Response of LGAD prototypes to gamma radiation

on behalf of Martin Hoeferkamp (University of New Mexico)
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This work is performed in the context of the ATLAS-HGTD and CMS-ETL working groups.

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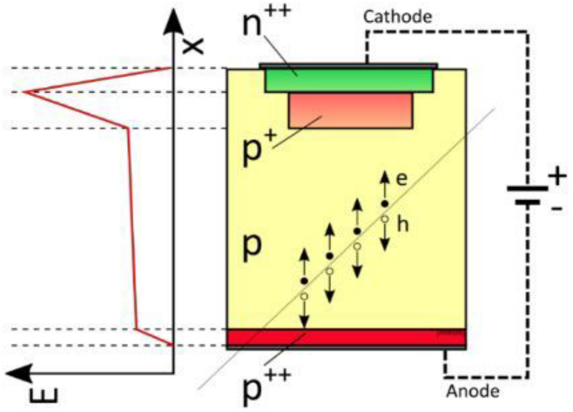
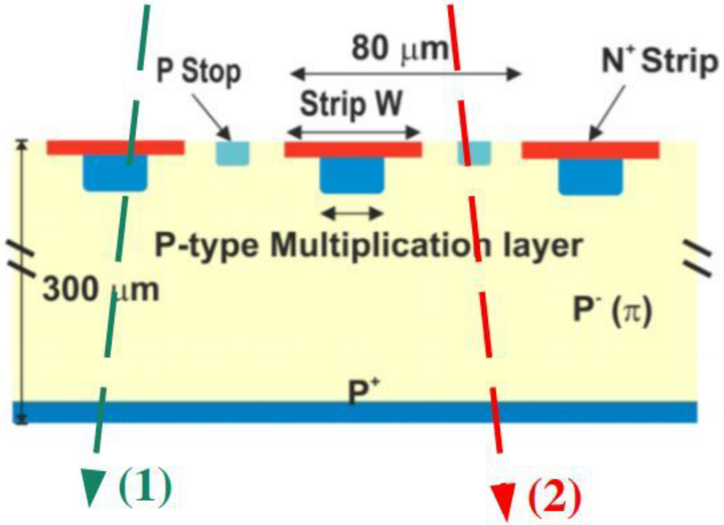




LGAD prototype structures have been fabricated by HPK in PINs, single LGADs, and 2x2 array configurations

Studies here are motivated by the need for the devices to withstand 2 MGy of ionizing dose (LHC benchmark)– which will accompany proton fluence integrated to $\sim 1.5 \times 10^{15}$ cm^{-2}.

We need better understanding of how oxide charge build-up and interface traps affect leakage current and charge collection.

An active area of LGAD research involves the problem of gain decrease as boron substitutional atoms deactivate in response to radiation damage - this is "acceptor removal"

These prototypes were produced with 4 different doping profiles in their gain layers. They were irradiated at the Sandia Gamma Irradiation Facility to 4 doses:

- 0.1 MGy
- 0.5 MGy
- 1.0 MGy
- 2.0 MGy

The gammas contribute both to ionizing damage at the surface and to NIEL (point defects from induced Compton electrons).

Note that thin (~50 μm) LGADs are a baseline option for timing detectors at CMS and ATLAS.

These prototypes are also scheduled for future exposure to proton irradiation (Los Alamos) up to 2.5×10^{15} n_{eq}/cm^2.

- The concept of the LGAD is based on a multiplication layer whose doping leads to high enough electric fields for impact ionization.

- Gain factors of ~10 significantly improve timing performance, especially in thin devices where timing is limited by Landau fluctuations.

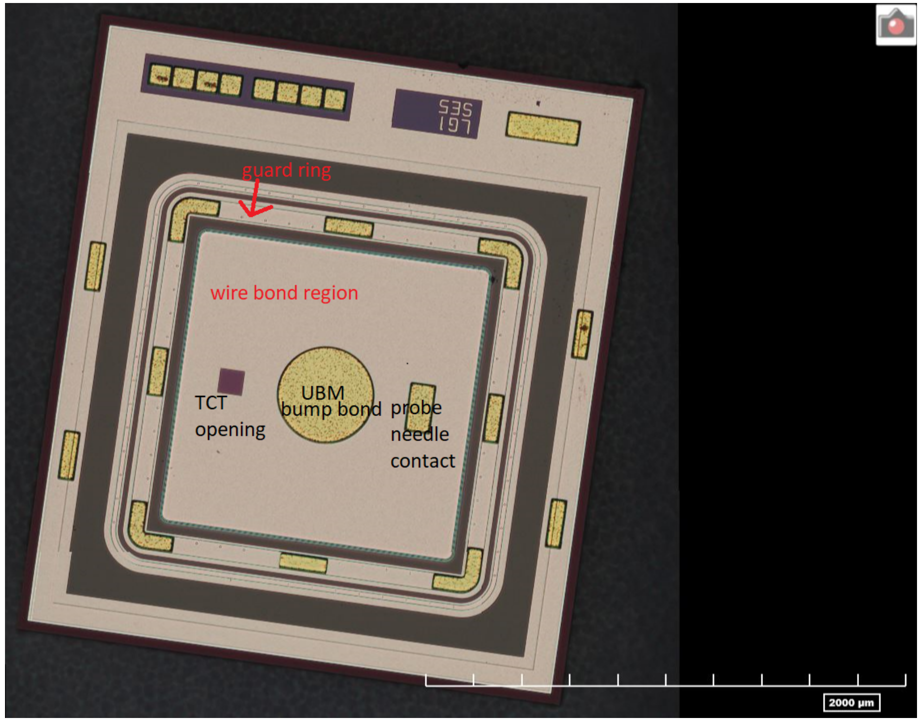
- Thin bulk is preferred to limit full depletion voltage, so that multiplication will onset before breakdown.

- Gain layer depletion voltage has been shown to correlate perfectly with charge collection performance.

See also: G. Kramberger et al., *Radiation Hardness of Thin Low Gain Avalanche Detectors*, Nucl. Instr. and Meth. 891 (2018) 68-77, arXiv:1711.06003.

Device structure

n^{++} (electrode) – 1.3 x 1.3 mm^2
p^{+} (gain layer) – 2.2 to 2.5 µm thick
p (bulk)
p^{++} (backside)



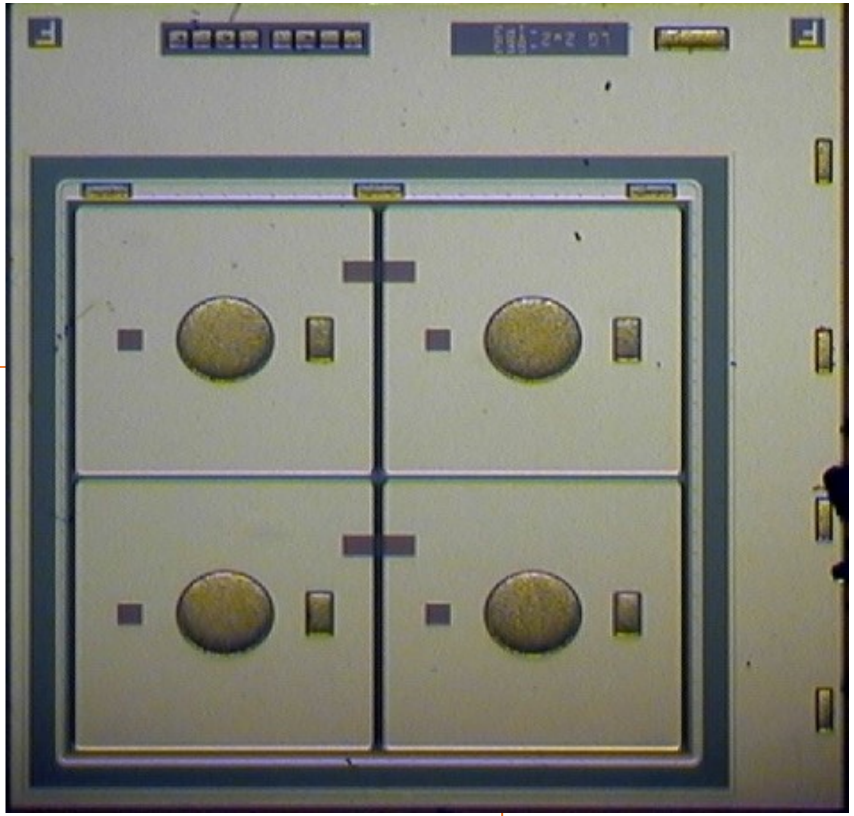
- 50 µm thick active layer
- 200 µm total thickness
- single guard ring
- variations with and without under-bump metallization (UBM)
- epitaxial Si grown on Czochralski substrate

- The four types were produced with different gain layer dopant concentrations:

Wafer (no UBM)	Wafer (with UBM)	c [10^{16} cm^{-2}]
28	25	4.3
33	31	4.5
37	36	4.6
43	42	5.0

studied at UNM

Very small (few percent) differences in dopant concentration have been shown to lead to very large gain differences.



The 2x2 arrays have the same properties as the smaller devices but variations on:

- inter-pad (IP) separations:
  30 µm
  40 µm
  50 µm
  70 µm

- distances from the active area to the edge
  300 µm
  500 µm

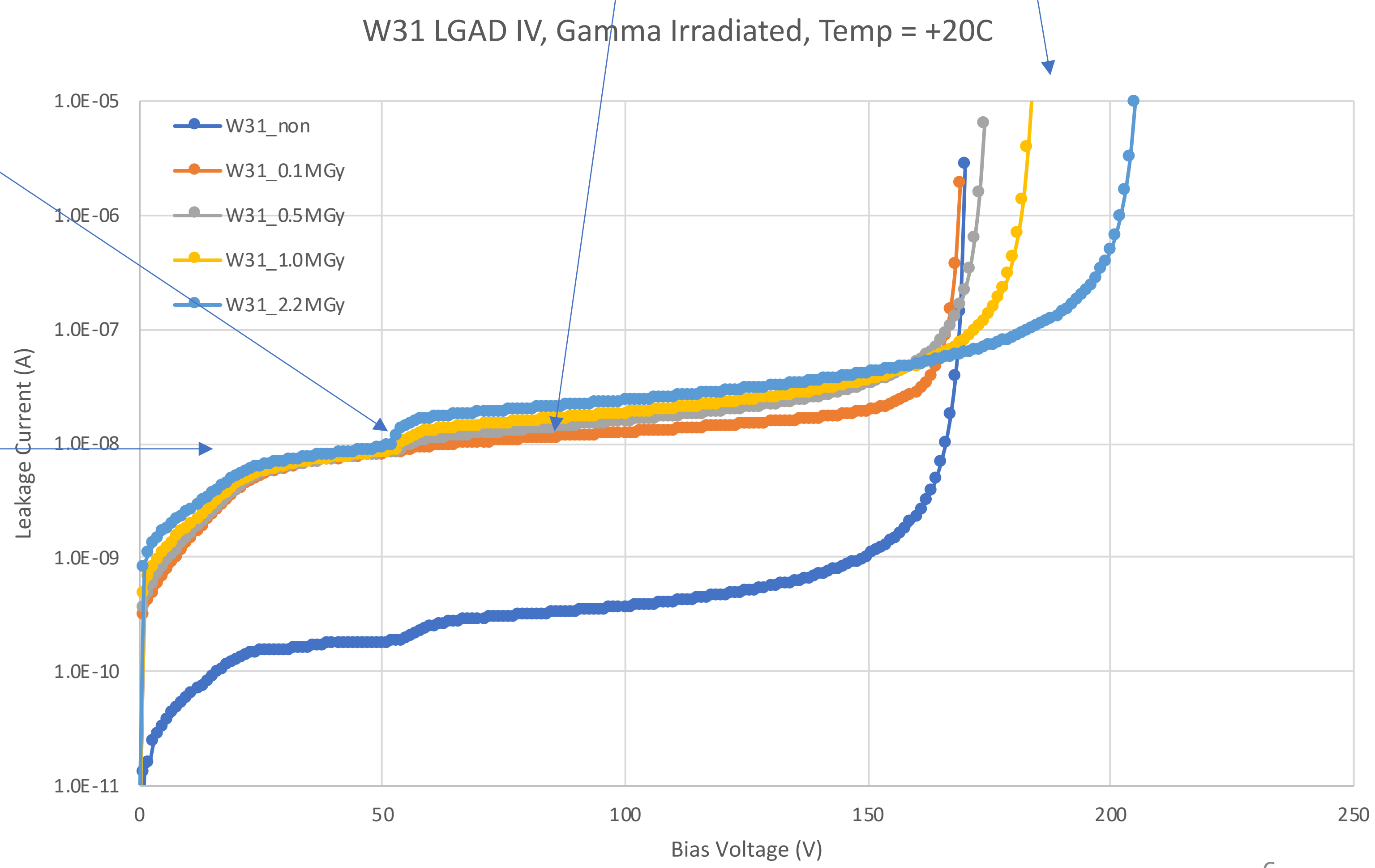
IV and CV measurements have been made at UNM of statistical samples from these prototype categories, prior to and after exposure to 0.1 – 2.2 MGy gammas

Example IV measurement of a single LGAD, unirradiated and for 4 doses

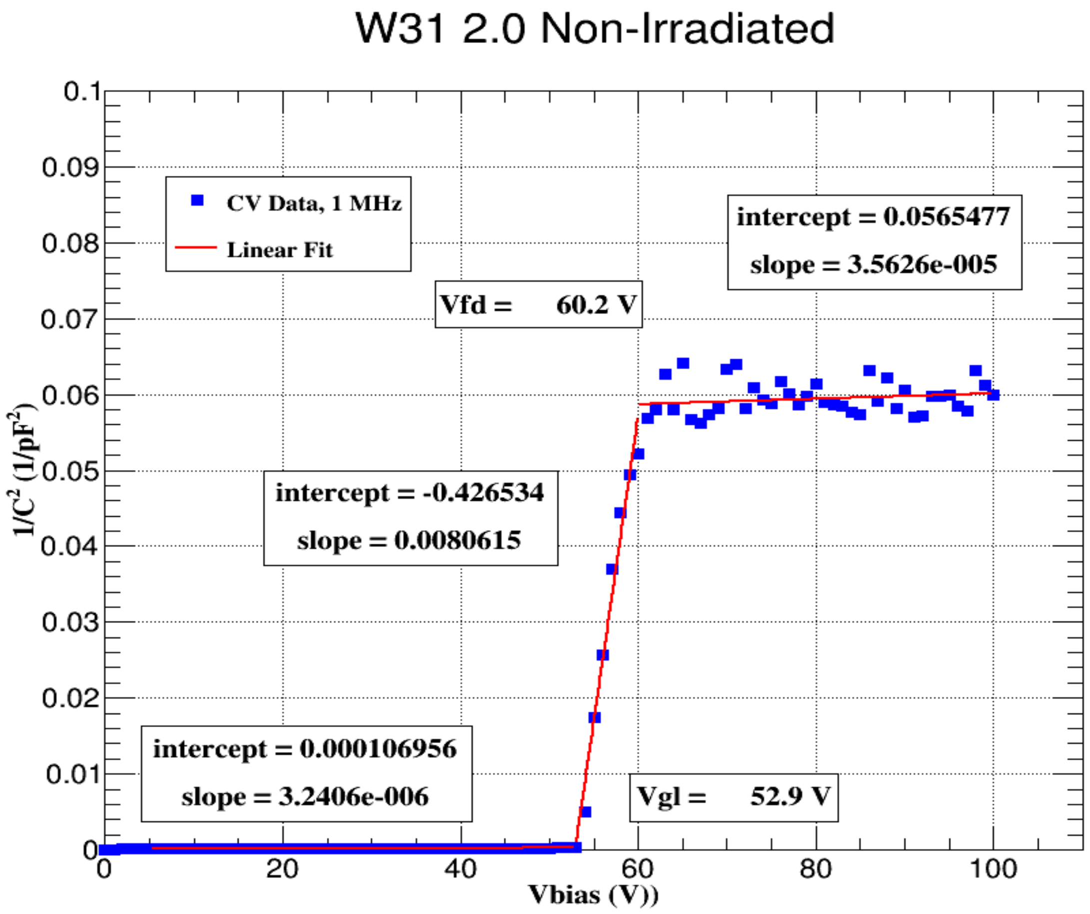
V_{bd} increases slightly with dose, Current saturates at 0.1 MGy

Gain layer saturates

Before bulk depletion, current increases by an order of magnitude due to surface component



Example CV of an unirradiated LGAD



Very small change in V_{gl} with gamma dose

LGAD		0.1	0.5	1	2			
W31	Pre-irrad	Pre-irrad	Pre-irrad	Pre-irrad	0.1MGy	0.5MGy	1.0MGy	2.2MGy
Vfd	60.0 V		61.1 V	60.2 V	60.2 V	60.0 V	59.4 V	56.3 V
Vgl	53.0 V		53.1 V	52.9 V	53.0 V	52.4 V	51.9 V	51.3 V

Outcome of the measurements on single LGADs:

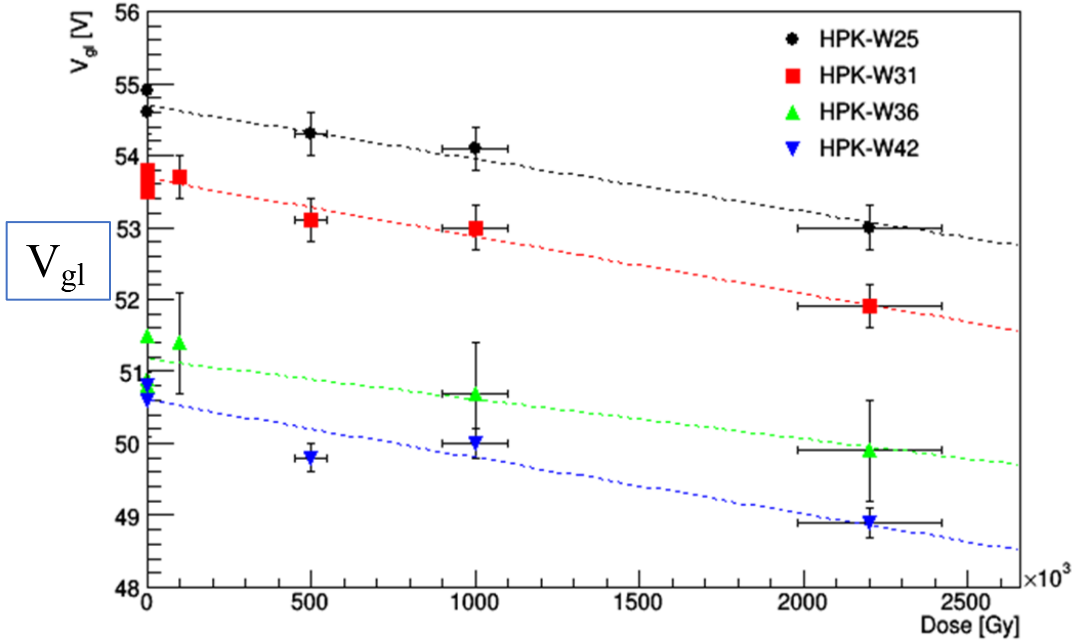
- The gain layer depletion voltage V_{gl} is very slightly affected by gamma radiation up to 2.2 MGy

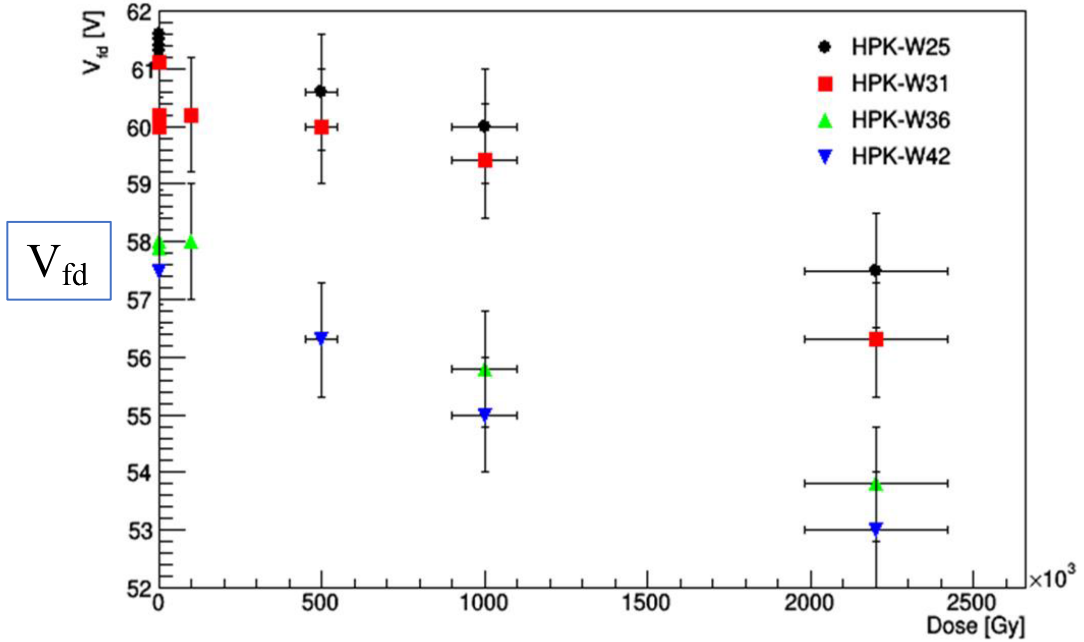
- Full depletion voltage, V_{fd}, (also observed through CV) decreases slightly with TID
    - indicating that effective positive space charge formation is occurring

- Breakdown voltage V_{bd} observed through IV measurements to increase slightly with TID
    - These outcomes are validated by measurements of breakdown in the PIN (pad) – see next slide

- Surface current rises at the relatively low TID of 0.1 MGy
    - This current is present below V_{gl}, i.e. below onset of gain, so it is not multiplied. The oxide charge / interface effects saturate at 0.1 MGy.

- Bulk damage by gamma-induced Compton electrons removes a small amount of acceptors; this reduces the gain (note observed small V_{gl} drop); so V_{bd} increases.





Role of the measurements on PINs:

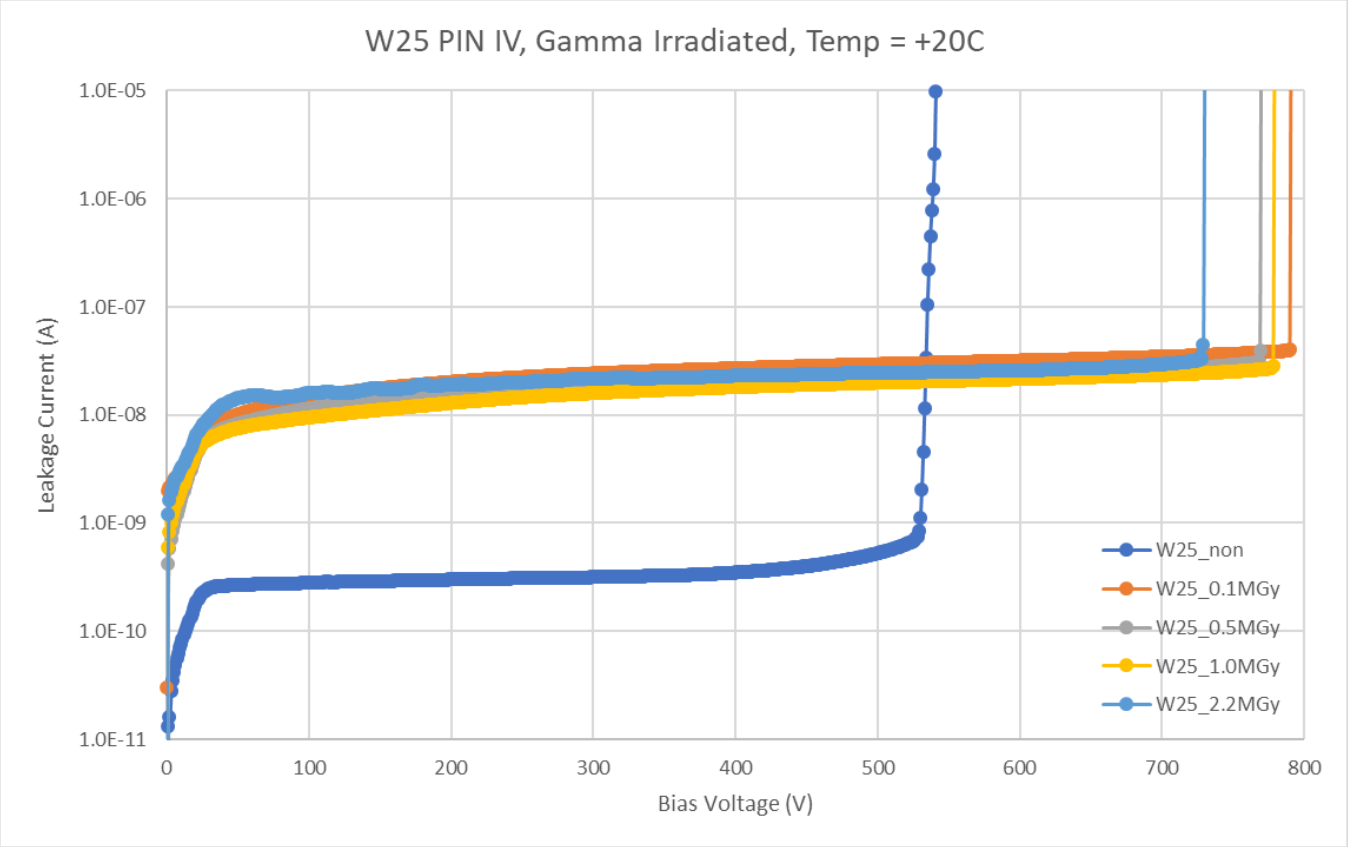
- The PINs have the benefit that they can tolerate very high bias voltage, sustain relatively little bulk damage, and have the same geometry as the LGADs but without the gain layer. When they break down, it is indicative of breakdown in the bulk, at the guard ring where the field lines are focused.

- Irradiation increases V_{bd} in the PINs up to nearly the bulk value of 800 V.

- The lowest dopant concentration shows the highest V_{bd}.

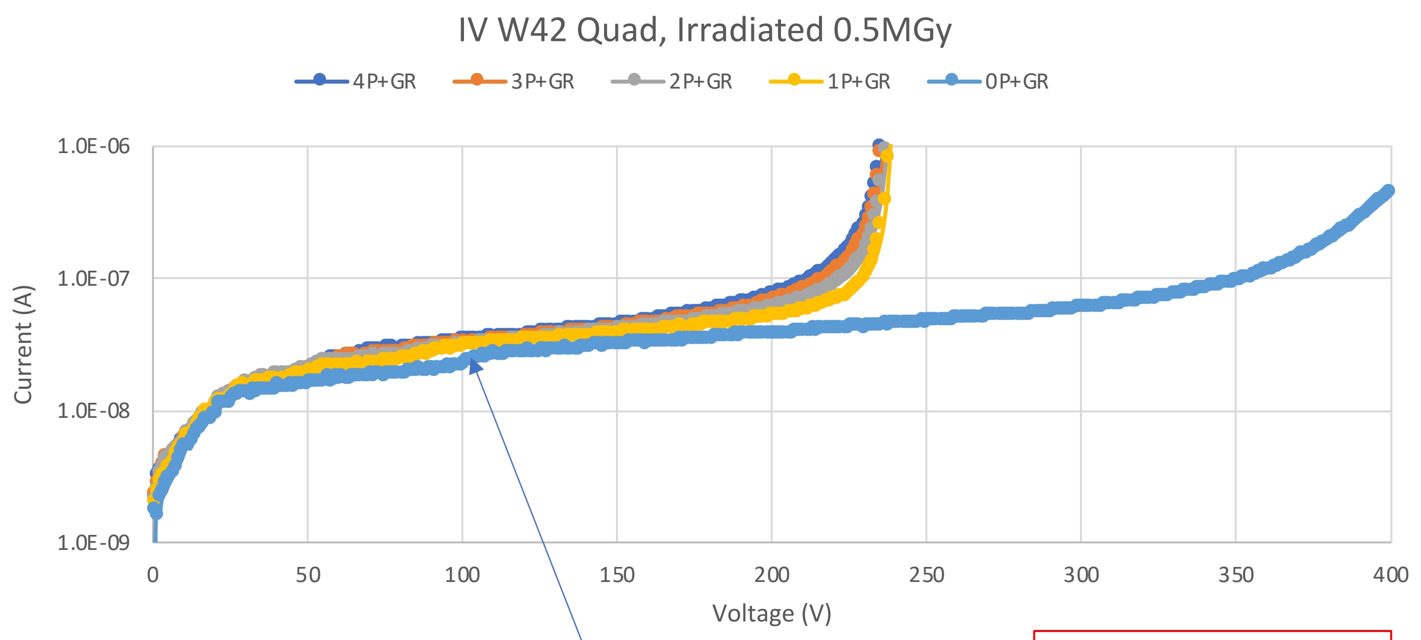
- Oxide charge saturation moderates the field, leading to increase in V_{bd}. This would be true for LGADs as well, if they broke down at the guard, but they break down at the pad first.

- Outcomes of measurements made following these gamma exposures correspond closely with outcomes following neutron exposures – breakdown also in the bulk.

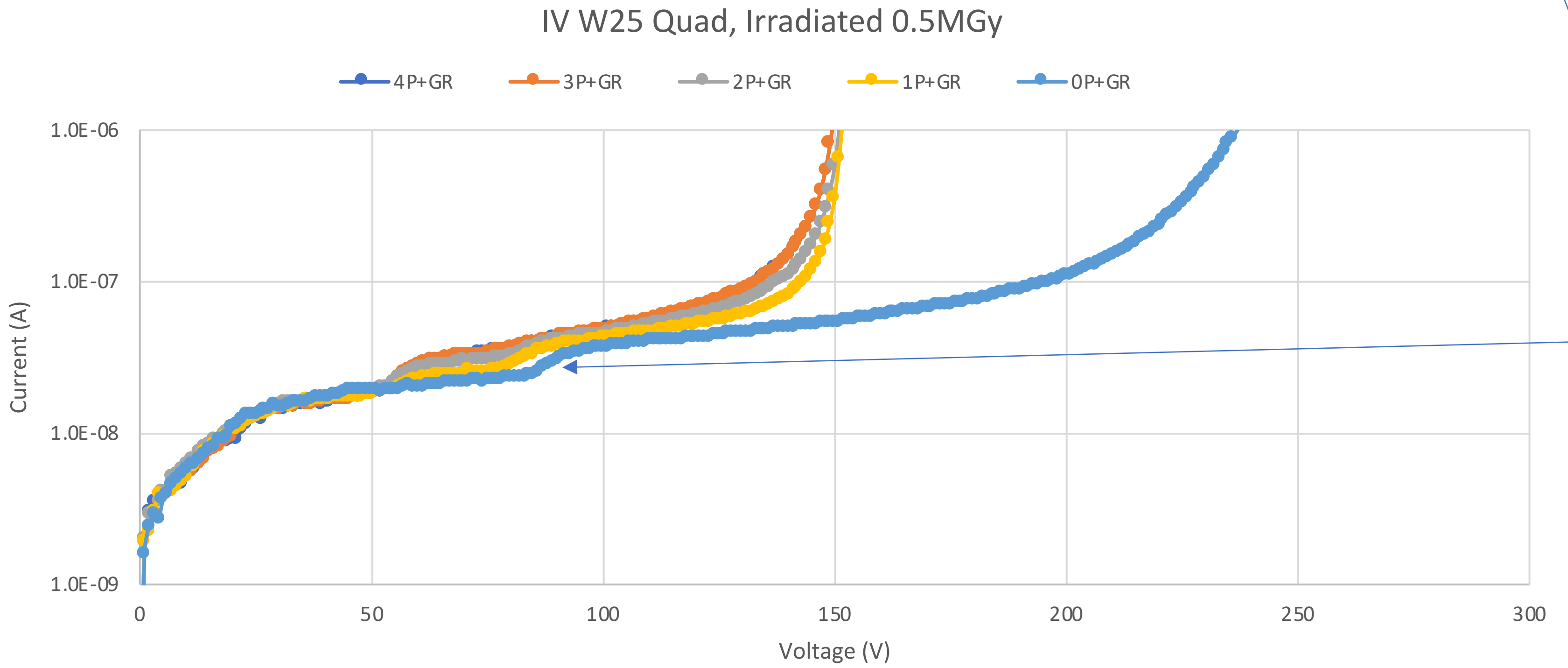


Sample IV's for PINs on Wafer 25

Example IV measurements on quad sensors with different gain layer dopant concentrations



$c = 5.0 \times 10^{16}$



Punch-through occurs at different applied bias

$c = 4.3 \times 10^{16}$

Outcome of the measurements on quad sensors (using for example Wafer 25 with inter-pad distance 30 μm):

- V_{bias} is applied to the back side of the chip.
- Current is measured with ground connected to guard ring plus 0, 1, 2, 3, or all 4 pads.
  - The issue: if a device is floating, its potential is determined by punch-through. This places a limit on the inter-electrode separation, because if one electrode breaks down, the breakdown can cascade to the neighbors.
  - The smallest possible inter-pad separation is preferred to maximize fill factor, but the separation must be large enough to prevent breakdown-cascade if a bump-bond is lost.
  - Results here suggest that inter-pad separation as small as 30μm may have this breakdown-cascade problem – so 50μm may be preferred - but since surface conditions after TID play a role, this option is still under study.

- Up to V_{gl}~54 V, only guard ring current is observed as the small depth of the gain layer provides little generation current
- After the gain layer depletes, further application of ~54 V – 62 V depletes the active layer. During this bulk depletion process, the voltage increase extends the depleted volume and so does not increase the electric field in the gain layer – *no multiplication*. Generation current $I_{leakage} \sim \sqrt{V}$ as usual.
- Around 80 V - 85 V the guard ring current increases with all pads floating: punch-through to the neighboring pads occurs.
- Once full bulk depletion is reached (~85 V), increased voltage increases current as the electric field and the gain increase.
- At ~95 V there is a knee in the IV characteristic as all 4 pads are depleted by punch-through.
- The voltage at which punch-through occurs is higher (100 V) for Wafer 42 than for wafers with lower gain layer dopant concentrations.

Conclusion from the quad sensor measurements: Irradiation to 2 MGy leaves the gain layer largely unaffected for all dopant levels, and currents remain high enough to permit usual operation.

What's next at UNM:

- Further IV and CV measurements on sensors with different inter-pad separations (40μm, 50μm, 70μm), before and after gamma exposure
  - In the 30μm samples, the oxide charge saturates around 0.1 MGy, leading to little change in current between 0.5 MGy and 2 MGy. Different pad configurations may lead to different breakdown scenarios.

- Continue to explore whether we can extrapolate from PINs to LGADs in terms of V_{bd} before and after dose.

- Can we estimate depletion voltage reliably from IV curves, with a fit to the region $V_{gl} < V < V_{fd}$ using $I \propto \sqrt{\frac{(V - V_{gl})}{(V_{fd} - V_{gl})}}$?

- Lowest dose PINs are on their way to the test beam

- Proton irradiations, followed by charge collection and timing studies, are coming up in 2021

- Compare other producers, as dopant profile may be significant