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

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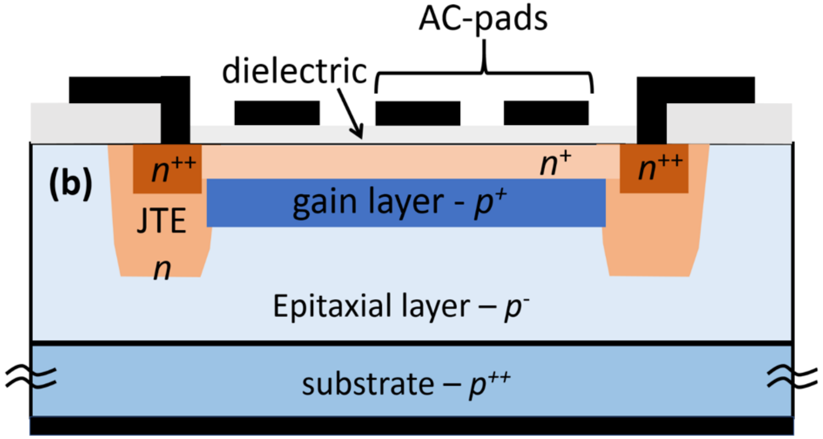
# I. The technology*

- Thin high-resistivity epitaxial p-type substrate, ~50 micron thickness, atop a ~500 micron p$^{++}$ Czochralski layer that provides ohmic contact and mechanical support.

- Deep p+ layer ("gain layer"); few-micron shallow n$^{+}$ layer adjacent to it creates junction; applied bias across this leads to E field extending into the bulk, with uniform parallel lines, able to induce electron impact ionization without significant hole ionization. Electrons multiply by factor 5 – 100. Signal current is primarily due to hole drift through the substrate. Collected electrons discharge slowly – negligible contribution to signal – suppressing noise.

- Metal electrodes are placed over a dielectric insulator at fine pitch, and signals are capacitively induced on them. Thin dielectric layer grown over the n$^{+}$ permits small channel dimensions and uniform efficiency across entire surface. Continuous n$^{+}$ layer can lead to low inter-pad resistance; maximize inter-pad resistivity by minimizing n$^{+}$ doping concentration.

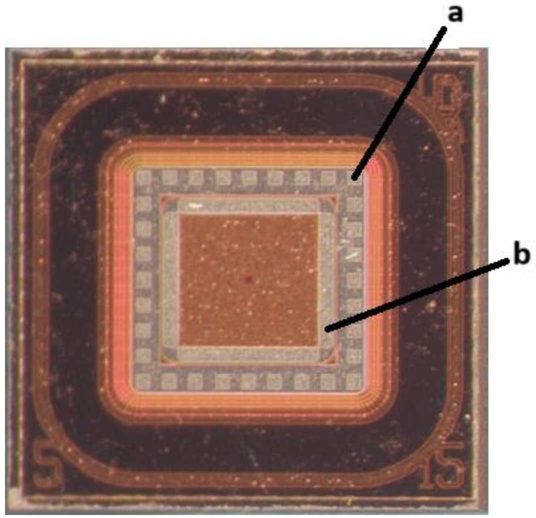
- Large signal, thin substrate: timing resolution ~ 10's of ps.



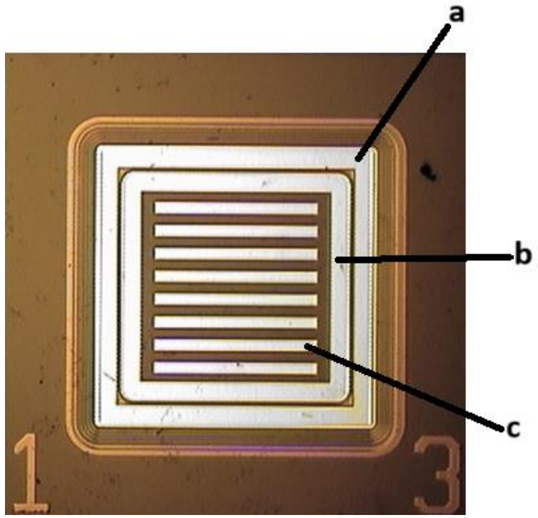
*G. Giacomini et al., NIM A 934 (2019) 52-57.

## The goal, the devices:

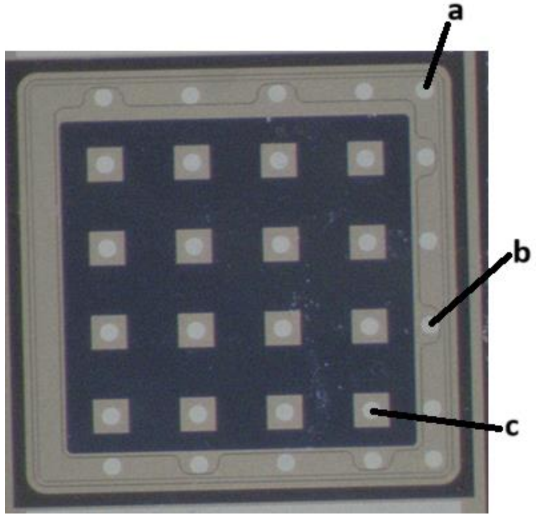
- Similar productions of DC-LGADs, pixel AC-LGADs, and strip AC-LGADs designed at BNL.
- Compare their responses following exposure to 400-MeV protons (FNAL ITA) and gammas (Sandia GIF).
- Irradiation campaigns and studies led by University of New Mexico.



DC-LGAD



strip AC-LGAD



pixel AC-LGAD

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 | pixel |
| Area of the $n^{++}$ layer ($mm^2$) | $2.05 \times 2.05$ | $1.3 \times 1.3$ | $2.05 \times 2.05$ |
| Area of the gain layer ($mm^2$) | $1.95 \times 1.95$ | $1.2 \times 1.2$ | $1.95 \times 1.95$ |
| Thickness of the active volume ($\mu$m) | 20 | 20 | 20 |
| Applied radiation species | gamma | proton | proton |

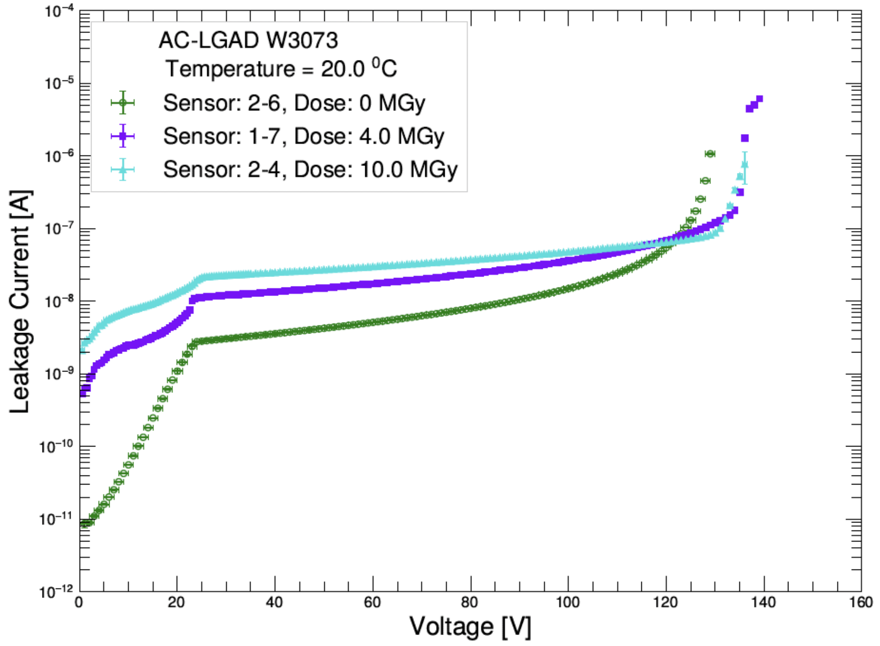
**The conditions:**

- Gamma doses: 0, 0.4, 4.0, 10 MGy
- 400-MeV proton fluences: 0 – 2.5 x$10^{15}$ $cm^{-2}$ [0 – 2.06 x $10^{15}$ $n_{eq}$ $cm^{-2}$]
- Proton-irradiated sensors annealed subsequently at 60°C for 80 minutes.
- Everything stored at $T < -28$°C when not under study.

# 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
- $R = I_{\text{leakage}}^{\text{irradiated}} / I_{\text{leakage}}^{\text{unirradiated}}$
- Observations: Following irradiation to 10 MGy,
  - $V_{\text{breakdown}}$ increases from 120 V to 130 V
  - $I_{\text{leakage}}$ increases by factor 6.3

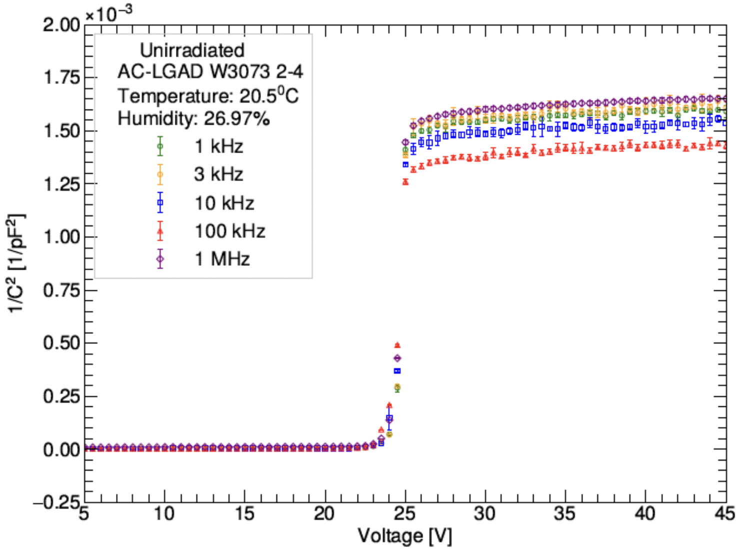
| Dose [MGy] | Sensor number | $I_{\text{leakage}}$ [nA] | $\mathcal{R}$ |
|---|---|---|---|
| 0 | 2–6 | 4.4 | - |
| 0.4 | 1–3 | - | - |
| 4.0 | 1–7 | 15.3 | 3.5 ± 0.1 |
| 10.0 | 2–4 | 27.3 | 6.2 ± 0.2 |



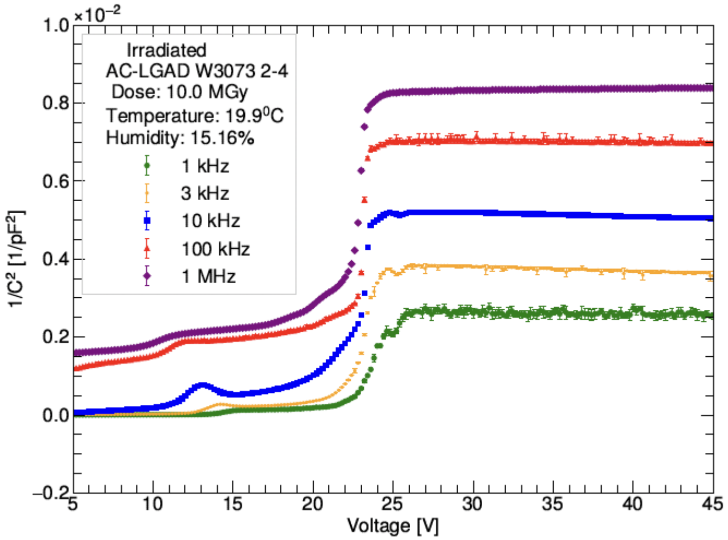
# Gamma irradiation of strip AC-LGAD, continued:

- CV trends’ frequency dependence enhanced by gamma exposure.
- Gamma exposure up to 10 MGy reduces $V_{depletion}$ by ~1 V.

unirradiated, CV



irradiated to 10 MGy, CV



| 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 |

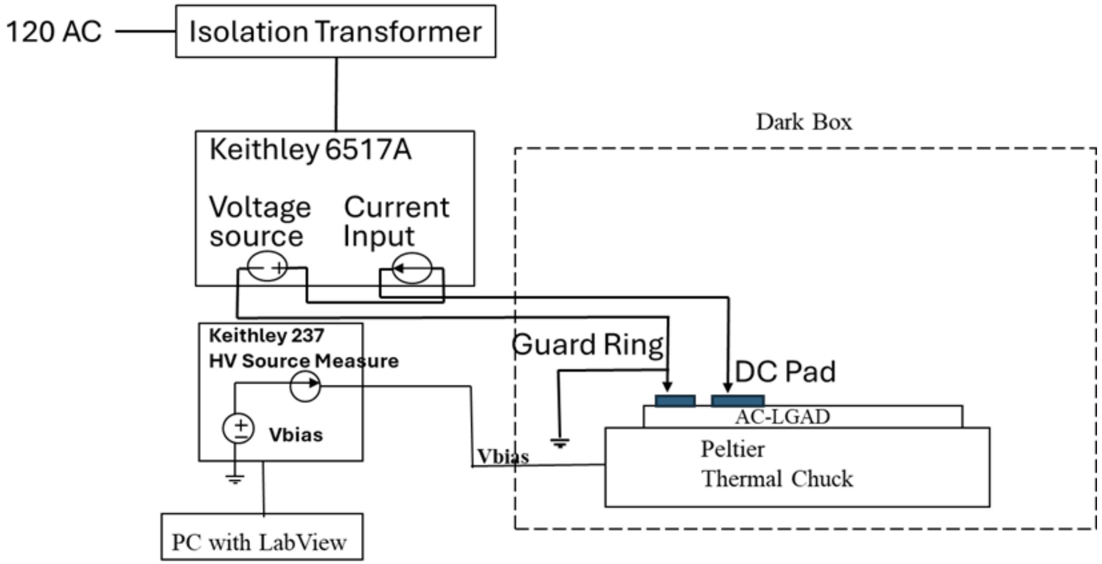
Values reported @ 10 kHz.

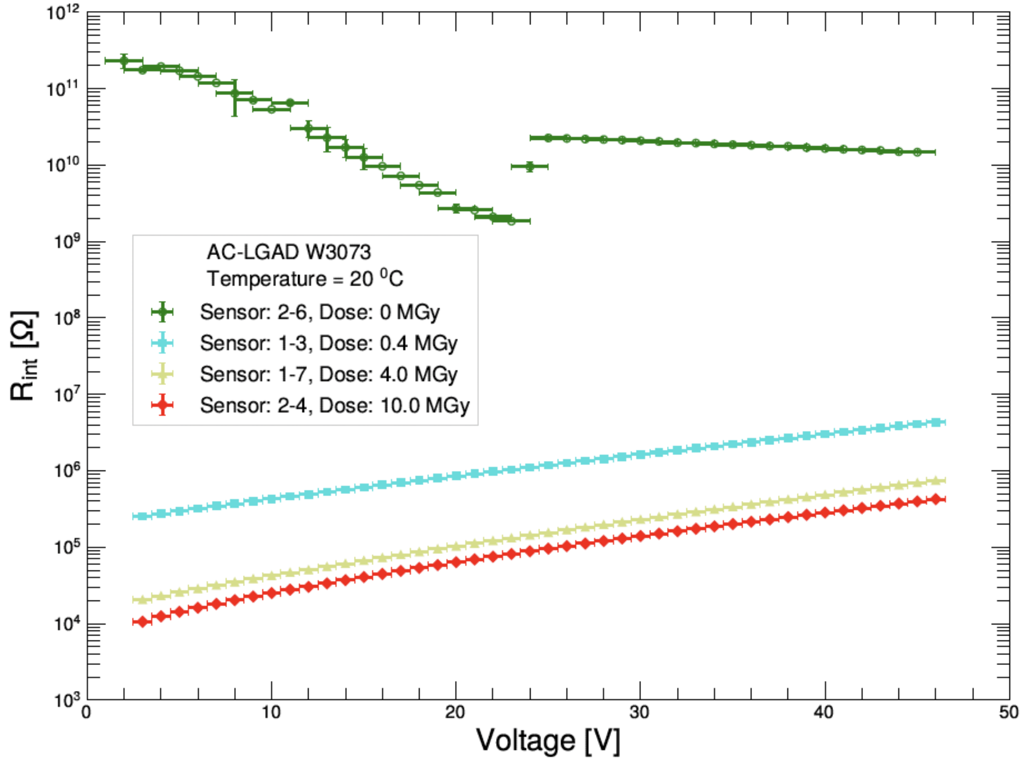
# Gamma irradiation of strip AC-LGAD, continued:

The resistance $R_{int}$ between the DC contact and the guard ring was measured to assess effects of gamma-induced surface damage.

- 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.

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.

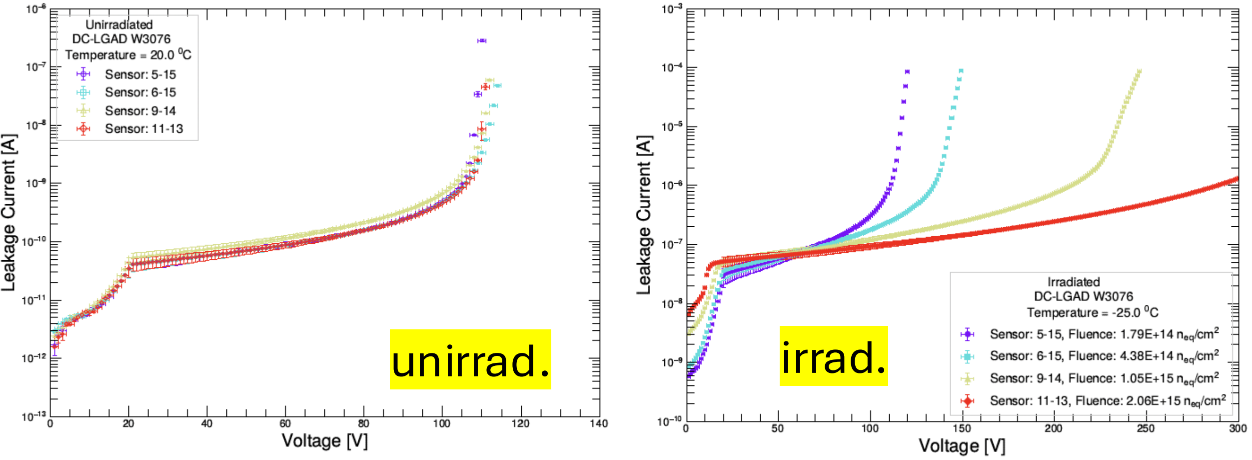




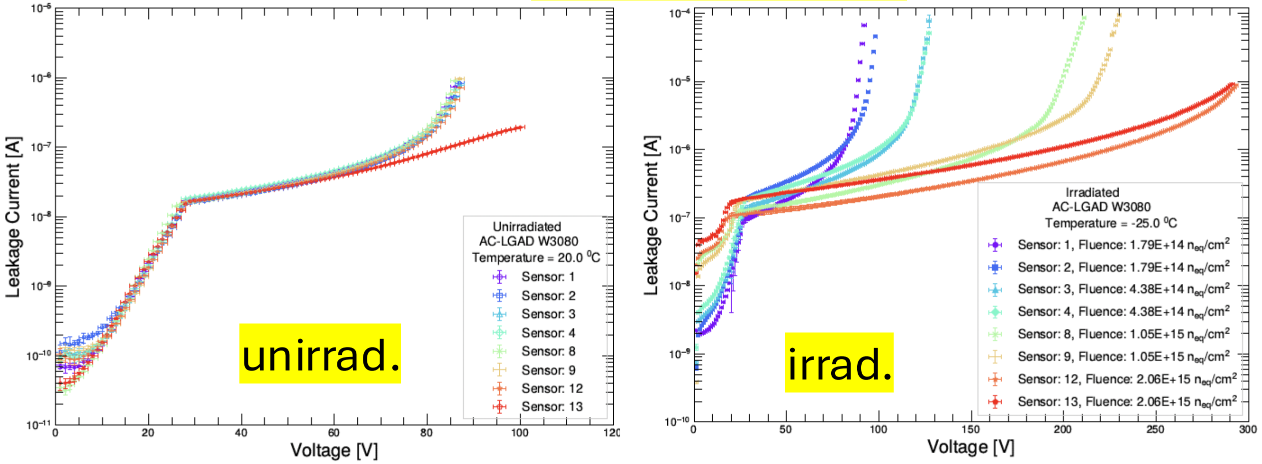
# Proton irradiation studies

- Application of 400-MeV protons in the range 1.8 – 21 x $10^{14}$ $n_{eq}/cm^2$ increases the AC-LGAD leakage current by factor ~765.
- Application of 400-MeV protons in the range 1.8 – 21 x $10^{14}$ $n_{eq}/cm^2$ increases the DC-LGAD leakage current by factor ~90k.

---DC-LGAD IV's---



---AC-LGAD IV's---



$$R = I_{\text{leakage}}^{\text{irradiated}} / I_{\text{leakage}}^{\text{unirradiated}}$$

| Fluence [400-MeV p/cm$^2$] | Fluence [$n_{eq}/cm^2$] | Sensor number | $I_{\text{unirradiated}}$ [nA] | $I_{\text{irradiated}}$ [$\mu$A] | $\mathcal{R}$ |
|---|---|---|---|---|---|
| $2 \times 10^{14}$ | $1.79 \times 10^{14}$ | 5-15 | 0.07 | 6.0 | 86000 |
| $5 \times 10^{14}$ | $4.38 \times 10^{14}$ | 6-15 | 0.07 | 6.6 | 94000 |
| $13 \times 10^{14}$ | $1.05 \times 10^{15}$ | 9-14 | 0.09 | 7.4 | 82000 |
| $25 \times 10^{14}$ | $2.06 \times 10^{15}$ | 11-13 | 0.07 | 6.9 | 99000 |

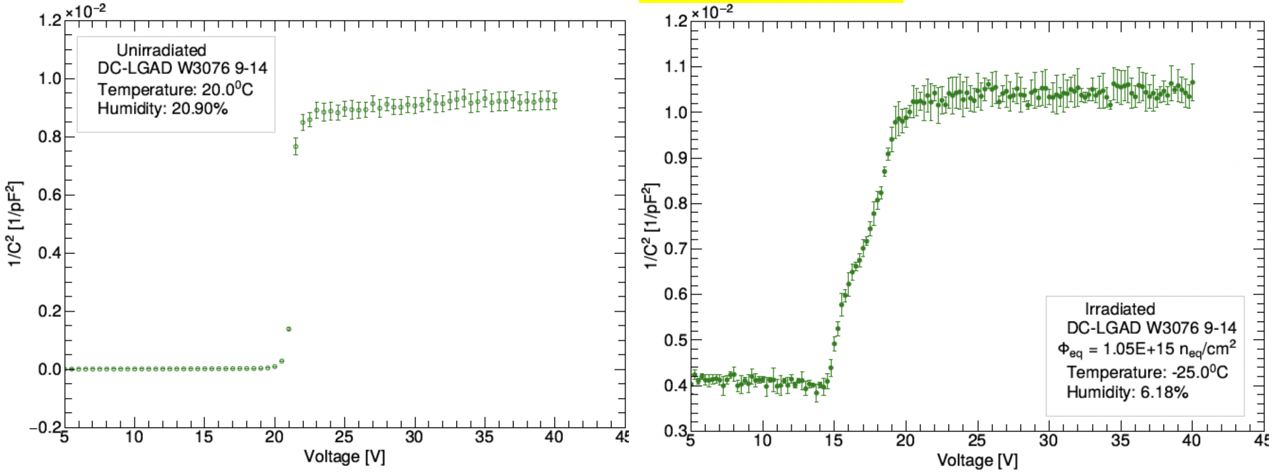
| Fluence [400-MeV p/cm$^2$] | Fluence [$n_{eq}/cm^2$] | Sensor number | $I_{\text{unirradiated}}$ [nA] | $I_{\text{irradiated}}$ [$\mu$A] | $\mathcal{R}$ |
|---|---|---|---|---|---|
| $2 \times 10^{14}$ | $1.79 \times 10^{14}$ | 1 | 31 | 19 | 619 |
| | | 2 | 27 | 26 | 952 |
| $5 \times 10^{14}$ | $4.38 \times 10^{14}$ | 3 | 29 | 23 | 783 |
| | | 4 | 33 | 30 | 921 |
| $13 \times 10^{14}$ | $1.05 \times 10^{15}$ | 8 | 28 | 17 | 603 |
| | | 9 | 30 | 25 | 843 |
| $25 \times 10^{14}$ | $2.06 \times 10^{15}$ | 12 | 28 | 14 | 496 |
| | | 13 | 28 | 25 | 904 |

*Leakage current values in these tables are normalized to temperature 20℃ and extracted at $V_{bias}$ = 50 V. Damage coefficient converting 400-MeV protons to 1-MeV neutron-equivalent is 0.84 (from: NIEL-all.pdf and protons.xls at rd50.web.cern.ch.).*

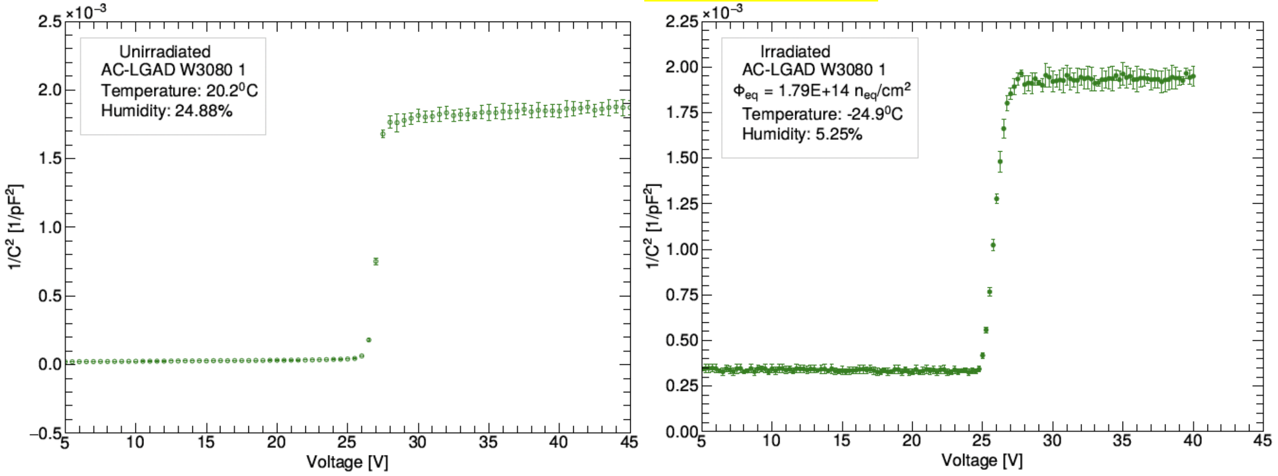
# Proton irradiation studies, continued:

- Application of 400-MeV protons:
  - up to a few x $10^{14}$ $n_{eq}/cm^2$ decreases depletion voltages $V_{gain\text{-}layer}$ and $V_{full\text{-}depletion}$ ~1-3 V in DC-LGADs and AC-LGADs.
  - at 1 – 2 x$10^{15}$ $n_{eq}/cm^2$ decreases depletion voltages $V_{gain\text{-}layer}$ and $V_{full\text{-}depletion}$ ~ 4-6 V in DC-LGADs and ~10 V in AC-LGADs.

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



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



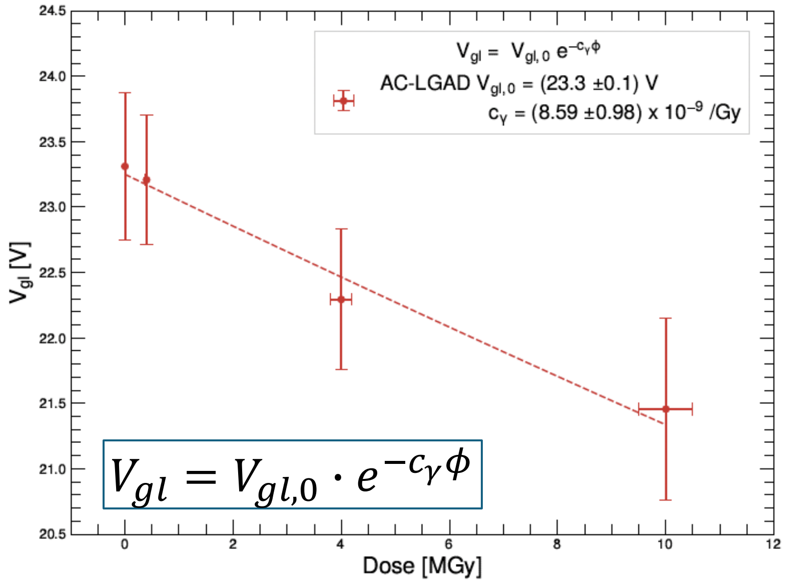
| **Sensor** | **Unirradiated** | | | **Fluence** | **Irradiated** | | |
|---|---|---|---|---|---|---|---|
| | $V_{gl}$ [V] | $V_{fd}$ [V] | $V_{bulk}$ [V] | $[n_{eq}/cm^2]$ | $V_{gl}$ [V] | $V_{fd}$ [V] | $V_{bulk}$ [V] |
| 5–15 | 20.3 ± 0.6 | 22.1 ± 0.6 | 1.8 ± 0.8 | 1.79E+14 | 19.1 ± 0.3 | 21.0 ± 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

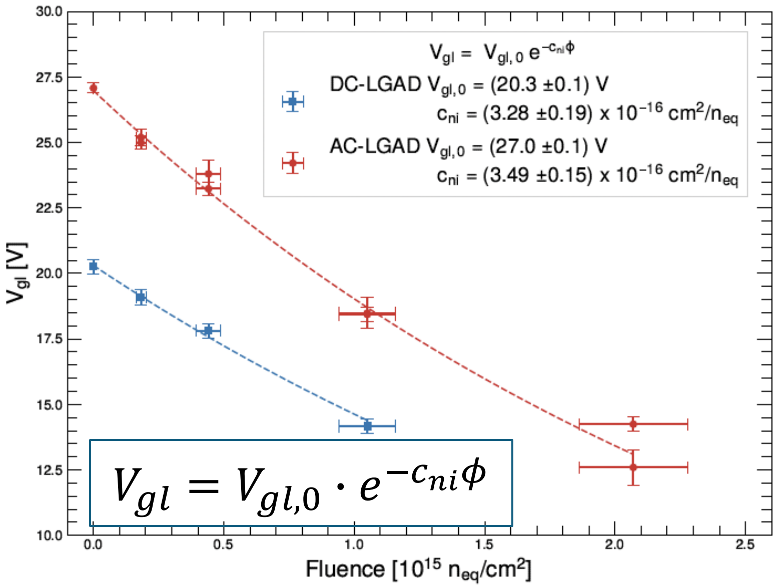
*Acceptor removal* is the process by which gain decreases as boron-substituted atoms deactivate due to radiation damage.

$V_{gl}$ versus ionizing dose



$$V_{gl} = V_{gl,0} \cdot e^{-c_\gamma \phi}$$

$V_{gl}$ versus non-ionizing dose



$$V_{gl} = V_{gl,0} \cdot e^{-c_{ni} \phi}$$

| AC-LGADs<br>wafer 3073<br>($c_\gamma$) | DC-LGADs<br>wafer 3076<br>($c_{ni}$) | AC-LGADs<br>wafer 3080<br>($c_{ni}$) |
|---|---|---|
| $(8.59 \pm 0.98) \times 10^{-9}\text{Gy}^{-1}$ | $(3.28 \pm 0.19) \times 10^{-16}\text{cm}^2/\text{n}_{eq}$ | $(3.49 \pm 0.15) \times 10^{-16}\text{cm}^2/\text{n}_{eq}$ |

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

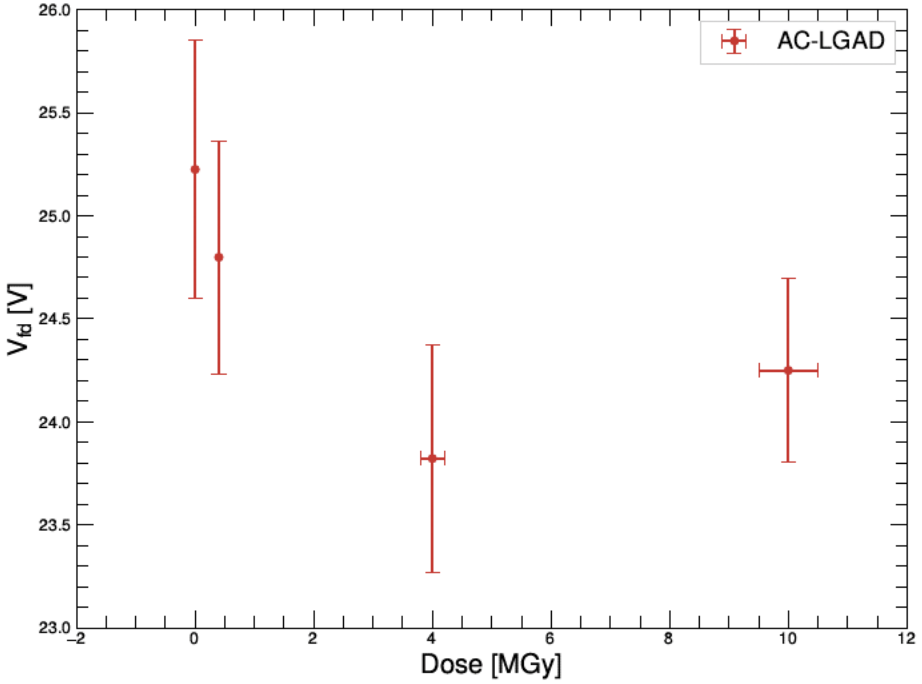
[1] M.R. Hoeferkamp et al., https://www.frontiersin.org/articles/10.3389/fphys.2022.838463.

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

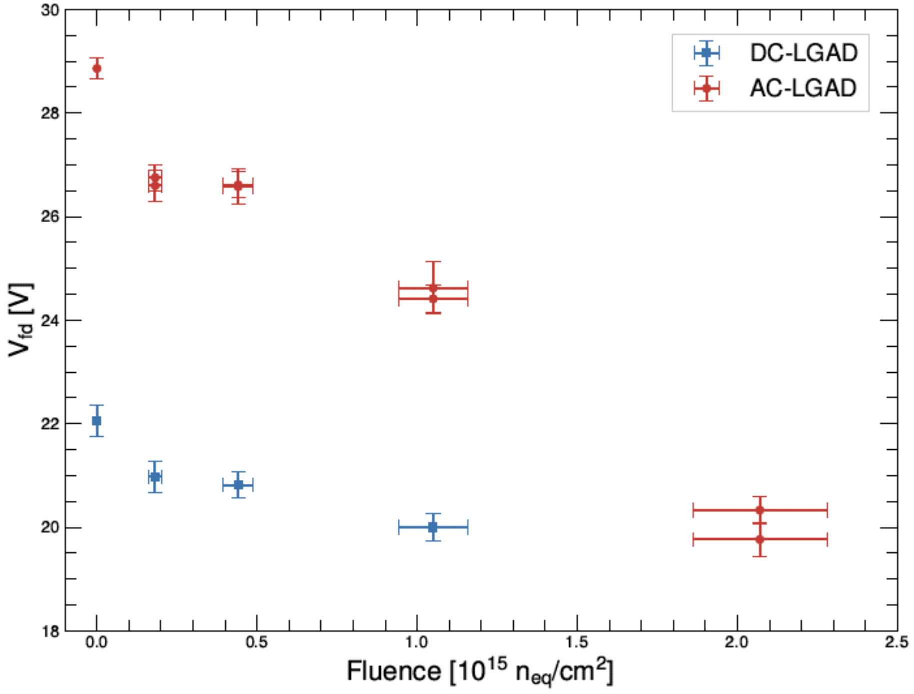
# Full depletion voltage

- $V_{fd}$ decreases with increasing radiation exposure in both DC- and AC-LGADs.
- The AC-LGADs start with a higher value of $V_{fd}$.

$V_{fd}$ versus ionizing dose



$V_{fd}$ versus non-ionizing dose



## Summary

- IV and CV are qualitatively consistent between pixels and strips after irradiation, and between DC- and AC-LGADs.

- Gamma irradiation of strip AC-LGAD:
  - Up to 10 MGy, little effect on depletion voltages, possibly reducing them by ~1 V.
  - Gamma irradiation introduces frequency dependence in capacitance.
  - Doses of 40 (100) MGy increase leakage current @ 20°C by factors of 3.5 (6.2).
  - Channel current rises from 5 nA unirradiated to 30 nA @ 10 MGy.
  - Breakdown voltage rises from 120 V to 130 V.
  - Interchannel resistance drops from $10^{10}$ Ω to < $10^{6}$ Ω, stabilizing around 4 MGy.

- Proton irradiation:
  - At 2.06 x $10^{15}$ $n_{eq}/cm^2$, leakage current @ 20°C rises by factor ~90k in DC-LGADs, factor ~765 in AC-LGADs.
  - Up to ~1 x $10^{15}$ $n_{eq}/cm^2$, depletion voltage drops 1 – 3 V in AC-LGADs.
  - For 1.05 – 2 x $10^{15}$ $n_{eq}/cm^2$, depletion voltage drops ~10 V in AC-LGADs

- Acceptor removal constants are consistent with measurements in complementary conditions.
  - $c_{\gamma} = 8.6 \times 10^{-9}$ $\mathrm{Gy}^{-1}$
  - $c_{ni} = (3.3 - 3.5) \times 10^{-16}$ $\mathrm{cm}^2/n_{eq}$

# Backup

## Uncertainties

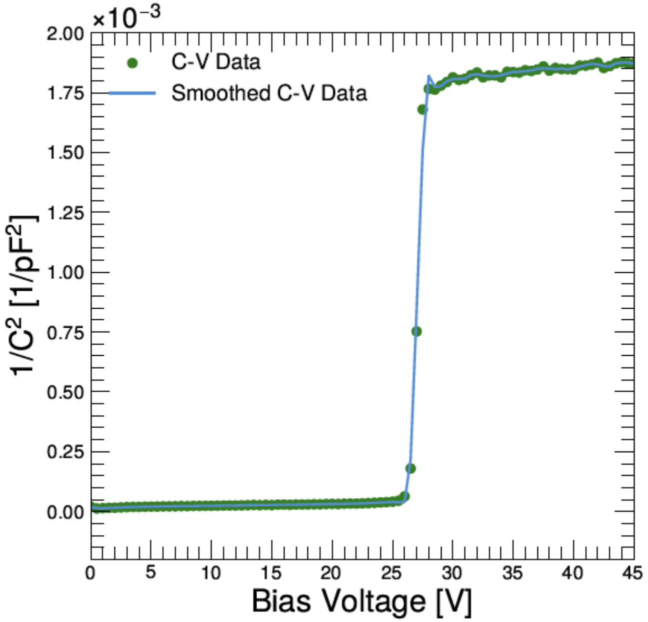
- Each IV data point is the average of 3 - 5 measurements.
- Each CV data point is the average of 3 measurements.
- The standard deviation for IV (CV) measurements is < 1% (< 3%).
- Systematic uncertainties include
  - size of measurement steps: 1V (0.5V) for unirradiated; 1V (0.25V) for irradiated.
  - ±0.5°C temperature uncertainty leads to ±1.82% uncertainty on leakage current, negligible uncertainty on capacitance.
  - Uncertainties due to instruments: Keithley 6487 (currents) – 0.15% + 100 pA [in the 2µA range], and 0.1% + 1 nA [in the 20µA range]; HP4284A (capacitance) - ±0.34%.
- Uncertainties on depletion voltages include covariance terms because $V_{gl}$ and $V_{fd}$ are extracted from datasets with common data points.

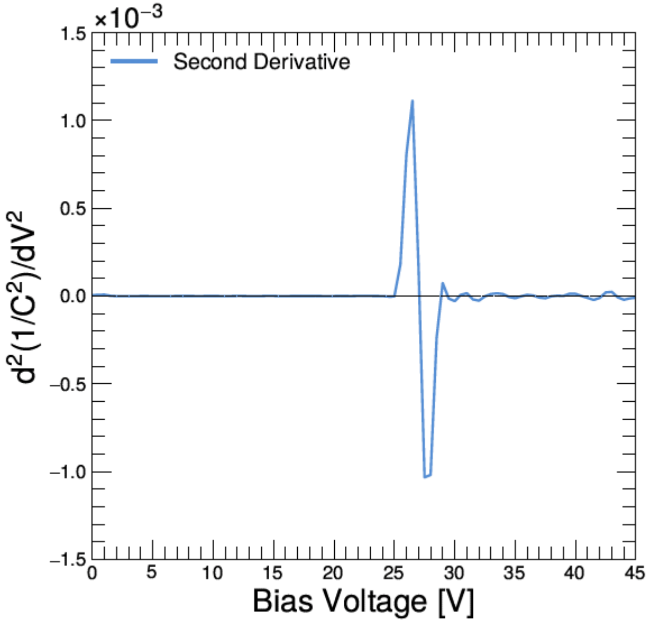
# Extraction of $V_{gl}$ and $V_{fd}$

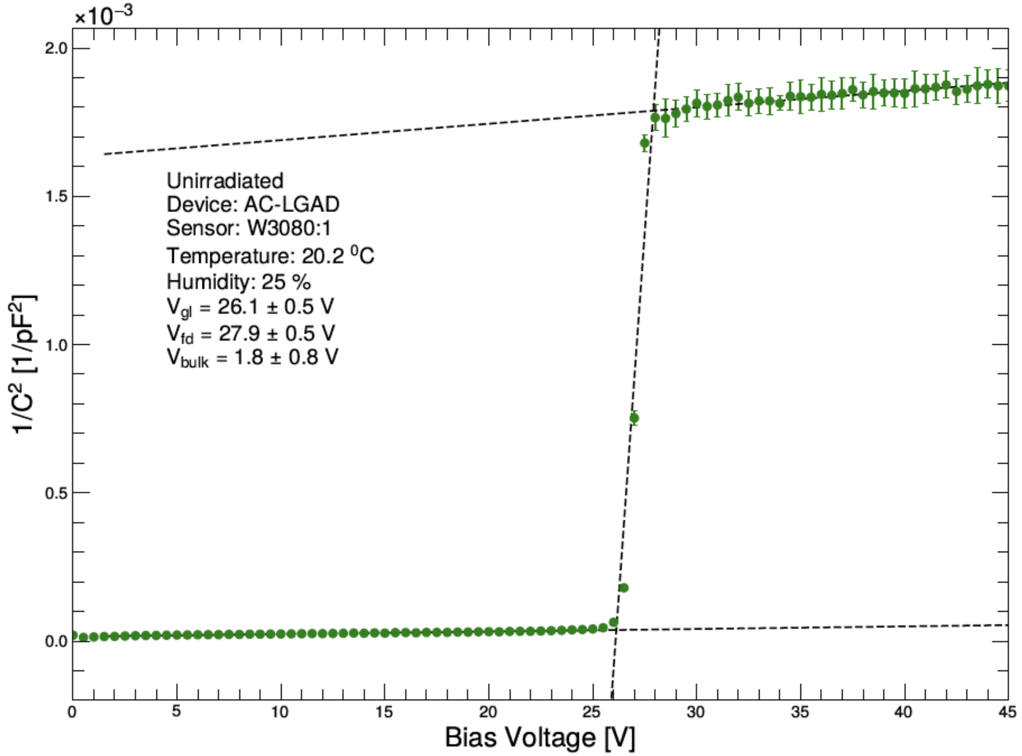
(upper left): Raw capacitance data vs. applied bias. Smoothed function obtained with Savitzky-Golay filter.*

(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).

## Dopant information for the AC-LGADs

- The dielectric is 100 nm of plasma etched chemical vapor deposition (PECVD) oxide deposited over a thin screen oxide layer of thickness 10 nm.
- The phosporus dose of the n-resistive layer is 2E13 $cm^{-2}$.
- The boron dose of the gain layer is 2E12 $cm^{-2}$.