# Deep Junction LGAD

RD50 November 18, 2021

**S. Ayyoub[b], W. Chen[c], C. Gee[a], G. Giacomini[c], R. Islam[b], S. M. Mazza[a], S. Mony[b], B. A. Schumm[a], A. Seiden[a], Y. Zhao[a]**

*[a]The Santa Cruz Institute for Particle Physics and the University of California, Santa Cruz, California, 95064*
*[b]CACTUS Materials, Inc., Tempe, Arizona, 85284*
*[c]Brookhaven National Laboratory, Upton, New York, 11973*

# Traditional LGAD

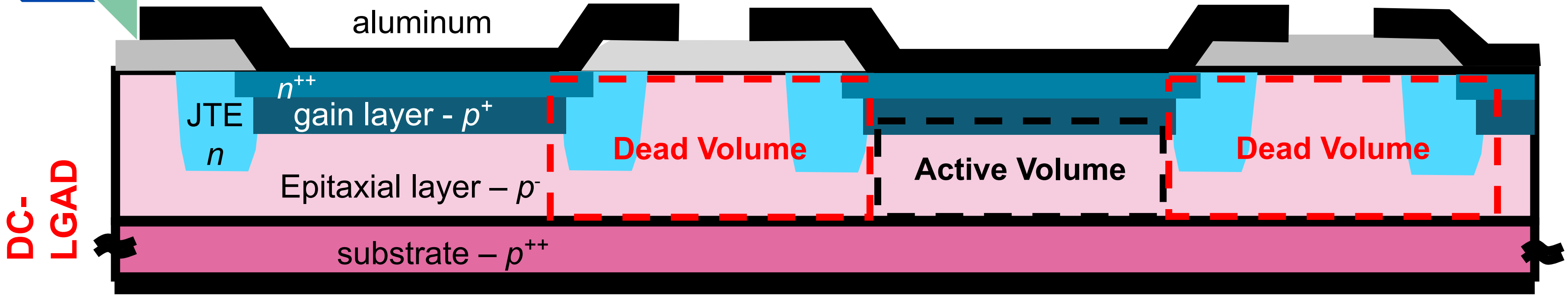
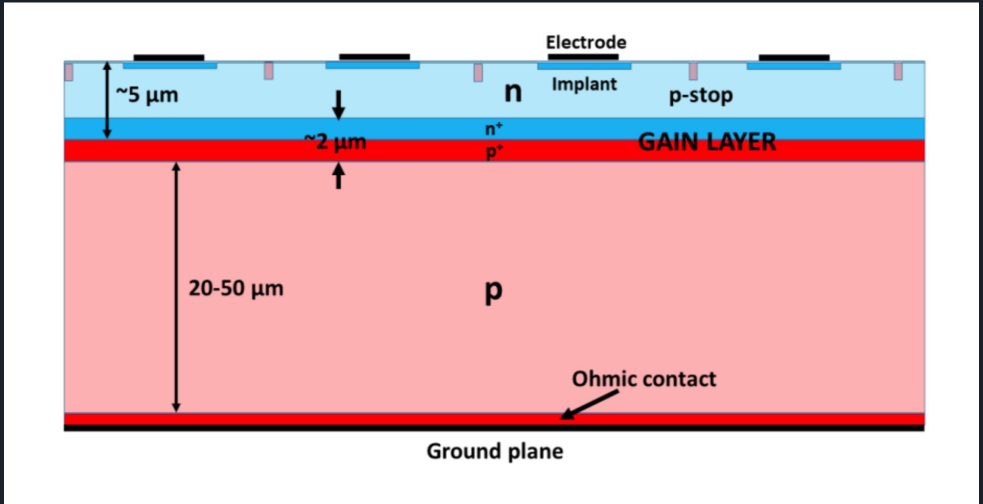



Diagram credit: BNL

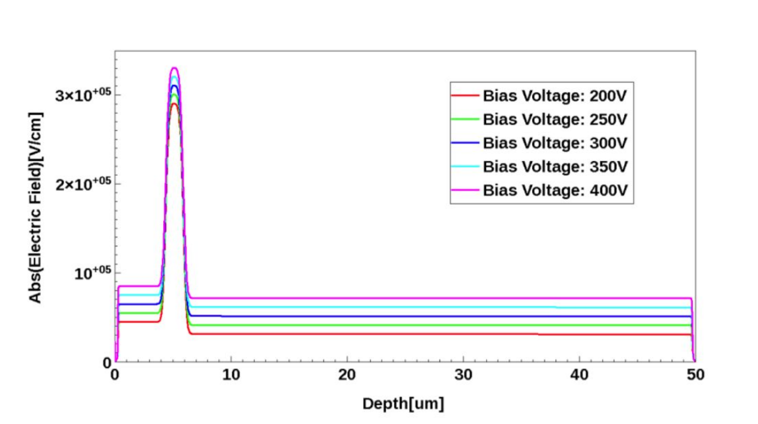
- Use "Junction Termination Extension" (JTE) to avoid breakdown between neighboring pixels
- Result of JTE is 50-100 um "dead volume" between channels
- LGAD granularity limited to millimeter scale

# Deep Junction LGAD (DJ-LGAD)

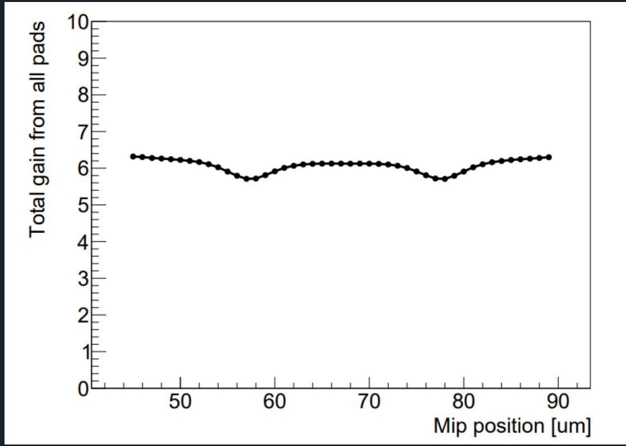



- Advantageous to bury high p-n junction several um below the surface of the sensor so fields low at surface, allowing conventional granularization
- Electric field in p-n junction is high enough to maintain drift-velocity saturation
- Maintains fine granularity on order of tens of microns
- Preserves direct coupling of signal charge to readout electrodes

# TCAD Simulations



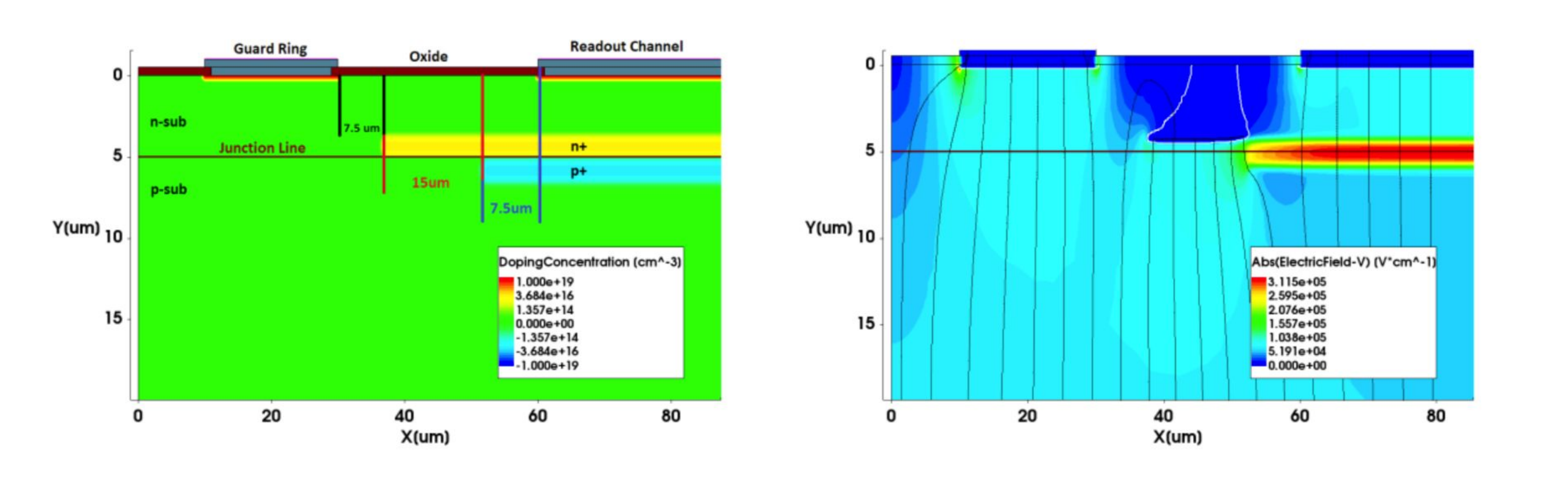

- Simulated electric field strength through the center of a channel as a function of applied reverse bias voltages
- Highly-doped n+ and p+ gain layers generate the peak region
- n-type diffusion region and p-bulk regions generate the lower field regions




Plots created by Y. Zhao

- Simulated pixel array with 20 um pitch
- Total sum of gain from all channels in terms of transverse position of incidence of a mip
- Uniformity across channels is within 5%

# TCAD Simulations




Simulations created by Y. Zhao

- Simulated doping profile cross section (left) and simulated electric field map (right) for the DJ-LGAD junction termination scheme
- Junction termination needed at edge of structure to avoid breakdown
- "Dead volume" only ~50 um at edge of sensor, and not between channels

# Fabrication Techniques for Achieving a Deep Junction

## Wafer-wafer Bonding (Cactus Materials)

- Create n+ and p+ gain layers on separate wafers via ion implantation
- Develop p-n junction gain layers using wafer-wafer bonding techniques

## Epitaxial Growth (BNL)

- Deep junction is created on conventional wafers used for LGADs
- Grow a 5 um thick p-type high resistivity epitaxial layer
- Implement n+ strip and pixel electrodes, DC-coupled using aluminum

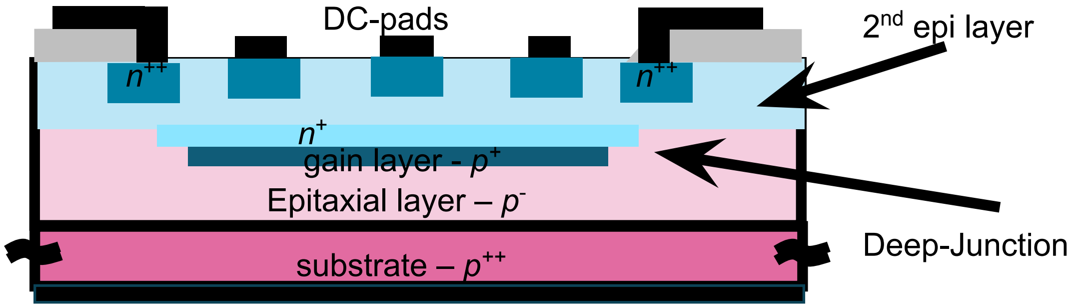
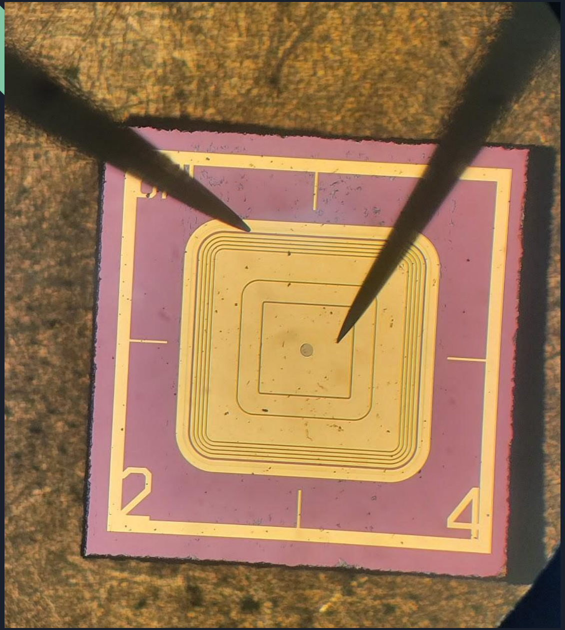
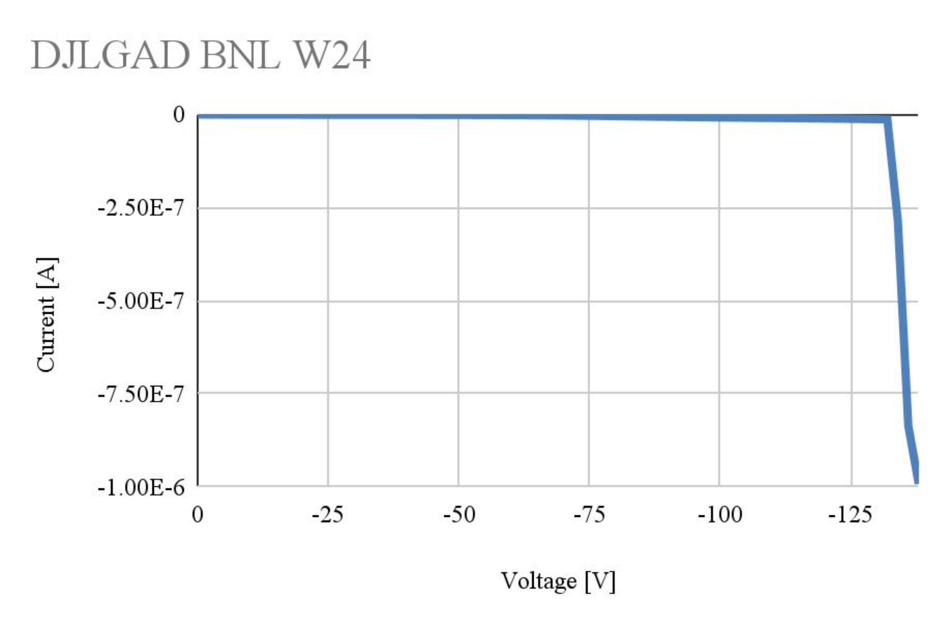



Diagram credit: BNL

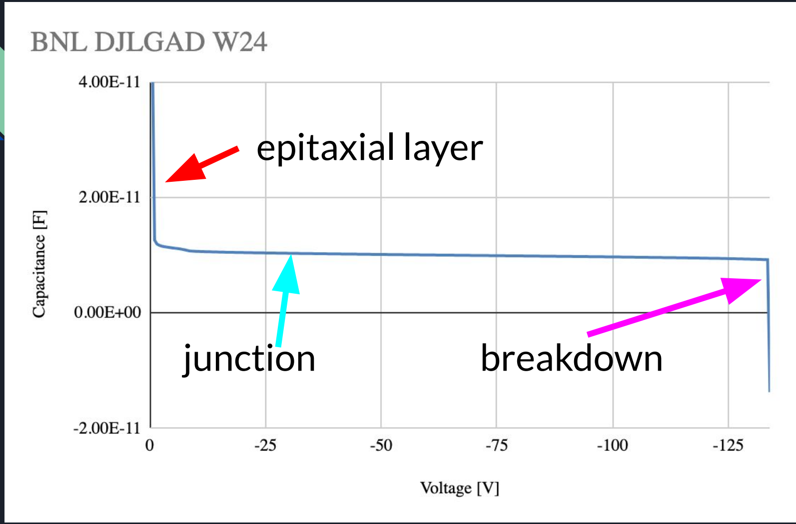
# BNL DJLGAD: IV measurements

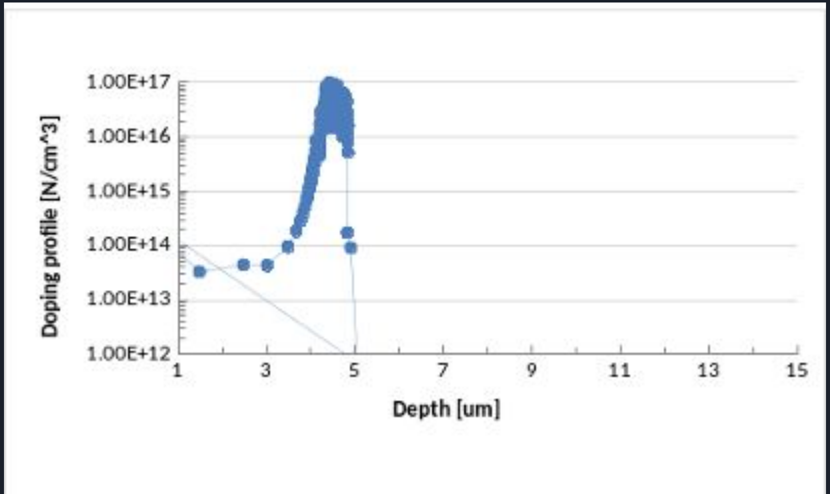





- Low current, but early breakdown: $V_{bd}$ ~ -130 V
- Consistent IV behavior between different wafers

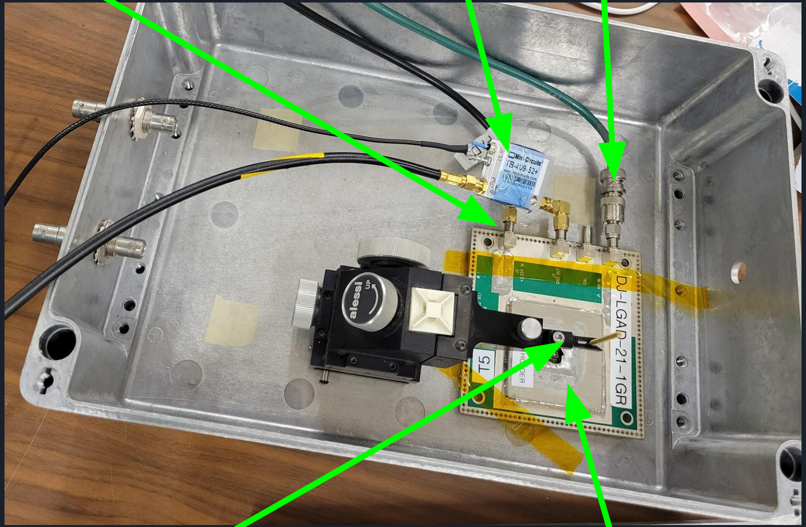
# BNL DJLGAD: CV measurements



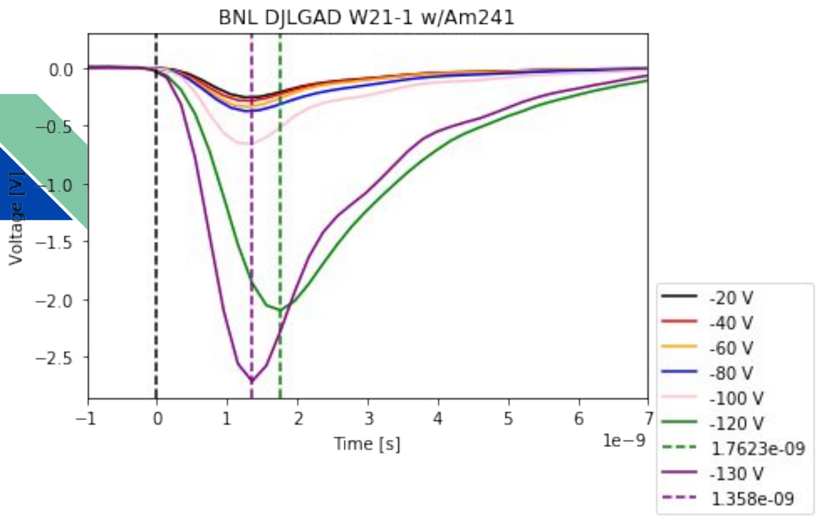



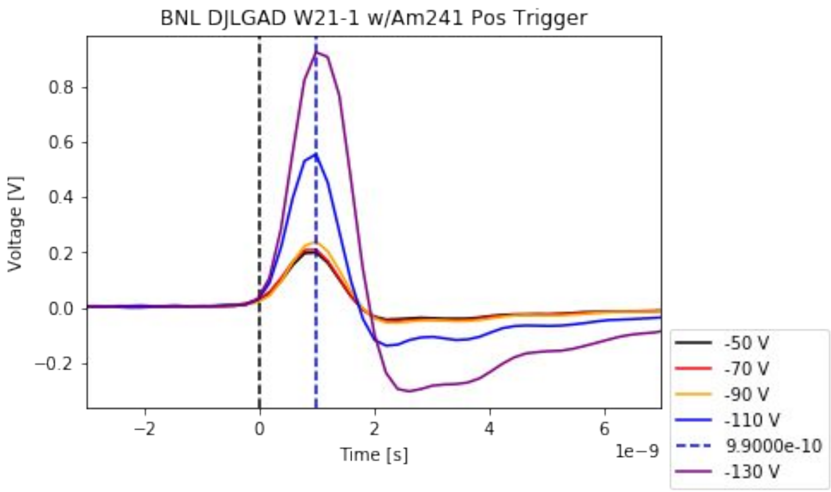

- Capacitance gives width of depletion region
- See sharp behavior from epitaxial layer in first few microns of sensor at low voltage, then slower in junction until reaching breakdown
- Can see in doping profile that breakdown occurs before junction fully depletes
- Field is too high and we starting 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

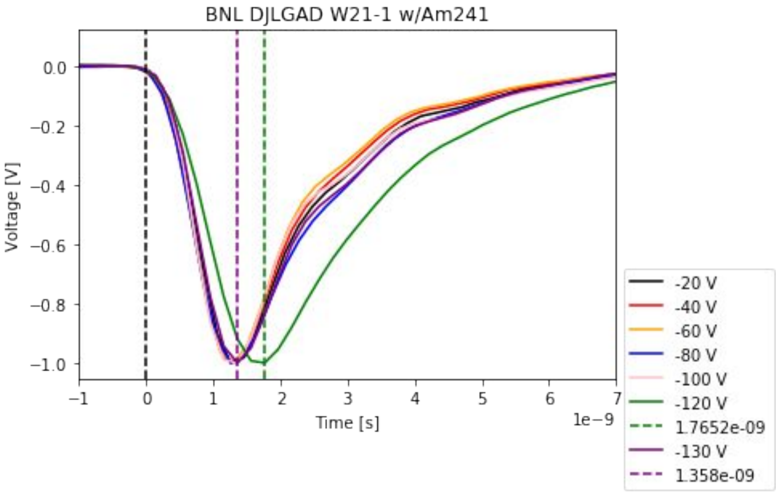
# Am-241 Source Measurements




- Mounted DJ-LGAD on read out board to measure sensor pulses on an oscilloscope with Am-241 source
- Vary bias voltage down to -130 V




- 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

# Conclusion and Future Plans

- DJ-LGAD burys the p-n junction several microns below the surface of the detector, with the goal of maintaining fine granularity
- First measurements taken on BNL-fabricated DJ-LGAD show that the sensor is breaking down before depletion due to too high of a doping concentration
- Cactus Materials is in the process of fabricating DJ-LGADs via wafer-wafer bonding, with a lower doping concentration

# Acknowledgements

This work was supported by:

- The United States Small Business Innovation Research (SBIR) Program.
- United States Department of Energy grant DE-FG02-04ER41286
- Launchpad Grant awarded by the Industry Alliances & Technology Commercialization office from the University of California, Santa Cruz.

# Backup

| Element | Doping Level (N/cm$^3$) | Extent In Depth |
|---|---|---|
| N isolation layer (N bulk) | constant doping of $3 \times 10^{12}$ | From 0 µm to beginning of N+ "gain plate" layer |
| N+ gain plate (upper half of gain layer) | Gaussian, peak doping $3 \times 10^{16}$ | peak at 4 µm, Gaussian width of 0.17 µm |
| P+ gain plate(lower half of gain layer) | Gaussian, peak doping $3 \times 10^{16}$ | Peak at 5.5 µm, Gaussian width of 0.17 µm |
| P drift region (P bulk) | constant doping of $3 \times 10^{12}$ | End of P+ "gain plate" layer to 50 µm |
| P stop | constant doping of $1 \times 10^{13}$ | 1 µm deep at surface, 1 µm wide |
| N++ implant (under electrode) | constant doping $1 \times 10^{19}$ | at surface |
| Gain layer doping tolerance (N+ and P+ varied together) | effective operation peak doping between $2.9 \times 10^{16}$ and $3.5 \times 10^{16}$ | |