Deep-Junction LGAD

A New Approach to Higher Granularity Fast Timing Detectors

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on behalf of the UCSC-SCIPP group

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RD50

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Overview

- **Quick overview of Low Gain Avalanche Detectors (LGAD)**
- **Existing approaches for higher granularity LGADs.**
- **New approach to higher granularity LGADs: Deep-Junction LGADs (DJ-LGADs).**
  - Updates for current stage of first prototype and simulation studies.

Low Gain Avalanche Detectors (LGADs)

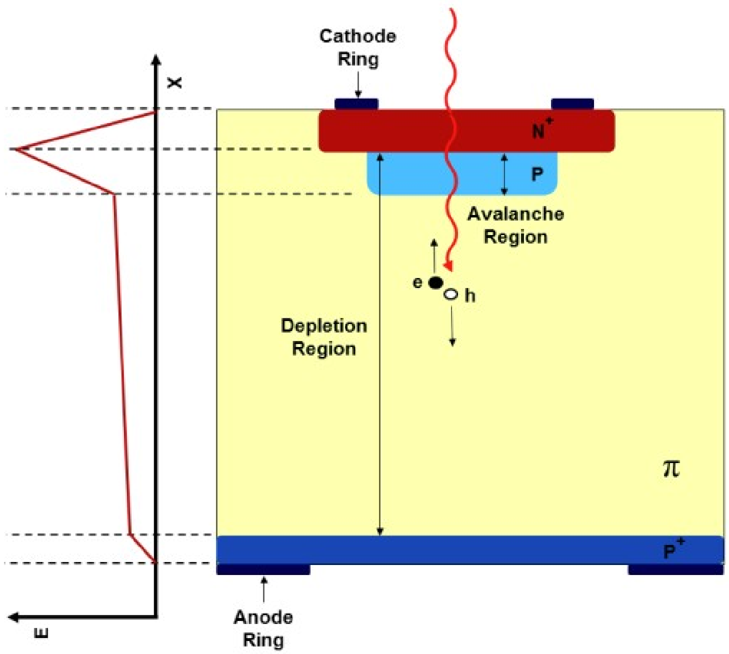
- **Silicon detector with highly doped thin multiplication layer (~10^{16} p++)**
  - provide high electric field that's capable for avalanche effect to happen.

- **Intrinsic modest internal gain (10-50):**
  - Good signal to noise ratio.

- **Allows thin active thickness (50 to 20 µm)**
  - Short rise time
  - less Landau fluctuations.

- **Fast Timing resolution < 30ps**

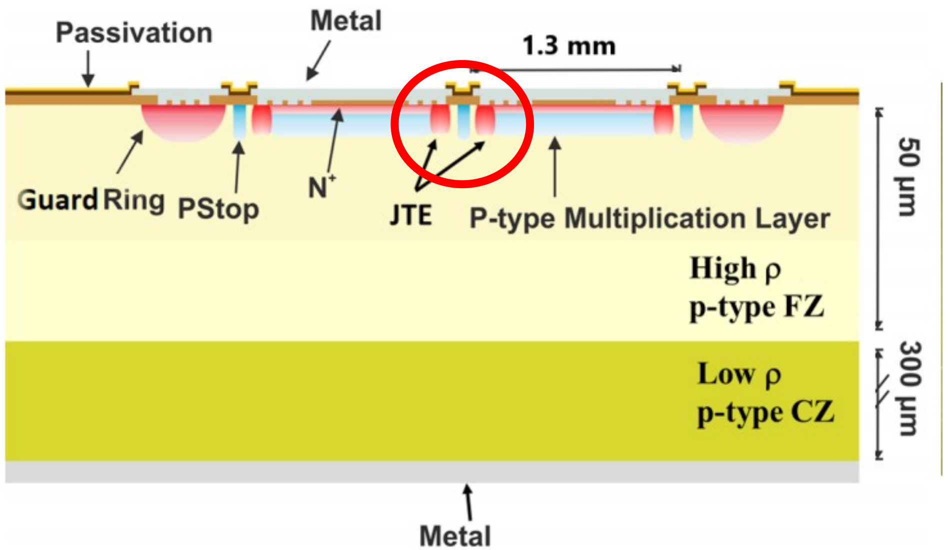
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$



Granularity Limitation of LGAD Arrays

- One of the current limitation of LGADs is achieving higher granularity.
  - Electrical insulation is required for LGAD array due to the high electric in the multiplication region.
    - Junction Termination Extension (JTE) is used between pads.
    - Inter pad gap 50 to 150µm.
    - Limits granularity to mm scale.

- The next generation colliders and 4D tracking detectors require sensors to have 50µm pitch (or less).

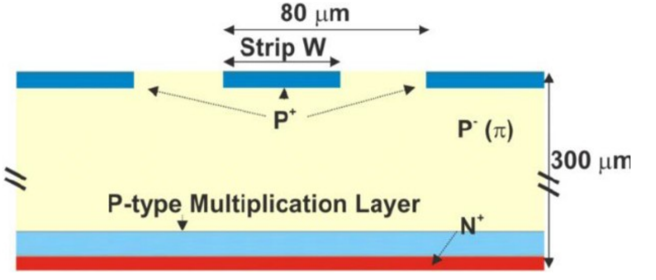


Existing Solutions for Higher Granularity

- Several promising approaches to increase granularity are proposed and under studying:

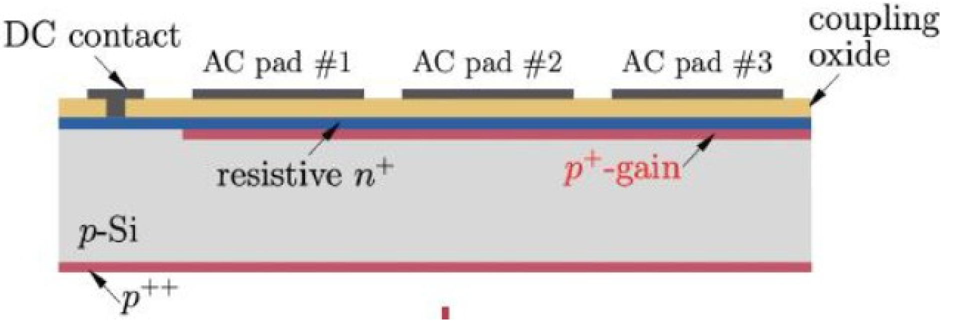
  1) Inversed LGAD (iLGAD)

  – Reverse position of the gain layer

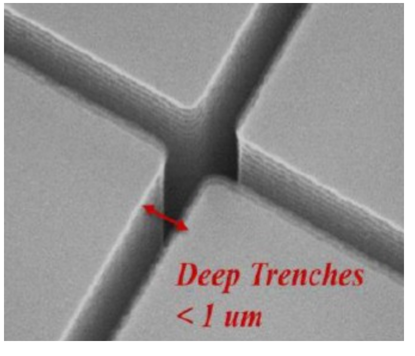


  2) AC-LGAD (US patent No.:9,613,993 B2, granted Apr.4, 2017)

  – AC coupling to the output



  3) Trench Isolated LGAD (TI-LGAD)

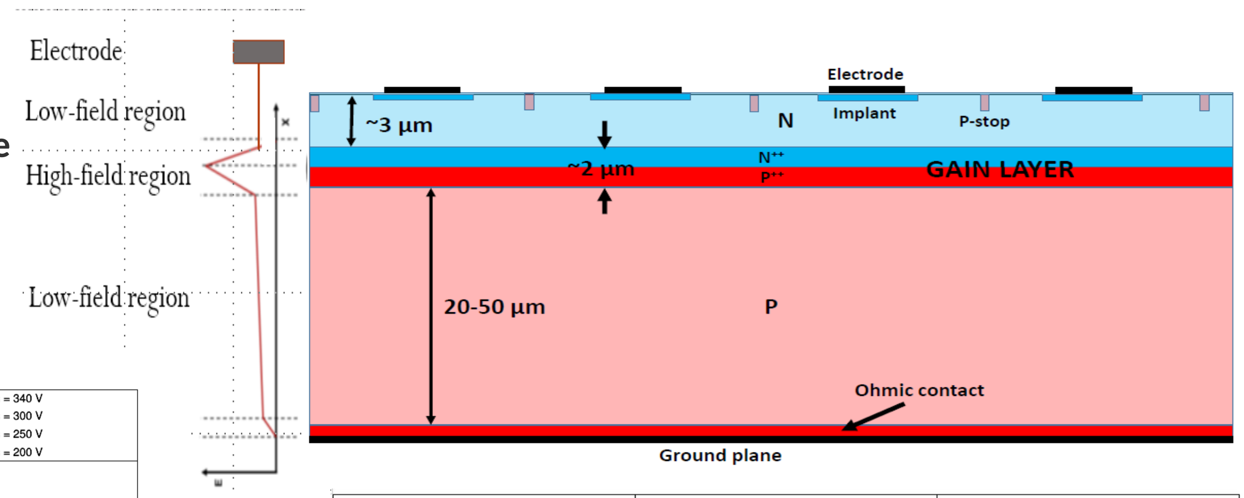


New Approach: Deep Junction LGAD

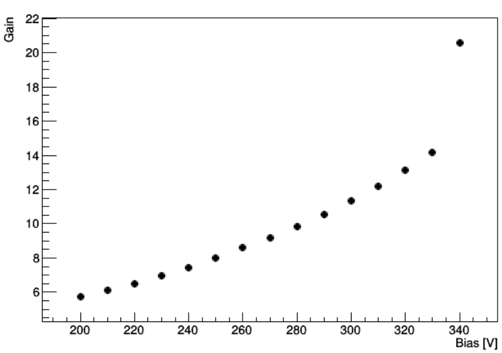
- **The idea of deep junction LGAD (DJ-LGAD) was first presented by S.Mazza**
  - See links on TREDI2020, 15th Trento Workshop
    https://indico.cern.ch/event/813597/contributions/3727775/attachments/1989522/3316390/020220_TREDI_DJ_LGAD_smazza.pdf
  - **We have received great feedback from the community, and updates on the sensor design will be shown in this presentation.**
- **Working principle and ideas of DJ-LGAD:**
  - **Localize the high electric field region within the sensors. Achieve by pairing p++ gain layer with n++ layer, and burying the junction ~5µm below the surface.**
  - **Addition of low doped n type substrate to lower the electric field near the surface. Allow usual (pixel) segmentation techniques to be used to increase granularity.**
  - **The n type substrate is DC coupling to the electrode.**

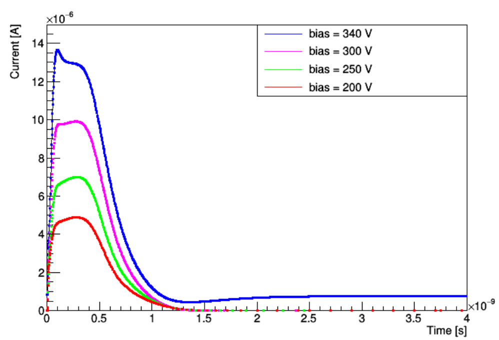
New Approach: Deep Junction LGAD

- Schematic and example of Sentaurus TCAD simulation result for the original design of 50µm DJ-LGAD (before additional studies reported)
  - Fast rise time,
  - Short collection time.
  - Modest Gain >10 is achievable



Element	Doping Level	Extent in Depth
N isolation layer	Constant doping of density 3e10 N/cm^3	From 0 µm (surface) to 4 µm
N^{++} gain plate (upper half of gain layer)	Gaussian doping, peak of 3e16 N/cm^3	Peak at 3 µm, falling to 5e12 at 4 µm (sigma = 0.17 µm, FWHM=0.4 µm)
P^{++} gain plate (lower half of gain layer)	Gaussian doping, peak of 3e16 N/cm^3	Peak @ 4.5 µm, falling to 5e12 at 5.5 µm (sigma = 0.17 µm, FWHM=0.4 µm)
P drift region	Constant doping of density 3e12 N/cm^3	4 µm to 50 µm



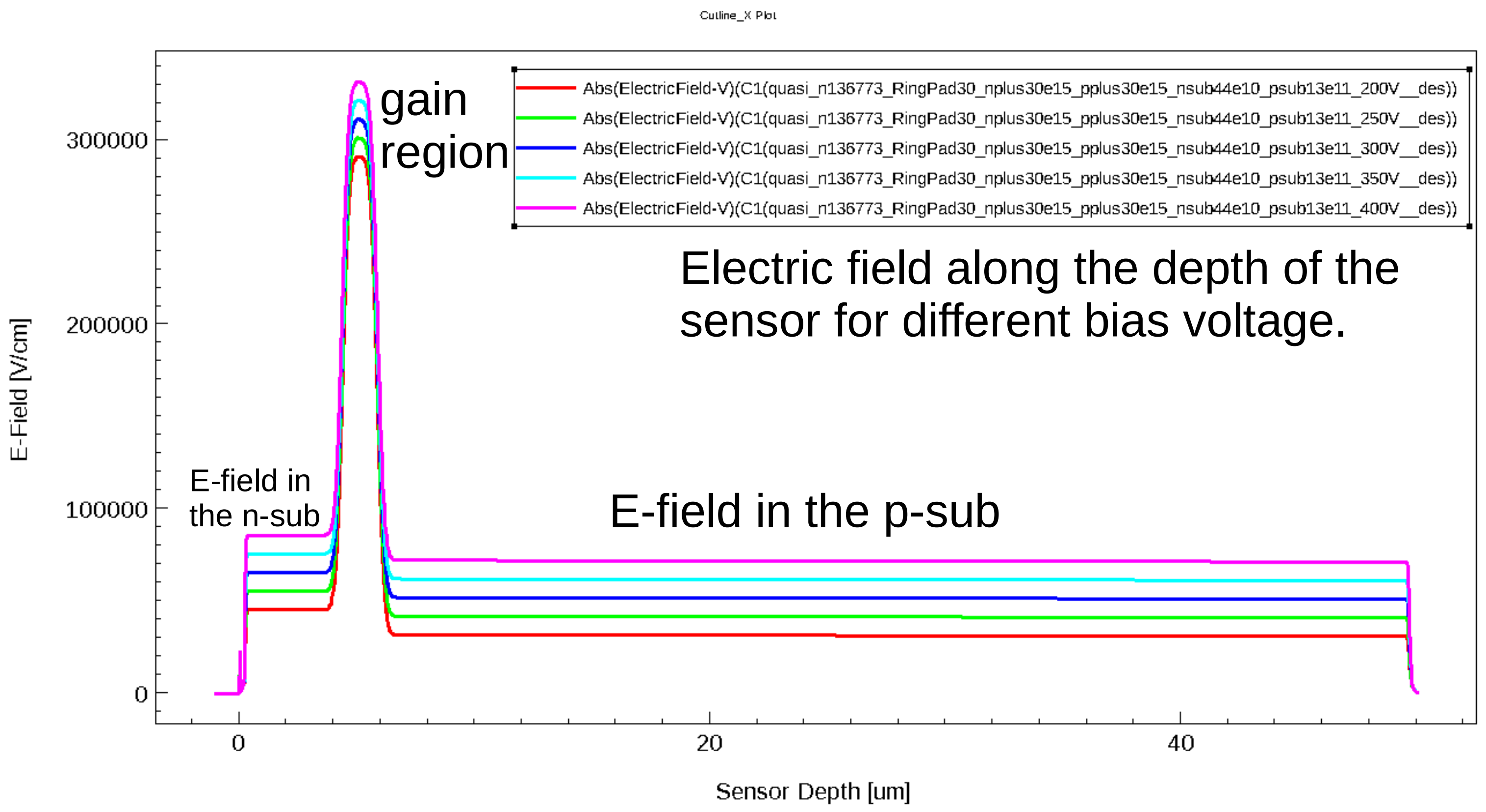


MiP simulation example of gain curve and temporal profile for 50um Thick DJ-LGAD

Patent Application SC 2019-978 (UCSC)
- C.Gee, S.Mazza, B.Schumm, Y.zhao

New Approach: Deep Junction LGAD

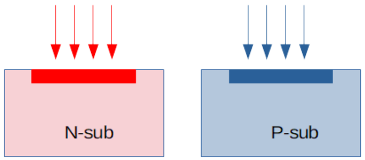
- The electric field along the depth of the sensor for different bias voltage is shown.
  - The multiplication/gain region (high field) is below the surface.
  - The addition of n type substrate bring the field down near the surface



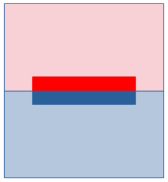
Current Stage of DJ-LGAD

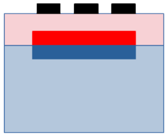
Design & Production Timeline

- **We are making progress toward producing the first prototype in collaboration with Cactus Materials Inc. (AZ)**
  - **The production is fully funded by the DoE SBIR “A New Approach to Achieving High Granularity in Low Gain Avalanche Detectors” (34b).**
  - **Wafer design is starting soon:**
    - Mask layout/design in a few weeks.
    - Finalizing parameters (doping, etc) during late Fall?
    - Have the first prototype by the end of the year.
  - **Single pad planer device will be produced in phase-1:**
    - **The deep junction will be attempted by wafer-to-wafer bonding.**
- **BNL also planned for production of first DL-LGAD prototype.**
  - **The deep junction will be attempted with epi growth approach.**
  - **Probably have the prototype within a year.**



Phosphorus (n++) and Boron (p++) implantation on low doped n and p type substrate correspondingly.


Wafer to wafer bonding.

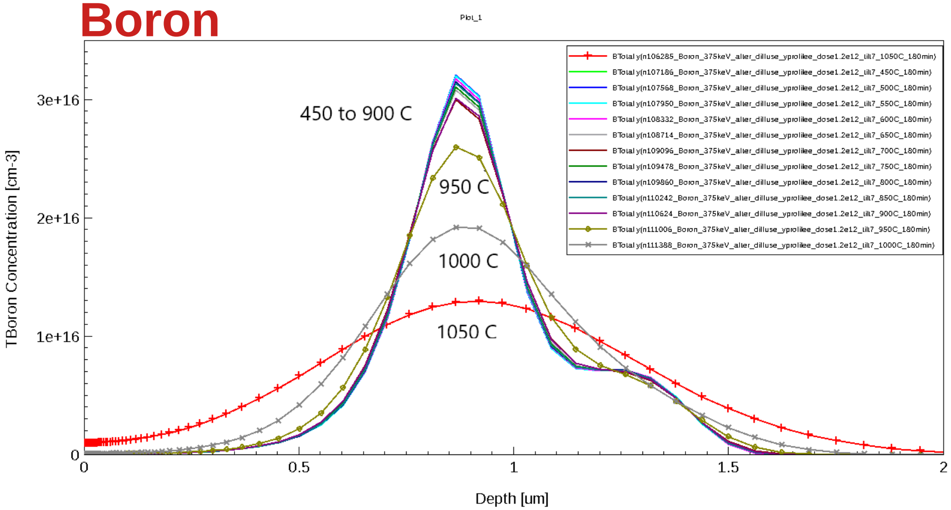

Etching the n substrate and putting electrodes and contacts

Current Stage of DJ-LGAD

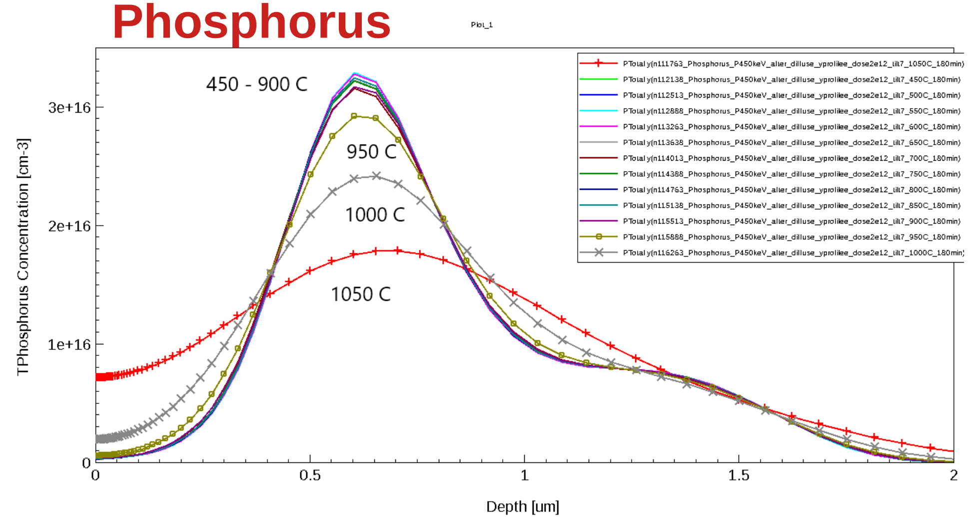
Implantation Energy, Annealing Temperature

- **Annealing step will be done at the stage of wafer to wafer boding.**
  - **No anneal step after implantation.**
- **Simulated annealing effect with different temperature for Boron and Phosphorus (3 hrs)**
  - **Maximum annealing temperature of 900C will be used.**
- **Example of simulated implantation energy:**
  - Boron : 375 keV → depth ~850nm, Phosphorus: 450 keV → depth ~600nm
- **Implantation dosage is still under study.**

Boron



Phosphorus

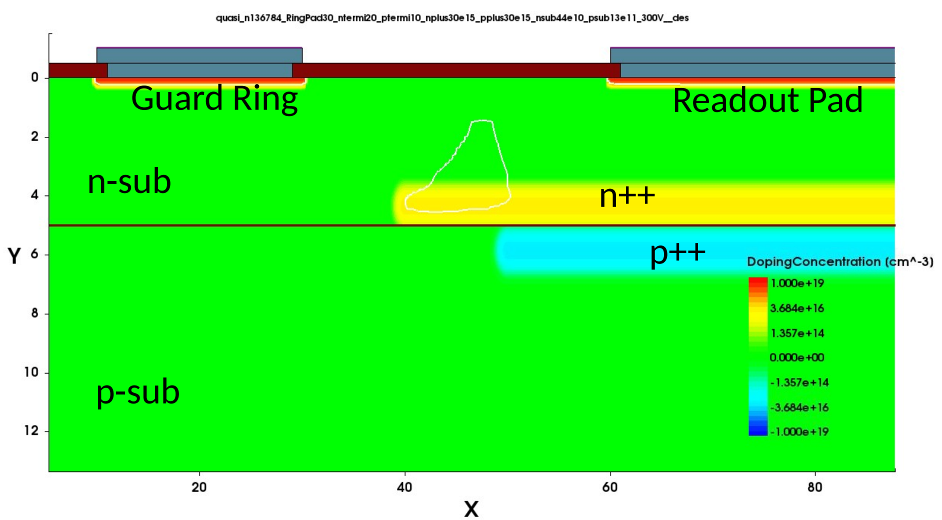


Current Stage of DJ-LGAD
Edge Termination

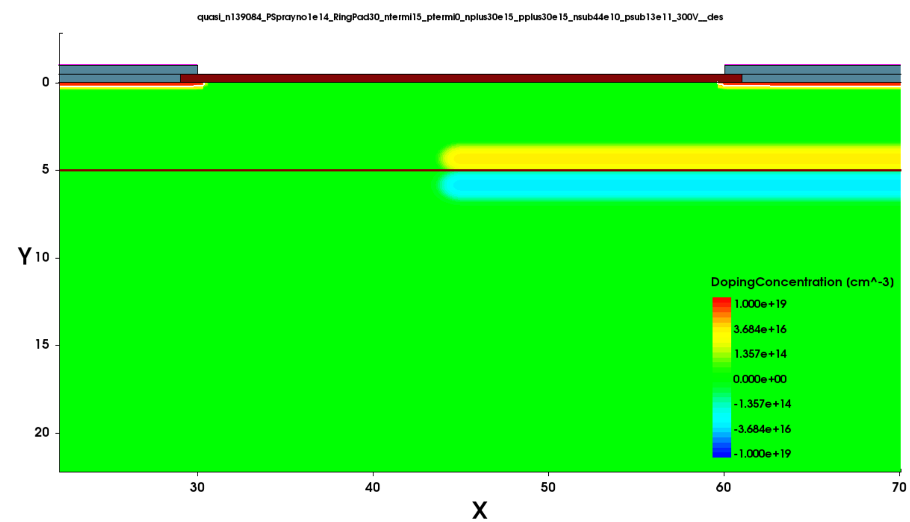
- The question of gain layer (n++ & p++) termination from the edge of the sensor was raised.
  - As suggested to avoid any possible high electric field region near the physical edge of the sensors to avoid early breakdown.
- We have proposed some possible approaches:
  - **Symmetric (right)** or asymmetric **(left)** n++ and p++ with limited lateral extension.

    e.g. the edge n++ and p++ is ~40µm away in X from the edge of the sensor.

Asymmetric termination



Symmetric termination



Current Stage of DJ-LGAD
Edge Termination

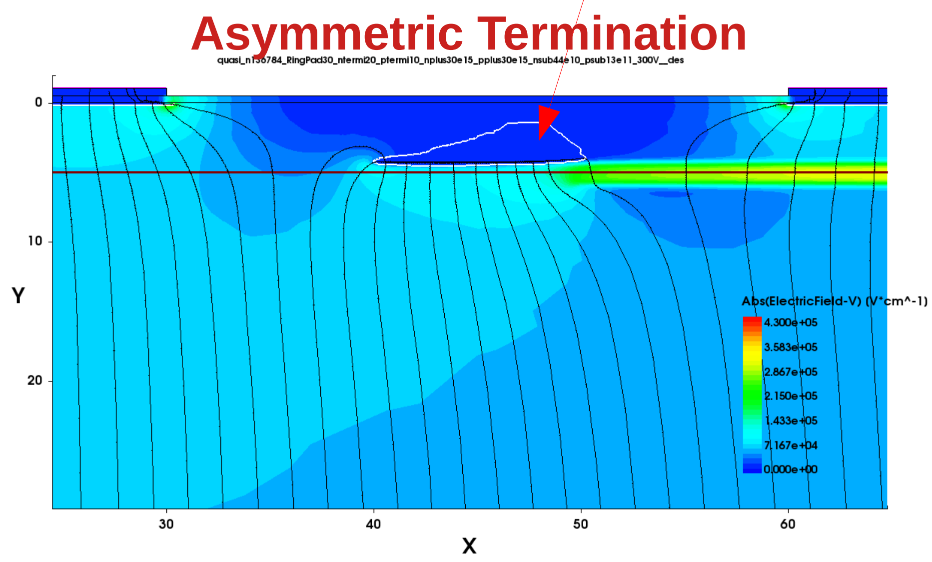
- **Example of 2D electric field map for these two configurations are shown:**
  - Color the indicates the value of abs(electric field)
  - The black lines are the electric field lines.

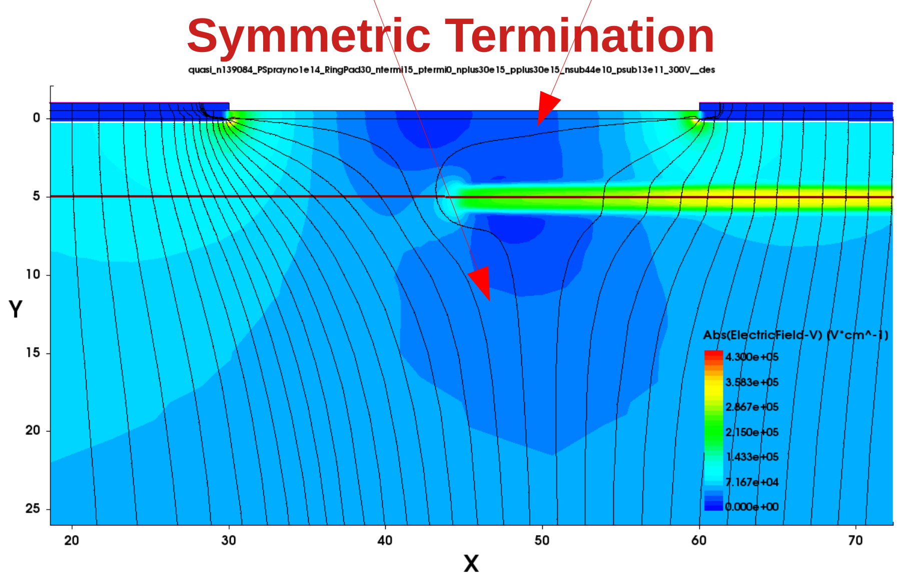
Asymmetric termination:

- **the region above the excessive part of n++ has very low field, and a small non-depleted region.**
- **No field lines across.**

Symmetric termination:

- **Lower field under the edge.**
- **Field lines are about to go around the edge.**

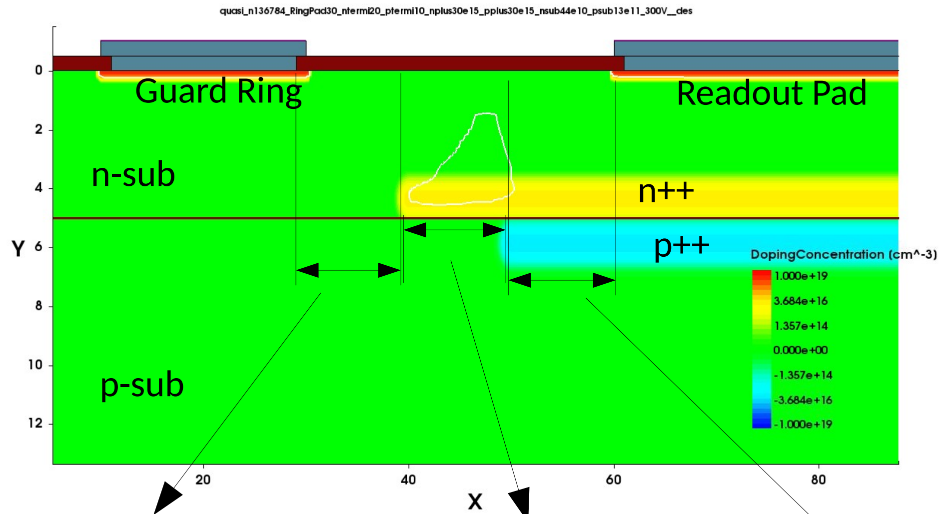




Current Stage of DJ-LGAD
Guard Ring to Pad Distance

- **Optimal Guard ring (GR) to pad distance, and the location of the gain layer termination are under investigation with simulation.**
  - **e.g. in the case of asymmetric termination, different distance of GR to n++, n++ to p++, p++ to pad are simulated. (see figure below for a 10/10/10 example)**
  - **Preliminary simulation studies show breakdown voltage varies with those parameters.**

Asymmetric termination



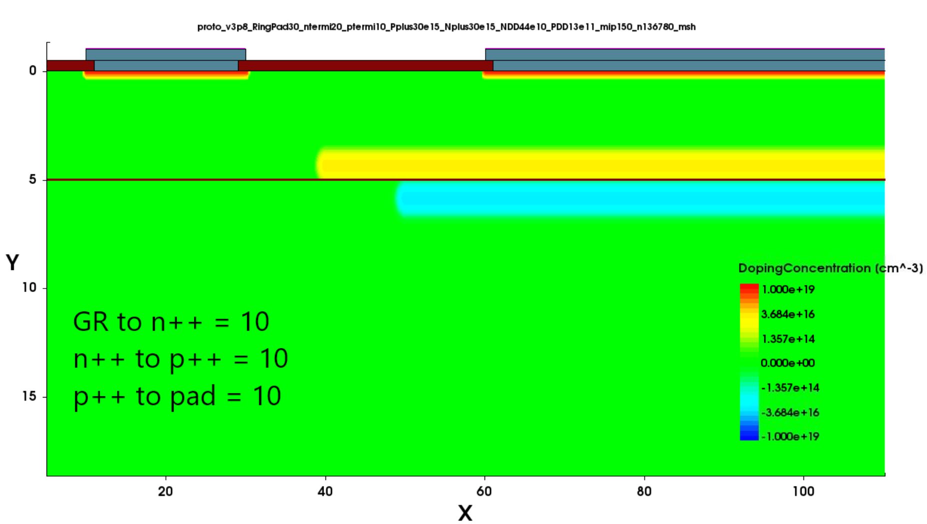
GR to n++ distance = 10um

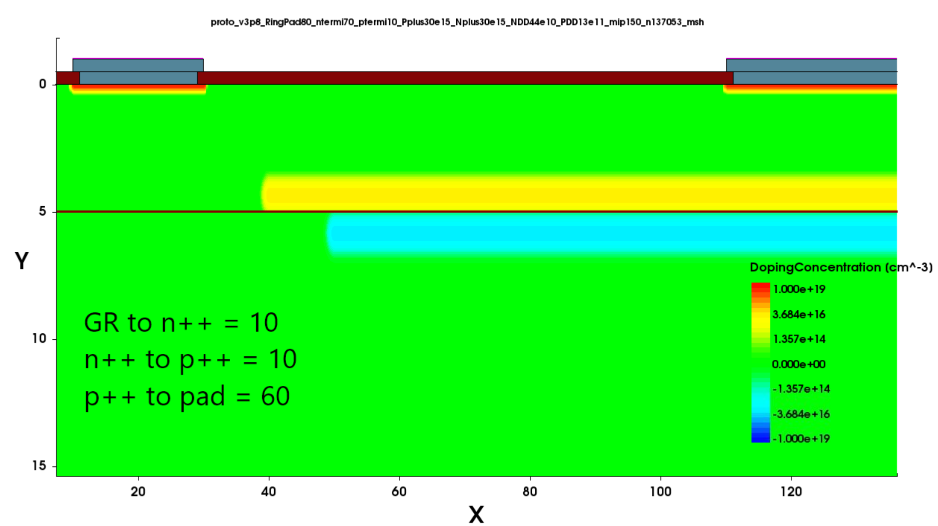
n++ to p++ distance = 10um

p++ to pad distance = 10um

Current Stage of DJ-LGAD
Guard Ring to Pad Distance

- Optimal Guard ring (GR) to pad distance, and the location of the gain layer termination are under investigation with simulation.
  - e.g. in the case of asymmetric termination, different distance of GR to n++, n++ to p++, p++ to pad are simulated. (see figure below for a 10/10/10 example)
  - **Preliminary simulation studies show breakdown voltage varies with those parameters.**
    - **For example, Simulation was done with 10/10/10 (30um of GR to pad distance) and 10/10/60 (80um of GR to pad distance) asymmetric gain termination configuration.**

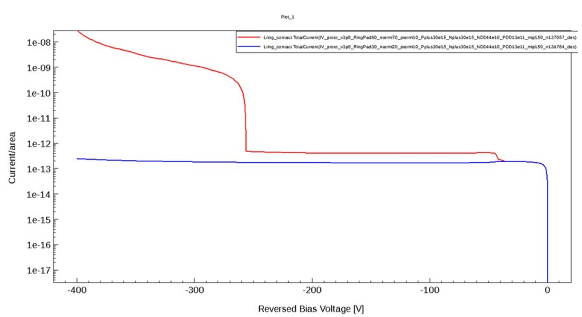




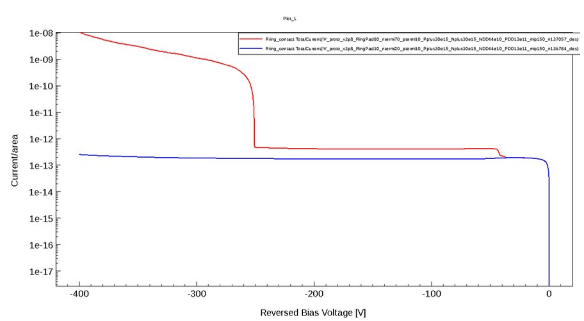
Current Stage of DJ-LGAD
Guard Ring to Pad Distance

- **Preliminary simulation studies show breakdown voltage varies with those parameters.**
  - For example, Simulation was done with 10/10/10 (30um of GR to pad distance) and 10/10/60 (80um of GR to pad distance) asymmetric gain termination configuration.
  - **I-V curve for the pad and left/right guard ring for these two configuration are different**
    - **10/10/60 configuration has a sign of early break down.**

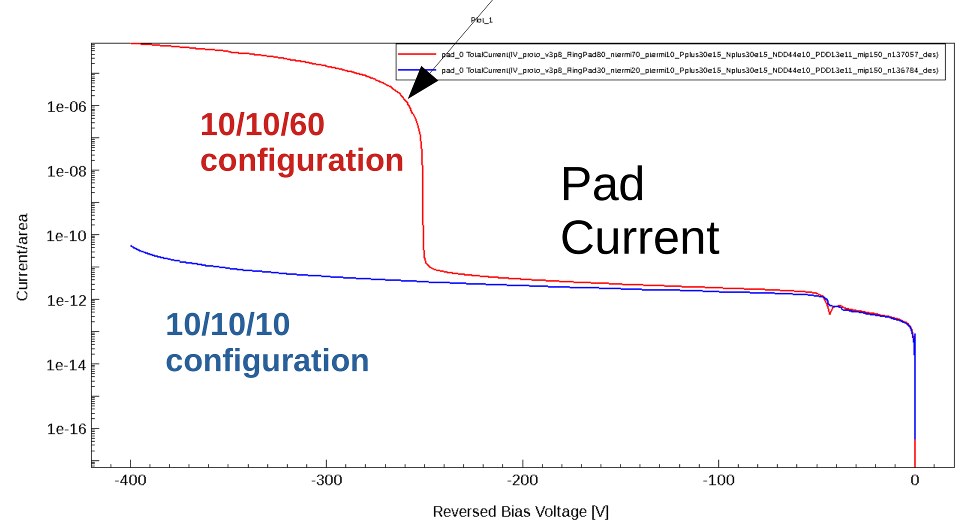
Left Guard Ring Current



Right Guard Ring Current



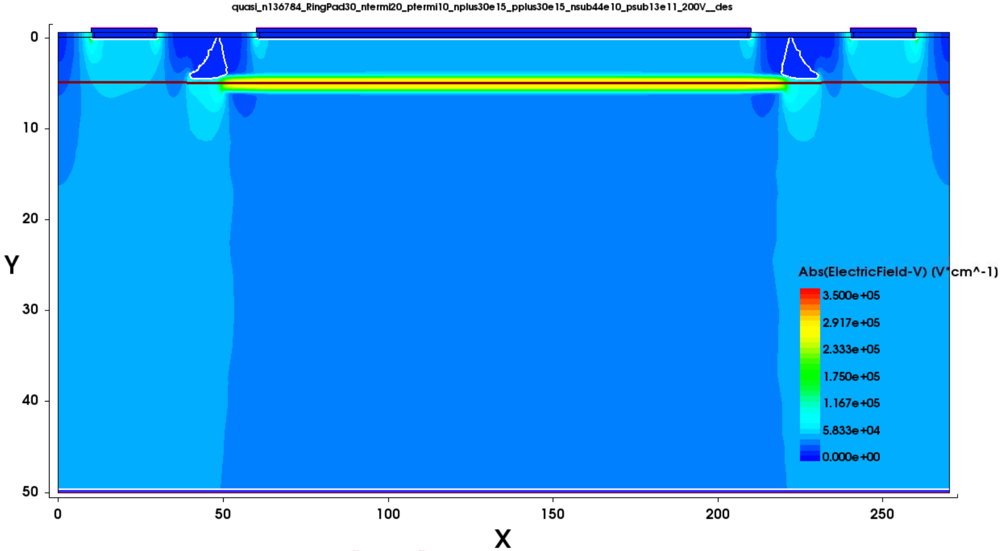
Voltage point of sign of breakdown



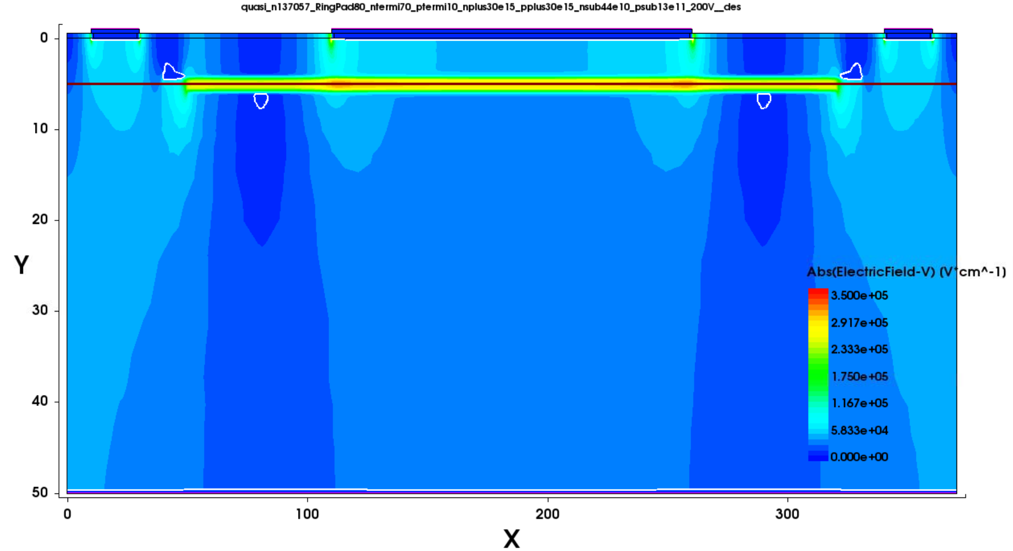
Current Stage of DJ-LGAD
Guard Ring to Pad Distance

- **Preliminary simulation studies show breakdown voltage varies with those parameters.**
  - For example, Simulation was done with 10/10/10 (30um of GR to pad distance) and 10/10/60 (80um of GR to pad distance) asymmetric gain termination configuration.
  - I-V curve for the pad and left/right guard ring for these two configuration are different

    10/10/60 configuration has a sign of early break down.
  - **2D electric map at 200V for these two configurations are shown**
    - **For 10/10/60 configuration, the field is lower in the GR-pad region due to large gap.**



10/10/10 configuration

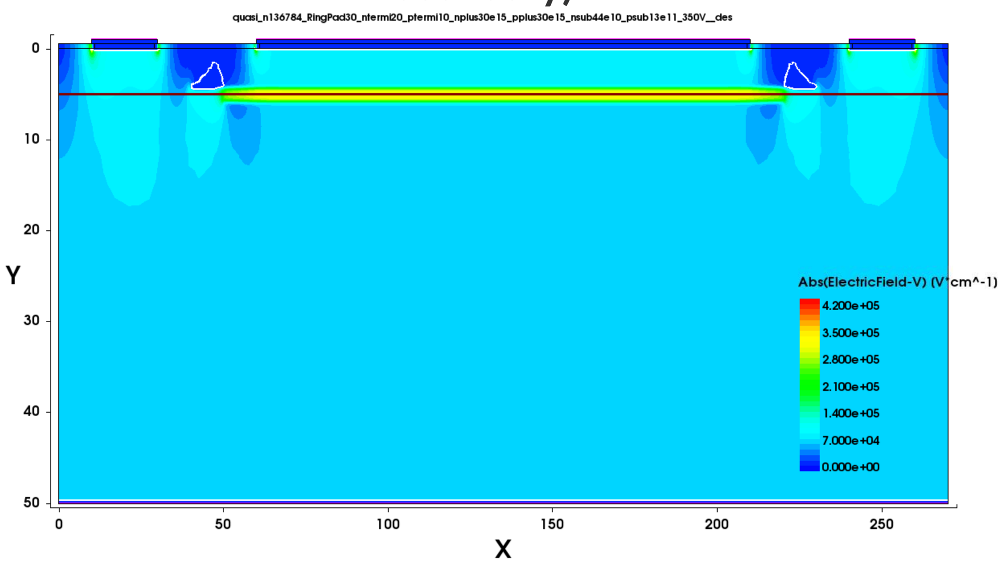


10/10/60 configuration

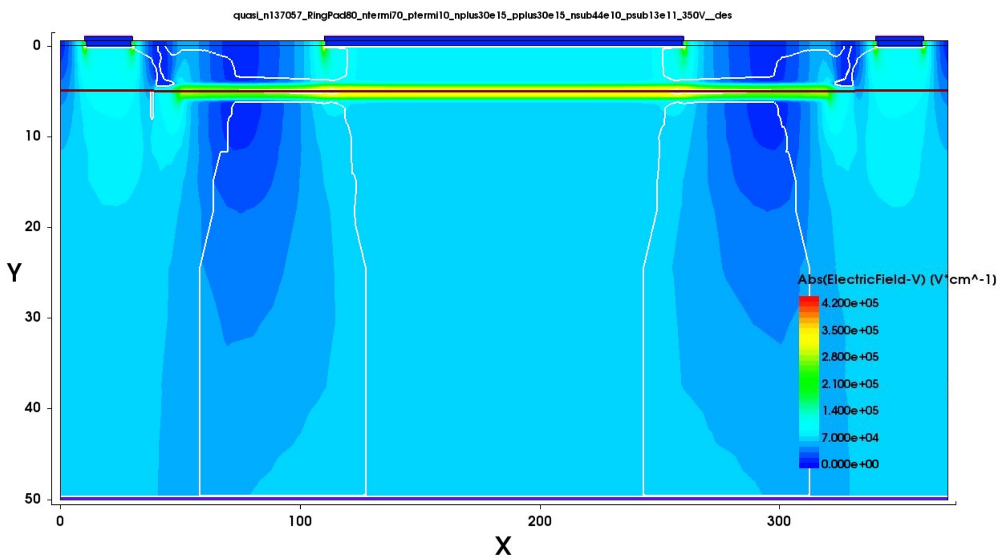
Current Stage of DJ-LGAD

Guard Ring to Pad Distance

- **Preliminary simulation studies show breakdown voltage varies with those parameters.**
  - For example, Simulation was done with 10/10/10 (30um of GR to pad distance) and 10/10/60 (80um of GR to pad distance) asymmetric gain termination configuration.
  - I-V curve for the pad and left/right guard ring for these two configuration are different
    - 10/10/60 configuration has a sign of early break down.
  - **2D electric map map at 350V for these two configurations are shown**
    - **As indicated in the IV, 10/10/60 configuration has indication of breakdown beyond 250V. There's strange depleted region within the sensor (surround by the white lines boundary)**



10/10/10 configuration

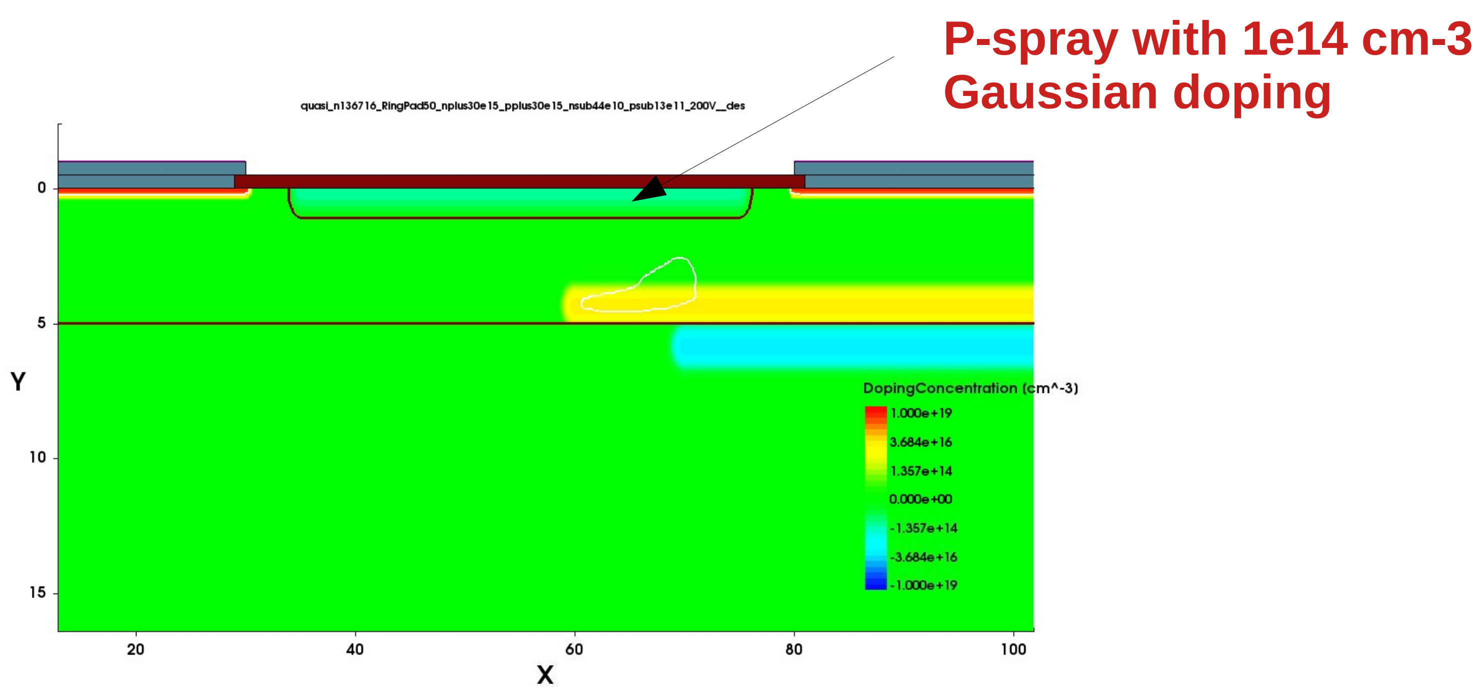


10/10/60 configuration

Current Stage of DJ-LGAD

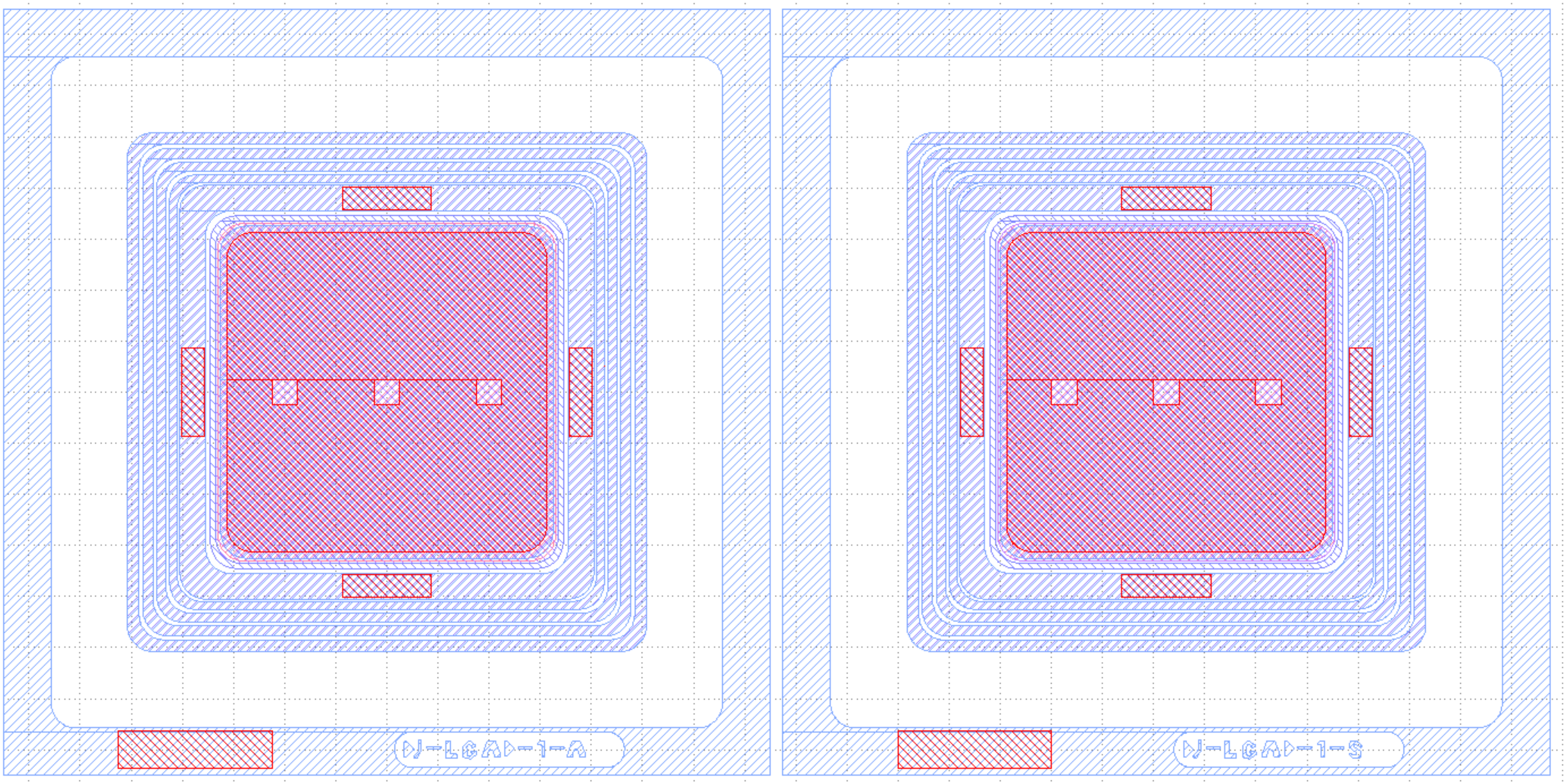
P-Spray/Stop Between Guard Ring and Pad

- Another simulation is to start looking into the adding p-spray/stop between the guard ring and the pad.
- A few parameters of p-spray/stop are requires more simulation studies:
  - P-spray/stop doping concentration level.
  - Width, or the distance between the p-spray and GR/pad.
  - Depth.



Current Stage of DJ-LGAD
Starting GDS Mask/Layout Design

- We are also working on the GDS layout with Cactus Materials Inc.
- Example of top surface layout is shown below.



Summary and Next

- Simulation studies are ongoing for phase-1 prototype production.
- The production with Cactus Materials Inc is fully funded by DoE SBIR, and the first prototype is expected as the end of the year.

- Next:
  - Mask and layout design.
  - Continue on simulation studies:
    - Replace gain layer analytic doping with implantation simulation
    - Optimize the implant dosage for fabrication.
    - Optimize the guard ring and pad distance, and the location of gain termination.

Acknowledgments

- **Institute of High Energy Physics (ihep, China) has provided helps on simulation.**

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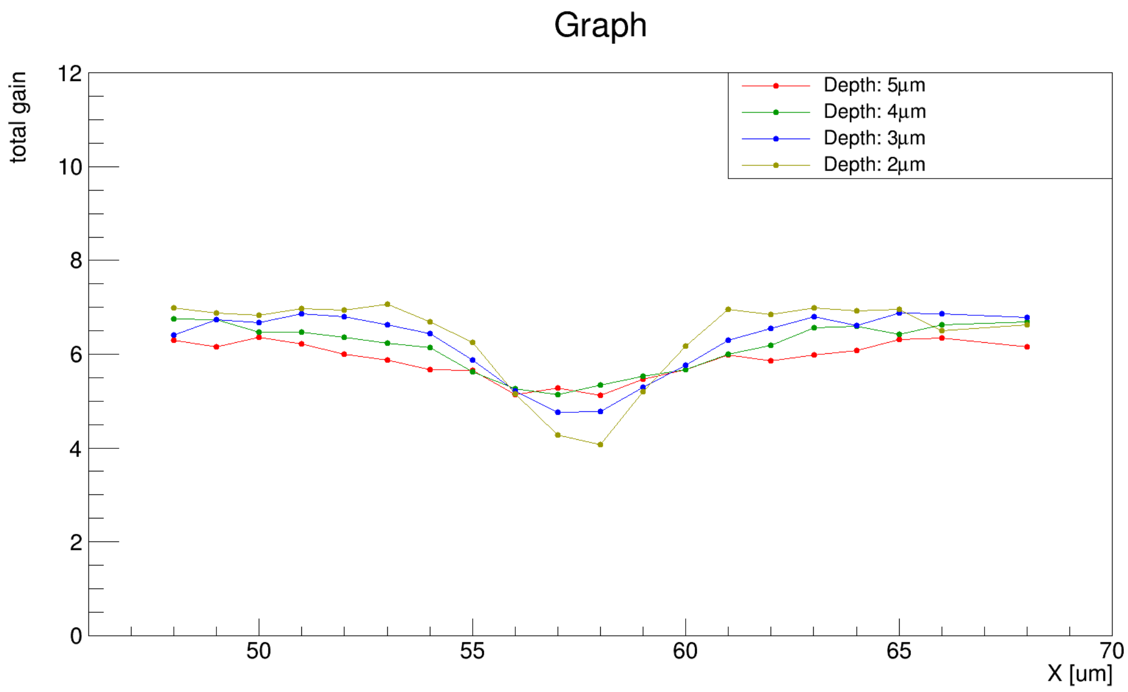
Backup

- **Junction depth.**
- **Choice of wafer resistivity.**
- **MiP induced signal for nearby pads in arrays.**

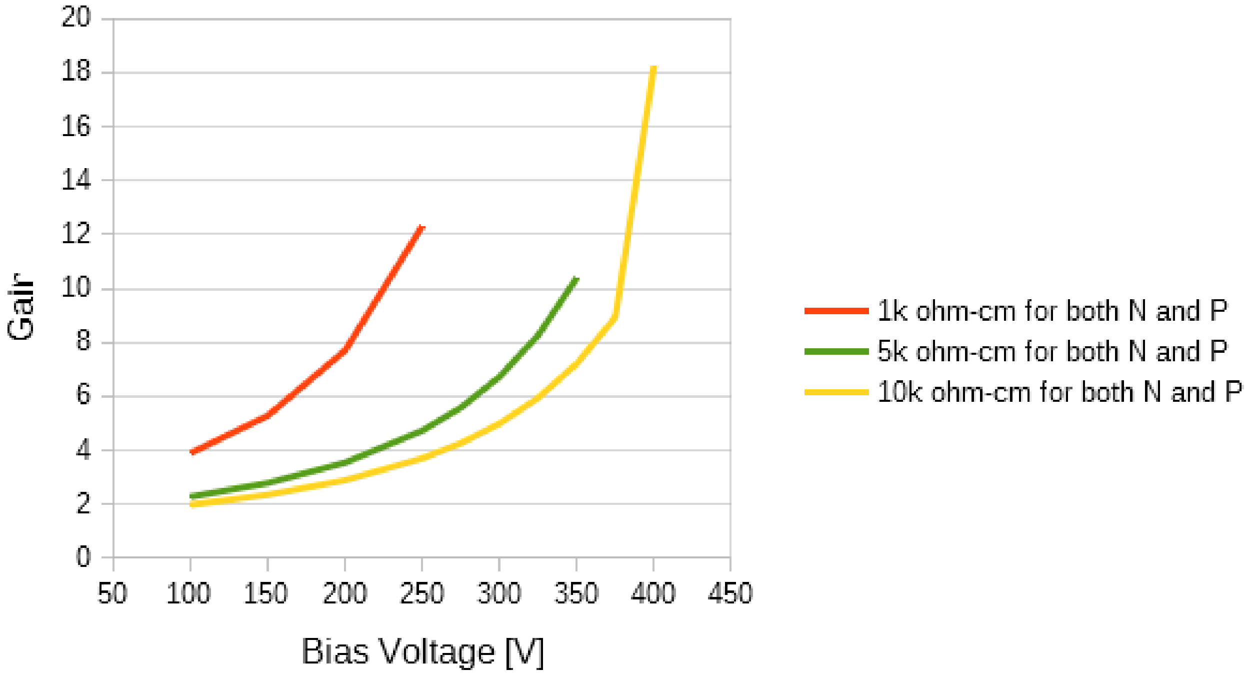
Current Stage of DJ-LGAD
Junction depth

- Some MiP simulations for pixelated structure have been done with different junction depths.
- The gain uniformity across pads seems to related to the junction depth.
- For the phase-1, junction with 5um below the surface will be produced.



Current Stage of DJ-LGAD
Choice of Wafer Resistivity

- **Wafer of resistivity of a least 1k Ω·cm for both n and p type substrate.**
- **10k Ω·cm or above will be used for the phase-1 prototype.**



Current Stage of DJ-LGAD
MiP induced signal for nearby Pads in Array

- **The plot shown is with original DJ-LGAD design.**
  - **MiP is injected into one of the pad of a pixelated/array setup.**