4th DRD3 week
on Solid State Detectors R&D
Nov 12th, 2025

THE UNIVERSITY OF NEW MEXICO

Response of AC-coupled Low Gain Avalanche Detectors to Ionizing and Non-ionizing Radiation Damage

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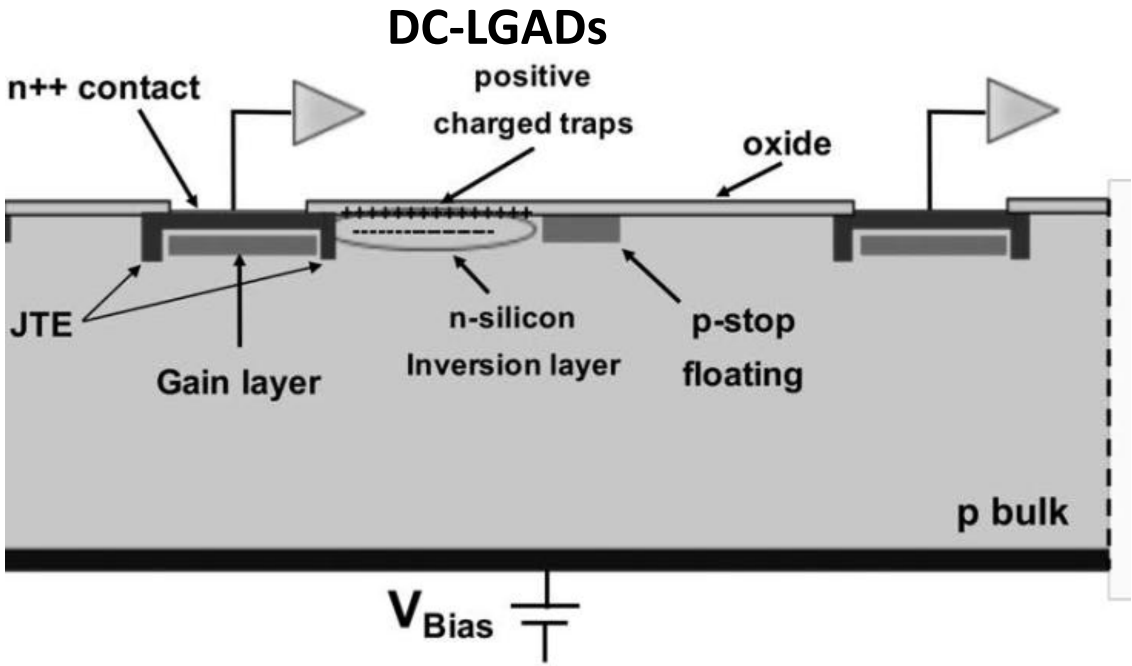
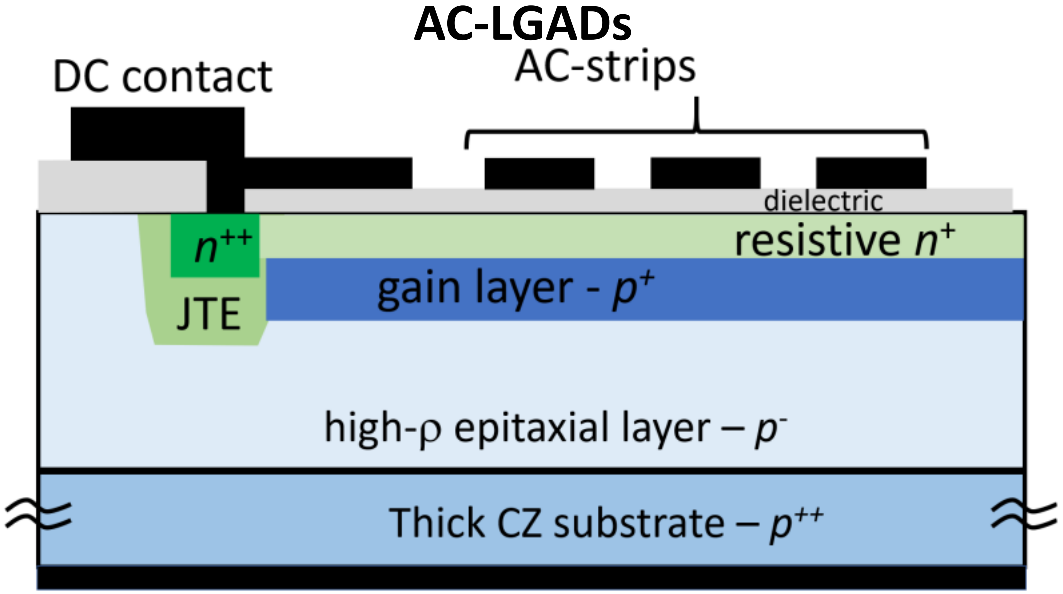
Introduction

- Low-Gain Avalanche Detectors (LGADs) have excellent timing performance due to a doped layer that provides a moderate gain (~10’s). Traditional DC LGADs’ spatial resolution is limited to ~ 1mm.
- Smaller pitches can be achieved in AC-coupled LGADs (AC-LGADs) by using a continuous gain-layer and capacitively coupling the signals through a thin dielectric layer to smaller AC pads.
- Current and capacitance vs Bias (IV/CV) characterization of unirradiated/gamma-/proton-irradiated LGADs designed at Brookhaven National Lab (BNL) have been studied at the University of New Mexico (UNM).
- Acceptor Removal constants were measured.

Difference between DC-LGAD and AC-LGAD



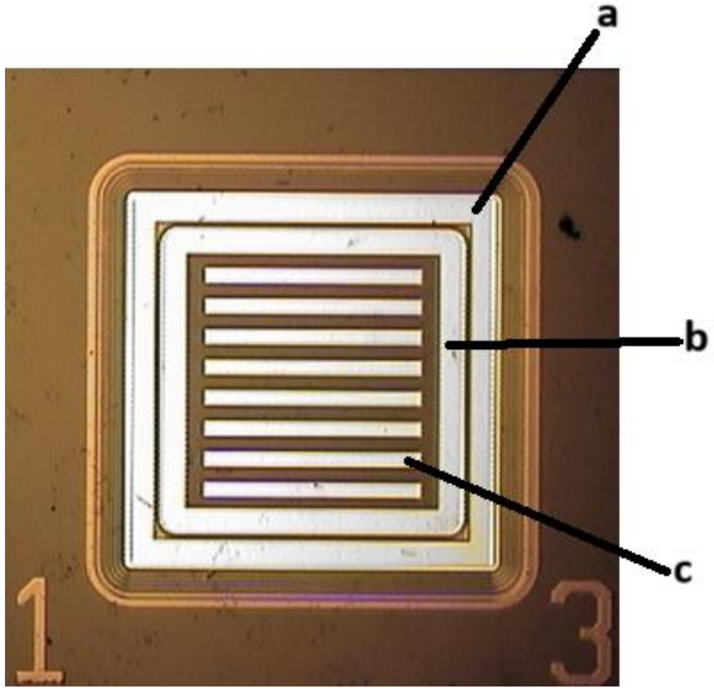


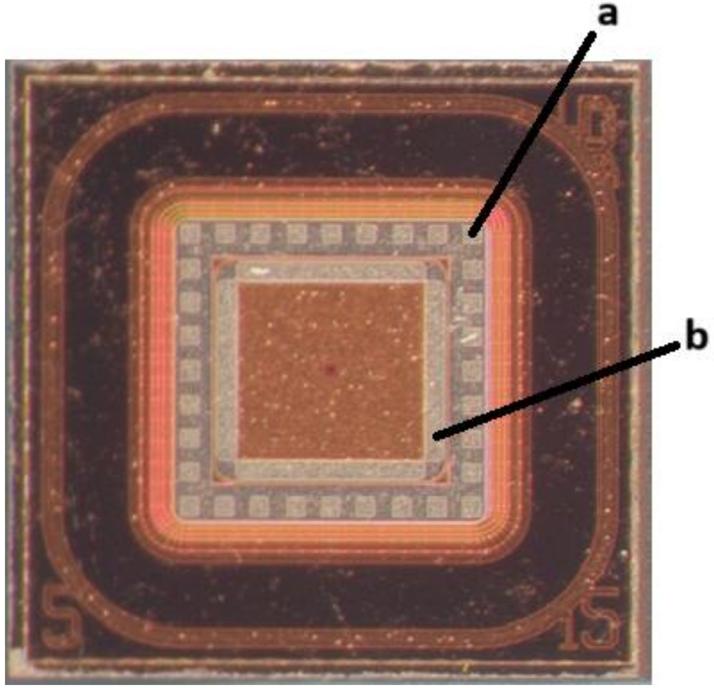
Junction Termination Extension (JTE) and p-stop/p-spray introduce no-gain region in traditional DC LGADs.

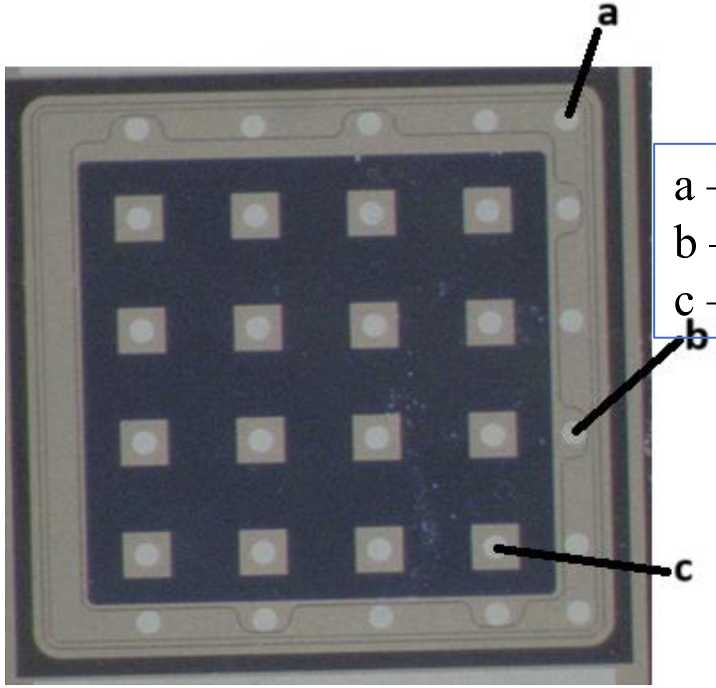
Signals can couple through the thin dielectric capacitively to AC-pads with smaller pitches.

- Thin high-resistivity epitaxial p-type substrate, ~tens of microns in thickness, atop a ~500 micron p^{++} Czochralski layer that provides ohmic contact and mechanical support.
- A doped layer that provides a moderate gain ~10's to provide large signals and make the timing resolution ~ 10's of ps.
- Traditional DC-LGAD: Due to the fill factor consideration, their spatial resolution is limited to ~ 1mm.
- AC-LGADs: by using a continuous gain-layer and coupling the signals capacitively through a thin layer of dielectric to smaller AC pads, the spatial resolution can reach ~10's of microns.

3 types of LGADs were irradiated by gamma and protons







a – guard ring
b – DC contact pad
c – AC pad or strip

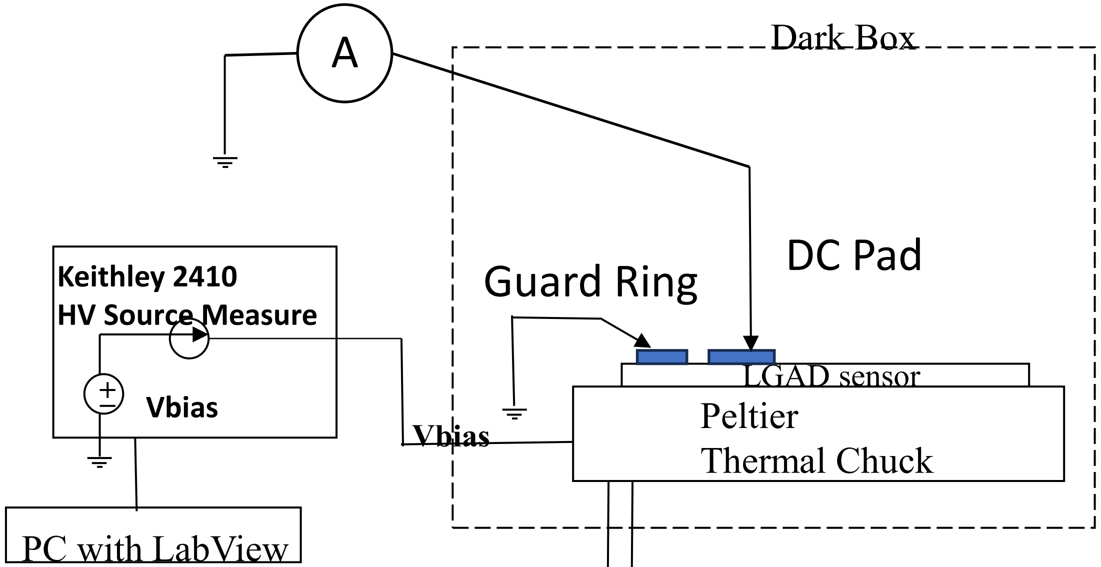
	AC-LGADs wafer 3073	DC-LGADs wafer 3076	AC-LGADs wafer 3080
Configuration	strip		pixel
Area of the n^{++} layer (mm^2)	2.05×2.05	1.3×1.3	2.05×2.05
Area of the gain layer (mm^2)	1.95×1.95	1.2×1.2	1.95×1.95
Thickness of the active volume (μm)	20	20	20
Applied radiation species	gamma	proton	proton

Gamma irradiation at Sandia National Laboratories' Gamma Irradiation Facility

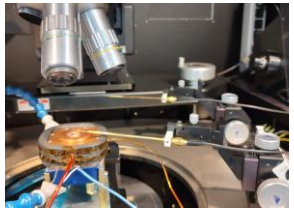
Proton irradiation (400MeV) at Fermi National Accelerator Laboratory

Configuration used for Current vs. Voltage (IV) Measurement

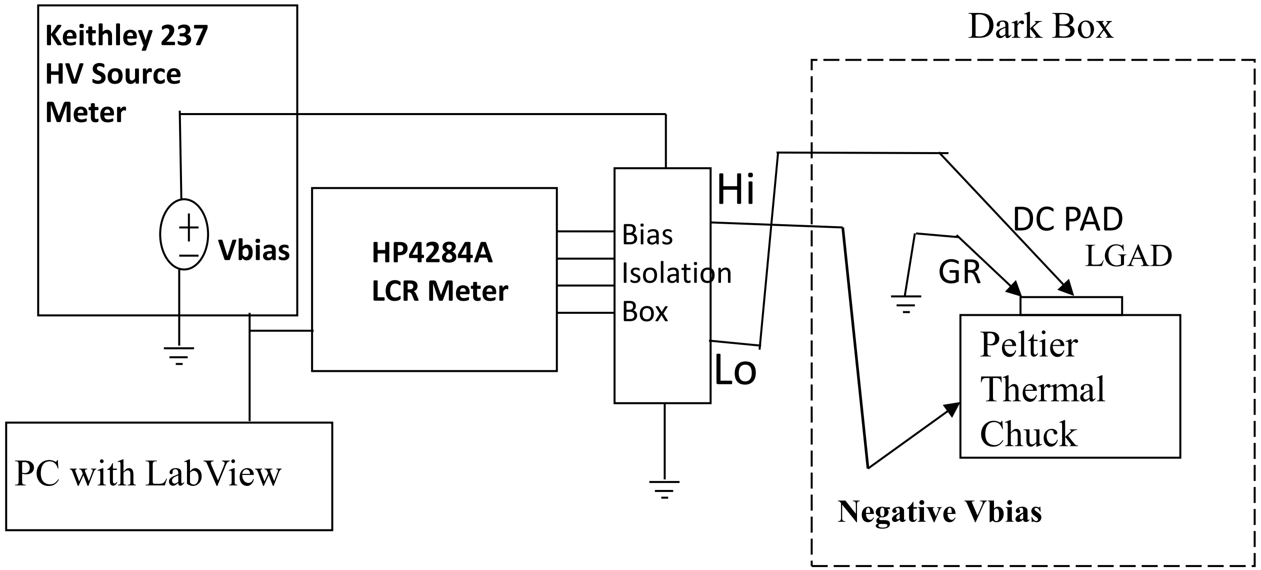
Keithley 6487 picoammeter powered through an isolation transformer



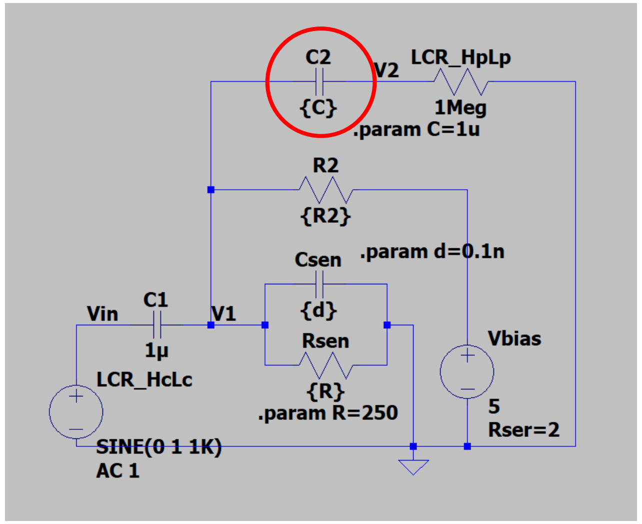
Peltier Constant Current Power Supply



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.



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

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

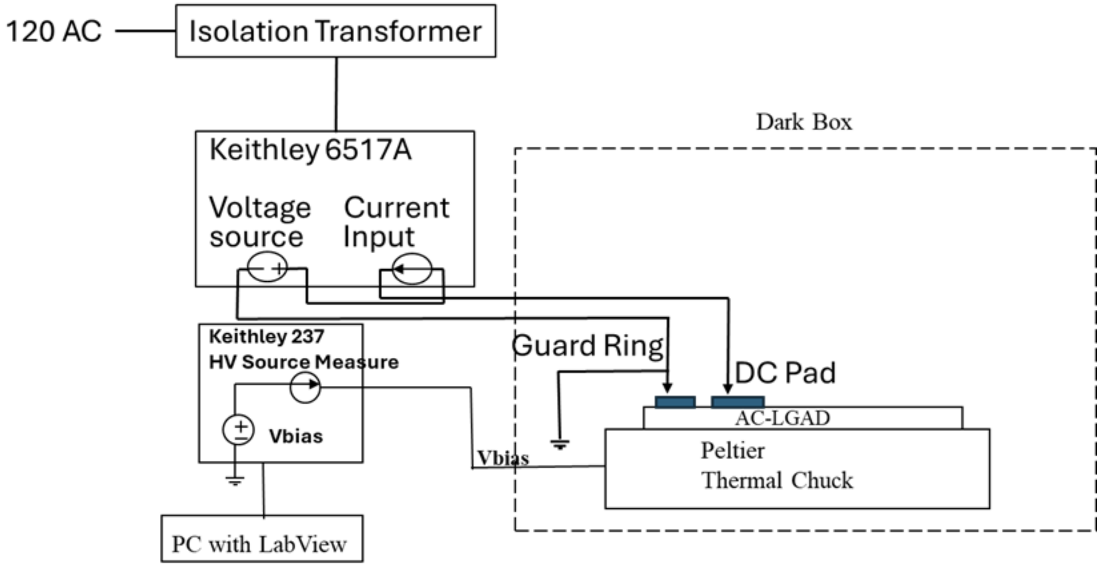
Bigger C_2, ω can make error smaller. However, too small Rsen requires an impractically big C2.

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

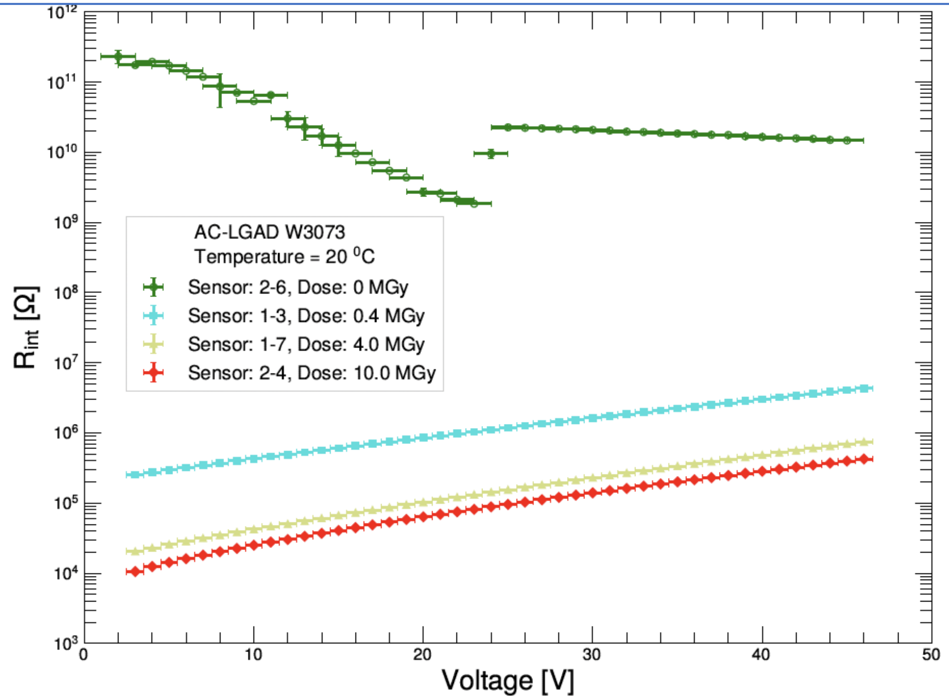
More details in backup slides

Inter-pad resistance of BNL LGADs between the DC contact and the guard ring was measured to assess the effects of gamma-induced surface damage.

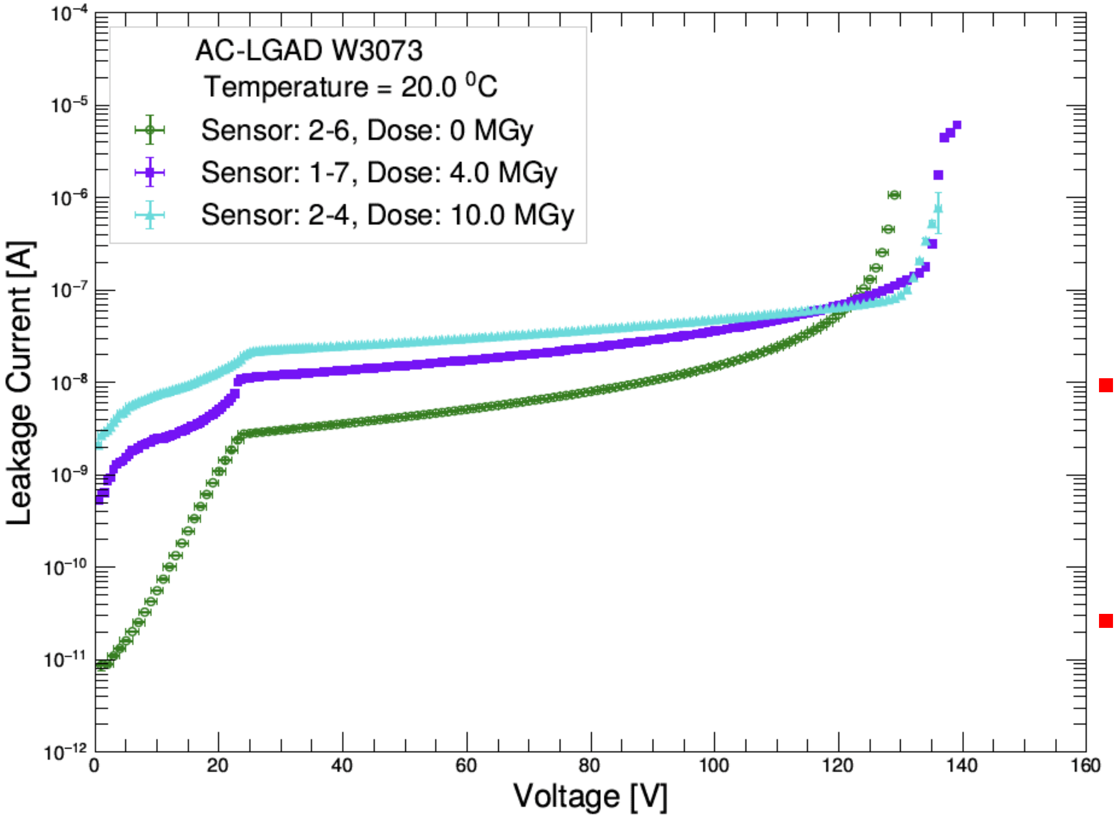
Irradiation with gammas has been shown to increase surface oxide charge density up to saturation at doses in the range 0.1 – 1 MGy. Resistance is then dominated by the oxide charge after that point. Decreasing resistivity for doses > 1 MGy is due to bulk damage in the form of point defects due to Compton electrons.



- A dip in R_{int} occurs in the unirradiated sensor at the onset of full depletion.
- Inter-pad resistance drops with increasing dose from 10^{10} Ω to below 10^{6} Ω, stabilizing around dose 4 MGy.



Leakage current and breakdown voltage increase after gamma irradiation



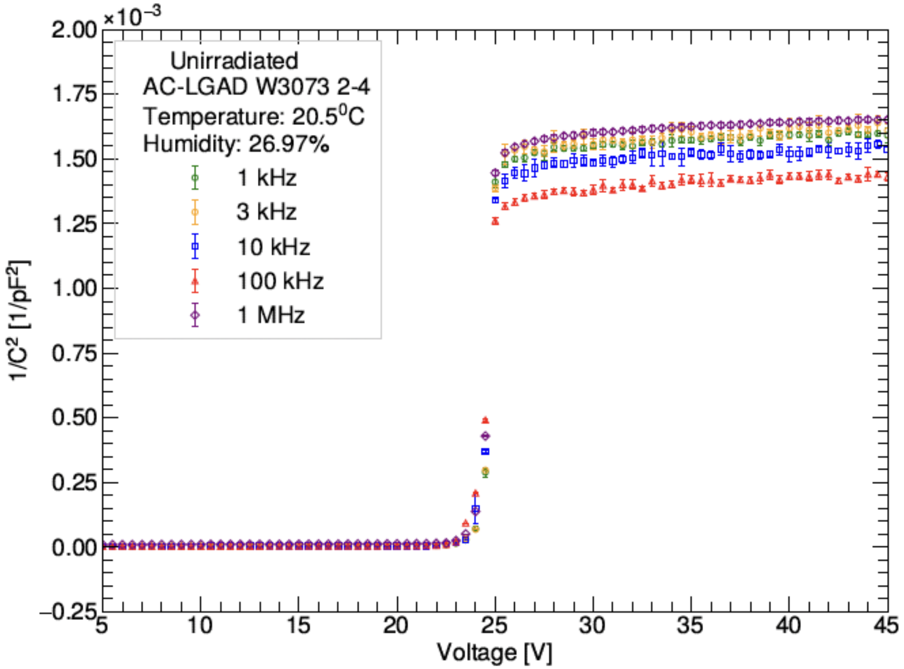
Gamma irradiation studies of strip AC-LGAD

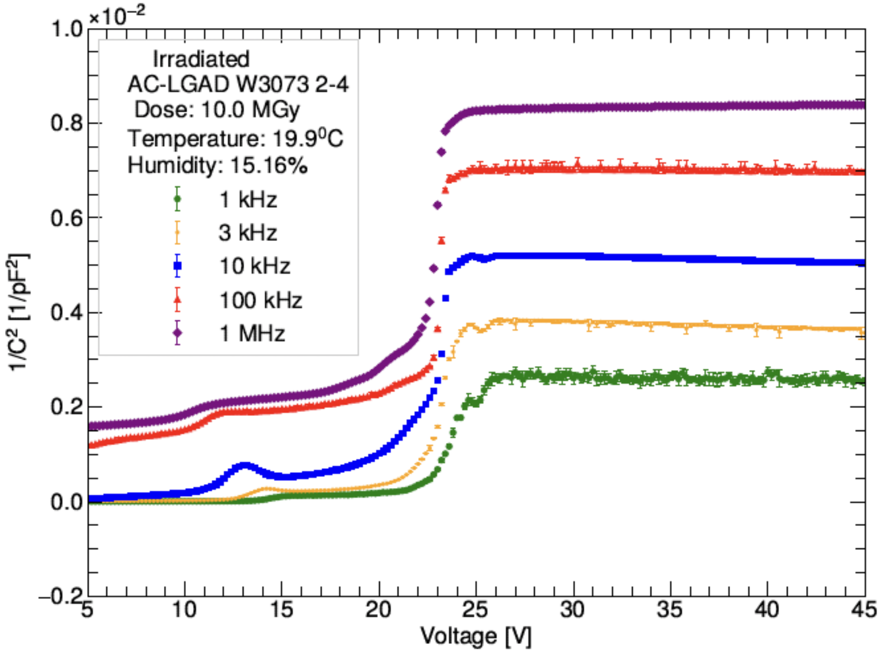
- Leakage currents collected at various temperatures T in the range 19.8 – 20.0 °C are scaled to values at T_{ref} according to
  - $I_{leakage}(T_{ref}) = I_{leakage}(T) \cdot \left(\frac{T_{ref}}{T}\right)^2 \cdot e^{-\frac{E_{eff}}{k_B}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)}$
  - $E_{eff} = 1.21$ eV
- Observations: Following irradiation to 10 MGy,
  - $V_{breakdown}$ increases from 120 V to 130 V
  - $I_{leakage}$ increases by factor 6.3 to ~6 nA.
- $R = I_{\text{leakage}}^{\text{irradiated}} / I_{\text{leakage}}^{\text{unirradiated}}$

Dose [MGy]	Sensor number	I_{leakage} [nA]	$\mathcal{R}$
0	2–6	4.4	-
0.4	1–3	-	-
4.0	1–7	15.3	3.5 ± 0.1
10.0	2–4	27.3	6.2 ± 0.2

Values measured at 50V

The gain layer depletion voltage decreases up to ~2V as gamma irradiation increases



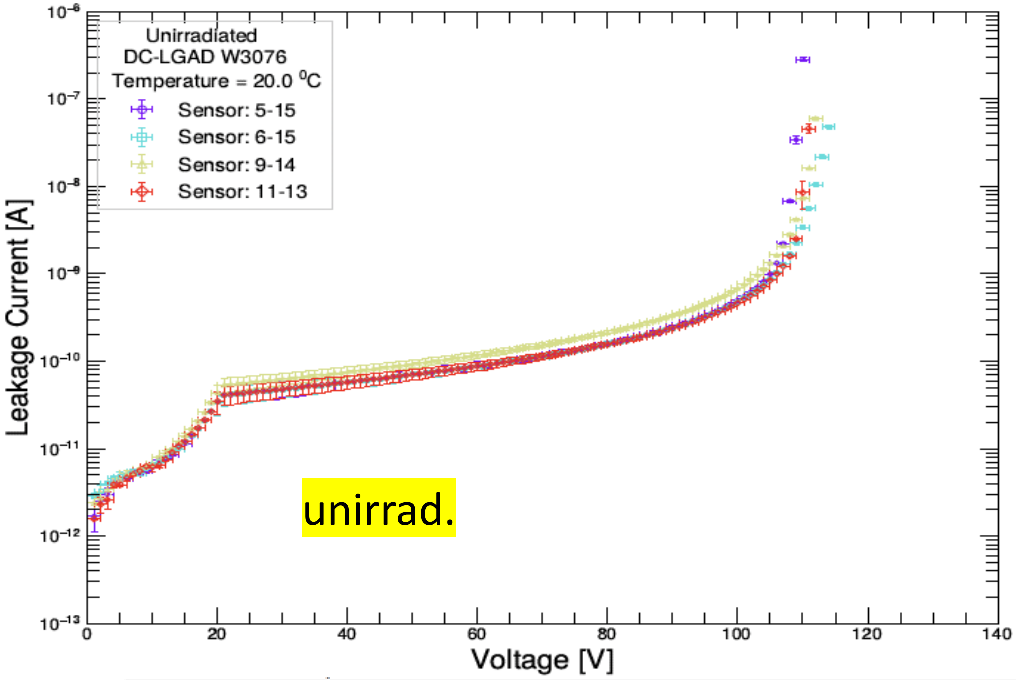


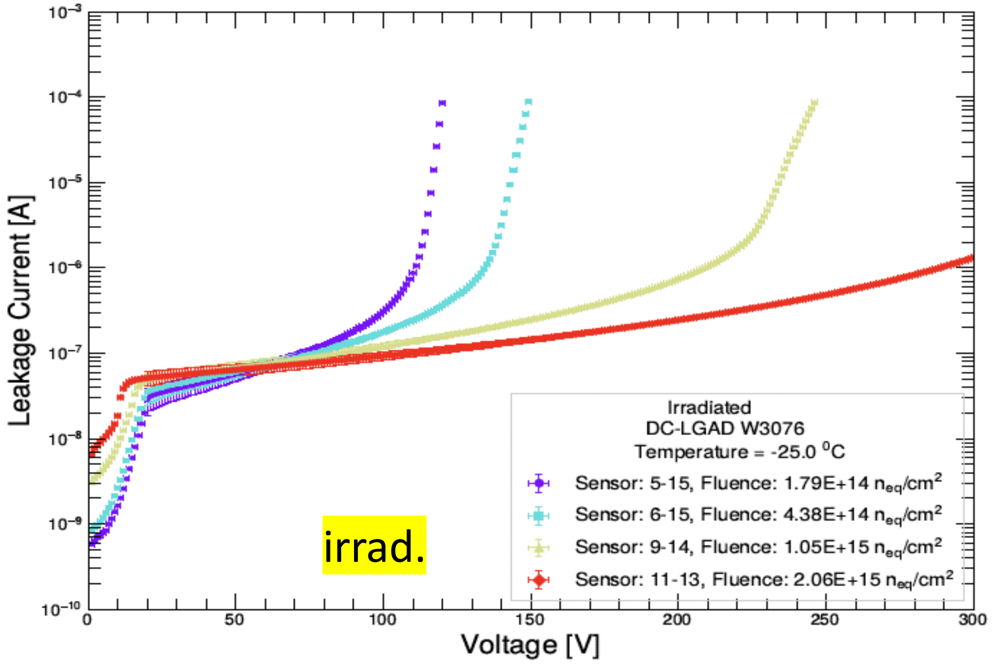
Gamma irradiation introduces frequency dependence in capacitance

Sensor	Unirradiated			Dose [MGy]	Irradiated		
	V_{gl} [V]	V_{fd} [V]	V_{bulk} [V]		V_{gl} [V]	V_{fd} [V]	V_{bulk} [V]
2–6	23.3 ± 0.6	25.2 ± 0.6	1.9 ± 0.9	0.0	–	–	–
1–3	23.3 ± 0.6	25.1 ± 0.6	1.8 ± 0.8	0.4	23.2 ± 0.5	24.8 ± 0.6	1.6 ± 0.8
1–7	23.2 ± 0.6	25.1 ± 0.6	1.9 ± 0.8	4.0	22.3 ± 0.5	23.8 ± 0.6	1.5 ± 0.8
2–4	23.7 ± 0.6	25.7 ± 0.6	2.0 ± 0.9	10.0	21.5 ± 0.7	24.2 ± 0.4	2.7 ± 0.9

Values reported @ 10 kHz.

For DC-LGADs, breakdown voltage increases with proton dose; leakage current increases to ~7 uA after proton irradiation.

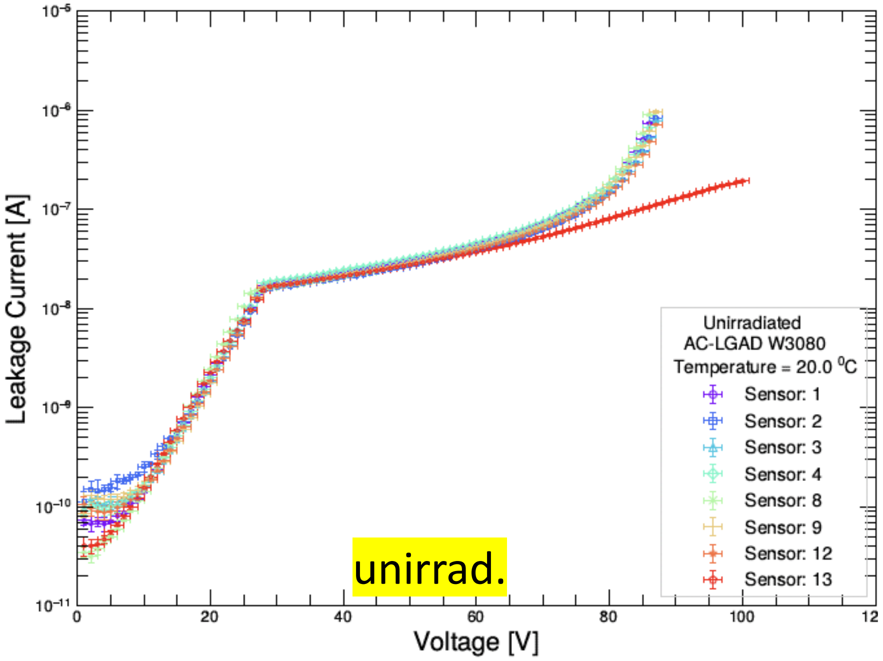


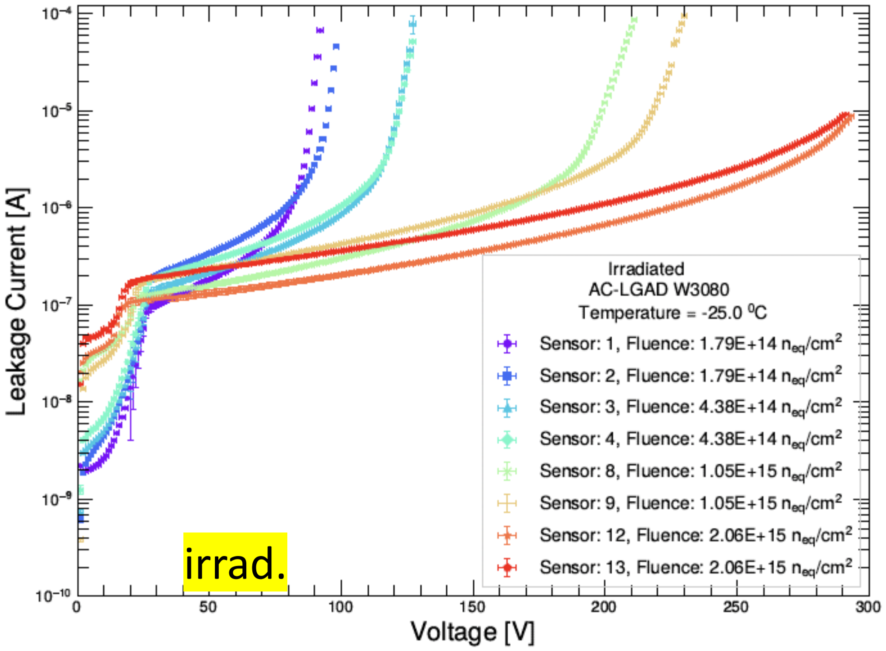


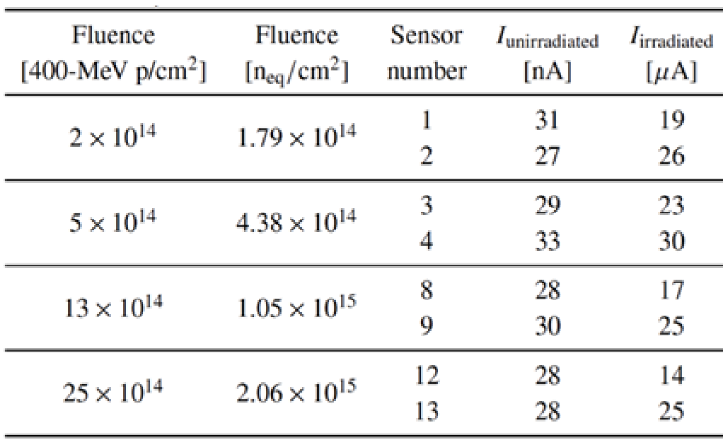
Fluence [400-MeV p/cm^2]	Fluence [n_{eq}/cm^2]	Sensor number	$I_{\text{unirradiated}}$ [nA]	$I_{\text{irradiated}}$ [μA]
2×10^{14}	1.79×10^{14}	5-15	0.07	6.0
5×10^{14}	4.38×10^{14}	6-15	0.07	6.6
13×10^{14}	1.05×10^{15}	9-14	0.09	7.4
25×10^{14}	2.06×10^{15}	11-13	0.07	6.9

Values measured at 50V

For AC-LGAD, breakdown voltage increases with proton dose; leakage current increases to ~22 uA.







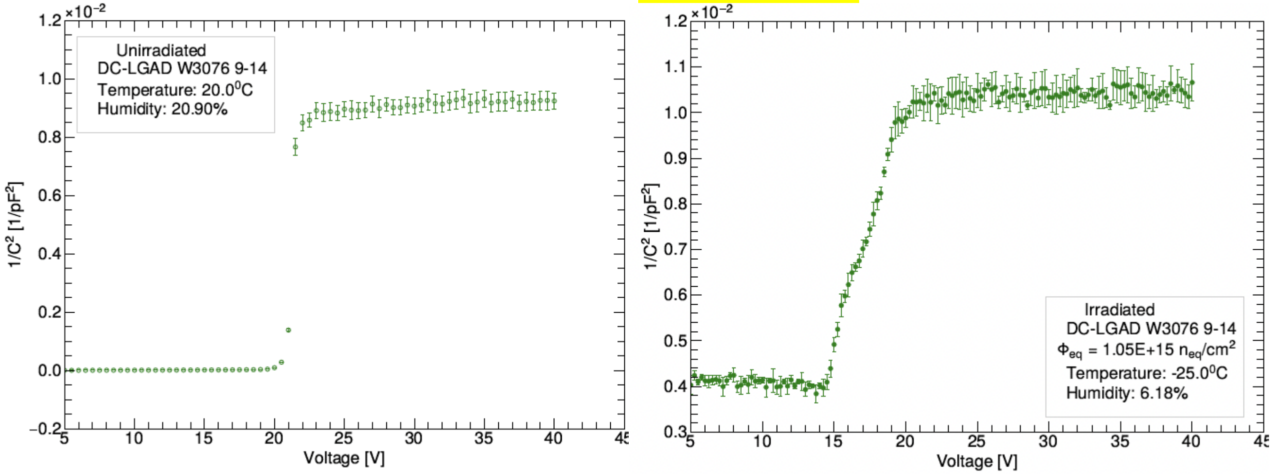
Fluence [400-MeV p/cm^2]	Fluence [n_{eq}/cm^2]	Sensor number	$I_{\text{unirradiated}}$ [nA]	$I_{\text{irradiated}}$ [μA]
2×10^{14}	1.79×10^{14}	1	31	19
		2	27	26
5×10^{14}	4.38×10^{14}	3	29	23
		4	33	30
13×10^{14}	1.05×10^{15}	8	28	17
		9	30	25
25×10^{14}	2.06×10^{15}	12	28	14
		13	28	25

Values measured at 50V

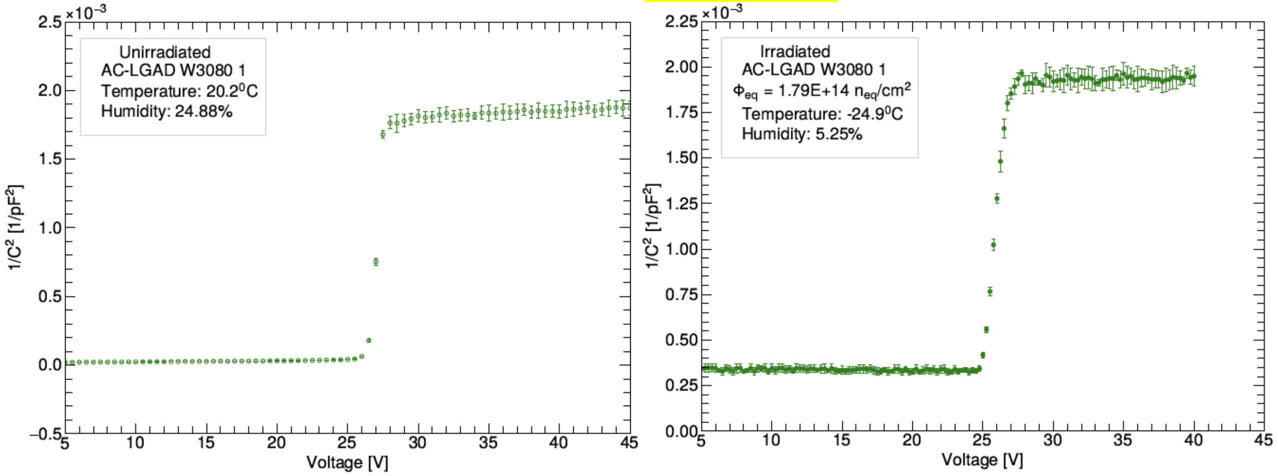
Given that the area of AC-LGADs is ~ x 2.5 of that of DC-LGADs, the change of leakage current after irradiation is qualitatively consistent between DC- and AC-LGADs.

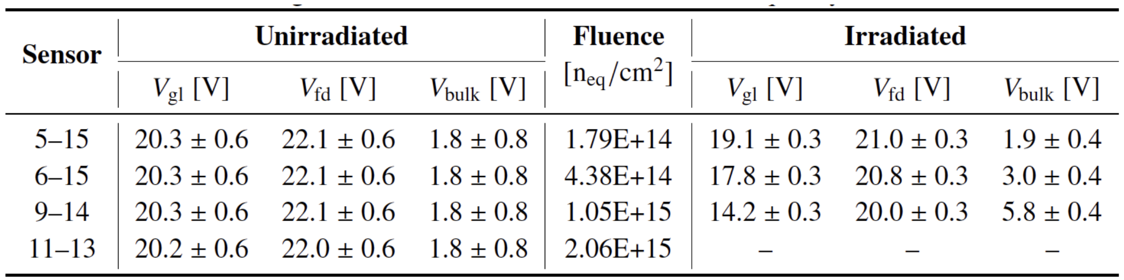
The gain layer depletion voltage decreases (up to ~ 10V) as proton irradiation increases

---DC-LGAD CV's---

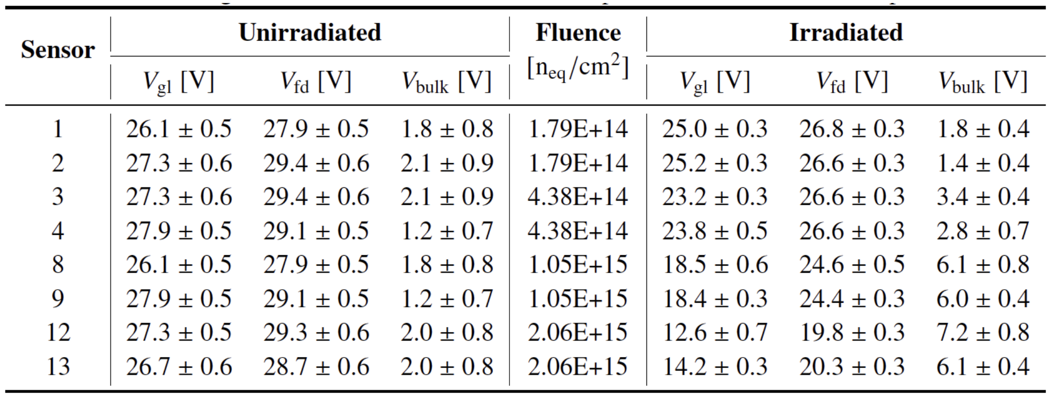


---AC-LGAD CV's---



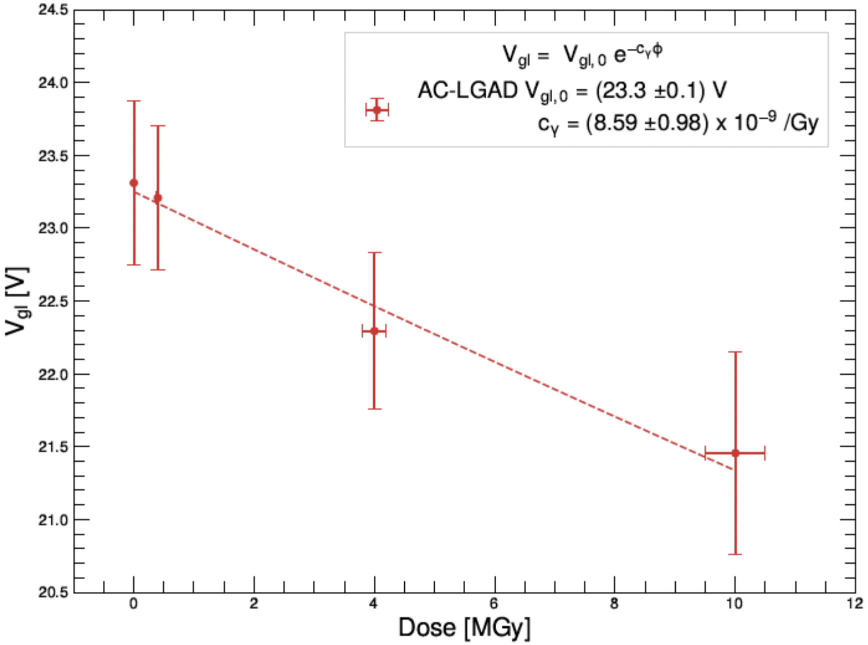


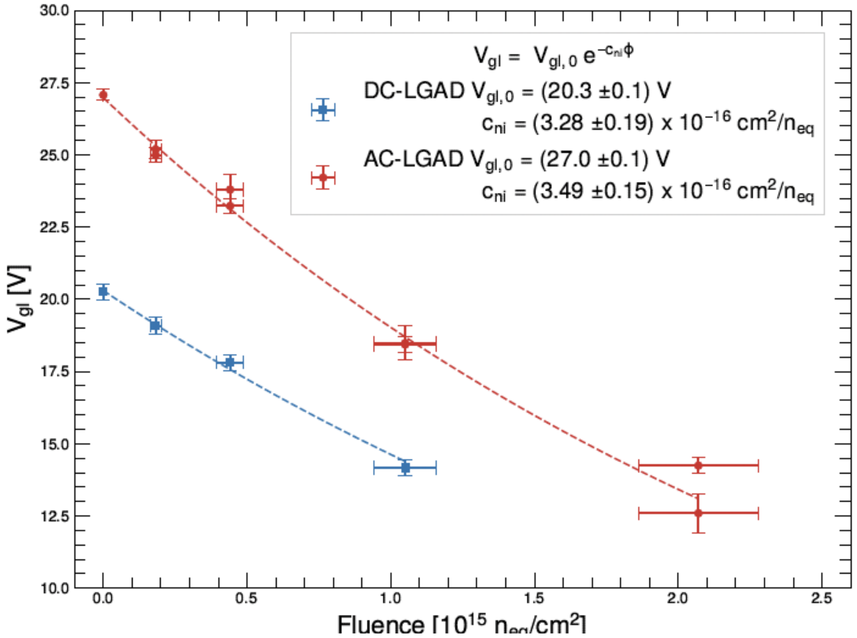
Sensor	Unirradiated			Fluence	Irradiated		
	V_{gl} [V]	V_{fd} [V]	V_{bulk} [V]	$[n_{eq}/cm^2]$	V_{gl} [V]	V_{fd} [V]	V_{bulk} [V]
5–15	20.3 ± 0.6	22.1 ± 0.6	1.8 ± 0.8	1.79E+14	19.1 ± 0.3	21.0 ± 0.3	1.9 ± 0.4
6–15	20.3 ± 0.6	22.1 ± 0.6	1.8 ± 0.8	4.38E+14	17.8 ± 0.3	20.8 ± 0.3	3.0 ± 0.4
9–14	20.3 ± 0.6	22.1 ± 0.6	1.8 ± 0.8	1.05E+15	14.2 ± 0.3	20.0 ± 0.3	5.8 ± 0.4
11–13	20.2 ± 0.6	22.0 ± 0.6	1.8 ± 0.8	2.06E+15	–	–	–



Sensor	Unirradiated			Fluence	Irradiated		
	V_{gl} [V]	V_{fd} [V]	V_{bulk} [V]	$[n_{eq}/cm^2]$	V_{gl} [V]	V_{fd} [V]	V_{bulk} [V]
1	26.1 ± 0.5	27.9 ± 0.5	1.8 ± 0.8	1.79E+14	25.0 ± 0.3	26.8 ± 0.3	1.8 ± 0.4
2	27.3 ± 0.6	29.4 ± 0.6	2.1 ± 0.9	1.79E+14	25.2 ± 0.3	26.6 ± 0.3	1.4 ± 0.4
3	27.3 ± 0.6	29.4 ± 0.6	2.1 ± 0.9	4.38E+14	23.2 ± 0.3	26.6 ± 0.3	3.4 ± 0.4
4	27.9 ± 0.5	29.1 ± 0.5	1.2 ± 0.7	4.38E+14	23.8 ± 0.5	26.6 ± 0.3	2.8 ± 0.7
8	26.1 ± 0.5	27.9 ± 0.5	1.8 ± 0.8	1.05E+15	18.5 ± 0.6	24.6 ± 0.5	6.1 ± 0.8
9	27.9 ± 0.5	29.1 ± 0.5	1.2 ± 0.7	1.05E+15	18.4 ± 0.3	24.4 ± 0.3	6.0 ± 0.4
12	27.3 ± 0.5	29.3 ± 0.6	2.0 ± 0.8	2.06E+15	12.6 ± 0.7	19.8 ± 0.3	7.2 ± 0.8
13	26.7 ± 0.6	28.7 ± 0.6	2.0 ± 0.8	2.06E+15	14.2 ± 0.3	20.3 ± 0.3	6.1 ± 0.4

Acceptor removal constants can be estimated from gain layer depletion voltages





AC-LGADs wafer 3073 (c_γ)	DC-LGADs wafer 3076 (c_{ni})	AC-LGADs wafer 3080 (c_{ni})
$(8.59 \pm 0.98) \times 10^{-9}\mathrm{Gy}^{-1}$	$(3.28 \pm 0.19) \times 10^{-16}\mathrm{cm}^2/\mathrm{n_{eq}}$	$(3.49 \pm 0.15) \times 10^{-16}\mathrm{cm}^2/\mathrm{n_{eq}}$

These acceptor removal constants are consistent with those measured for DC-LGADs by a different producer under complementary conditions.[1,2]

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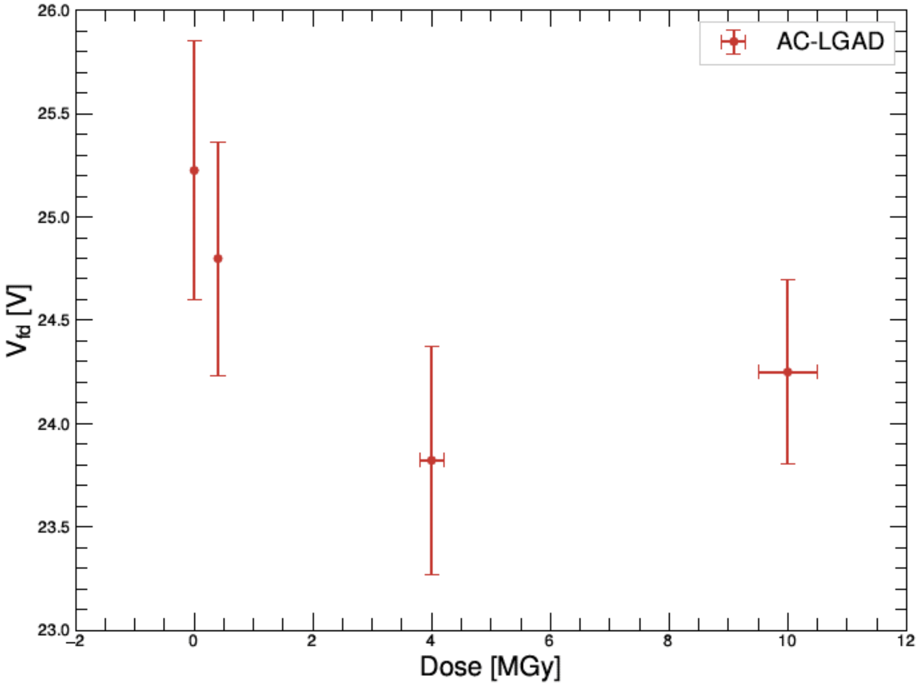
[1] M.R. Hoeferkamp et al., https://www.frontiersin.org/articles/10.3389/fphys.2022.838463.

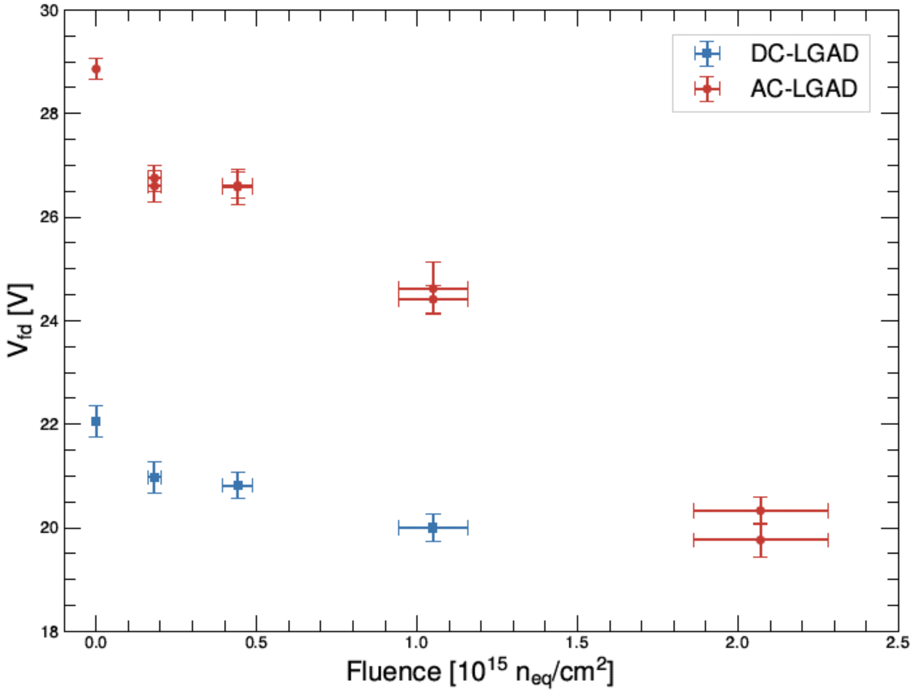
[2] J. Sorenson et al., 2024 JINST 19 P05012.

Full depletion voltage decreases with increasing irradiation exposure.

V_{fd} versus ionizing dose



V_{fd} versus non-ionizing dose



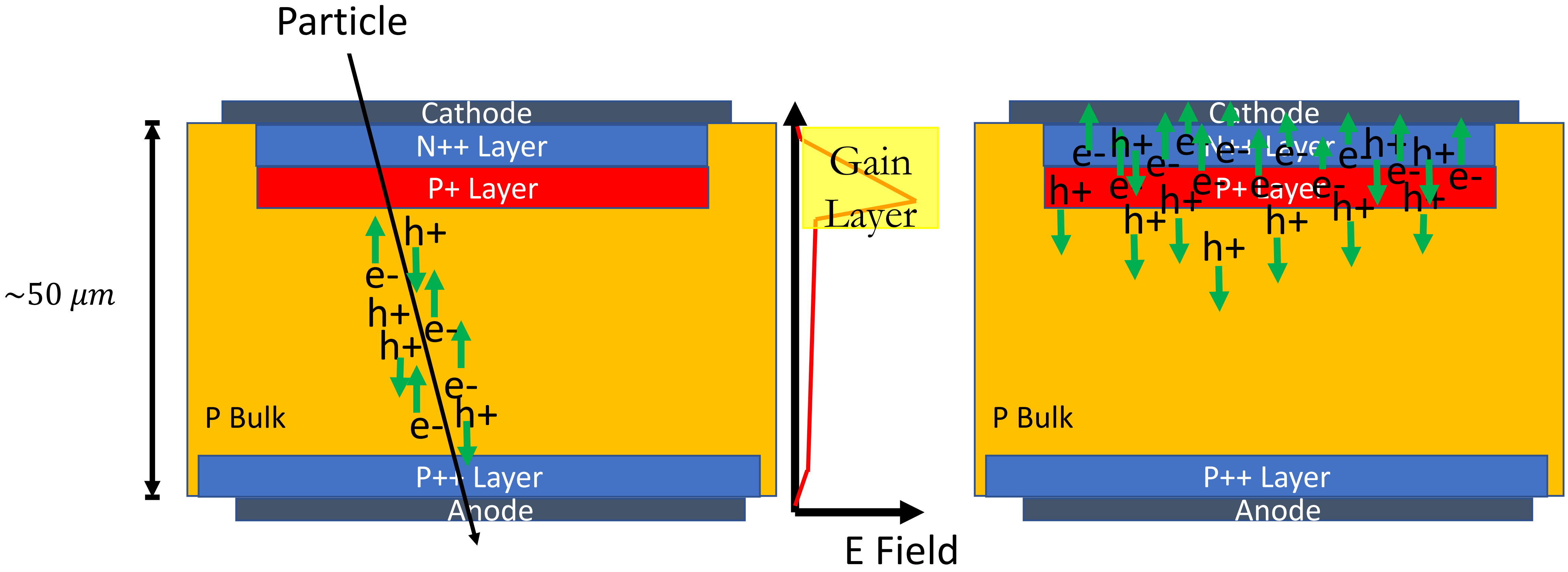
Summary

- BNL AC/DC-LGADs were irradiated by gammas/protons.
- Gamma irradiation of strip AC-LGADs:
  - Leakage current increases ~10's of nA and breakdown voltage increases <10%;
  - Inter-pad resistance decreased up to 10^6 times after gamma-irradiation;
  - Measured capacitance is affected by the low inter-pad resistance and shows frequency dependence;
  - Gain layer depletion voltage decreases up to ~2V.
- Proton irradiation of DC-LGADs and Pixel AC-LGADs:
  - Leakage current increases ~10's of uA and breakdown voltage up to ~100's of volts;
  - Gain layer depletion voltage decreases up to ~10's of volts.
- Acceptor removal constants are consistent with measurements in complementary conditions.
  - $c_\gamma = 8.6 \times 10^{-9}$ Gy^{-1}
  - $c_{ni} = (3.3 - 3.5) \times 10^{-16}$ cm^2/n$_{eq}$

Thank You!

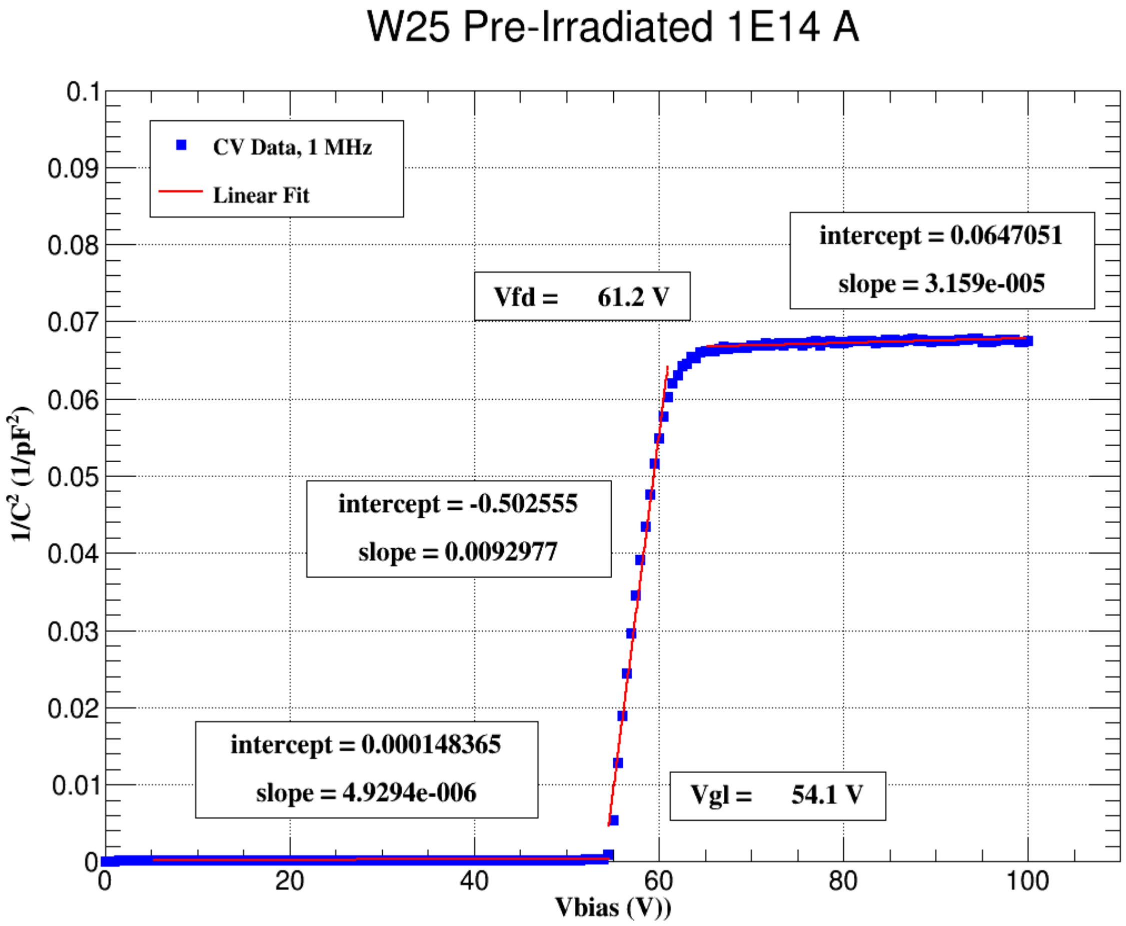
Backup Slides

How LGAD works

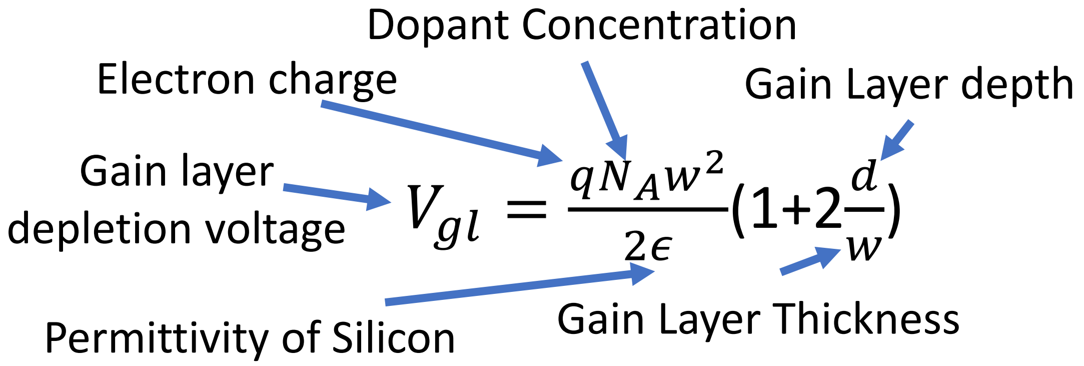


In silicon sensors, charge multiplication happens when charge carriers drift in a region with an electric field (E) greater than about 300 kV/cm. The additional P+ (or gain) layer, when depleted, locally generates an electric field high enough to activate the avalanche process.

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

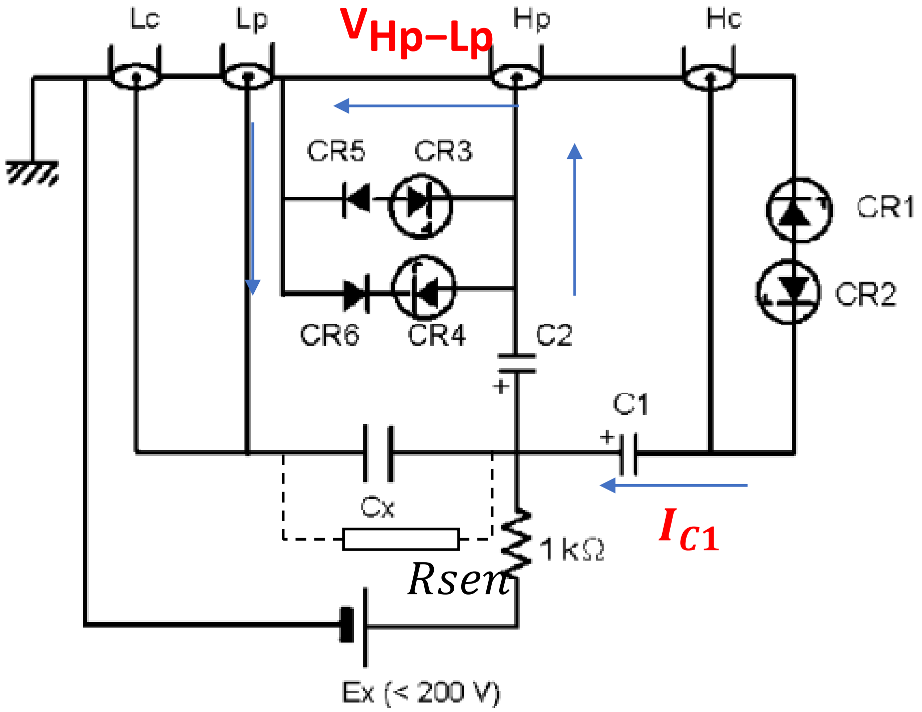


The depletion voltage of the gain layer depends on the dopant concentration, which is impacted by radiation fluence



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

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

$$\text{Capacitance value} \geq \frac{1}{10\pi f}$$

(f: measurement frequency (Hz))

DC withstand voltage: > Ex

C2: Blocking capacitor

Capacitance value: 1 μF

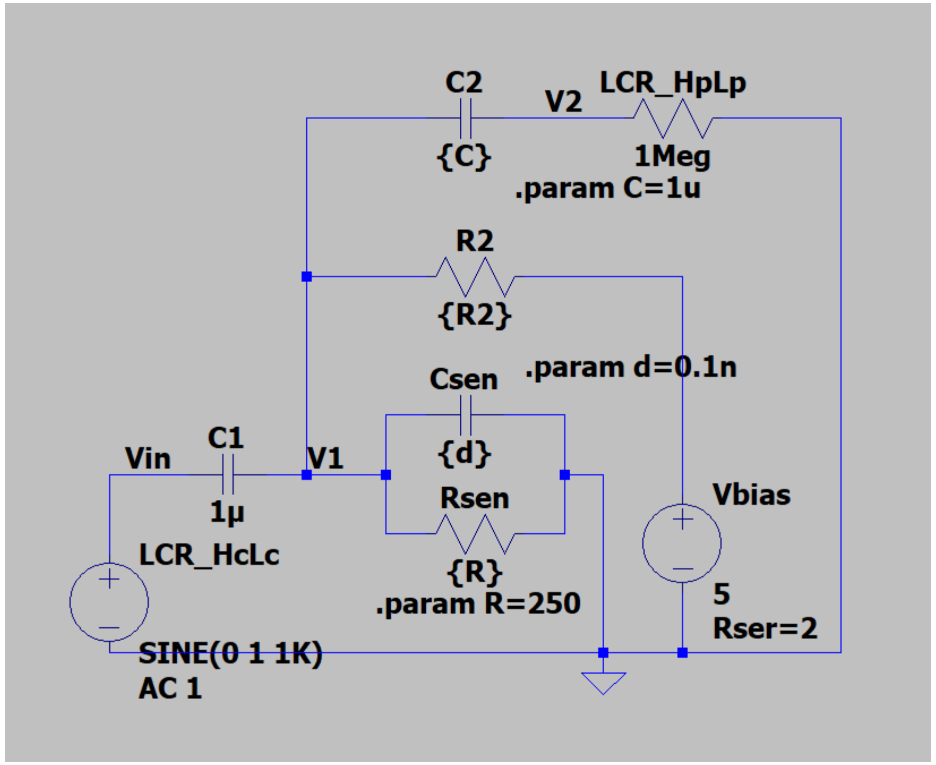
DC withstand voltage: Ex

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

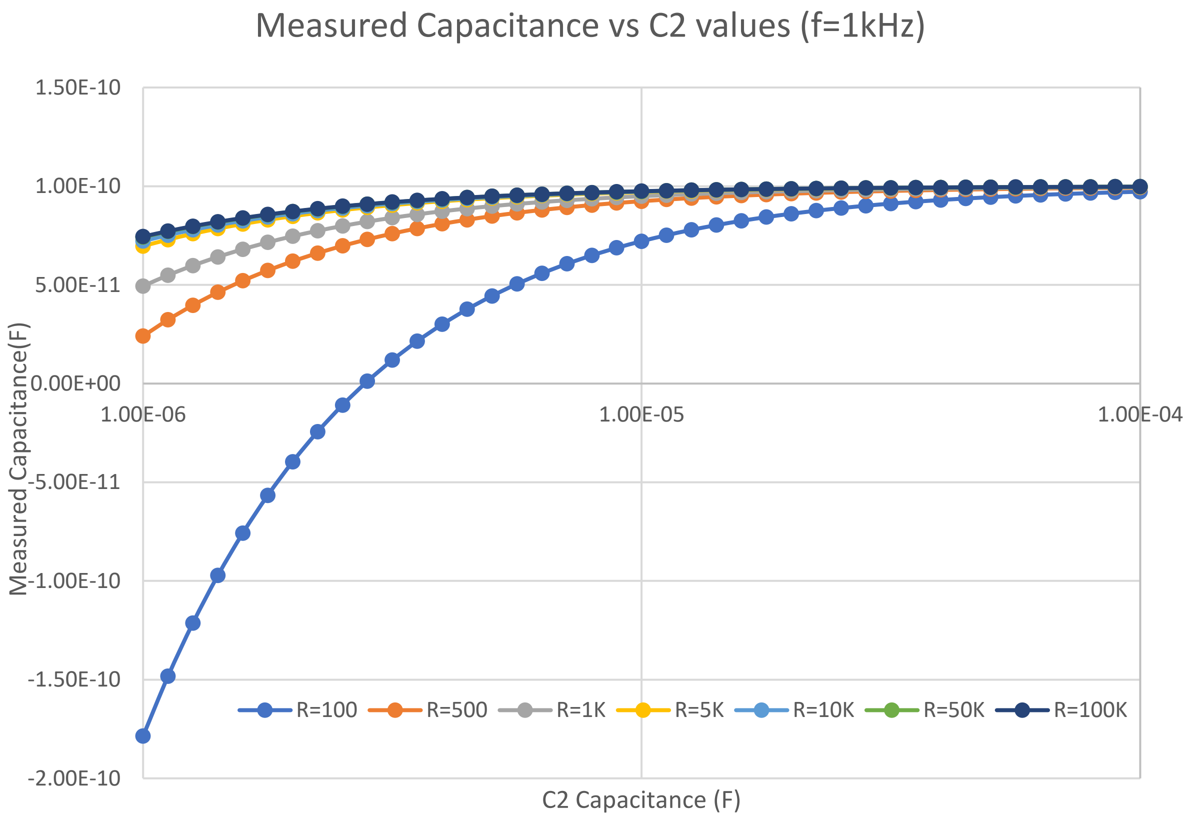


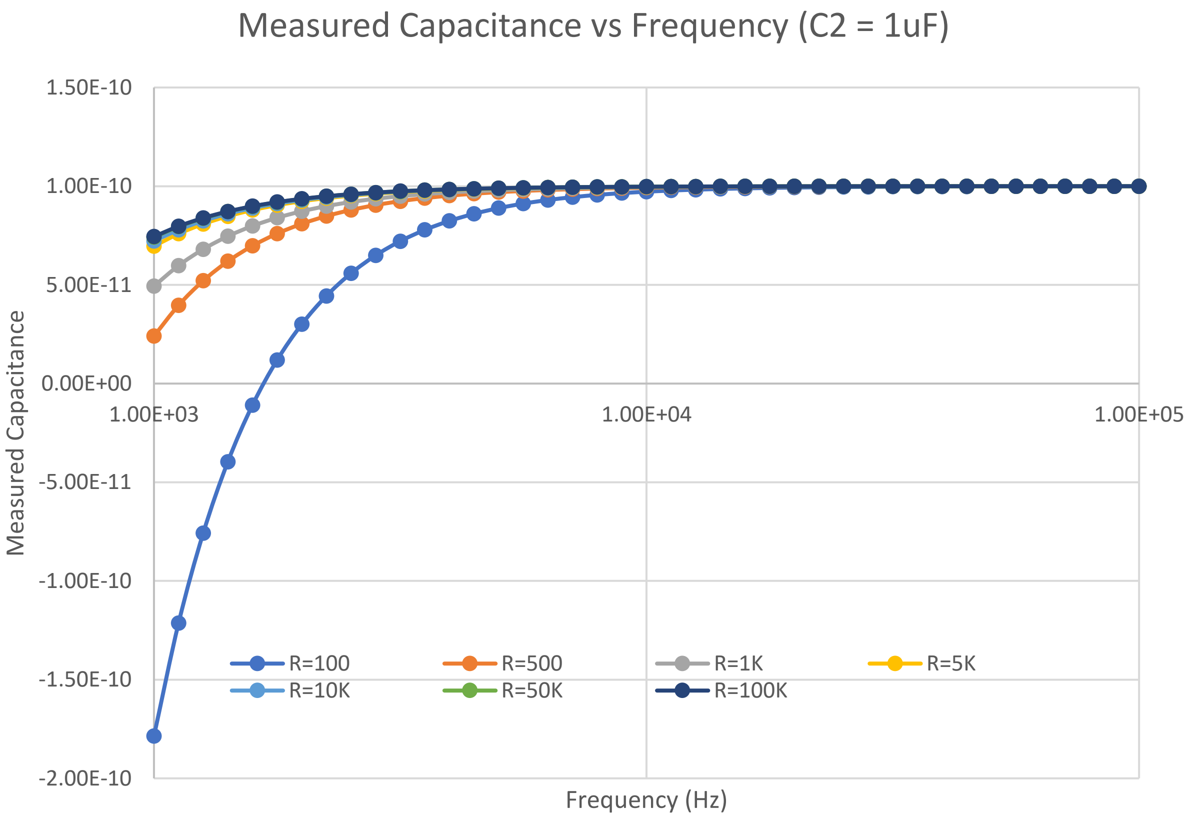
$$C_{measured} = C_{sen} - \left(\frac{1}{Rsen} + \frac{1}{R2}\right)\frac{1}{C_2 R_{HpLp}\omega^2}$$

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

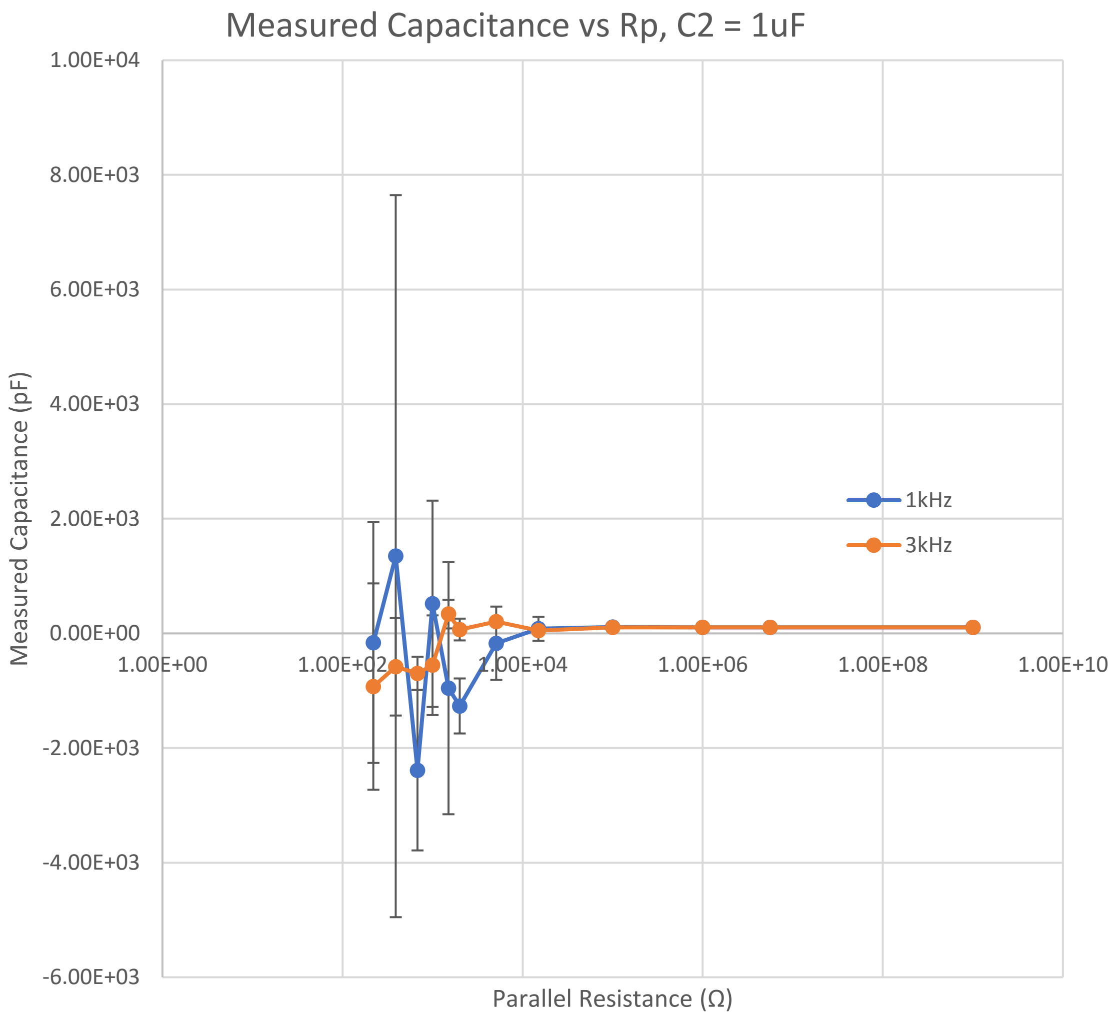
Bigger C_2, ω can make error smaller. However, too small Rsen requires an impractically big C2.
Bigger $R2$ can reduce error. However, R2 can't not be too big because it would take too much time to make Vbias stable.

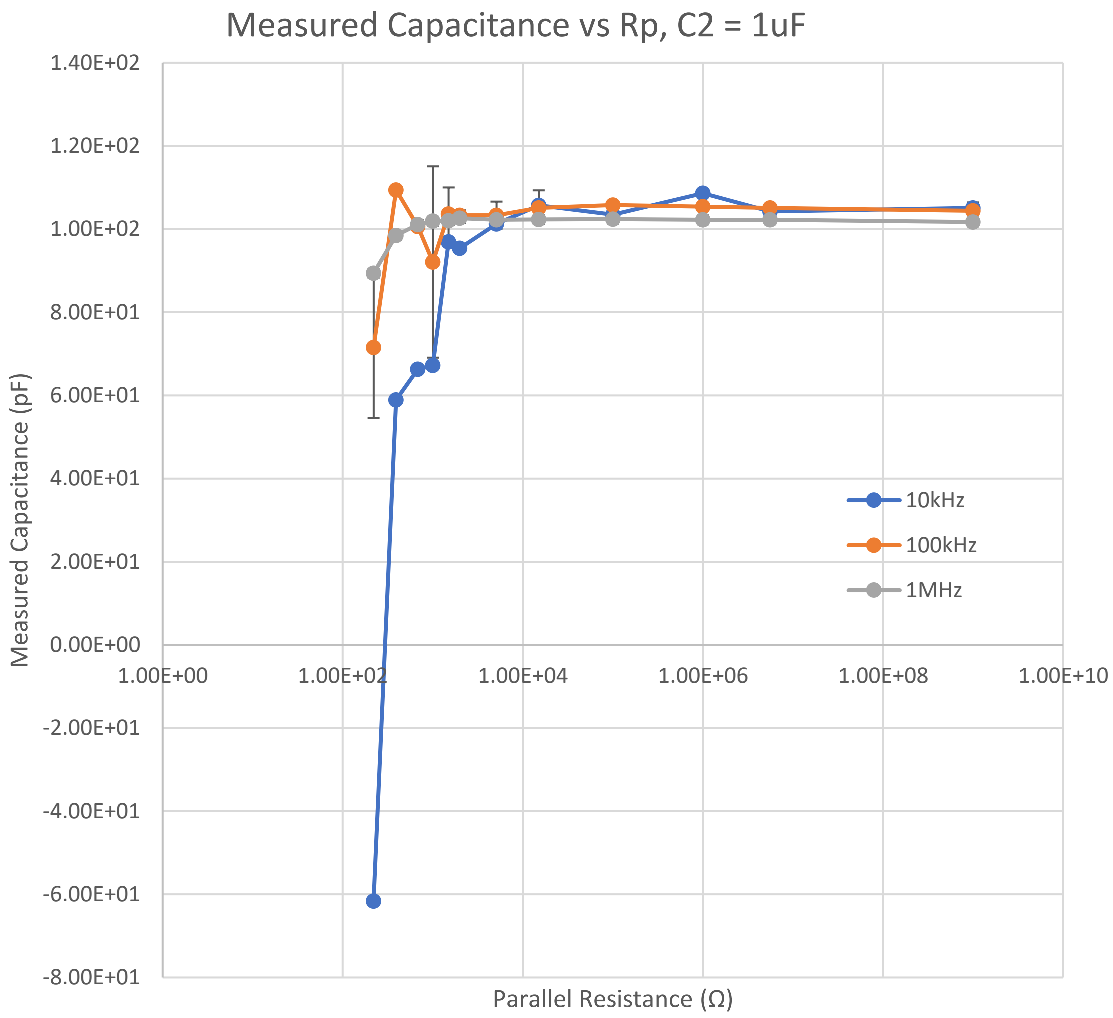
Simulation with LTSpice shows that the error decreases as C2 increases, while as frequency and parallel resistance increase.



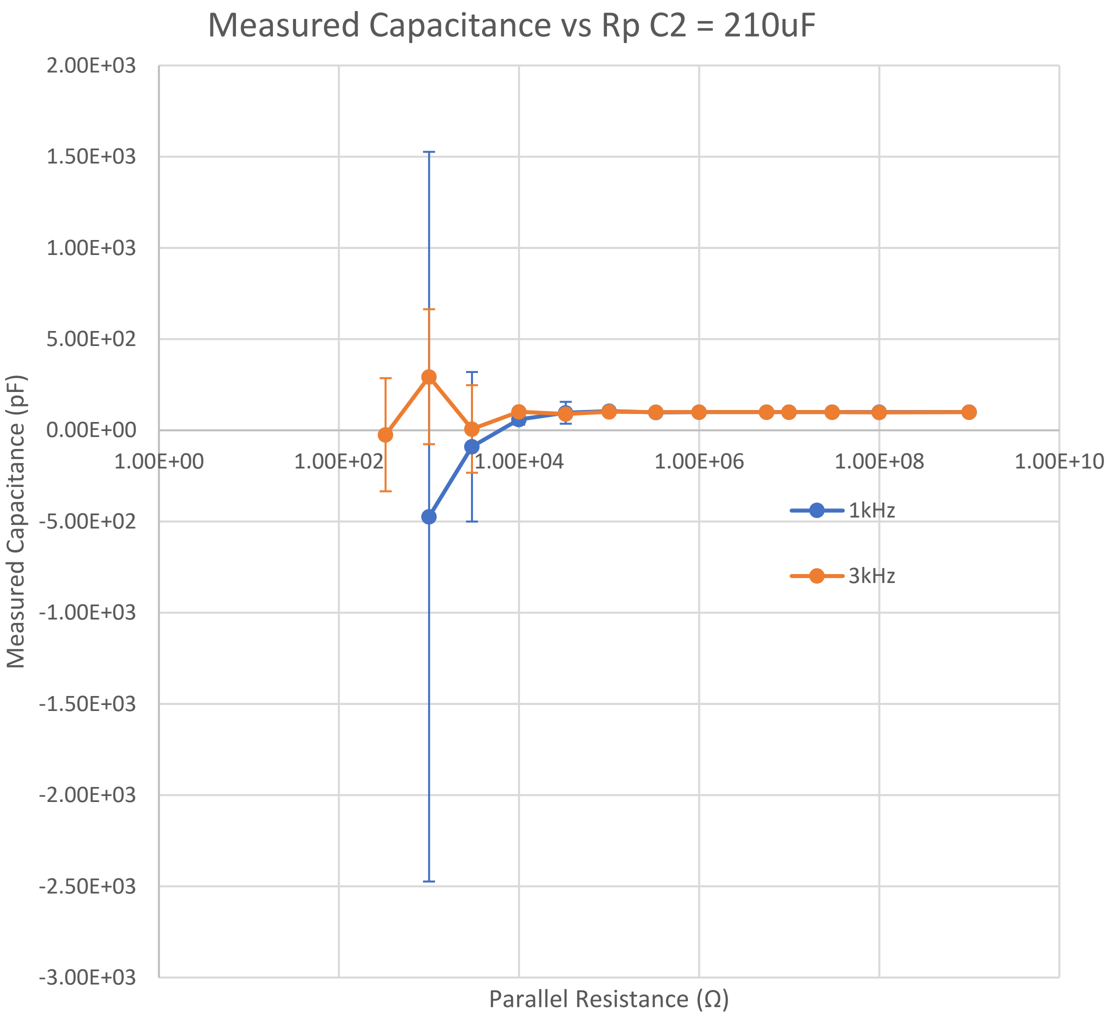


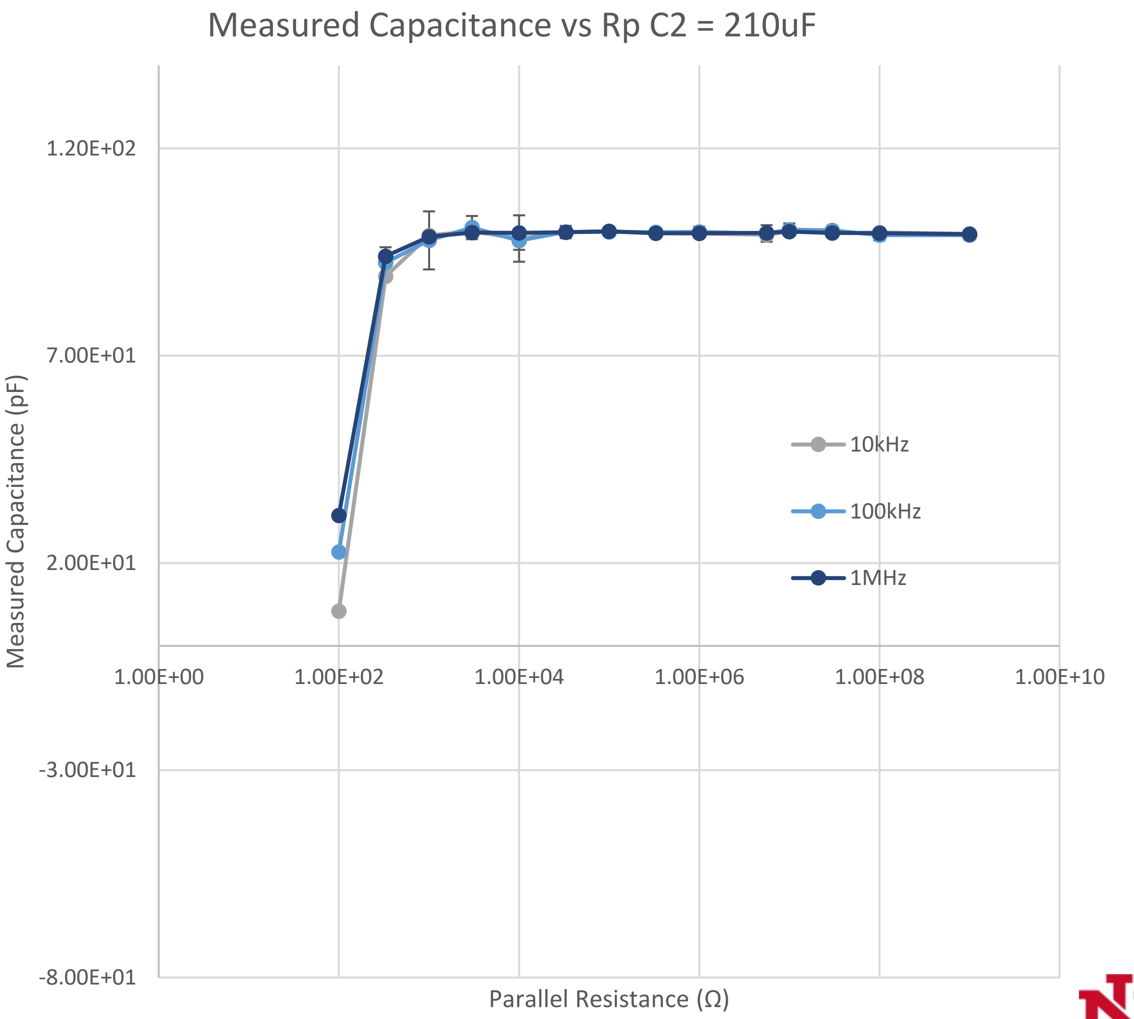
Test Measurement with a 100pF ceramic capacitor and different parallel resistors shows that lower Rp can cause bigger errors.



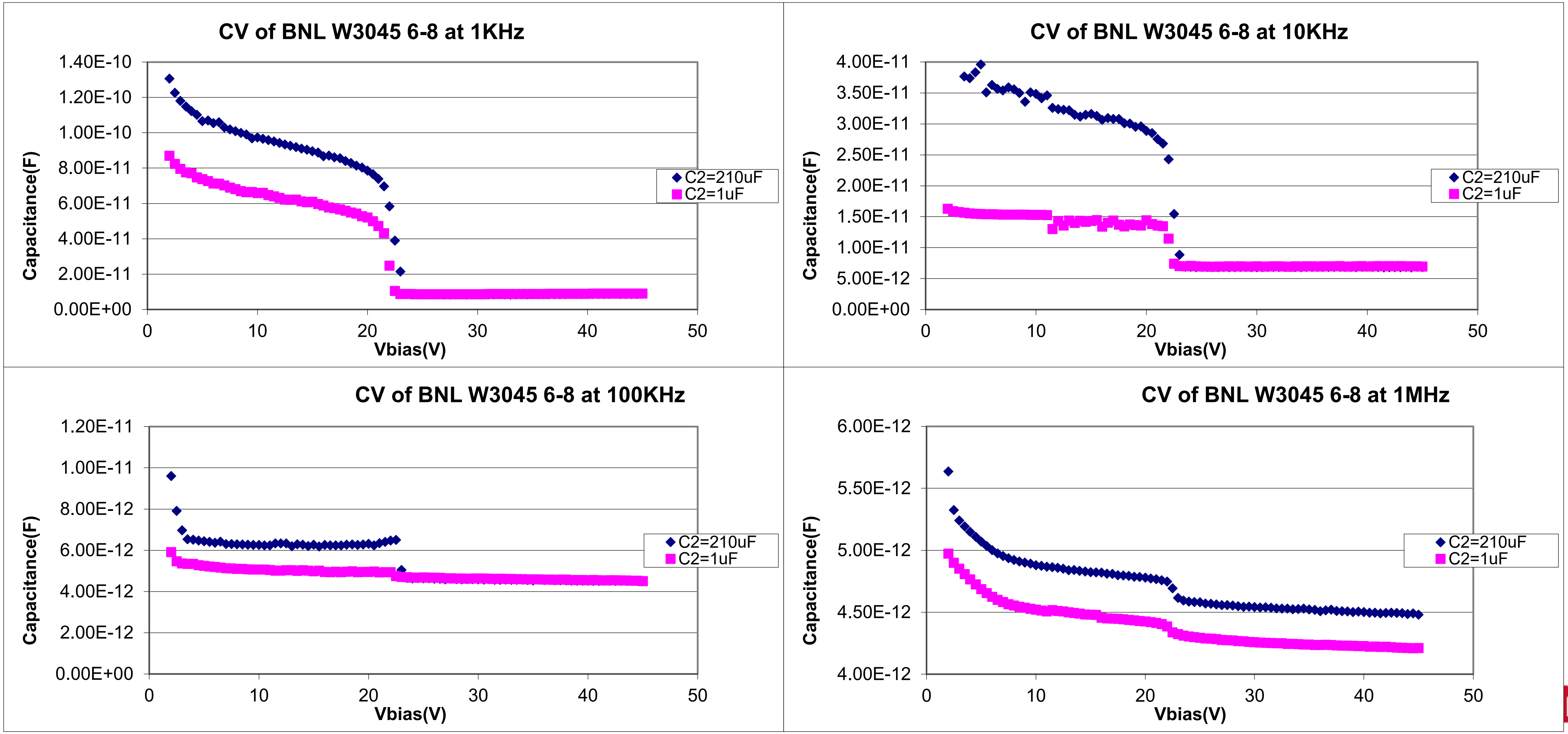


Test Measurement with a 100pF ceramic capacitor shows a bigger C2 (=210uF) can improve the capacitor measurement.





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

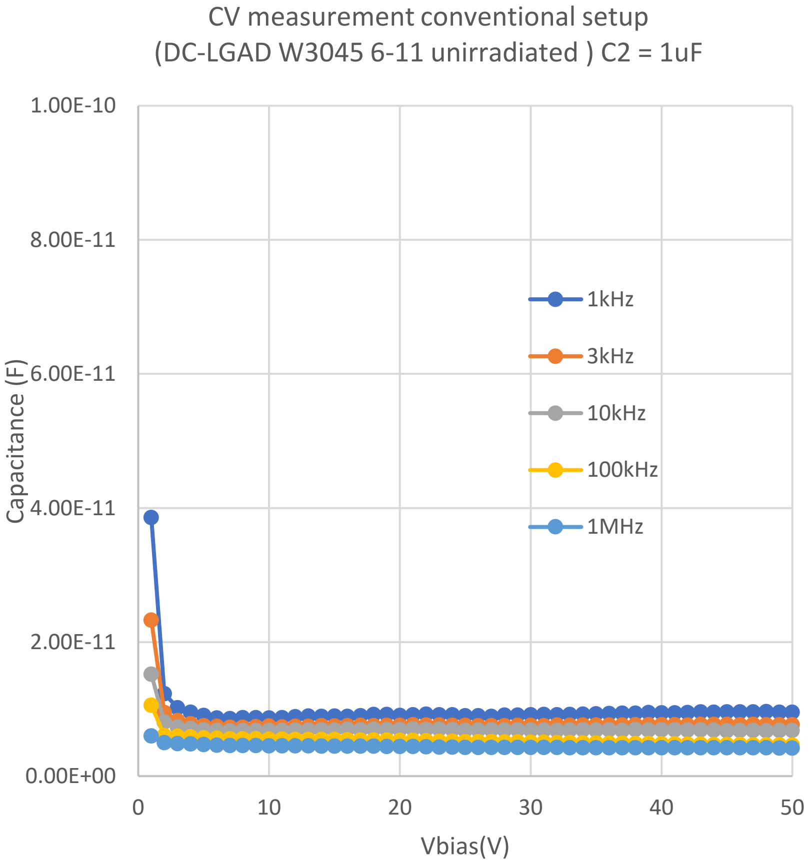

CV of BNL W3045 6-8 at 1KHz

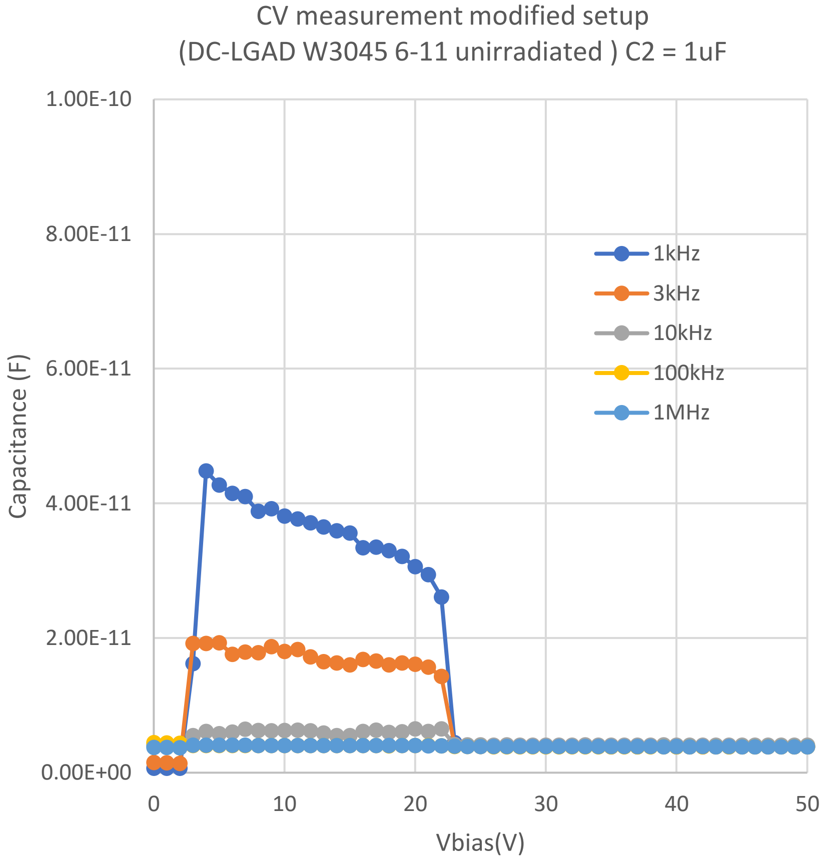
CV of BNL W3045 6-8 at 10KHz

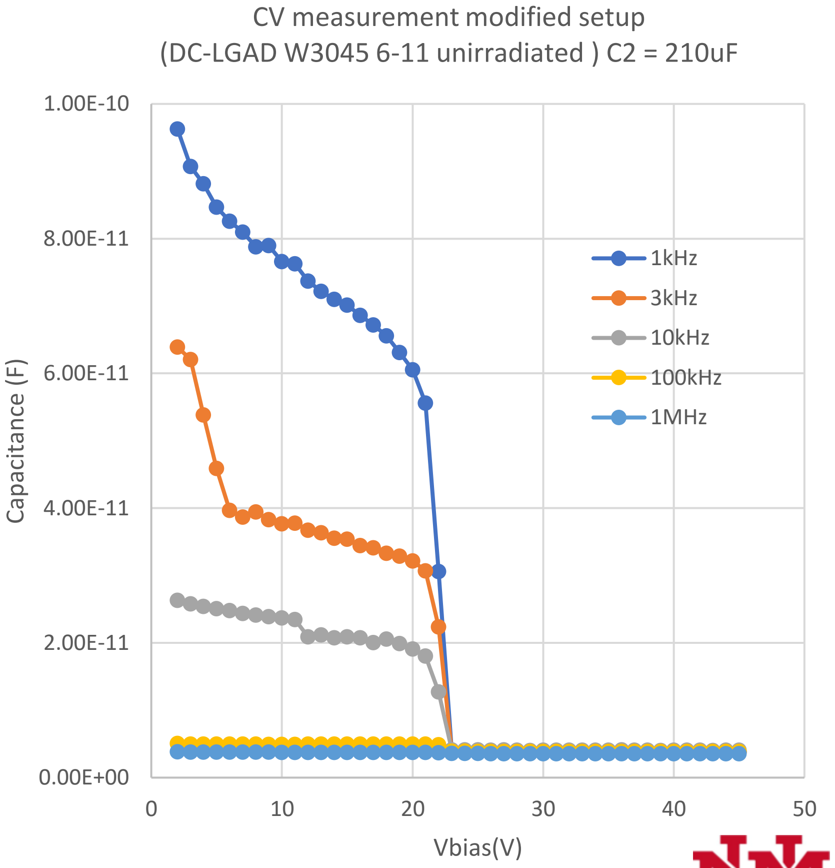
CV of BNL W3045 6-8 at 100KHz

CV of BNL W3045 6-8 at 1MHz

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


CV measurement conventional setup
(DC-LGAD W3045 6-11 unirradiated) C2 = 1uF


CV measurement modified setup
(DC-LGAD W3045 6-11 unirradiated) C2 = 1uF

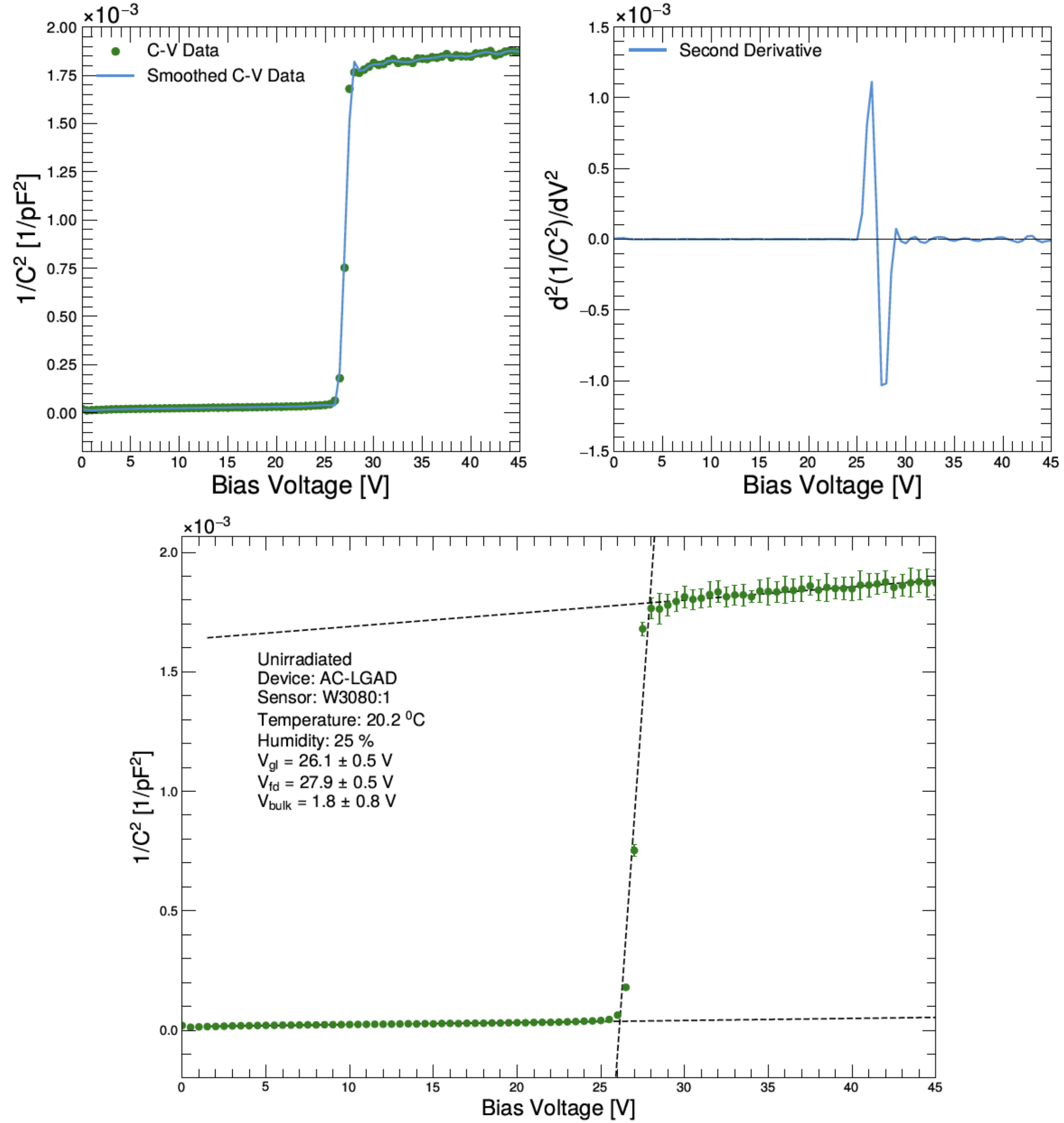

CV measurement modified setup
(DC-LGAD W3045 6-11 unirradiated) C2 = 210uF

Extraction of V_{gl} and V_{fd}

(upper left): Raw capacitance data vs. applied bias. Smoothed function obtained with Savitzky-Golay filter.*

(upper right): Second derivative of the smoothed function. Spikes define limits V_1 and V_2 of the data to which 3 fitted lines are applied.

(bottom): Data selected from the smoothed function are used to fit three lines in regions separated by V_1 and V_2. Lower and upper crossing points define V_{gl} and V_{fd}.



*Anal. Chem. 36, no. 8, 1627-1639 (2002).