Development of Deep-Junction Low Gain Avalanche Diode for High Granularity Timing Detectors

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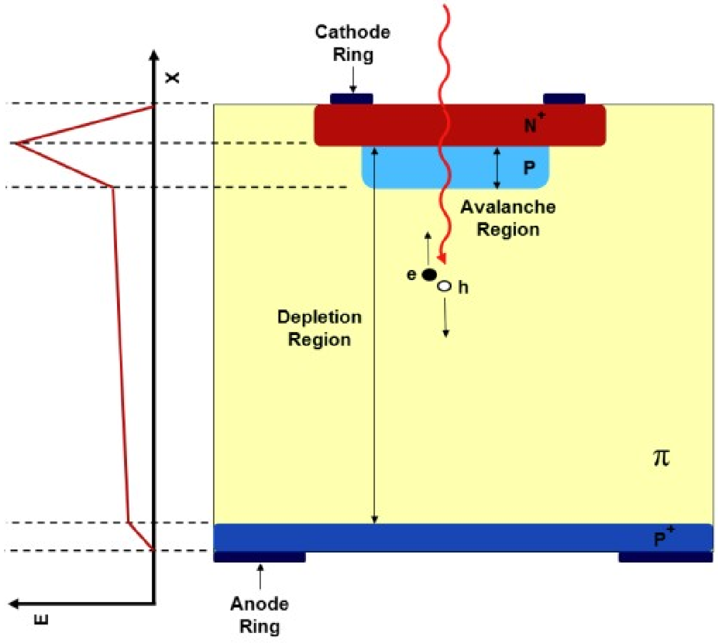
Conventional LGAD and the Granularity Limitation

Low Gain Avalanche Detector

- **Low Gain Avalanche (LGAD) is type of silicon based detector that made used of highly doped (p+) layer which provide internal moderate gain of ~ 10 to 50.**
- **The active thickness can reduce down to 20 to 50um, while the internal gain helps maintain detectable signal.**
  - The thin active thickness provides short rise time, less Landau fluctuation.
- **Capable to provide timing resolution < 20ps for mip.**
- **Very Radiation hard**
  - survive up to fluence of 6e15 neq/cm2
- **Current and proposed application:**
  - HGTD for ATLAS upgrade.
  - TOF for the Electron-Ion Collider
  - PIONEER Rare Pion decay experiment
  - Low energy X-ray detection



Granularity Limitation of Conventional LGAD

- **Conventional LGAD pixel requires Termination Extension (JTE) structure that prevent premature breakdown between channels**
  - **The dead area ~ 30-100 um between channels.**
  - **Granularity is limited to millimeter scale.**
- **Several promising approaches to increase granularity are proposed and under study:**
  - Inversed LGAD
  - AC-LGAD, (SCIPP, UCSC patent)
  - Trench Isolated LGAD

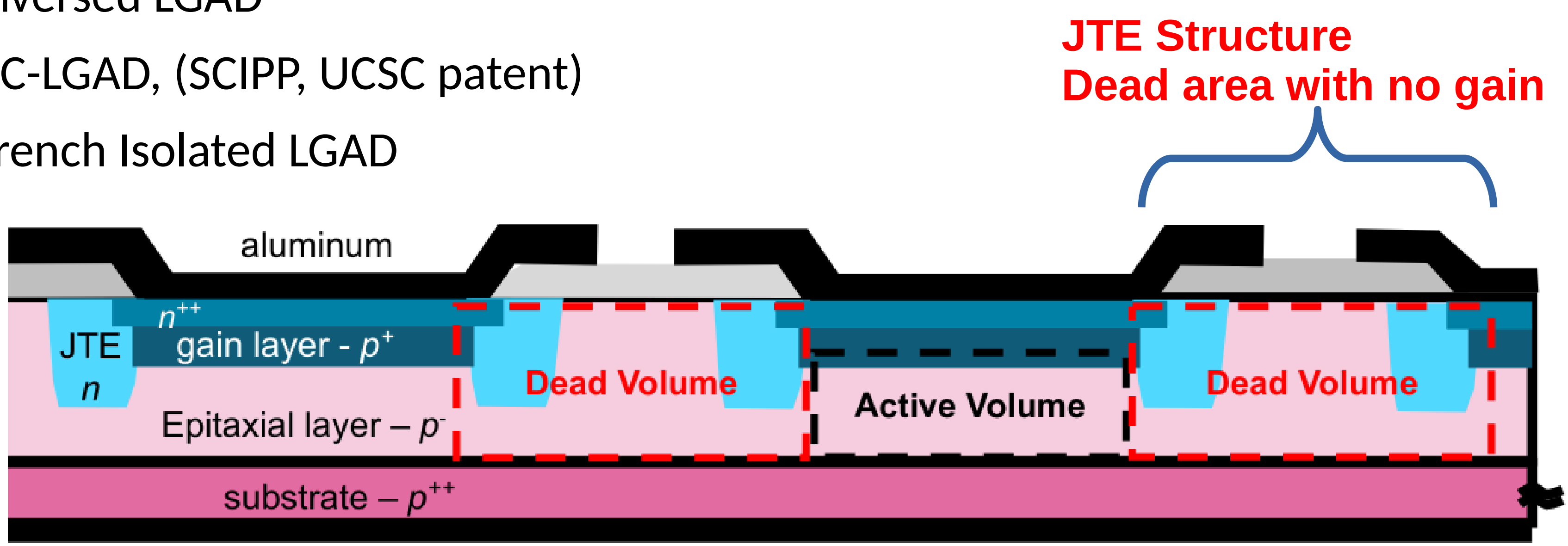
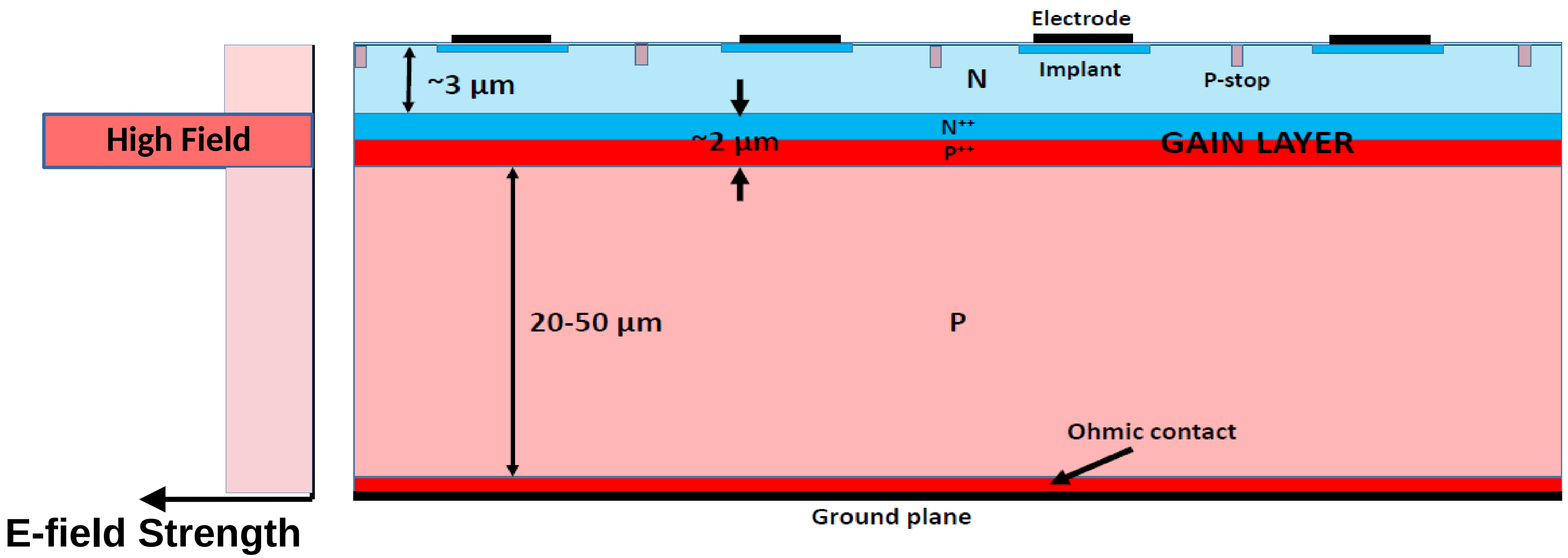


Diagram credit:BNL

New Approach:
The Deep Junction LGAD

Deep Junction LGAD Concept

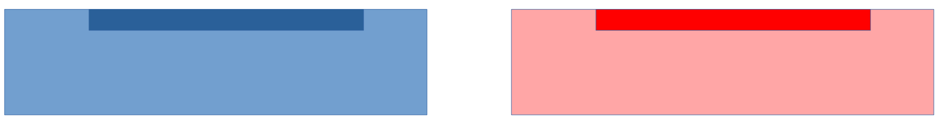
- The term “deep junction” arise from the use of a p-n junction buried several microns below the surface of the device
  - Keep E-field low at surface, allowing conventional pixelization/segmentation
  - Maintains fine granularity and charge uniformity across channels
  - Preserves DC coupling of signal to readout electrodes.
- (Designed by C. Gee, S. Mazza, B. Schumm, Y. Zhao, patent pending)



Two Approaches for Manufacturing Deep Junction

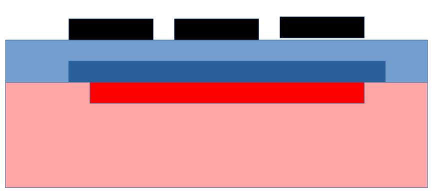
- **We are in collaboration with Cactus Materials Inc and BNL to produce DJ-LGAD prototype.**
- **Two approaches to achieve deep junction:**

Gain Layer Implantation on N and P type substrate



Wafer-wafer bonding

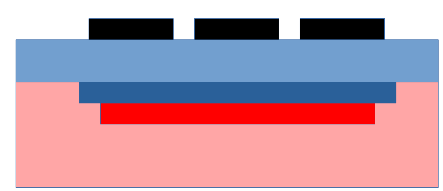
Etching N substrate deposit electrodes and implants



Gain Layer Implantation Similar to Conventional LGAD, but with higher energy

Epitaxial growth of high resistivity N type layer

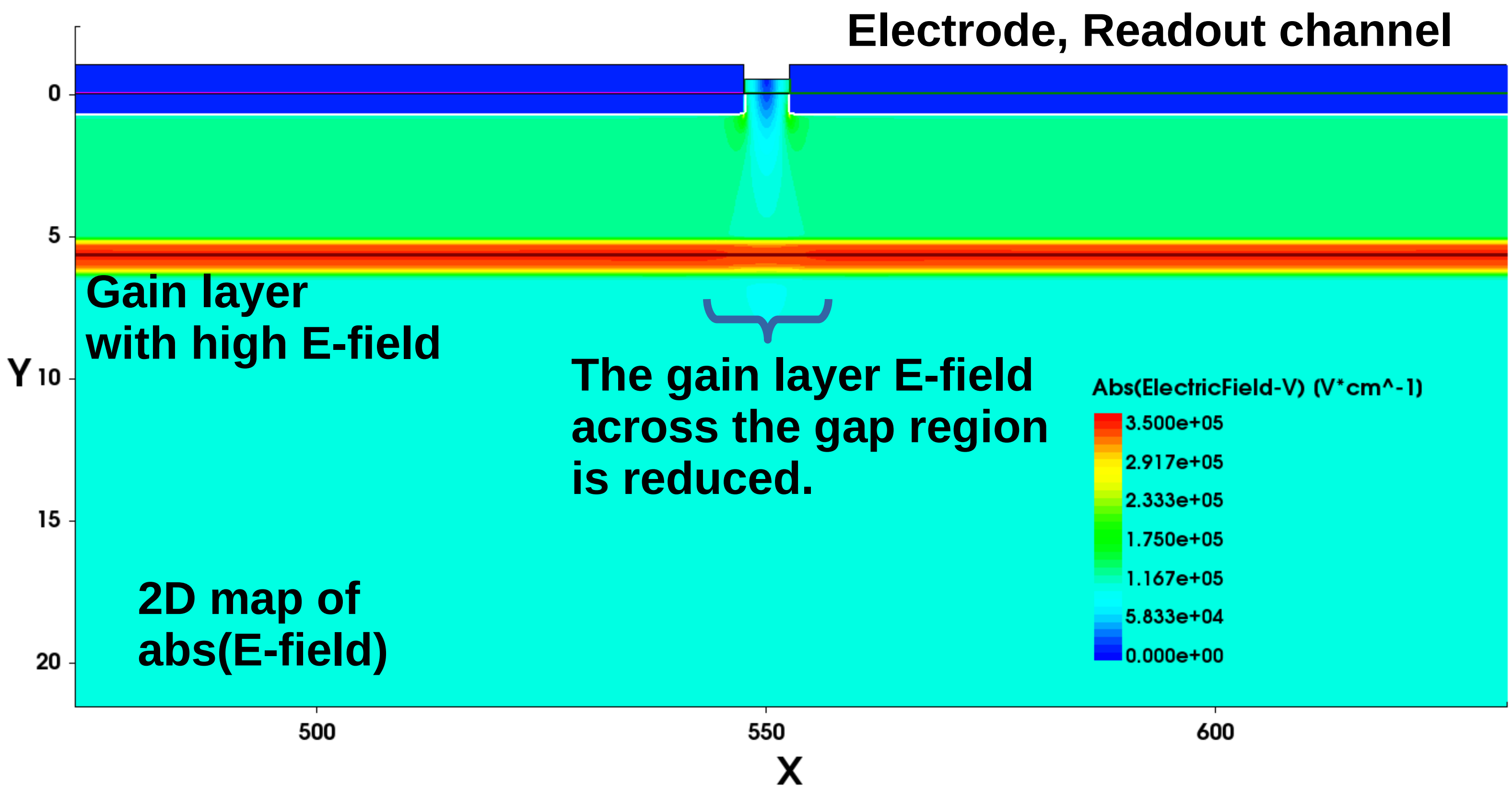
Deposit electrodes and implants



TCAD Simulation & Prototype Fabrication

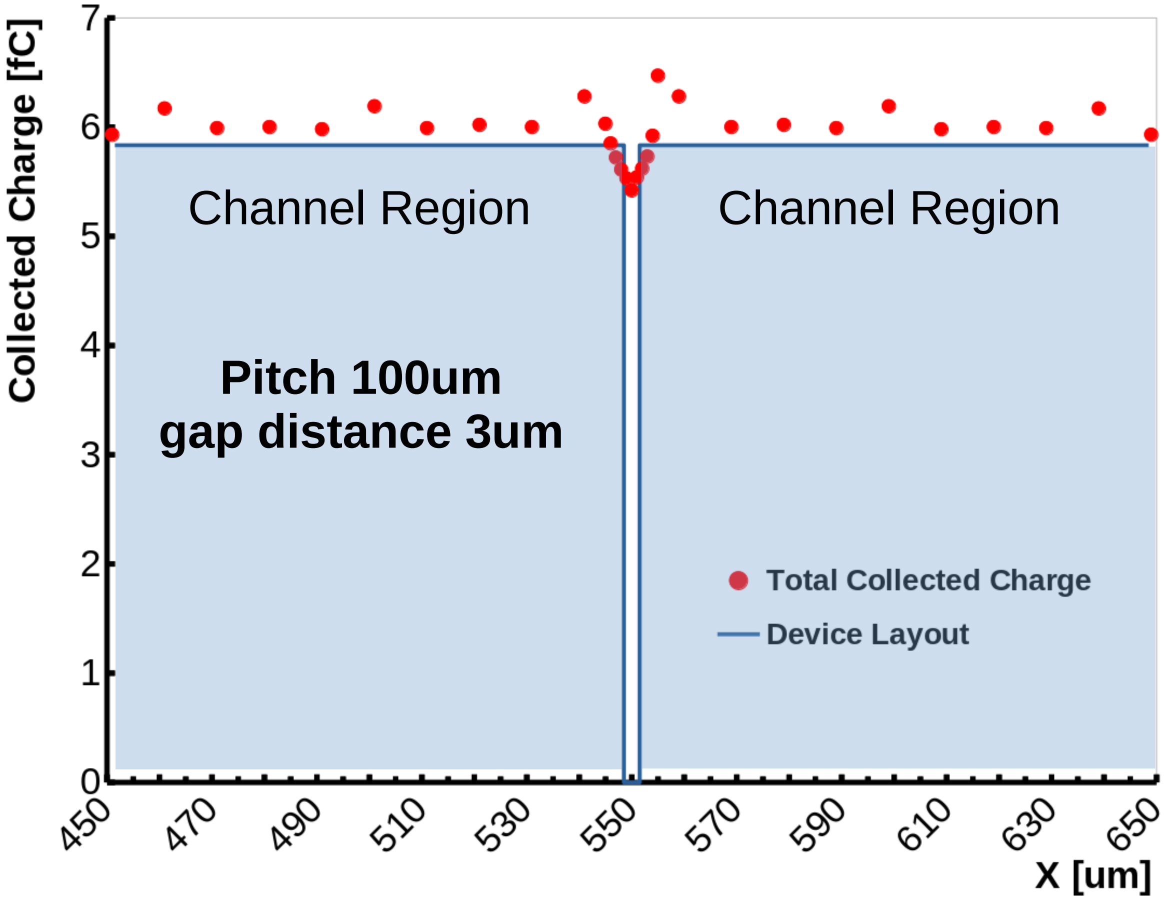
TCAD Simulation of DJ-LGAD

- **The idea of DJ-LGAD with epitaxial growth approach is simulated with TCAD.**
- **Primary goal of DJ-LGAD is to achieve preserve charge uniformity across channels.**
  - **The E-Field strength across the gain layer is affected by the inter-channel distance.**



TCAD Simulation of DJ-LGAD

- **The idea of DJ-LGAD with epitaxial growth approach is simulated with TCAD.**
- **One important goal of DJ-LGAD is to achieve preserve charge uniformity across channels.**
  - **The collected charge is studied by simulating minimum-ionization particle (mip) injection at different x location across the channels.**



The collected charge across channel is uniformly

~5% of collected charge is reduced across the gap region

Status of Prototype Fabrication

- **We work closely with manufacture, and using TCAD studies to provide feedback and guidance on optimizing fabrication parameters, e.g.**
  - Implantation energy for gain layer
  - Effects of different anneal temperature
  - Range of epitaxial layer resistivity
- **The first prototype led by BNL was produced using epitaxial approach, but the gain layer doping was too high and only depleted the epitaxial and n+ gain layer**
  - Optimized implantation dosage was studied and proposed for the 2nd prototype.
- **The second prototype fabrication with wafer-wafer bonding approach is in progress.**
  - Expect to receive samples for lab testing in late August

Conclusion

Conclusion

- Conventional LGAD pixel arrays have large dead (no gain) region across channels due to the JTE structure.

- We proposed the Deep Junction LGAD design with buried gain layer.
  - High field region is away from the surface, allow conventional pixelization with very fine inter-channel gap.
  - The gain layer is continuously across channels, which increase the charge uniformity across channels.
  - Simulation study on charge uniformity of DJ-LGAD shows ~5% charge reduction across gap region.

- Second prototype fabrication is in progress. New samples are expected to be available for lab testing in August.

Thank You!

Acknowledgment

Funding & Acknowledgment

- **This work was support by:**
  - **The United States Small Business Innovation Research (SBIR) Program.**
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The Deep Junction LGAD Working Group

- **Collaborated groups:**
  - **The Santa Cruz Institute for Particle Physics, UCSC**
  - **Cactus Material Inc.**
  - **Brookhaven National Laboratory**

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Backup

Signal Response from Simulated MIP

- **The signal response from mip injected at two different location is shown.**
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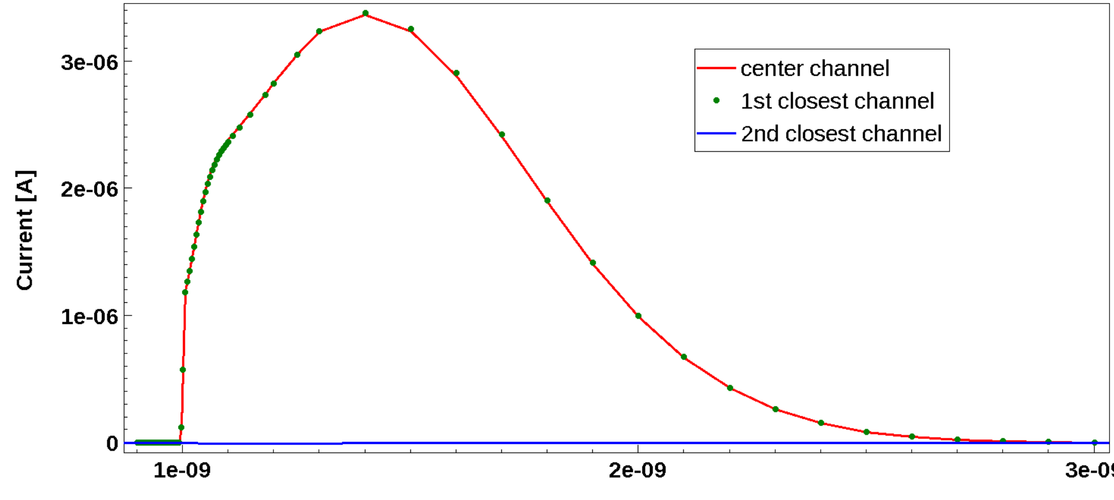
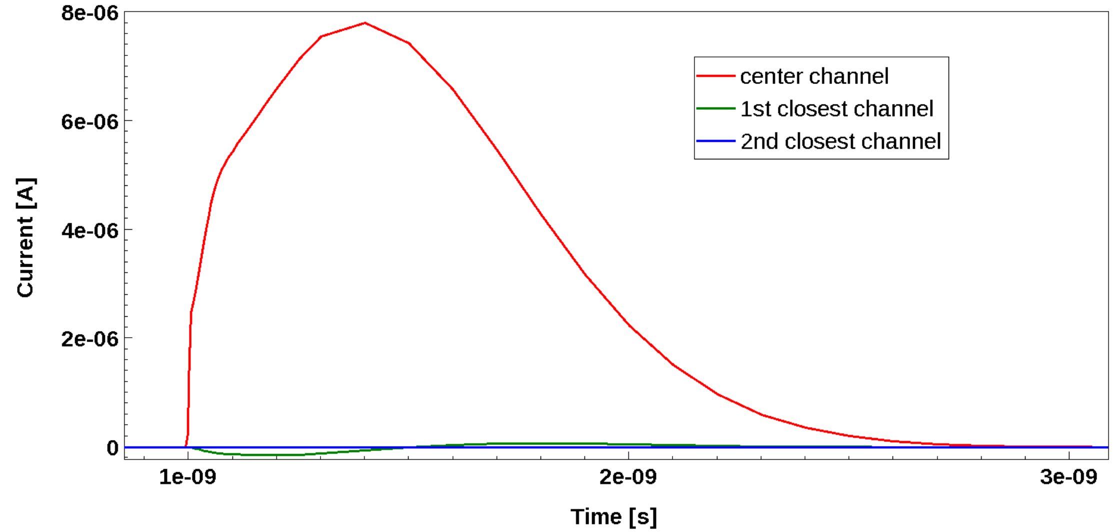
MIP is injected at the center of the gap between channels.

The signal is split evenly between the channels



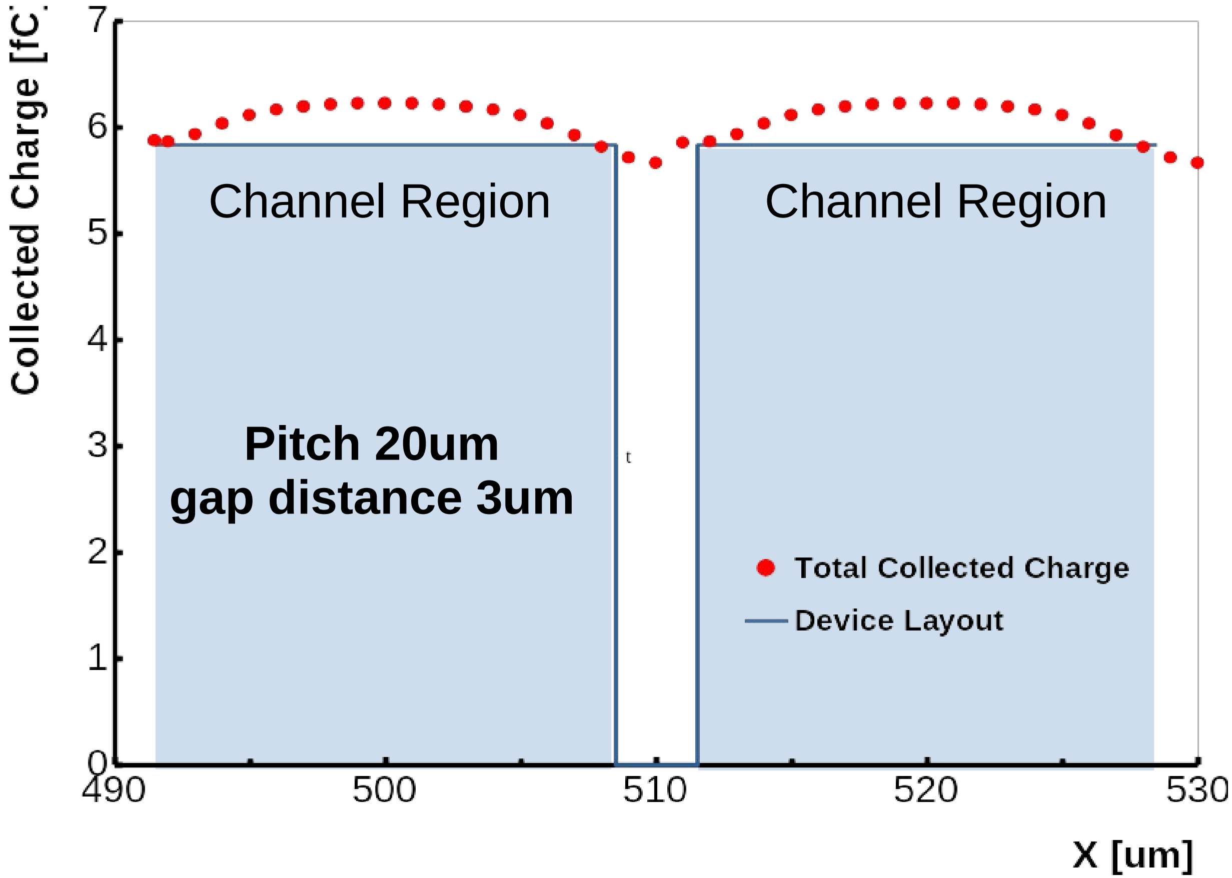
MIP is injected at the center of a channel.

The channel of where the mip is injected picks up all the signal.



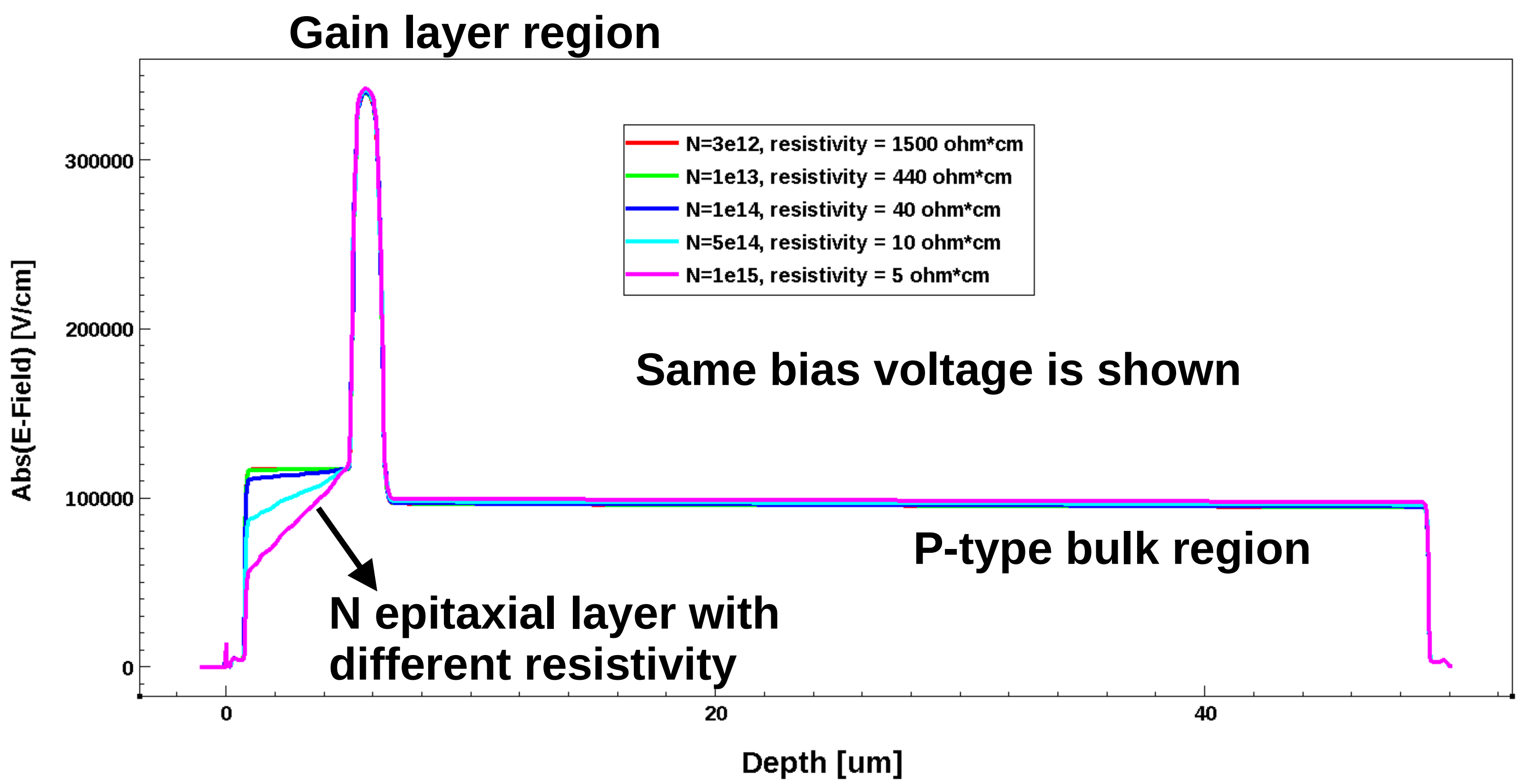
Simulation with Very Fine Pitch Segmentation

- Since the critical field region is buried, the surface segmentation/pixelization can be made with very fine pitch and inter-channel distance.
- Simulation with 20um pitch & 3um inter-channel distance also shows good charge uniformity



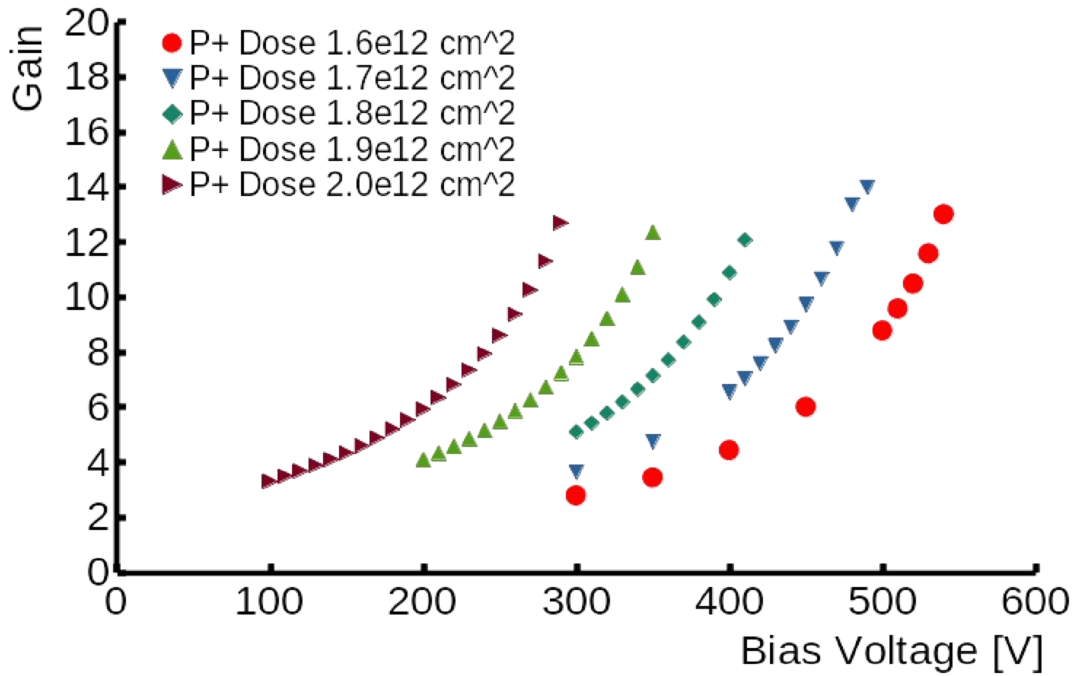
Electric Field in Epitaxial Layer

- **DJ-LGAD operates under full-depletion. The epitaxial layer is also depleted under reverse biasing.**
- **The field within the epitaxial layer is affected by the resistivity.**



Gain vs Bias Voltage for P+ Implant Dosage

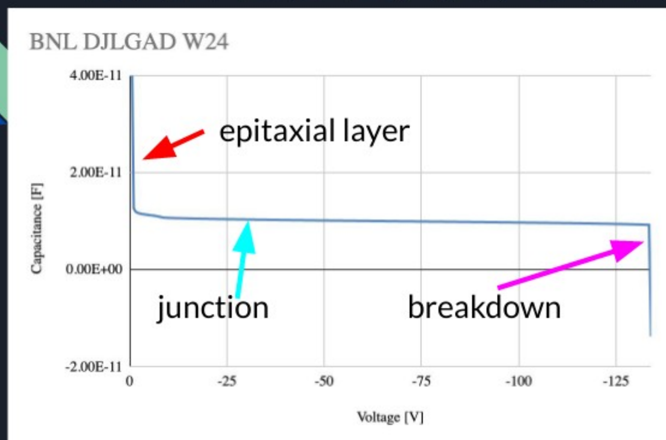
- **The following plot shows the gain vs bias voltage curve for signal response of the channel where a mip is injected.**
- **The gain is computed as the collected charge ratio of a DJ-LGAD device to a PiN diode with same geometry and thickness but without gain layer.**
- **The P+ dosage dependence on gain is studied in simulation as shown in the figure**
  - Simulation starts to diverge for dosage > 2.3e12 cm^2. High current occurs before full depletion (and only N+ is depleted).

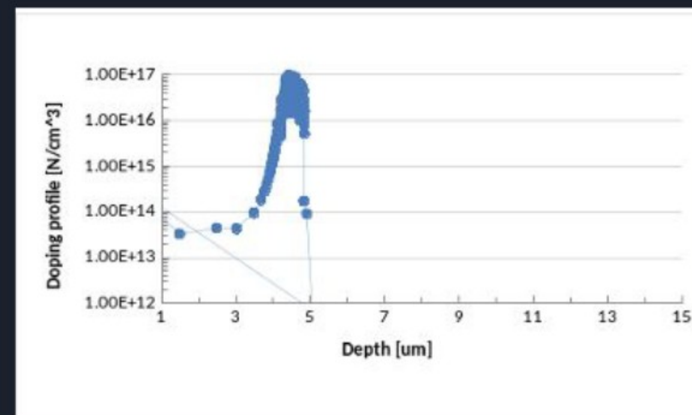


First Prototype C-V

- **Doping concentration for the first DJ-LGAD prototype was extracted through C-V measurement.**

BNL DJLGAD: CV measurements





- Capacitance gives width of depletion region
- See sharp behavior from epitaxial layer in first few microns of sensor at low voltage, then slower in junction until reaching breakdown
- Can see in doping profile that breakdown occurs before junction fully depletes
- Field is too high and we starting getting hole multiplication, so need to reduce doping
- When we tried increasing temperature, a higher breakdown voltage achieved, which means hole depletion is being suppressed at higher temperatures and we would benefit from a lower doping concentration

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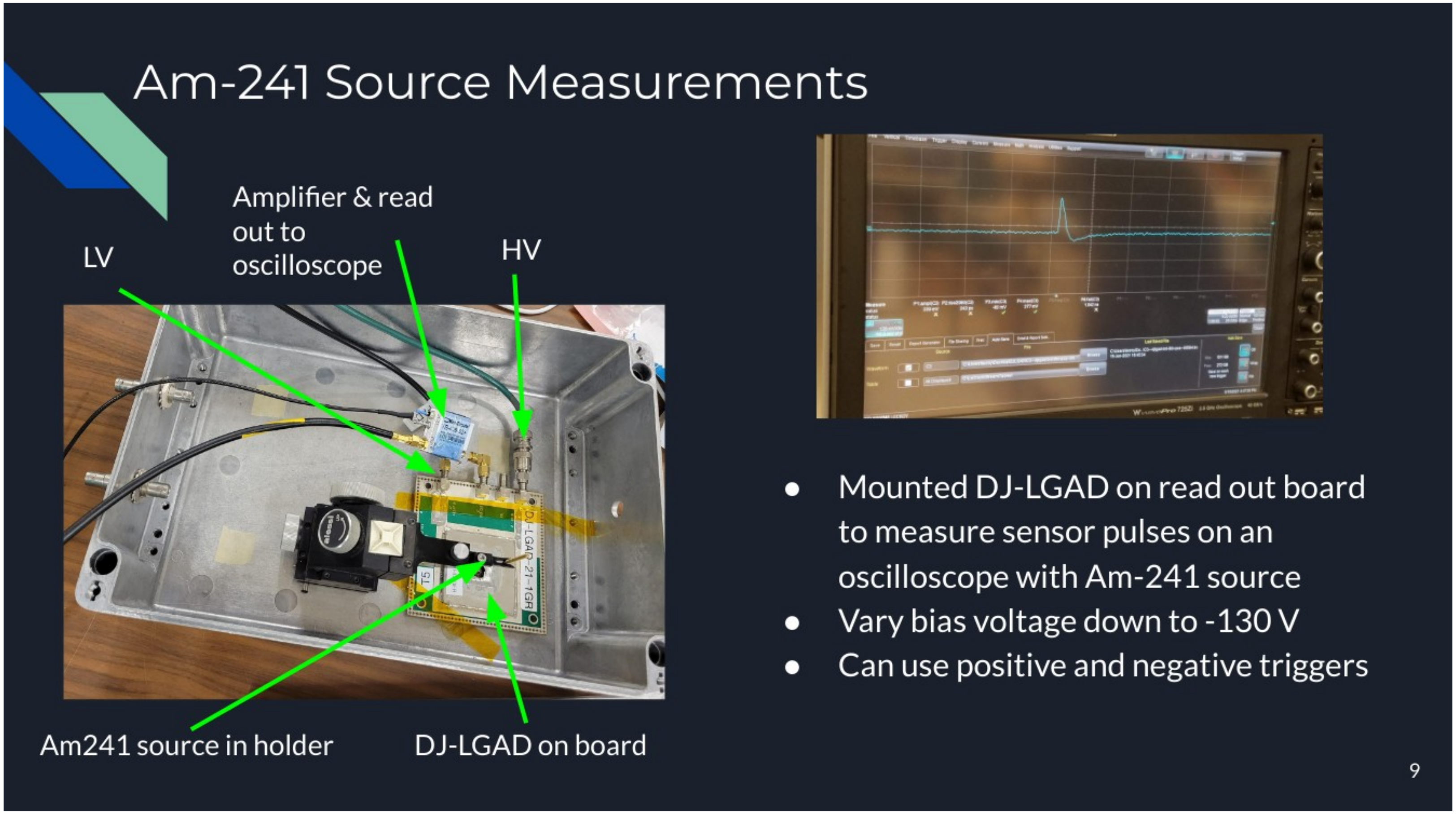
Credit: C. Gee
Talk on RD50 Nov 2021

Alpha Particle Injection with First Prototype

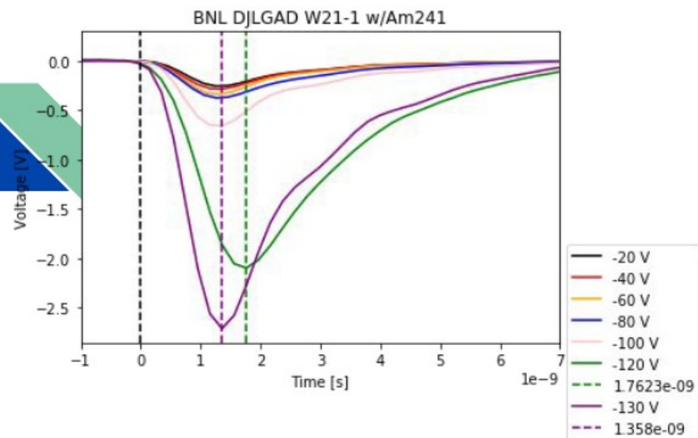
- **Alpha particle with ~5MeV energy is injected.**

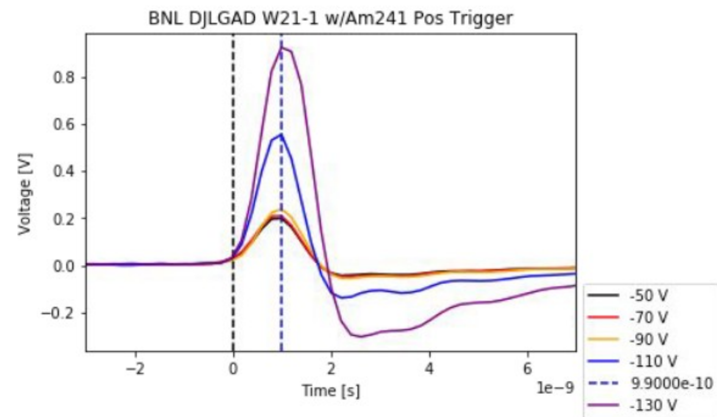


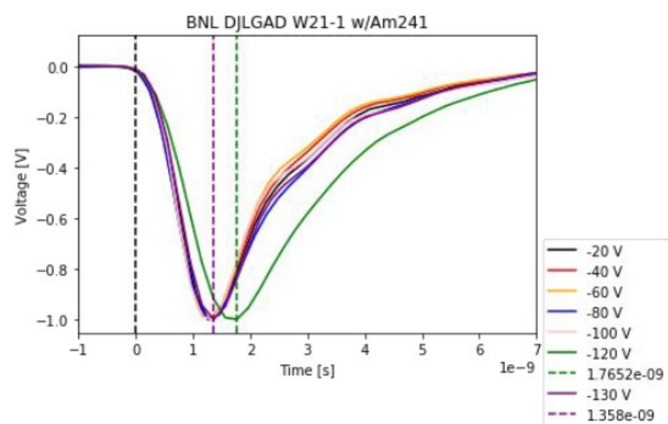
Credit: C. Gee
Talk on RD50 Nov 2021

Alpha Particle Injection with First Prototype

- **Signal response from the injected alpha particle**







- Unnormalized (left top) and normalized (left bottom) pulses from non-depleted DJ-LGAD at various reverse bias voltages
- Pulses likely from the pin diode in the top 5 um epitaxial layer
- Pulses observed from pos and neg triggers
- Not particularly fast since sensor isn't depleted

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Credit: C. Gee
Talk on RD50 Nov 2021