低增益雪崩探测器芯片设计
LGAD Sensor Design

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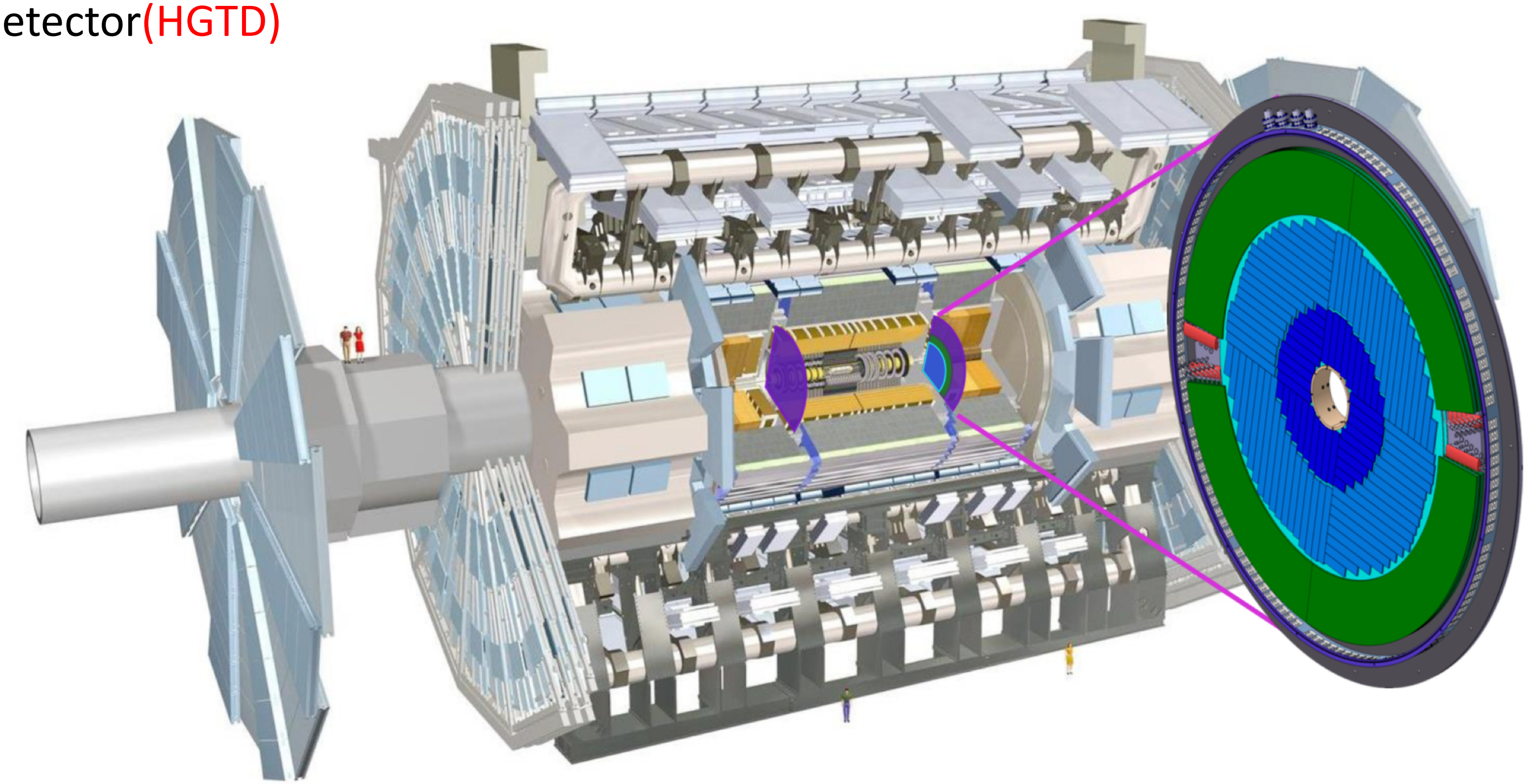
HL-LHC and ATLAS HGTD Upgrade

The High-Luminosity Large Hadron Collider (HL-LHC) project aims to crank up the performance of the LHC in order to increase the potential for discoveries after 2025.

ATLAS will upgrade endcap calorimeter aiming for High-Granularity Timing Detector(HGTD)

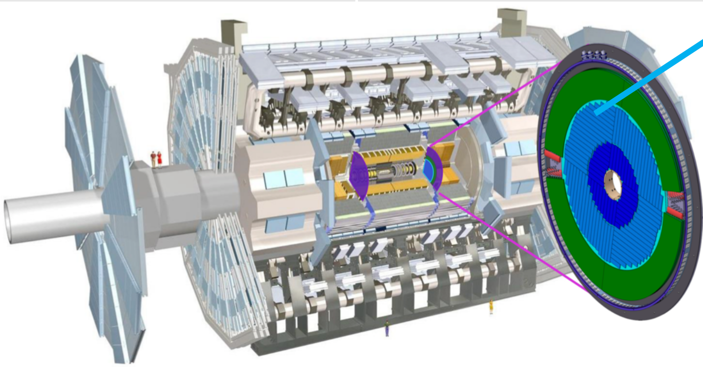


Position of the two vessels for the HGTD within the ATLAS detector

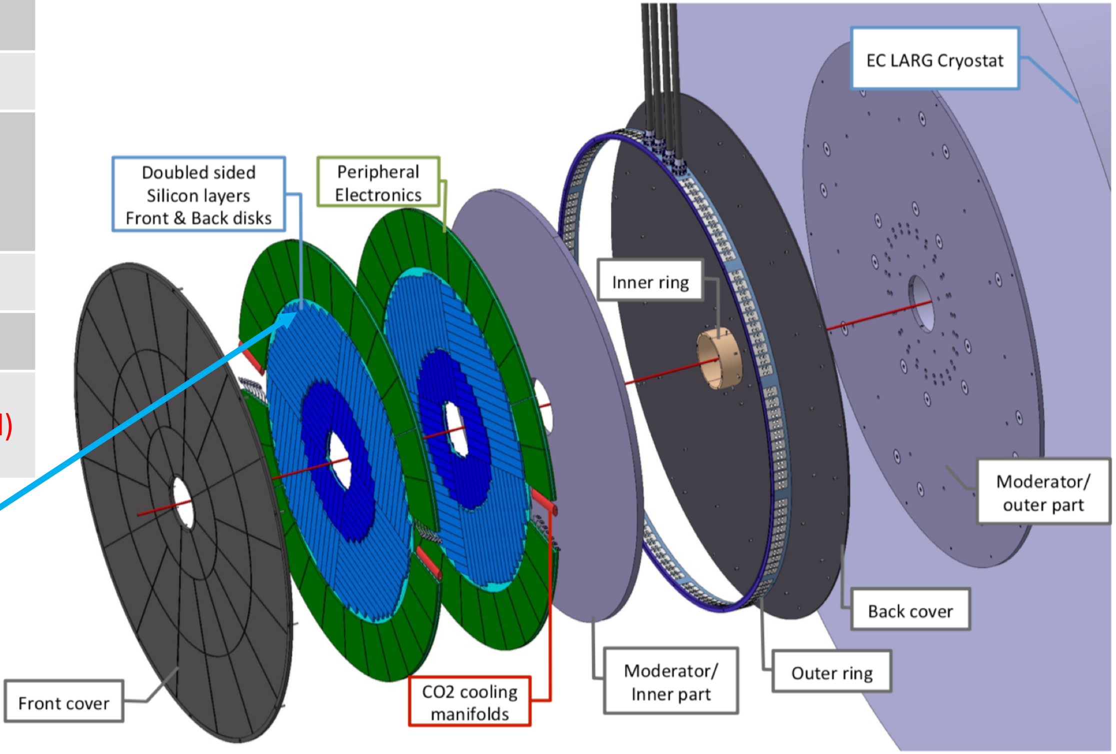
HGTD Overview

HGTD Main Parameters	
Pseudo-rapidity coverage	2.4 < |η| < 4.0
Position of active layers in z	z = ±3.5 mm
Radial extension: Total Active area	 110mm < r < 1000mm 120mm < r < 640mm
Pad size	1.3mm×1.3mm
Active sensor thickness	50 μm
Average time resolution per hit (start and end of lifetime)	≈ 40 ps (start) ≈ 75 ps (end)

LGAD!!! 40ps!!!



Position of the two vessels for the HGTD within the ATLAS detector



Various components of HGTD

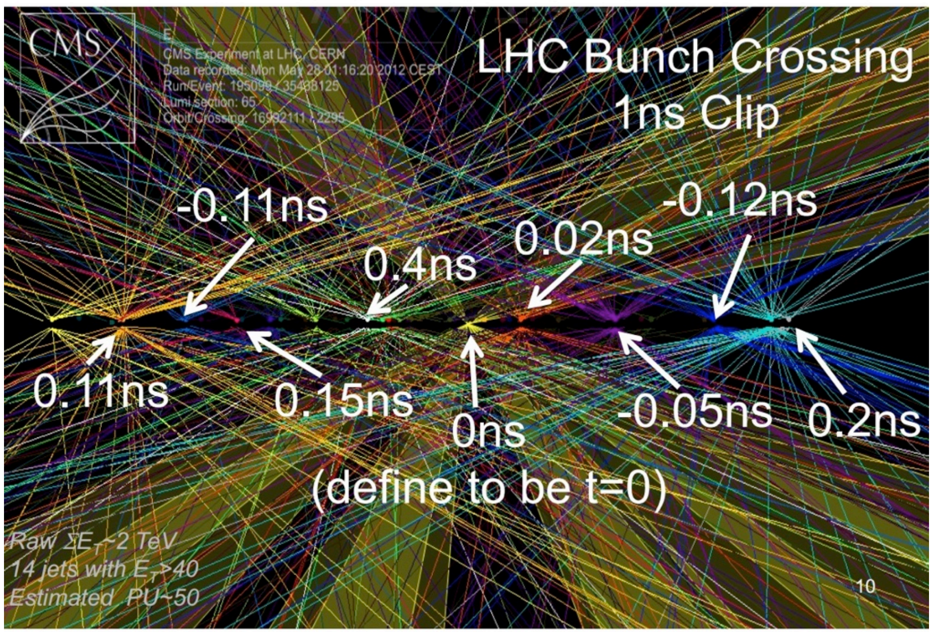
Timing Verification

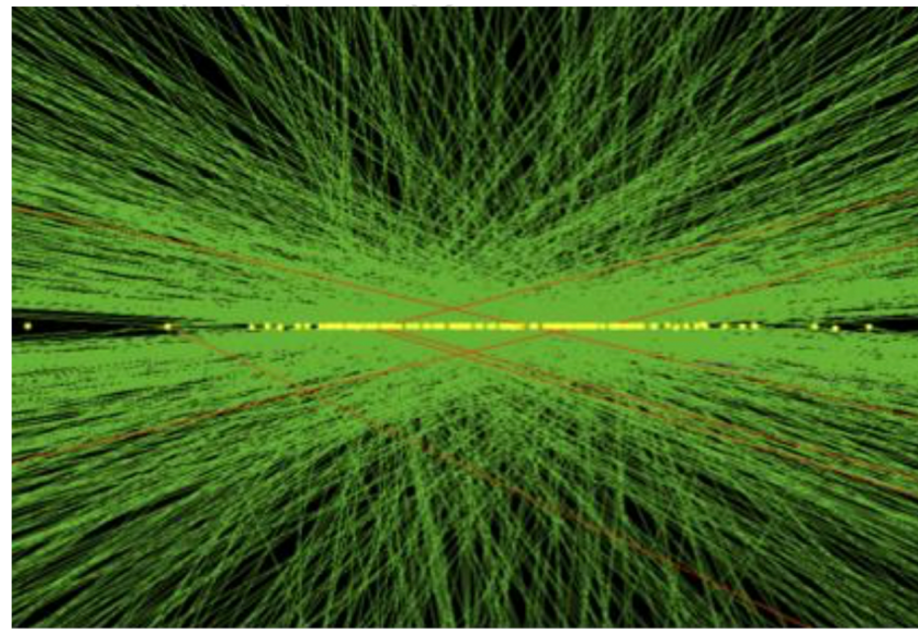
LHC Run-2 instantaneous luminosity

$2 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

HL-LHC instantaneous luminosity

$7.5 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$



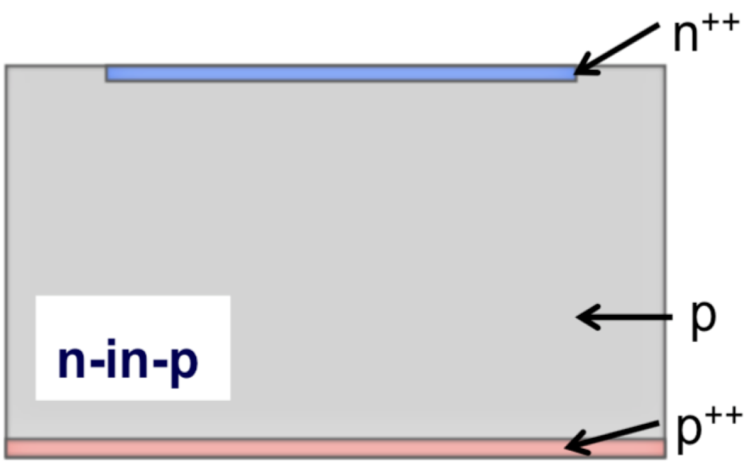


50 inelastic collisions in one bunch crossing

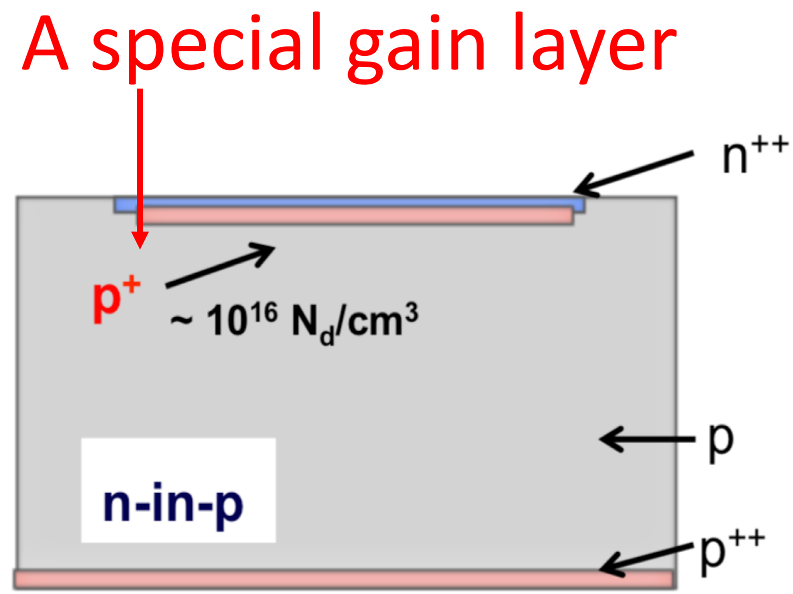
200 inelastic collisions in one bunch crossing

LGAD vs Traditional Silicon Detector

The Low-Gain-Avalanche-Diode (LGAD) is similar to Traditional Detector except:



Traditional silicon detector

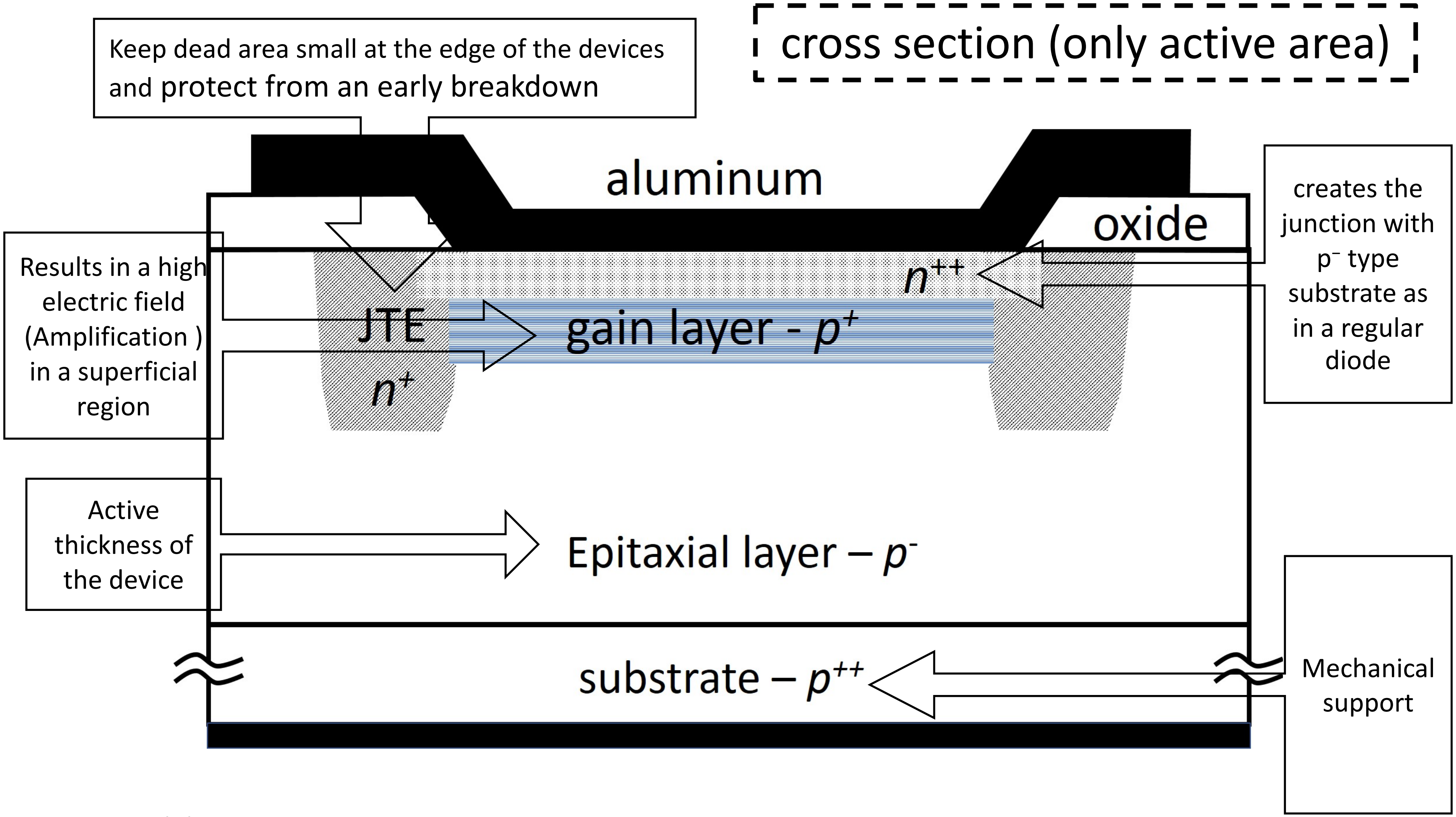


Low gain avalanche detector

Avalanche Photon Detectors (APD) with gain in the 100's.
Silicon Photon Multipliers (SiPM) with a gain of about 10000.

(LGAD) with a gain of 10-20.

LGAD Structure



International LGAD Production

At present, LGADs have been produced in five manufacturing sites:

One very large company (Hamamatsu Photonics (**HPK**), Japan)

Two research institutes (**CNM**, Spain and Fondazione Bruno Kessler (**FBK**), Italy)

A smaller commercial manufacturer (**Micron**, UK)

A national laboratory (Brookhaven National Lab (**BNL**), USA)

Manufacturer	Wafer Size (inch)	Thickness (μm)	Gallium Substitution	Carbon Implantation	5x5 Array	15x15 Array
CNM	4-6	30-300	√	√	√	
FBK	6	60-300	√	√	√	
HPK	6	20-80			√	√
BNL	4	50				
Micron	4	100-300				

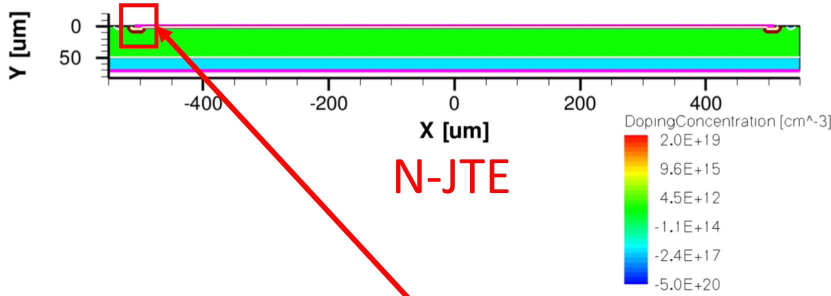
*Additional Carbon (C) implantation or the substitution of B by Gallium (Ga) are investigated as candidates for **improved radiation hardness.**

Challenges for IHEP

Fabrication in China->IHEP 1st LGAD tape out

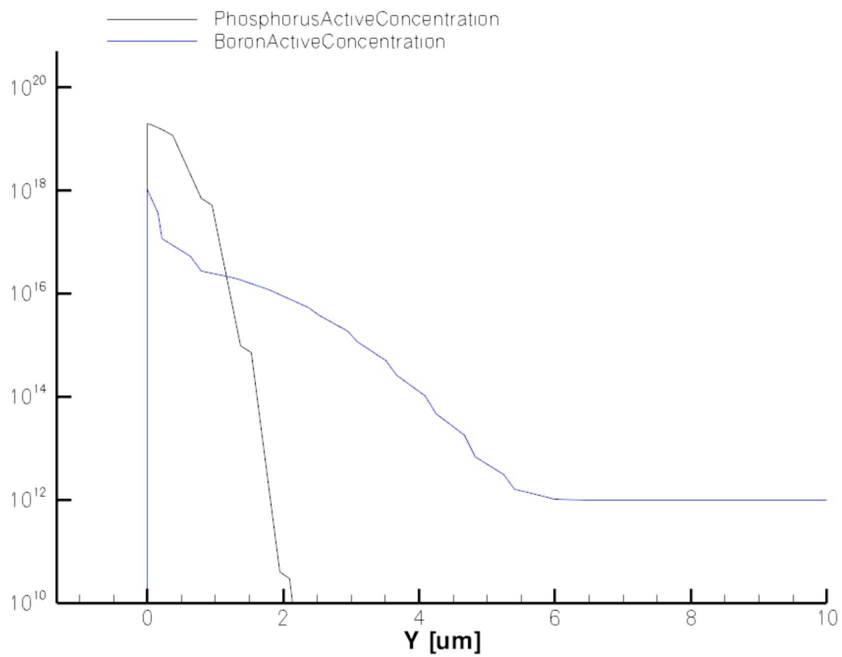
Radiation hardness->IHEP 2nd LGAD tape out

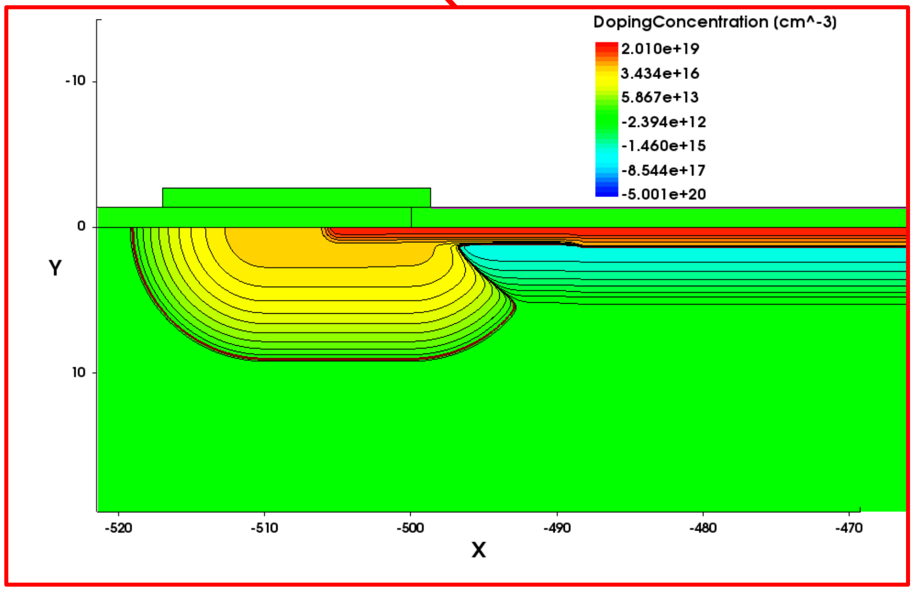
IHEP LGAD Baseline Design Doping



N^{++} layer and P^{+} gain layer

N-JTE

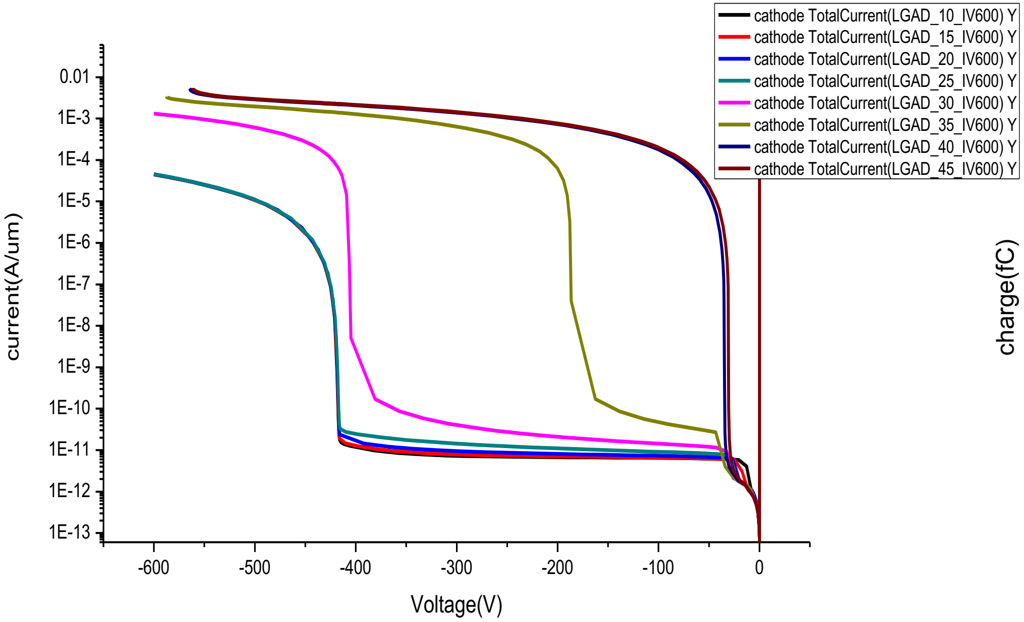




Gain Layer Doping Optimization

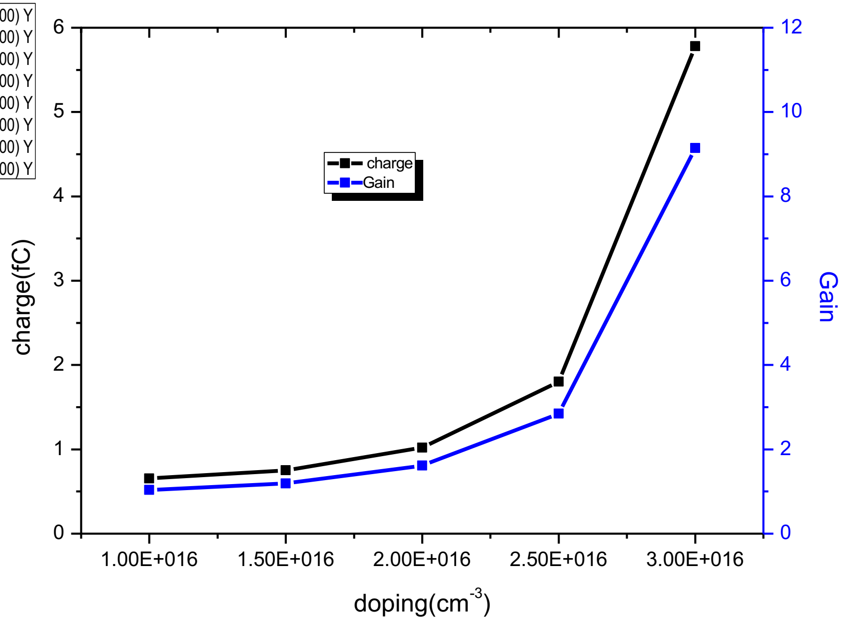
Gain Layer Doping Concentration vs Breakdown Voltage

Doping Concentration≤$3\times10^{16}\mathrm{cm}^{-3}$

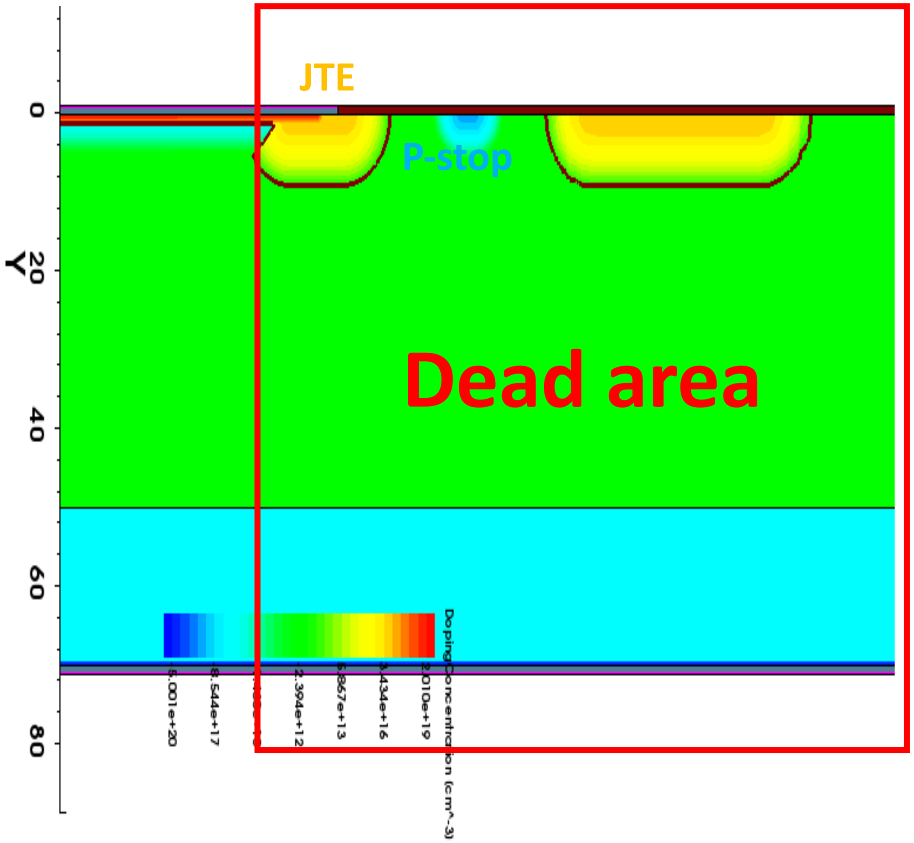


Gain Layer Doping Concentration vs Gain and Charge

Doping Concentration≥$3\times10^{16}\mathrm{cm}^{-3}$

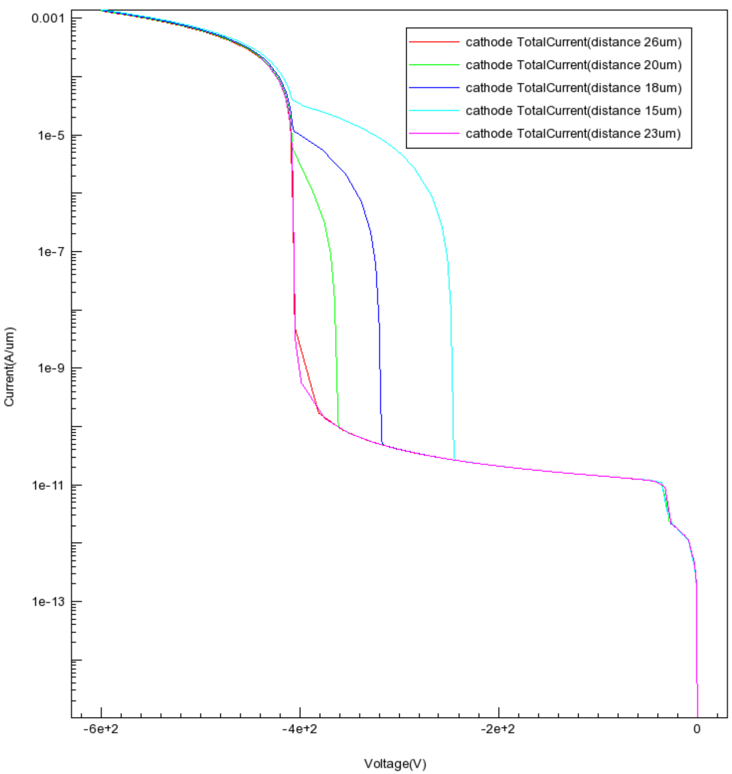


JTE Optimization



JTE and P-stop Gap vs Breakdown Voltage

Gap>23μm

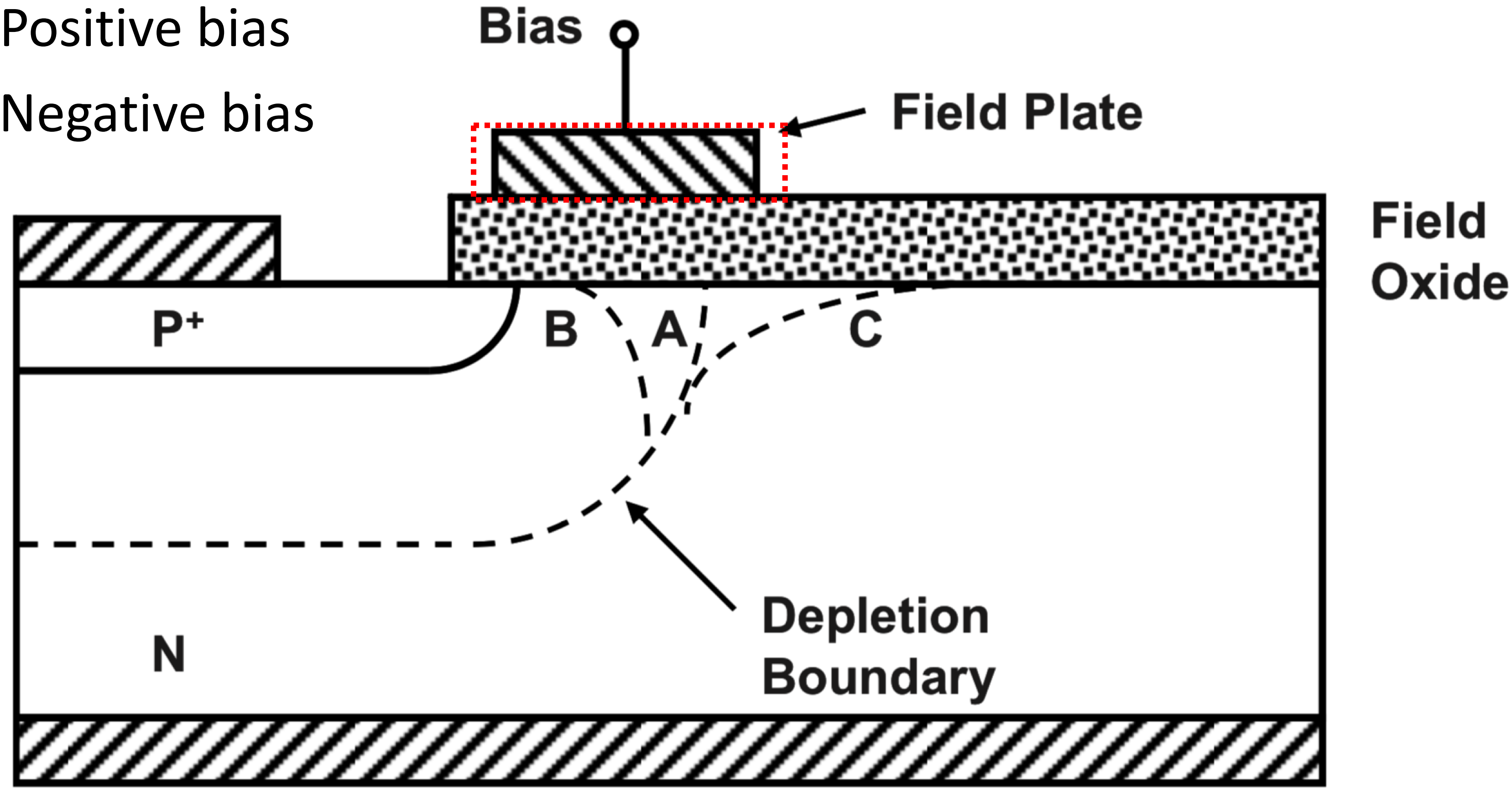


Field Plate

A. No bias voltage

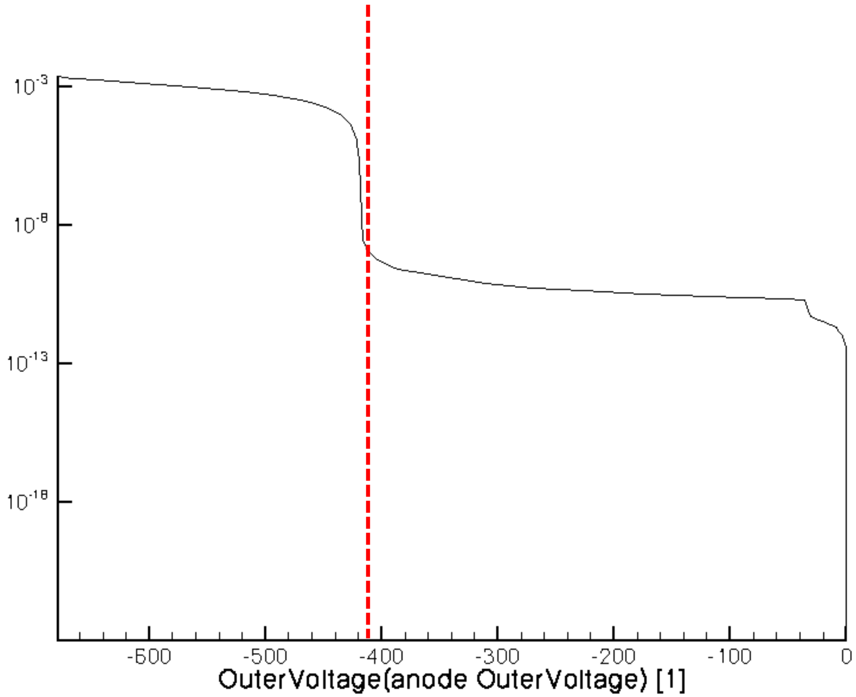
B. Positive bias

C. Negative bias

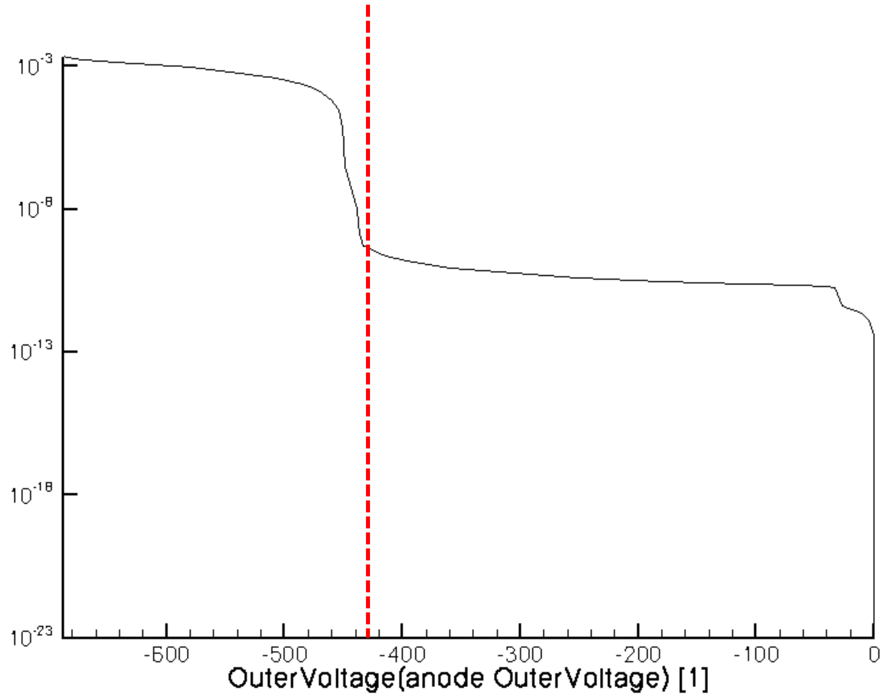


Field Plate Optimization

IV simulation without Field plate
Breakdown Voltage ≈ -410V

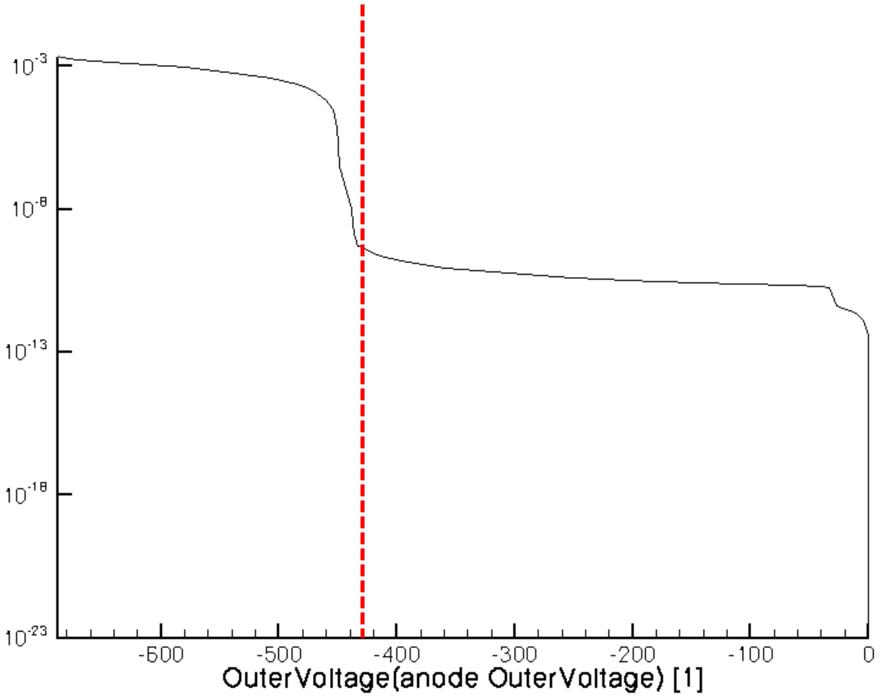


IV simulation with Field plate
Breakdown Voltage ≈ -433V

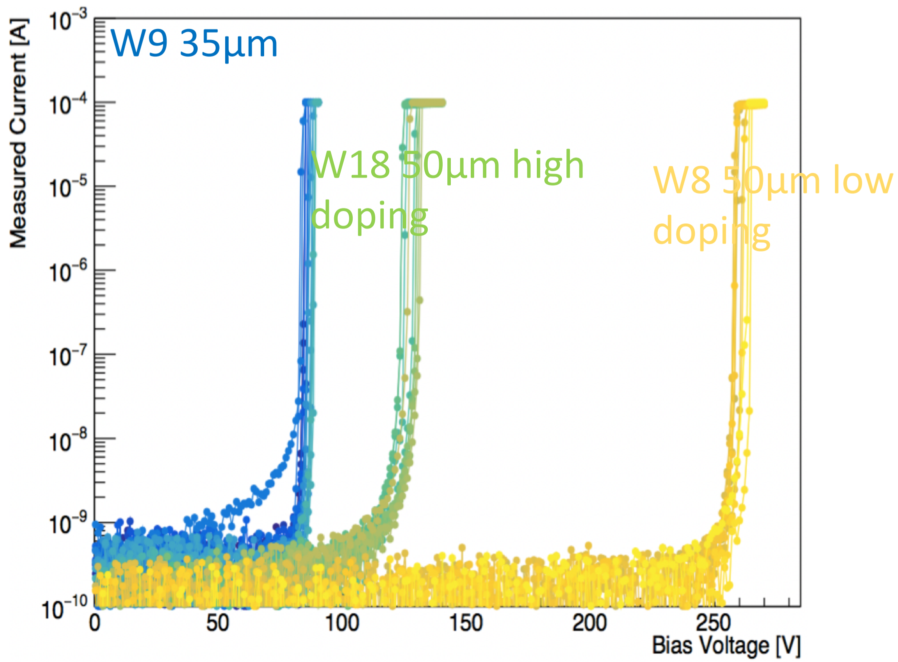


IV Simulation and Measurement

IHEP LGAD IV simulation
Breakdown Voltage ≈ -433V

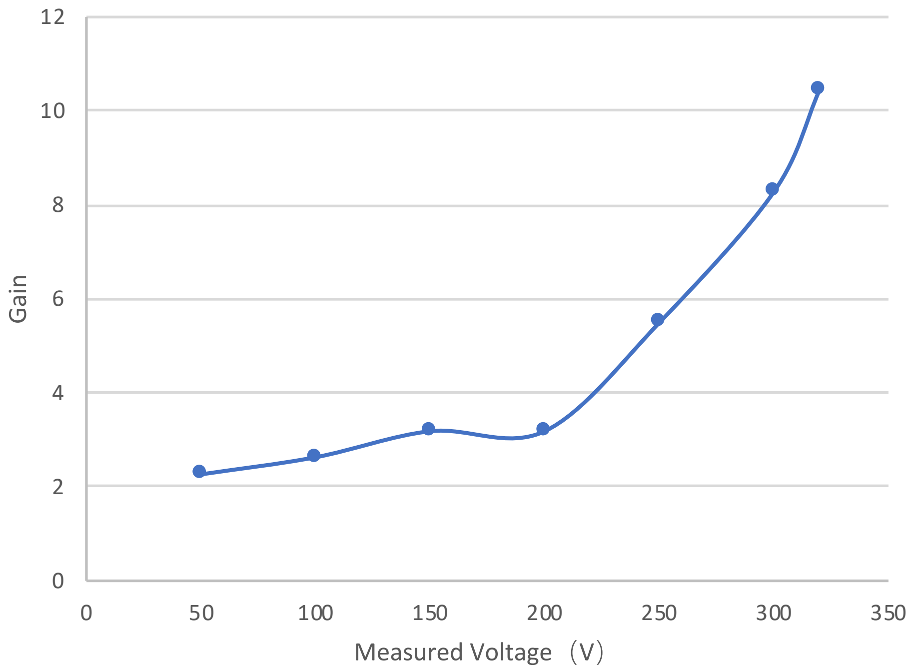


HPK LGAD IV measurement
Breakdown Voltage ≈ 80V 120V 250V

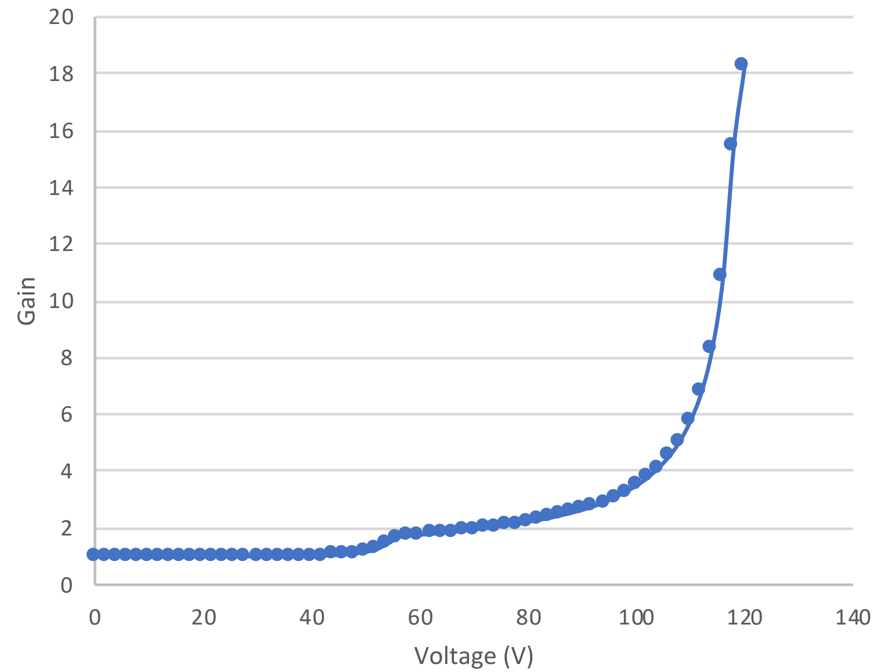


Gain Simulation and Measurement

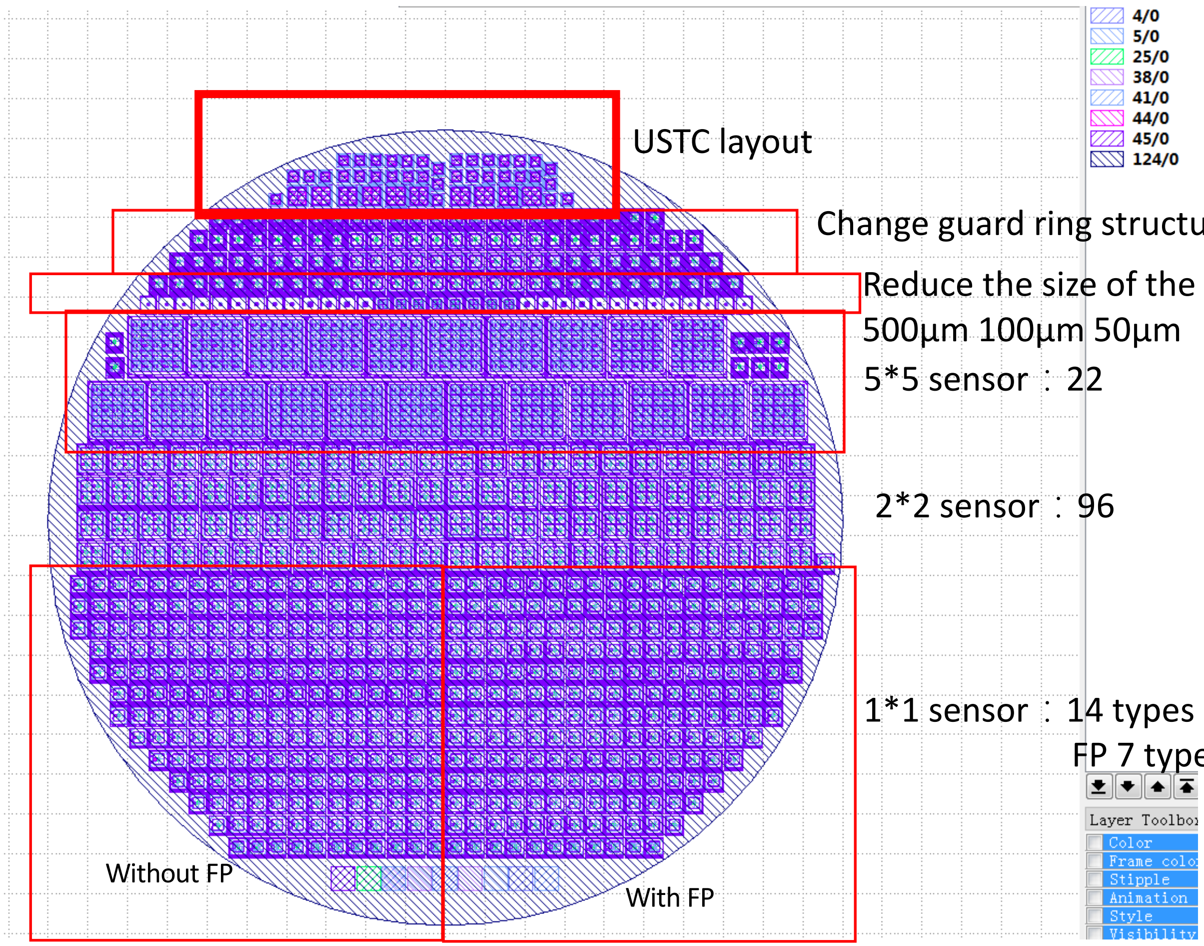
IHEP LGAD Gain simulation
Gain = 10.45@-320V



HPK W17 LGAD Gain measurement
Gain=10.8@118V



IHEP LGAD Wafer Layout



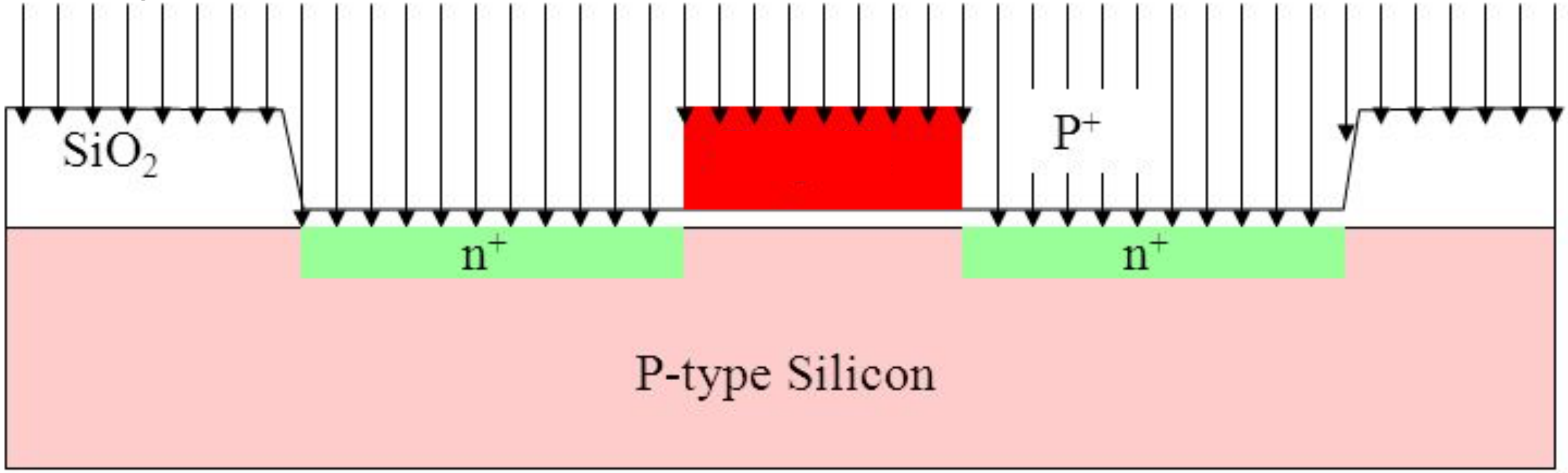
4/0	JTE and WN-ring
5/0	P-stop and DC-stop
25/0	open zone
38/0	p layer
41/0	n+
44/0	contact
45/0	metal
124/0	mark not mask

7 masks totally

Submitted already

Fabrication Process

1. Implant Phosphorus with N-JTE and WN-ring mask
2. Implant Boron with P-stop and DC-stop mask
3. Implant Boron with P^+ layer mask !!!
4. Diffusion
5. Implant Phosphorus N^{++} layer with mask
6. Implant Boron from back without mask



Timescale

IHEP 1st LGAD

2019 April - 2019 May:
Process Design

2019 May - 2019 June:
Sensor Fabrication

2019 June - 2019 July:
Sensor Test

IHEP 2nd LGAD

2019 July - 2019 August:
Design Irradiation Sensor

2019 September - 2019 October:
Sensor Fabrication

2019 November - 2019 December:
Sensor Test

感谢国家重点实验室的支持!
Thanks for SKL Funding!
感谢各位的耐心聆听!
Thanks for your listening!

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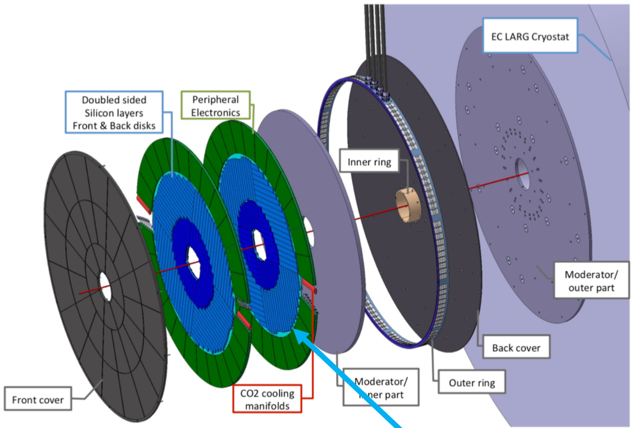
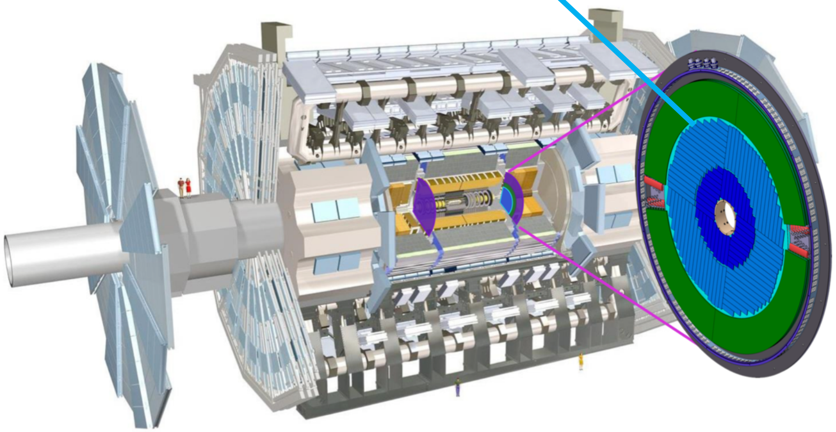
Backup

HGTD Position and Main Parameter

Global view of the various components of HGTD



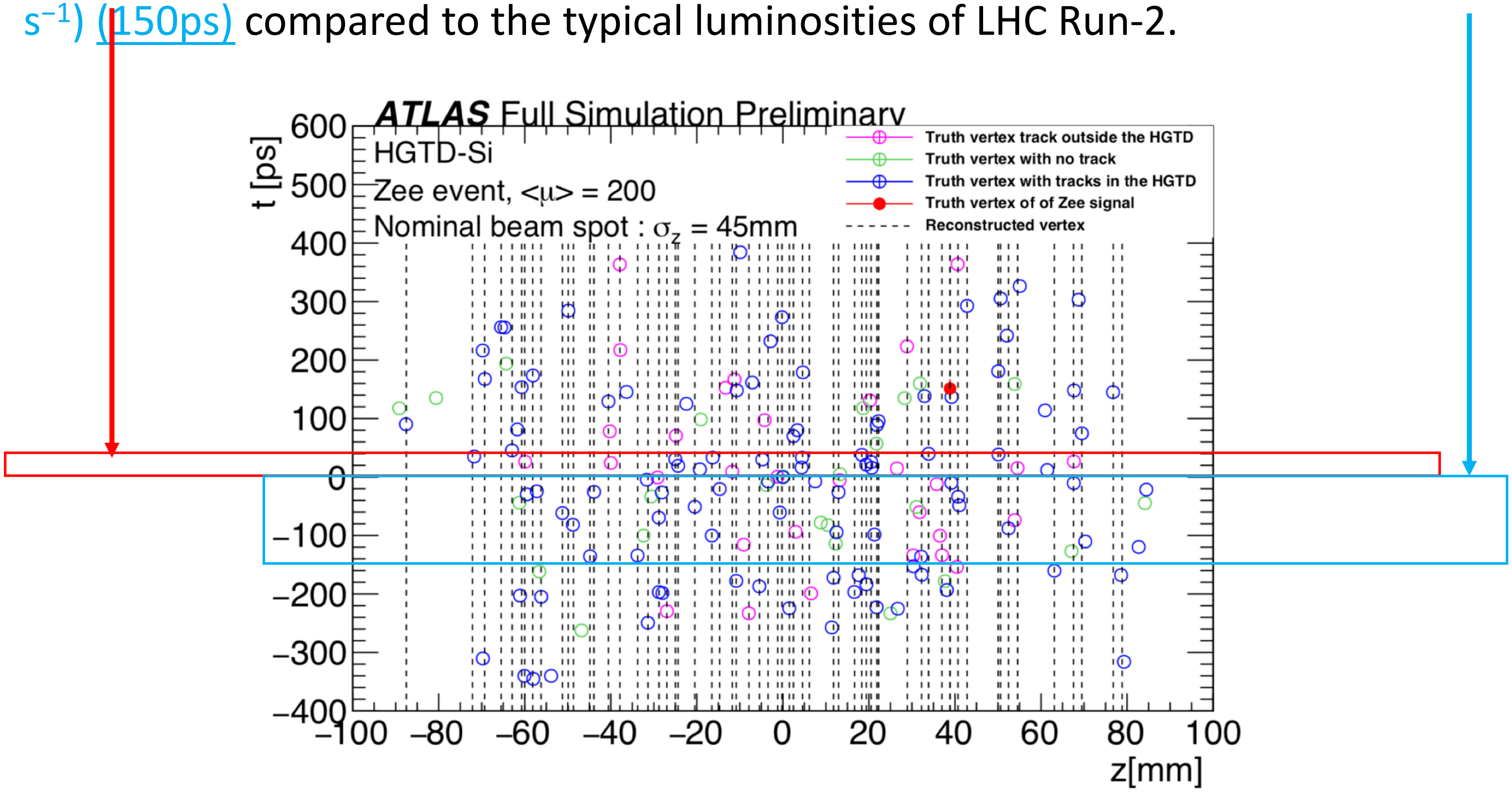
Position of the two vessels for the HGTD within the ATLAS detector



Main parameters of the HGTD	
Pseudo-rapidity coverage	$2.4 < \|\eta\| < 4.0$
Thickness in *z*	75 mm (+50 mm moderator)
Position of active layers in z	$z = \pm 3.5$ mm
Radial extension: Total Active area	 110mm < r < 1000mm 120mm < r < 640mm
Pad size	1.3mm×1.3mm
Active sensor thickness	50 μm
Collected charge	> 2.5 fC
Number of channels	3.59 M
Active area	6.4 m^2
Average time resolution per hit (start and end of lifetime)	≈ 40 ps (start) ≈ 75 ps (end)
Average time resolution per track (start and end of lifetime)	≈ 30 ps (start) ≈ 50 ps (end)

High-Granularity Timing Detector

The instantaneous luminosity of the HL-LHC will reach up to 7.5×10^{34} cm^{-2} s^{-1} (40ps) corresponding to an increase by an approximate factor of 5 (2×10^{34} cm^{-2} s^{-1}) (150ps) compared to the typical luminosities of LHC Run-2.



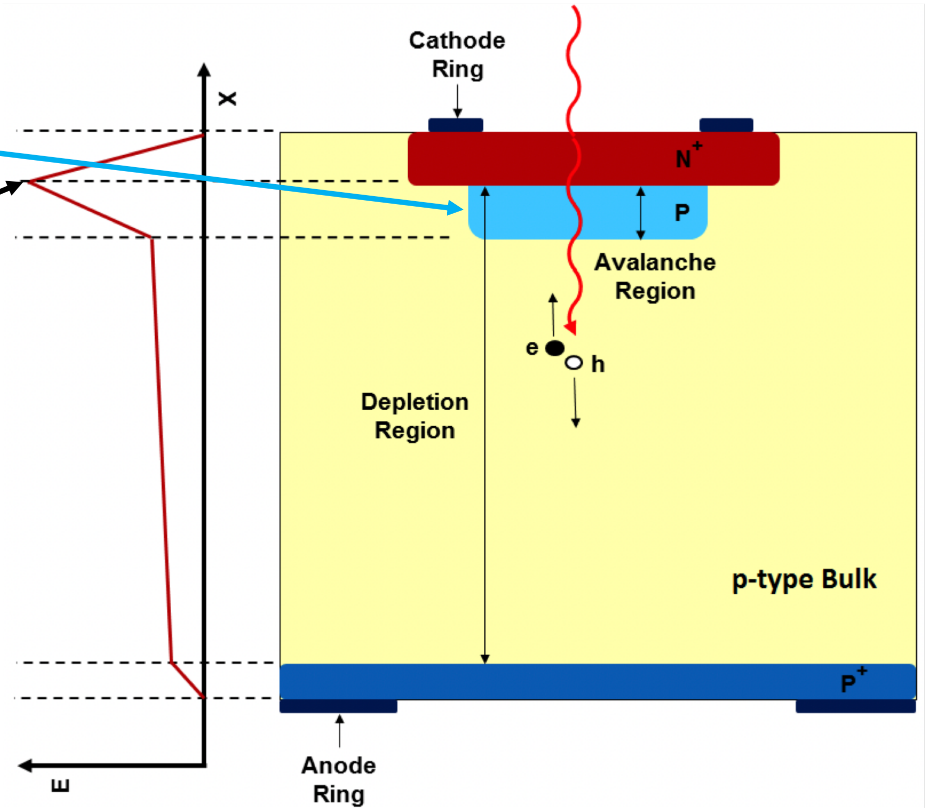
Low Gain Avalanche Detector Sensor

LGADs make use of the n^{++}-p^{+}-p structure (n^{++} is N^{+}, p^{+} is P, and p is π in the figure)

① Highly doped n-type thin layer.

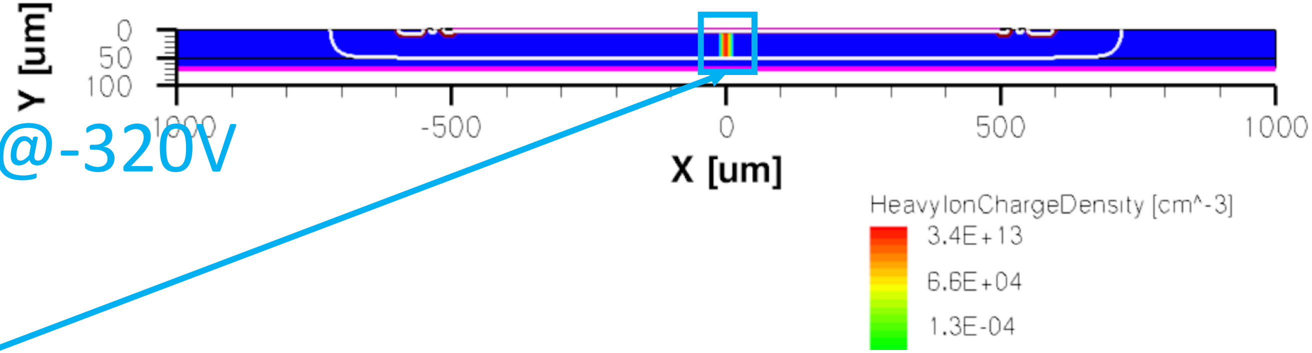
② A moderately doped p-type multiplication (gain) layer.

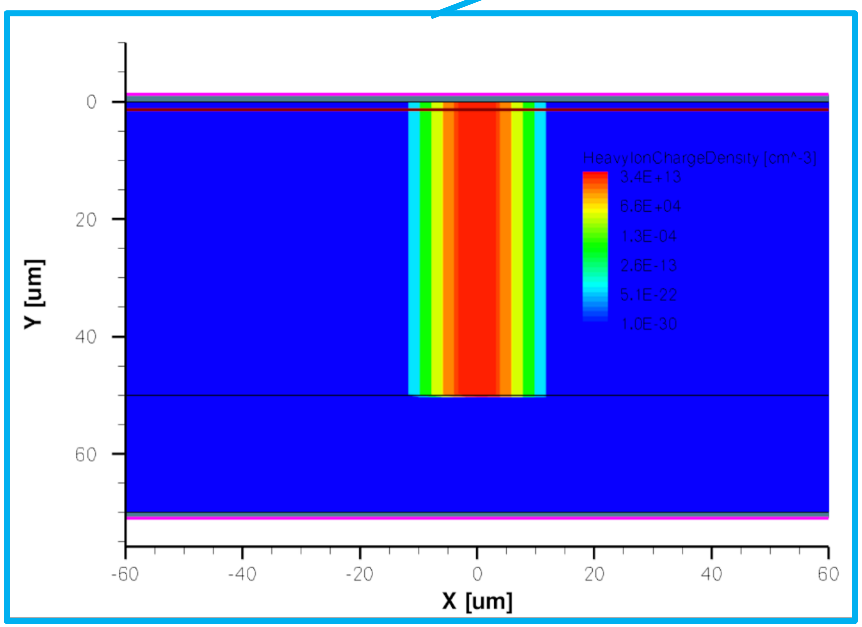
High E-field region in the gain layer allows impact ionization

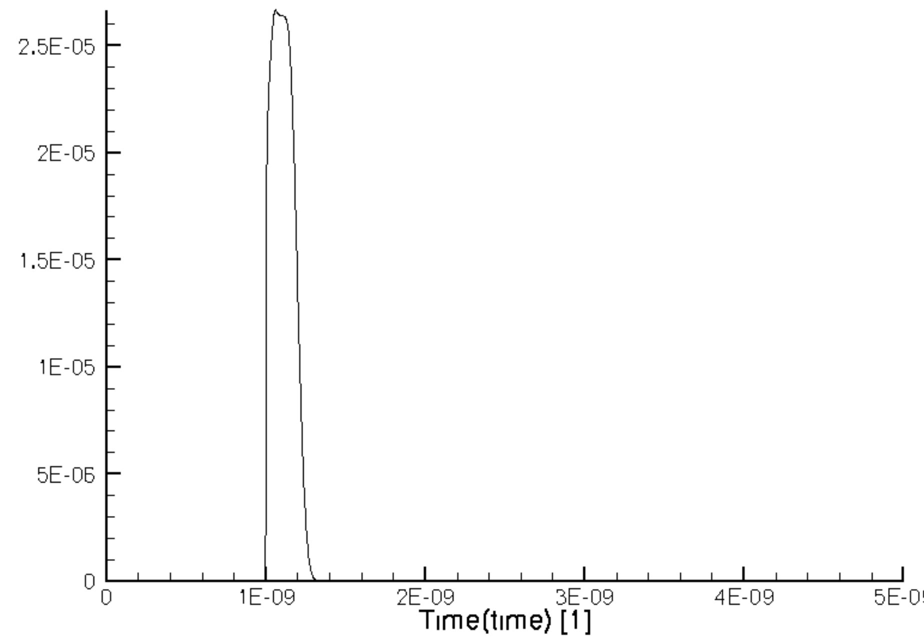


Gain Simulation Method

Gain= 10.45@-320V



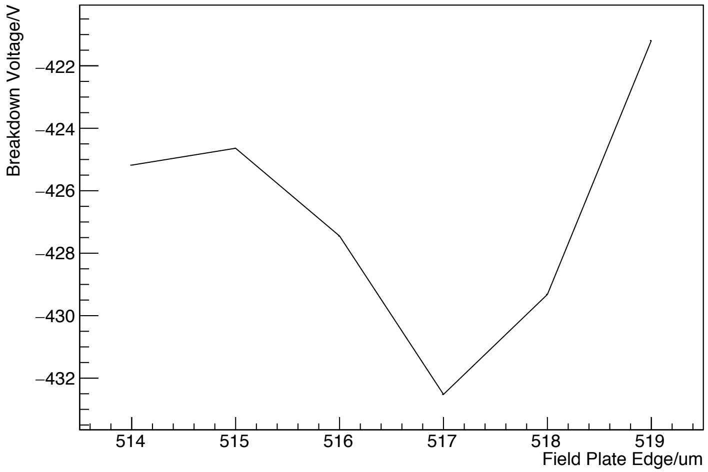


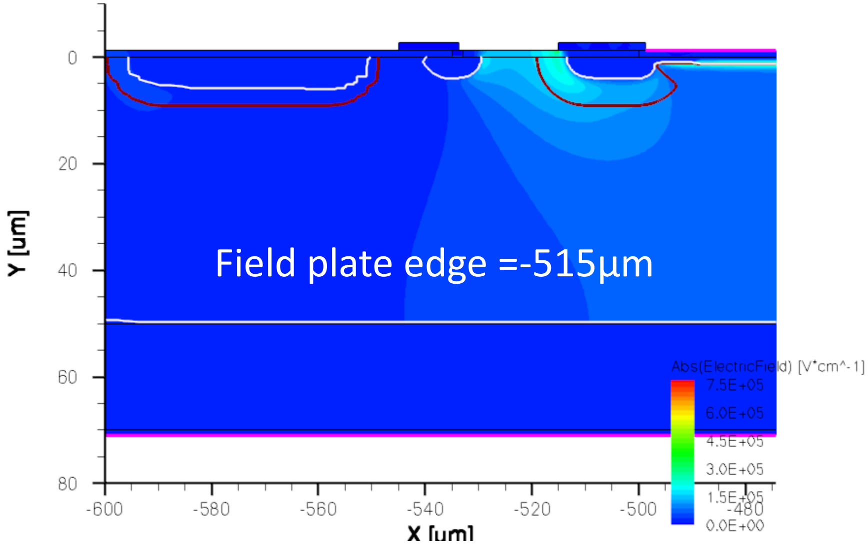


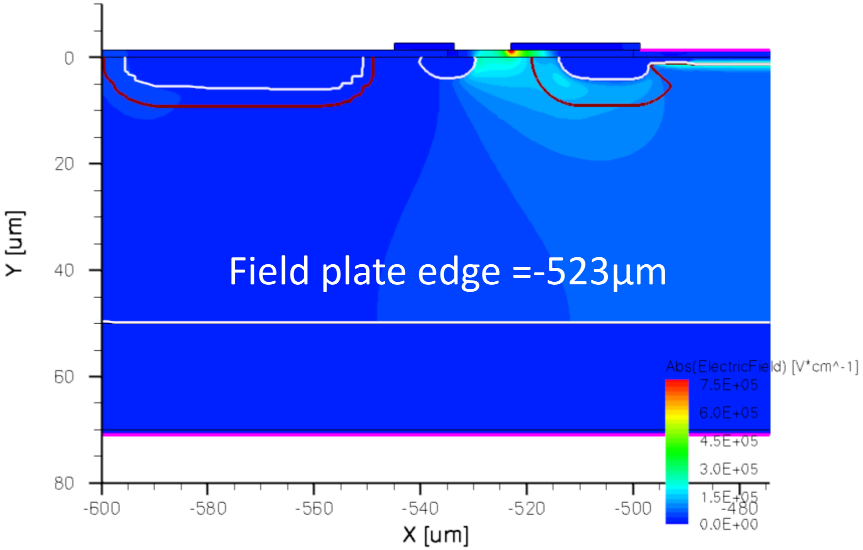
Field Plate Optimization

Field plate will highly dominate Breakdown Voltage especially for the real fabrication process chip.

Plot on the right indicate best field plate edge(size) for IHEP LGAD sensor.

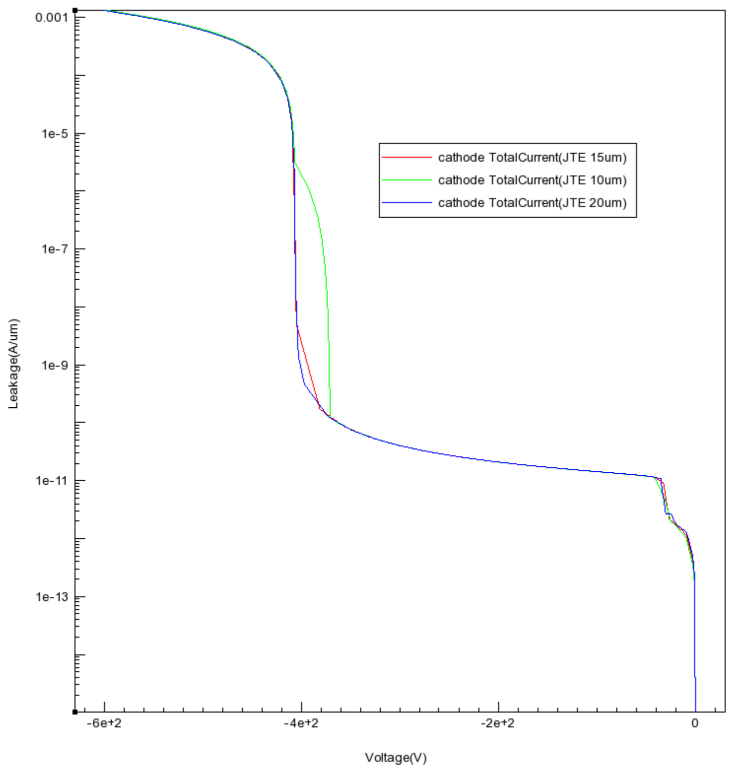




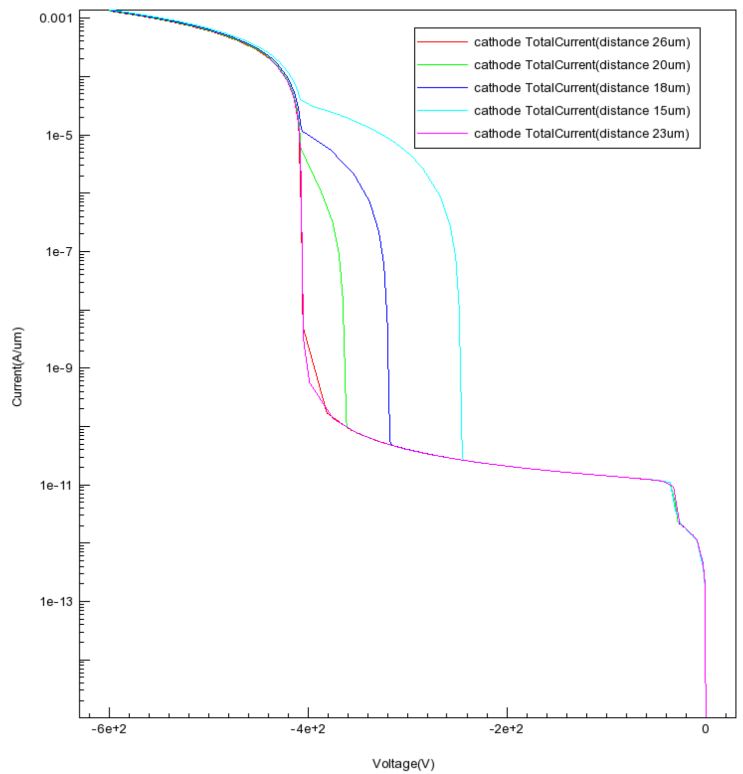


JTE Optimization

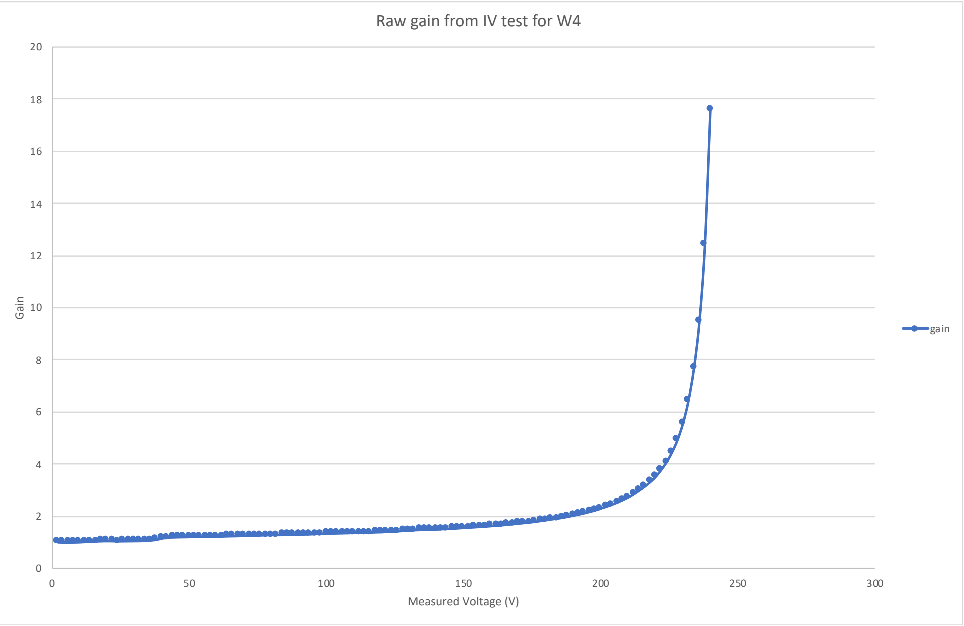
JTE Width vs Breakdown Voltage
Width>15μm

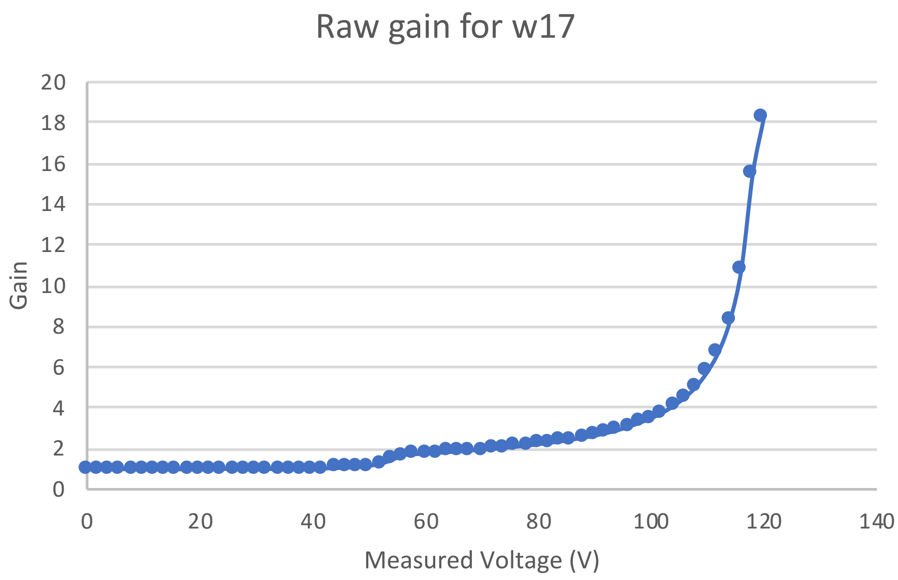


JTE and P-stop Gap vs Breakdown Voltage
Gap>23μm



Gain Measurement Data





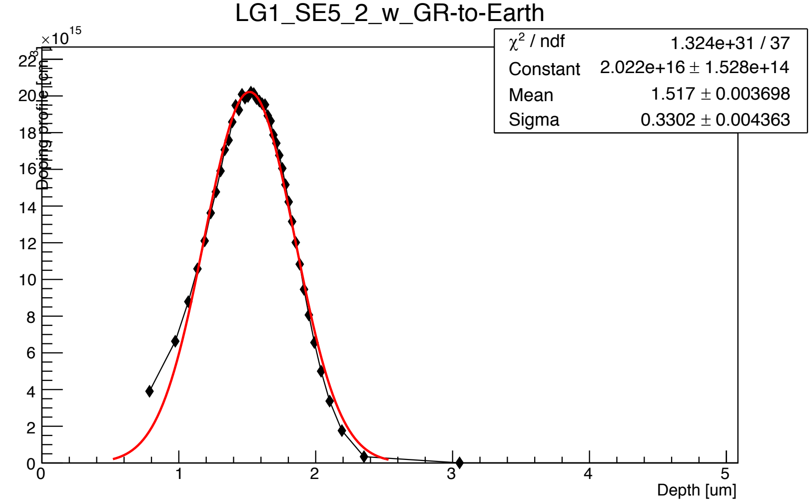
LGAD Sensor Test Schedule

IHEP people has tested CNM and HPK LGAD sensors for ATLAS HGTD Upgrade Group.

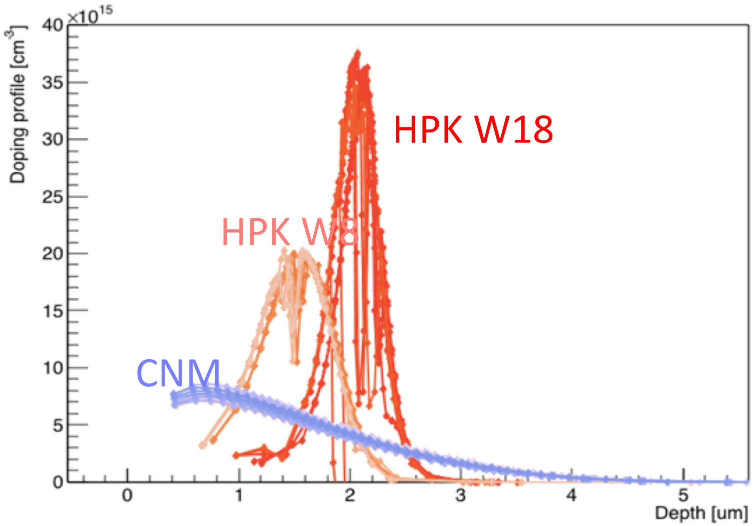
Test items:

- IV and CV Measurement
- Gain Measurement
- Time resolution Measurement
- Radiation hardness Measurement

Those test result will help ATLAS HGTD Upgrade Group check sensor performance and provide useful LGAD design indication for IHEP.

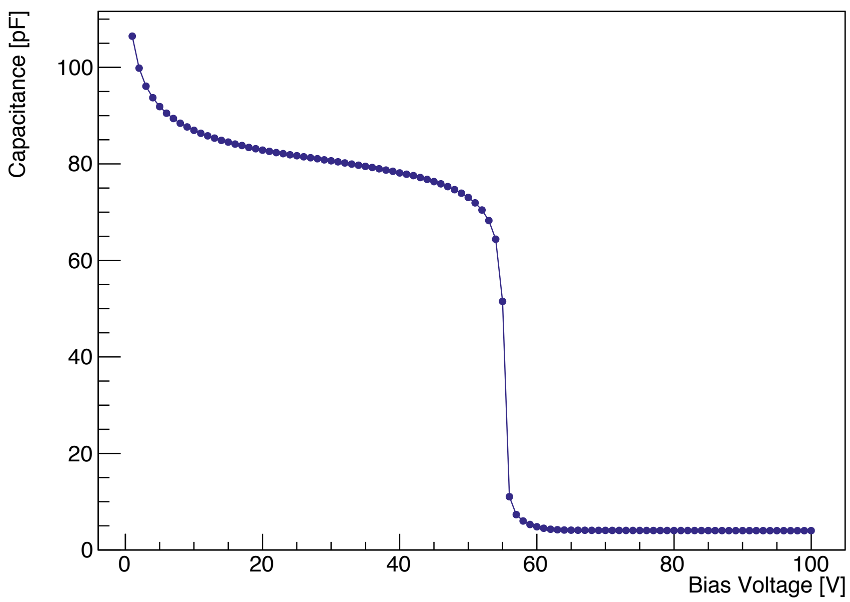


CNM and HPK LGAD Sensor CV Measurement

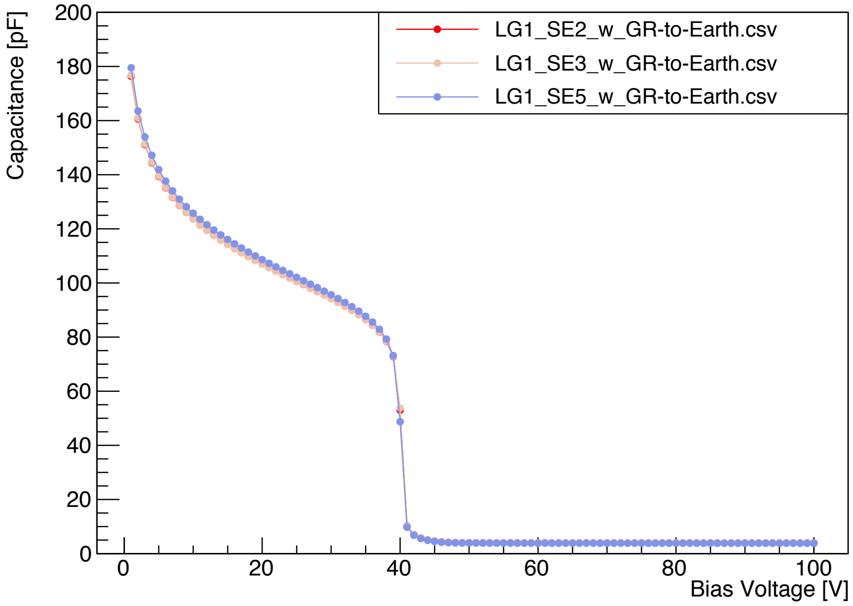


CV Measurement

HPK W18 LGAD CV measurement
Depletion Voltage ≈ 55V



HPK W8 LGAD CV measurement
Depletion Voltage ≈ 40V



CV to Doping Profile

The doping profile of a MOS structure can be obtained from C-V measurement results. The width of the depletion layer and the change in capacitance with applied bias voltage depend on doping concentration. The doping profile is calculated from the following equations:

$$N(W) = \frac{2}{q \cdot \epsilon_{si} \cdot \epsilon_0 \cdot A^2} \left[\frac{d}{dv} \left(\frac{1}{C^2} \right) \right]^{-1}$$

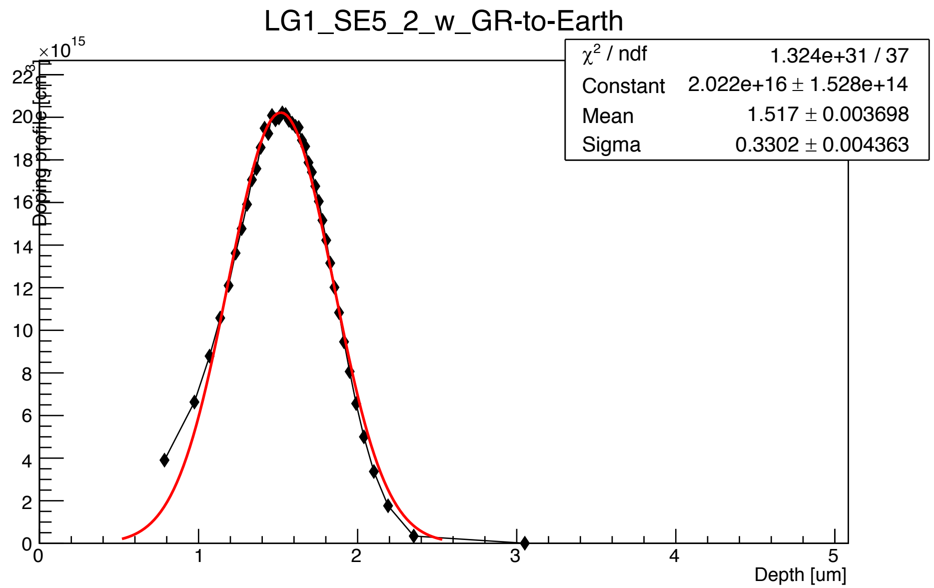
$$W = A \cdot \epsilon_{si} \cdot \epsilon_0 \left(\frac{1}{C} - \frac{1}{Cox} \right)$$

where

- C is the measurement capacitance, in Farads; and
- W is the depth, in cm.

$$\frac{d(1/C_j^2)}{dV_a} = -\frac{2}{q\varepsilon_s} \frac{N_a + N_d}{N_a N_d}$$

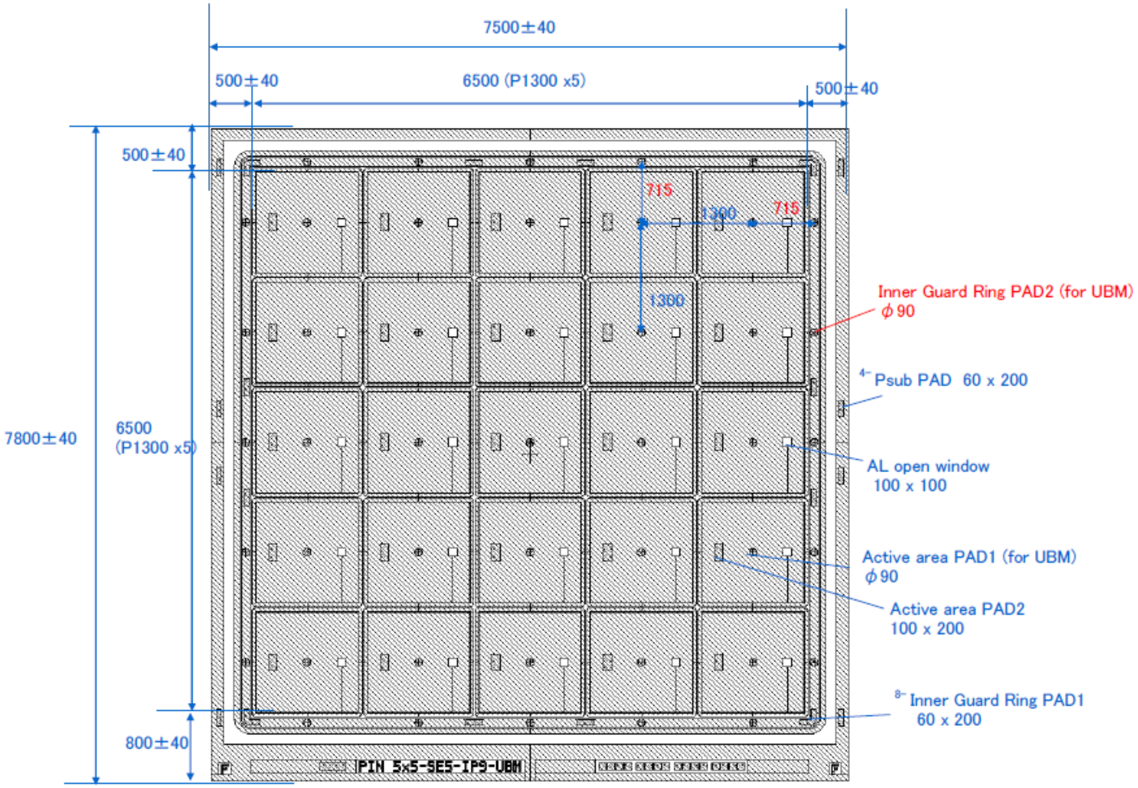
$$N_d = -\frac{2}{q\varepsilon_s} \frac{1}{\frac{d(1/C_j^2)}{dV_a}}, \text{if } N_a >> N_d$$



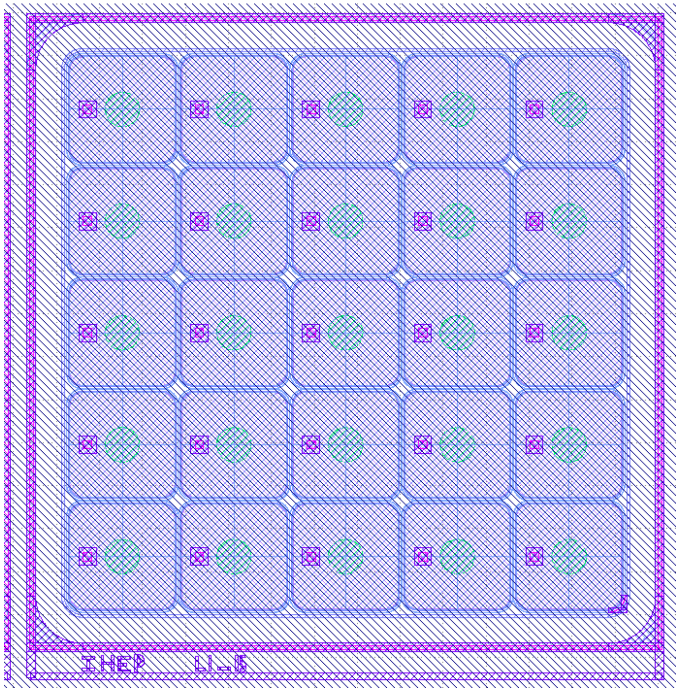
The depth equals depletion region width.

Both doping concentration and the corresponding depth can be obtained at each voltage, yielding a doping concentration profile.

Sensor Size and Position in Pad

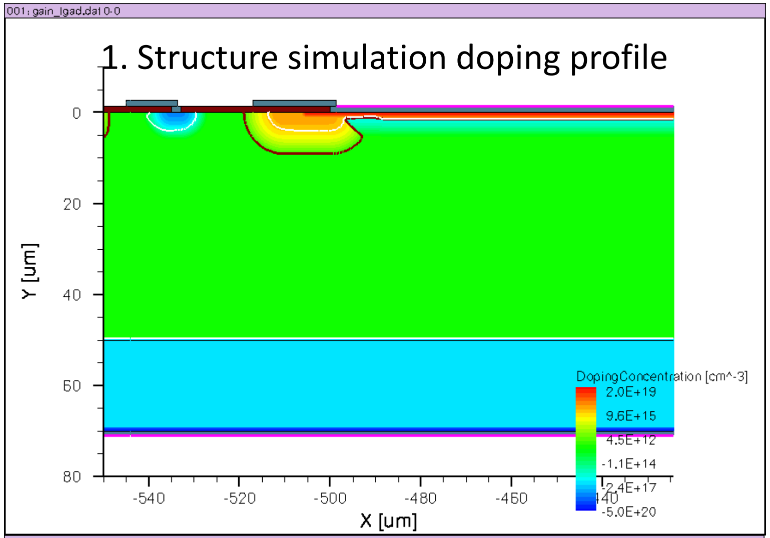


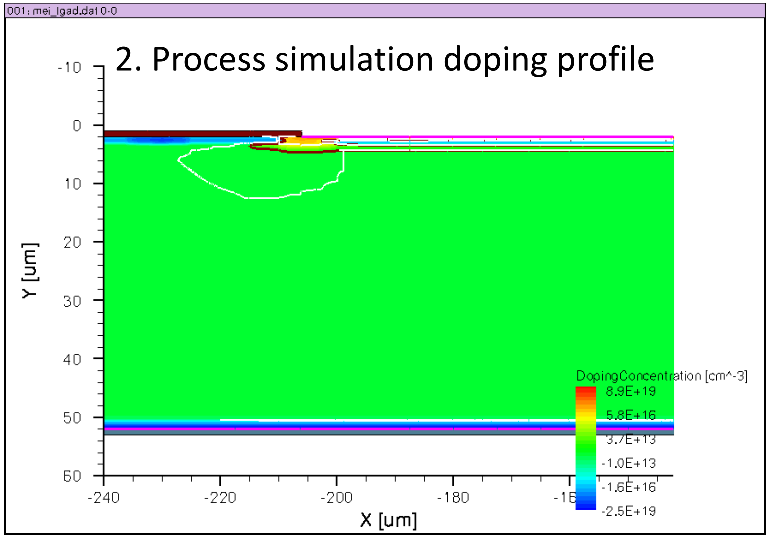
HPK 5*5 Sensor

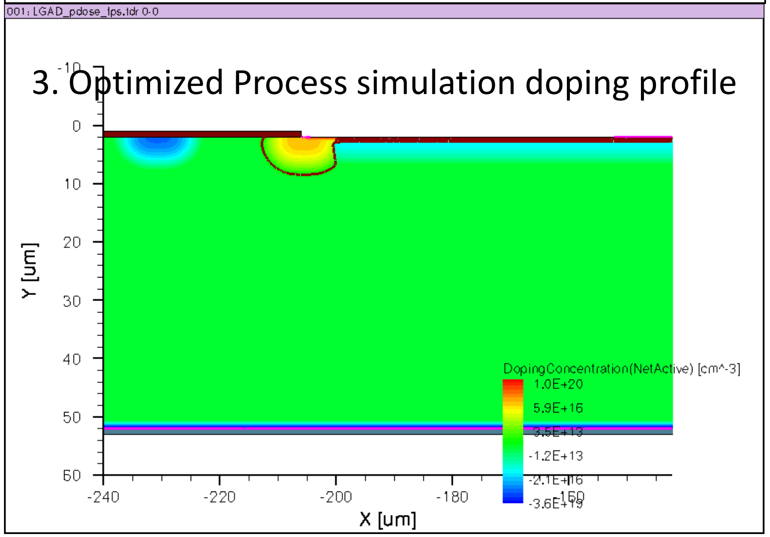


IHEP 5*5 Sensor

Process Simulation



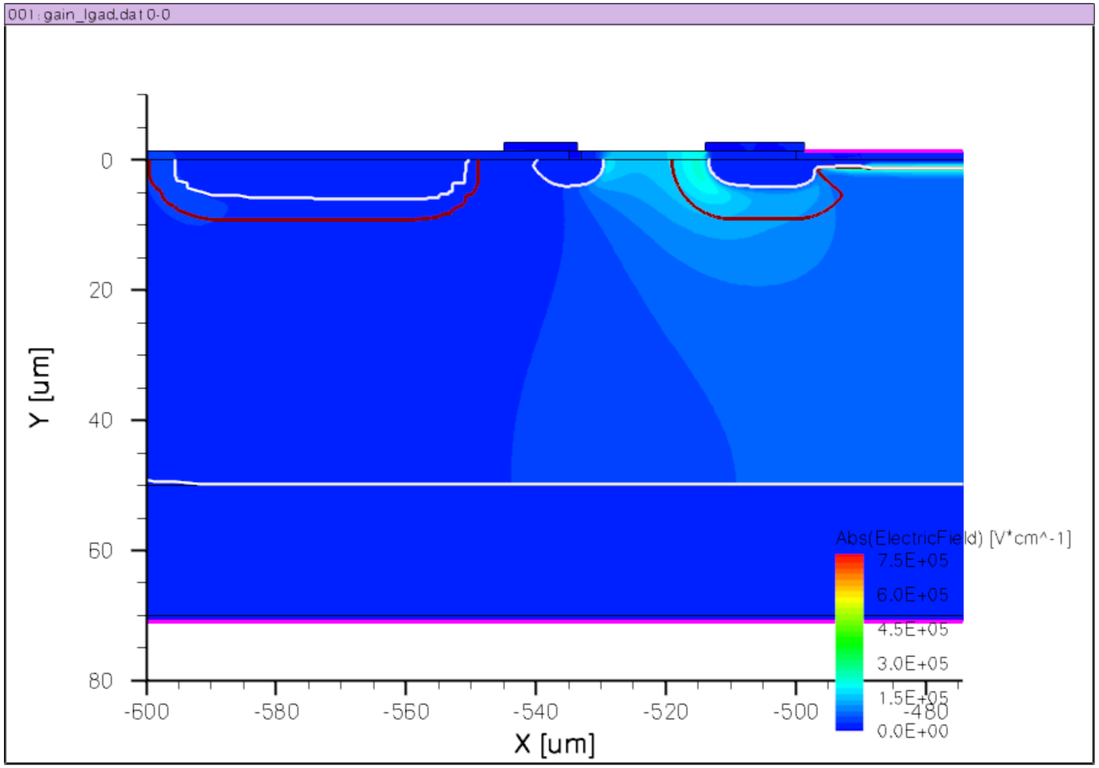




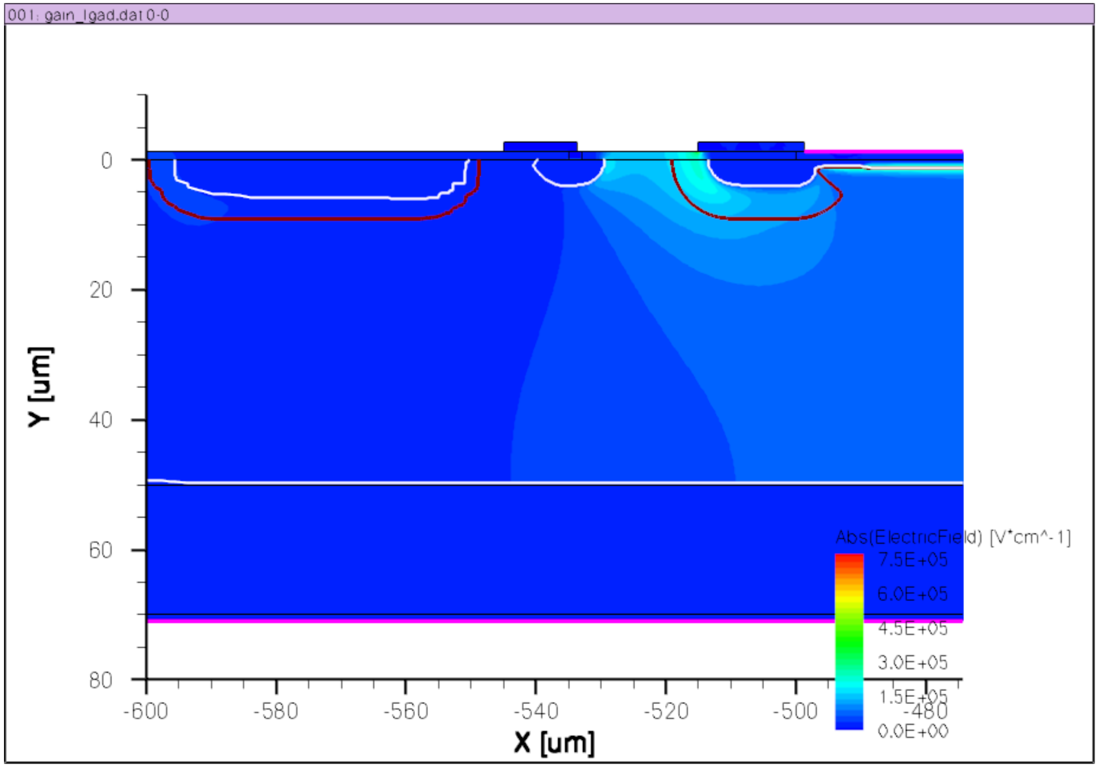
Define process parameters:

Process simulation will help find a solution to fabricate real sensor having similar doping profile as structure simulation sensor.

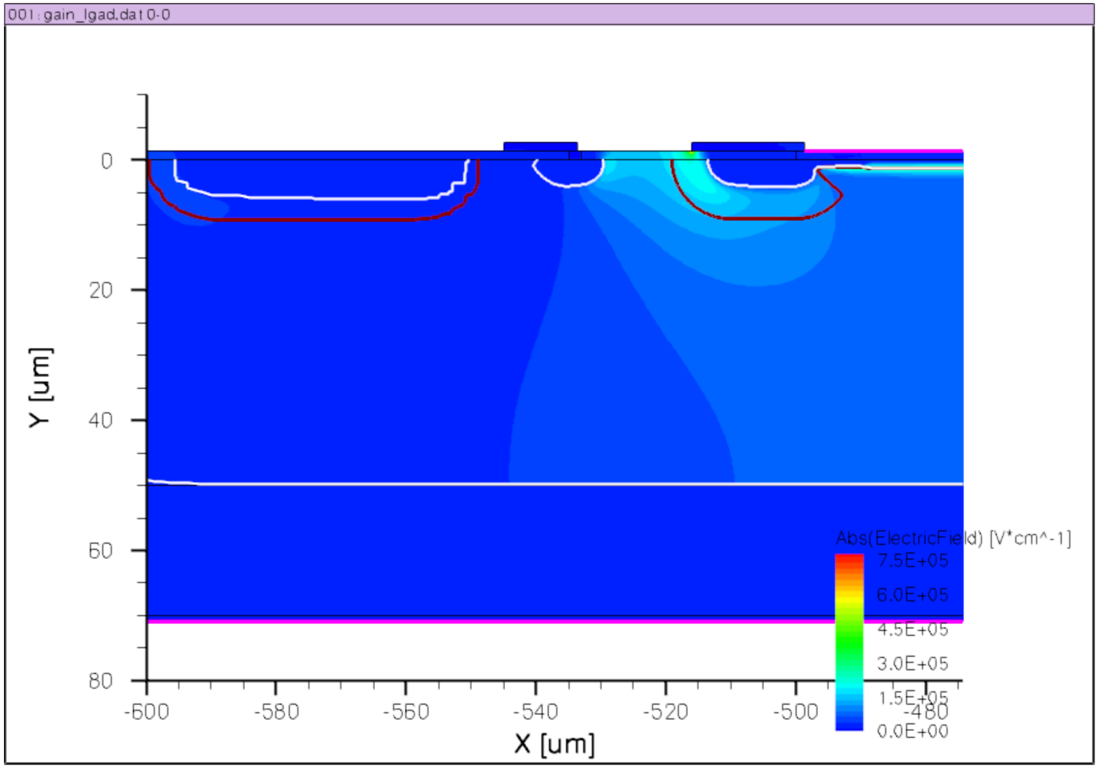
Field Plate Edge = ± 514



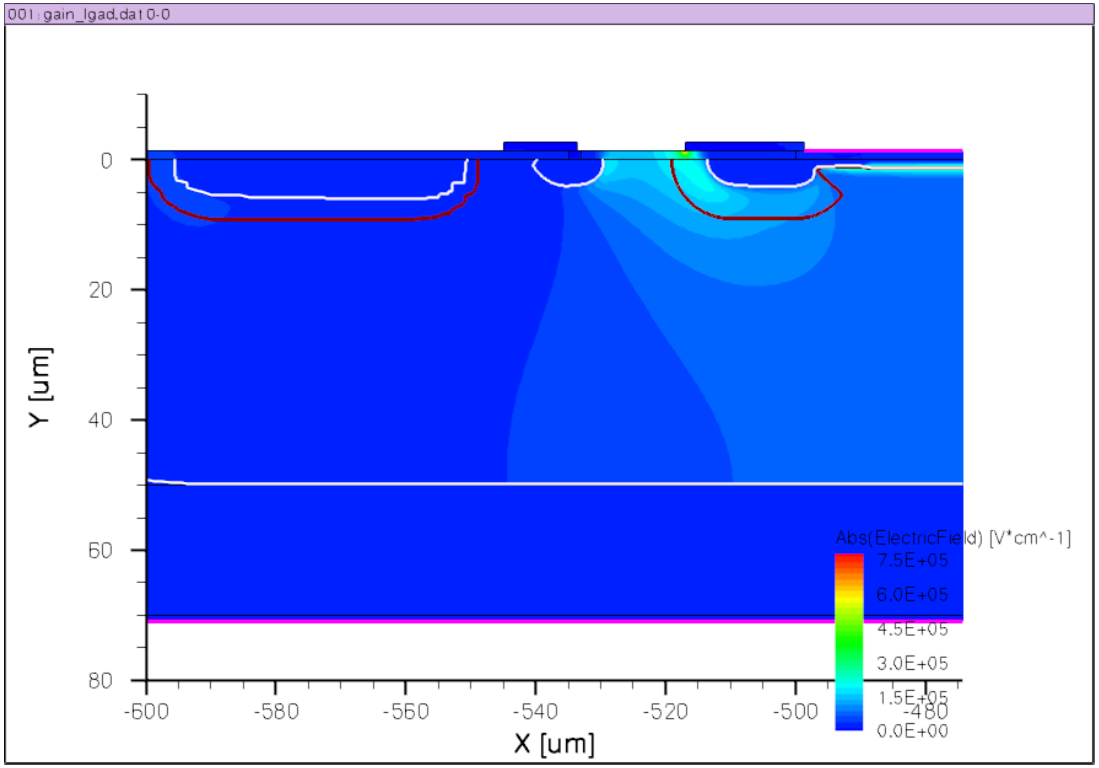
Field Plate Edge = ± 515



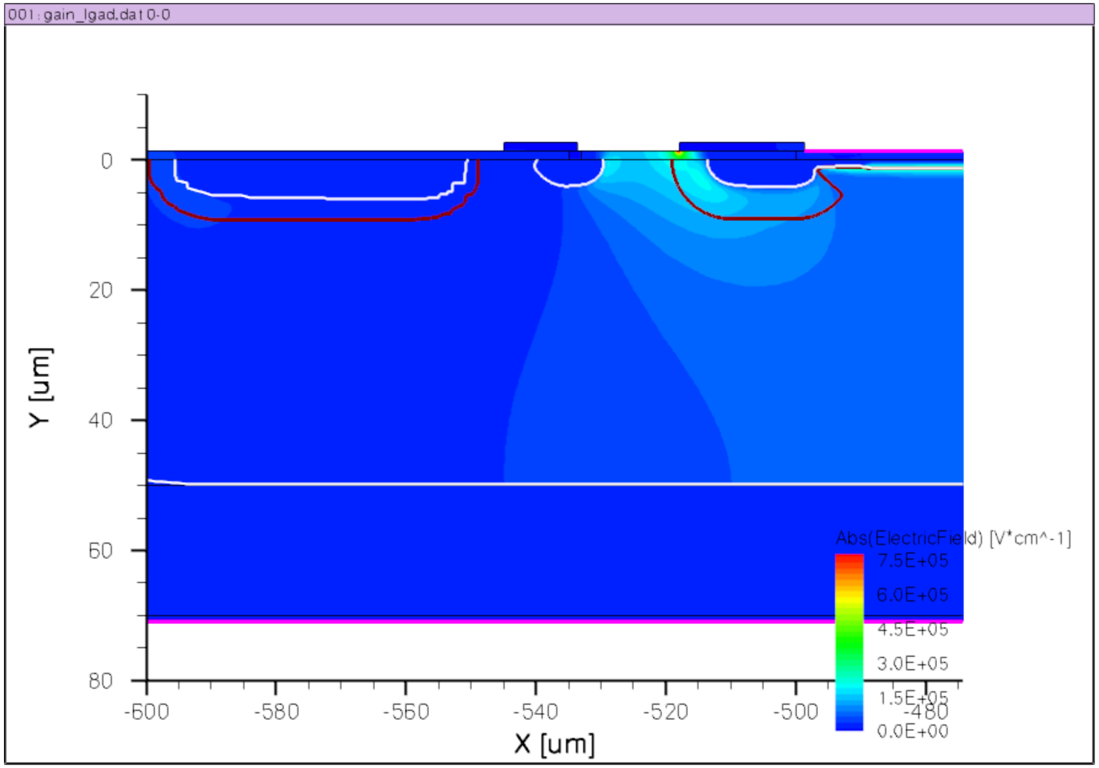
Field Plate Edge = ± 516



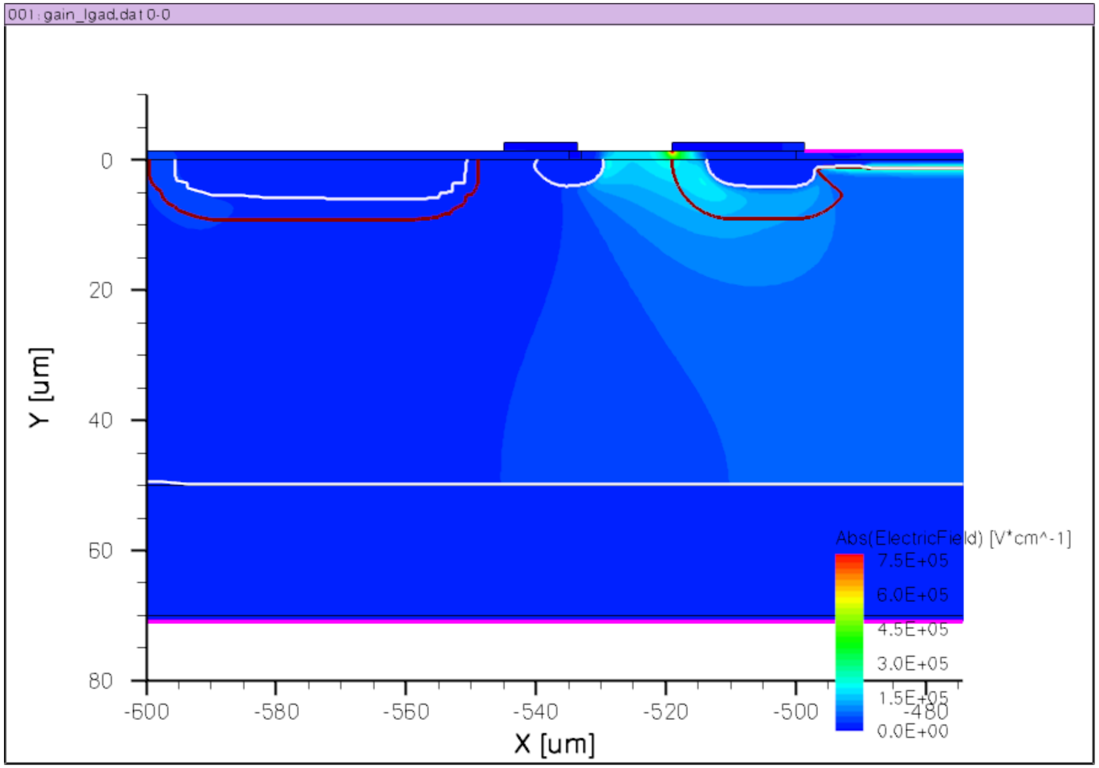
Field Plate Edge = ± 517



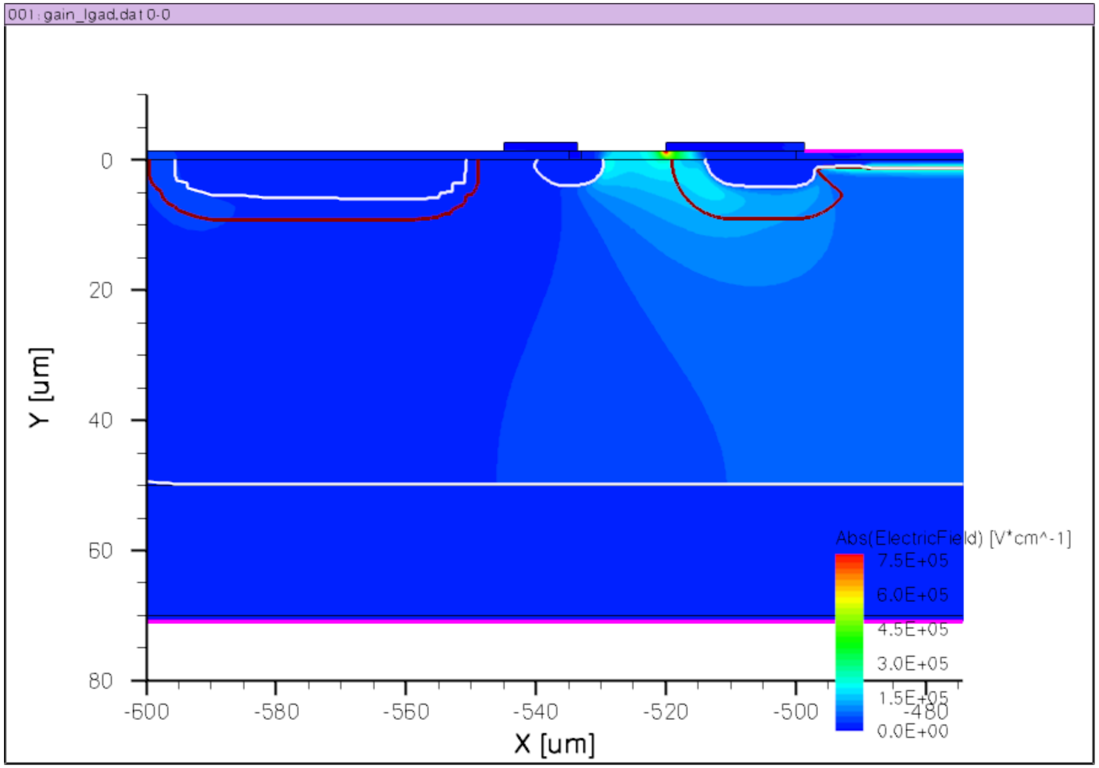
Field Plate Edge = ± 518



Field Plate Edge = ± 519



Field Plate Edge = ± 520



Field Plate Edge = ± 523