CPAD 2024

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THE UNIVERSITY OF NEW MEXICO

Characterization of the response of Brookhaven AC-LGADs to gamma irradiation

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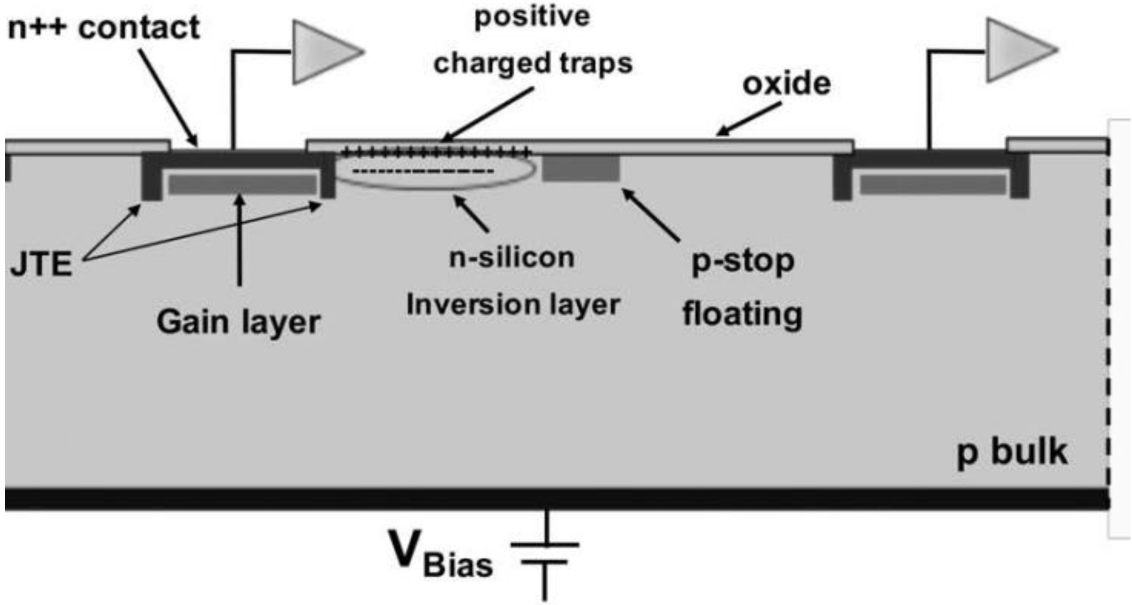
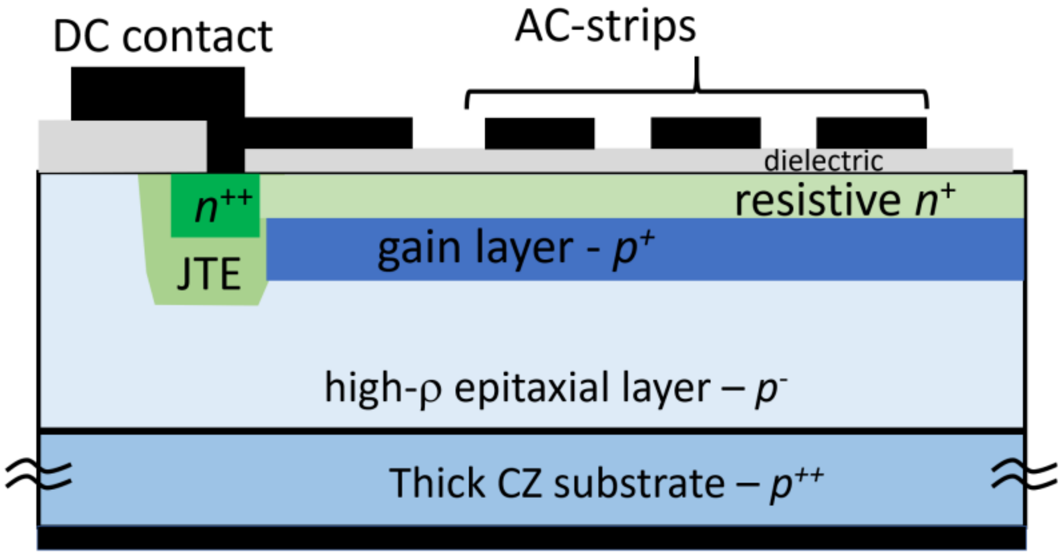
Outline

- Low-Gain Avalanche Detectors (LGADs) have excellent timing performance due to a doped layer that provides a moderate gain (~20). Traditional DC LGADs have no-gain regions. Due to the fill factor consideration, their spatial resolution is limited to ~ 1mm.
- Smaller pitches can be achieved in AC-coupled LGADs (AC-LGADs) by using a continuous gain-layer and coupling the signals capacitively through a thin layer of dielectric to smaller AC pads.
- Characterization measurements of unirradiated/gamma-irradiated LGADs designed at BNL are underway at UNM.

Difference between DC-LGAD and AC-LGAD

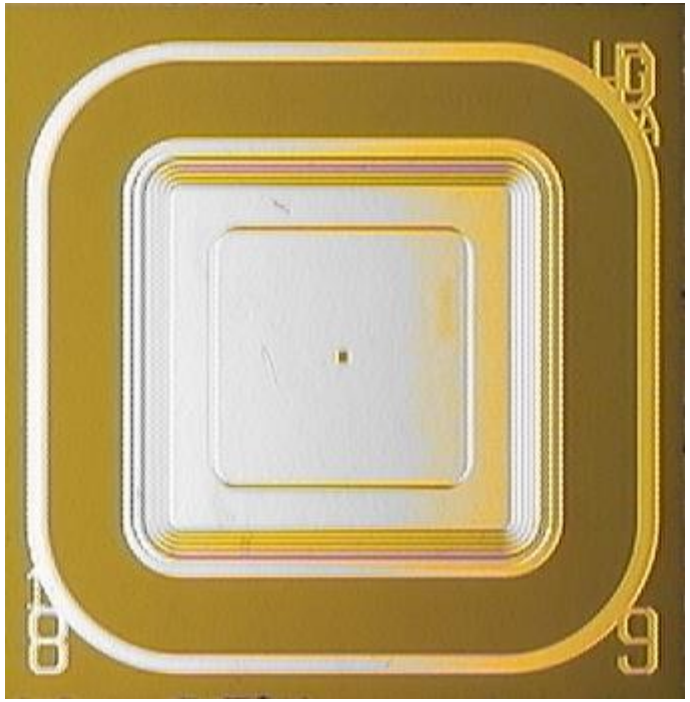


Junction Termination Extension (JTE) and p-stop/p-spray introduce no-gain region in traditional DC LGADs.

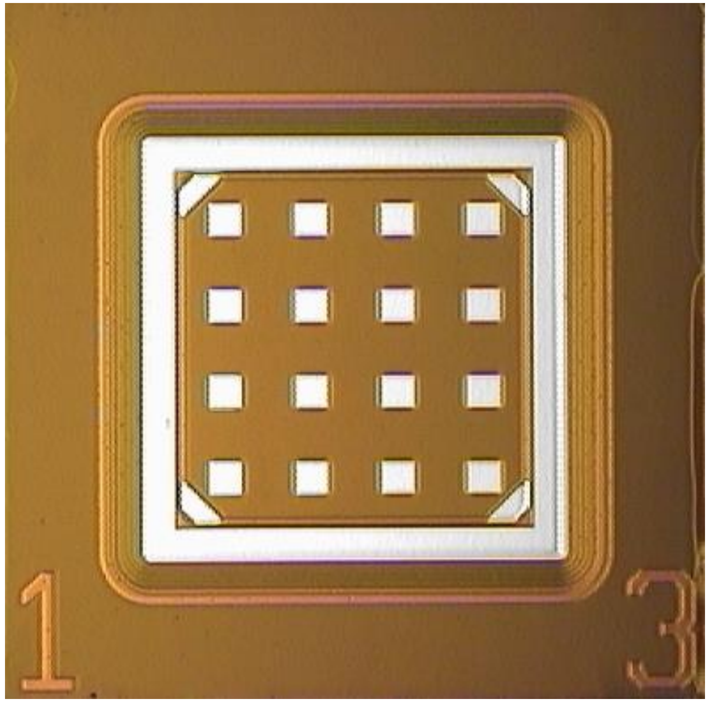


Signals can couple through the thin dielectric capacitively to AC-pads with smaller pitches.

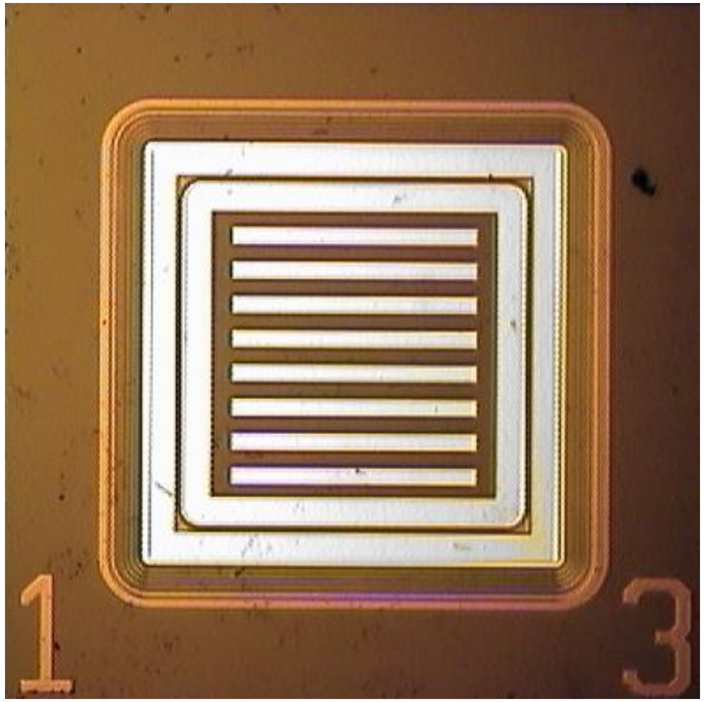
3 types of LGADs were irradiated at Sandia National Laboratories' Gamma Irradiation Facility from 40 MRad to 1 GRad



W3045 DC-LGAD
50um thick active layer
1um gain layer thickness

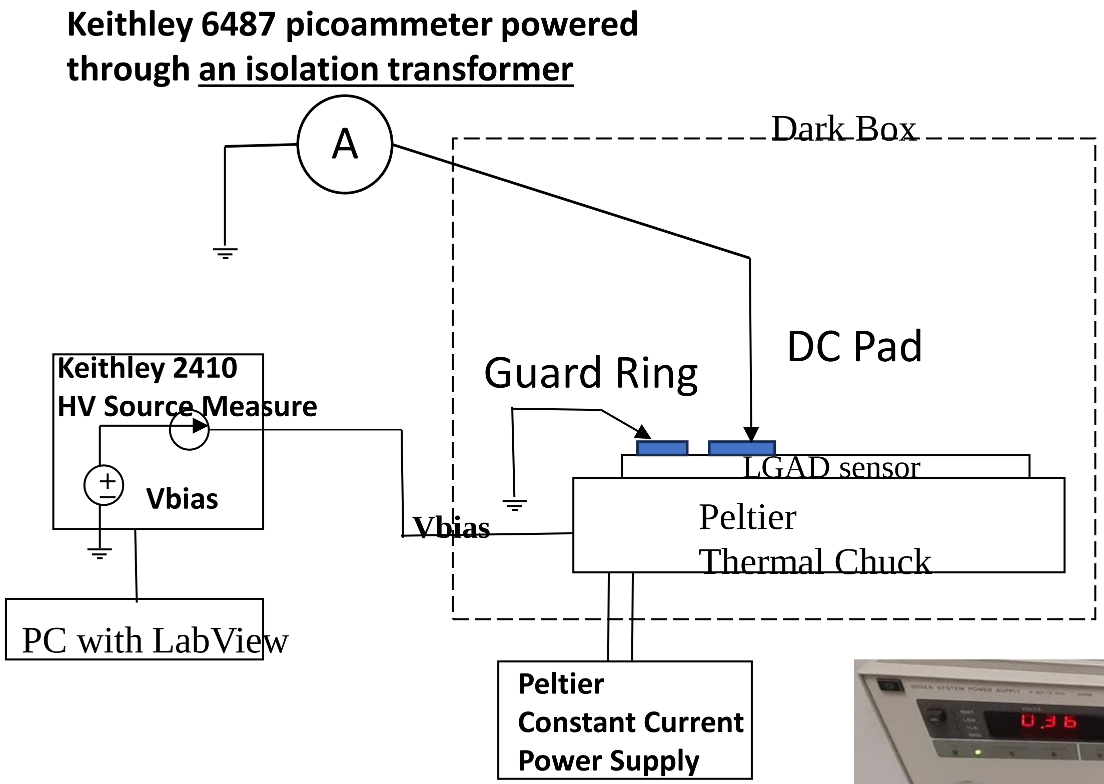


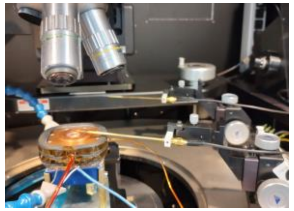
W3051 pixel AC-LGAD
50um thick active layer
1um gain layer thickness



W3073 strip AC-LGAD
20um thick active layer
1um gain layer thickness

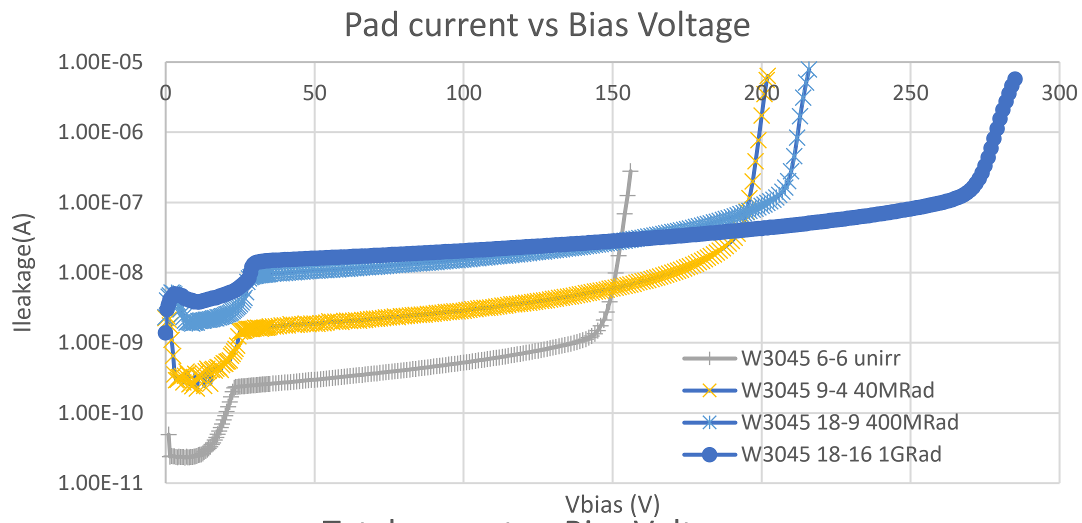
Guard ring current of some BNL LGADs can be a few orders of magnitude higher than pad current, especially after gamma irradiation. Current vs. Voltage (IV) setup has been modified to measure the DC pad current (“Pad current”) and DC pad + guard ring current (“Total Current”).

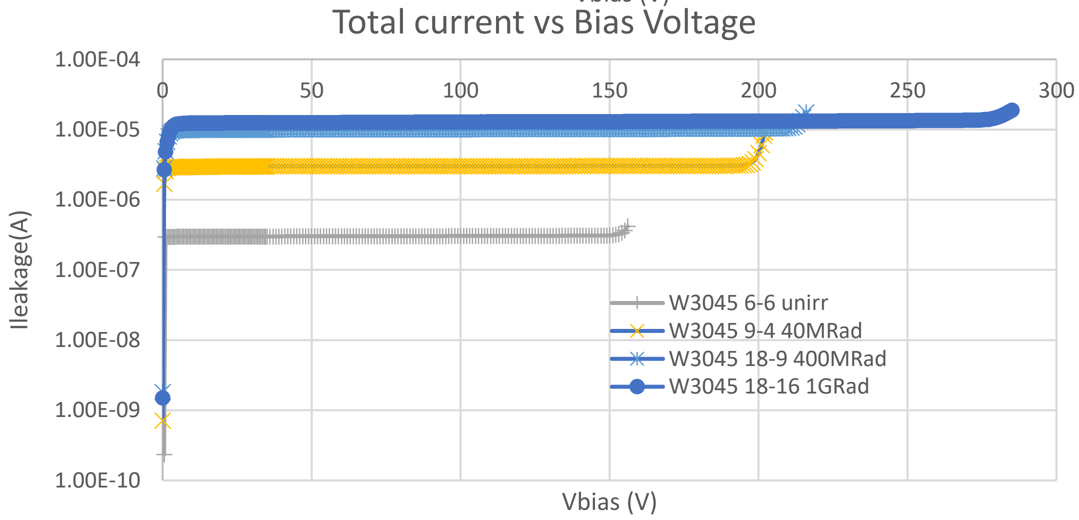




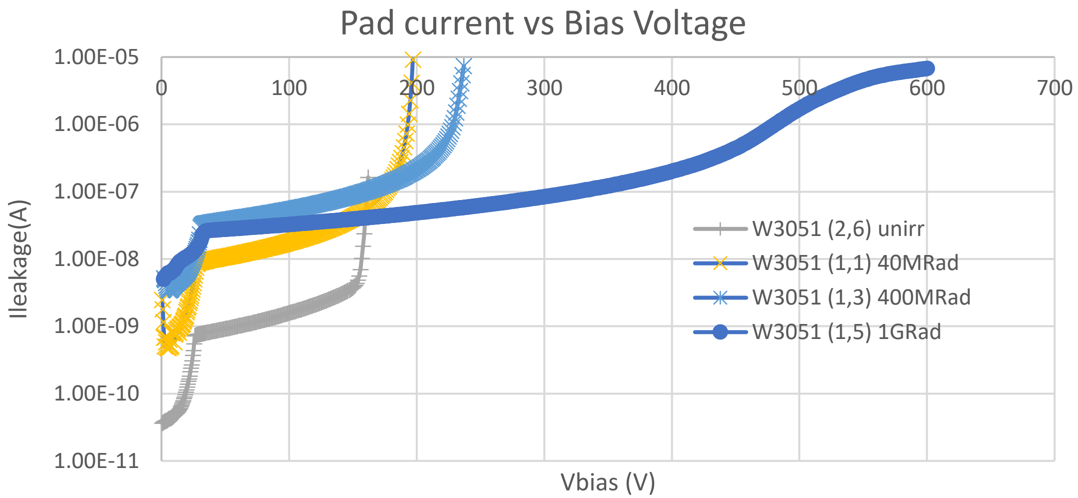
The results show that for 50um thick LGADs (DC and pixel AC), pad current before full depletion, total current, and breakdown voltage increase with gamma dose.

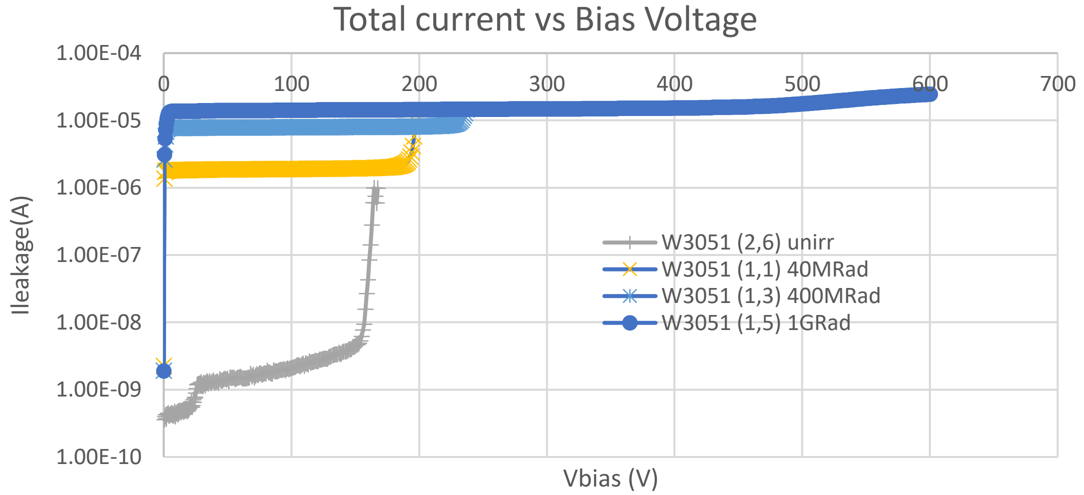
DC-LGADs



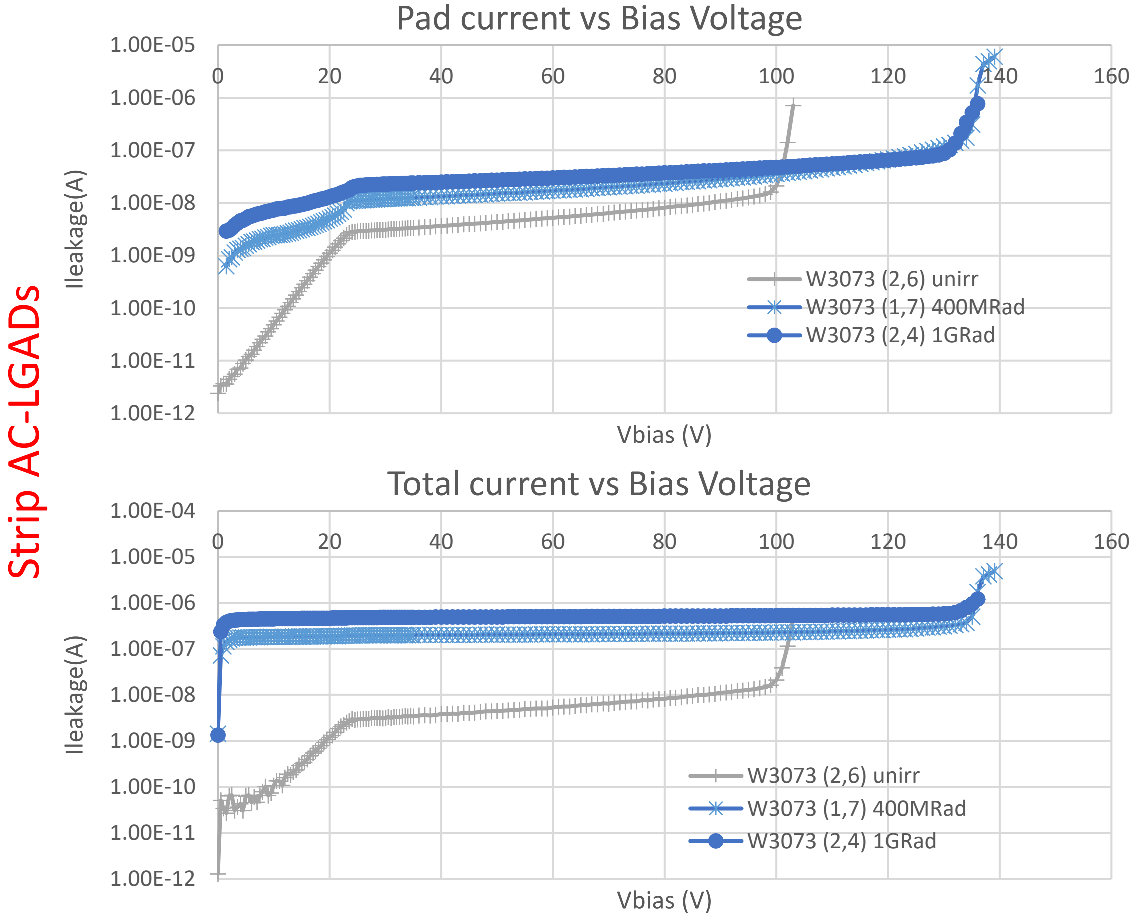


Pixel AC-LGADs



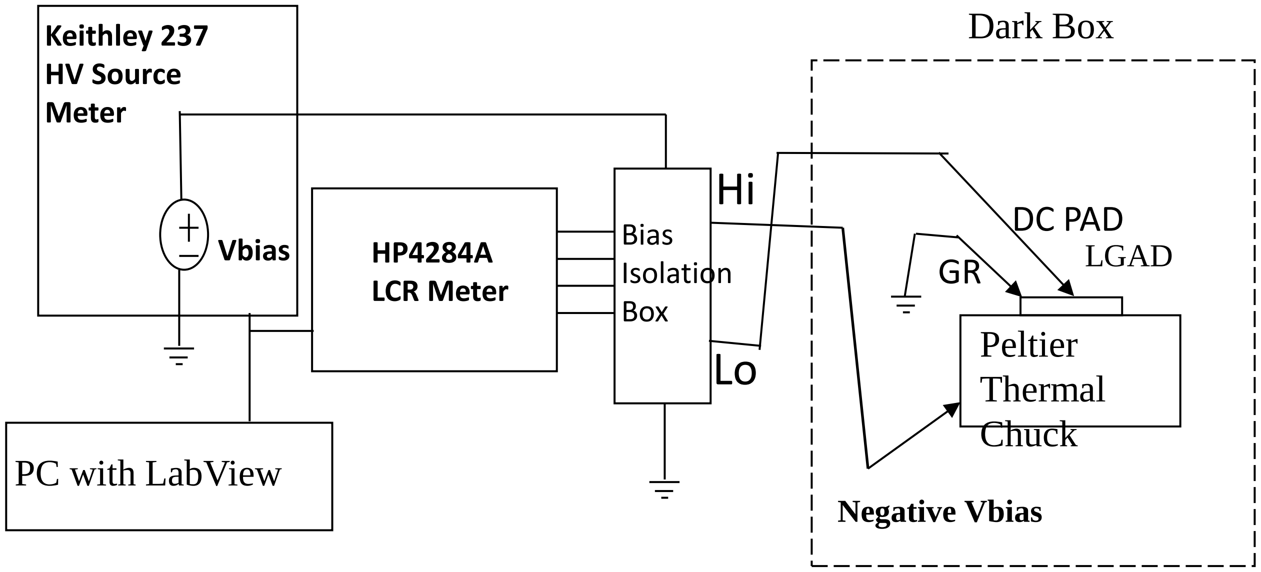


For 20um thick LGADs (AC strip), both pad current and total current increase with gamma dose. The breakdown voltages of irradiated ones are higher than unirradiated ones. However, the breakdown voltage of one irradiated at 400 Mrad is about the same as the one by 1 GRad.

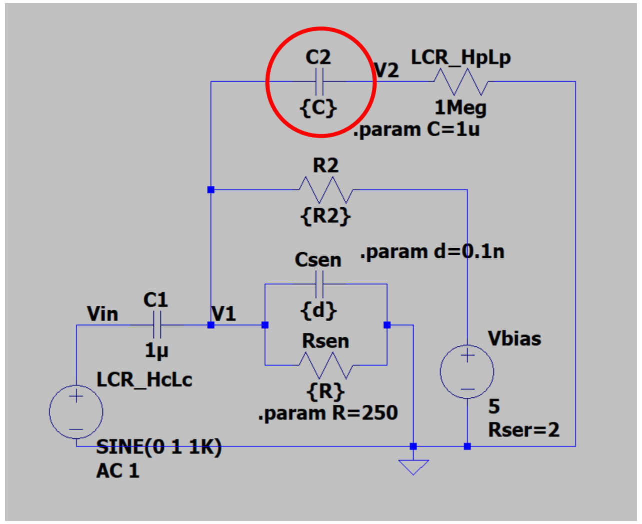


	PAD current (A) Total Current (A) Breakdown voltage (V) (Typical value)			
	0 Rad	40 MRad	400 MRad	1 GRad
DC-LGAD (50 um)	$5x10^{-10}$A $3x10^{-7}$A 145V	$5x10^{-9}$A $3x10^{-6}$A 190V	$2x10^{-8}$A $1x10^{-5}$A 205V	$2x10^{-8}$A $1.5x10^{-5}$A 270V
Pixel AC-LGAD (50 um)	$2x10^{-9}$A $2x10^{-9}$A 155V	$2x10^{-8}$A $2x10^{-6}$A 175V	$1x10^{-7}$A $8x10^{-6}$A 225V	$1x10^{-7}$A $1.5x10^{-5}$A 460V
Strip AC-LGAD (20 um)	$5x10^{-9}$A $5x10^{-9}$A 100V	n/a	$2x10^{-8}$A $2x10^{-7}$A 130V	$3x10^{-8}$A $5x10^{-7}$A 130V

Configuration used for CV measurement



A key capacitor in the bias isolation box has higher value (210uF) than the recommended one (1uF) by the manufacturer.



$$R_{sen} = R_{bulk}(\omega, V_{bias}) \parallel \left[R_{intpad}(\omega, V_{bias}) + R_{GR}(\omega, V_{bias})\right]$$

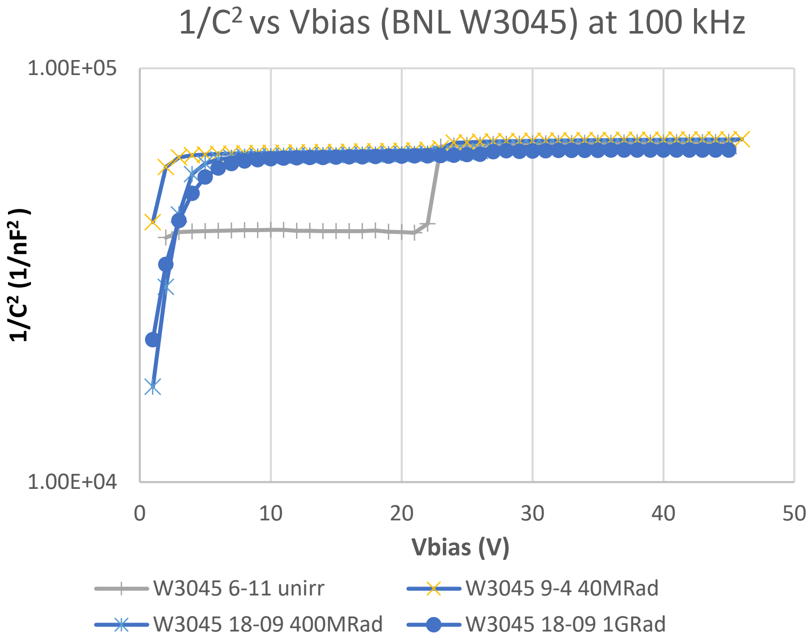
$$C_{measured} = C_{sen} - \left(\frac{1}{Rsen} + \frac{1}{R2}\right)\frac{1}{C_2 R_{HpLp}\omega^2}$$

More details in backup slides

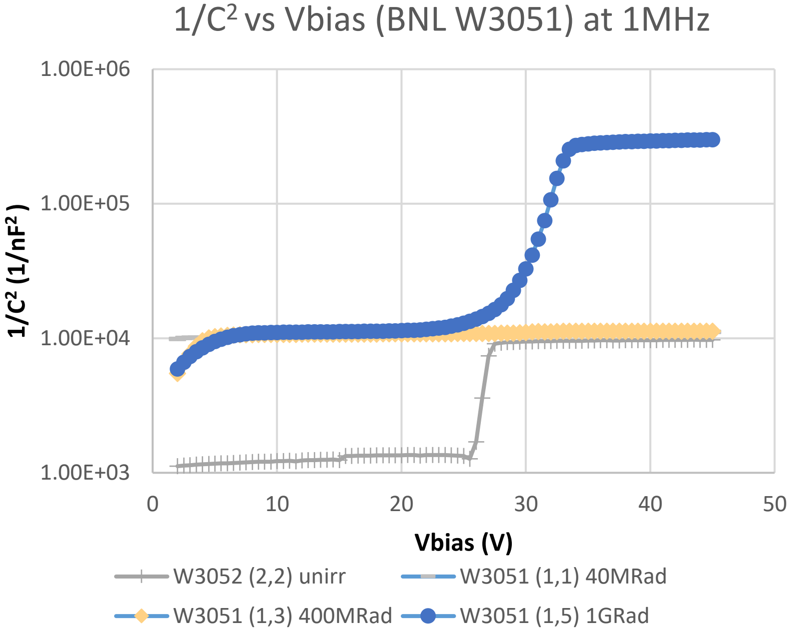
Bigger C_2, ω can make error smaller. However, too small Rsen requires an impractically big C2.

Bigger $R2$ can reduce error. However, R2 can't be too big because it would take too much time to make Vbias stable.

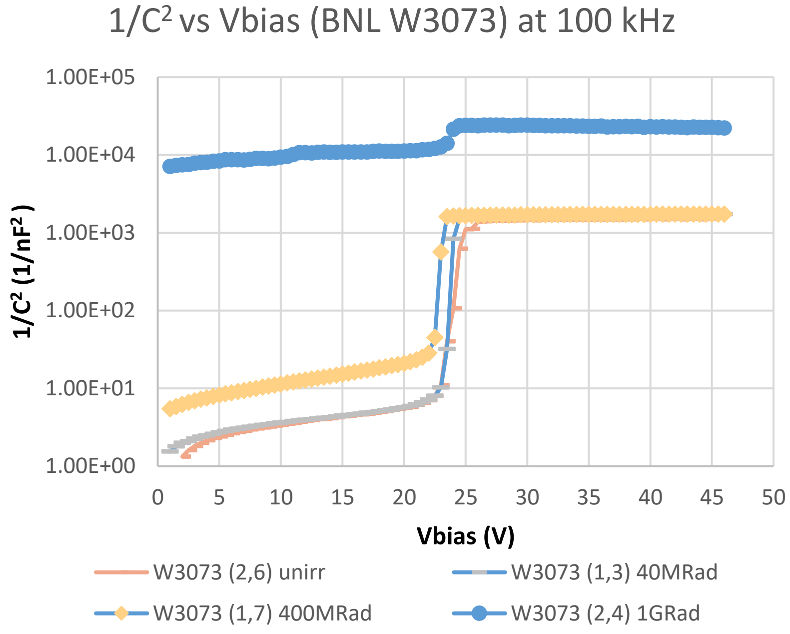
The clearest features are seen from the measurements of the strip AC-LGADs (20 um).



DC-LGADs



Pixel AC-LGADs

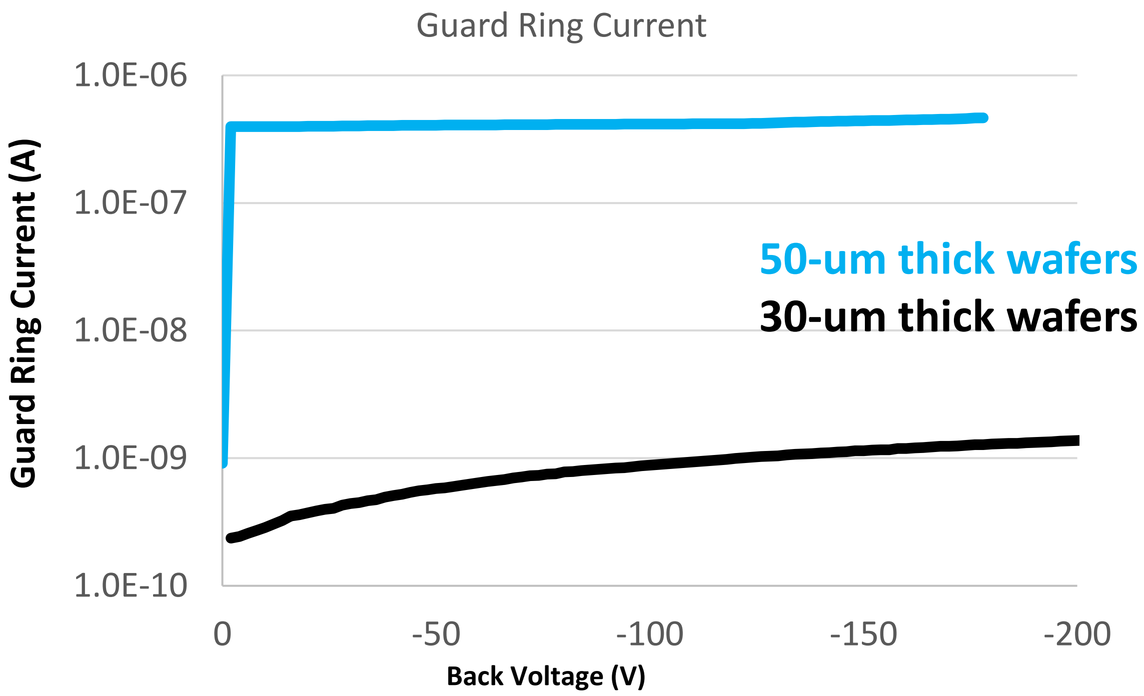


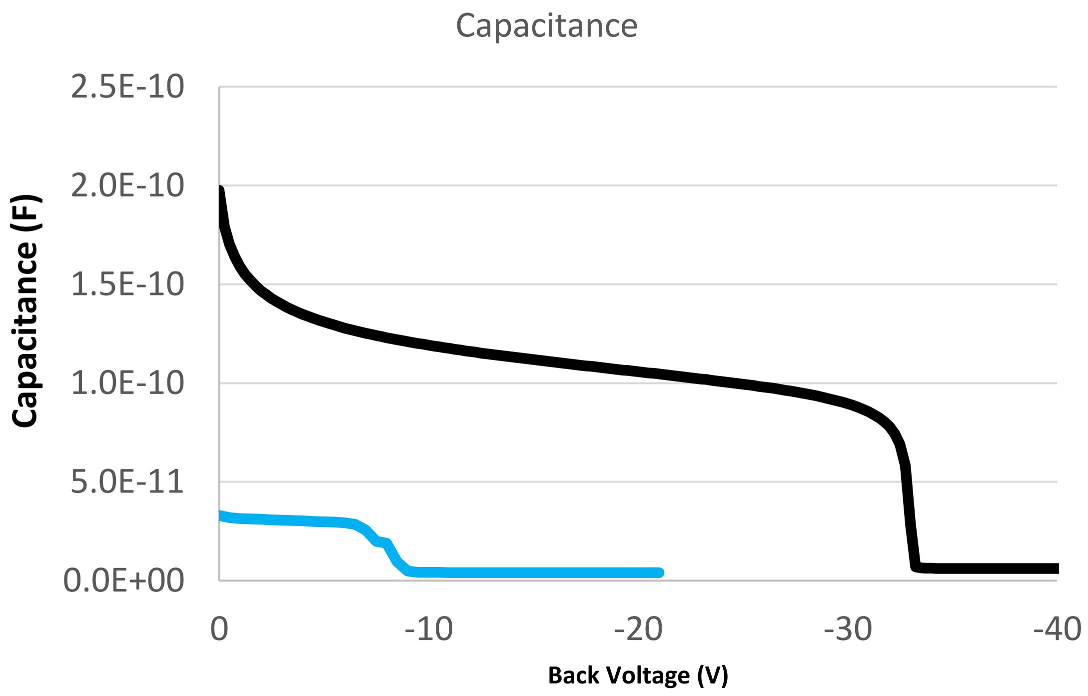
Strip AC-LGADs

	Gain-Layer Depletion voltage (V) / Full Depletion voltage (V) (Preliminary estimate)			
	0 Rad	40 MRad	400 MRad	1 GRad
DC-LGAD (50 um)	22.0/23.0	?	?	?
Pixel AC-LGAD (50 um)	26.0/27.4	?	?	31.1/33.6
Strip AC-LGAD (20 um)	23.9/25.4	23.5/24.5	22.6/23.5	23.7/24.2

Strange effect on “thick” epitaxial layers

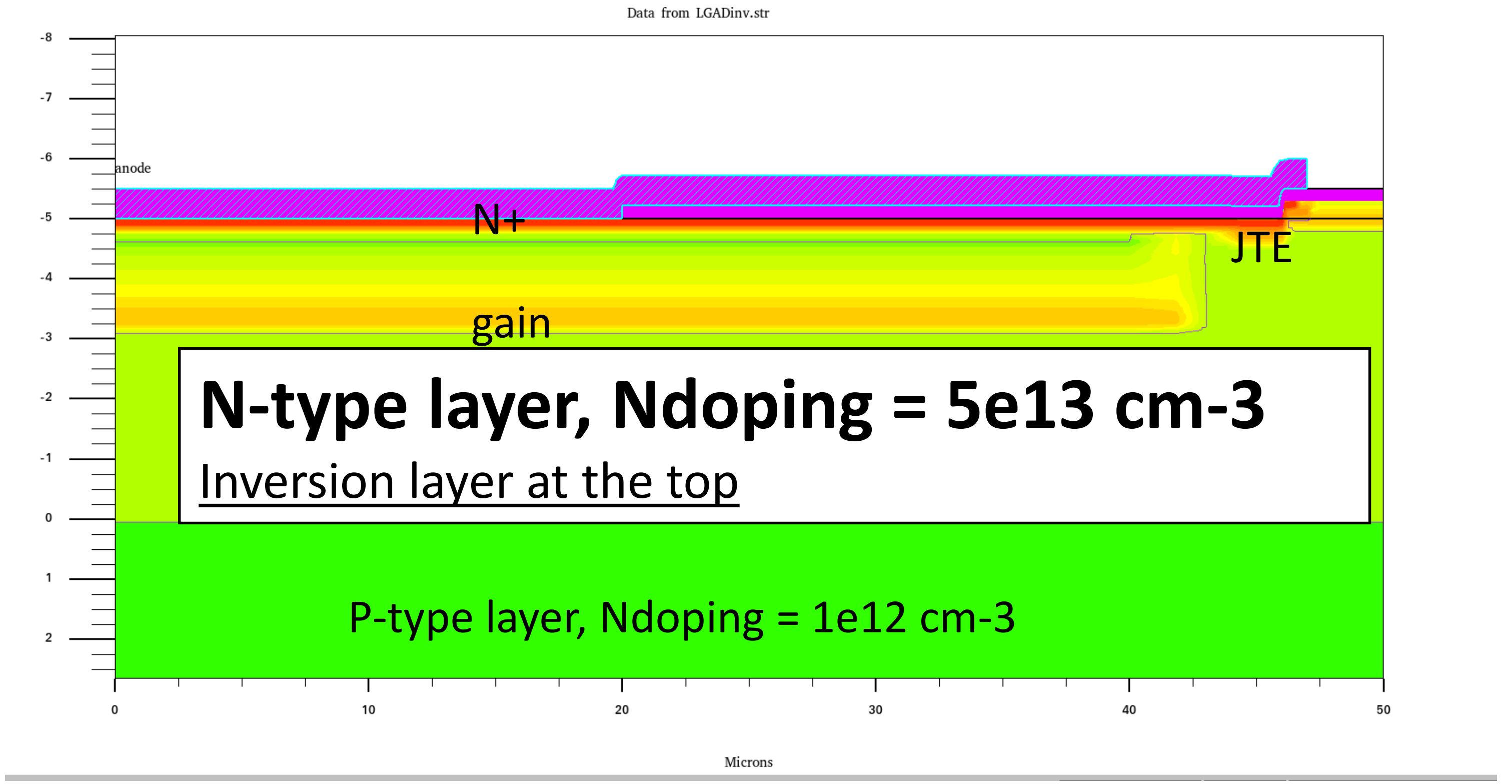
On devices built on 50-um thick wafers, C-Vs are odd – the gain layer seems not to be present – and guard ring current high and erratic.
Effect not present in devices built on 20 and 30 um thick epi, which have been processed in parallel.
Gain is however present in 50 um thick devices, as experienced with gain measurements



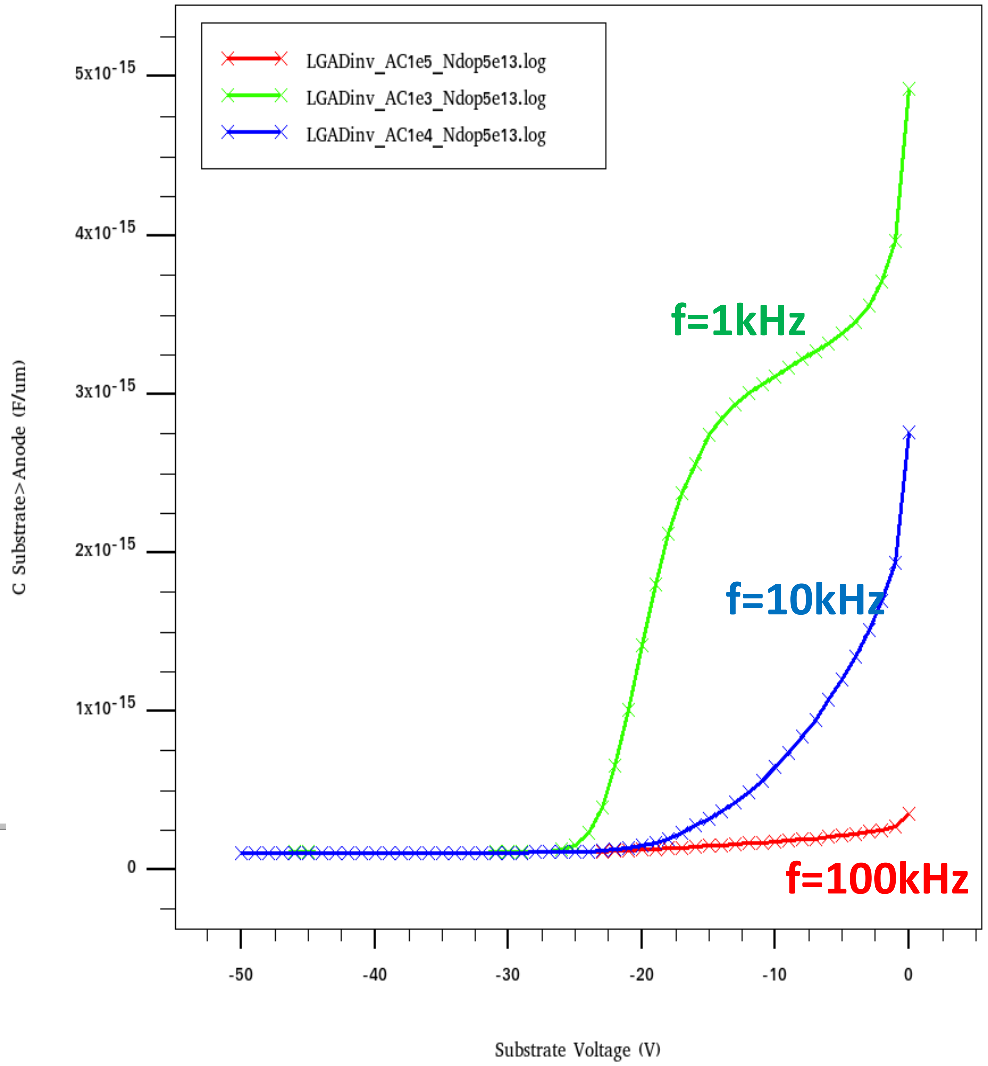


Effect seen also by other supplier and explained with an “inversion” at the interface.
Solution? Start with initial substrates of lower resistivity – if substrate is depleted at > 5V, no effect on LGAD performance

TCAD simulations



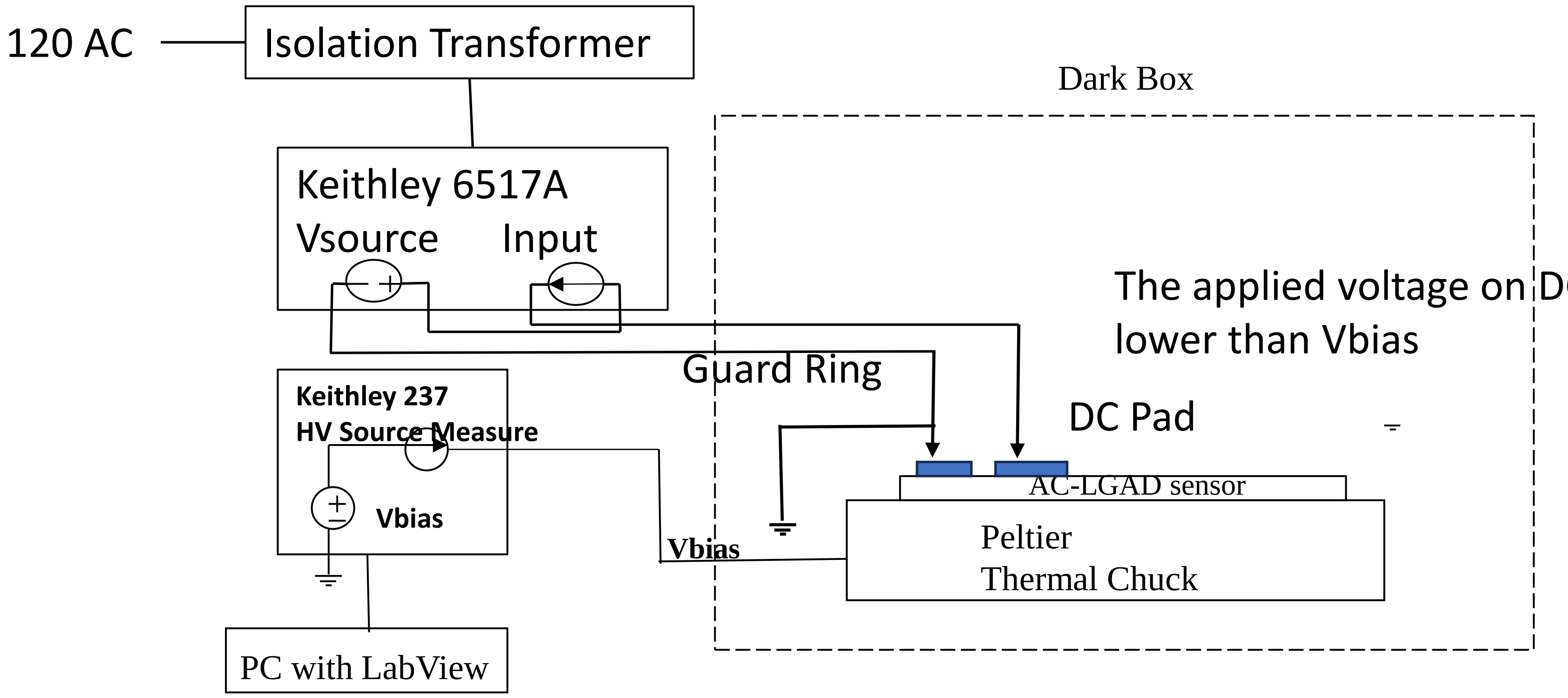
Capacitance for different frequencies



Correct CV for very low f

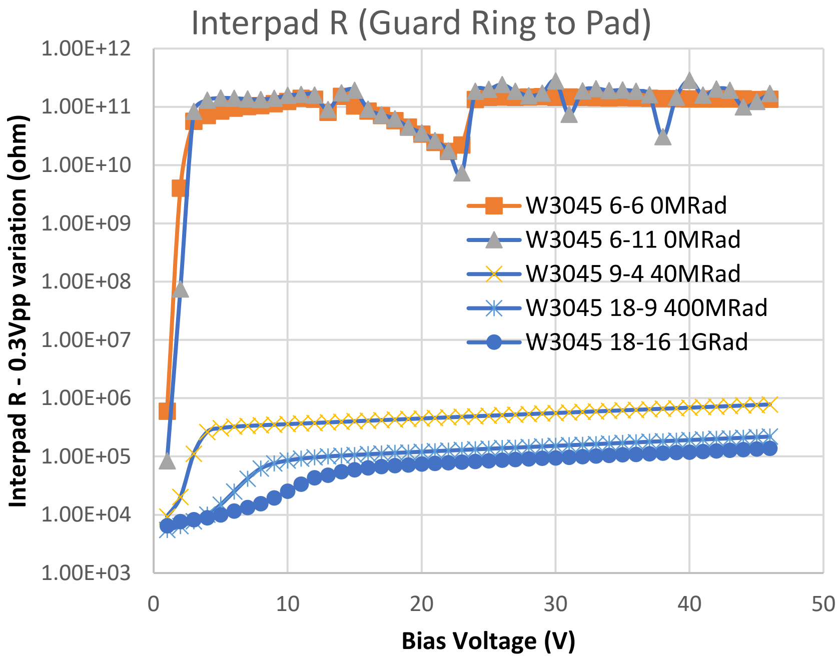
The effect can be simulated qualitatively, although we cannot measure the degree of inversion happening at the surface, nor its extension or effective doping.

Inter-pad resistance measurement between DC pad and guard ring has been set up to investigate surface damage caused by gamma-irradiation

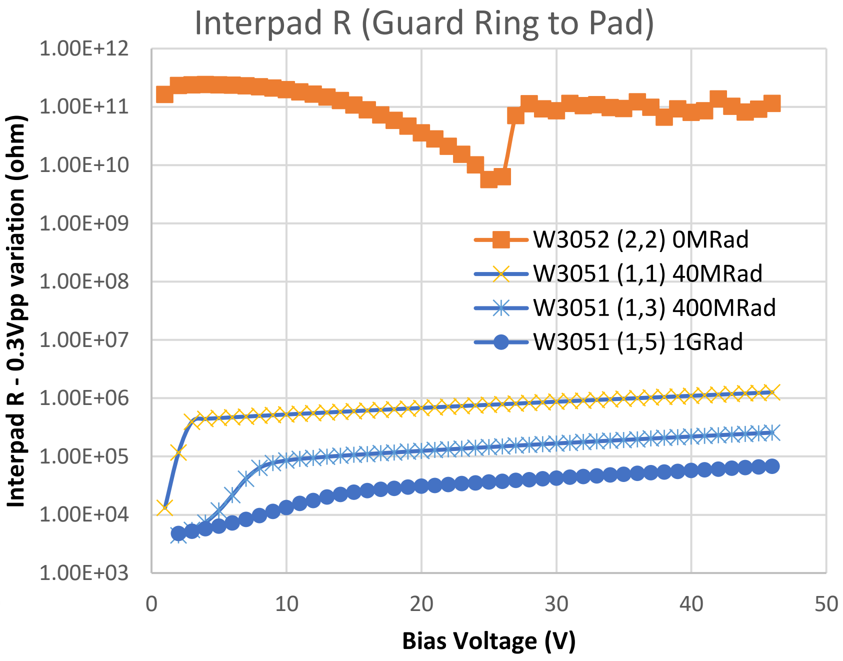


The applied voltage on DC Pad can't be lower than Vbias

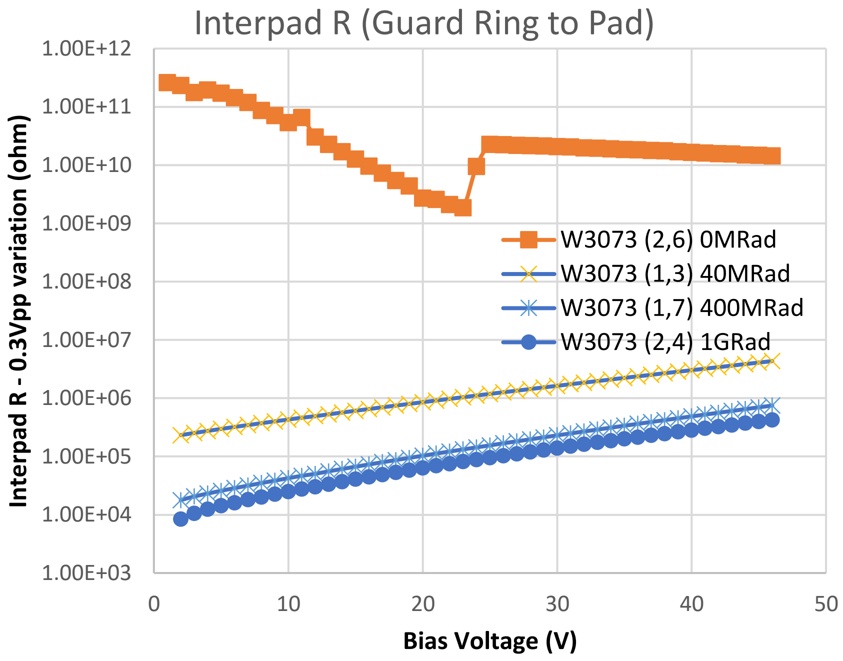
Inter-pad resistance of BNL LGADs measured with interpad voltage (DeltaV) from -0.3V to 0.3V shows that for gamma-irradiated LGADs, inter-pad R decreases by up to 10^6.



DC-LGADs



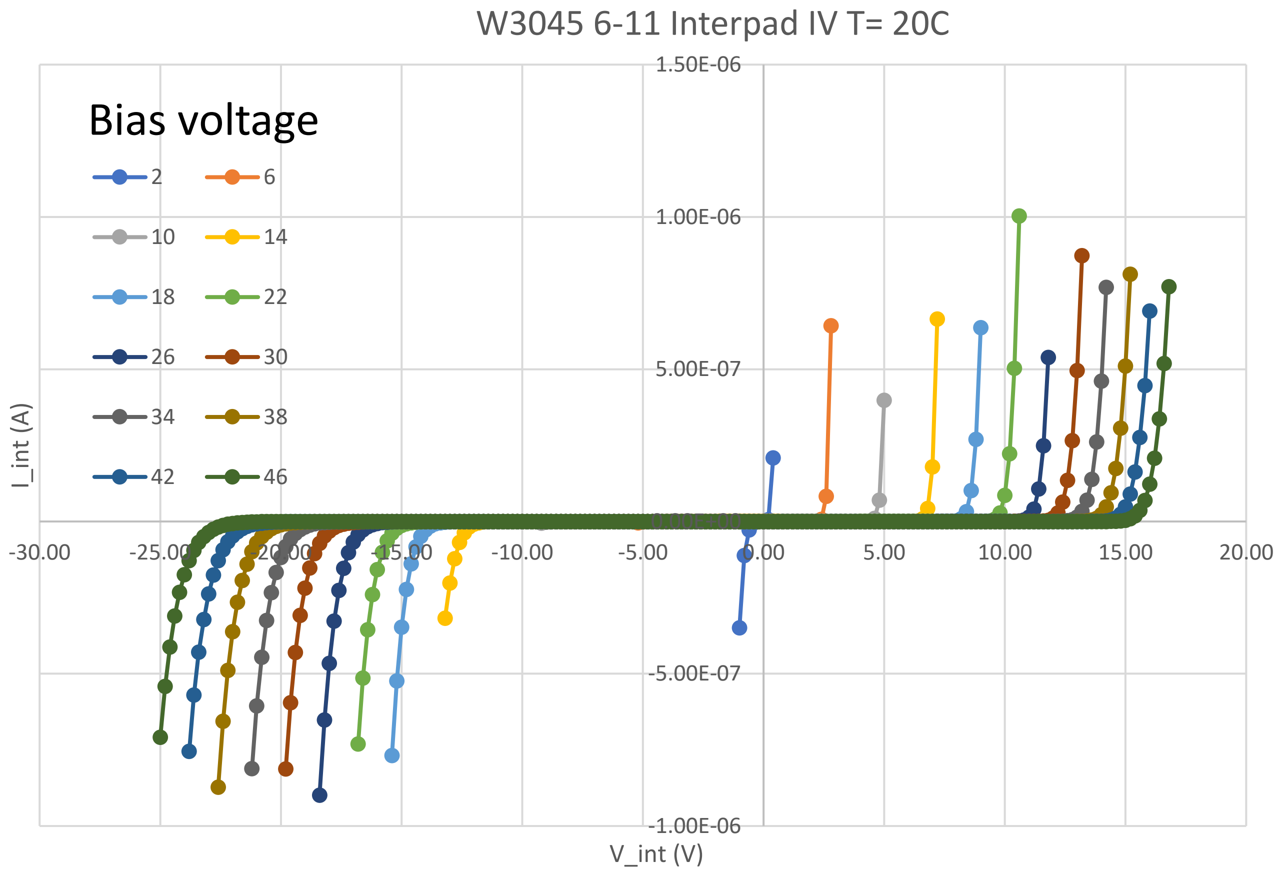
Pixel AC-LGADs

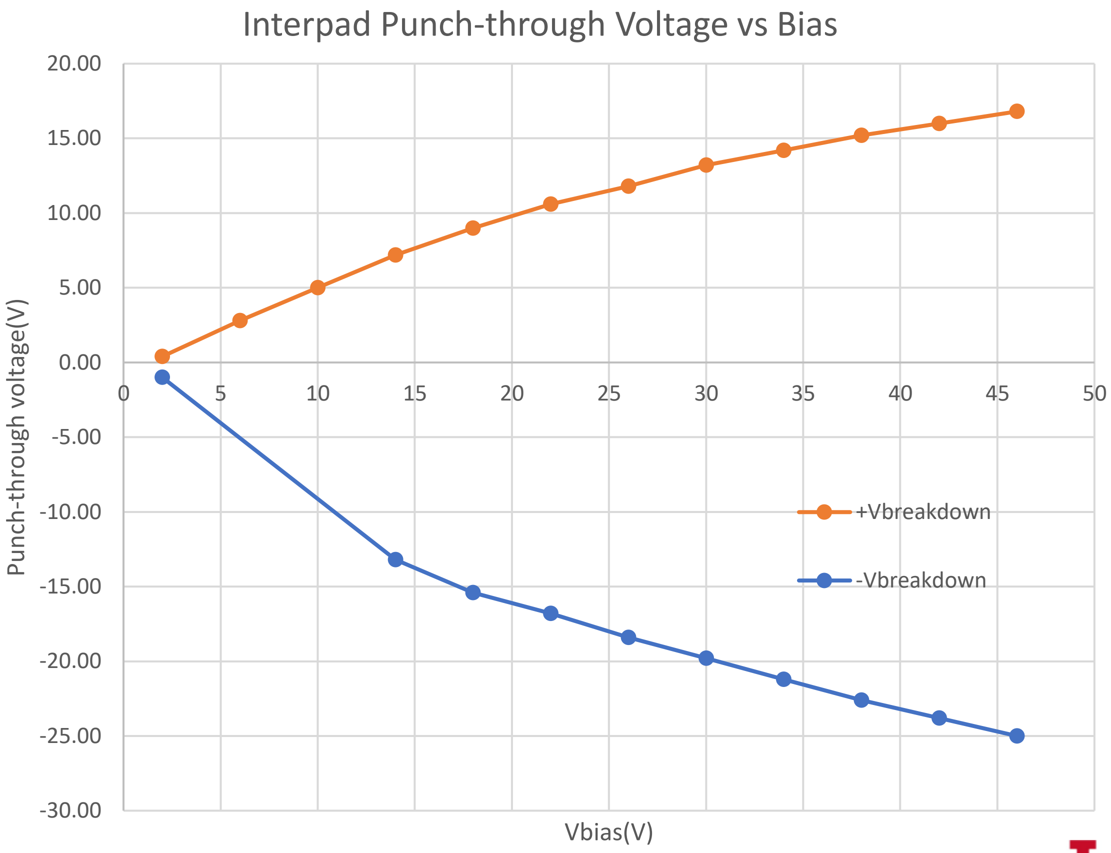


Strip AC-LGADs

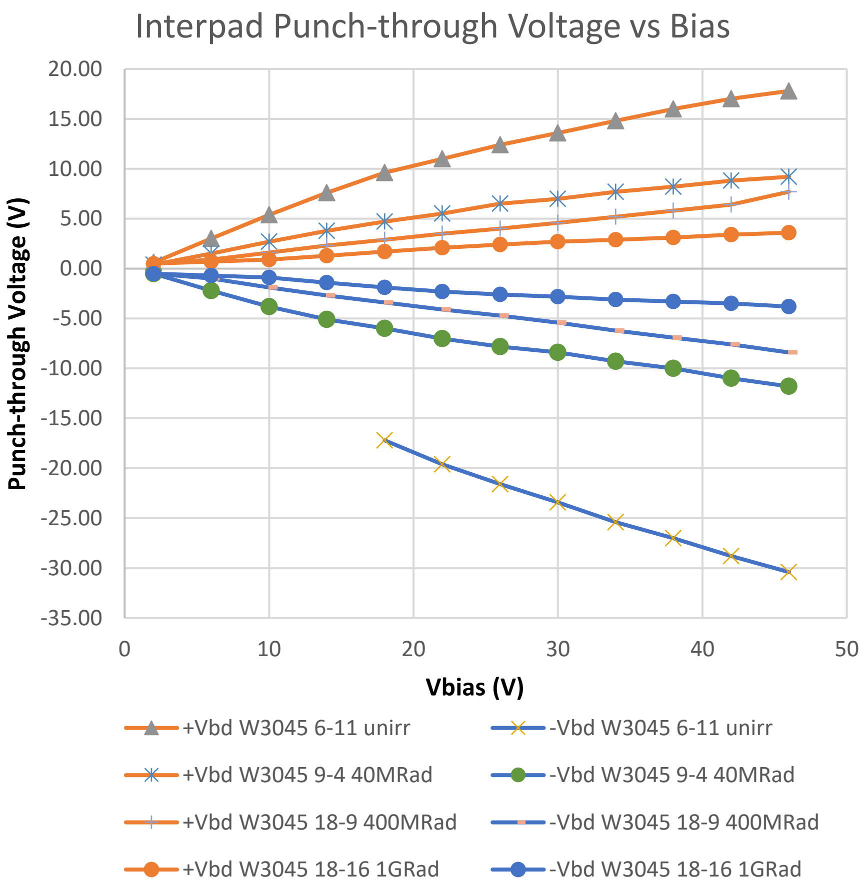
For unirradiated LGADs, there are “dips” around the depletion voltages.

A full range scan of inter-pad I vs inter-pad V shows that at certain inter-pad voltages depending on bias voltages, punch-through starts. The magnitude of punch-through voltage increases with the bias voltage.

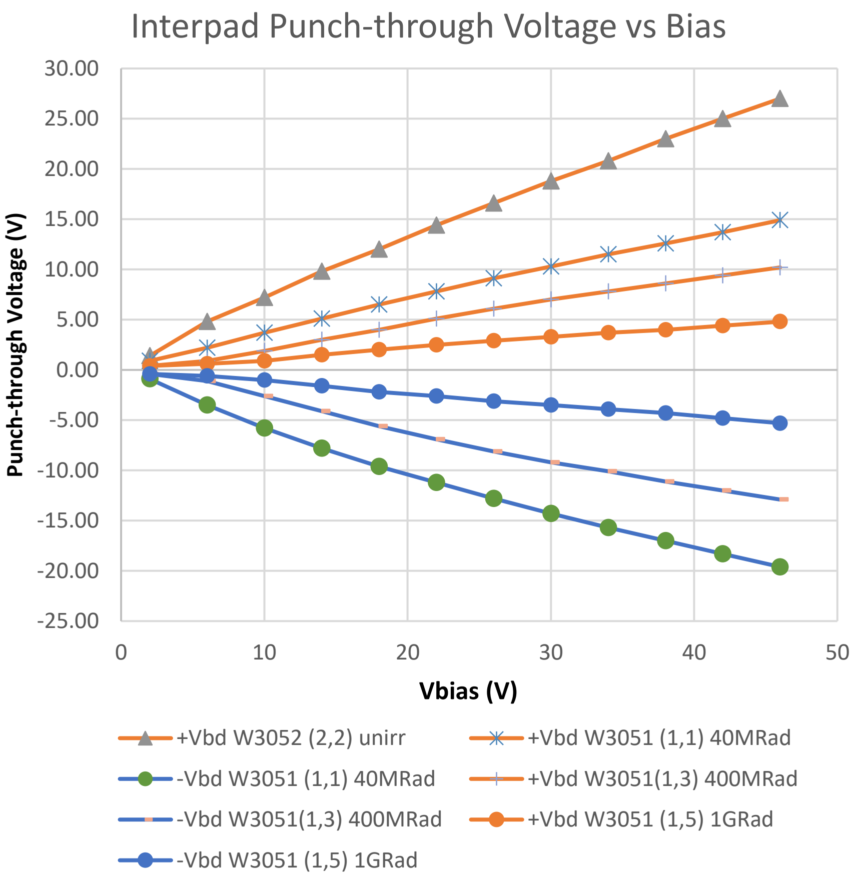




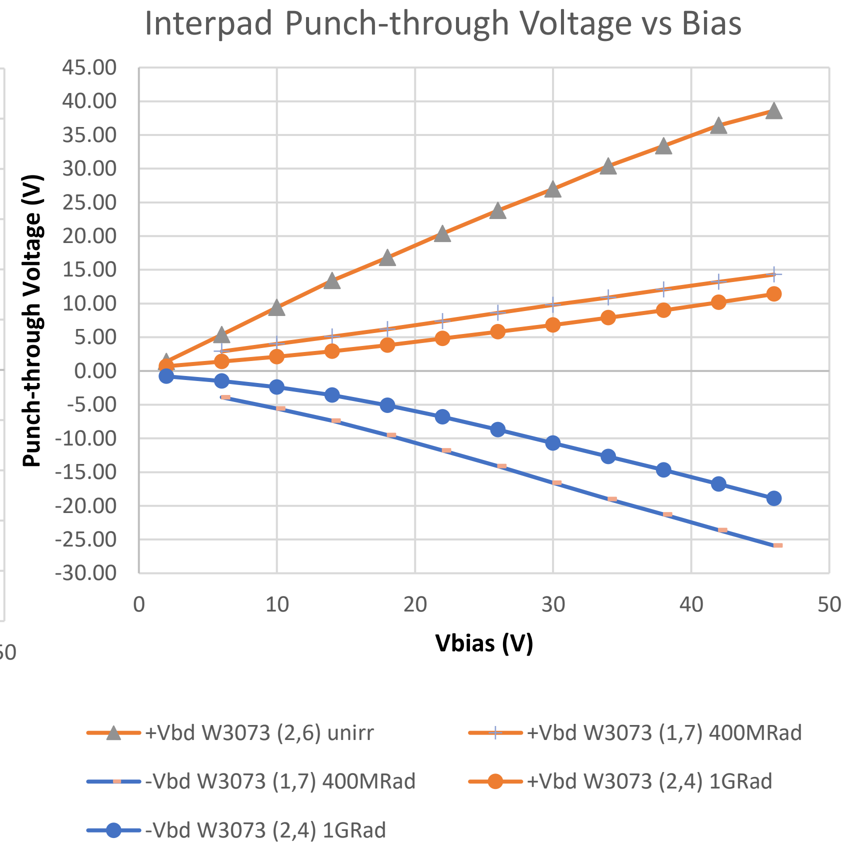
The punch-through voltage magnitude increases with bias voltage and decreases with gamma dose.



DC-LGADs



Pixel AC-LGADs

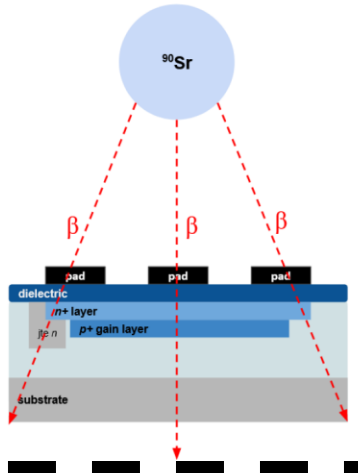


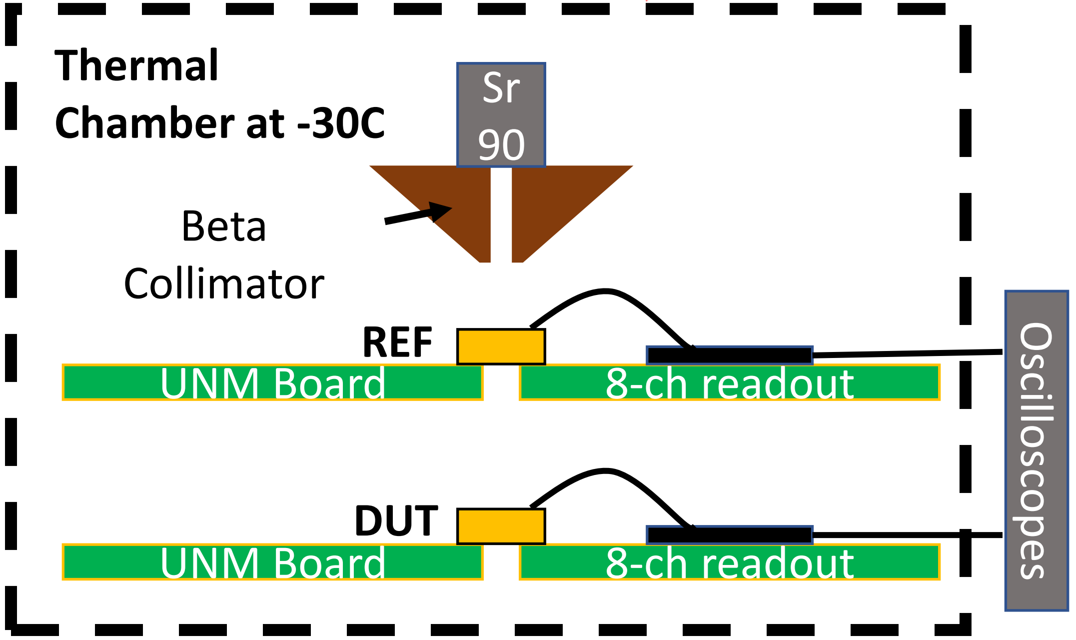
Strip AC-LGADs

Note, there are detectors which don't have punch-through at negative inter-pad voltages before reaching bias voltage.

Beta source setup will be used to study cross-talk/signal-sharing, timing/charge collection

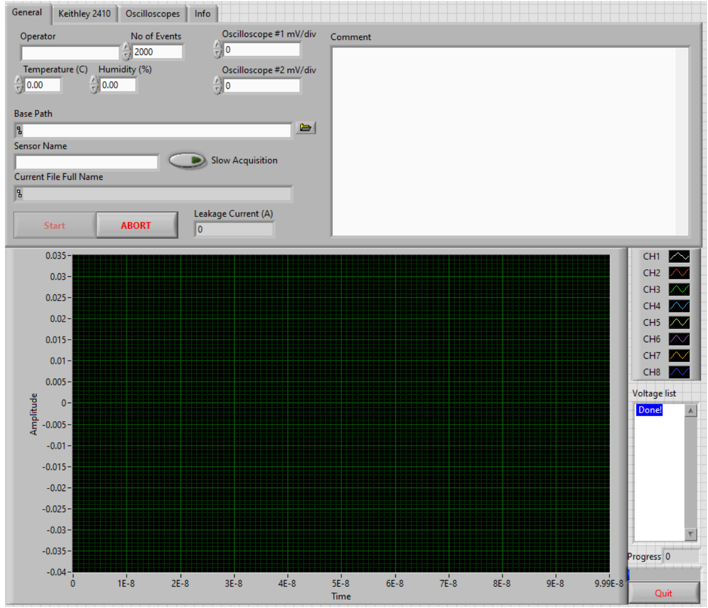
- Signal from SiPM, or with an LGAD on a readout board, can be used as the trigger,.
- Cross-talk/signal-sharing can be studied: using ^{90}Sr to emit electrons isotropically to study the cross-talk: any channel with the highest peak is the leading channel; then ratios between the leading channel and the neighboring channels are calculated.
- Timing will be studied by stacking two boards together and comparing the time of arrival. Charge collection will be done for DC PAD.
- Multiple-channel data acquisition software and multi-channel readout boards have been designed and implemented at UNM.

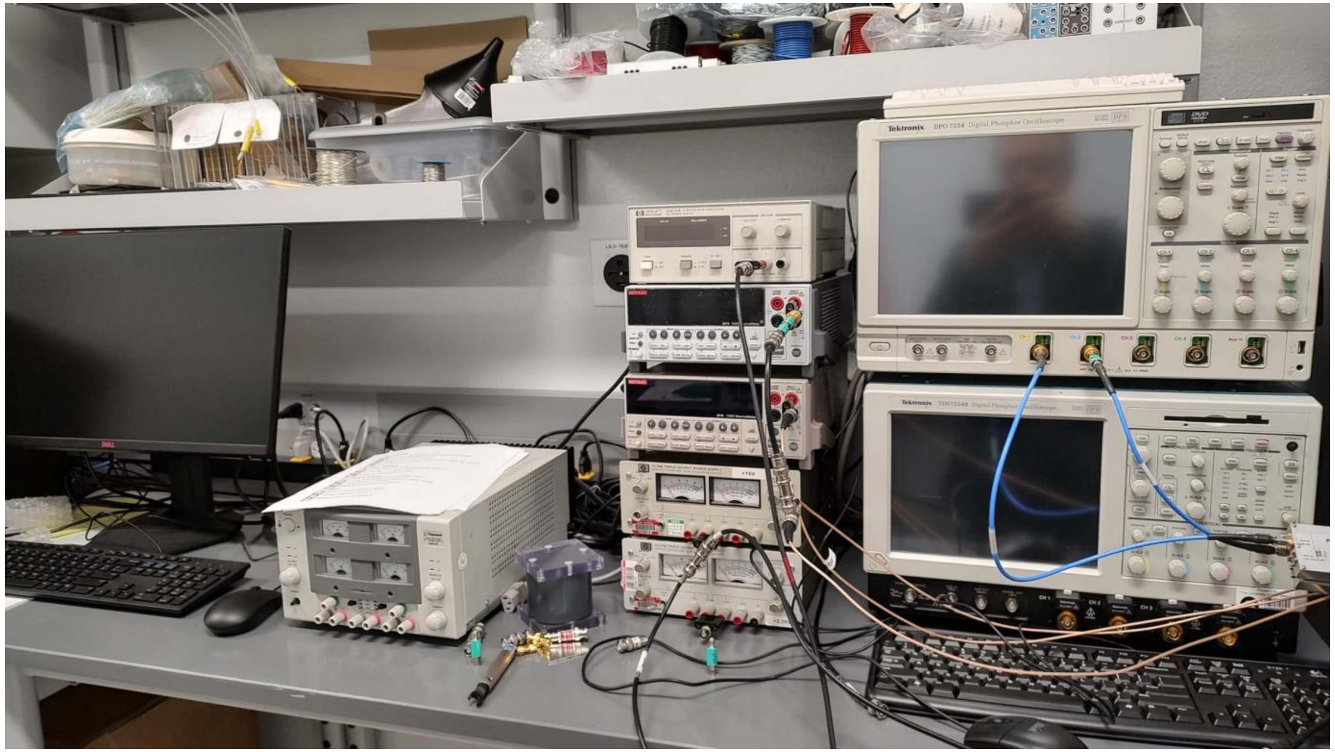




LabView software for multiple channel DAQ using two oscilloscopes has been developed and is being tested

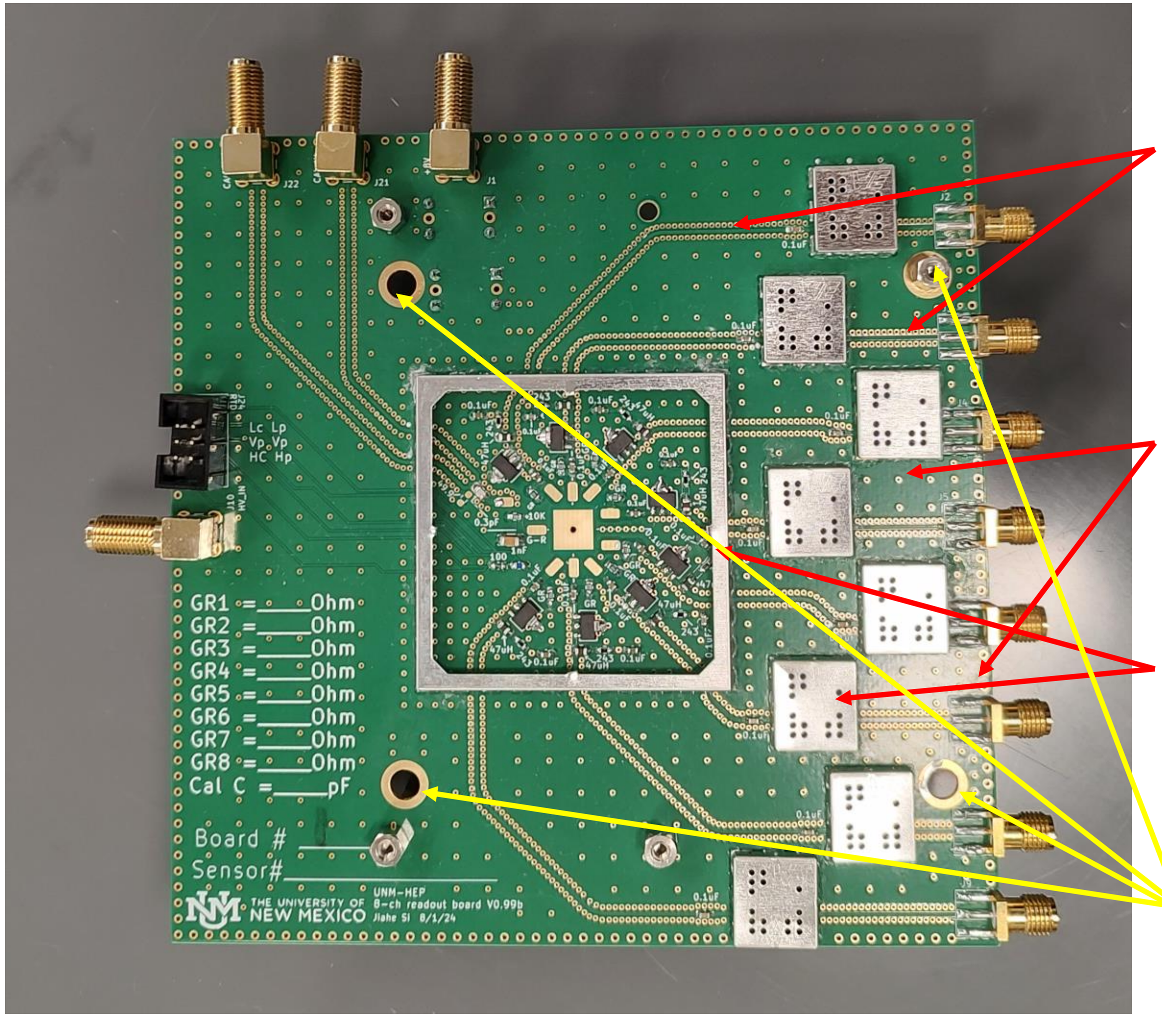
- LGADs are mounted on the 8-channel readout board developed by UNM.
- 4 channels of Tektronix DPO 7254 oscilloscope with 2.5GHz bandwidth, 40GS/s sampling rate is used.
- 4 channels of Tektronix TDS 7254B oscilloscope with 2.5GHz bandwidth, 20GS/s sampling rate is used.





- LabView Data Acquisition (DAQ) program has been written to collect data from 2 oscilloscopes.
- 1 to 8 channels from either/both oscilloscopes can be collected by the DAQ program.
- Data is saved in CVS format.

8-ch readout board has been designed and built. Testing with LGAD and the LabView DAQ software is ongoing.



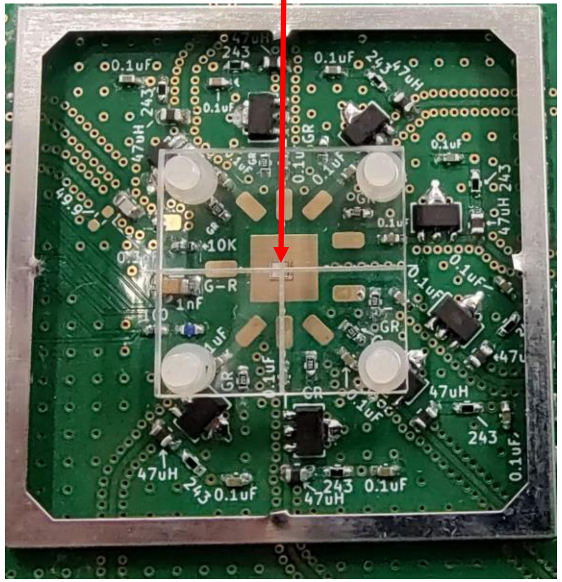
Vias, track width and clearance were set such that the characteristic line impedance is 50ohm

The zones without tracks and parts are filled with copper (grounded) with vias

EMI gaskets are used to shield the unwanted external RF signals.

Four positioning holes are connected to ground plates so that the boards can be connected to the chassis ground.

Markers on the board and a crosshair gadget are used to align the detector to the center



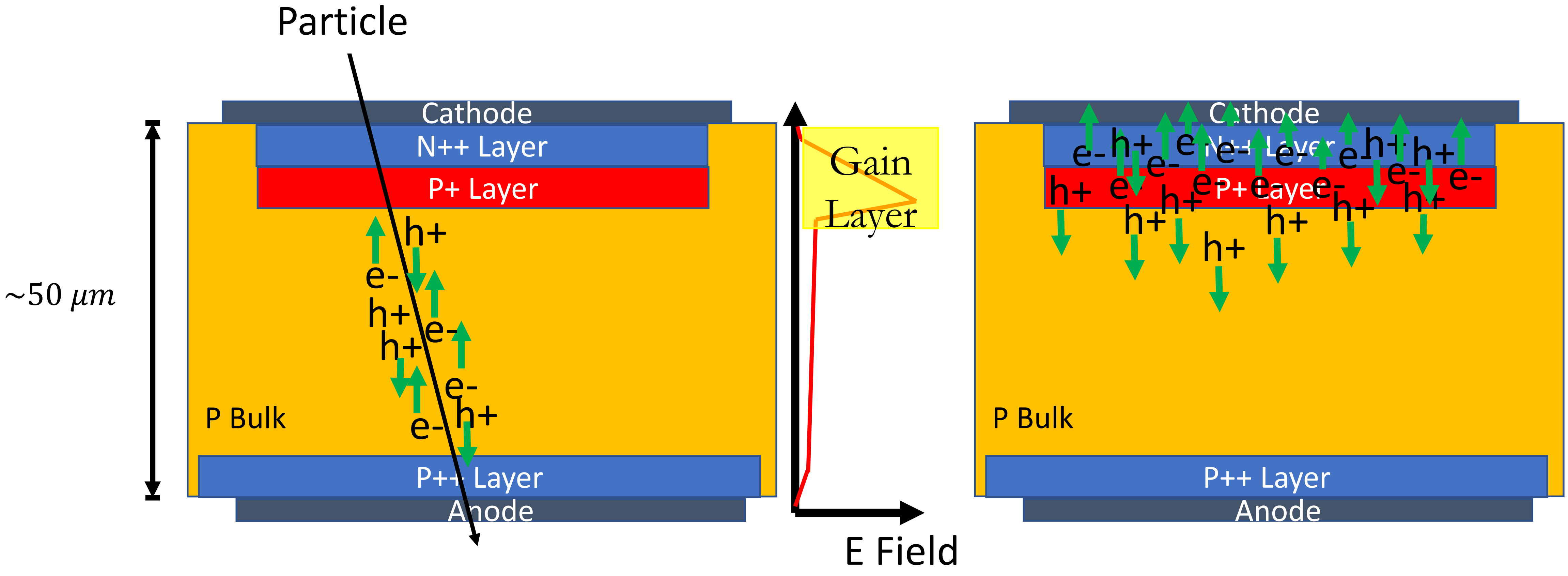
Summary

- Different AC/DC-LGADs were irradiated by gammas.
- Measurements of IV, CV, and inter-pad resistance have been made:
  - Both pad and total current increase with gamma dose;
  - Pad current between depletion and breakdown lies in the range 10^{-9} to 10^{-7} A for all gamma-irradiated samples.
  - Before breakdown, guard ring current of gamma-irradiated LGADs is up to 10^3 times higher than pad current.
  - Breakdown voltage increased after gamma-irradiation by up to a factor of 3.
  - CV measurement for gamma-irradiated LGADs was difficult; it was improved by changing a key capacitor in the isolation box and measurement configuration; typical gain-layer voltage is 22V (for DC-LGAD), 26V (for pixel AC-LGAD), and 24V (strip AC-LGAD) before irradiation.
  - Inter-pad resistance decreased up to 10^6 times after gamma-irradiation, the punch through voltage also decreases with gamma dose.
- Cross-talk/signal-sharing, Timing/charge collection measurement is being set up.

Thank You!

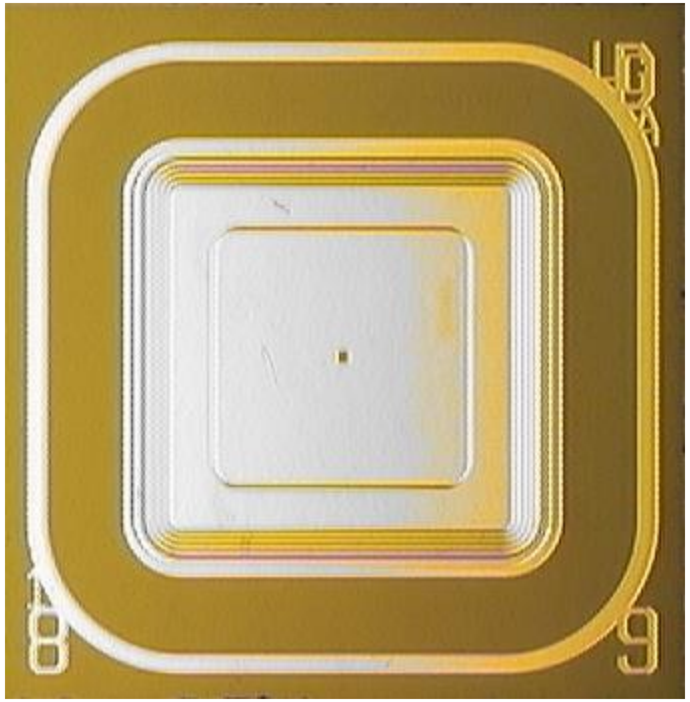
Backup Slides

How LGAD works

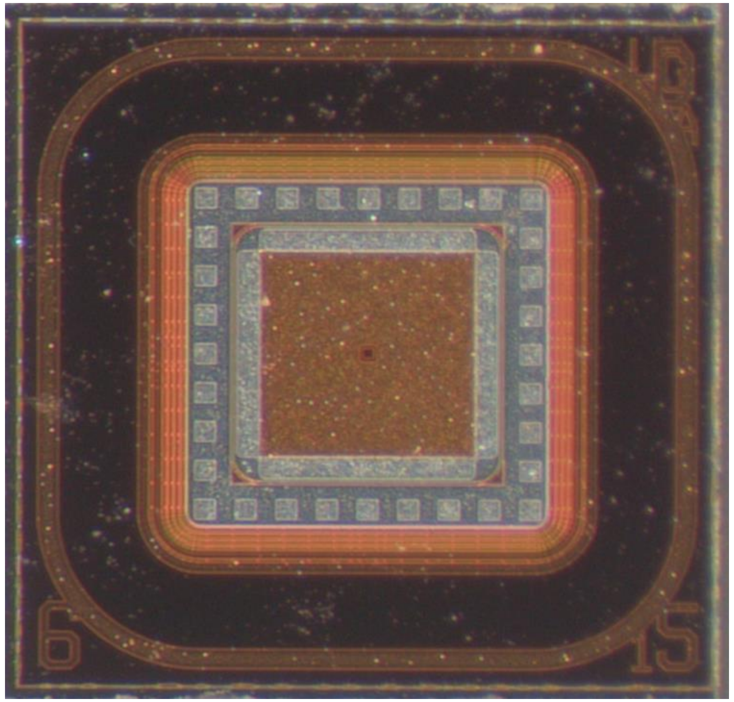


In silicon sensors, charge multiplication happens when charge carriers drift in a region with an electric field (E) greater than about 300 kV/cm. The additional P+ (or gain) layer, when depleted, locally generates an electric field high enough to activate the avalanche process.

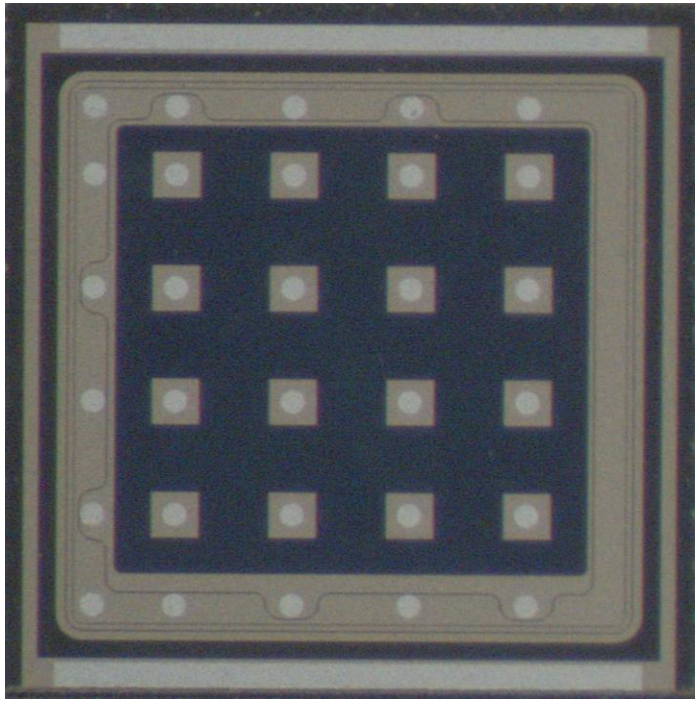
3 types of LGADs had been irradiated at Fermi National Accelerator Laboratory (FNAL) by 400 MeV protons 2×10^{14} to 2.5×10^{15} neq/cm^2



W3045 DC-LGAD
50um thick active layer
1um gain layer thickness

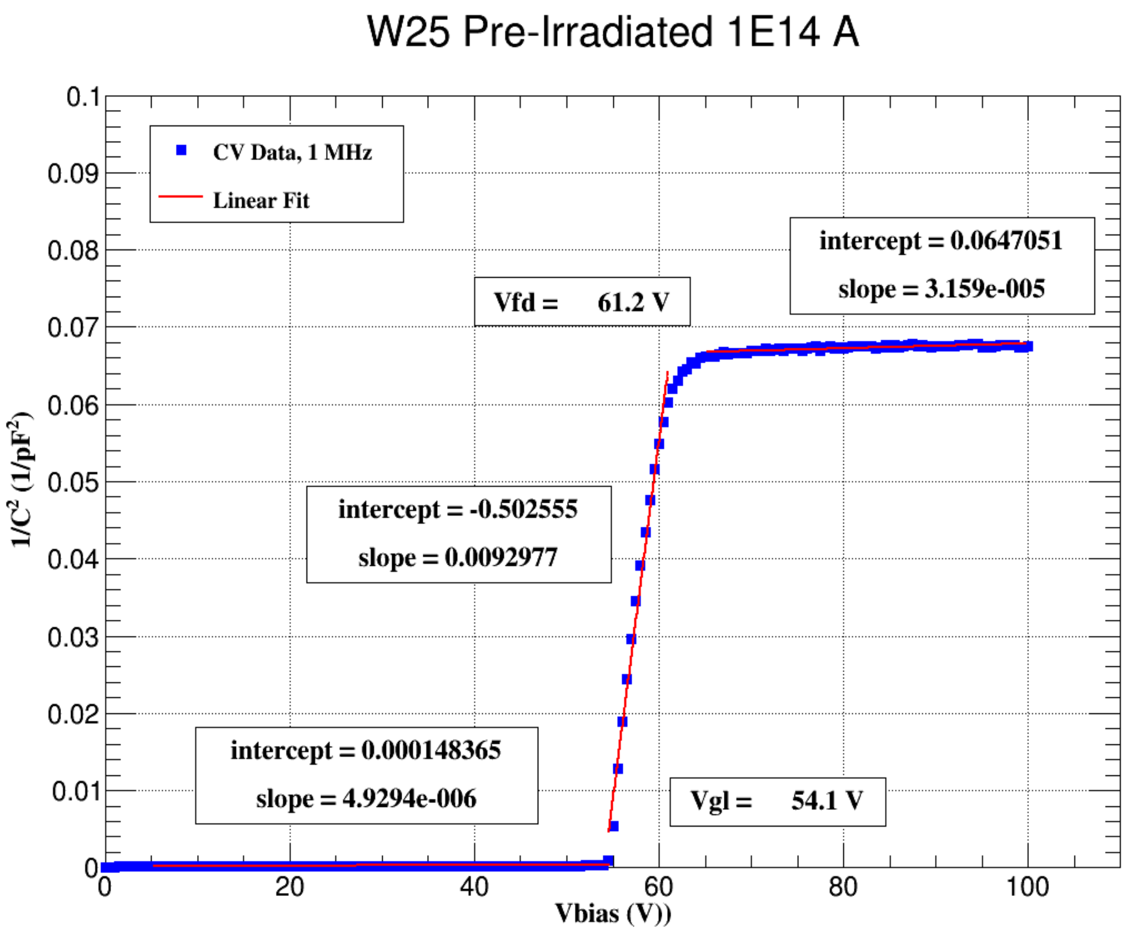


W3076 DC-LGAD
20um thick active layer
1um gain layer thickness



W3080 pixel AC-LGAD
20um thick active layer
1um gain layer thickness

CV Measurements are used to extract the gain layer depletion voltage V_{gl} and full depletion voltage V_{fd}



The depletion voltage of the gain layer depends on the dopant concentration, which is impacted by radiation fluence

$$V_{gl} = \frac{qN_A w^2}{2\epsilon}\left(1+2\frac{d}{w}\right)$$

Dopant Concentration (N_A)

Electron charge (q)

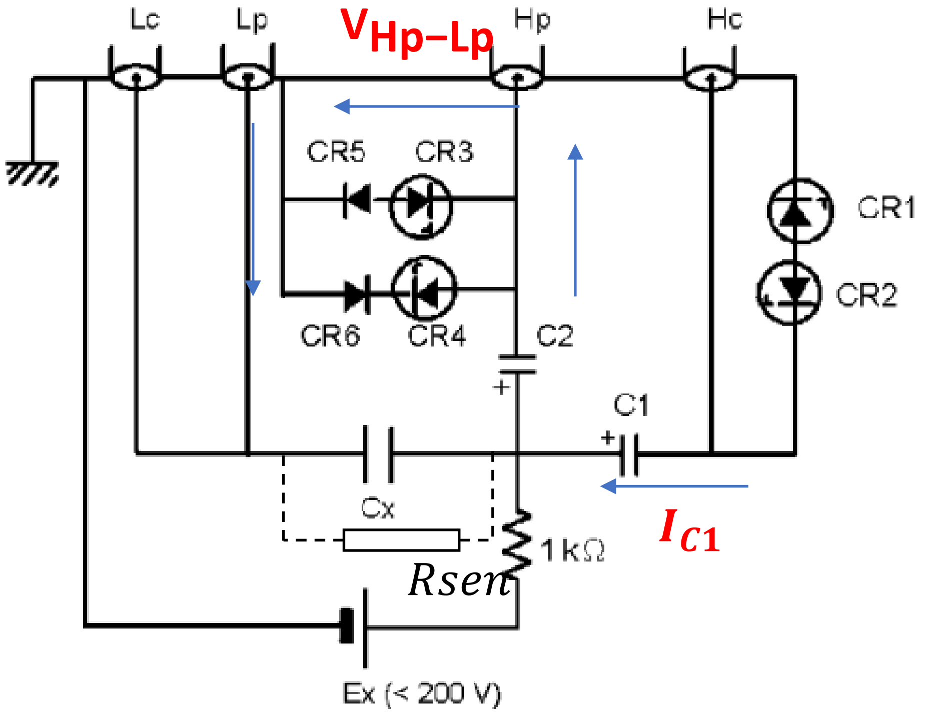
Gain Layer depth (d)

Gain layer depletion voltage (V_{gl})

Permittivity of Silicon (ϵ)

Gain Layer Thickness (w)

Manufacturer recommended bias isolation box was used for the CV measurements. Gamma-irradiation can cause surface damage and lower the equivalent parallel resistance of the detector. A study of how the values of the parts in the circuit can affect the measurement is needed.



$$C_{measured} = Re[\frac{1}{j\omega}(I_{C1}/V_{Hp-Lp})]$$

where Cx: Sample capacitor

Ex: External DC bias voltage source

C1: Blocking capacitor

Capacitance value ≥ $\frac{1}{10\pi f}$

(f: measurement frequency (Hz))

DC withstand voltage: > Ex

C2: Blocking capacitor

Capacitance value: 1 μF

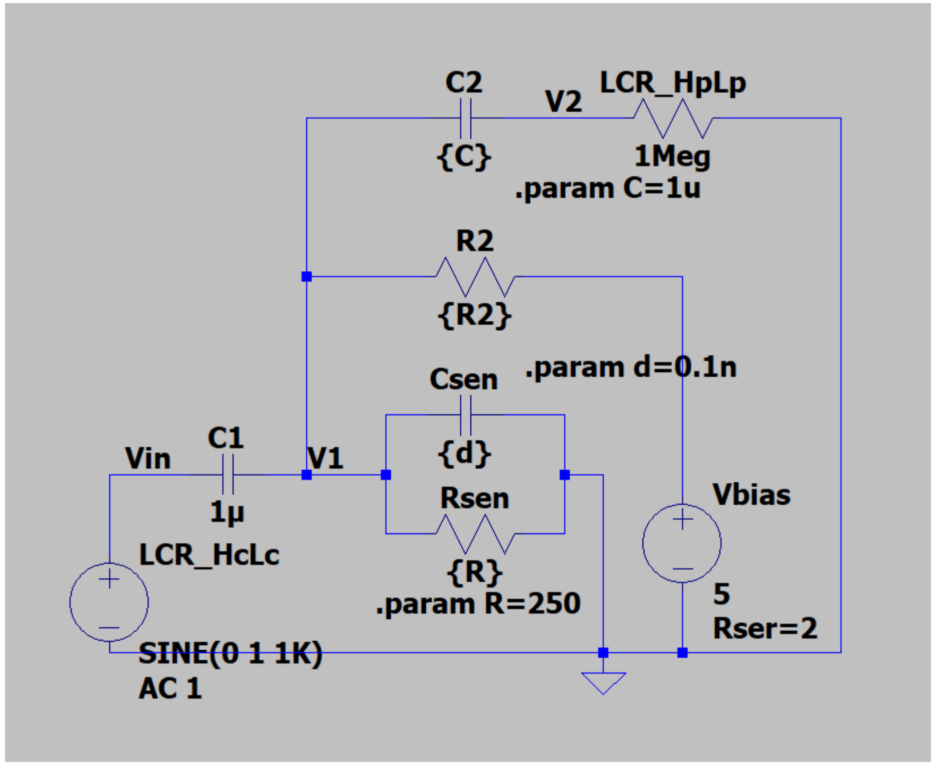
DC withstand voltage: Ex

CR1, CR2: Diode-zener, 47 V, 5% 1 W

CR3, CR4: Diode-zener, 3.3 V, 5% 1 W

CR5, CR6 : Diode-power, 200 V, 1 A

Smaller equivalent parallel resistance of the DUT can cause bigger discrepancy between the measured value and real value of the DUT capacitance

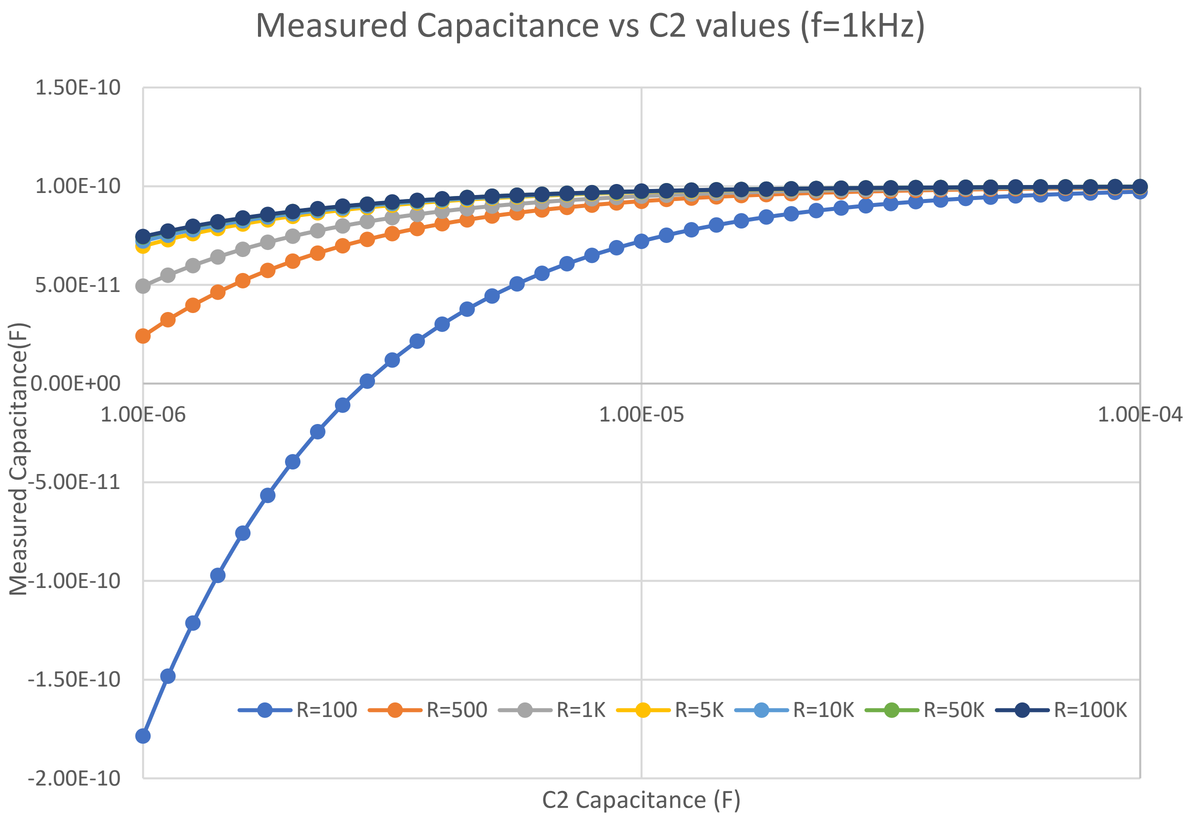


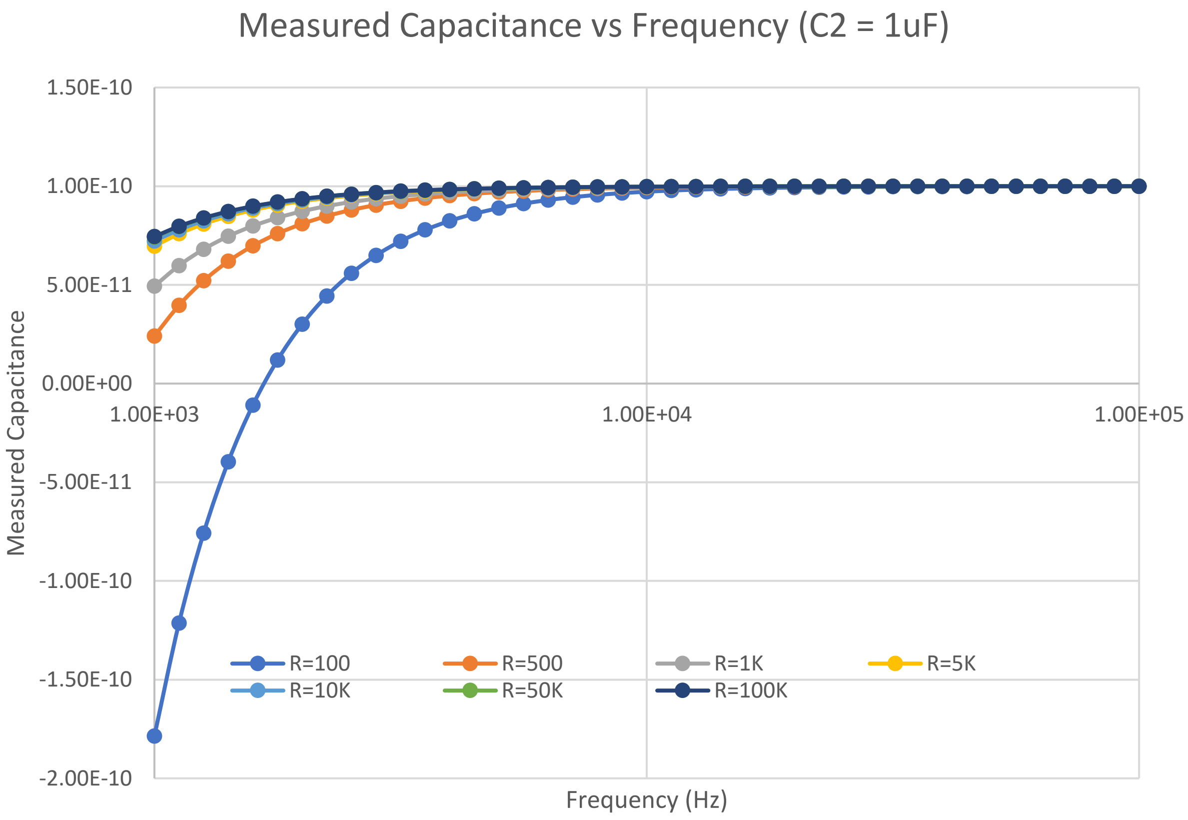
$$C_{measured} = C_{sen} - \left(\frac{1}{Rsen} + \frac{1}{R2}\right)\frac{1}{C_2 R_{HpLp}\omega^2}$$

$$R_{sen} = R_{bulk}(\omega, V_{bias}) \parallel \left[\mathrm{R_{intpad}}(\omega, V_{bias}) + \mathrm{R_{GR}}(\omega, V_{bias})\right]$$

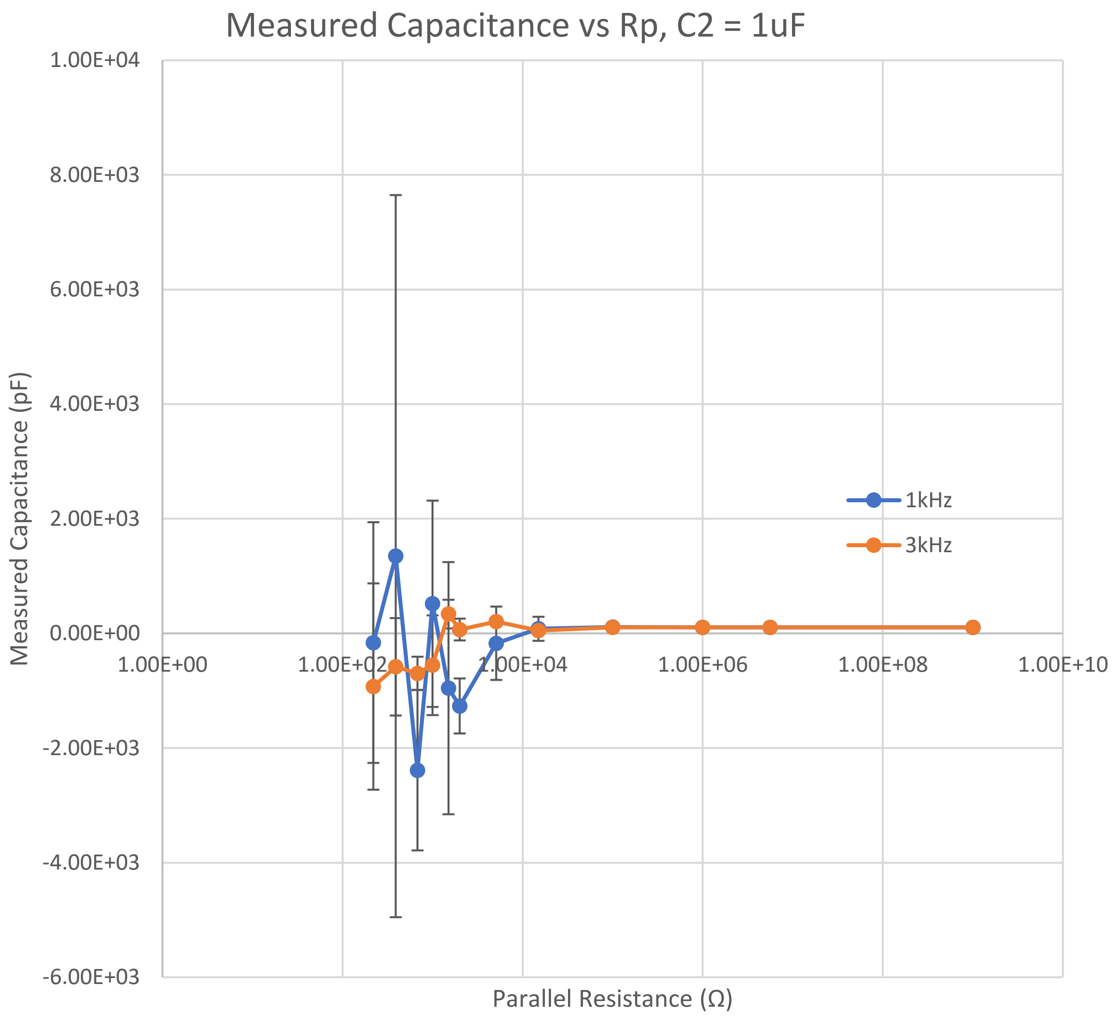
Bigger C_2, ω can make error smaller. However, too small Rsen requires an impractically big C2.
Bigger $R2$ can reduce error. However, R2 can't not be too big because it would take too much time to make Vbias stable.

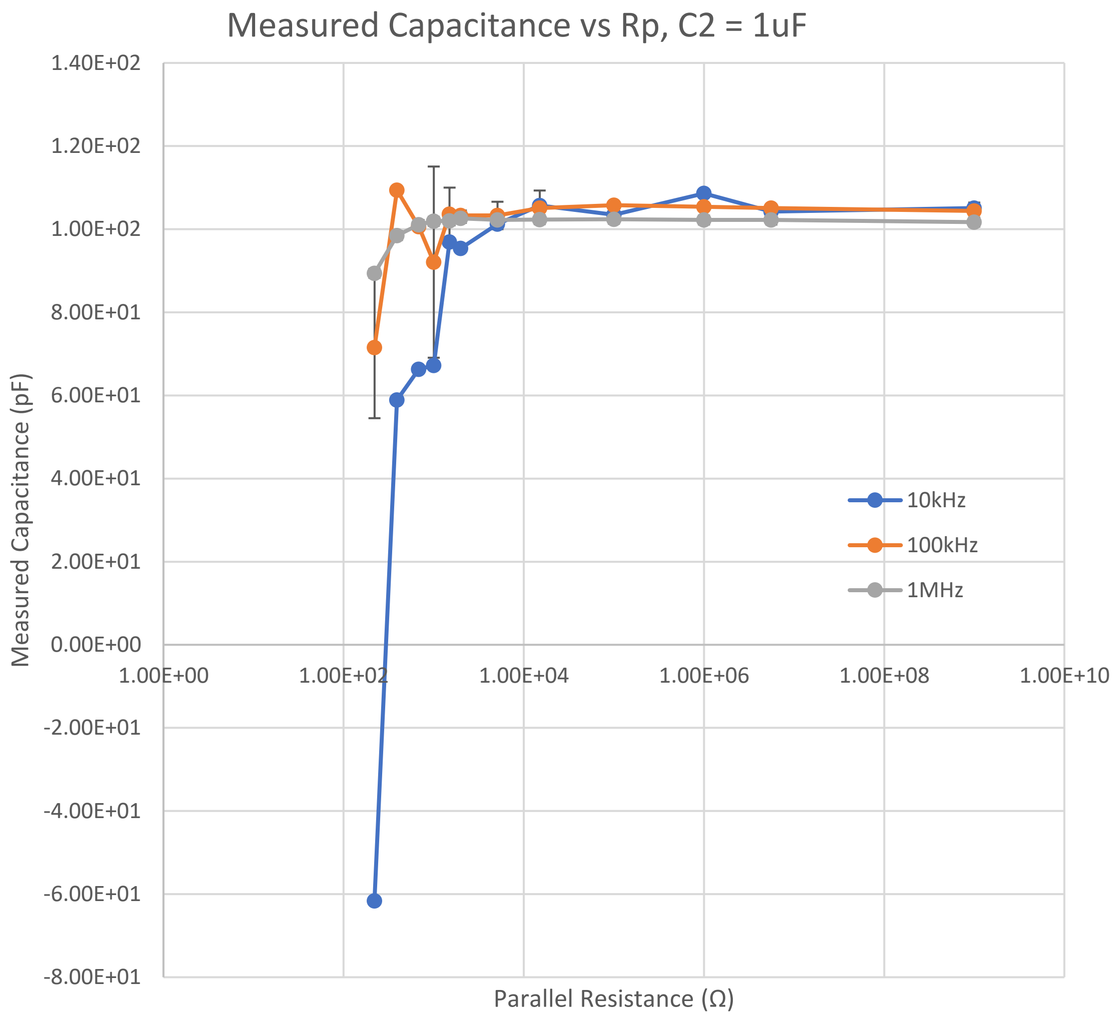
Simulation with LTSpice shows that the error decreases as C2 increases, while as frequency and parallel resistance increase.



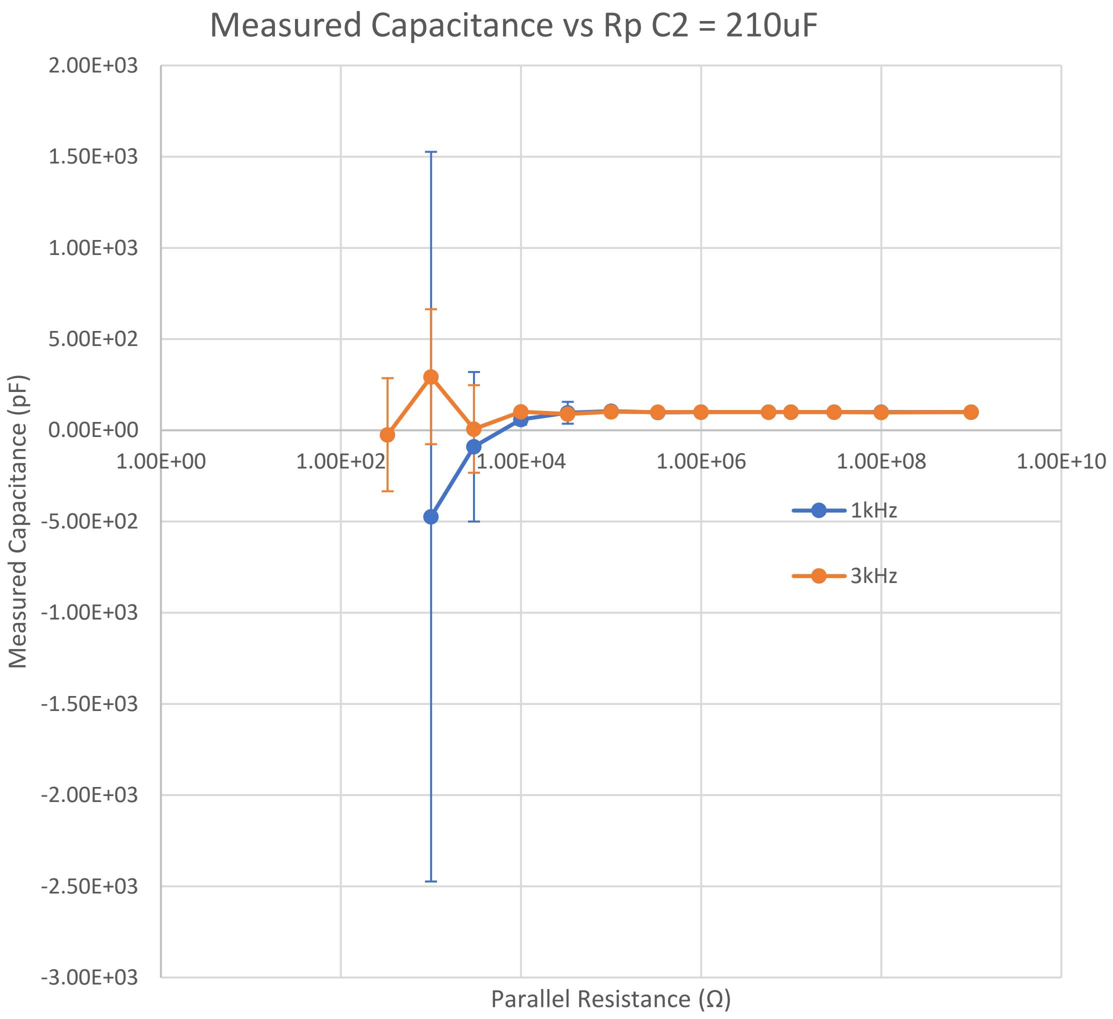


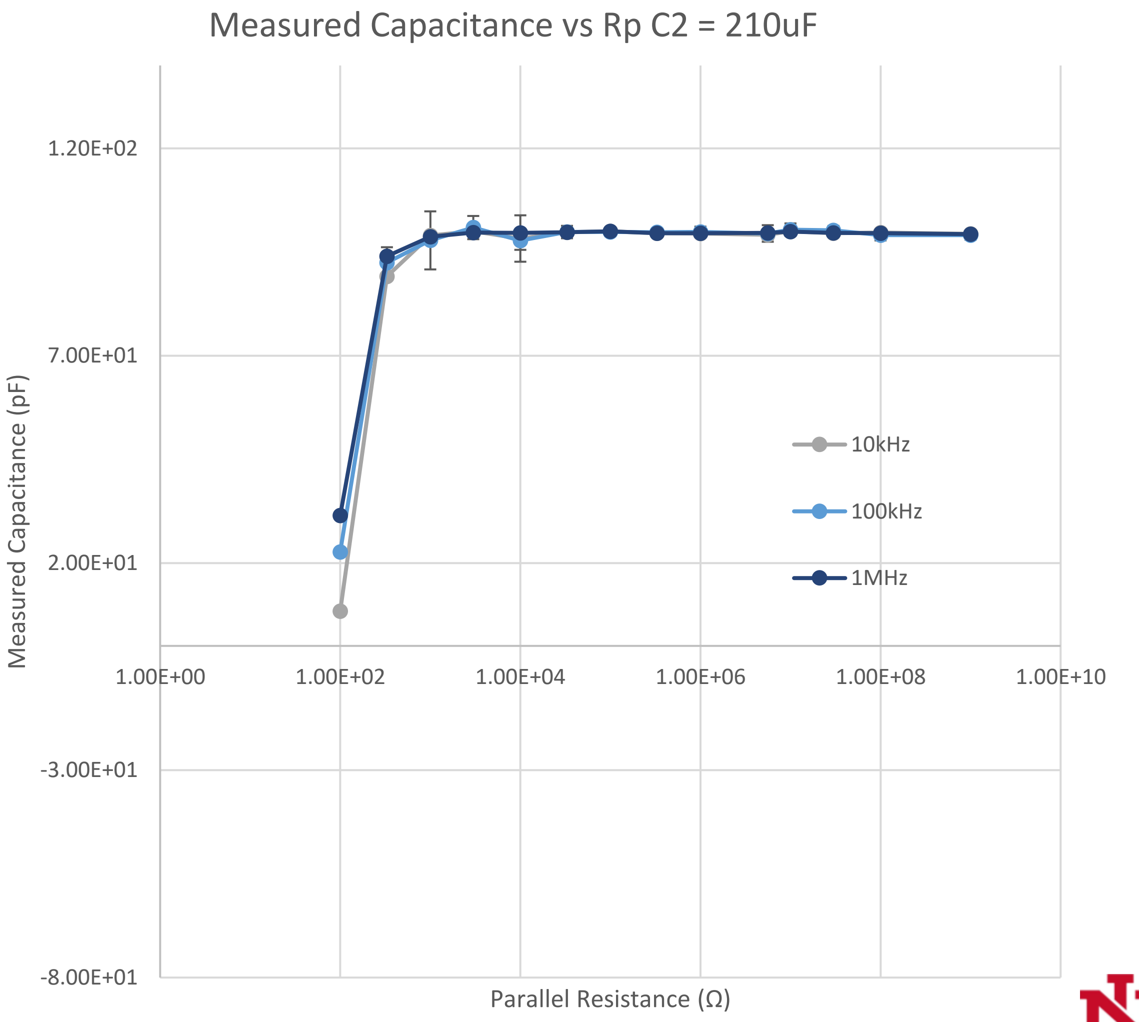
Test Measurement with a 100pF ceramic capacitor and different parallel resistors shows that lower Rp can cause bigger errors.



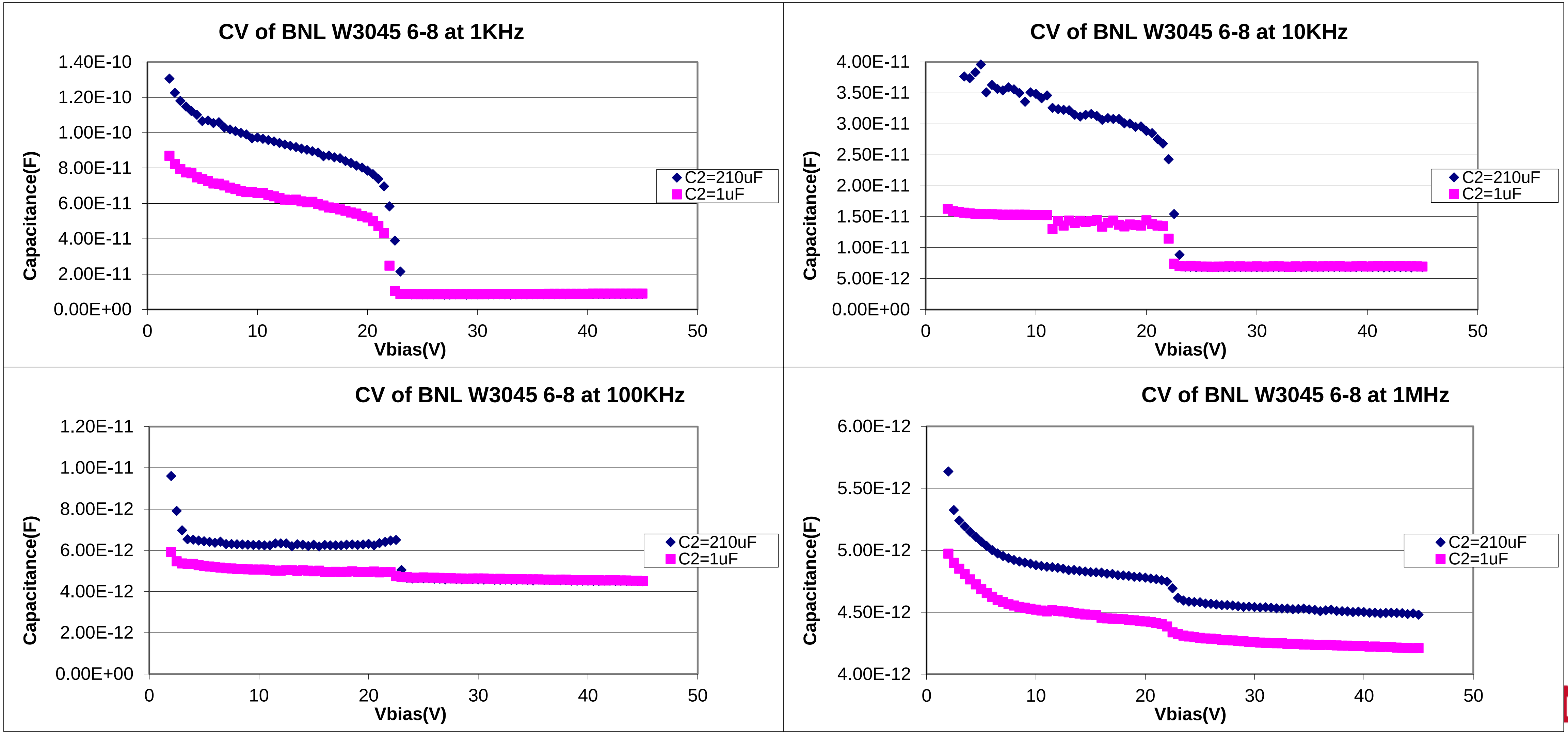


Test Measurement with a 100pF ceramic capacitor shows a bigger C2 (=210uF) can improve the capacitor measurement.

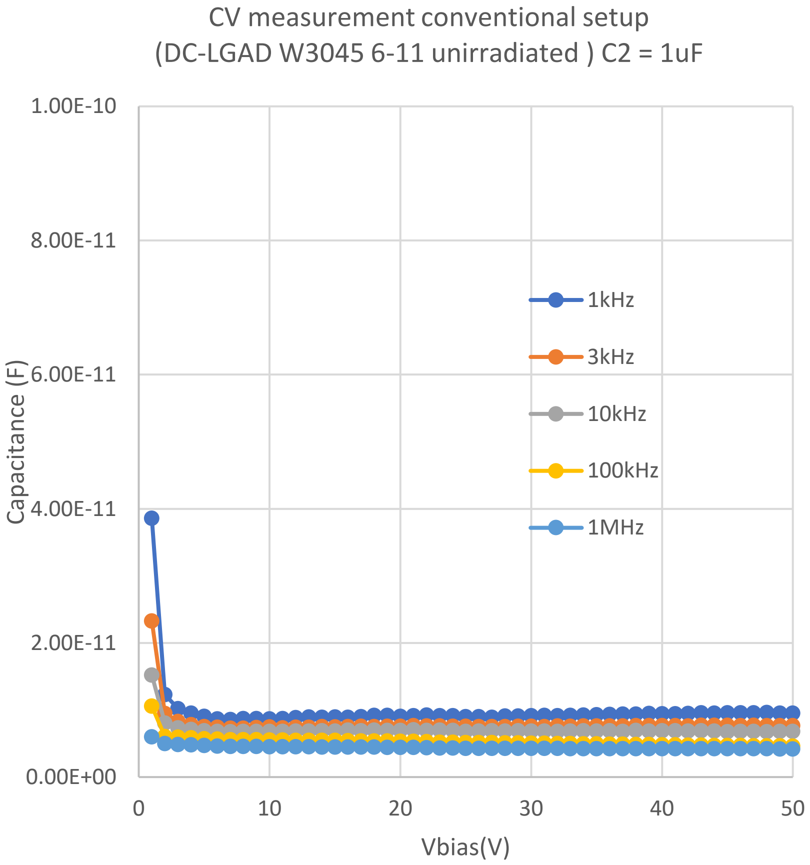


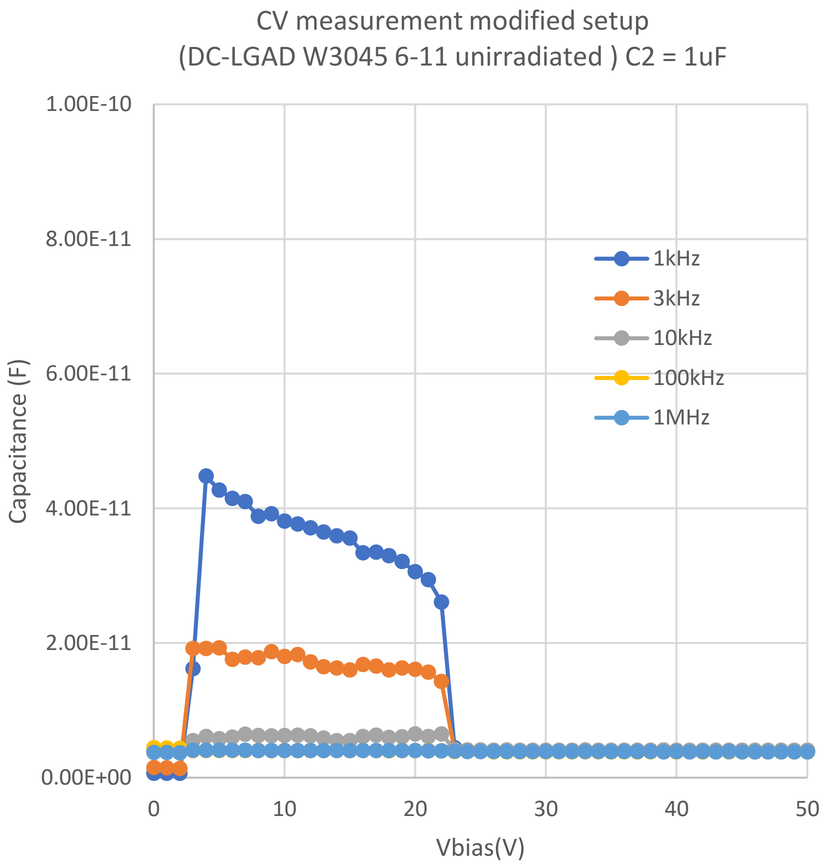


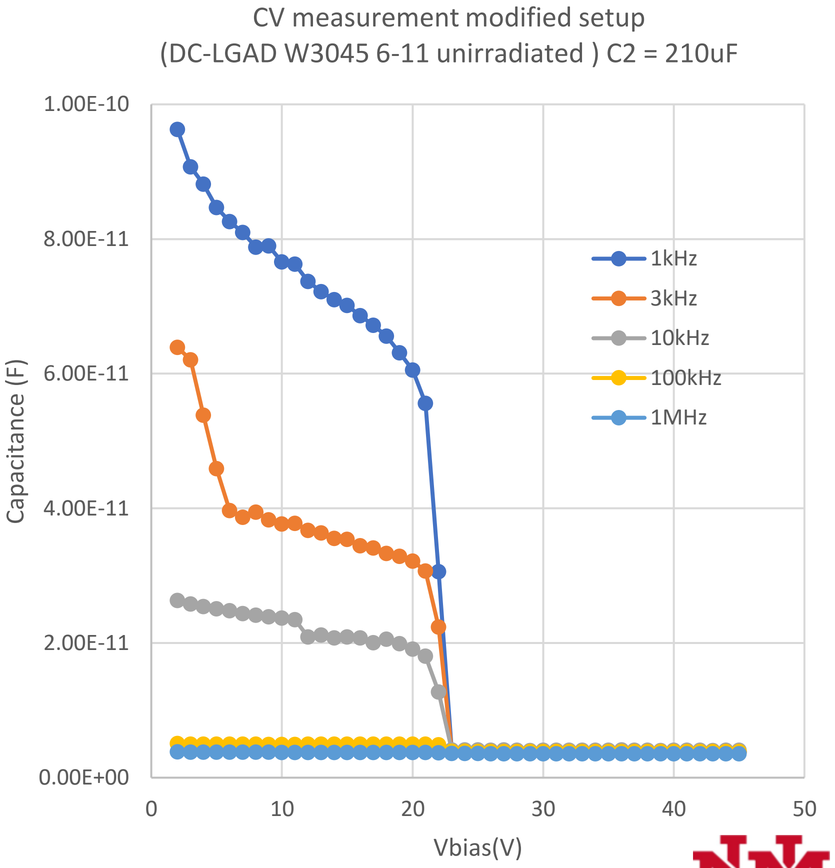
Bigger C_2 can make error smaller. However, measured capacitance also decreases as test frequency increases.



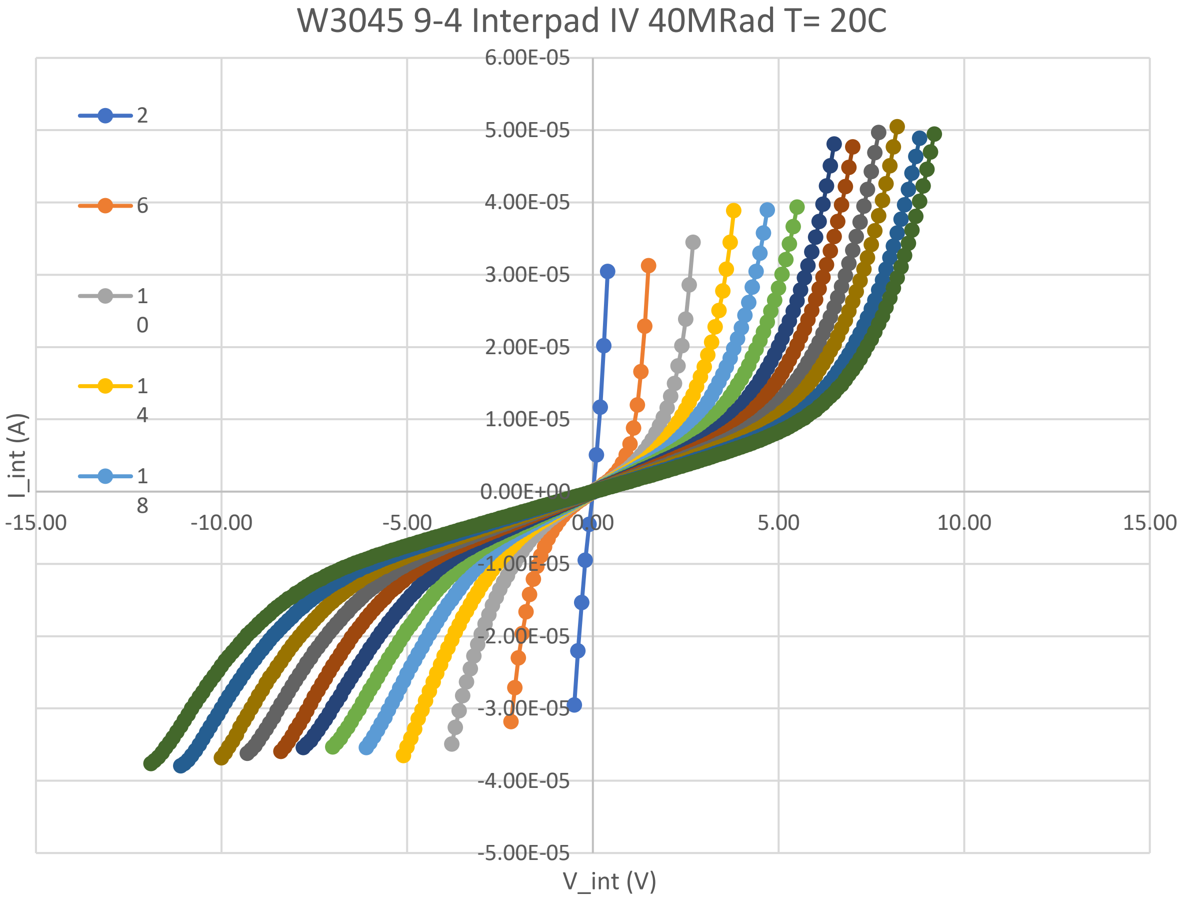
With the new setup and a big C2, the feature is much clearer than the conventional setup.

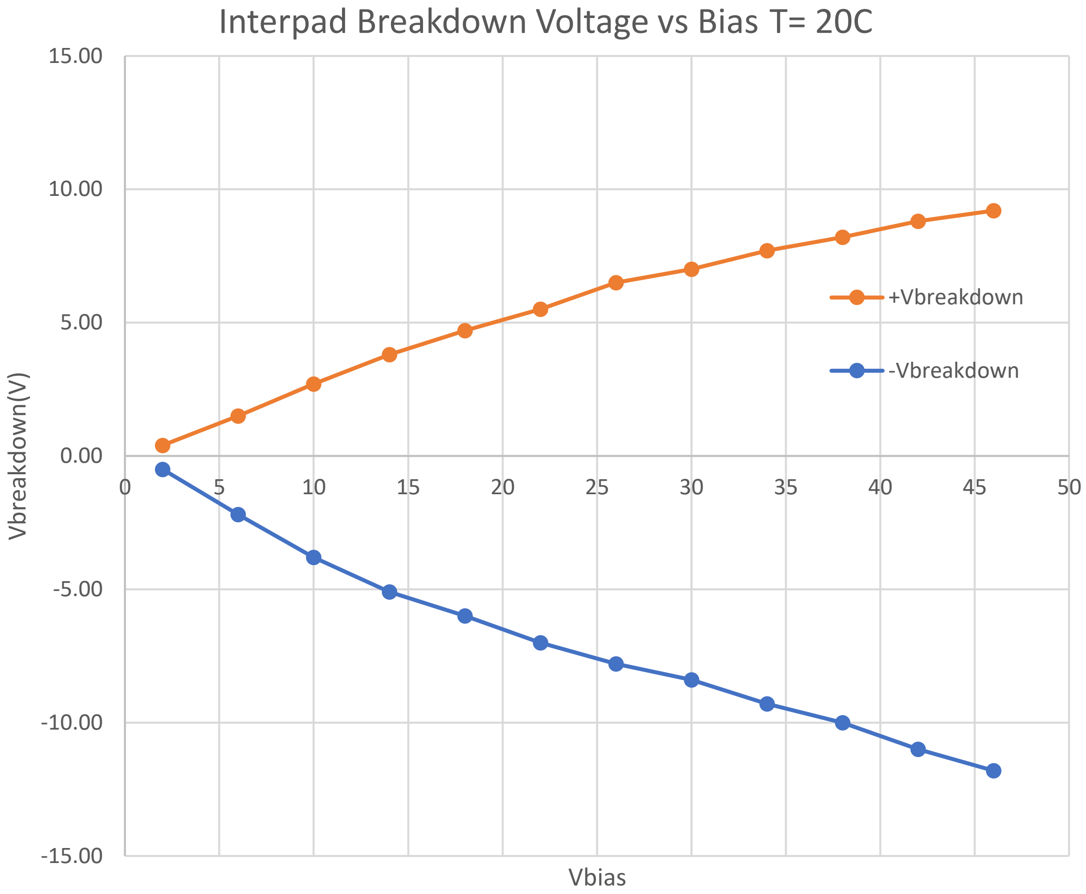






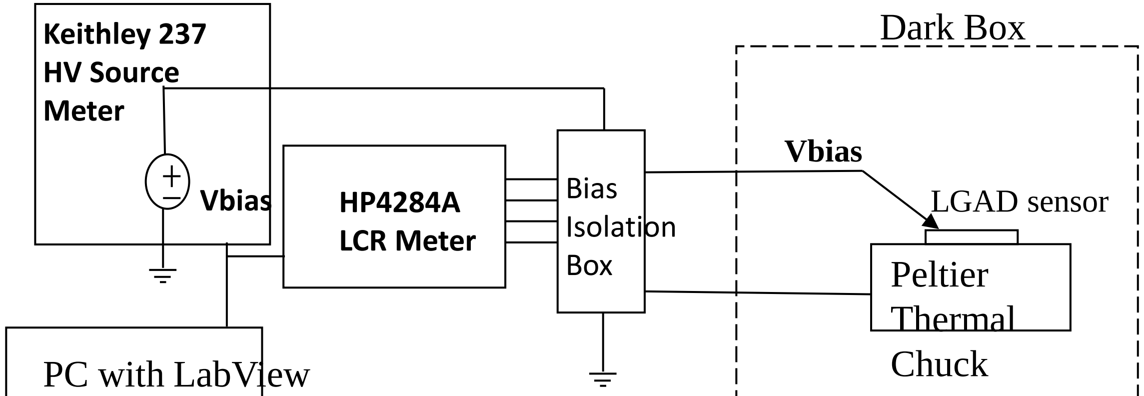
For gamma irradiated sensors, the inter-pad current is a few orders of magnitude higher.



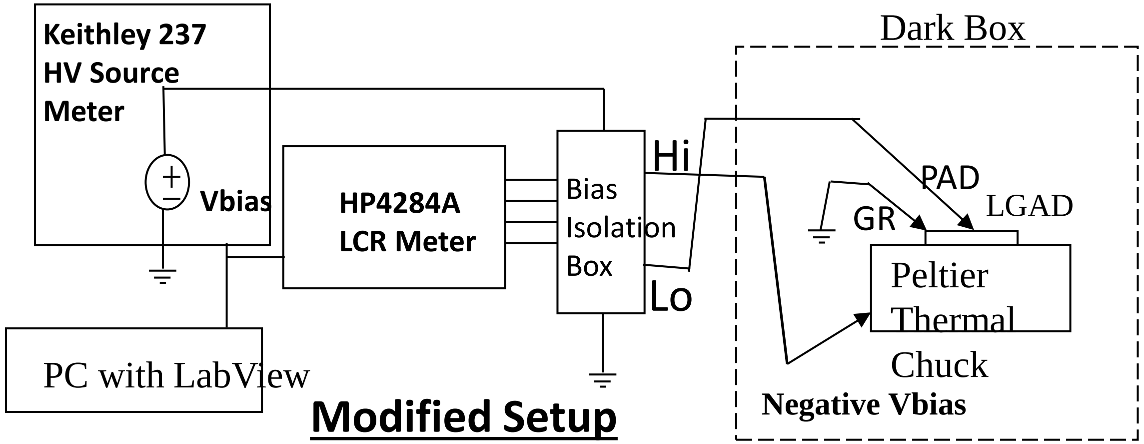


W3045 9-4 gamma irradiated @ 40 MRad DC-LGAD

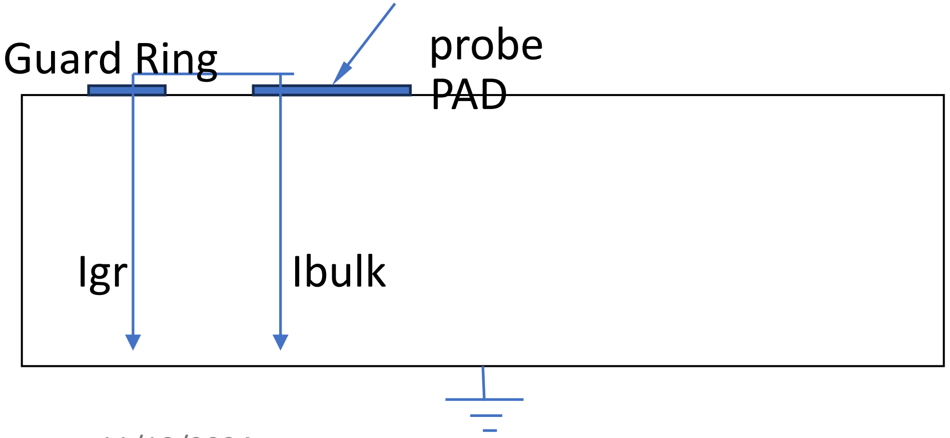
If only one probe is landed on PAD(D) with Guard Ring floating, large guard ring current must flow from the probe, it causes breakdown behavior, and results in a low inter-pad effective resistance (dVint/dIint).



Conventional Setup



Modified Setup

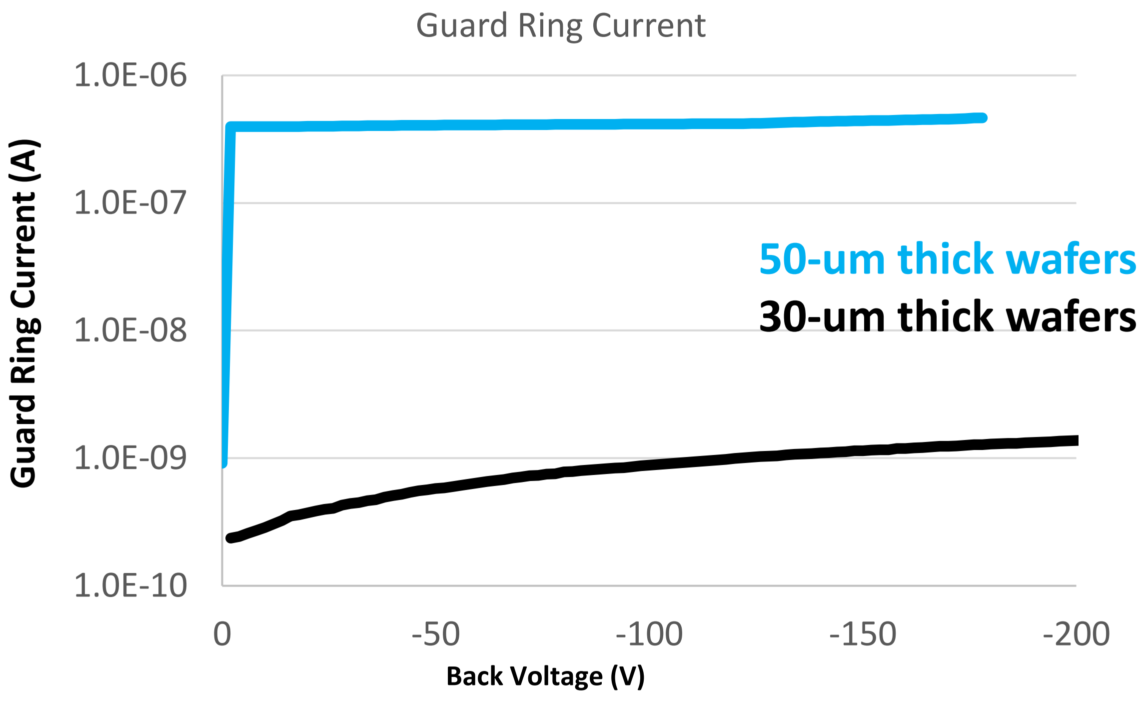


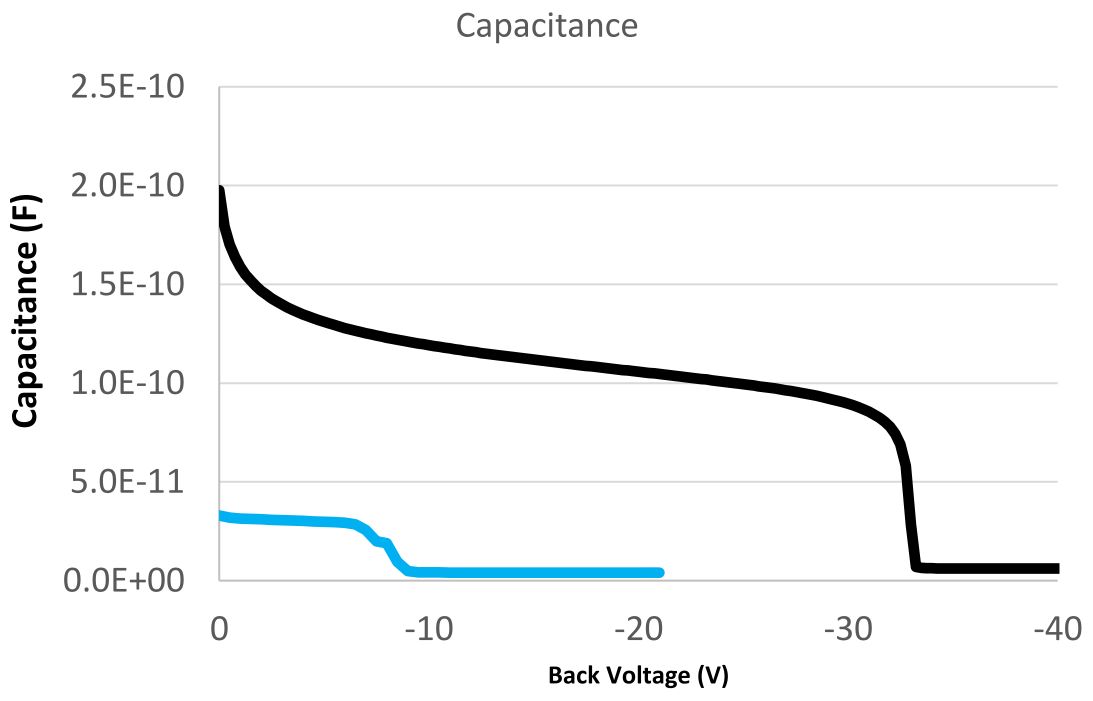
Our conventional setup could make the inter-pad breakdown and the effective inter-pad resistance (dVint/dIint) low with high guard ring current.

A modified configuration is used to make the guard ring grounded with negative bias voltage applied to the back of the LGADs. The test level also affects capacitance measurement (more in backup slides).

Strange effect on “thick” epitaxial layers

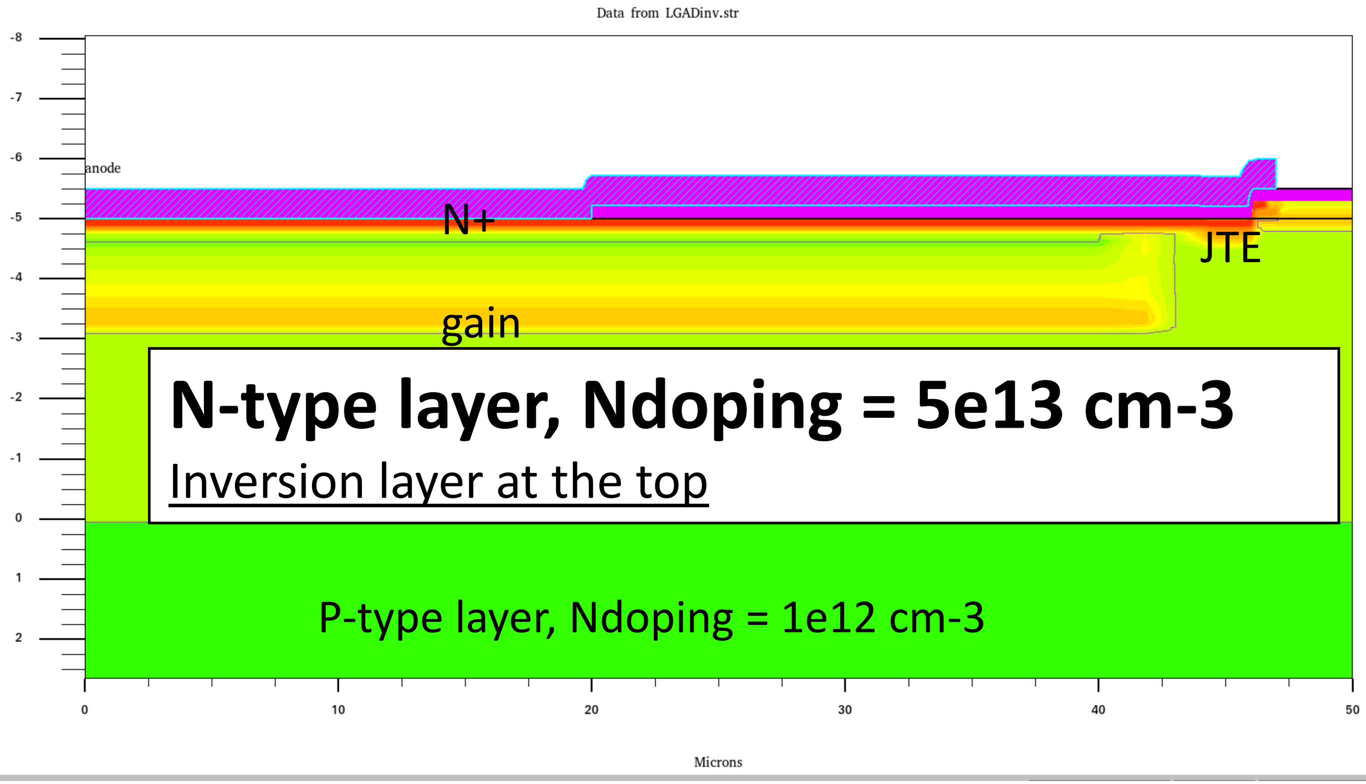
On devices built on 50-um thick wafers, C-Vs are odd – the gain layer seems not to be present – and guard ring current high and erratic.
Effect not present in devices built on 20 and 30 um thick epi, which have been processed in parallel.
Gain is however present in 50 um thick devices, as experienced with gain measurements



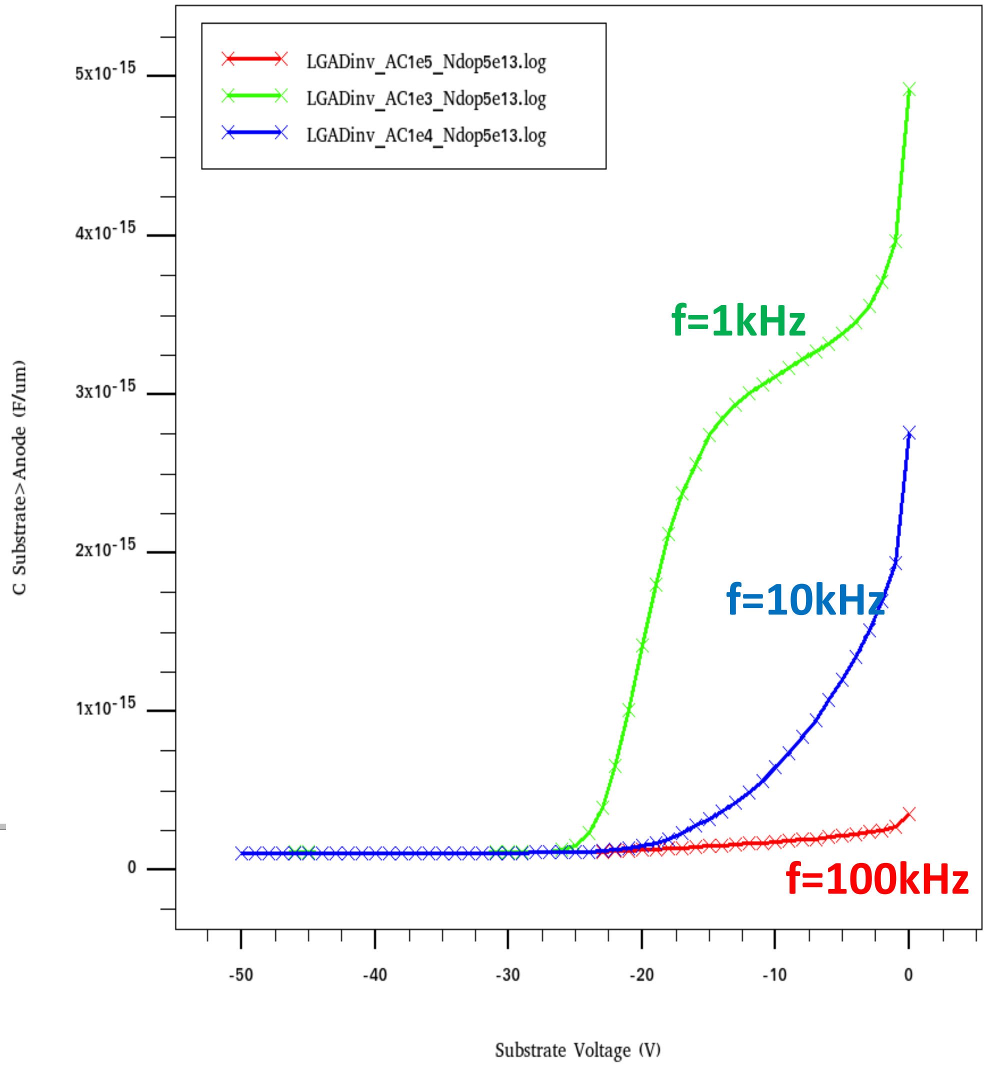


Effect seen also by other supplier and explained with an “inversion” at the interface.
Solution? Start with initial substrates of lower resistivity – if substrate is depleted at > 5V, no effect on LGAD performance

TCAD simulations



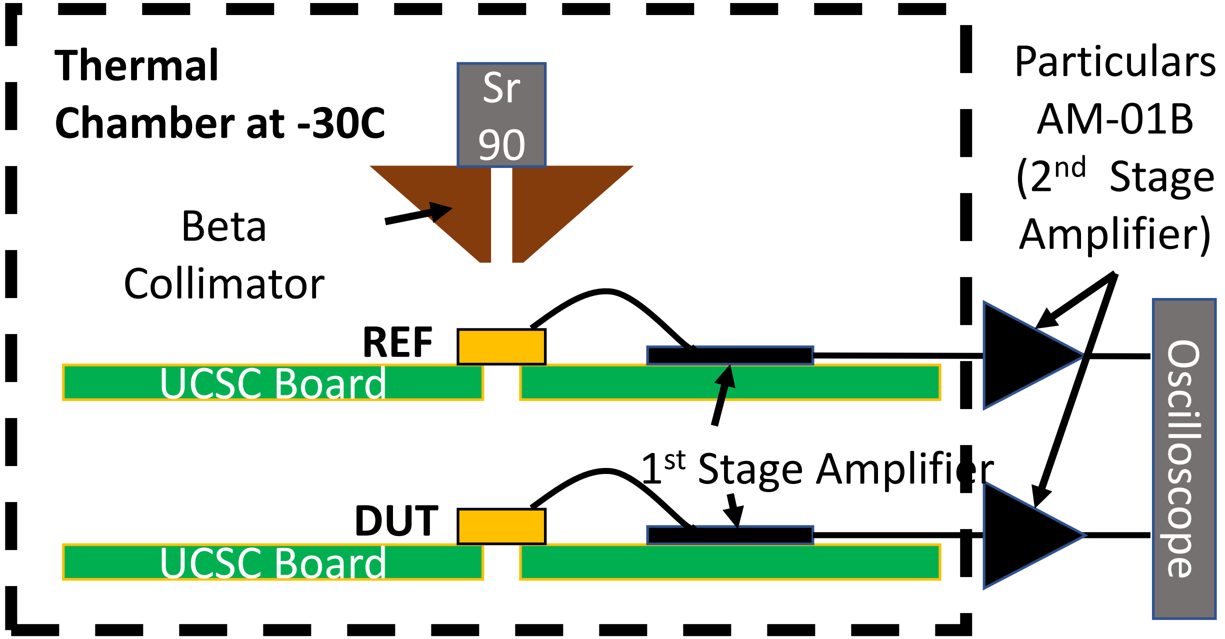
Capacitance for different frequencies

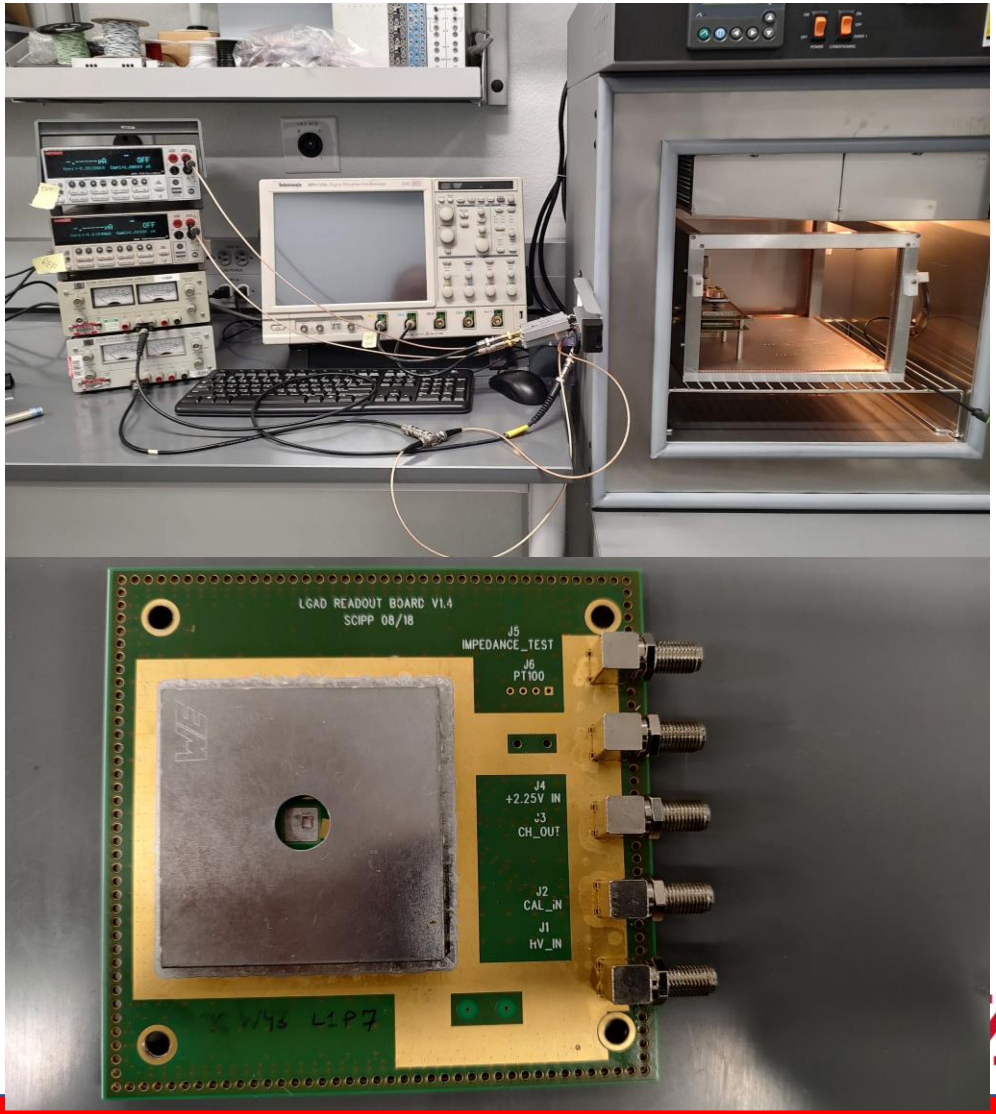


The effect can be simulated qualitatively, although we cannot measure the degree of inversion happening at the surface, nor its extension or effective doping.

Correct CV for very low f

β-source setup is used to study the timing performance of LGADs

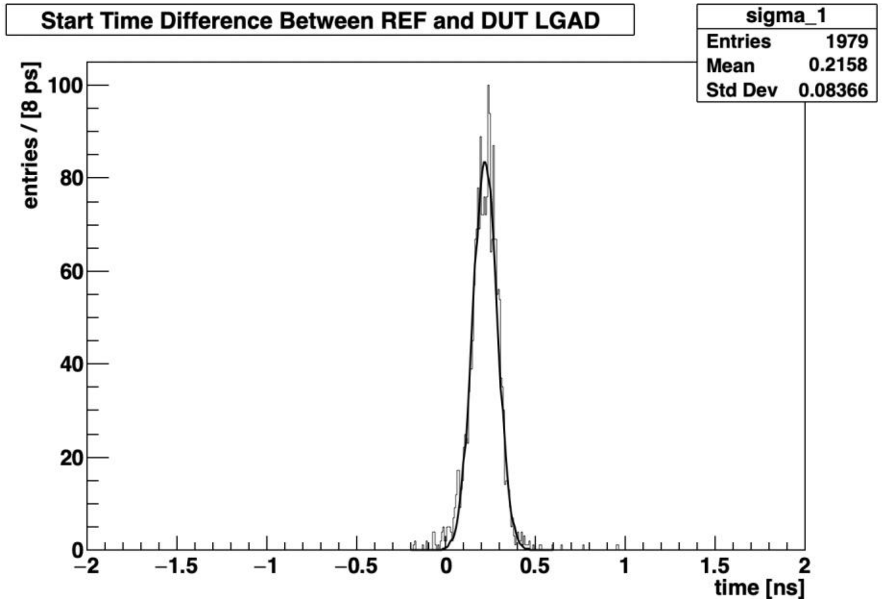


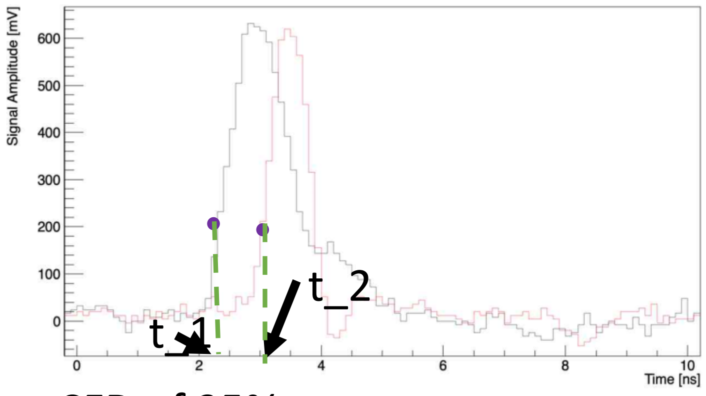


- LGADs are mounted on the single channel readout board developed by UCSC.
- Tektronix DPO 7254 Oscilloscope with 2.5GHz bandwidth, 40GS/s sampling rate is used.
- Shortest cables are used to connect to the oscilloscope for best signal-to-noise performance.

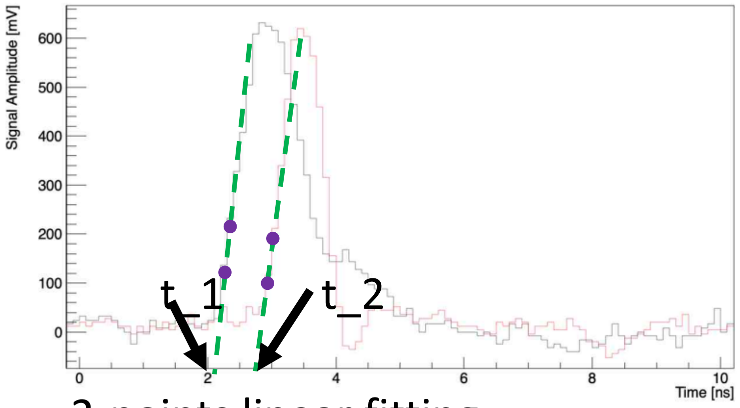
3 methods were used to calculate the resolution

- Only signals triggering both REF and DUT channels are collected.
- The resolution is calculated from the temporal deviation of ~2000 events.
- Constant Fraction Discriminator (CFD) method of 25%, 2-point linear fitting, and 4-point linear fitting were used, the differences are within a few percent.
- Equation $\sigma_{tot}^2 = \sigma_{REF}^2 + \sigma_{DUT}^2$ is used to calculate the resolution.

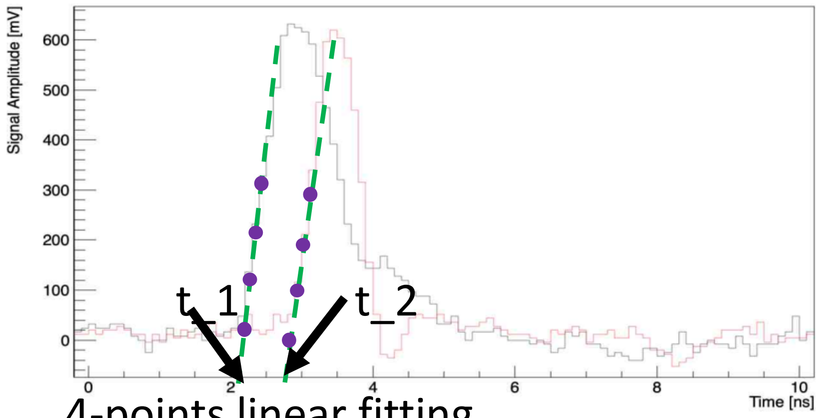




CFD of 25%



2-points linear fitting



4-points linear fitting

Laser TCT from Particulars is being set up.

Particulars Large Laser TCT system

Optical table

The actual design includes p-stops to limit inter-pad current, guard rings, and junction termination extensions which mitigate breakdown voltage, and other features.

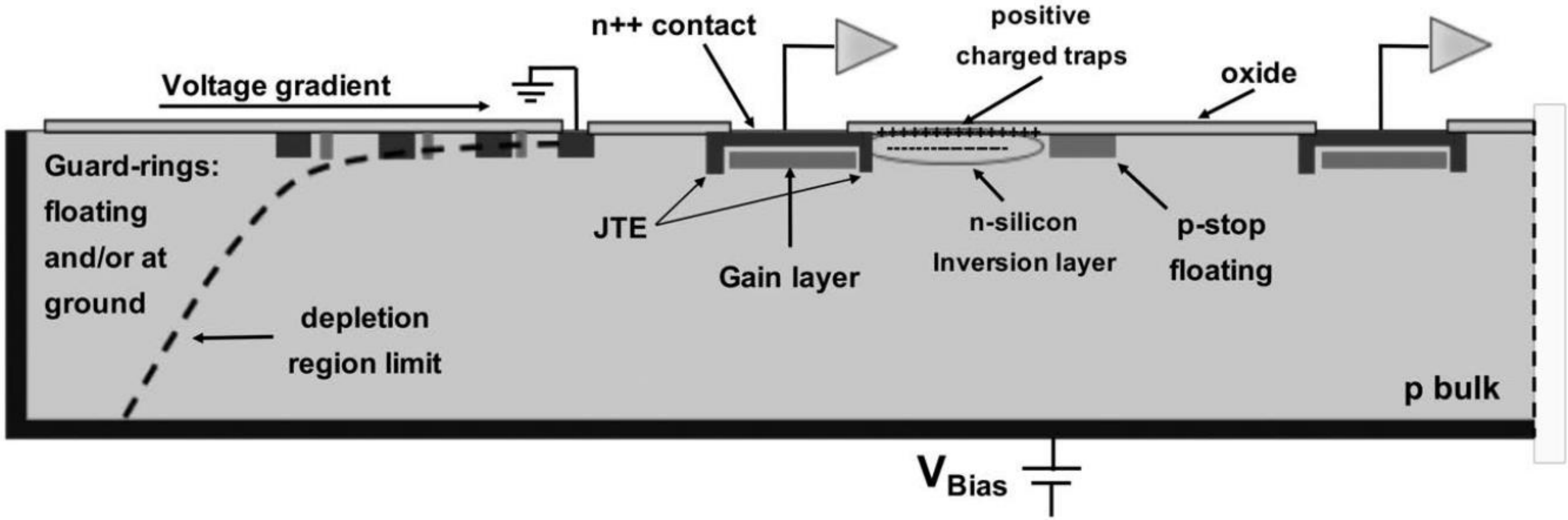


Figure 2.21 Cross cut of a multi-pads UFSD (not to scale) with a schematic view of the building blocks of the device. From the device physical edge: guard-rings, pad with JTEs, inter-pad region with *p*-stop.

An Introduction to Ultra-Fast Silicon Detectors p33

An Introduction to Ultra-Fast Silicon Detectors p84

Using the information provided by the $C(V)$ measurements, it is possible to:

1. extract the gain layer implant profile (amplitude, width, depth) by computing the active doping concentration $N_A(d)$ as a function of depth d. This is obtained by first calculating d from the value of C with

$$d = \frac{\varepsilon_{Si} A}{C} \tag{4.4}$$

and then the doping density at that depth d with:

$$N_A = \frac{2}{\varepsilon_{Si} q A^2 \frac{\partial 1/C^2}{\partial V}}, \tag{4.5}$$