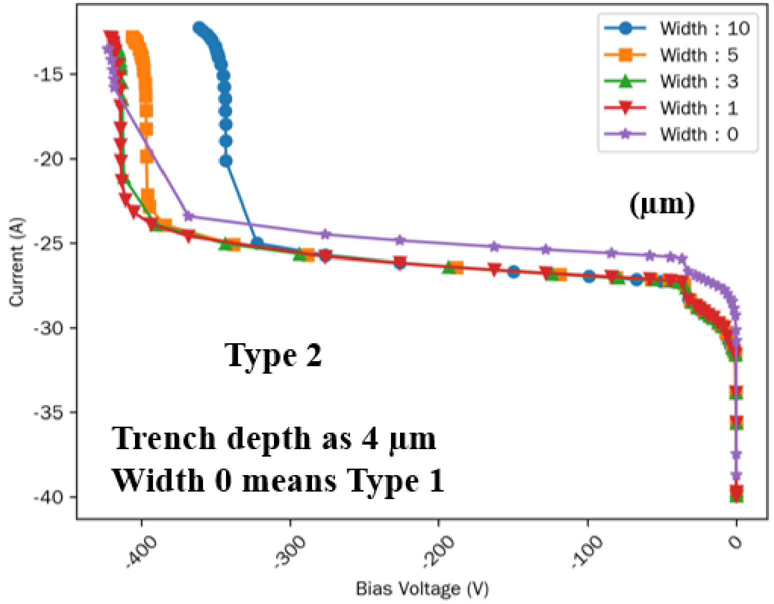
Type 3



Isolated AC-LGAD Simulation and Design

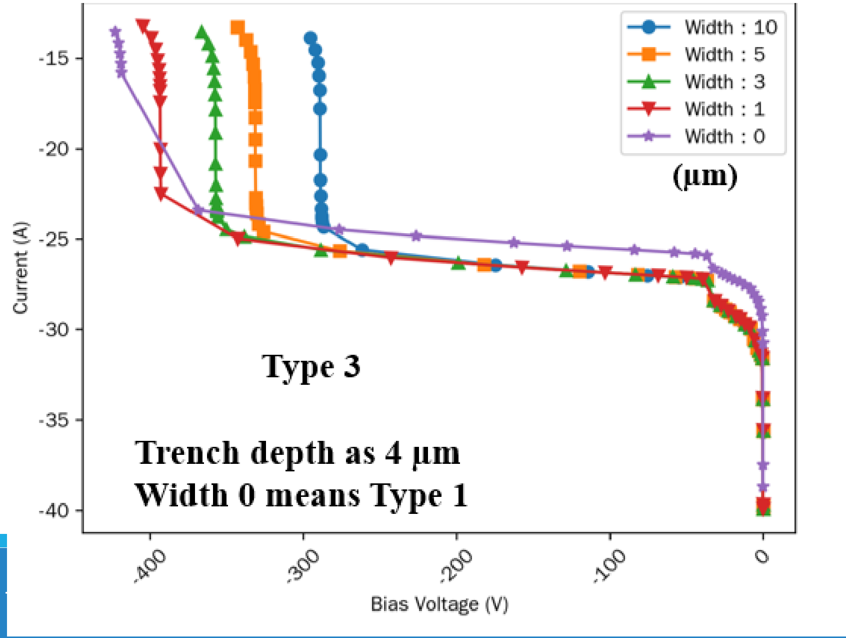


Type 2&3



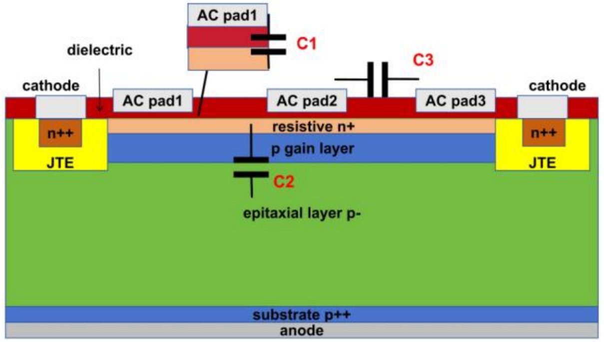
Trench width:

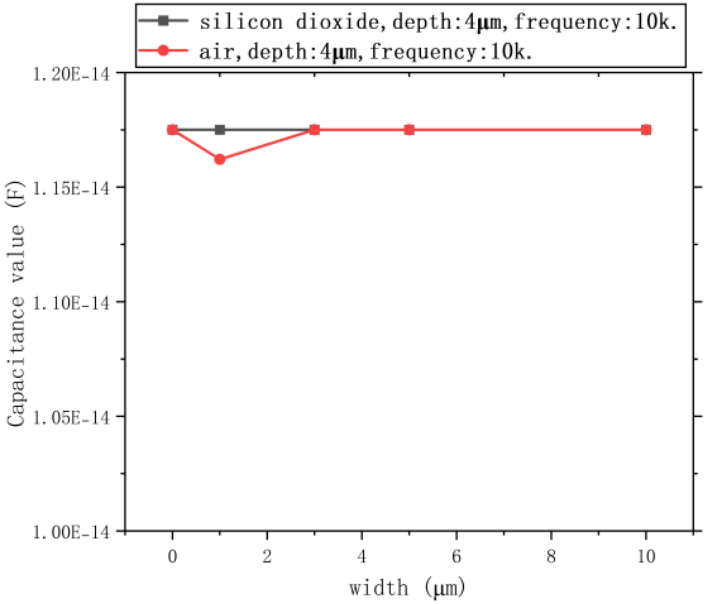
- I-V performance will change as changing the trench width[type 2 and type 3].
- Breakdown voltage V_{bd} and operation voltage will decrease as increasing the trench width since the electrical field changes



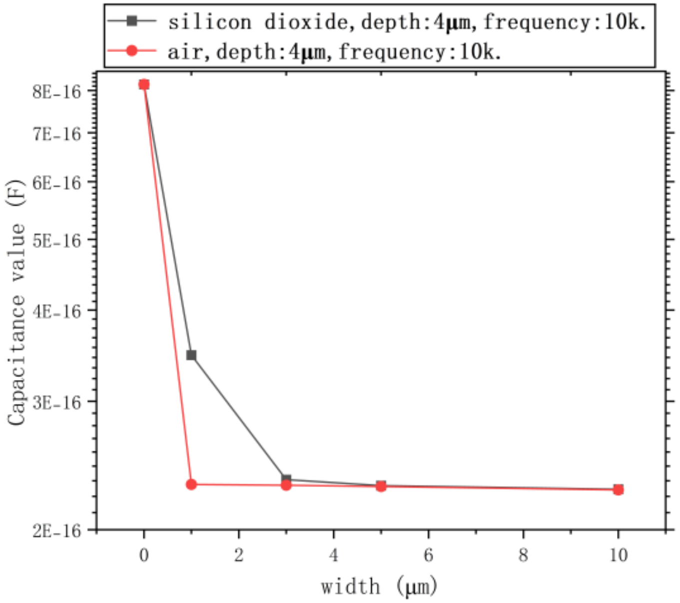
Isolated AC-LGAD Simulation and Design

- Depleted bulk capacitance and inter-strip capacitance significantly reduced for AC-LGAD with Si oxide and vacuum(low-k) isolation structures.

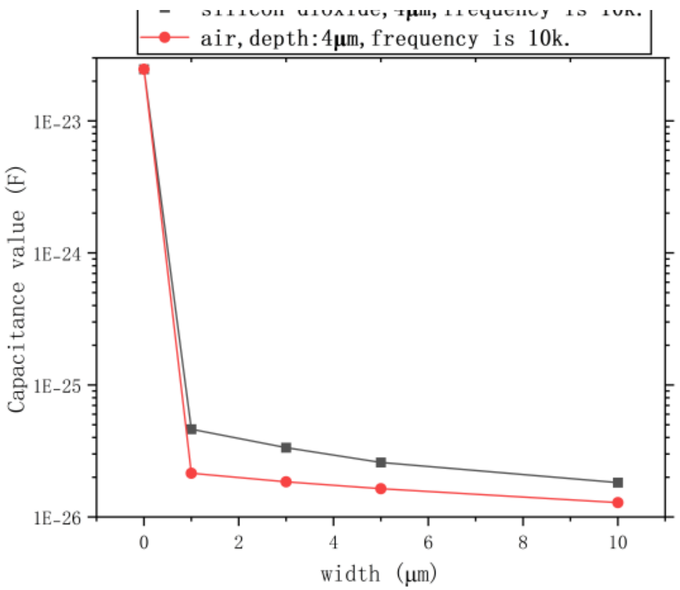




(a) Coupling capacitance



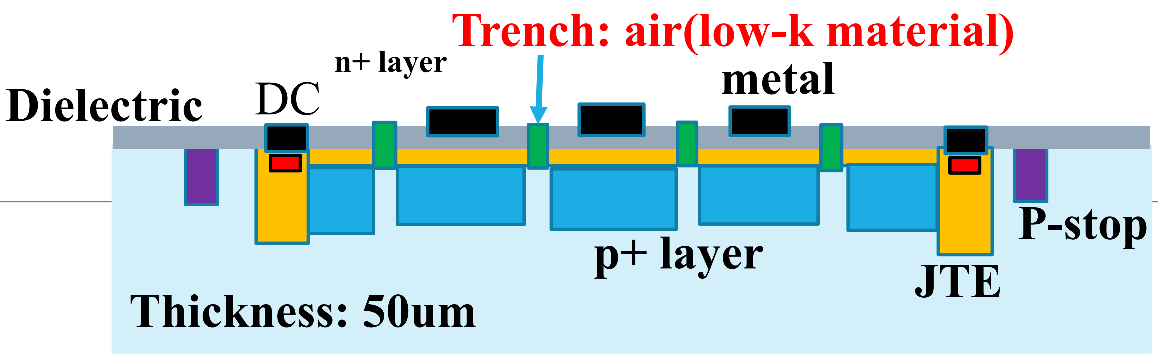
(b) Bulk capacitance



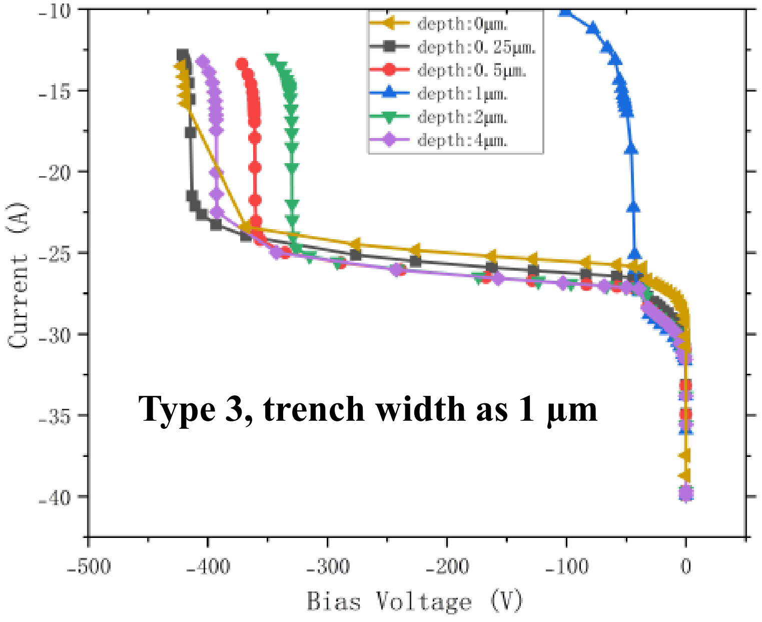
(c) Inter-pad capacitance

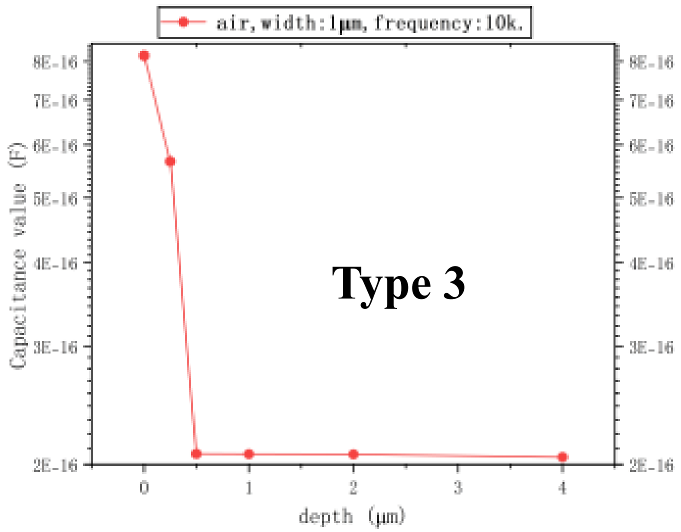
Isolated AC-LGAD Simulation and Design

Trench depth

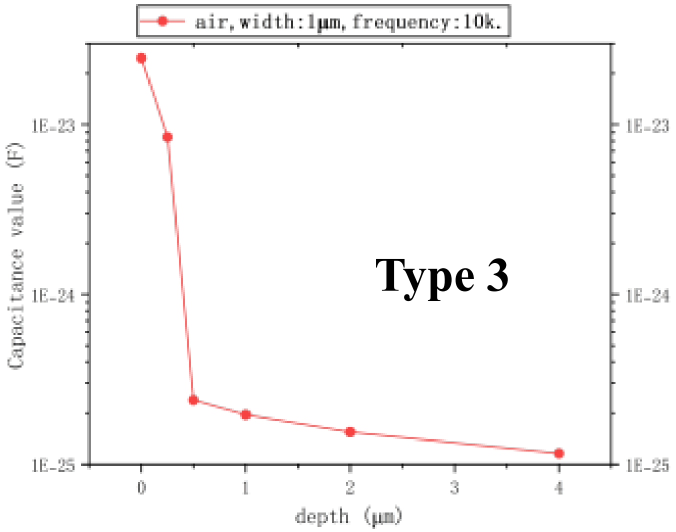


Type 3





bulk capacitance

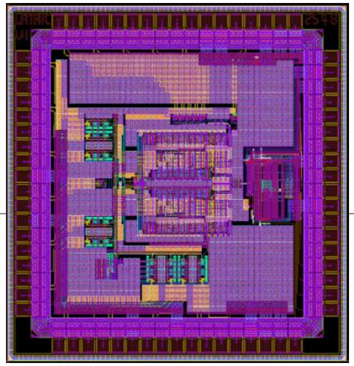


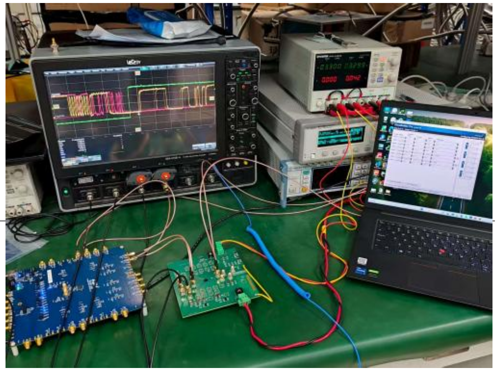
Inter-strip capacitance

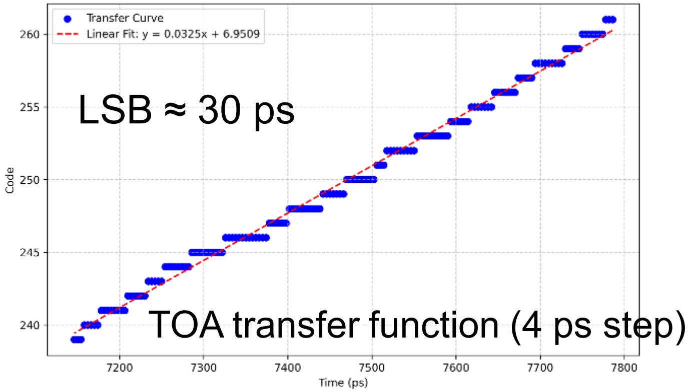
- Trench isolation depth be simulated and IV changes as changing the trench depth.
- Depleted bulk capacitance and inter-strip capacitance significantly reduced for AC-LGAD as the depth increasing.

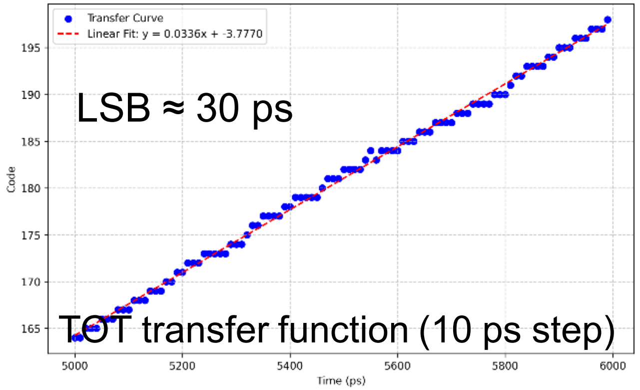
LGAD Readout ASIC (LATRIC)

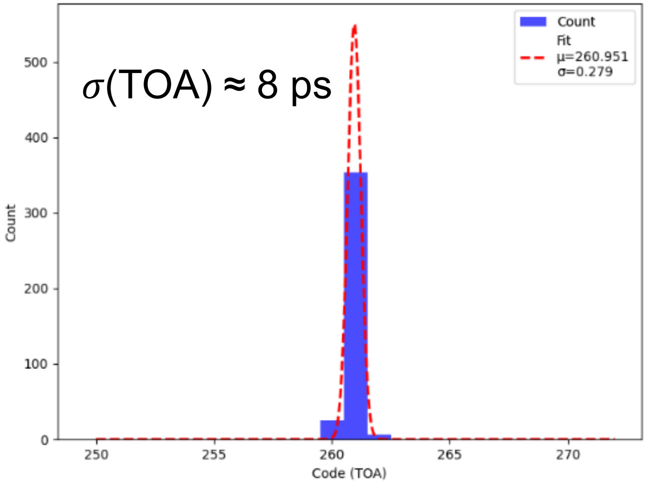
- **The first LGAD readout ASIC prototype, LATRIC-V0, submitted for tape-out in April, was delivered in August**:
  - The ASIC integrates a pre-amplifier, a discriminator, a TDC, and a serializer for data output.
  - **The LSB is 29.8 ps, meeting the 30 ps design goal.** TDC power consumption is 0.1 mA (1.2 V) @ 0.5 MTPS (Mega-Trigger Per Second), 0.3 mA @ 1 MTPS, and 0.5 mA @ 2 MTPS.
- **The 8-channel LATRIC-V1 was submitted for tape-out in October.**

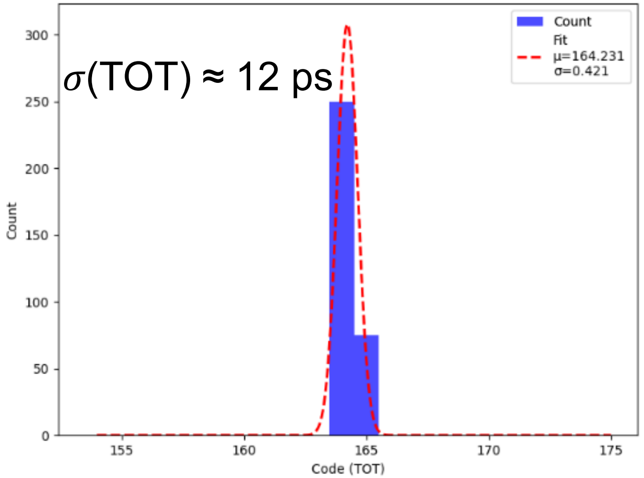


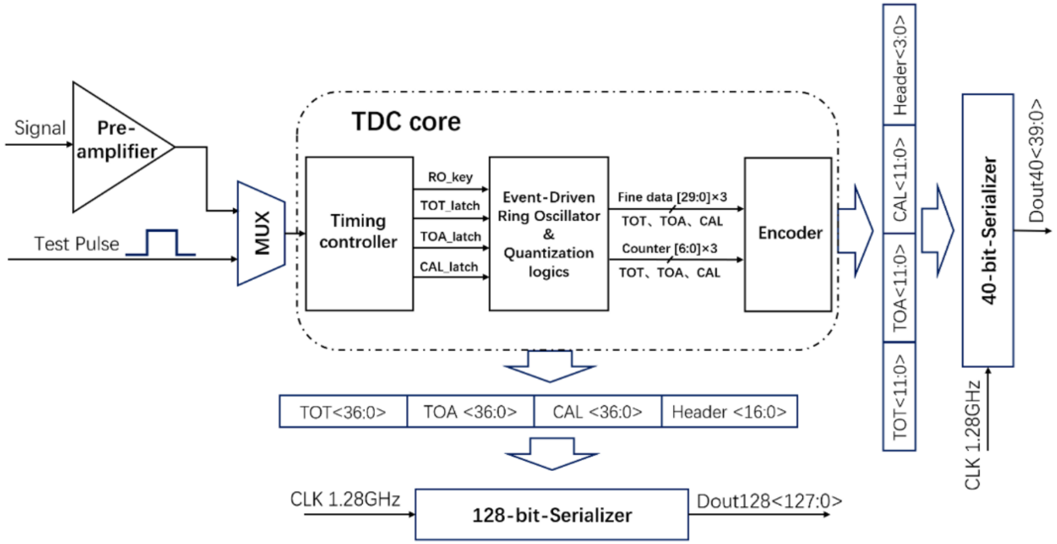










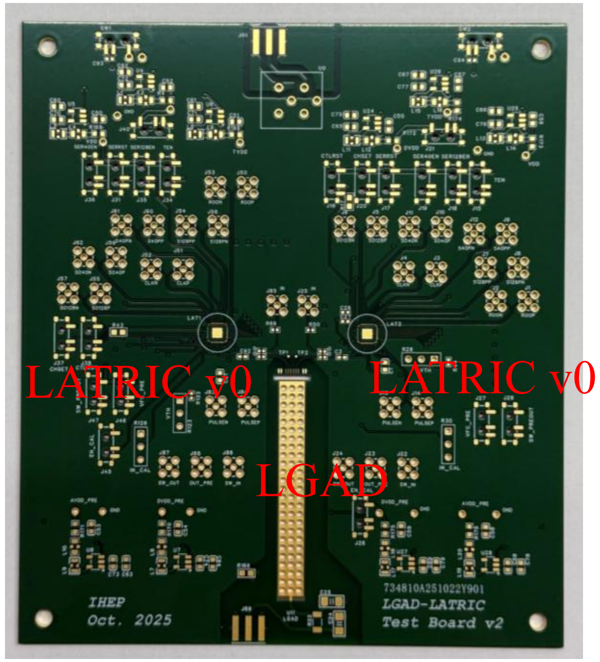


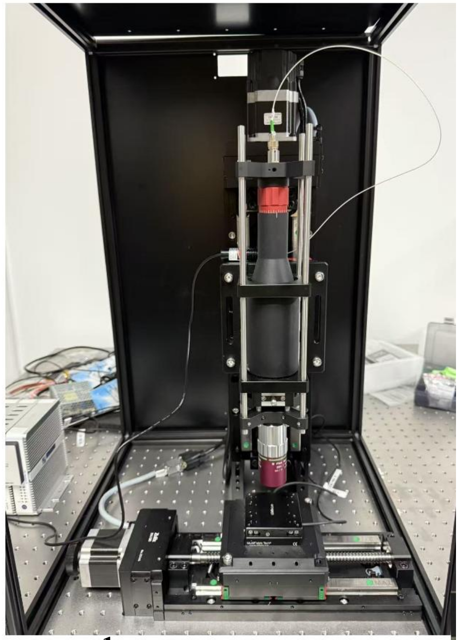
Summary and Next step

Summary

- For AC-LGAD Structure and process parameters: Simulation, design and fabrication and test of prototype
- IHEP AC-LGAD Sensor with optimized structure and process parameters show good timing(<40ps) and spatial resolution(<10um), including TID results.
- AC-LGAD with long strip is simulated and designed, fabrication ongoing. Will be delivered in December.
- ASIC for readout AC-LGAD is fabricated and tested. Timing performance~10ps

- Performance evaluation of AC-LGAD and DC-LGAD with 1cm, 2cm, 4cm long strips
- Test of LGAD + ASIC [LATRIC v0 LGAD readout ASIC]





laser test setup

- Beam test is planned in middle of 2026 [CERN PS]

Thanks

Goal: Develop LGAD based silicon sensors with a spatial resolution better than 10 µm and a timing resolution in the range of 30-50 ps as Timing Tracker for Future Electron Collider

	Participants
IHEP	Institute of high energy physics, Chinese Academy of Sciences
IME	Institute of Microelectronics, Chinese Academy of Sciences
JSI	Jozef Stefan Institute, Ljubljana
USP	University of São Paulo
UCG	University of Montenegro
SDU	Shandong University
SJTU	Shanghai Jiao Tong University
ZZU	Zhengzhou University

DRD3 WG2 Project: LGAD based Timing Tracker Development for Future Electron Collider

Research package

1. AC-LGAD simulation and design
2. AC-LGAD fabrication
3. AC-LGAD lab testing: IV, CV, timing resolution, spatial resolution
4. AC-LGAD beam test
5. Radiation performance study (TID, neutron, proton)
6. Position reconstruction methods
7. The applications of LGAD for other particle experiment and outside of particle physics

Explore the AC-LGAD's application as photo detector or X-ray detector

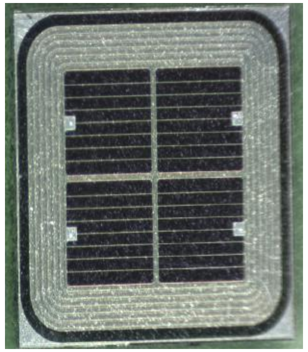
CDS: https://cds.cern.ch/record/2918306

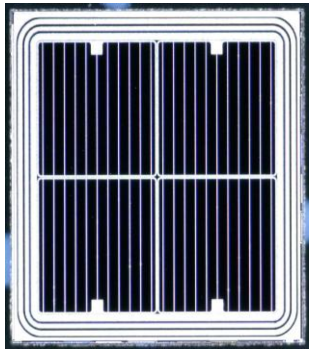
Contact: Mei Zhao, zhaomei@ihep.ac.cn

Back up

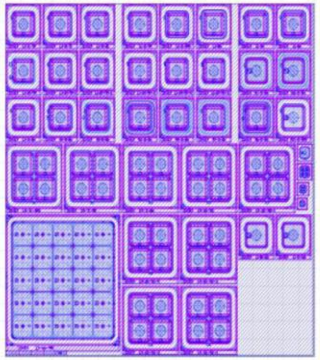
LGAD Development at IHEP

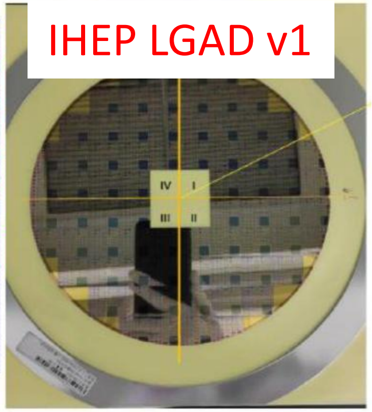
IHEP-NDL(2019)



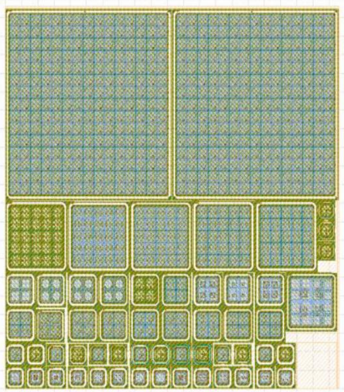


IHEP LGAD v1 (2020.9)

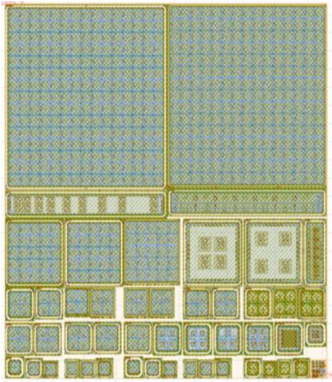


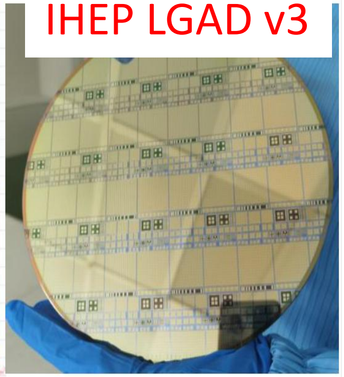


IHEP LGAD v2 (2021.6)

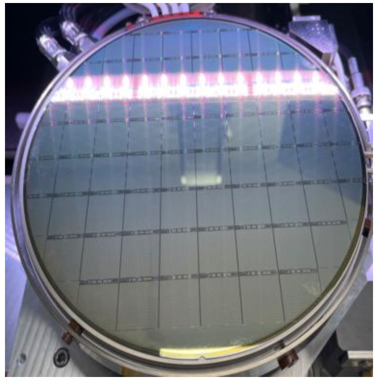


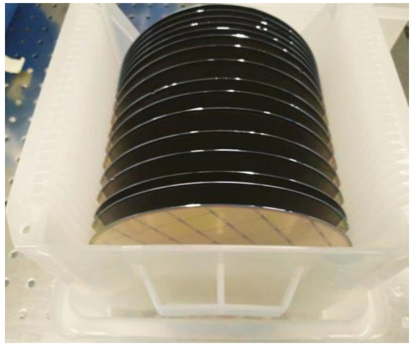
IHEP LGAD v3 (2022.5)



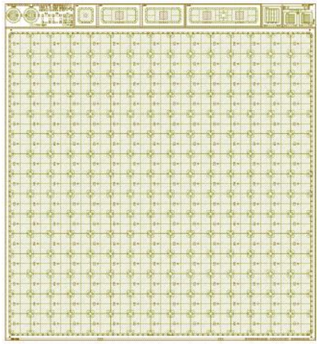


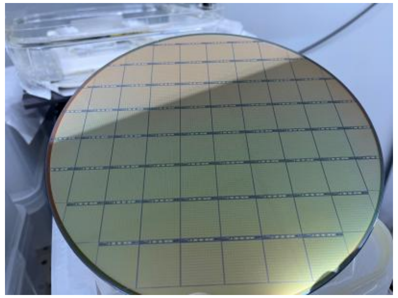
Pre-production for ATLAS (2023.7)

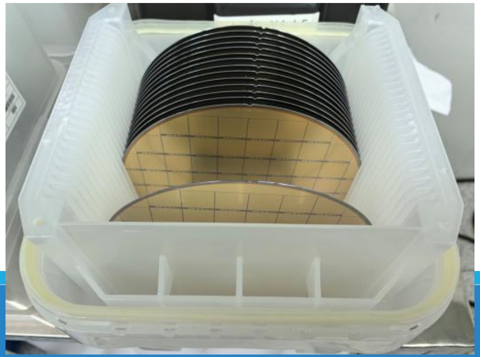


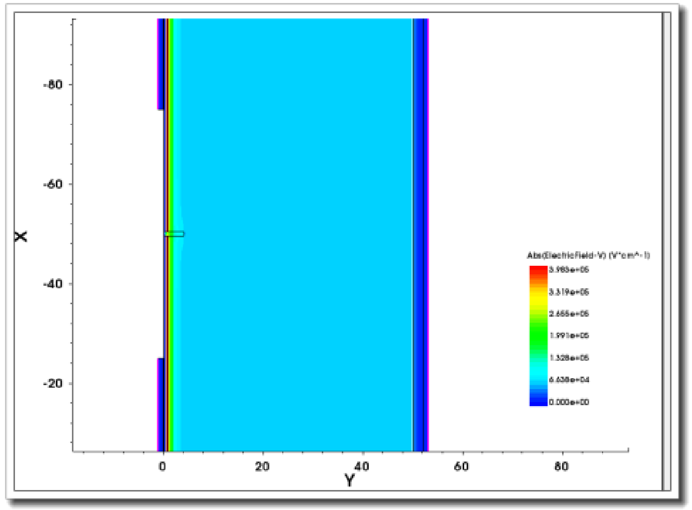


Mass production for ATLAS (2024.8)

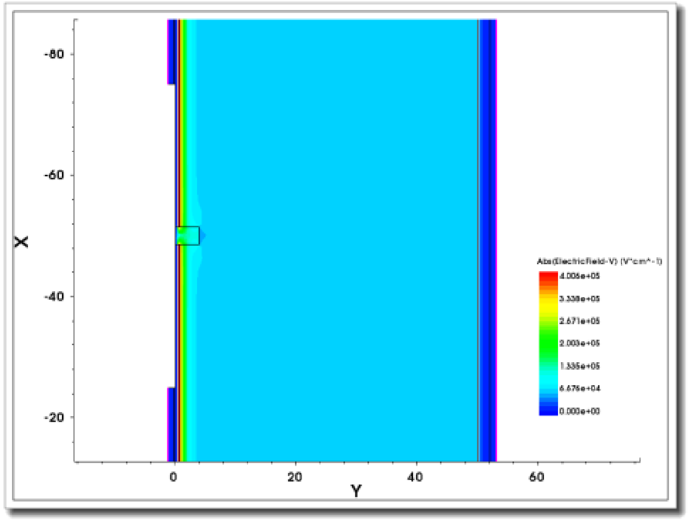




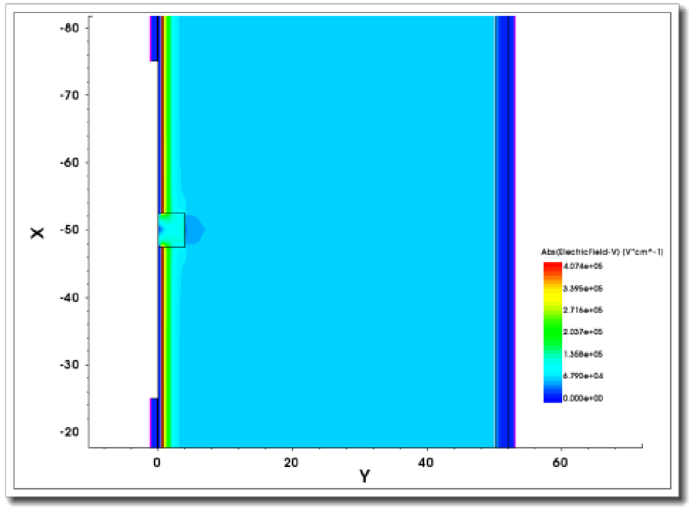




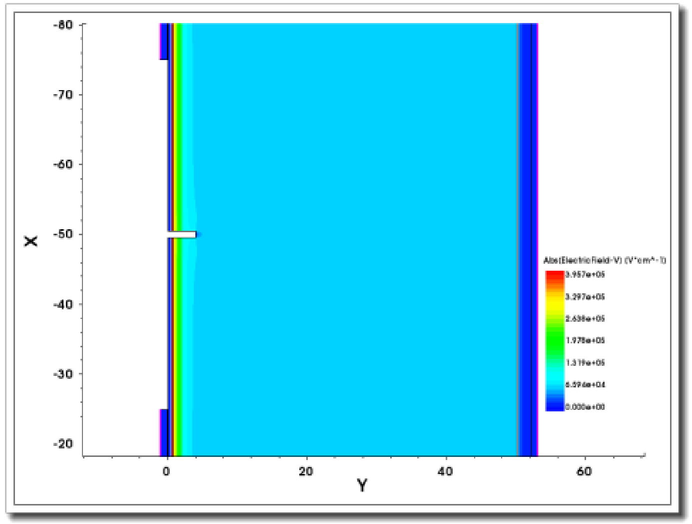
(a) SiO_2, 1 μm



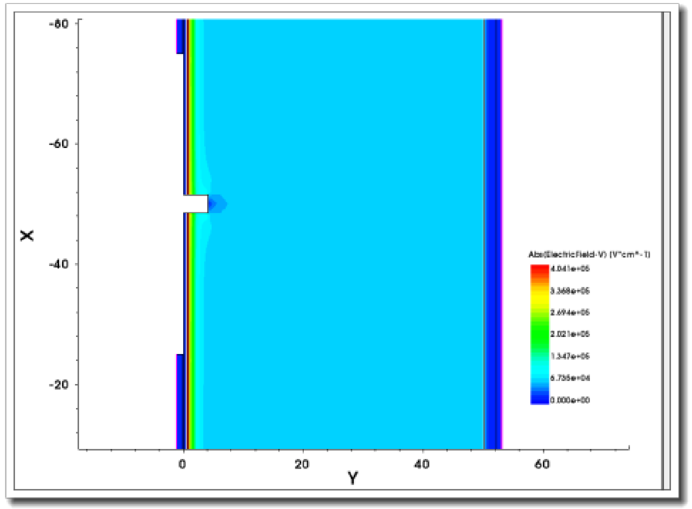
(b) SiO_2, 3 μm



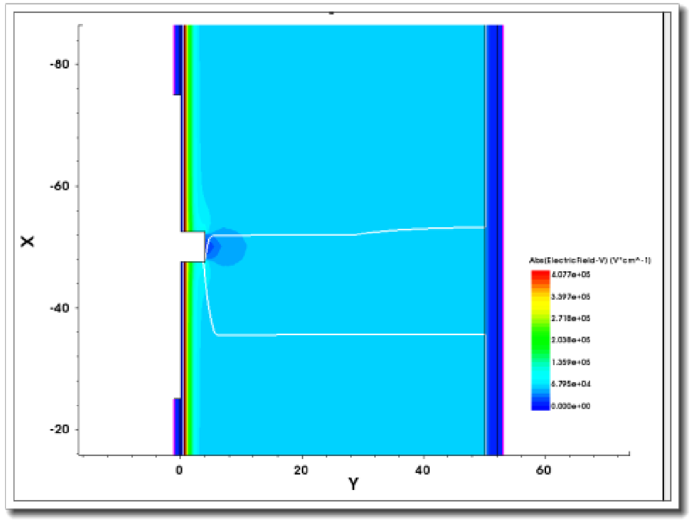
(c) SiO_2, 5 μm



(d) Air, 1 μm



(e) Air, 3 μm



(f) Air, 5 μm