A New Approach to Achieving High Granularity in Low-Gain Avalanche Detectors (Phase II-NCE)

Rafiqul Islam, PhD. Cactus Materials, Inc. (PI)

Collaborator:
Bruce A Schumm, PhD. UCSC, Santa Cruz Institute for Particle Physics
Gabriele Giacomini, PhD, Brookhaven National Lab

Acknowledging the support of the US Department of Energy

CACTUS MATERIALS, INC.

SEMICONDUCTOR | PHOTONICS | FOUNDRY SERVICES

5G/6G

Advances in RF Power

Hybrid Microelectronics

III-V FOUNDRY

COMMERCIAL LEAP AHEAD TECHNOLOGY HUB

Integration of technologies with CMOS (3D Integration by wafer bonding)

Wide Band Gap Device Fabrication (Silicon Carbide)

AI HARDWARE

Advances in Materials and Fabrication Process

Advances in CMOS Integration of Novel Neuromorphic Materials

ELECTRONIC WARFARE

Fabrication   Packaging

PRODUCTS

DETECTORS & LASERS (Silicon, IR, VCSEL)

Radiation Hardened Microelectronics

FOUNDRY (Compound III-V, Silicon Carbide)

3D Hub: 3D Integration using Wafer bonding

FOUNDRY IN TEMPE, ARIZONA

PARTNERS & CUSTOMERS

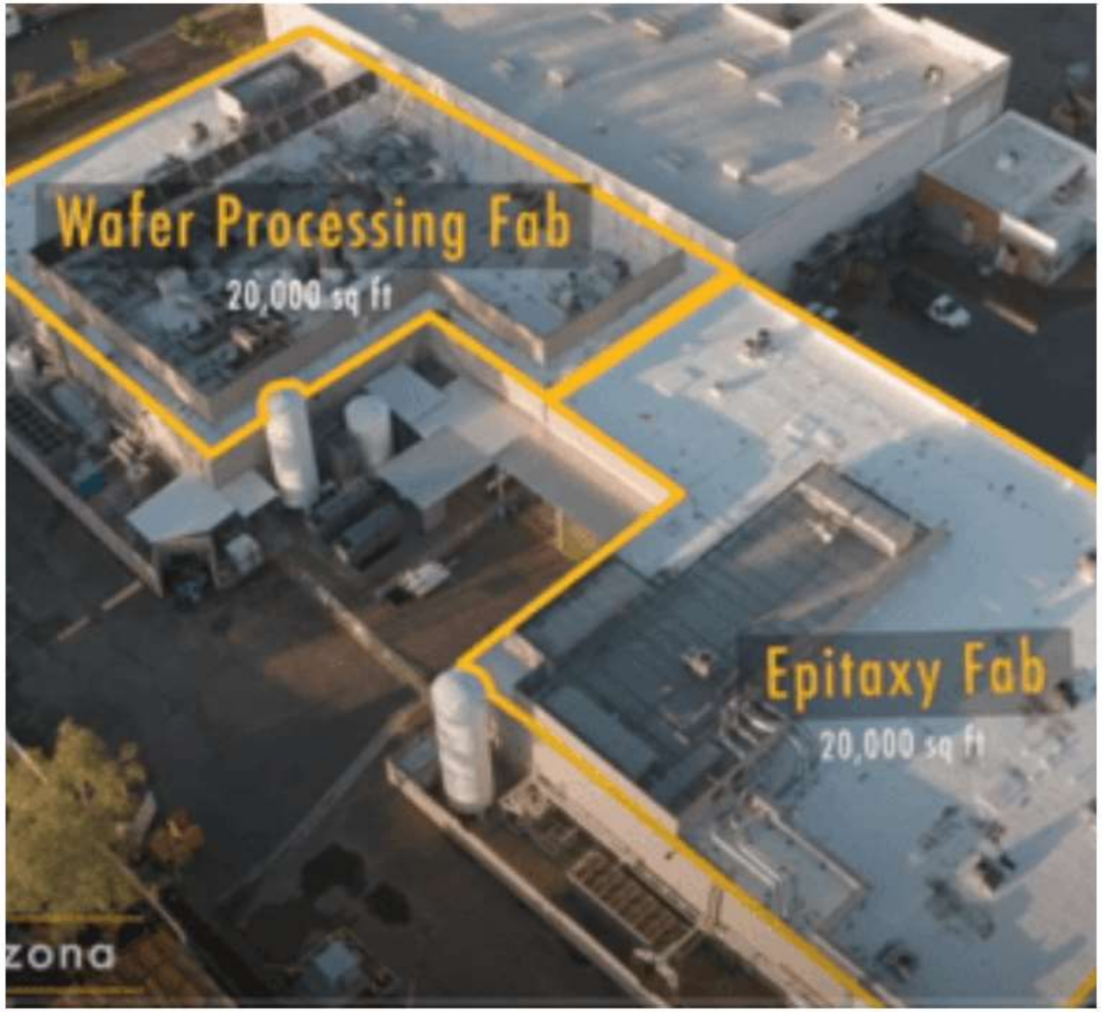
xfab, NASA, AIR PRODUCTS, Brookhaven National Laboratory, ASU, Fermilab, Veeco, JPL, Raytheon Technologies, GTS, Niterra, skywater, EUROQUARTZ, optiPulse

HIGH-VOLUME MANUFACTURING FACILITY

40,000 sq ft in total, 22,000 sq ft class 100 clean room

Click here to see the 6-minute video of our facility

Tempe Arizona facility



State-of-the-art 44,000 ft2 facility

Class 100 Clean Room

2 MBEs (Molecular Beam Epitaxy)

2 MOCVD (Metal Organic Chemical Vapor Deposition)

100+ pieces of advanced equipment & tools

Design, develop, and manufacture compound semiconductors

Appendix A - Facility

Facility acquired end of 2022

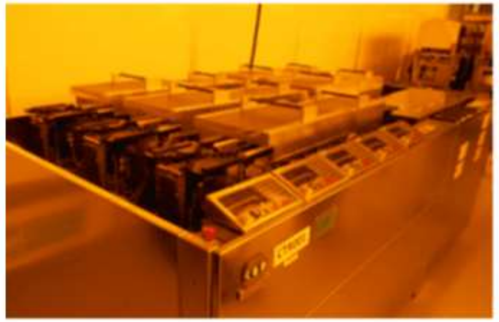
1 Veeco GEN2000 MBE

1 Veeco Dual GEN200 MBE

Appendix B - Facility

Expected DOD Trusted Supplier Q1 2024

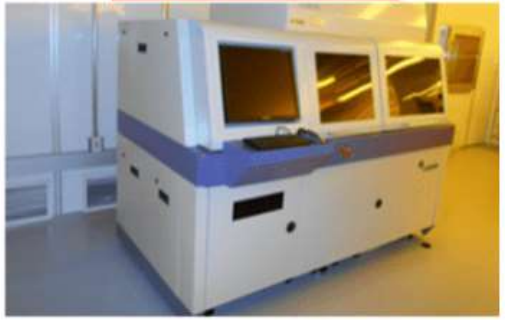
SVG 8600 Resist Coater



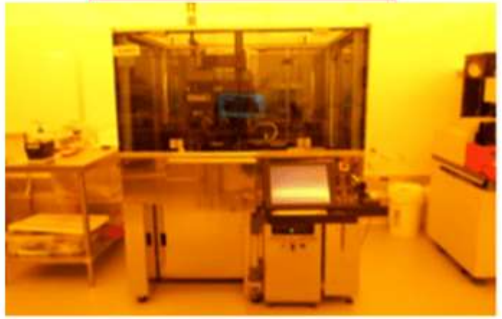
WaFab Acid Etch Hoods

Matrix SiO_2/Si_3N_4 RIE

Camtek Condor AOI



Karl Suss MA-150e Aligner



WaFab Solvent Liftoff Hood

CHA MK50 Metal Evaporator

Disco DFL7161 Laser Dicer

[Click here to see the 6-minute video of our facility]

Proprietary technology

71 patents issued
54 patents pending

This enables us to capture a large portion of the $4.1 Billion serviceable obtainable market.

We own the technology related to manufacturing process.
40 patents are U.S.A. patents.
The remaining are global patents which enable us to have complete control.

Leadership team

Rafiqul Islam, PhD,
CEO

Ron Elwood, CPA, CFO

Iqbal Ali, PhD

Andrew Schwinger
Director of Business Development

Terry Hales
J.D. General Counsel

Roger Spencer, M.S., MBA
Head of Sales

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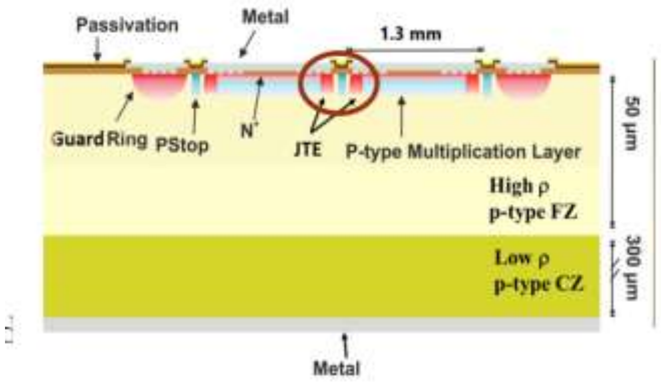
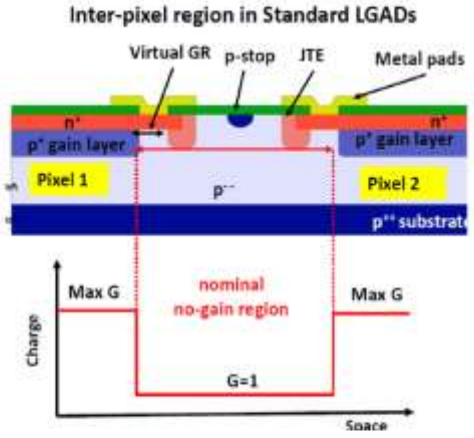
LGAD Arrays

- Granularity is a current limitation for LGADs
- Due to high fields in the multiplication layer the pads needs electrical insulation
  - Protection structure: Junction Termination Extension (JTE)
  - Causes inter pad (IP) gap to 50-150 um, also changes with applied bias voltage
  - Limits LGAD granularity to mm scale
- However, 50 um pitch (and lower) is required for next generation colliders and 4D tracking
  - At least some level as the ATLAS new inner tracker (ITK)
- **Several possible solutions are being investigated at Cactus Materials, Inc.**
  - Deep Junction LGADs (Current Phase II-NCE)
  - Radiation Hardened AC LGADs
  - Trench Isolated LGADs
  - Double sided inverted LGADs
  - Focal Plane Detector

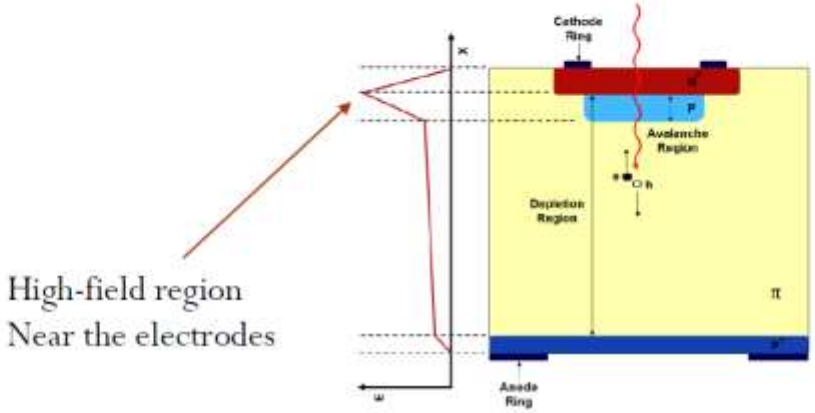


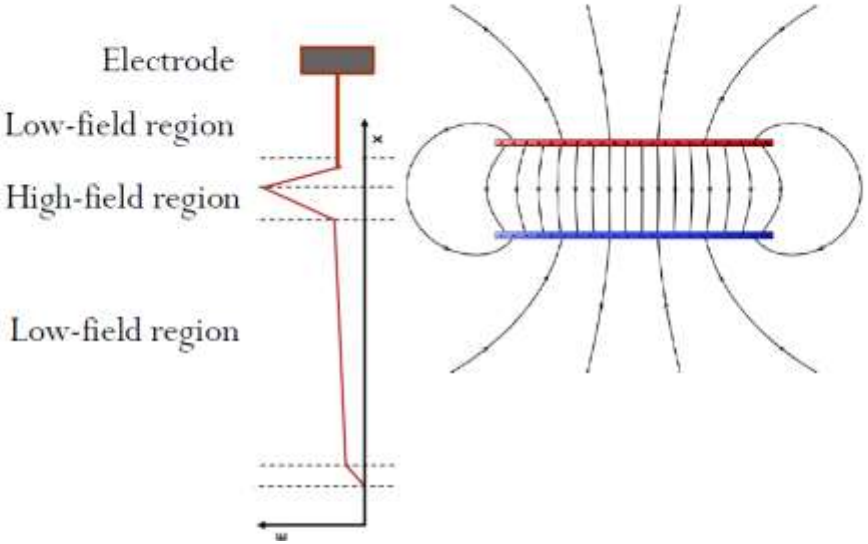


Picture Credit: FBK, Trento, Italy

A new approach: Deep Junction

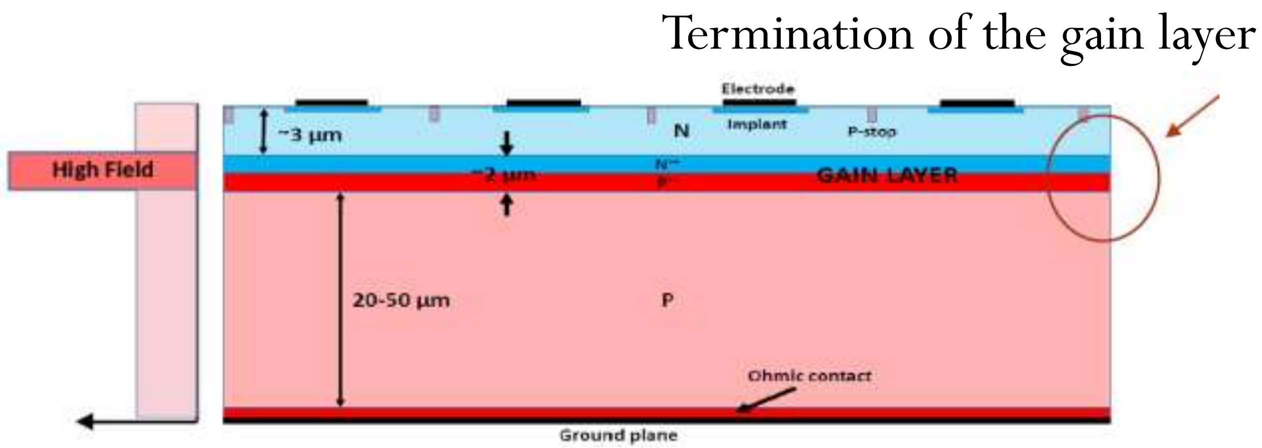
- Granularity limit caused by high field near the electrode
  - What if the field is kept low while maintaining gain?
- Basic inspiration is that of the capacitive field
  - Large between plates, but surrounded by low field regions beyond the plates
- Use symmetric P-N junction to act as an effective capacitor
- Localized high field in junction region creates impact ionization
- Bury the P-N junction so that fields are low at the surface allowing conventional granularity

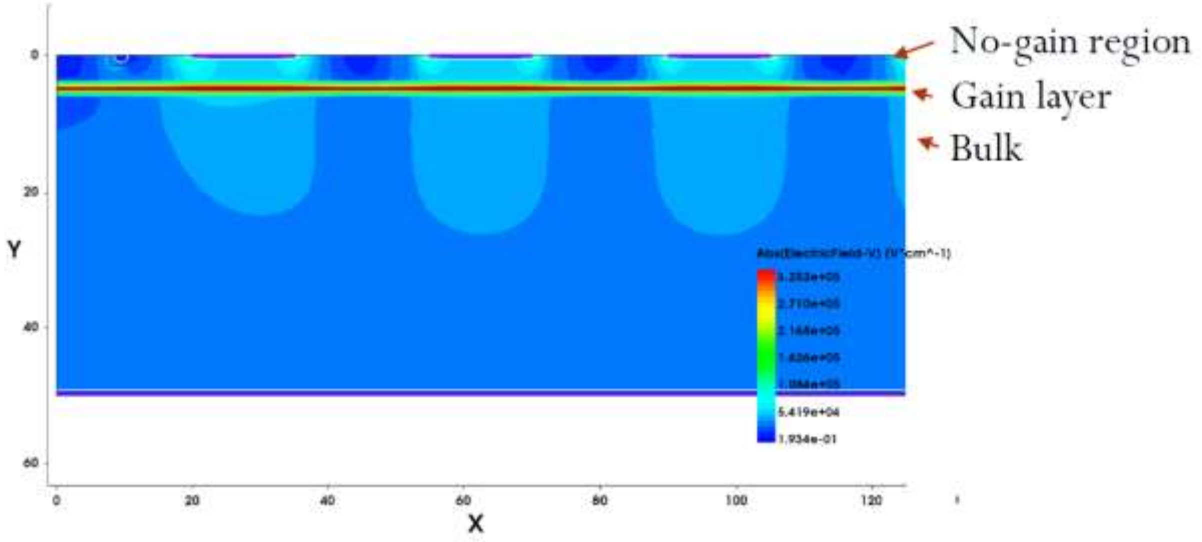




A new approach: Deep Junction

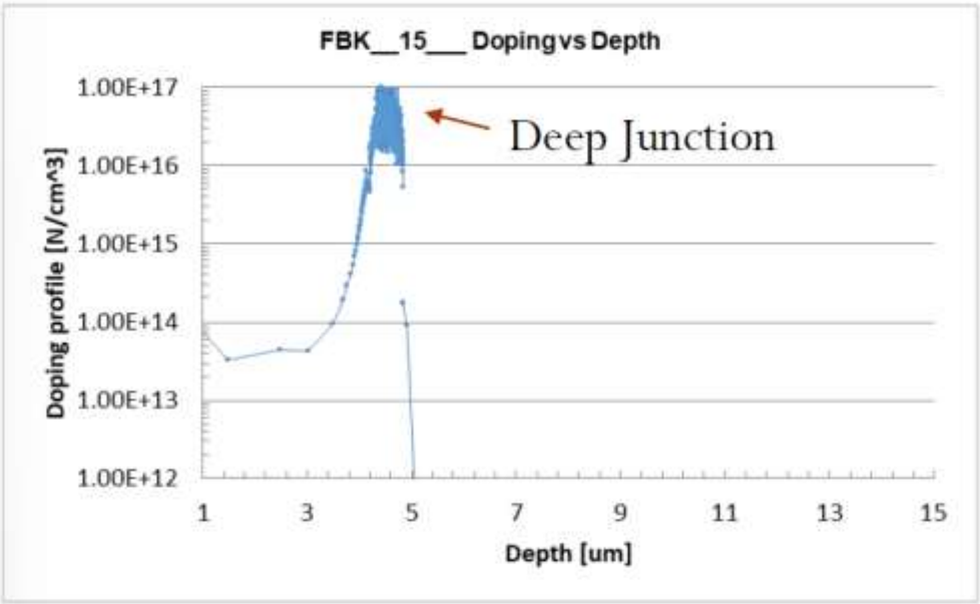
- P++ gain layer paired with a N++ layer that lowers the field
    - Junction is buried ~5 um inside the detector
- Tuning of N+ and P+ parameters important
    - Low field outside of the electrodes while maintaining sufficient gain
    - No need for a JTE
    - Different termination of the gain layer designed
- DJ-LGAD design studied with TCAD Sentaurus
- Production is ready to deploy at Cactus





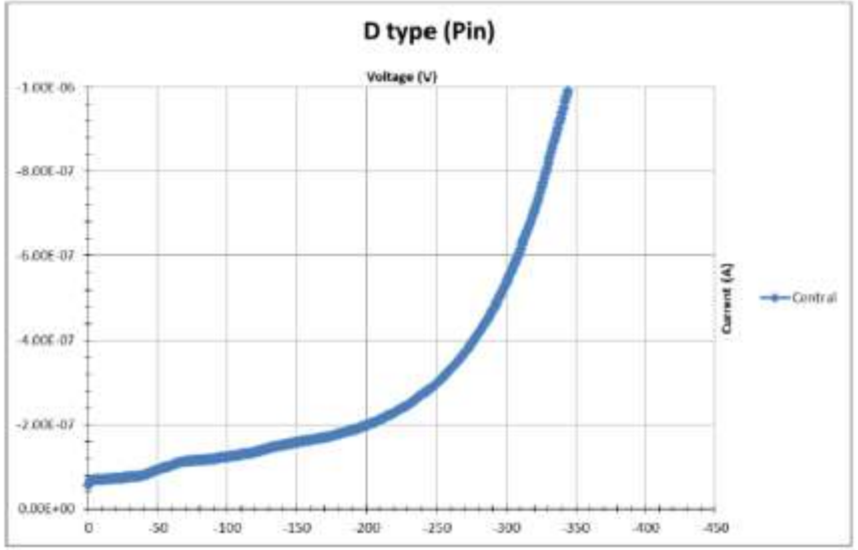
A new approach: Deep Junction

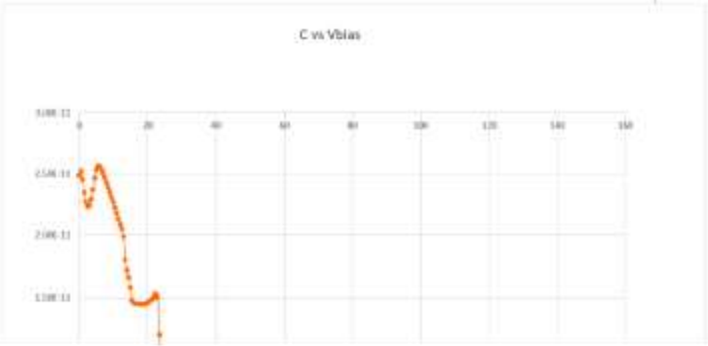
- Prototypes were performed in both epitaxy and wafer bonding(w2w) approaches:
- Prototypes can fully deplete and show gain
- 2x1 arrays were produced and show minimal IP gaps
    -

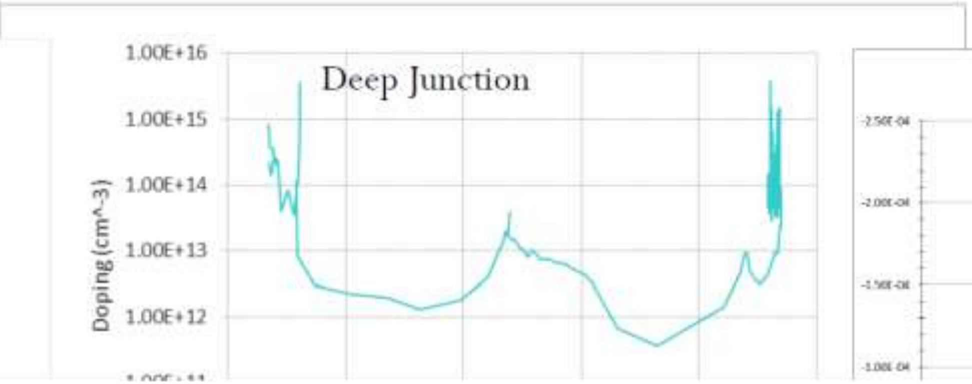


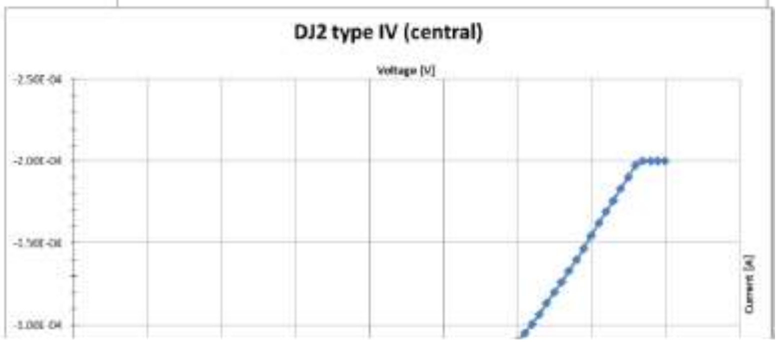
DJ-LGAD: Results

- D-type, standard PiN with deep junction, Current <1uA
- DJ-type, deep junction ending below the active area, High current (100s uA
  - The sensor is also very noisy, not usable
- DJ2-type, deep junction ending under the Guard ring,
  - Manageable current (10s uA), BV seems to be very high
  - CV shows deep junction structure, thickness seems higher than expected
- DJ3-type, 2x1 array, termination as DJ2, Manageable current (10s uA)



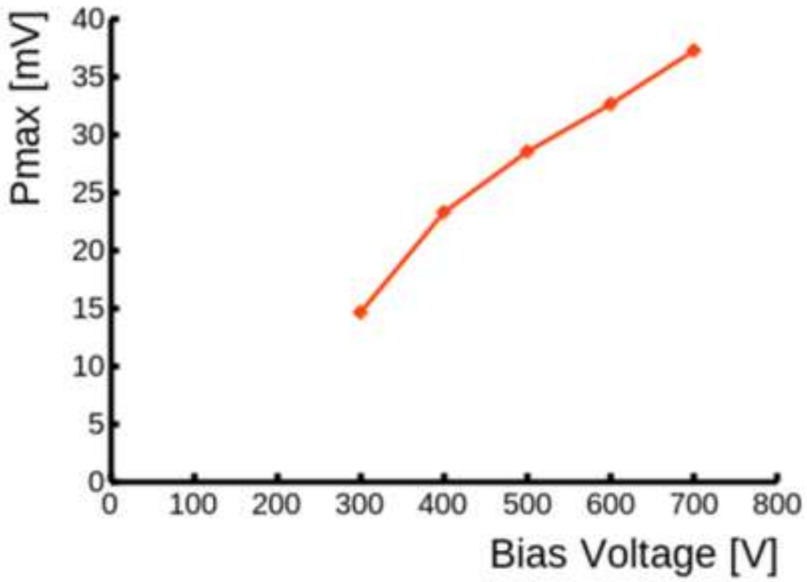


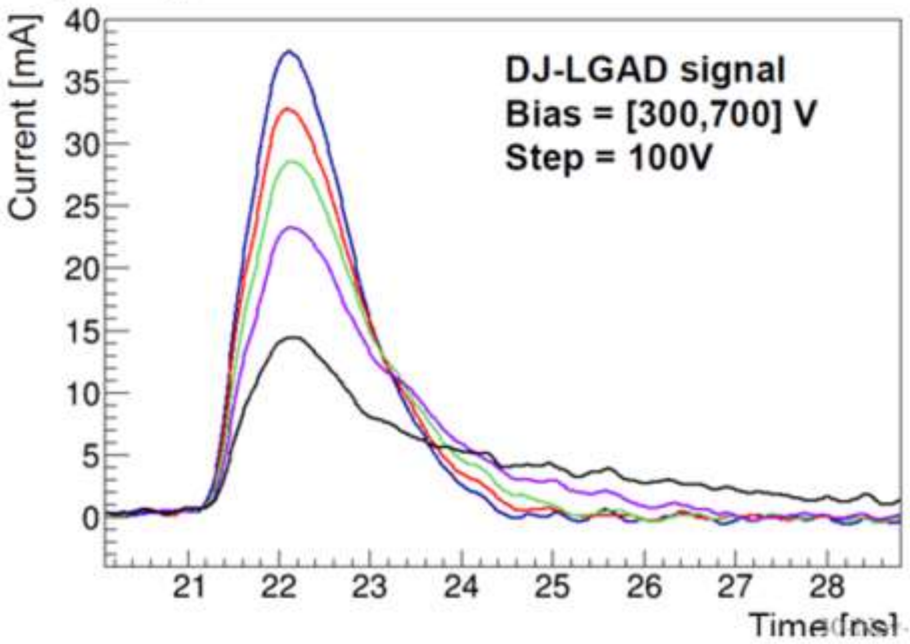




DJ-LGAD: Charge Collection Studies

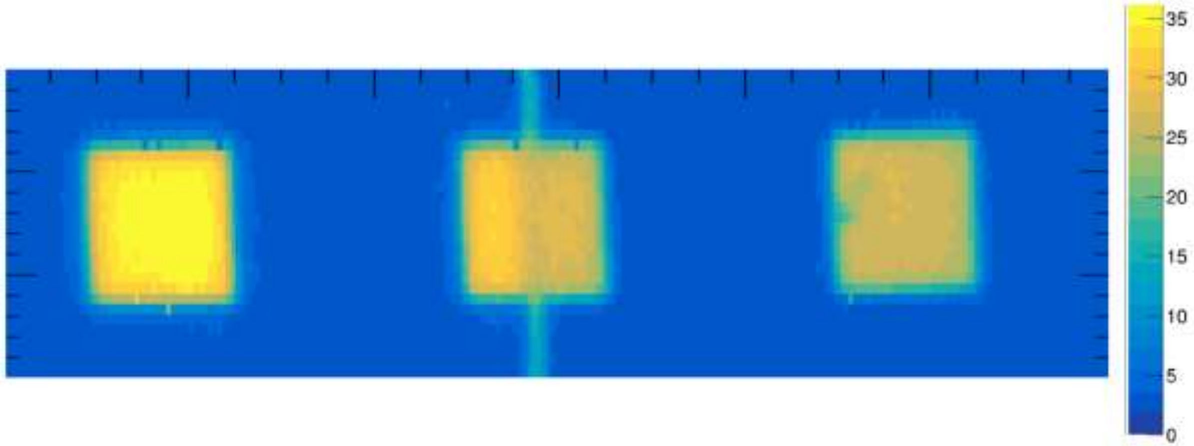
- Sensor mounted on UCSC 1ch and 4ch board, test with Sr90 source with know trigger sensor to study MiP response
  - Read out by fast oscilloscope, trigger on the trigger sensor
- **Rise time ~ 580 ps, similar to a typical 50-60um LGAD,** Breakdown >700V
- **Measured gain of ~ 3 to 5**
  - Lower than conventional LGAD
  - Optimization of the gain layer doping is required for future prototype

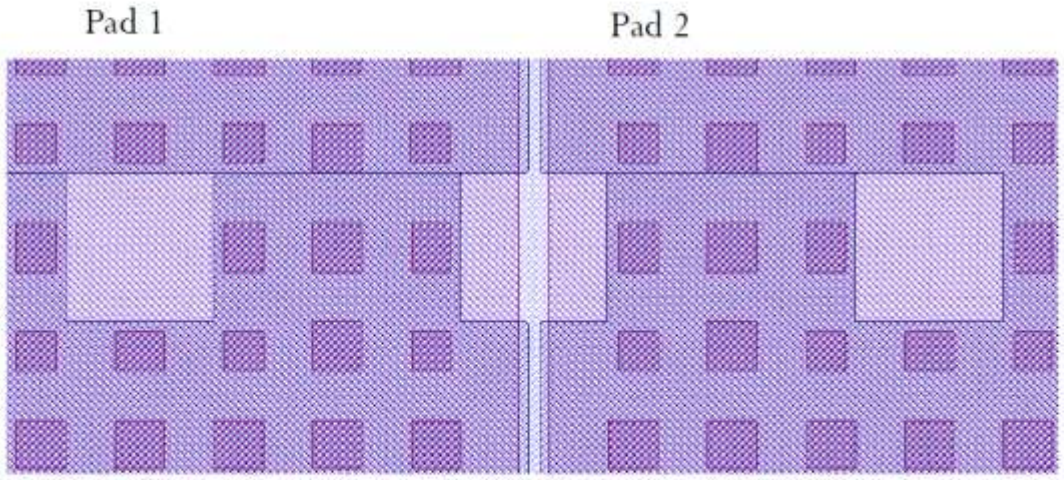




DJ-LGAD: Laser Studies

- **DJ-LGAD 2x1 array prototype is studied with IR Laser scan**
  - Digitized by fast scope, laser spot size is 10-20 um
- Pmax values in terms of the laser beam location are shown for sum of channels
  - Sensors have 3 open areas in the metal, one in each pad and in between pads
  - In the scan the blue low signal region corresponds to the metal
  - The sum of the two signals is more or less constant on the sensor (no gain loss in between pads)



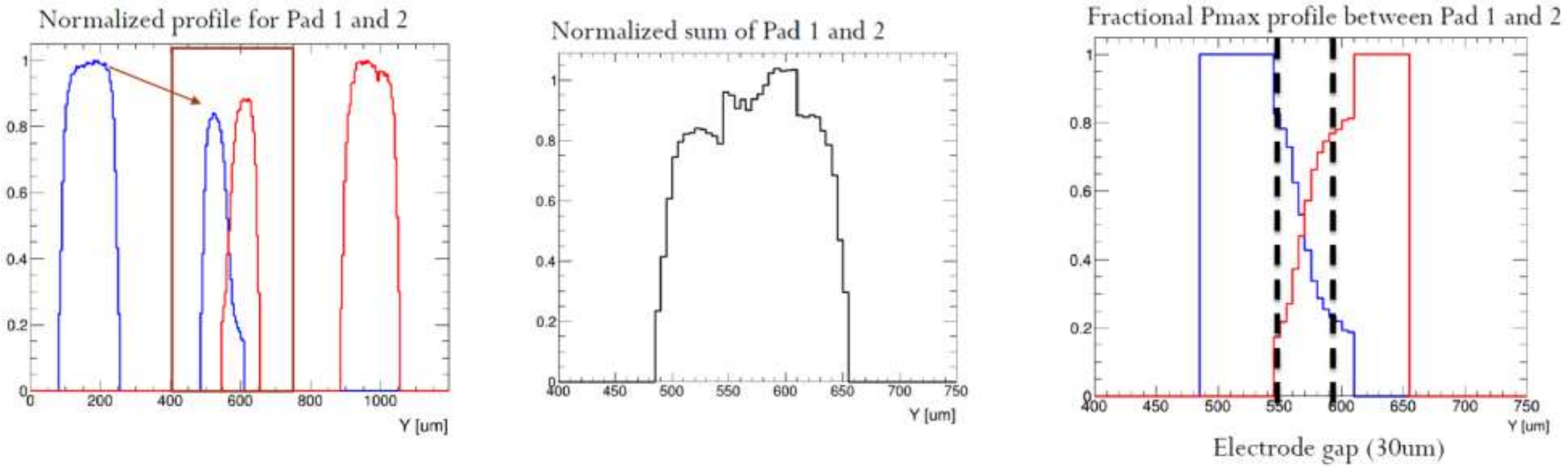


DJ-LGAD: Laser Studies

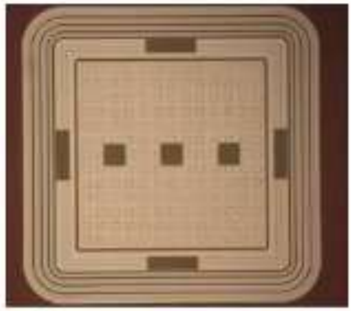
- **1D profile fractions shows a slightly lower signal next to the gap**
  - 2D simulation shows the field in the gain layer is reduced in the inter pad region
- Zoom in the inter pad region (nominal electrode gap is 30um)
  - Sum of signal show almost no reduction in the gain
  - Minor cross talk in a 50 um region between pads

The pmax fraction of an individual strip is defined as:

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



Application Ecosystems



Cactus Materials Device

OEM Relationships

Nuclear Physics & HEP

Electron-Ion Collider (EIC)

X-ray imaging with high frame rate

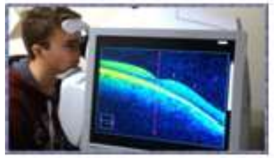
4D tracking

Medical Imaging (ex. PET)

CMS

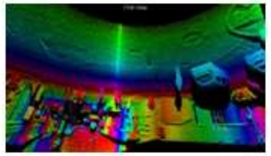
ATLAS

Potential Consumer



Medical / Cosmetic

Optical Comm. Data Centers



Defense

Scaling

- Looking to raise fund for scaling:
  - $5M for silicon detector production ramp-up – Q4, 2023
    - Uses: Working Capital
- Cactus Materials, Inc. secured facility for high volume production
  - Detector production and eliminating supply chain and manufacturing bottleneck in-house manufacturing
- Strategic partnership:
  - Defense contractors; DOE contracts
  - System validation with partners

Customers

U.S. DEPARTMENT OF ENERGY

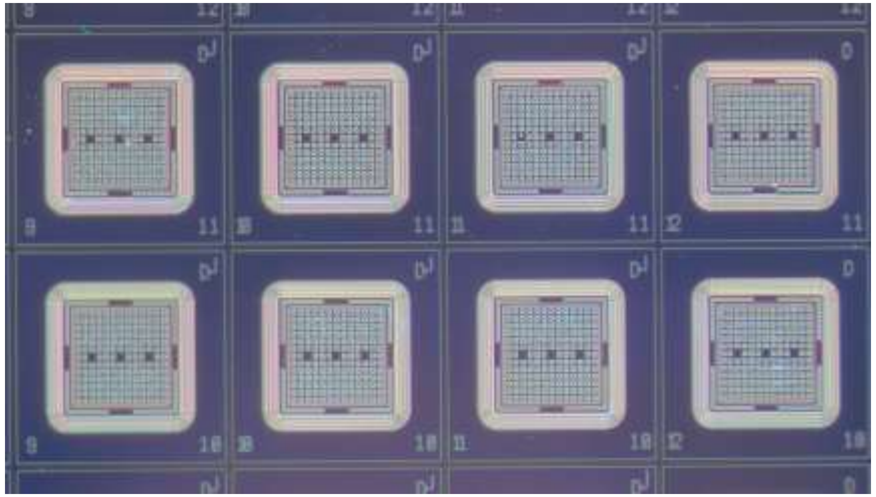
NASA

Defense customer

- <u>Explore</u> contract to provide chips/wafers to DOE and other national/research labs around the world
- Other potential defense and commercial customer engagement are in progress
- Strengthening business development by focusing on commercial applications.
  - Distribution model (Thor Labs, Edmund Optics, OSI)
  - Direct specific customers require customized products

Conclusions

- DJ-LGAD: a device with deep gain layer
  - Avoid high field near the electrodes while maintaining gain
- Demonstrated that the deep-junction can be fabricated with epitaxial growth and w2w wafer bonding
  - Shows very good signal/charge uniformity across the channels
  - Almost no IP-gap is present between pads, small cross talk
- Future production will address
  - Very large leakage current -> reduce the current to level of conventional LGADs
  - The gain is lower than conventional LGADs -> optimize the doping
- This transformational technology can be used for many types of devices
  - Cactus's Materials Inc. wafer bonding capability can be extended to other absorber High-Z materials (III-V materials; GaSb, GaAs, InP)



THANK YOU

Cactus Materials, Inc.

www.cactusmaterials.com

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