

Hot QCD Matter 2025 (Series 3)

Investigation of Breakdown and Timing Performance in Post-Irradiated JTE-Guarded 4H-SiC LGADs Using TCAD

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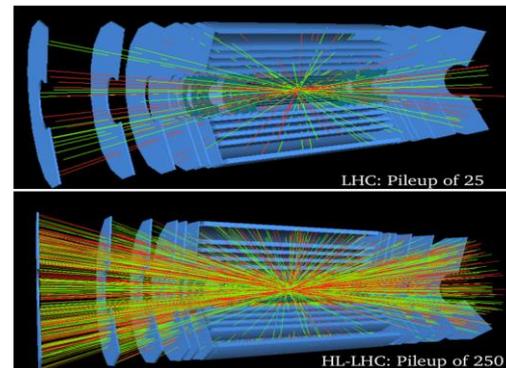
September 04 , 2025

- Motivation
- 4D Tracking for High-Resolution Detection
- Introduction to LGADs
- Challenge at High Voltages
- Results and Discussions
 - Detector geometry
 - Gain vs Bias
 - Time Resolution
 - Post-Irradiation studies
- Conclusions

Why Upgrading Tracking Detectors Matter?

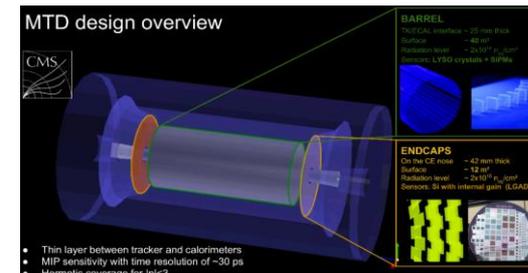
- The LHC will be upgraded to HL-LHC
- The luminosity of HL-LHC would be 7 times of nominal instantaneous luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)
- This increase will lead to a large number of collision pile-up.
- A major task is disentangling primary interactions from pile-up.

Development of large area silicon detectors," Tech. Rep. ATL-UPGRADE-PROC-2012-003, CERN, 2012. arXiv:1201.5469.



Simulated pile-up in LHC vs HL-LHC

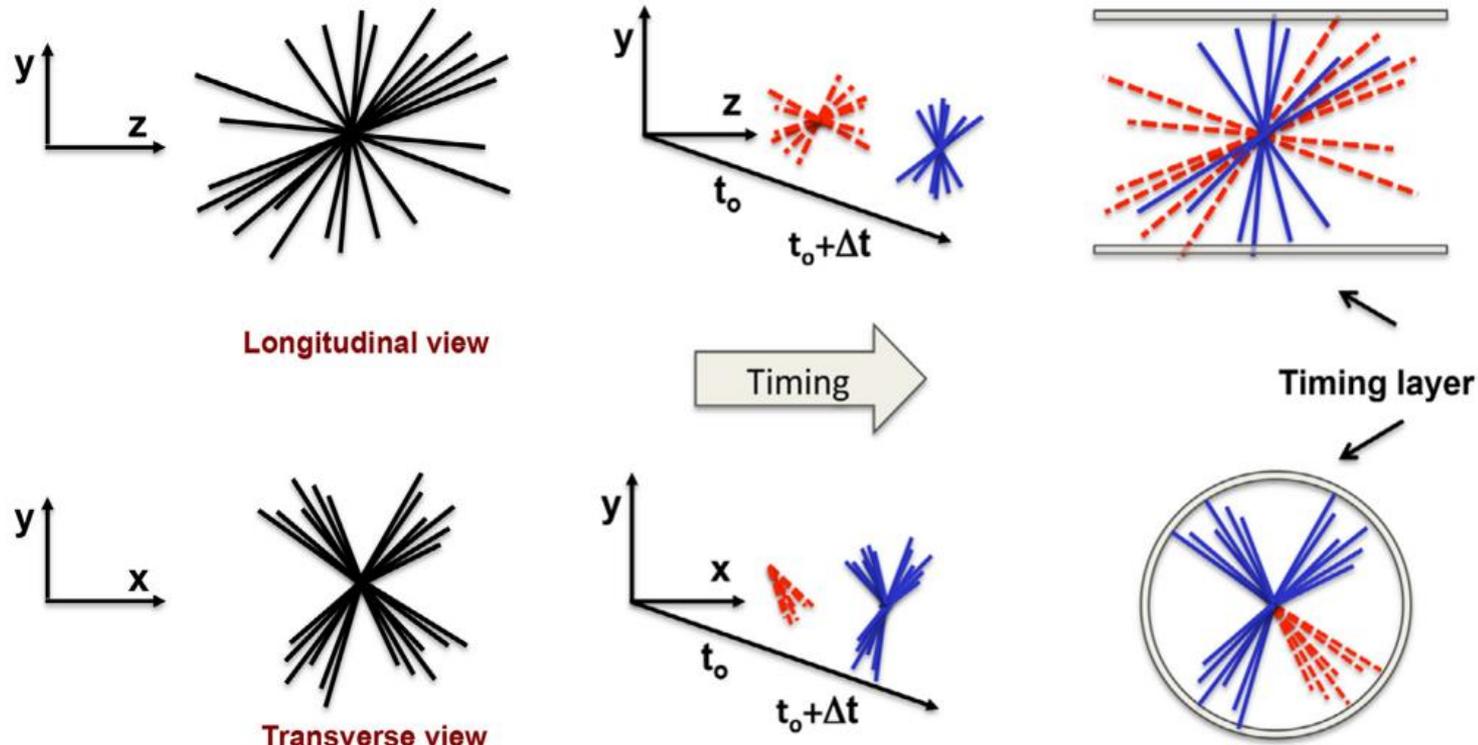
Markovic, Lazar. (2023). Progress on characterization of LGAD sensors for the CMS ETL. 095. 10.22323/1.427.0095.



MTD placement in CMS detector

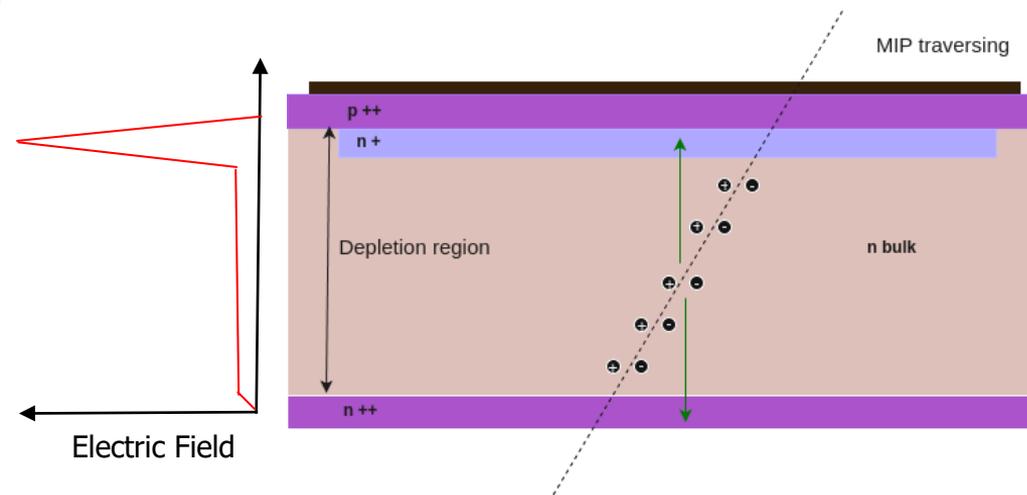
4D Tracking for High-Resolution Detection

N. Cartiglia et al., 4D tracking: present status and perspectives, *Nucl. Instrum. Meth. A* **1040** (2022) 167228.



Using time information to resolve signal.

Introduction to Low Gain Avalanche Diodes (LGAD)

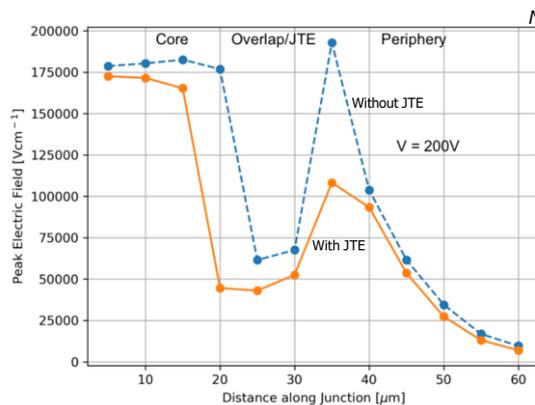


Schematic structure of a typical p-in-n LGAD

- **LGAD:** Silicon or similar semiconductor based detectors modeled on PiN diode structure with a doped multiplication layer.
- **Reverse Biasing:** Widens depletion region, creating a strong electric field.
- **Impact Ionisation:** Incident particles generate electron-hole pairs in the bulk.
- **Avalanche Multiplication:** Electrons create more electron-hole pairs in the multiplication layer ($E \approx 300$ kV/cm)
- **Fast Response:** High electric field ($E \approx 30$ kV/cm) ensures rapid collection of charge carriers.
- **Simulation software:** Silvaco TCAD

Challenge at High Voltage

- SC detectors requires very high bias voltage for full detector depletion for a high doping
- Strong electric field crowds at device edges and sharp corners
- Solution is Junction Termination Extension (JTE) to laterally spread depletion region
- Smooth redistribution of electric field lines at periphery
- Improves detector reliability and extended operational lifetime



N. Moffat et al., JINST 13 (2018) C03014

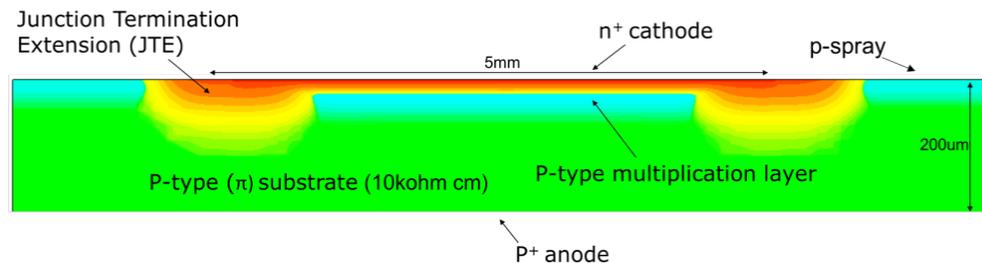
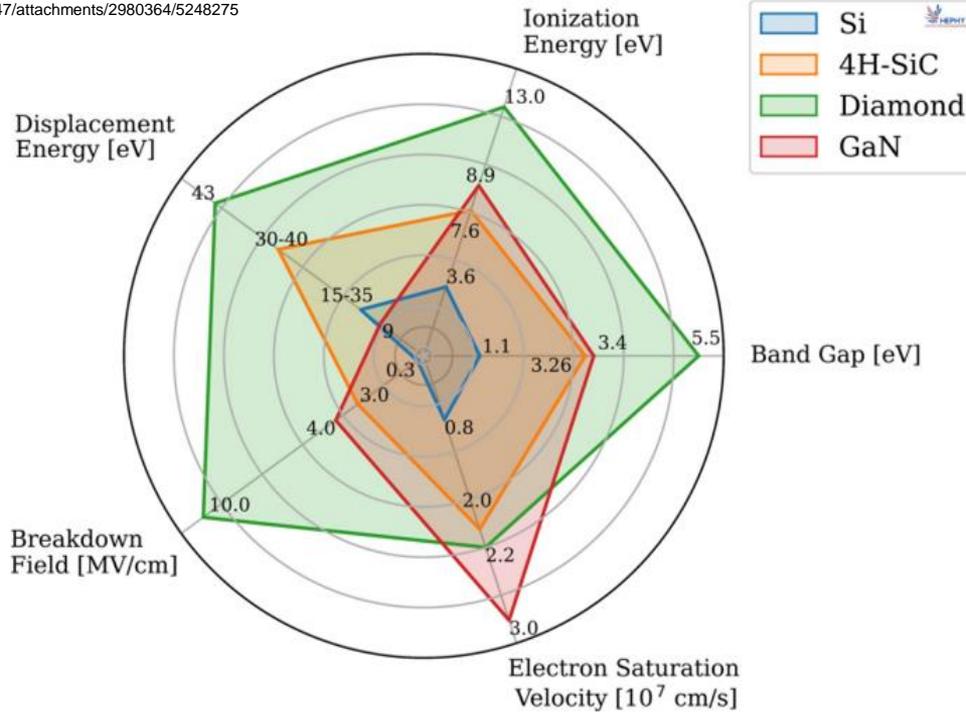


Image of a JTE implanted LGAD

Electric Field variation along x-axis

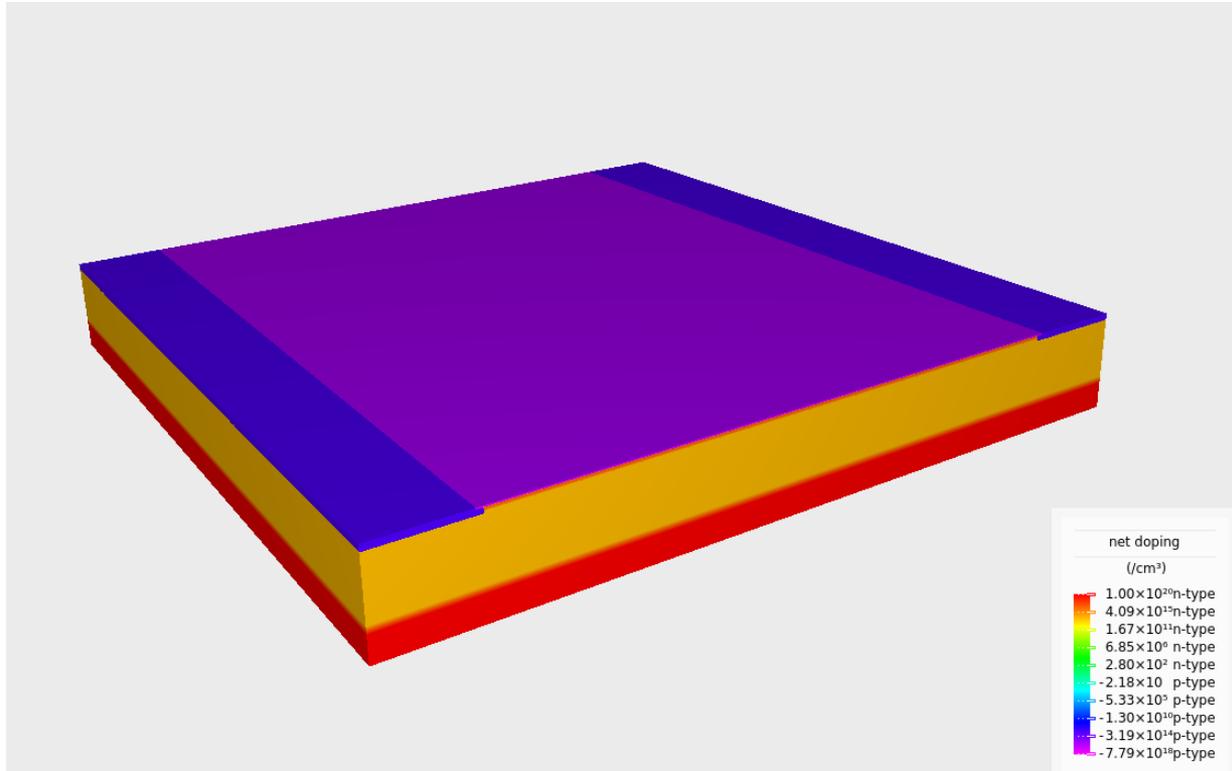
4H-SiC as LGAD Bulk

<https://indico.cern.ch/event/1439336/contributions/6242447/attachments/2980364/5248275>



Comparison of different parameters of different materials

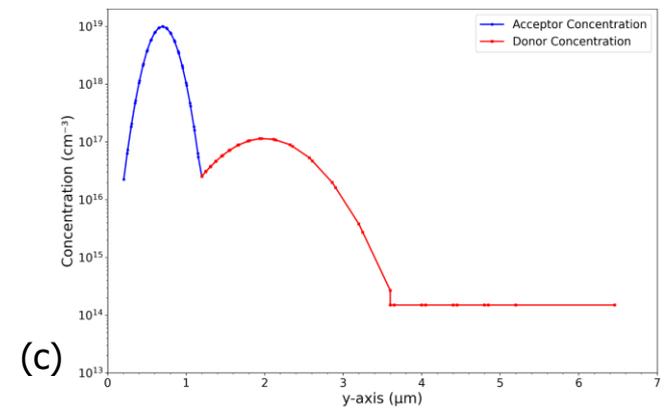
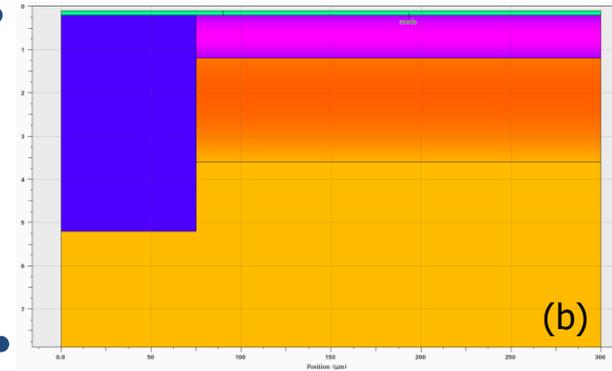
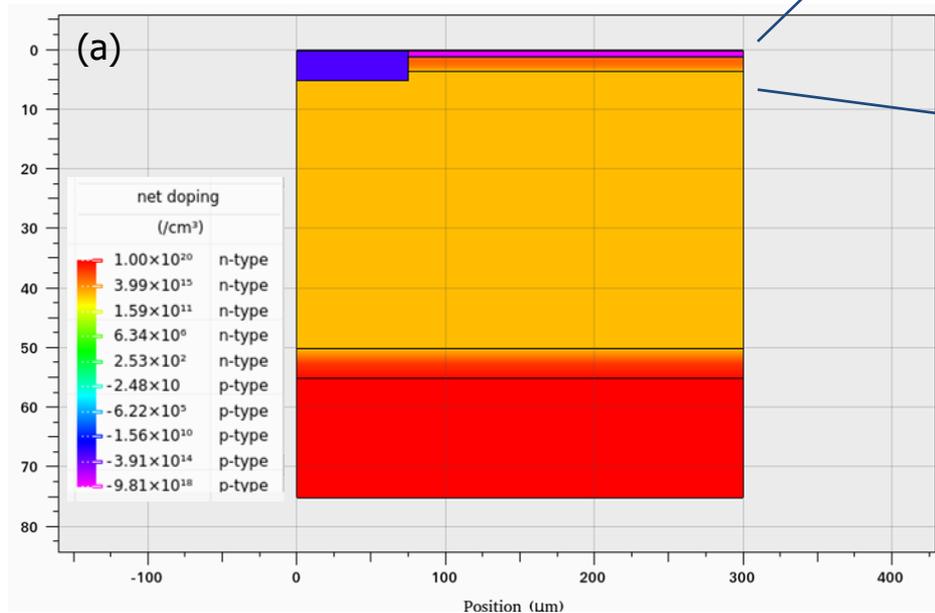
Results and Discussions



Visualization of LGAD geometry used in this work.

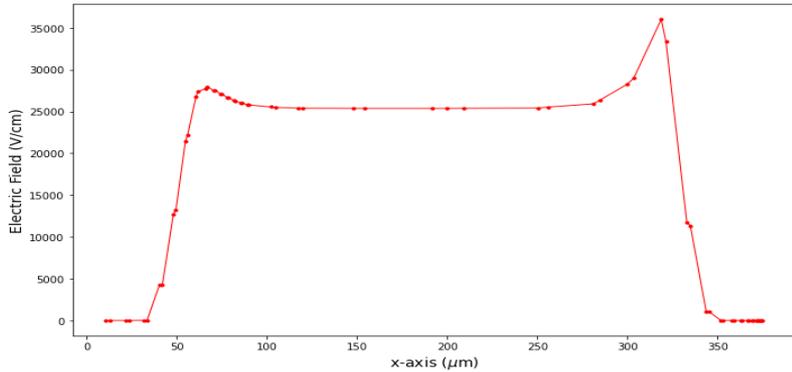
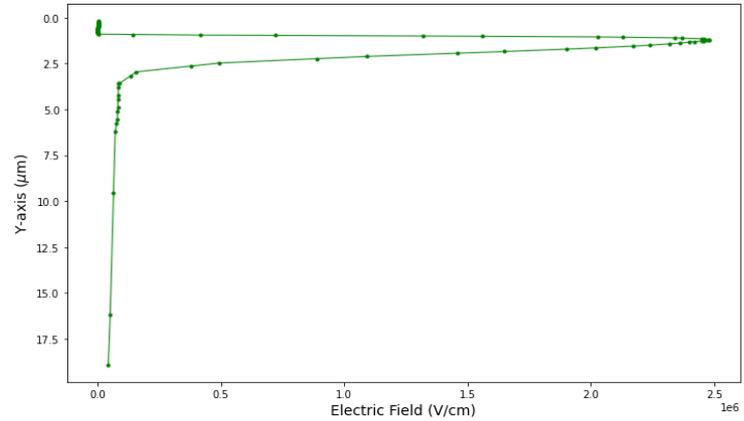
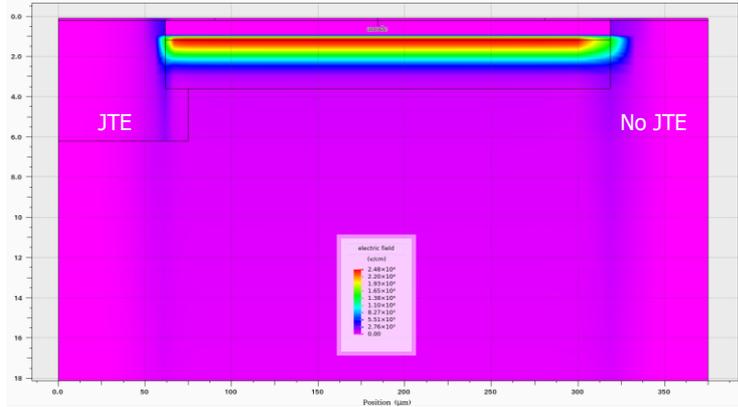
2D Geometry and Doping Profile

- Simulated 2D mirrored half of device.
- Gaussian doping profile in implanted layers and uniform in grown layers.
- Shallow implant gain layer achieves smooth transition to epi.
- Buffer between epi and subtraction to avoid junction effects.



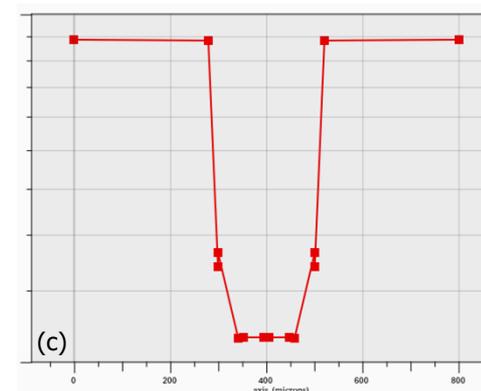
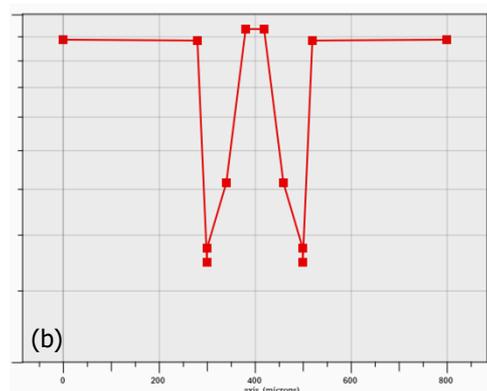
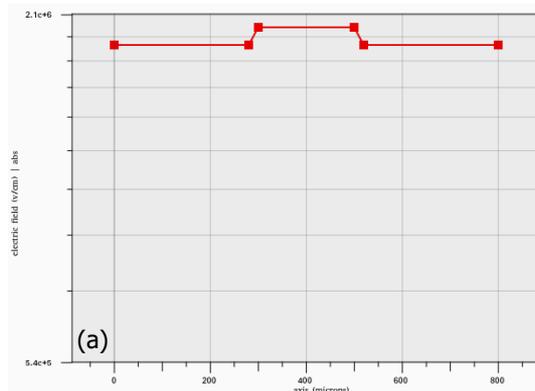
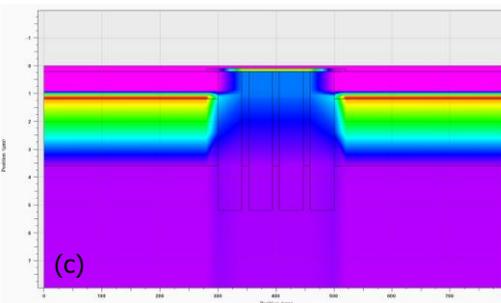
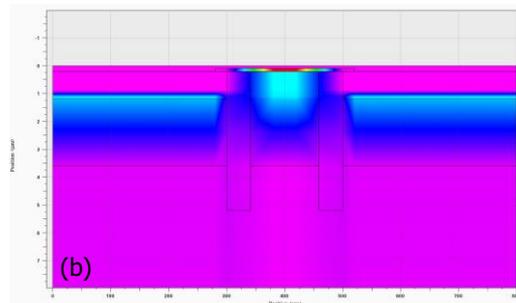
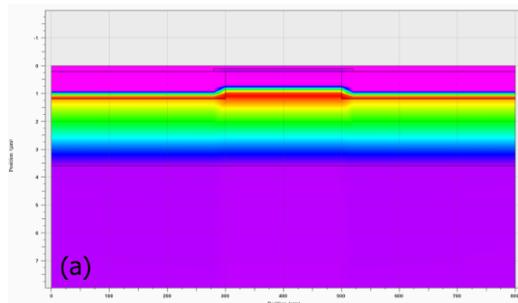
LGAD structure simulated in TCAD (a), the doping concentration (c), at the multiplication region (b).

Electric Field Profile in LGAD



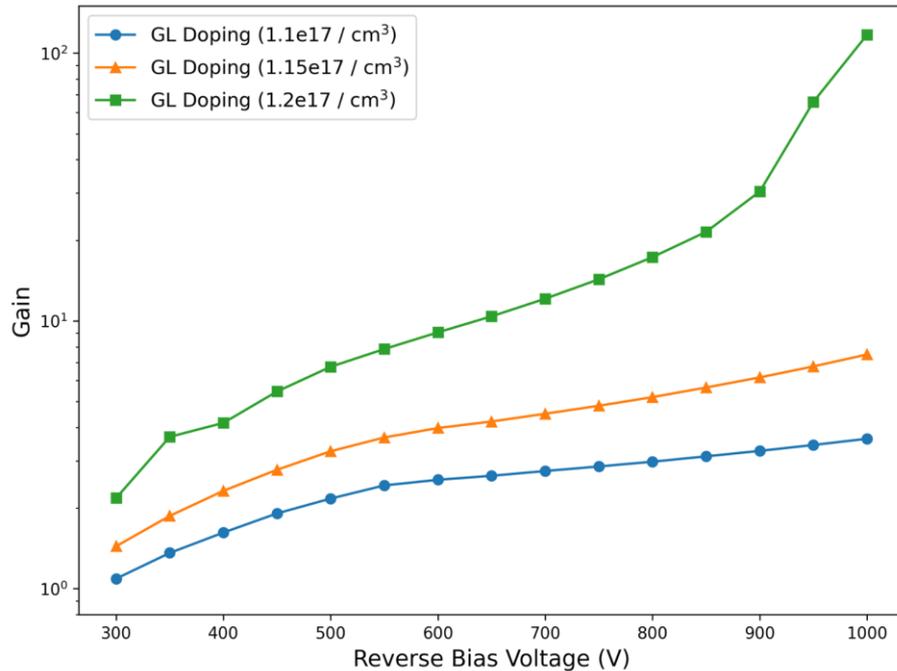
- Electric Field peaks at the junction of p++ and gain layer.
- The peak intensity is $\sim 2.5 \times 10^6$ V/cm.
- Epitaxial layer has a low magnitude steadily decreasing field.
- In this LGAD, adding a JTE helps slowly dissipate the electric field near the junction edges.

Electric Field inside the LGAD along the x and y directions



Electric Field Profile in LGAD at the multiplication junction.
The effect of adding (a) no JTE, (b) 2 JTEs, (c) 4 JTEs
Adding multiple JTEs help slowly dissipate the electric field.

→ Gain of the detector with increasing Reverse Bias.

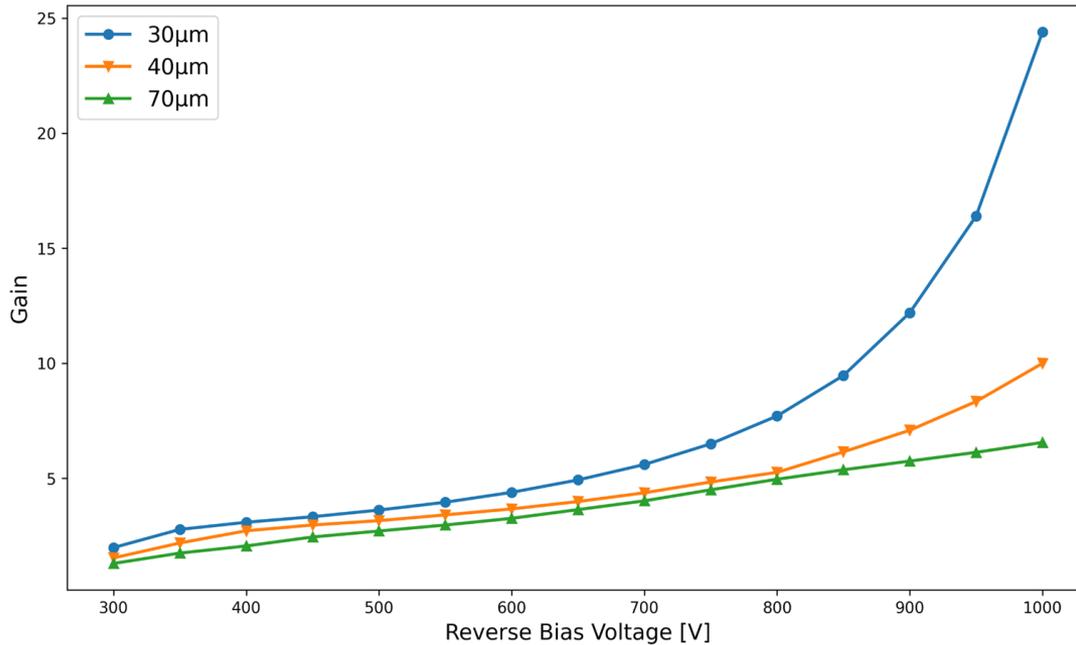


Gain vs Bias Voltage for different gain layer doping concentration

- $\text{Gain} = Q_{\text{LGAD}} / Q_{\text{PiN}}$
- The study is done for three doping concentrations of the gain layer
- The temperature is fixed at 300 K.
- The epitaxial thickness is kept 50 μm .
- Gain increases with the increase in doping and bias.

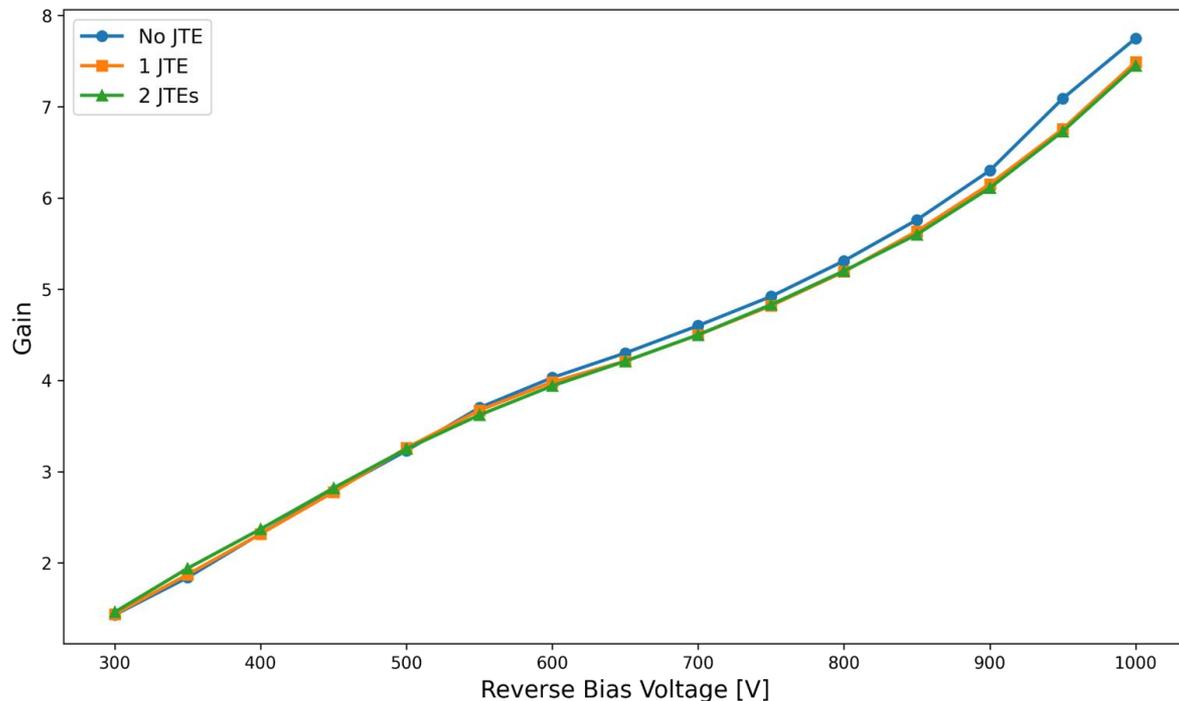
Effect of Epitaxial Layer Thickness

→ Gain for various detector thickness.



Gain vs Bias Voltage for varying epitaxial layer thickness.

- The study is done for four different thicknesses.
- The temperature is fixed at 300K.
- The gain layer doping is kept at $1.15 \times 10^{17} / \text{cm}^3$.
- Gain increases with the decrease in epitaxial thickness.

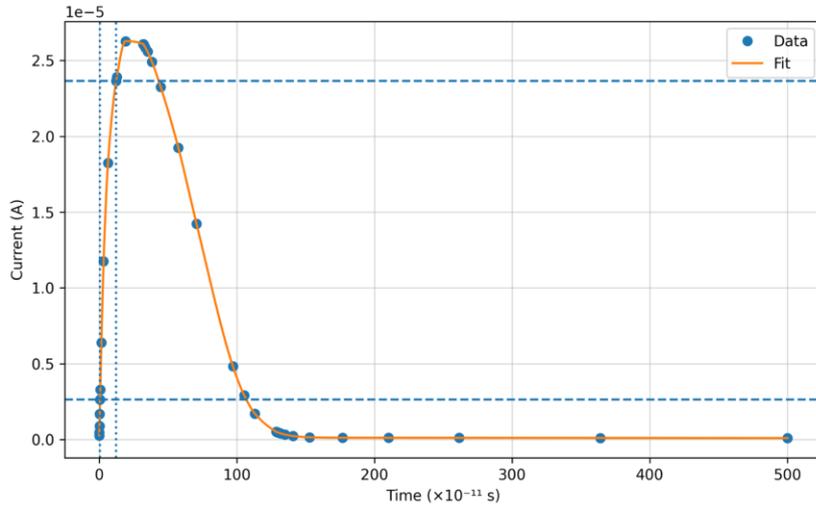


Gain vs Bias Voltage for the LGAD with and without JTE

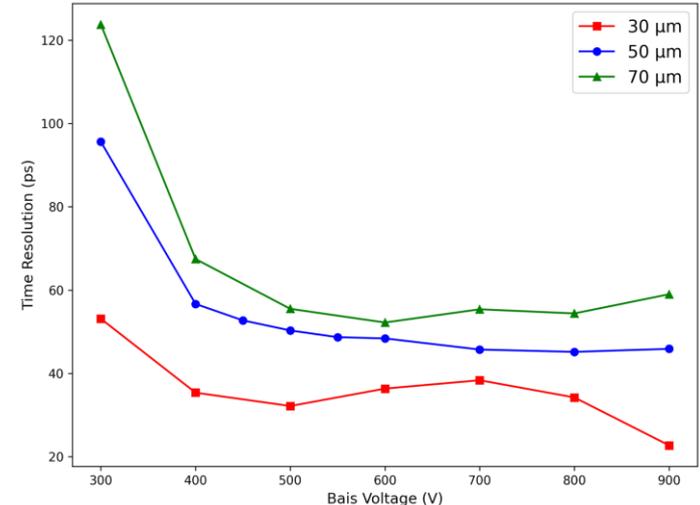
- The study is done for a 50 μm epi layer at a gain layer doping of $1.15 \times 10^{17} / \text{cm}^3$
- The data shows no major gain change for introducing multiple JTE

Current Pulse and Time Resolution

- The current pulse here is shown for gain layer doping $1.15 \times 10^{17} / \text{cm}^3$ at 600 V .
- The temperature is fixed at 300 K.
- The epitaxial thickness is kept 50 μm .
- Time resolution for different thickness of epi layer is shown.

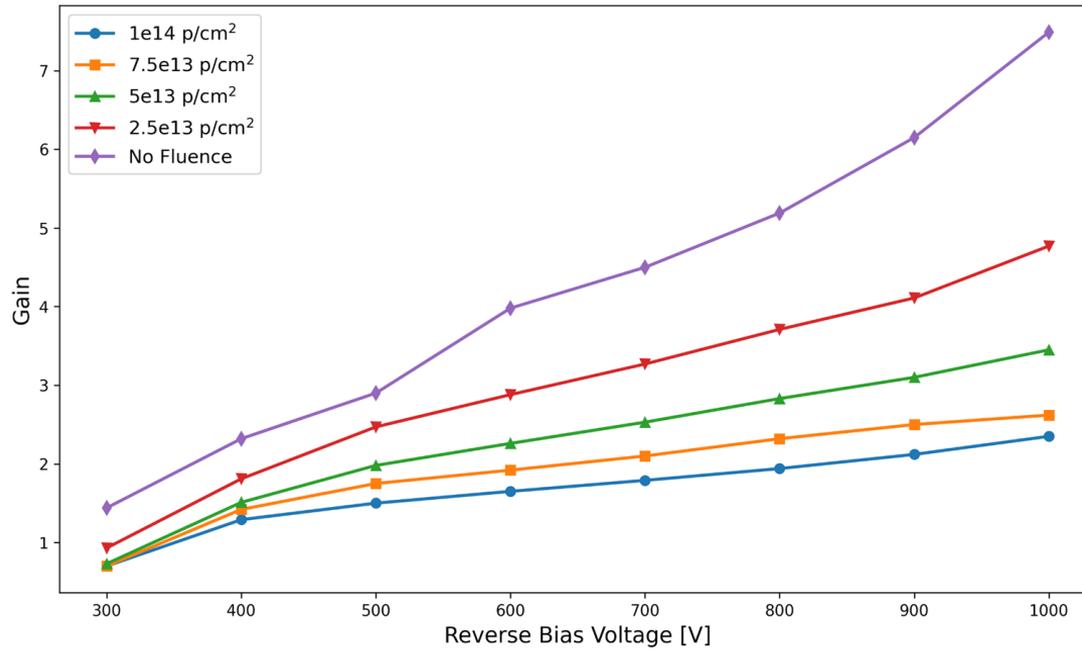


Current pulse generated



Time Resolution vs Reverse Bias

→ Gain of the detector with increasing Fluence.



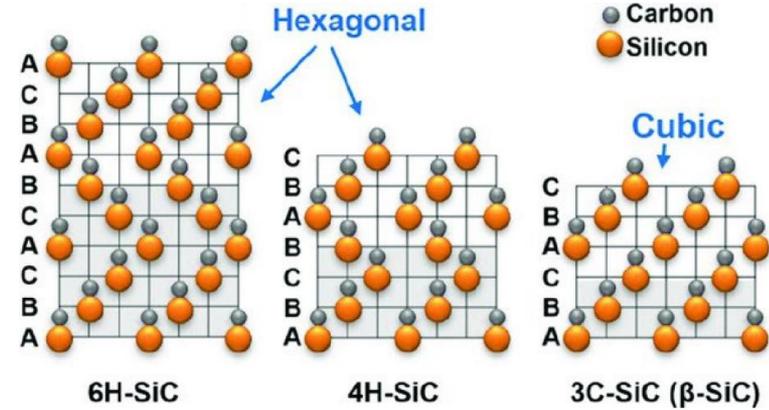
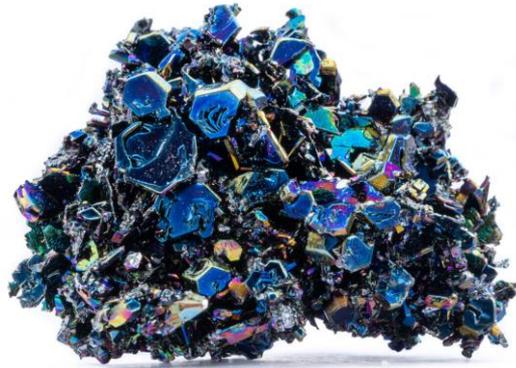
Gain vs Bias Voltage for different fluences

- The study shows gain of the detector at various proton fluence levels.
- The study is done for a 50 μm epi layer at a gain layer doping of $1.15\text{e}17 / \text{cm}^3$
- The data shows a clear gain quenching with the rise in the fluence level.

- Silvaco TCAD simulations reveal 4H-SiC LGAD behavior across doping, bias, thickness, and radiation fluence.
- JTE at the junction termination smooths edge electric fields, enabling more stable operation at higher bias
- Gain rises exponentially with increase in gain-layer doping and decrease in thickness.
- Thicker epitaxial layers degrade detector performance and timing unless fully depleted at operating bias, i.e. they require higher voltages.
- Radiation fluence quenches the gain, but operating at higher bias partially recovers detector response.
- SiC-LGADs exhibit excellent radiation tolerance with stable operation at high bias voltages.

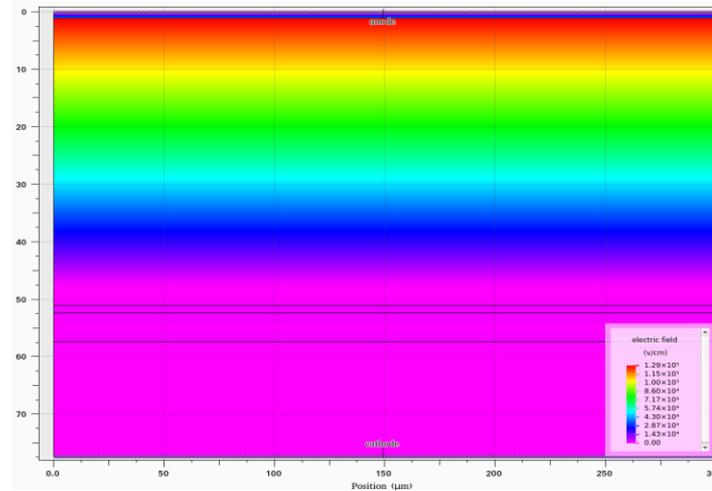
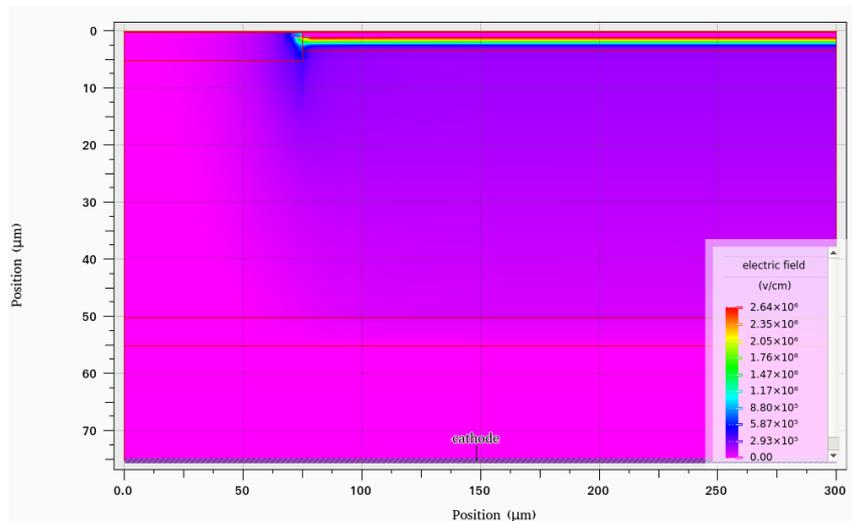
Thank You

Back Up



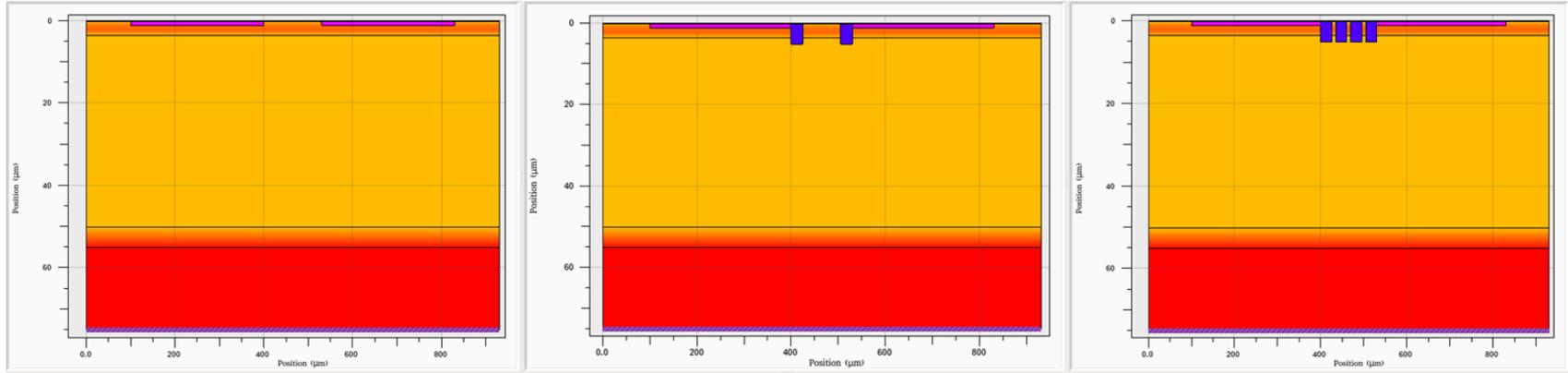
4H-SiC crystal (left) and Lattice Structure (right)

Electric Field Profile of PiN vs LGAD



Electric field profile in an LGAD (left) and PIN diode (right) at 400V

Breakdown study (Doping)



LGAD geometry where pixels are separated using No JTE (left), 1 JTE (middle) and 2 JTE (right).

Breakdown study (Potential)

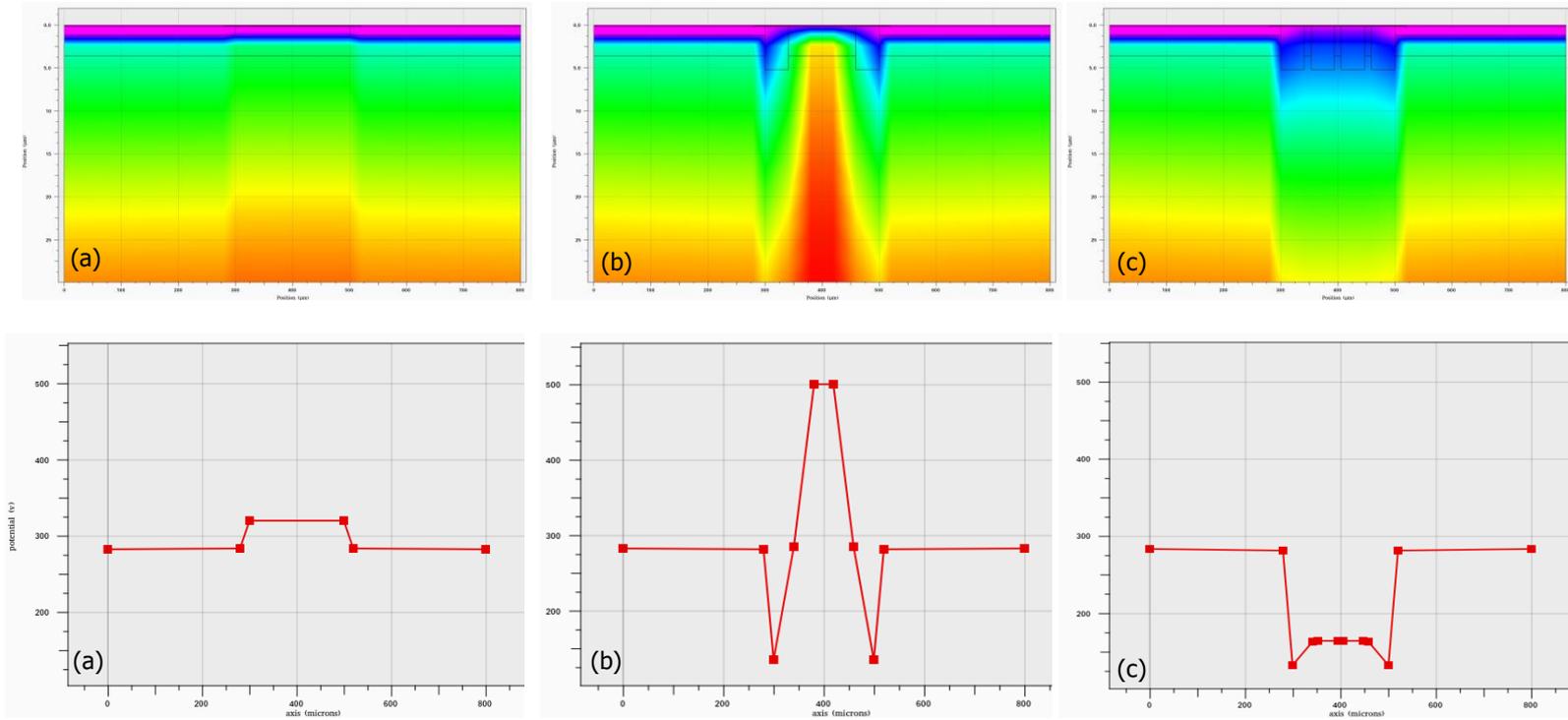
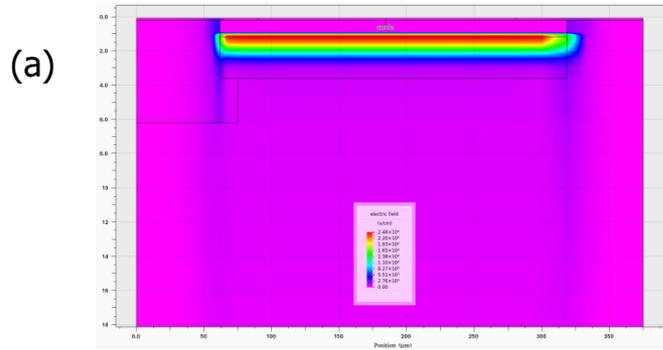


Fig 21: Potential Profile in LGAD with (a) no JTE, (b) 1 JTE, (c) 2 JTE

Breakdown study (Electric Field)



- The variation of Electric field in x- axis is plotted
- Adding a JTE helps slowly dissipate the electric field near the edges.
- The early breakdown due to junction effects can be resolved

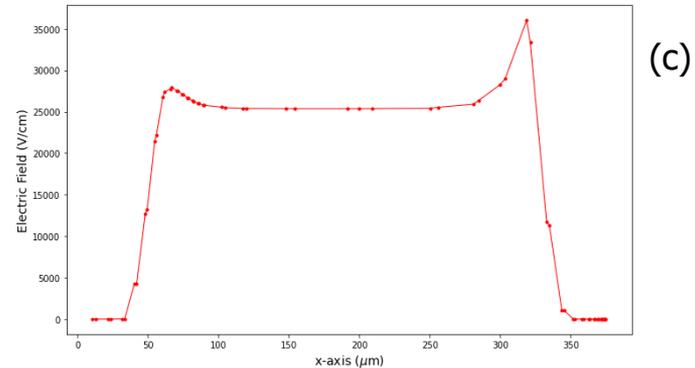
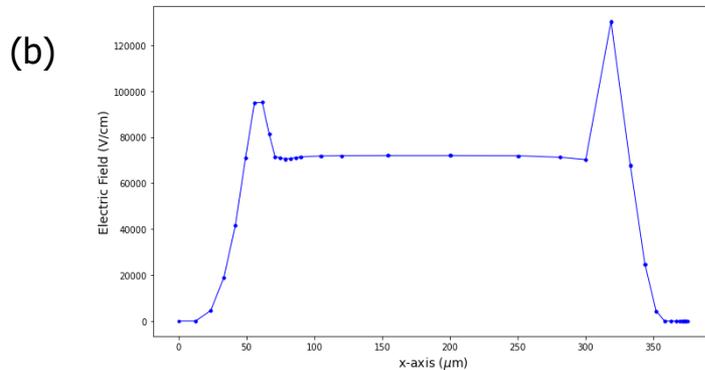


Fig 22 : Asymmetric LGAD structure with JTE on one side (a) with electric field profiles at 400V taken near Junction Boundary (b) and at the middle of epitaxial layer (c).