Development of Ultrafast Silicon Sensors for Precision Timing and 4D Tracking

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Overview

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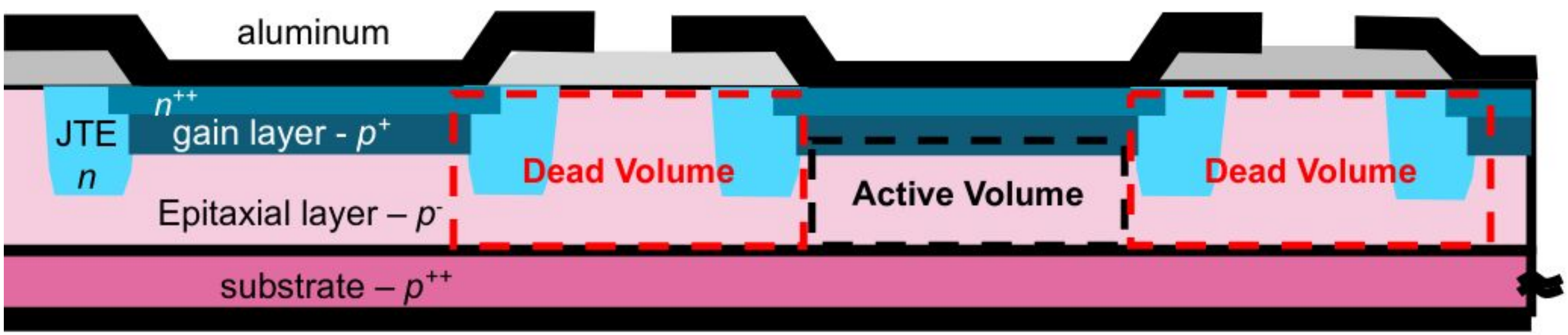
Review of LGAD Technology

LGAD Technology

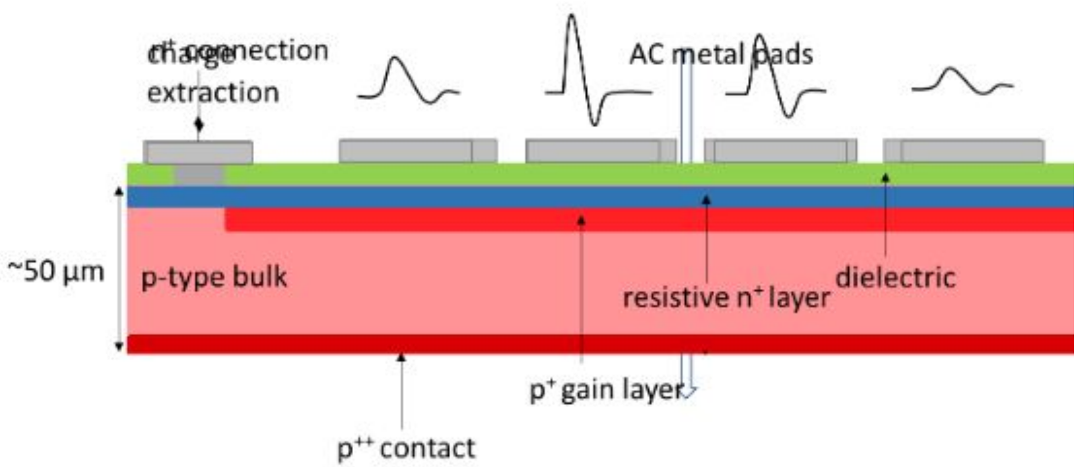
- **Low Gain Avalanche Detector (LGAD) is type of silicon based detector that made used of highly doped (p+) layer which provide internal moderate gain of 10 to 50:**
  - Very thin active thickness. (20 to 50um).
  - Very Radiation hard (survive up to fluence of 6e15 neq/cm^2)
  - Capable to provide timing resolution < 20 ps for mip.
- **However, JTE structure is required to prevent premature breakdown:**
  - Large dead area between channels (~30 to 100um)
  - Granularity is limited to mm scale.
- **Variant design of LGAD that help resolving this limitation:**
  - **Maturing design AC-LGAD**
  - **Promising prototype: Trench-Isolated & Deep-Junction LGAD (focus on this today)**

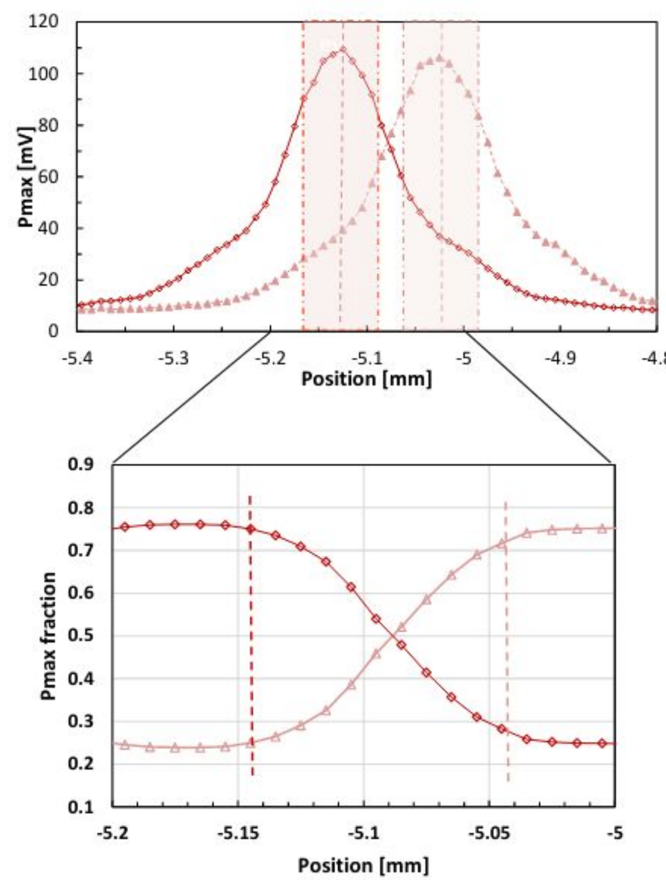


Variant of LGAD Designs

AC-coupled LGAD (AC-LGAD)

- The gain layer is continuous, which contains a highly doped p+ layer and a resistive n+ layer.
- The signal is AC-coupled through a dielectric layer.
- Strong sharing of charge between metal pads.
- Very high fill factor.
- Current development:
  - Pad geometry
  - Impact of strip length
  - Exotic pad geometries possible

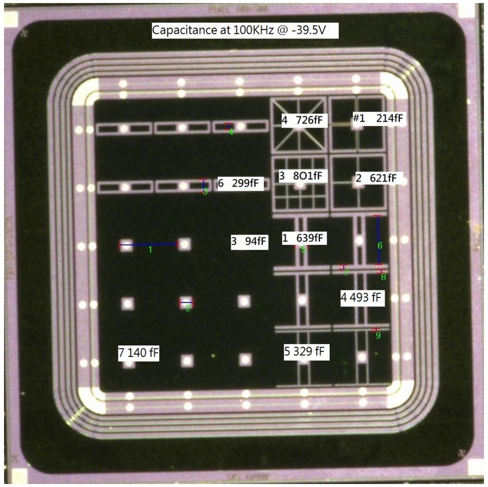


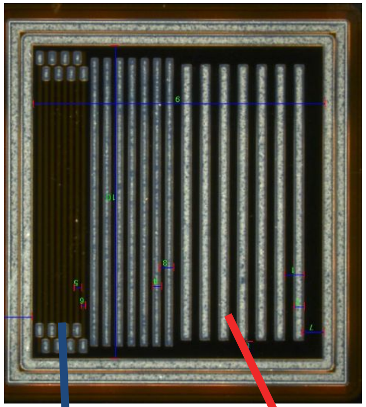


AC-coupled LGAD (AC-LGAD)

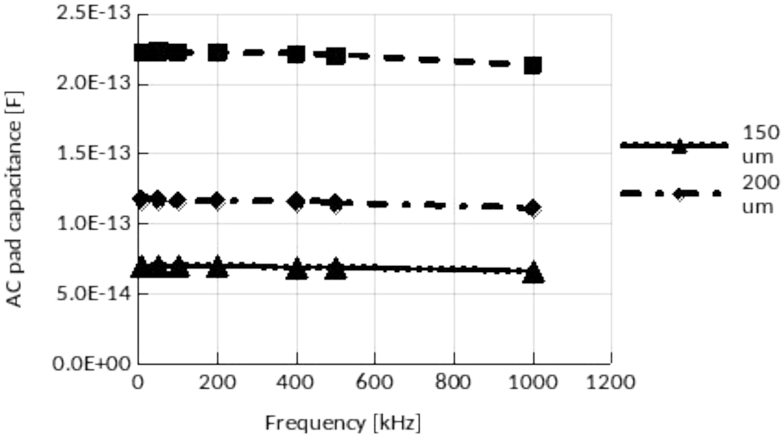
- The capacitance of AC-LGAD with different pad geometries and strip length are measured at UCSC.

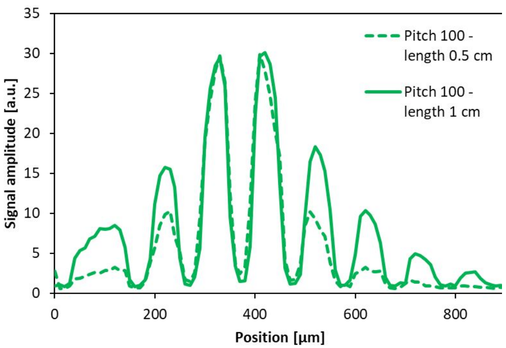
Pad geometries: Reduction of capacitance by decreasing metal area

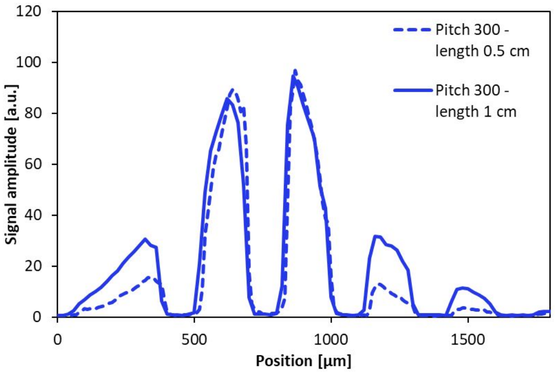




Strips: more signal sharing over small pitch, AND more sharing in sensors with longer strips

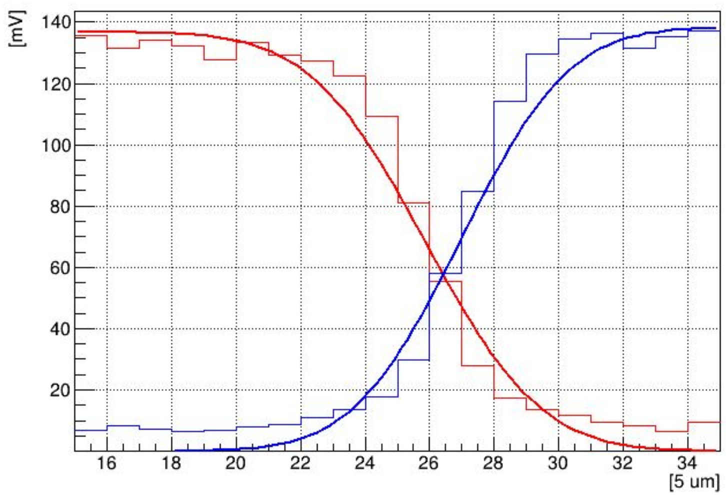


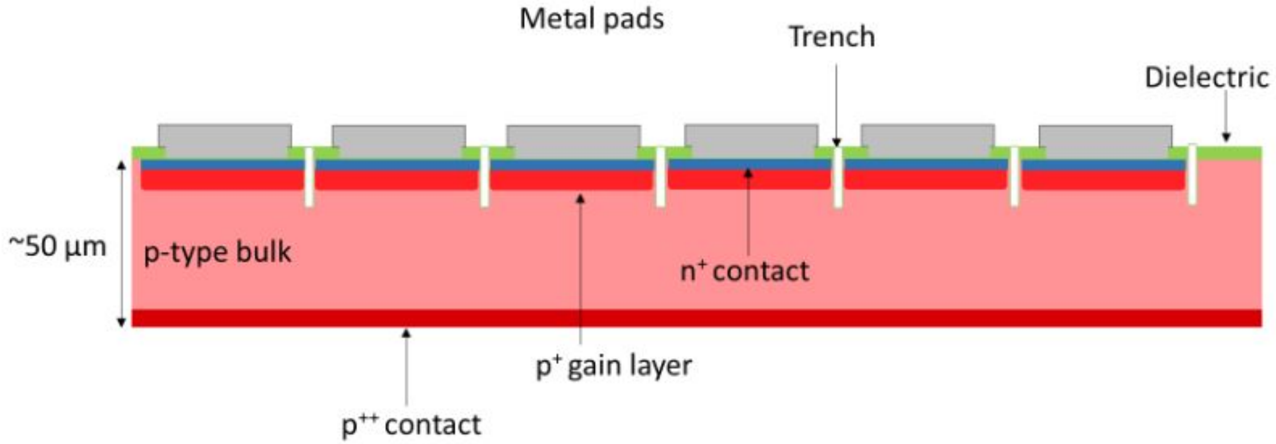




Trench-Isolated LGAD (TI-LGAD)

- DC coupled readout from metal pads.
- Gain layer is segmented with etched trench instead of conventional JTE structure with implant:
  - Very high fill factor.
  - No charge sharing.



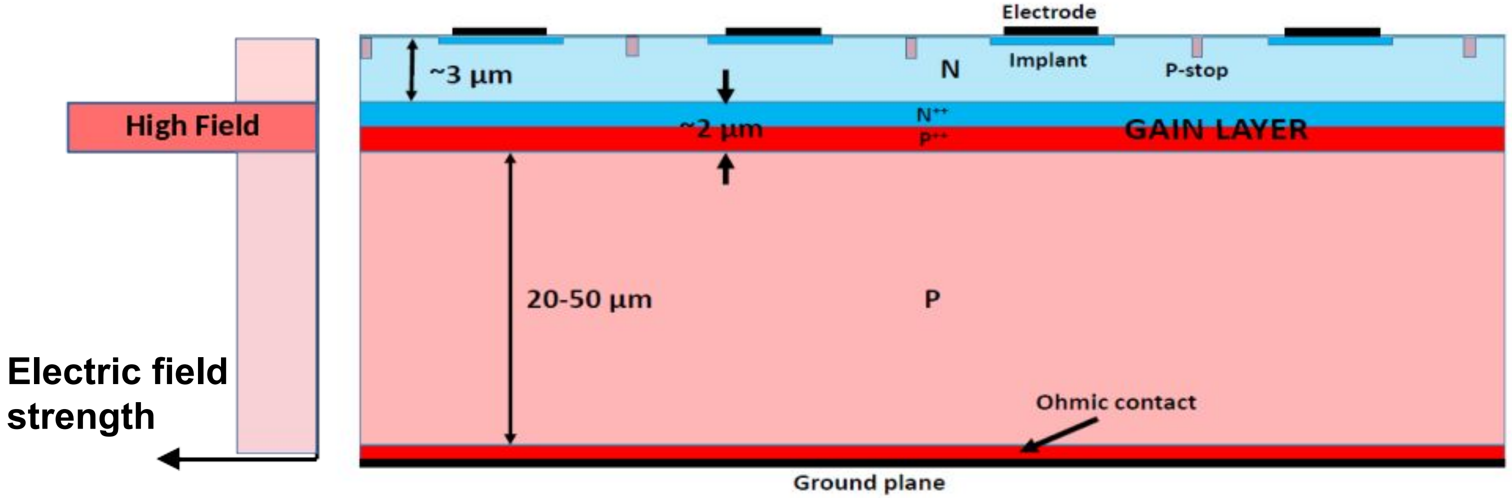


TI-LGAD Produced by FBK

Data taken by
Miguel Godoy

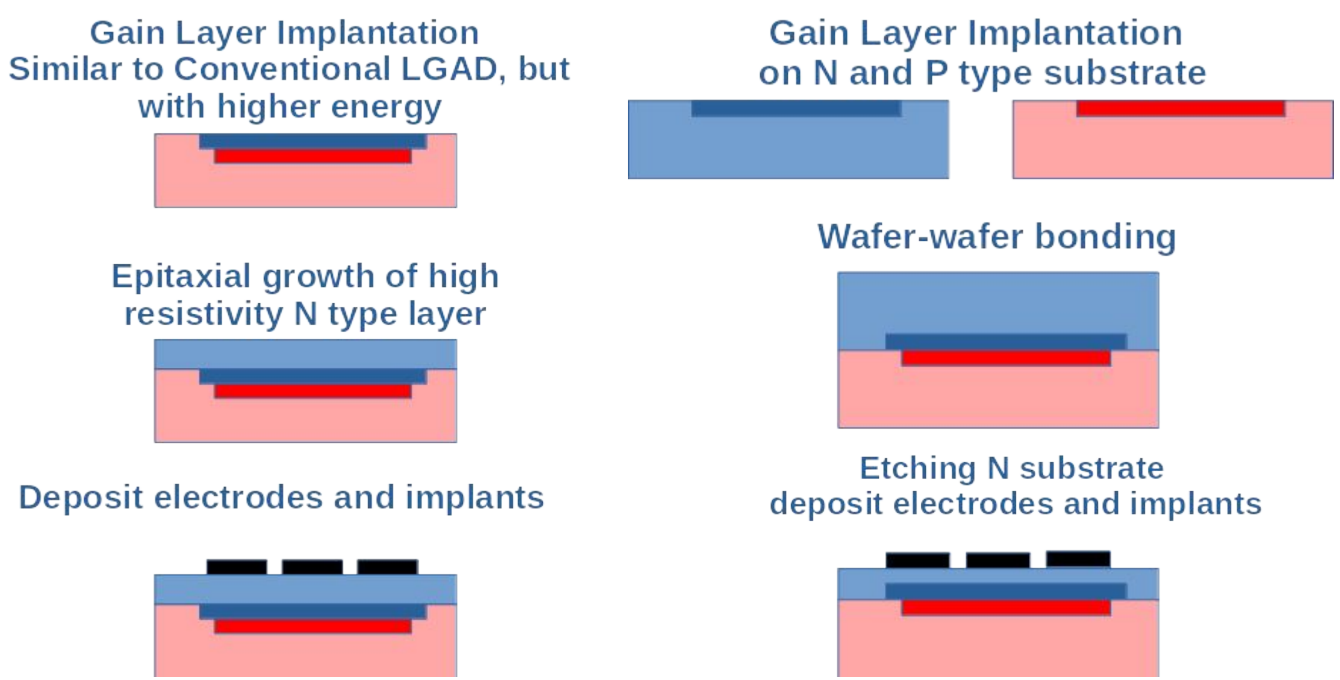
Deep-Junction LGAD Concept

- **The term "deep junction" ariase from the use of a p-n junction buried several microns below the surface of the device.**
- The Deep Junction concept has several features:
  - The electric field is low at the surface → **no JTE structure is required for pixelization/segmentation.**
  - The gain layer is continuous across channels, so the dead region is reduced → **maintain good charge uniformity**
  - **Preserved DC coupling of signal to readout electrodes.**



DJ-LGAD Prototype Manufacturing

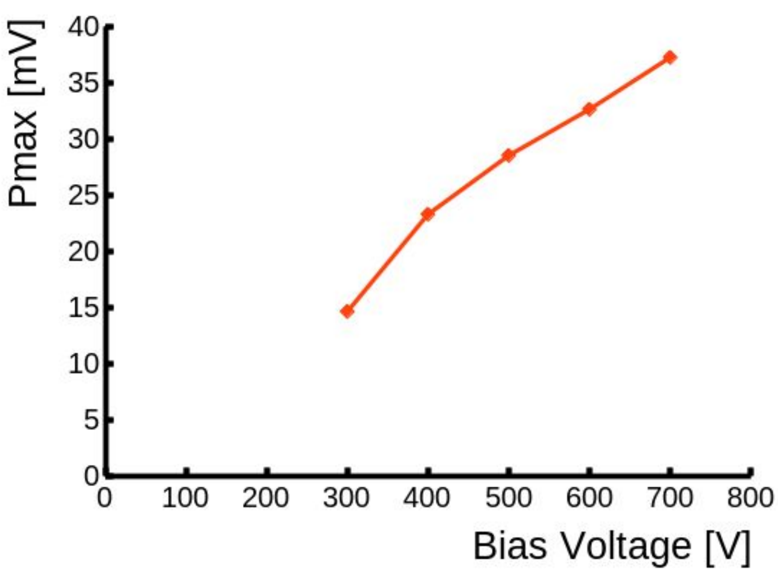
- **There are two approaches to achieve deep junction:**
  - **Epitaxial growing above the deep junction.**
  - **Wafer-to-wafer bonding (with substrate etching)**
- The 2nd DJ-LGAD prototype with wafer-wafer bonding was made in collaboration with Cactus Material Inc & Brookhaven National Laboratory (BNL)

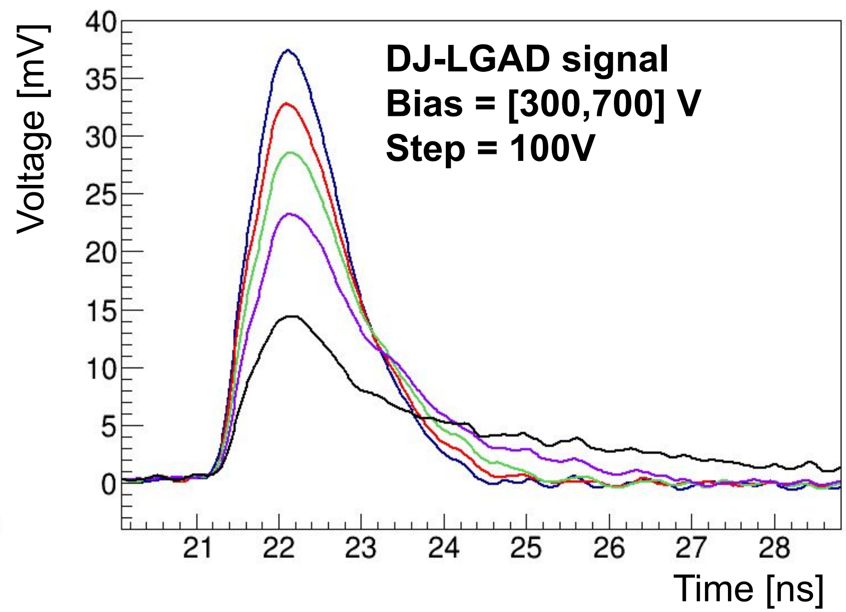


Results from Deep-Junction LGAD Prototype

Charge Collection using IR Laser

- **IR laser is used for charge injection to study the response.**
- The pmax and signals are shown in terms of bias voltage.
  - **Rise time ~ 580 ps, similar to a typical 50-60um LGAD.**
- **Measured gain of ~ 3 to 5,**
  - Lower than conventional LGAD
  - Optimization of the gain layer doping is required for future prototype

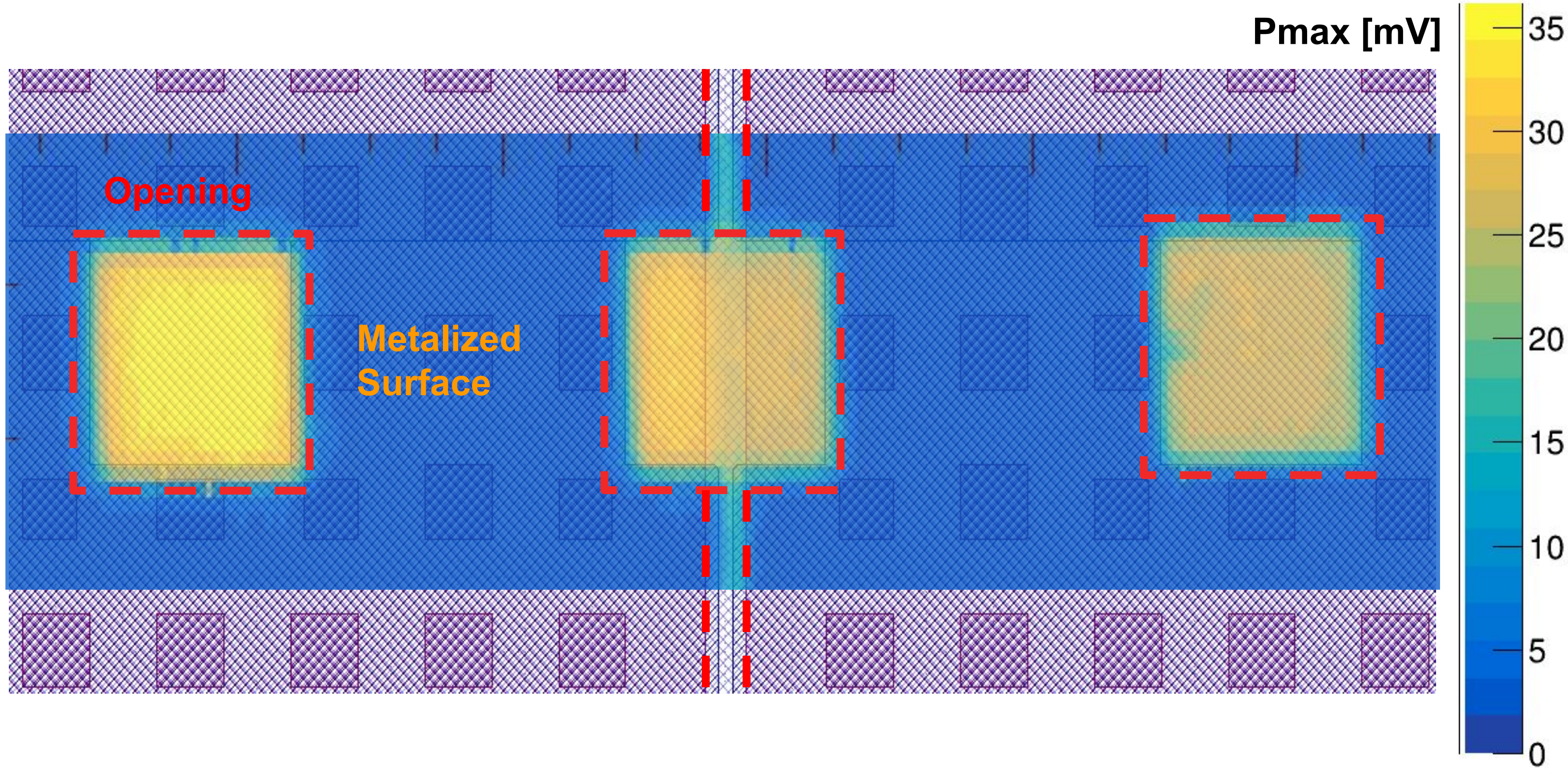




Data taken by Miguel Godoy

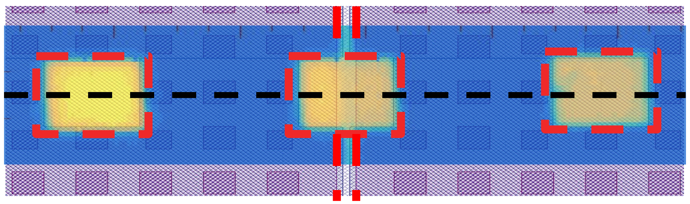
IR Laser TCT Scan

- **DJ-LGAD 2x1 array prototype is studied with IR Laser scan.**
  - both pads are readout simultaneous to a digital scope.
- The pmax values in terms of the laser beam location are shown for both channels.
  - no signal region, color blue, is due to surface metal



Scan over Interpad Region

- **The pmax projection of the cutline across the two pads are shown:**
  - Pmax > 6 is used to remove 3 sigma noise events.

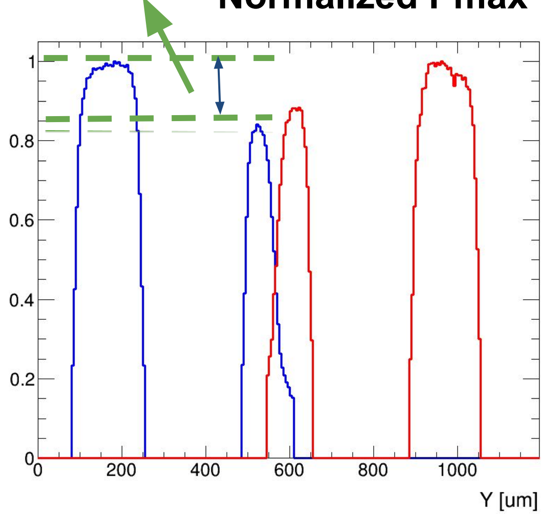


The pmax fraction of an individual strip is defined as:

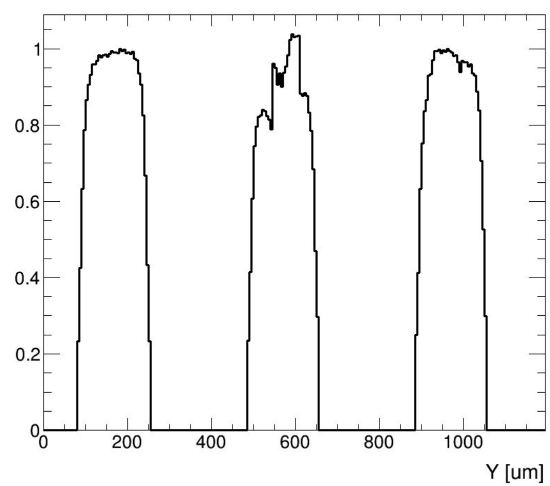
$$pmax\ fraction\ (channel) = \frac{pmax\ (channel)}{\sum pmax}$$

Field degradation due to geometric effect near IP region. See backup

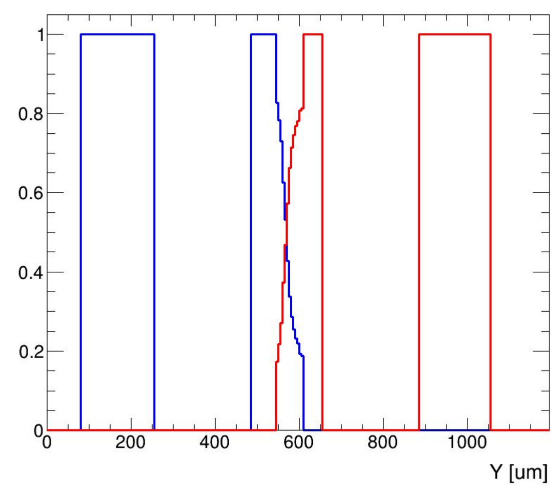
Normalized Pmax



Sum of normalized Pmax

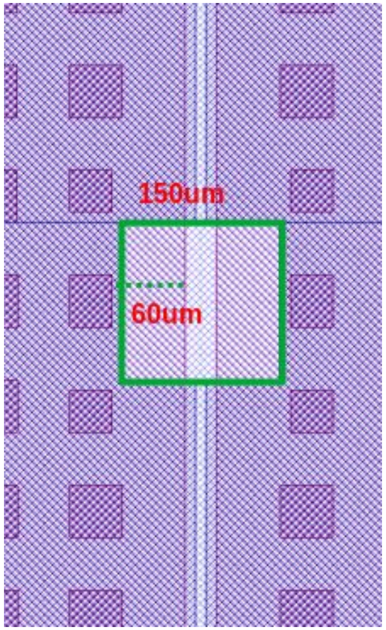


Pmax Fraction

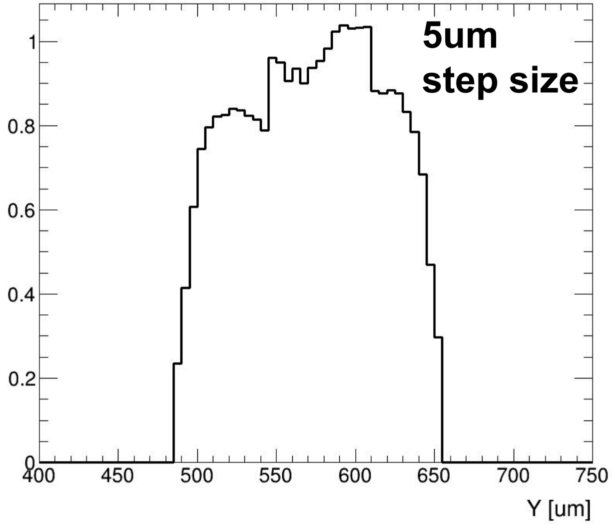


Scan over Interpad Region

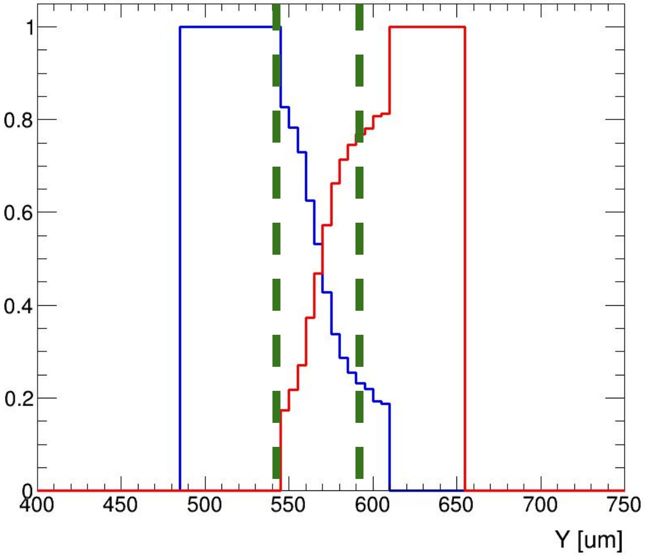
- **The opening around the interpad region is a 150x150um square**
  - **The edge of opening to the edge of the pad is 60um**
  - **The nominal interpad gap is 30 um**



Sum of normalized Pmax



Pmax Fraction



Small signal pick up across the gap is observed.

No significant signal loss at the gap region, as expected from the continuous gain layer.

Summary

- **Presented variant LGAD designs**
  - **AC-LGAD, TI-LGAD & DJ-LGAD.**
- **Presented the results of first working DJ-LGAD prototype:**
  - **The Deep-Junction idea is promising.**
  - **Shows very good signal/charge uniformity across channels.**

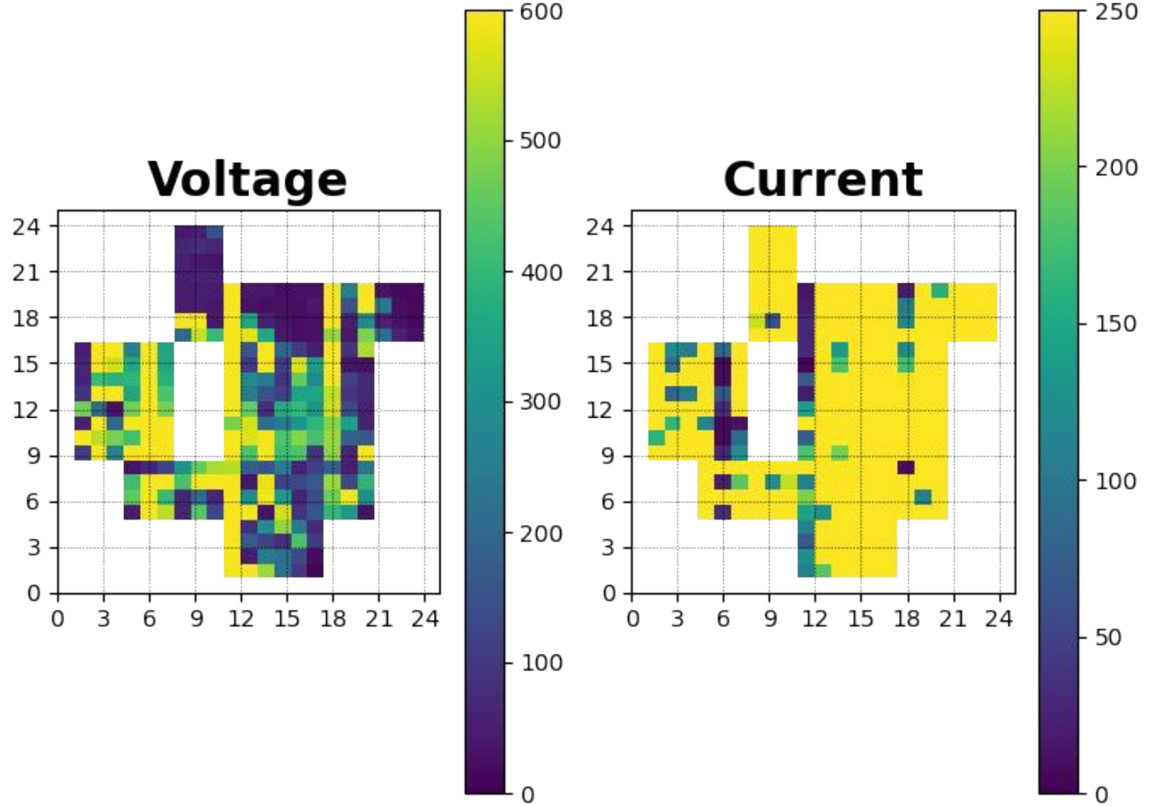
Future production for DJ-LGAD:

- **DJ-LGAD currently have very large leakage current, we need to reduce the current to level of conventional LGAD.**
- **The gain is lower than conventional LGAD, we need to optimize the doping in the future prototype.**

Backup

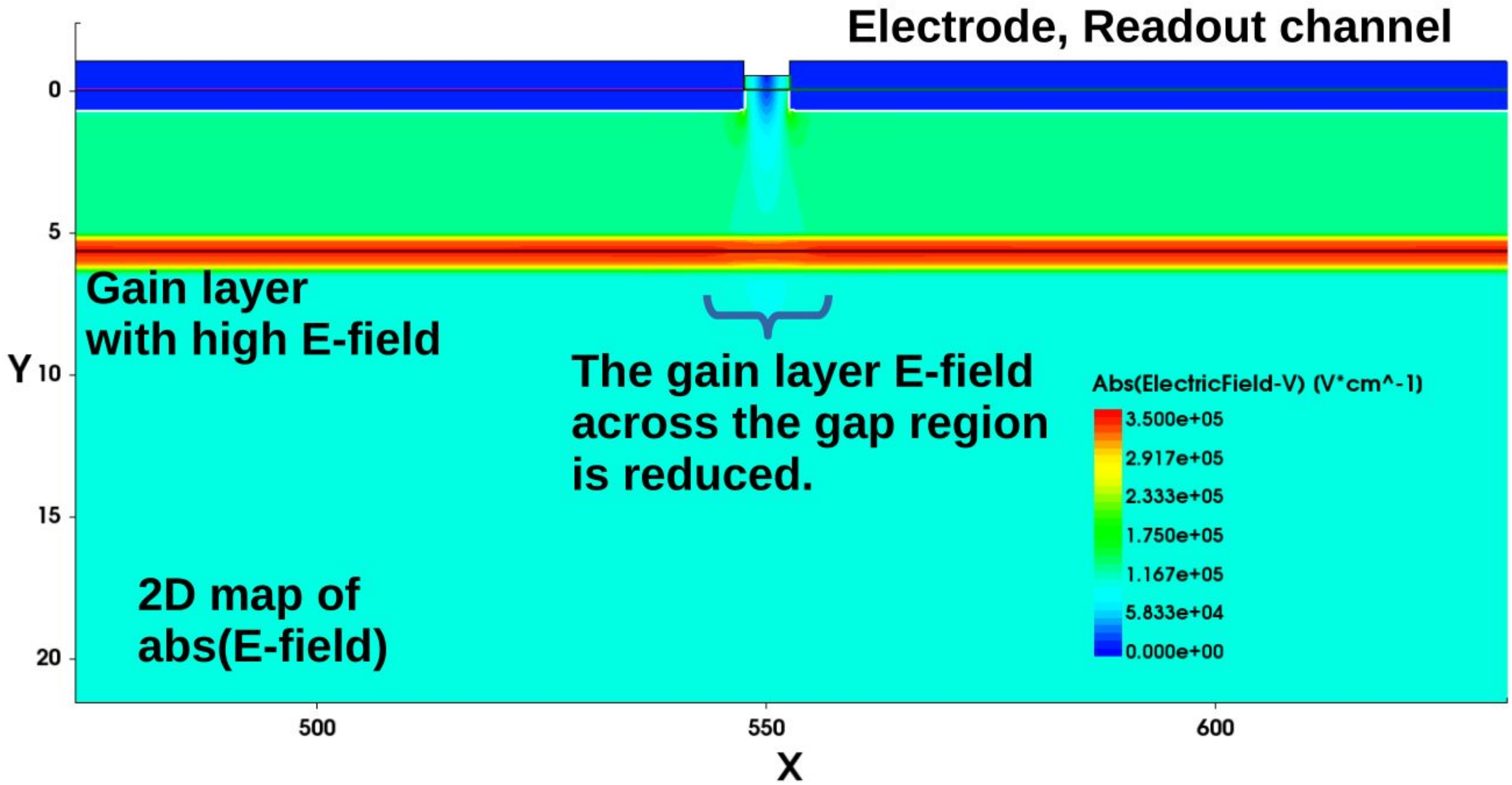
Max Voltage & Current Map

- The DJ-LGAD currently has extremely large leakage current, and breakdown voltage vary significantly across dice over the same wafer.
- The current level is of order of > 100uA.



Field Degradation Cross Pads

- 2D simulation shows the field in the gain layer is reduced in the interpad region.



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