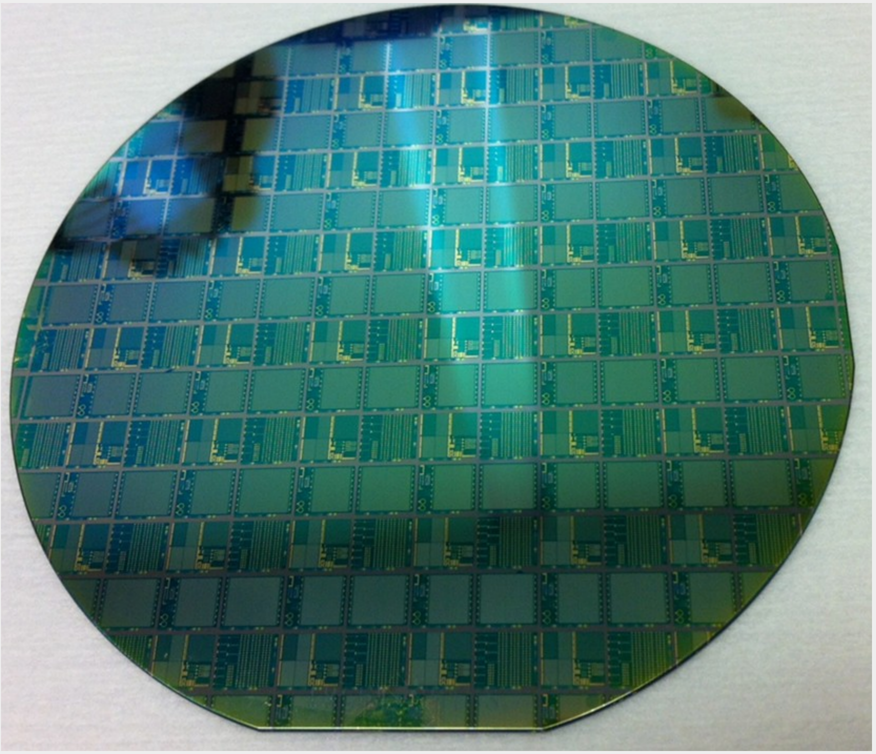
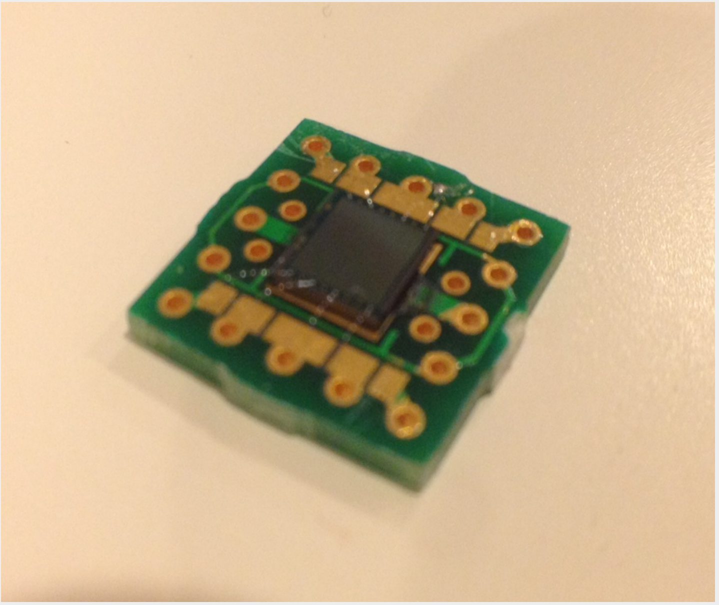
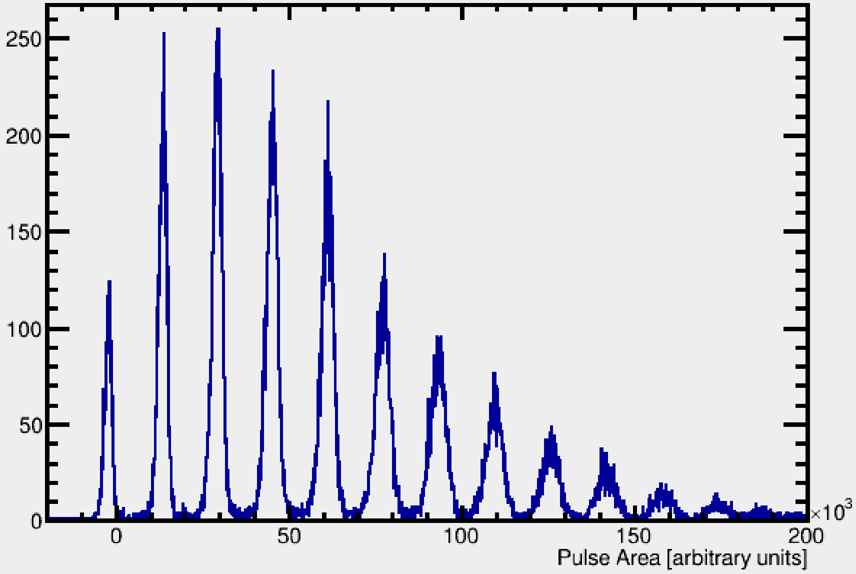
Studies of GaInP based SPAD arrays







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LightSpin Technologies, Inc.

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Geiger mode light detectors for HEP

For HEP and related fields:
demands likely to increase for radiation and B-field tolerant technologies for visible light detection (eg optical calorimetry)

Silicon based SPAD arrays (SIPM/MPPC) already highly optimized, impressive performance:
- detection efficiency
- speed, noise
- spectral response, ...

However, challenges remain to preserving a high figure of merit for detector performance in collider environments with large integrated particle flux on detector elements.

This talk:
- Motivation for exploring compound semiconductors, specifically GaInP
- Overview of new GaInP SPAD arrays
- Initial look at newly fabricated devices

Why explore GaInP?

- **Large bandgap**
  => potential for low thermal noise ?
- **Low intrinsic carrier concentration**
  => resistance to bulk damage ?

GaInP/GaAs widely used in electronics industry
=> relatively low cost manufacturing

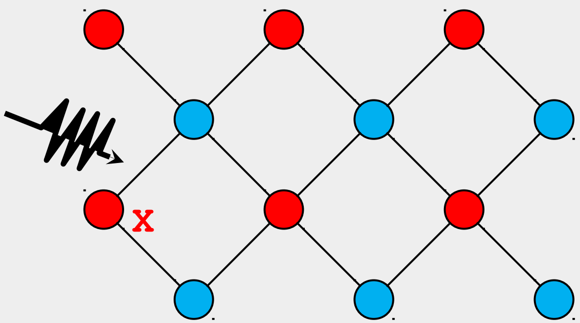
	n_i
Silicon	1E10/cm^3
GaAs	2E6/cm^3
GaInP	300/cm^3

Properties at 300K	**GaInP**	**GaAs**	**Si**
Band gap E_G [eV]	1.9	1.42	1.1
Long wavelength cutoff [nm]	650	870	900
Intrinsic carrier concentration ni [cm^{-3}]	3.0E02	2.0E06	1.0E10
τ_G [usec] (~defect concentration)	0.001	0.1	50,000
Effective DCR @ 25C, 25% DE [Mcps/mm^2]	0.075	5.000	0.050
Measured DCR @ 25C, scaled to 25% DE [Mcps/mm2]	25	133	0.044

E. S. Harmon, M. Naydenkov, J. Bowling, "High performance compound semiconductor SPAD arrays," Proc. SPIE. v. 9858, Advanced Photon Counting Techniques X, 98580C. (2016)
http://dx.doi.org/10.1117/12.2225112

Why try GaInP for rad hard(er) devices?

Bulk defects: materials property, measured
Increased by radiation induced displacement, leads to enhancement in DCR



Induced generation rate:

$$G(\Phi) = n_i / \tau_{SRH(\Phi)} = n_i \times (K \times \Phi) \times (Area \times W)$$

	n_i	K	G (Φ) cps/mm²
Silicon	1E10/cm³	0.10E-6 cm²/s	1.0E-3 × Φ
GaAs	2E6/cm³	1.25E-6 cm²/s	2.5E-6 × Φ
GaInP	300/cm³	1.25E-6 cm²/s	3.8E-10 × Φ

- n_i: intrinsic carrier concentration
- K: lifetime radiation damage factor
- Φ: radiation flux
- W: thickness of active region (~1um)

"Intrinsically rad hard" material

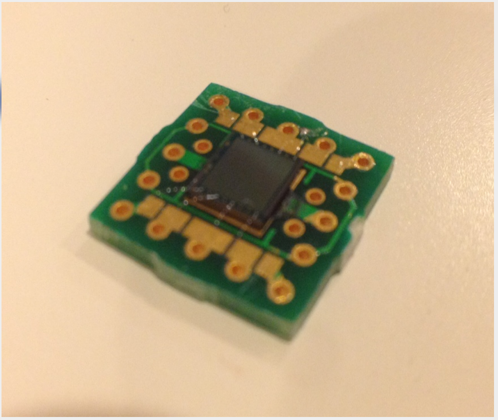
Beyond intrinsic properties, ultimate performance depends on engineering:
- Si: surface treatment SiO_2 vs. Si_3N_4
- GaAs, GaInP:
  Surface passivation: imperfect dielectric vs. perfect single-crystal, etc.
  Native defects, field shaping, epitaxy, … other?

=> engineering + physics problem

Tested devices

GaInP Photomultiplier Chips™

LightSpin Technologies, Inc.



Development cycle has iterated over
multiple "generations" of design and manufacturing choices.

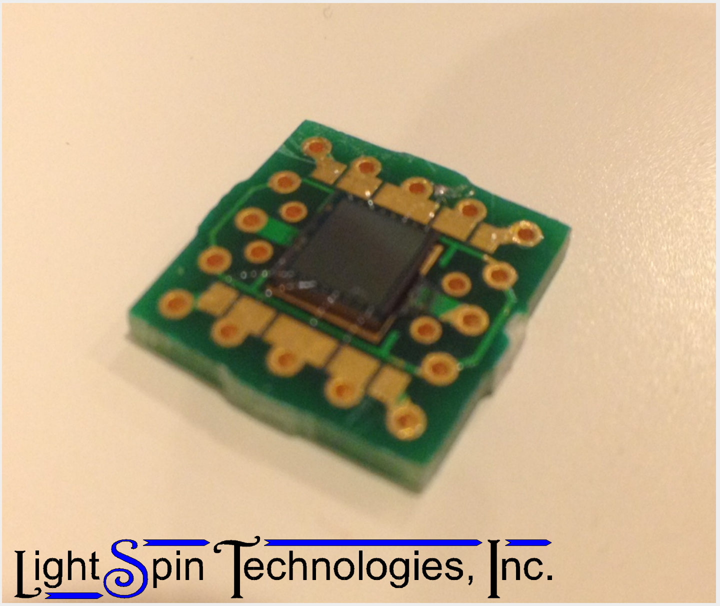
Earlier versions have also included GaAs and AlGaAs variants

Generation 5.0x
- produced first GaInP arrays with good performance properties [reported at CPAD 2016]
- demonstrated high gain, S/N, lower leakages, reasonable 1PE resolution

Generation 5.1
- same epitaxy, processing improvements compared to Gen 5.0
- AlGaAs window, trenching around arrays
- dielectric encapsulation: 10 nm Al_2O_3, 35 nm Si_3N_4.
- AR coating, ¼ λ at 420 nm, < 10% reflectivity 375 – 575 nm (normal incidence)

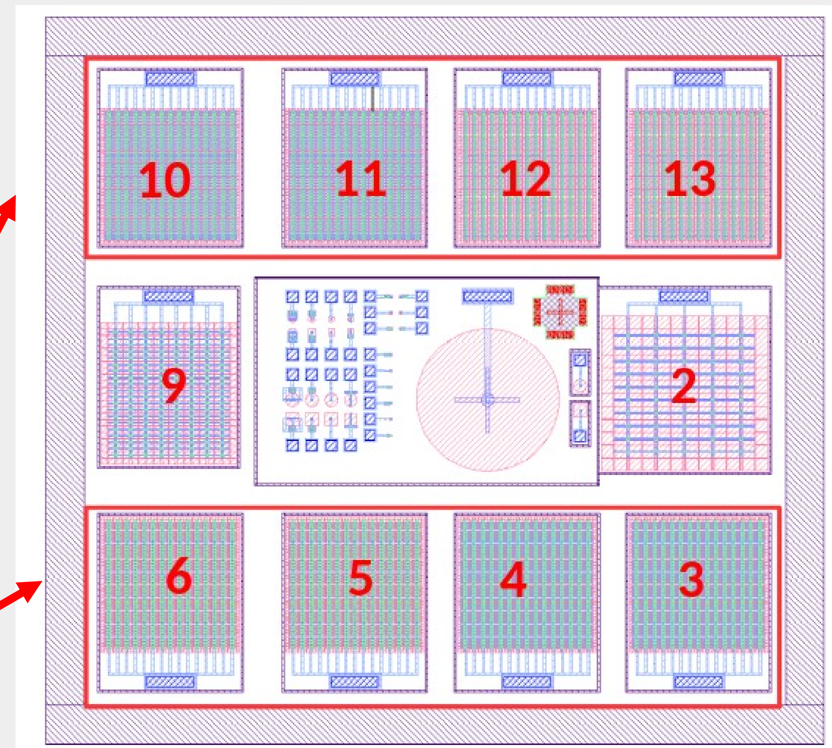
Generation 5.2
- similar epitaxy, but obtained from different manufacturer
- AlInP window, more stable against oxidation. Noticeably improved surface processing in general.
- deeper trenching around arrays, sidewall protected with dielectric
- some improvements in fill factor
- expect improvements in external QE, leakage vs Gen 5.1

Tested devices: Gen 5.1,5.2 physical layout



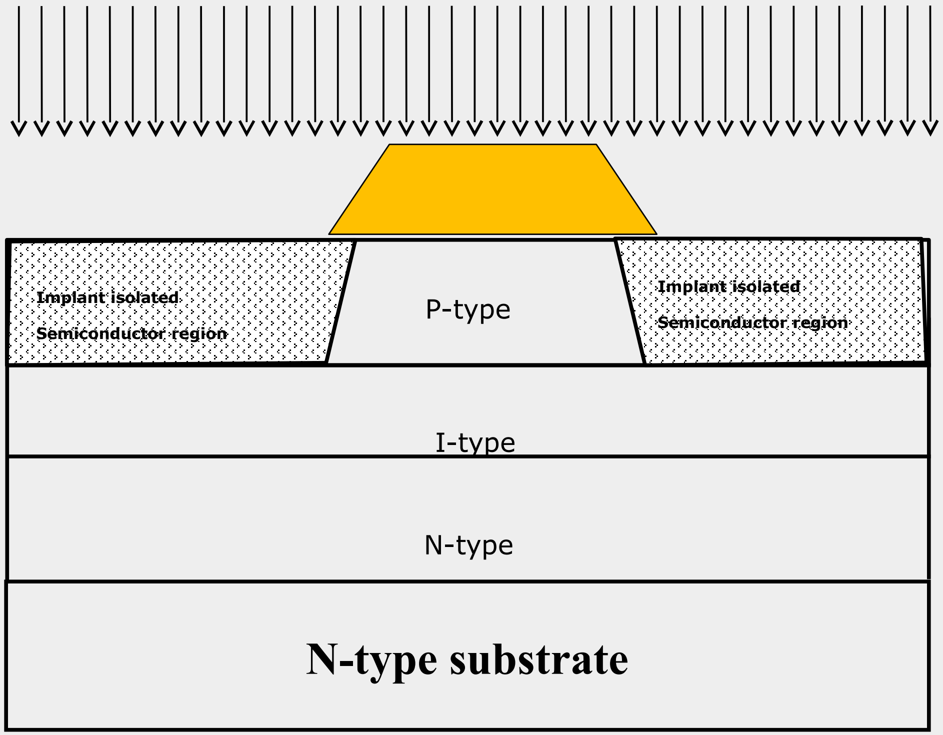
GaInP Photomultiplier Chips™

0.75x1.2mm arrays
1200 ~25u SPADs

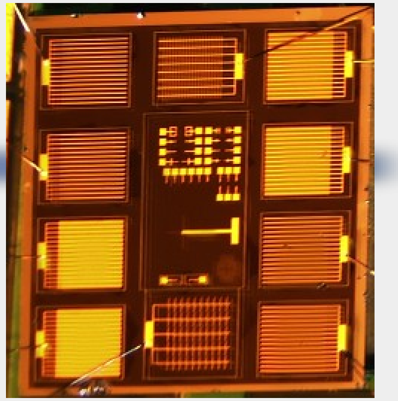


- Arrays 3, 4, 10, 11 include ~190 fF/SPAD bypass capacitor in quench circuit
- Trenching around each array to reduce surface leakage

Tested devices



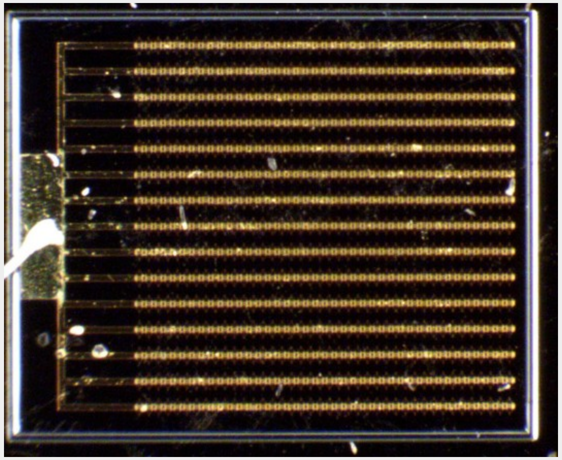
Multi-device chip on carrier



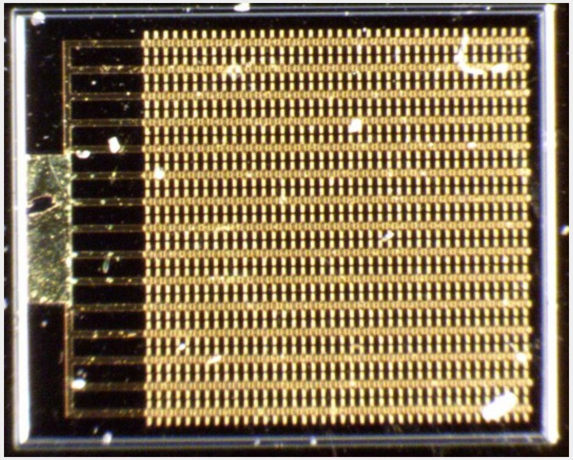
Close-up of arrays

1x1.5mm 25u arrays

no bypass C



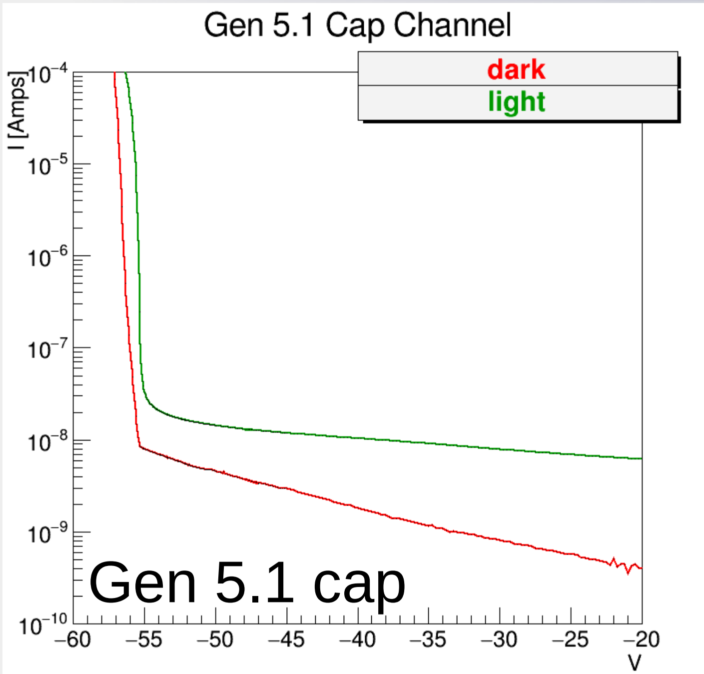
w/ bypass C



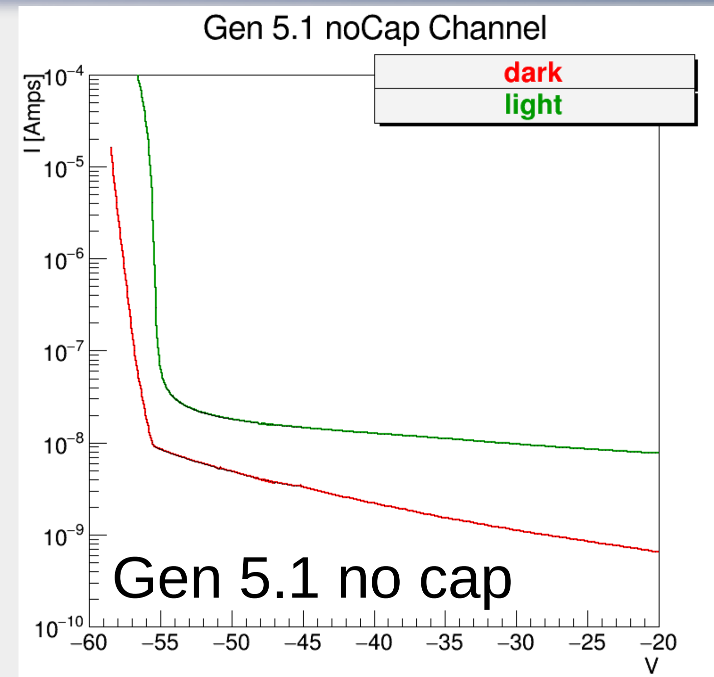
- Planar approach uses implant isolation to form a virtual beveled edge mesa structure.
- Same approach used for quench resistor (adjustable 100kΩ—1TΩ/□)
- Add trenching to physically separate arrays
- Applicable to other semiconductor materials

[US009076707B2, US009627569B2]

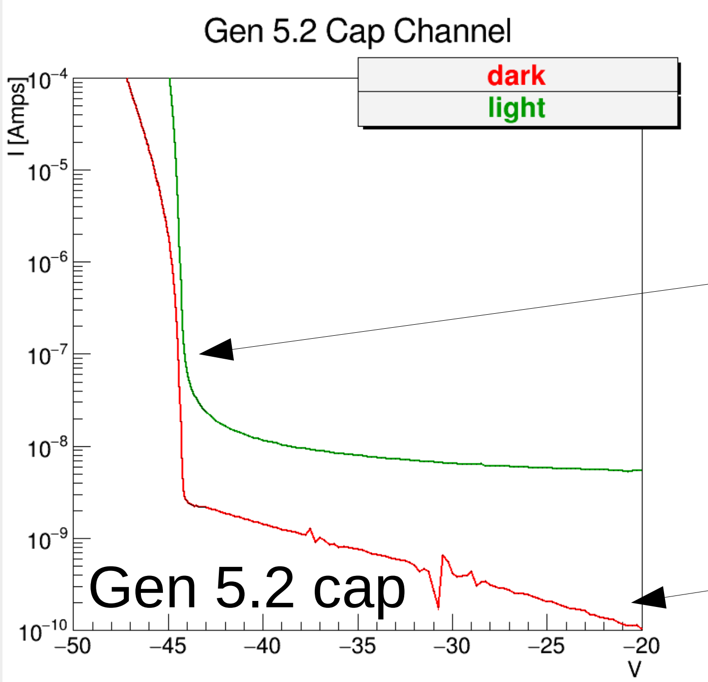
Breakdown characteristics: Light vs. Dark IV



larger FF

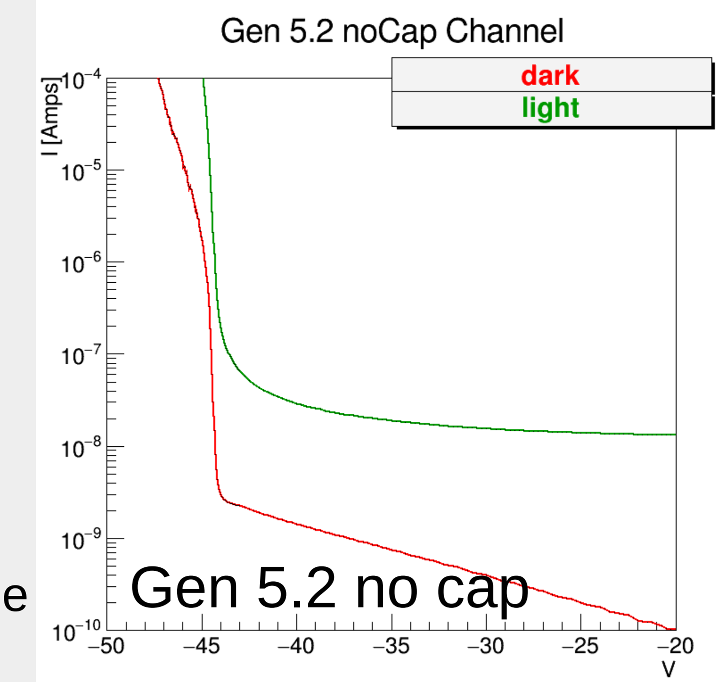


larger external QE

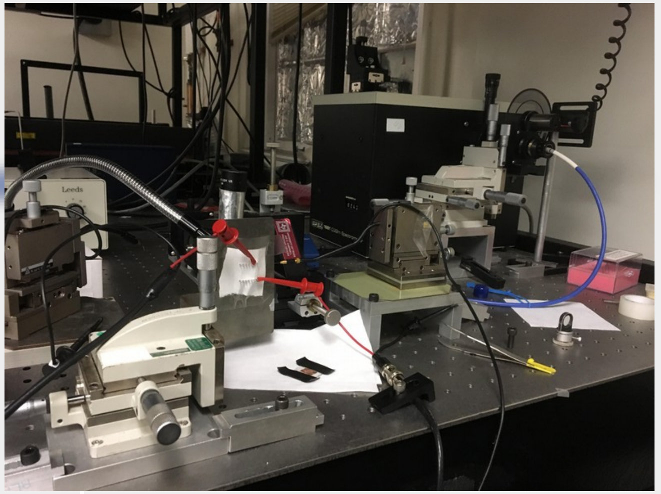


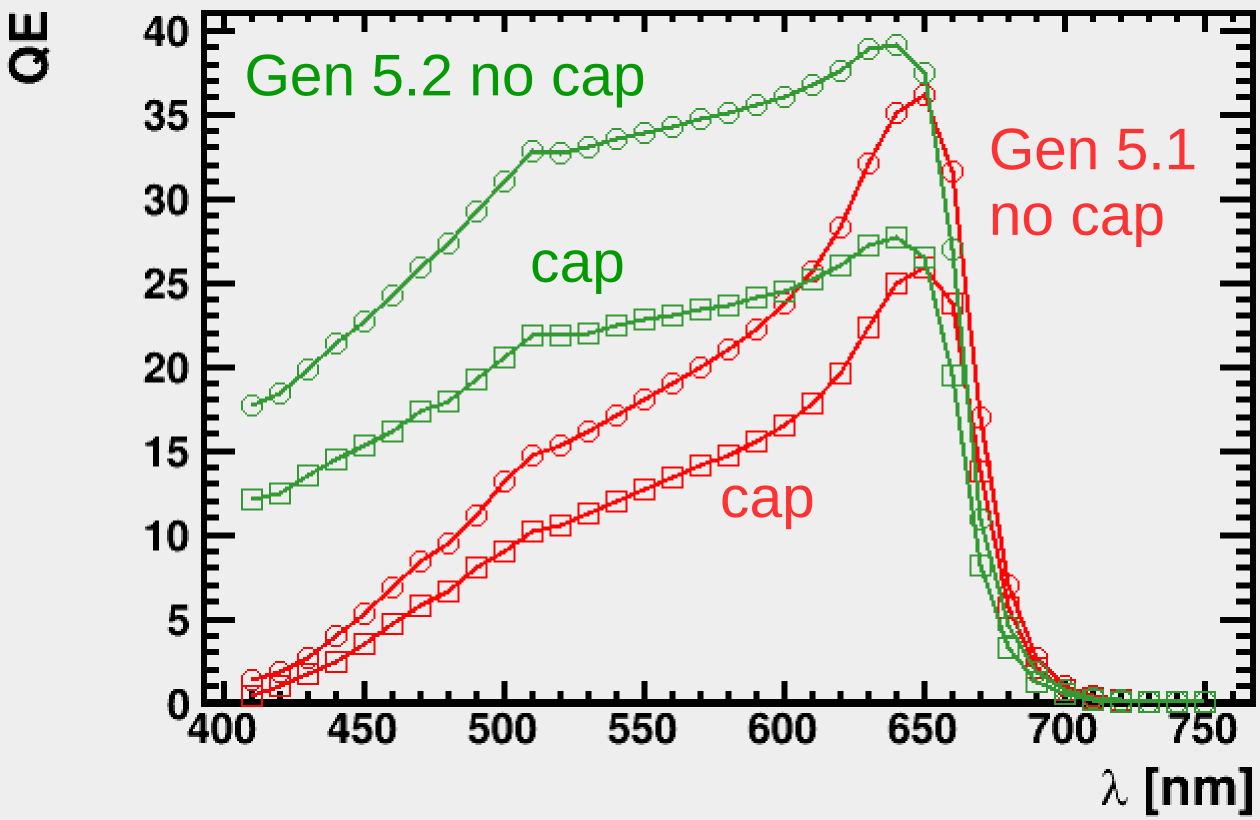
~10V shift in Vbr wrt G5.1. Doping concentrations?

Improved leakage



External QE

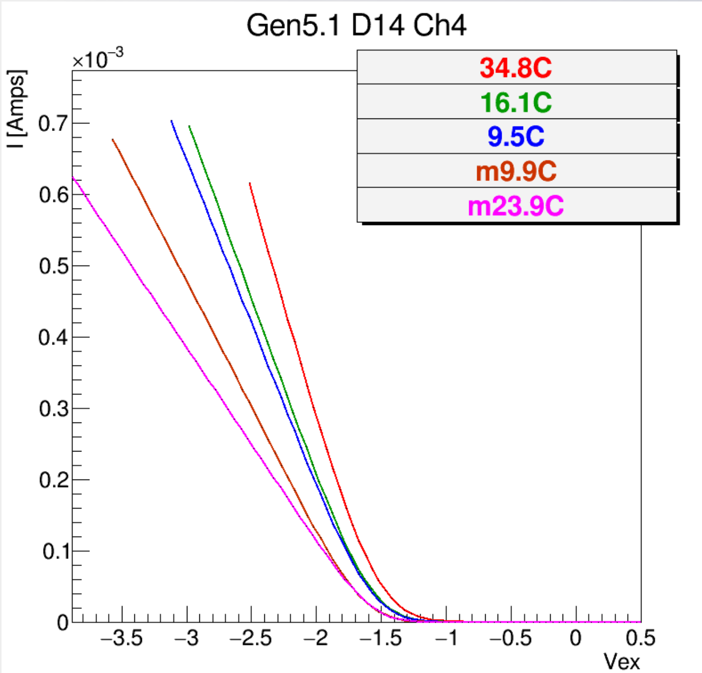




Gen 5.2: improved window, AR coating, FF

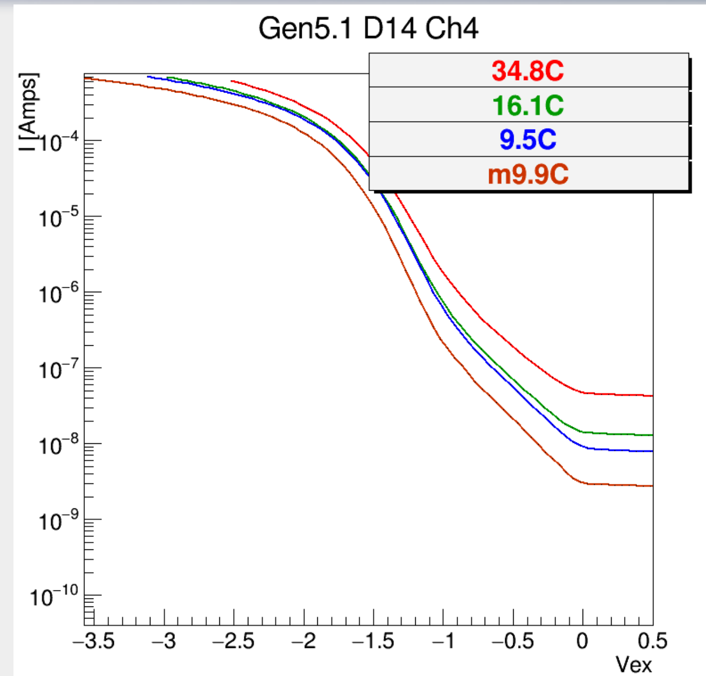
Thanks for help from J. Campbell's team at UVa

Current vs V_{ex} vs Temperature

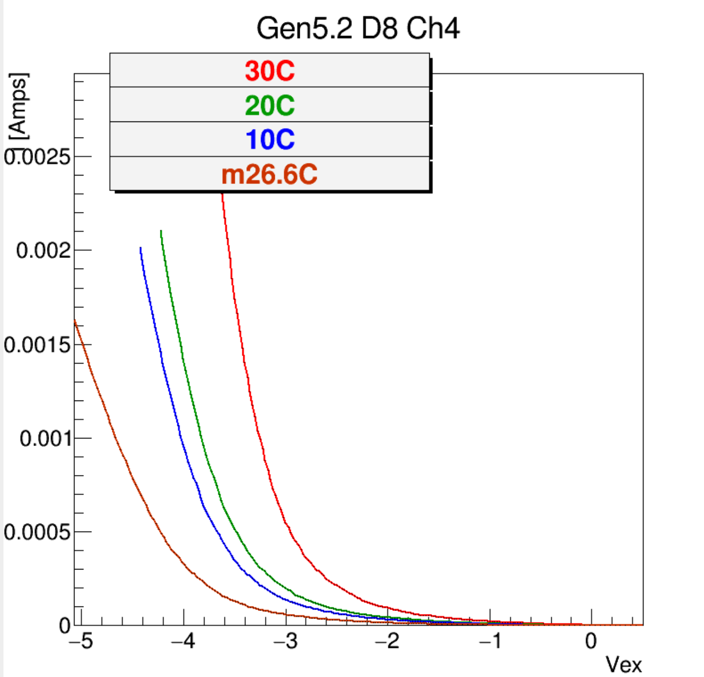


<=Gen 5.1=>

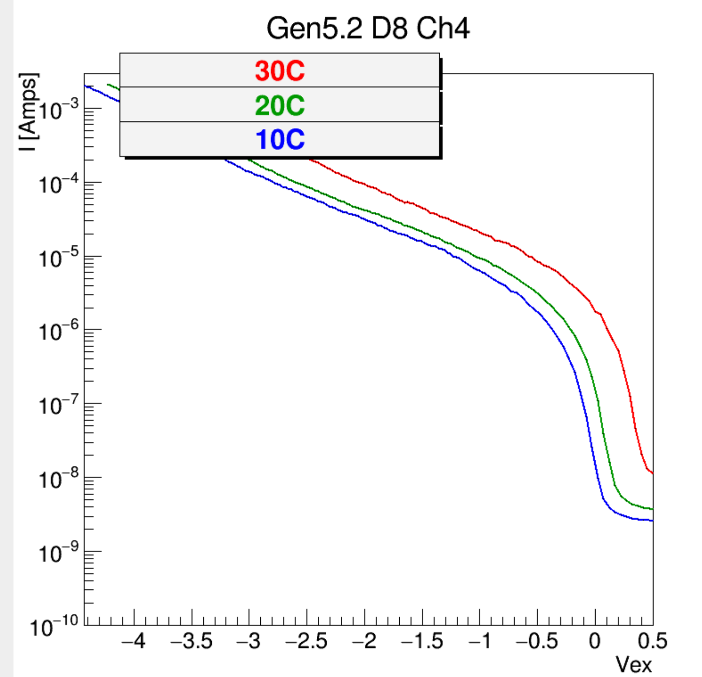
<=Linear



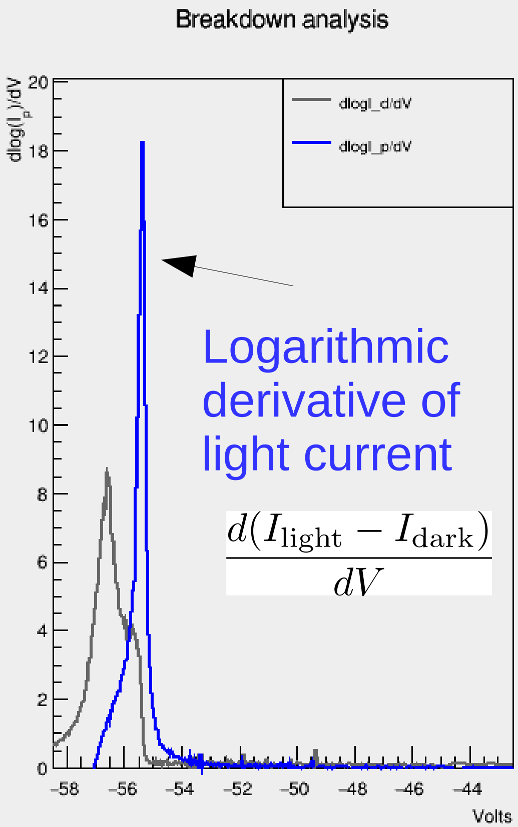
Log=>

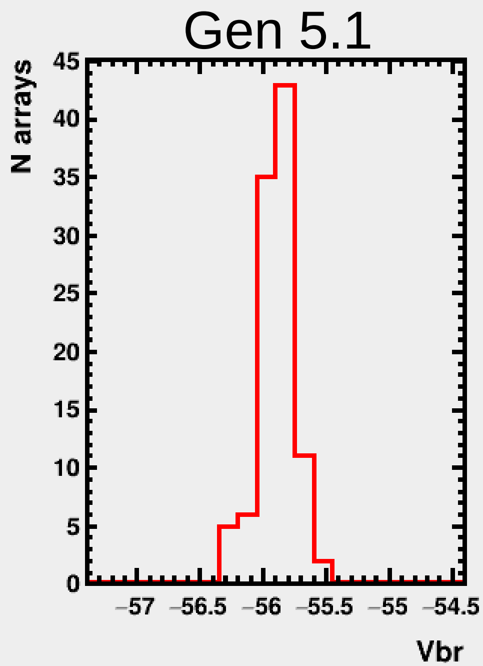


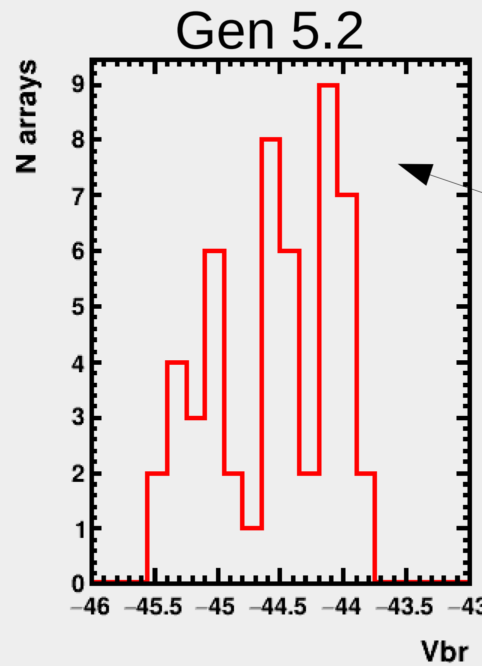
<=Gen 5.2=>



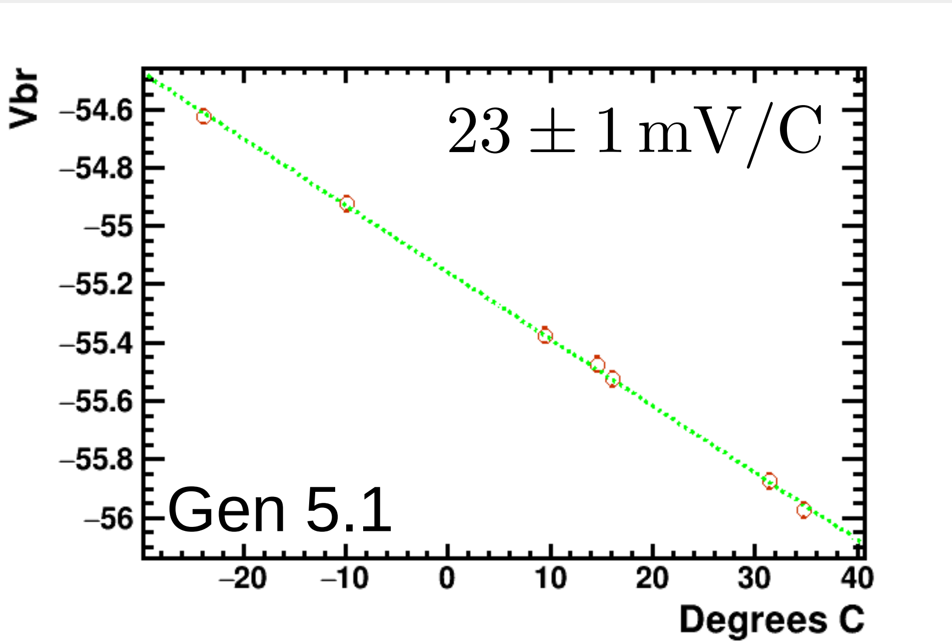
Vbr

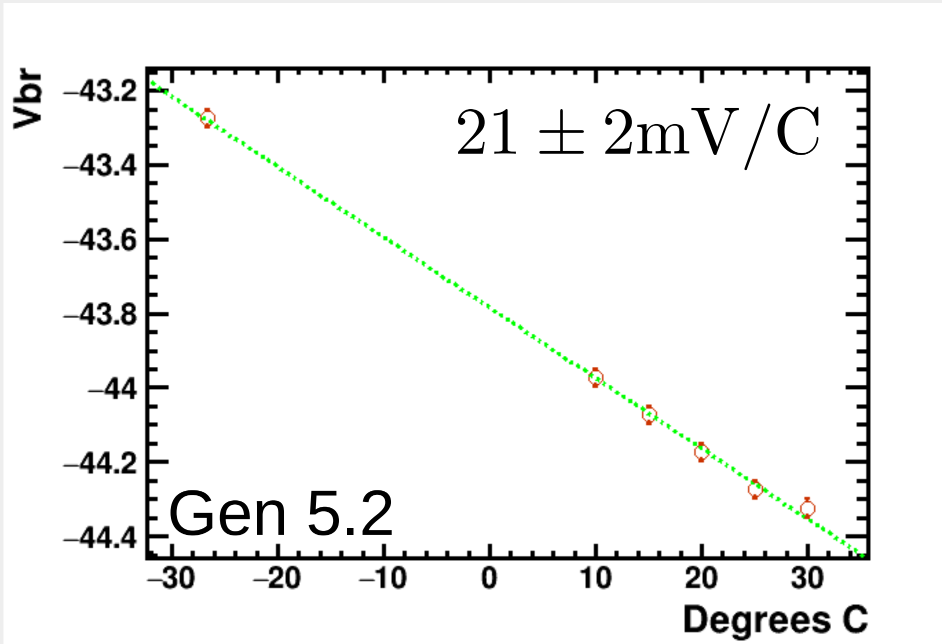




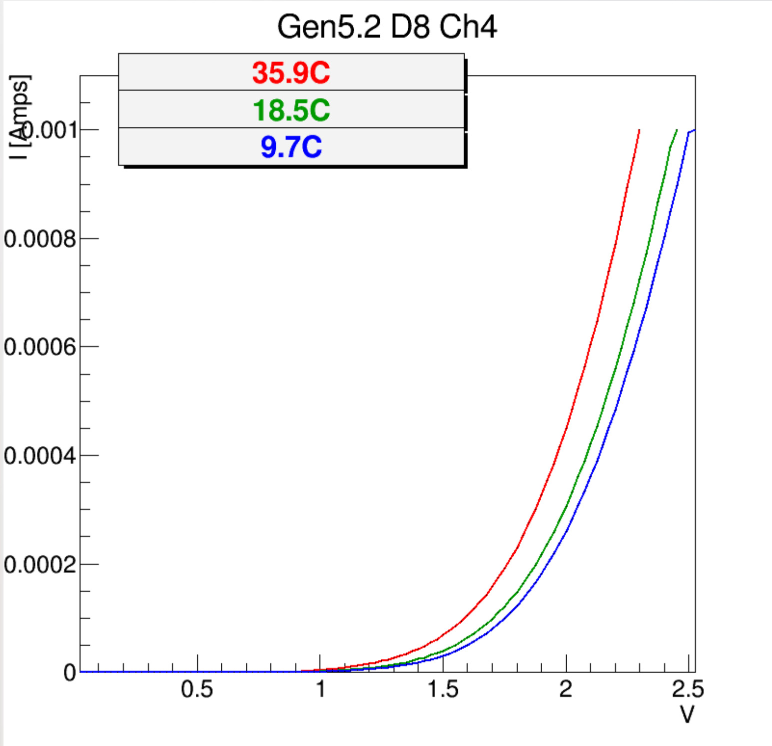


Larger variation => processing effects?





Rq

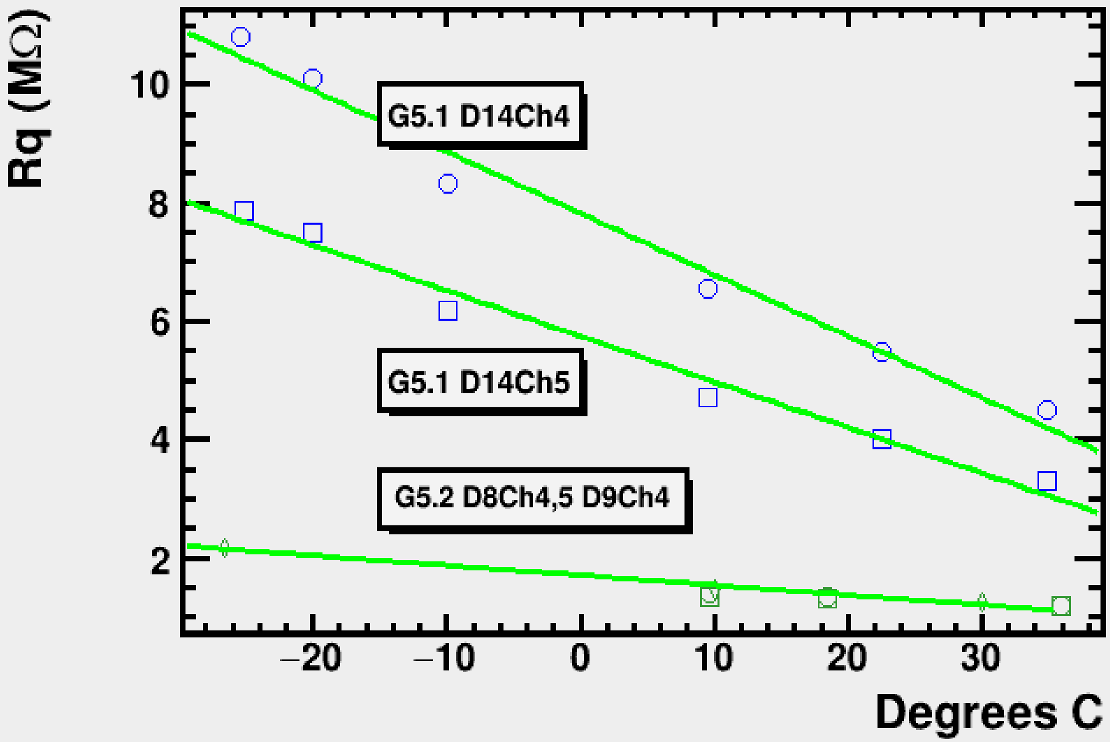


<= Measure using forward voltage curve

$$\frac{\Delta R_q}{dT}(20\,\mathrm{C})$$

~ 1.8%/C Gen 5.1

~ 1.2%/C Gen 5.2

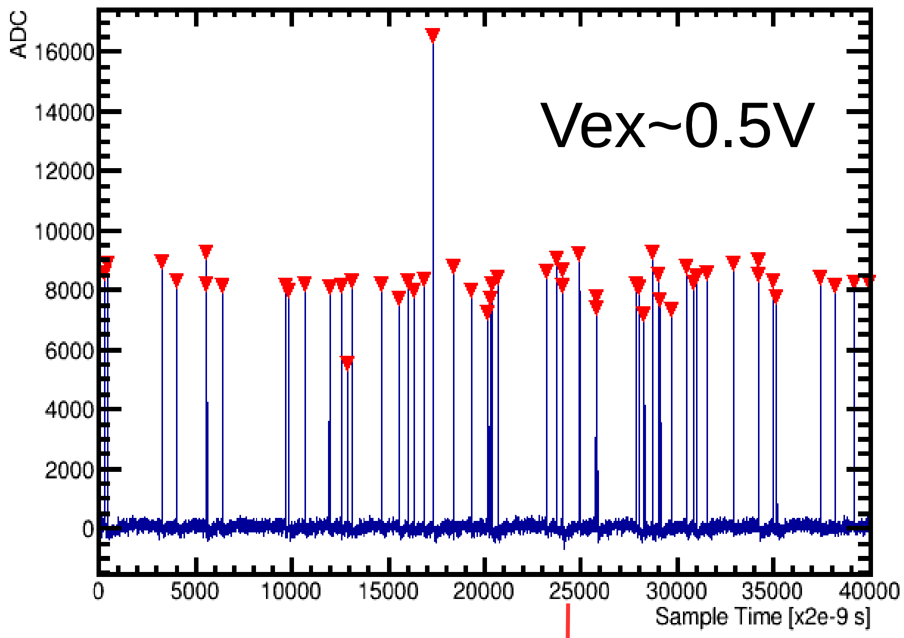


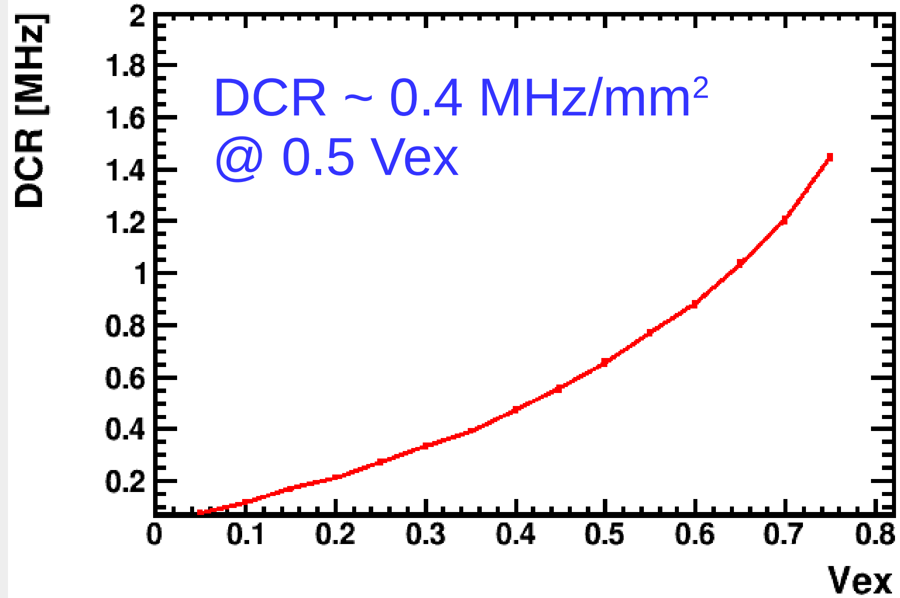
Large absolute deviations in Rq for Gen 5.1

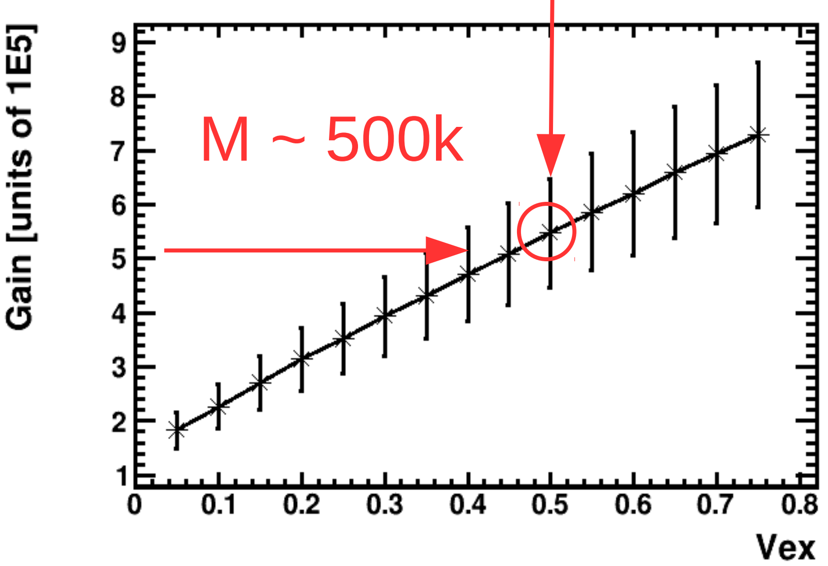
Better uniformity on Rq values in Gen 5.2 process

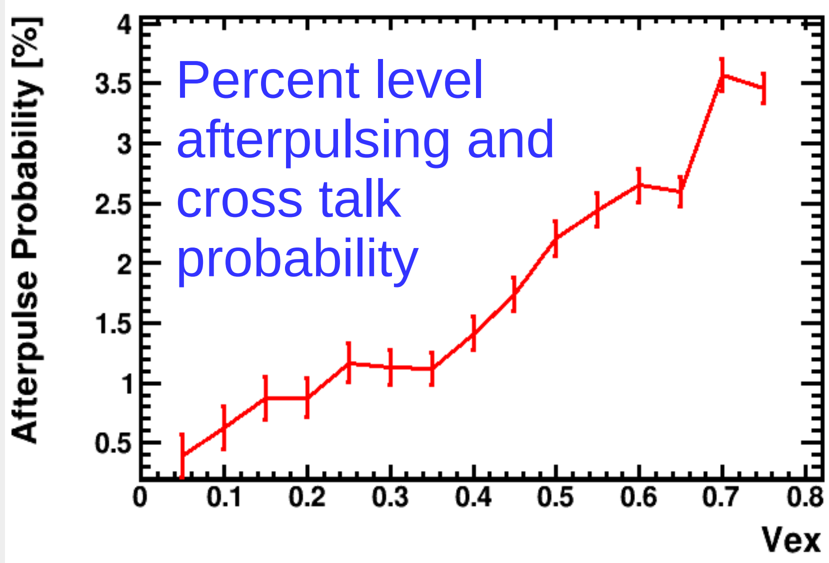
Gen 5.1
D14 Ch 4
23 C

Dark Pulse Spectrum



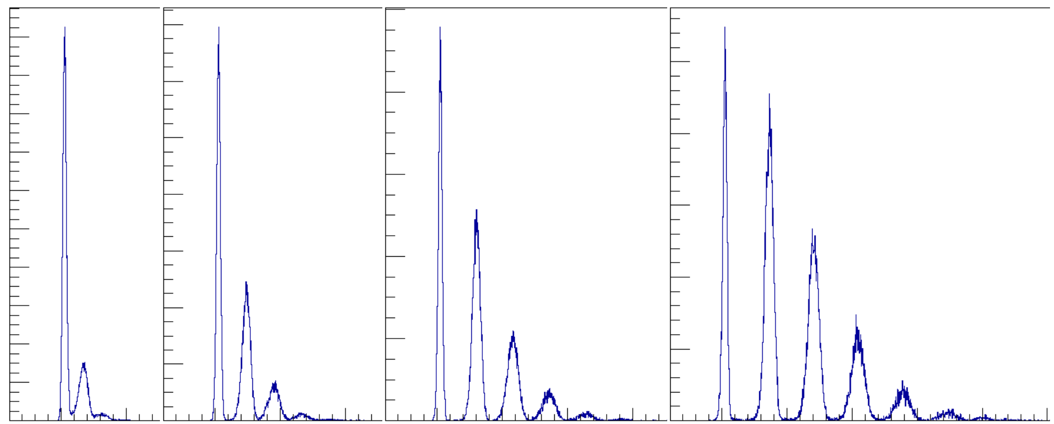






Gen 5.1 Pulse spectra (area distributions)

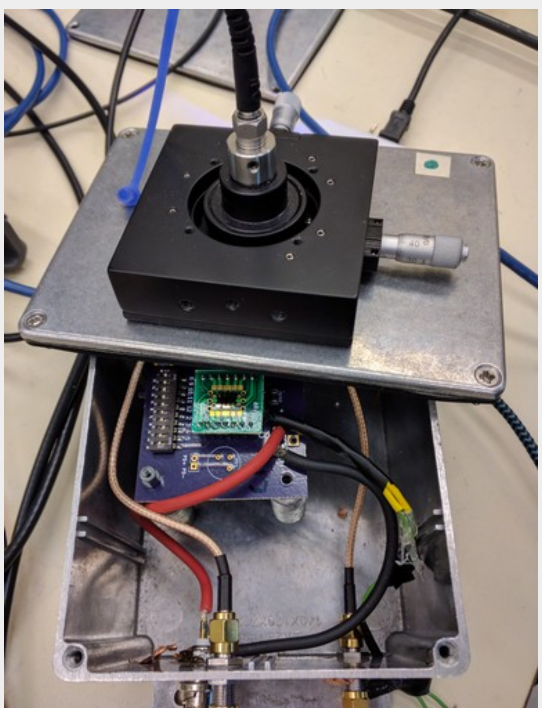
Fixed light pulses --- > increasing bias

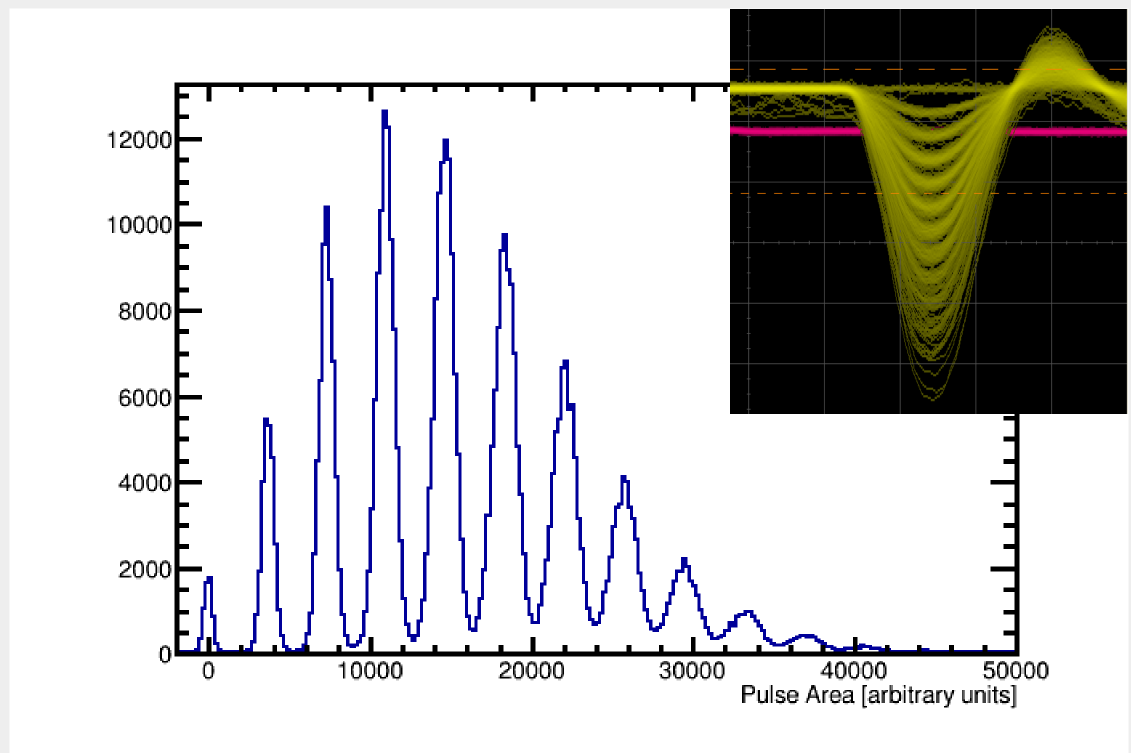


Arbitrary units

Illumination with ~200ps laser pulse

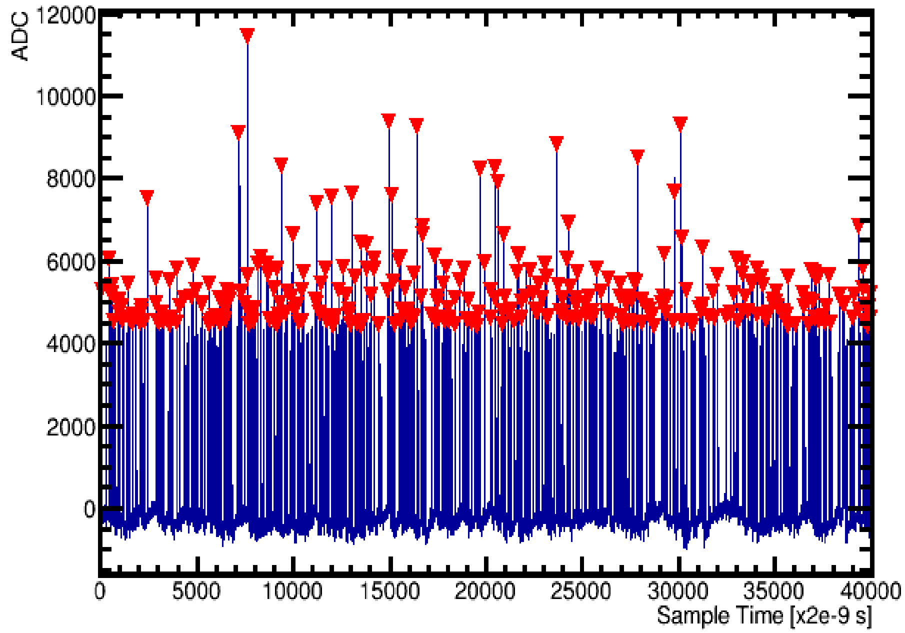
Very good photon counting resolution

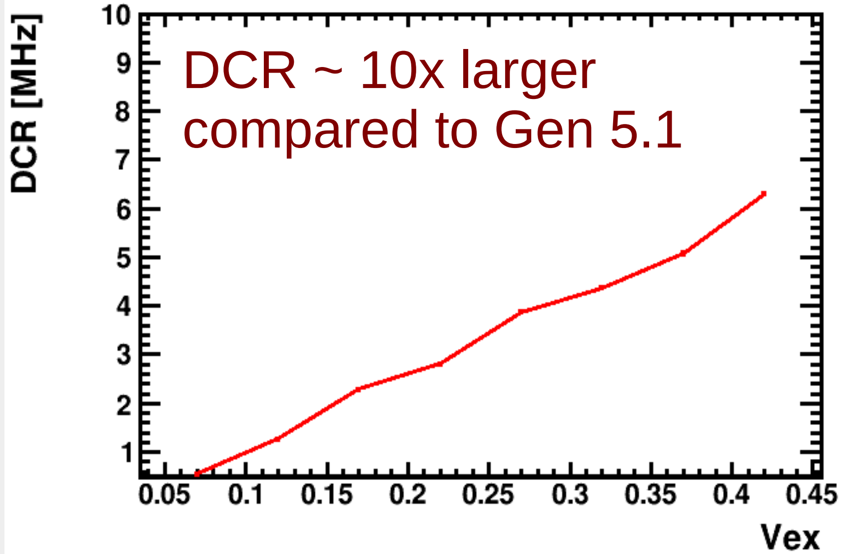




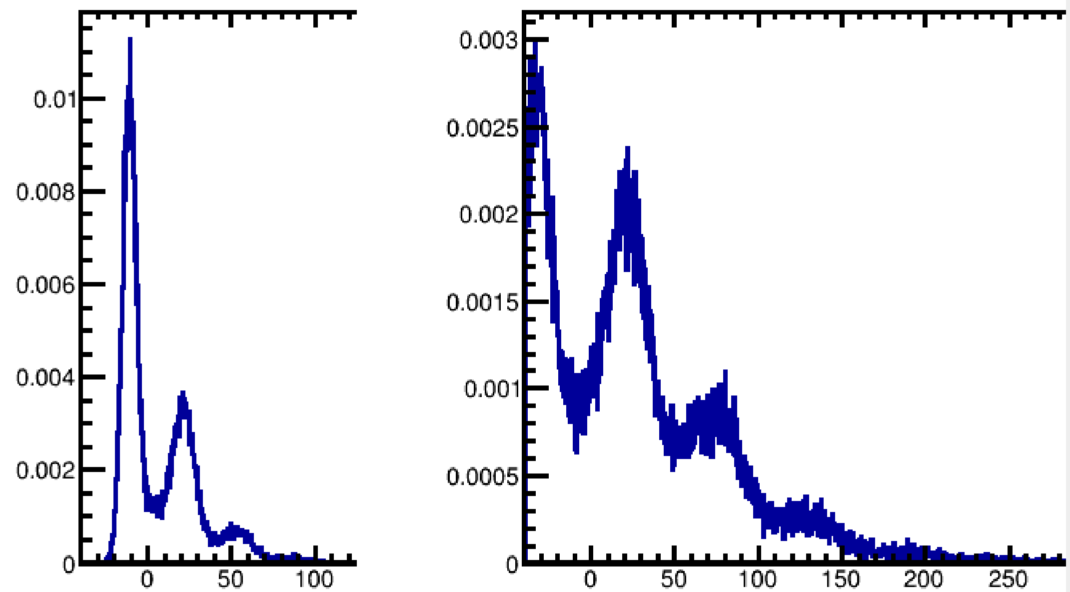
Gen 5.2
D8 Ch 3
23 C

Dark Pulse Spectrum





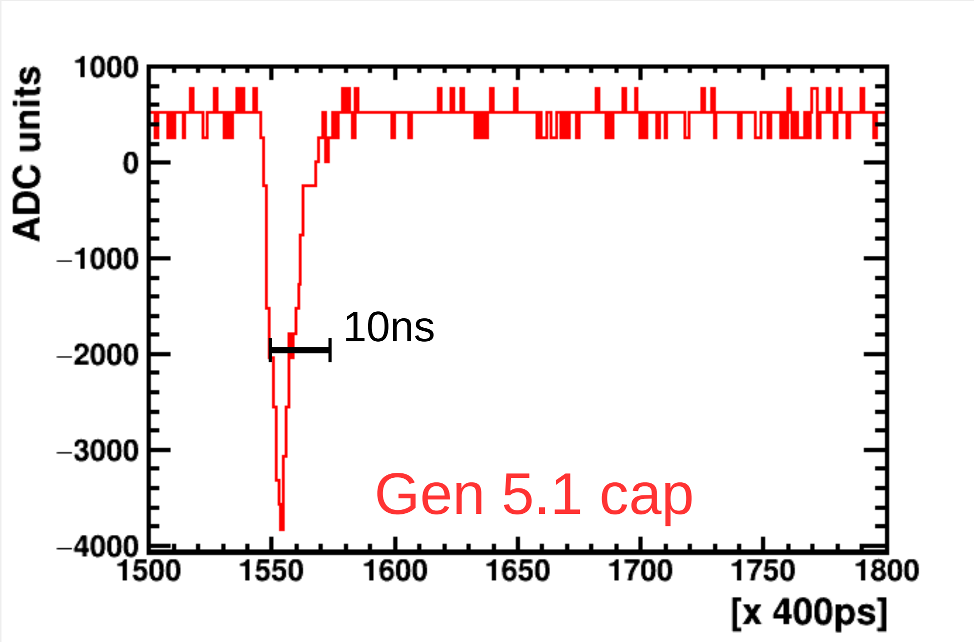
Fixed light pulses --- > increasing bias

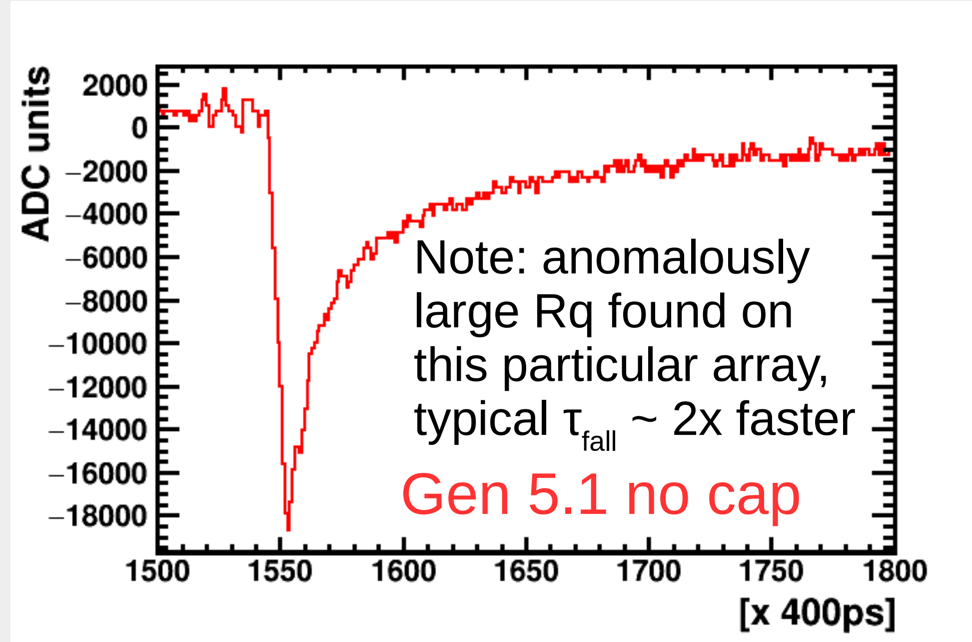


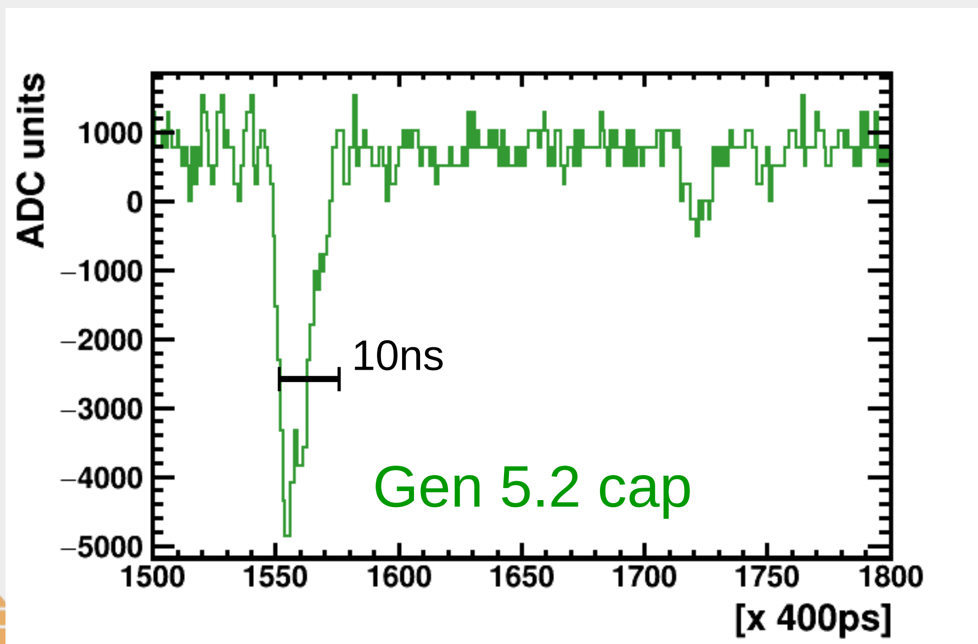
Reasonable separation, but significantly poorer resolution

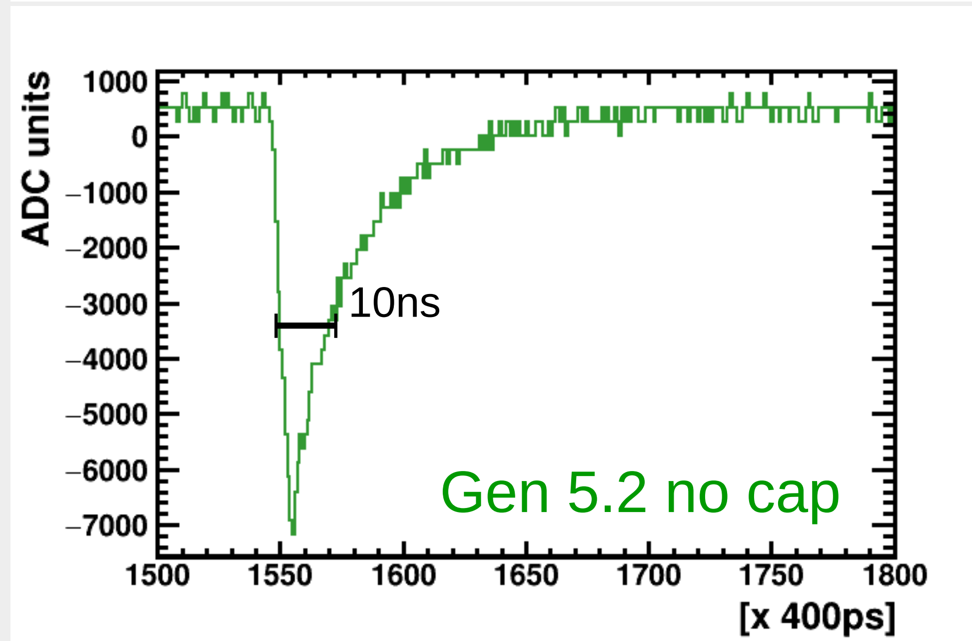
Pulses less uniform compared to Gen 5.1 samples

Pulse shapes





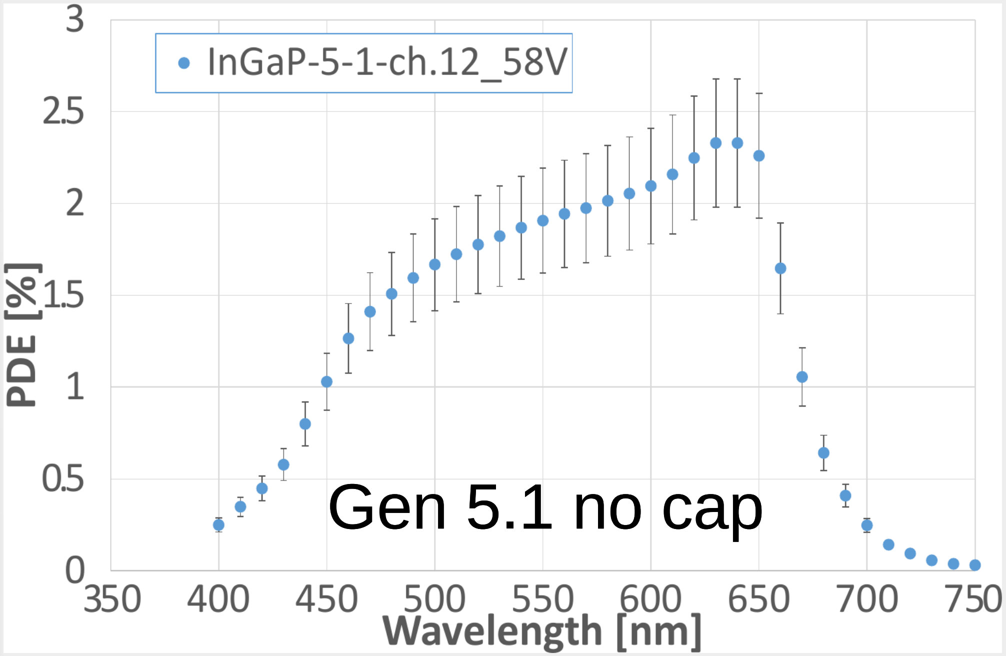


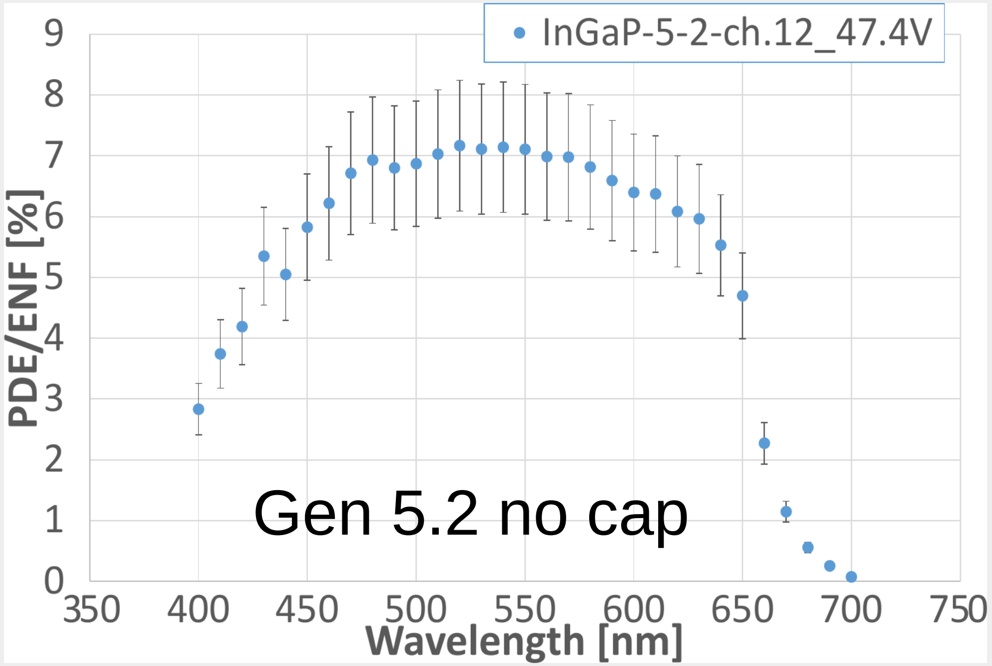


1st PDE Measurements

From I. Musienko (Notre Dame, Institute for Nuclear Research RAS)

No cap channels





June 1 ‘17 – radiation exposures

Expose GaInP and Si devices in 217 MeV proton cyclotron

Test GaInP side-by-side with SIPM device up to proton fluence of 1e12 p/cm^2

G51: Gen 5.1 0.75x1.2mm^2, 25u
G52: Gen 5.2 0.75x1.2mm^2, 25u

W : MMPC 1.3x1.3mm^2, 25u
X : MMPC 3x3mm^2, 25u
M : MMPC 3x3mm^2, 10u

	NIEL (MeV/(g/cm^2))		Average NEIL of GaAs & Si
	GaAs	Silicon	GaInP??
217 MeV protons	2.54E-3	1.78E-3	2.66E-3
1 MeV Neutrons	2.92E-4	3.59E-03	1.94E-3
Ratio to 1 MeV N	12.1	0.5	1.37 (~1:1?)

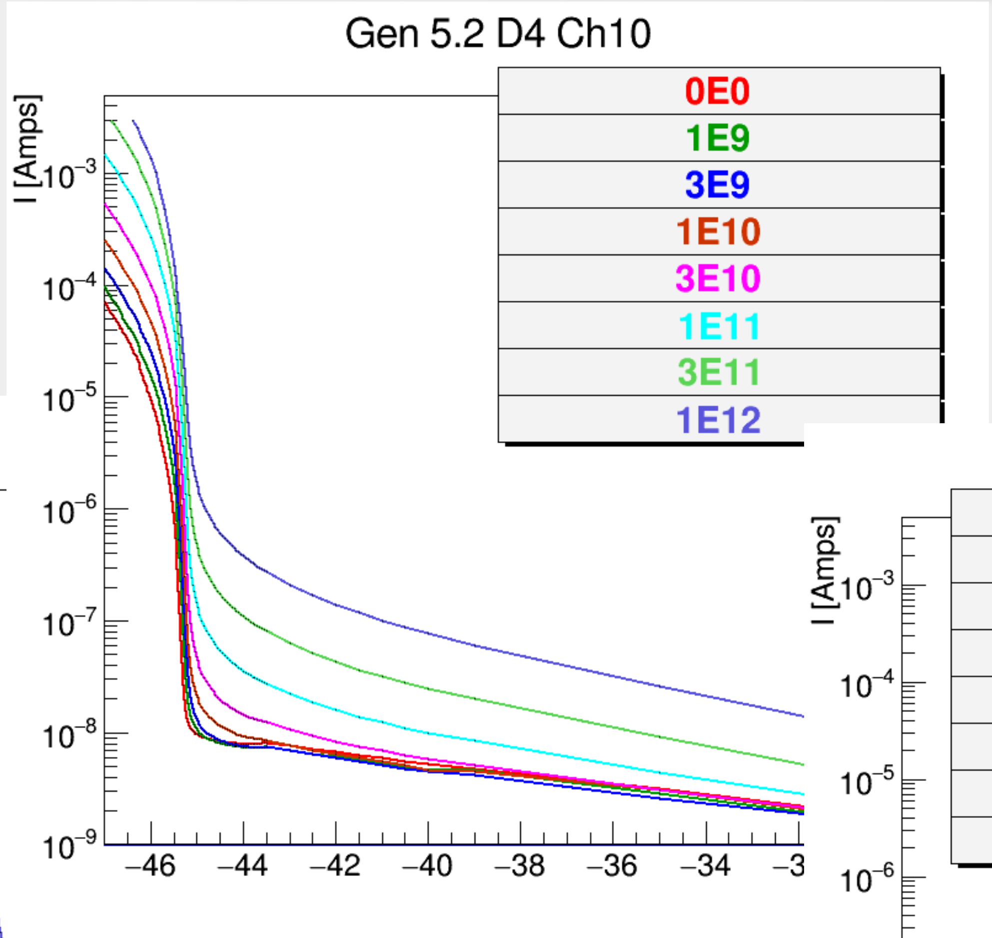
How to normalize to 1 MeV-Neutron equivalent (displacement) damage?

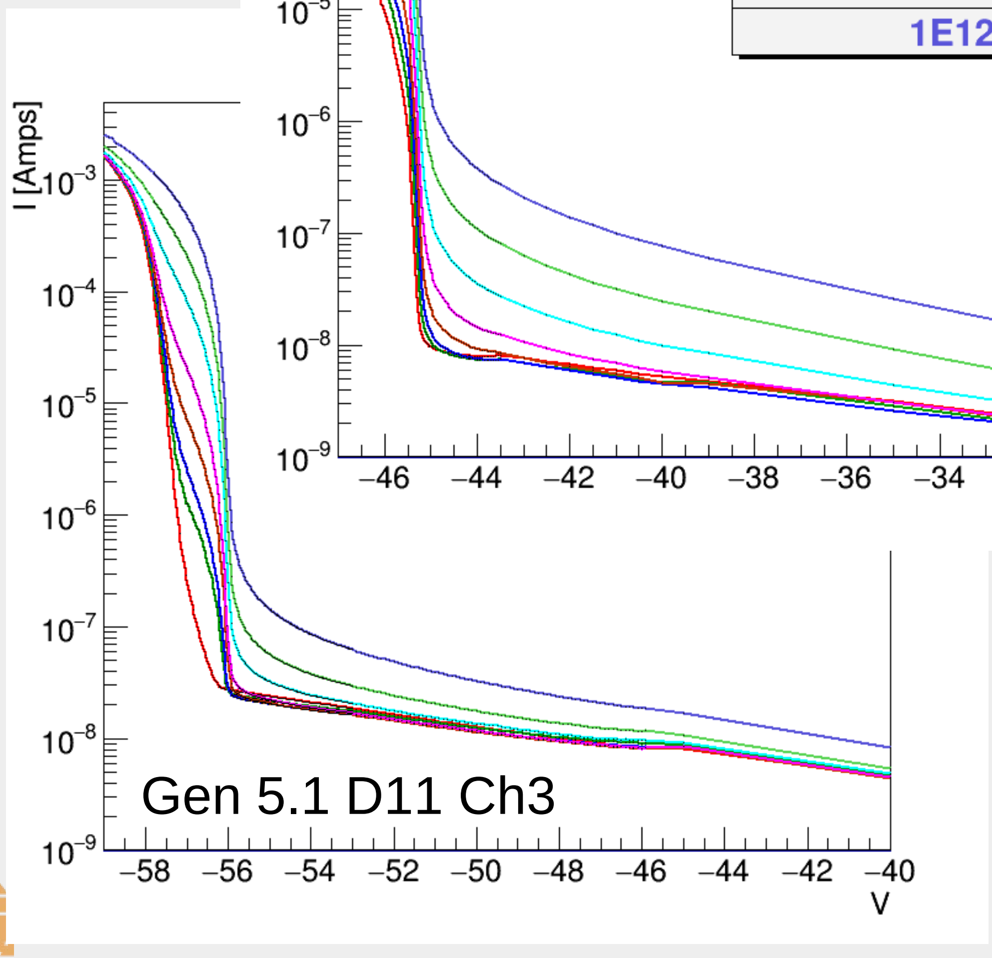
GaAs, Si well known. Average of their densities, close to GaInP.

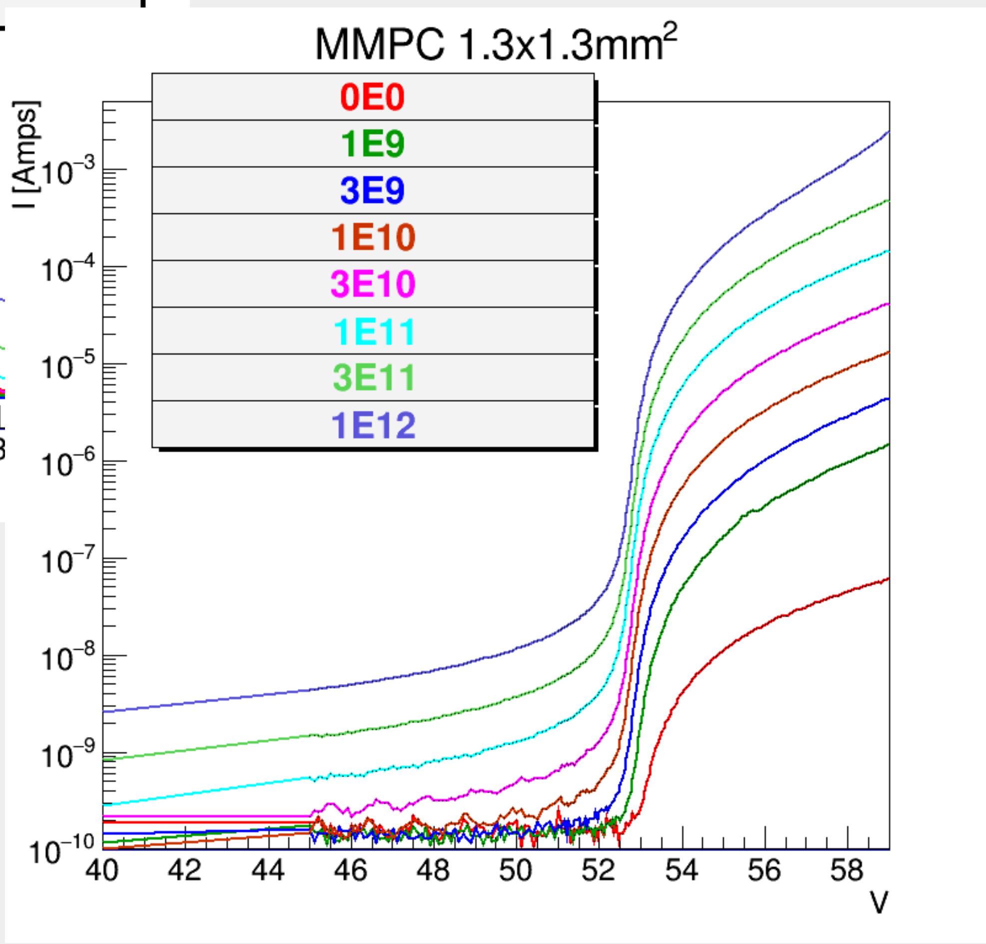
Don’t take this seriously => test in parallel w/ Si devices

I_{dark} vs proton fluence

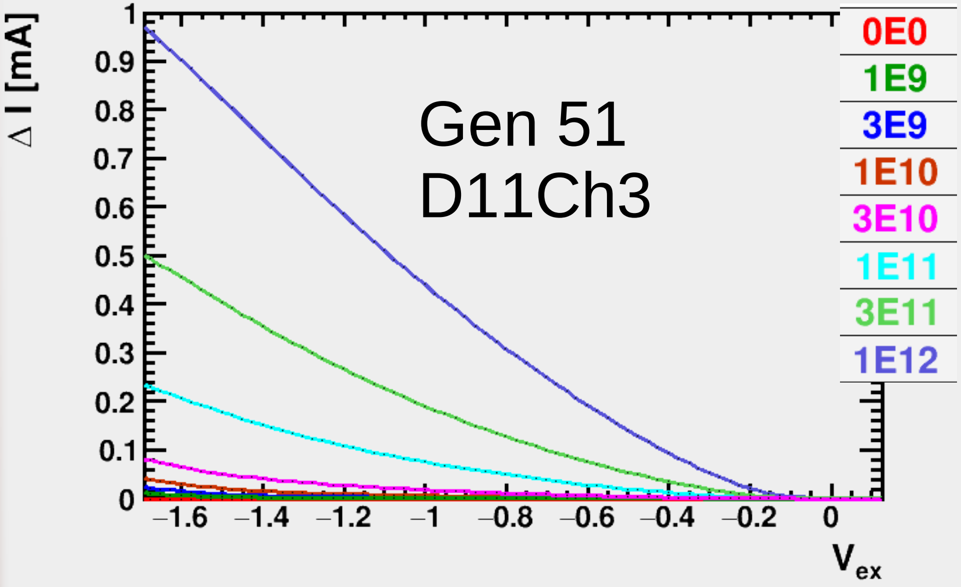
In situ measurements

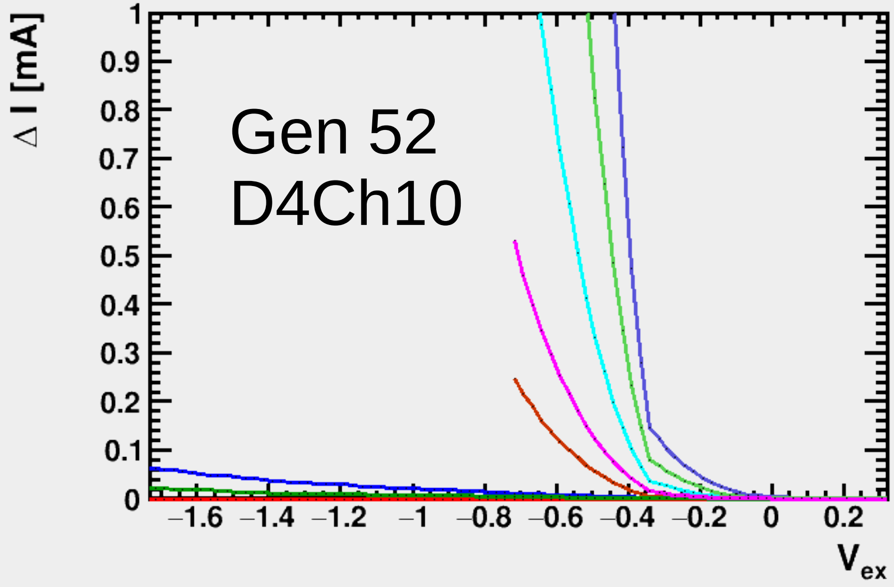


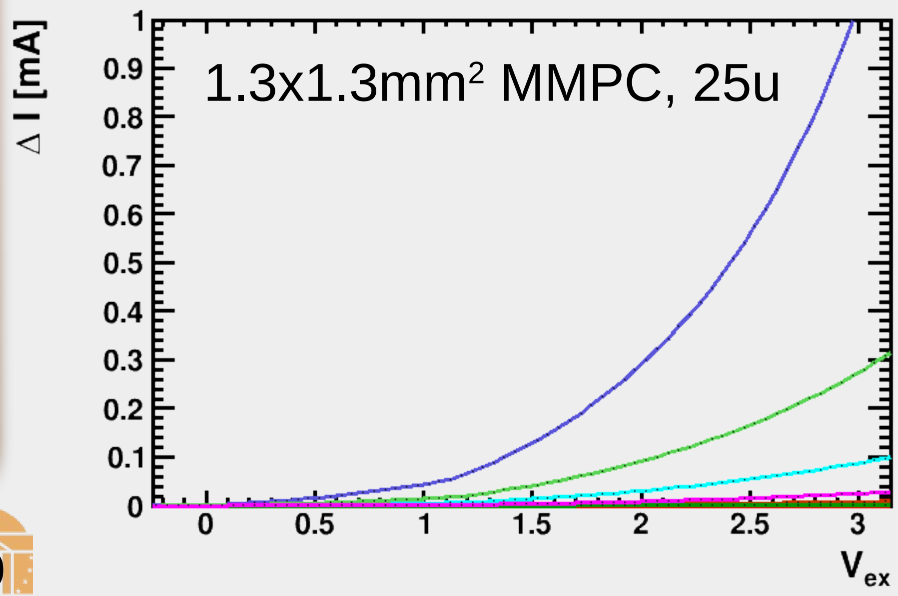


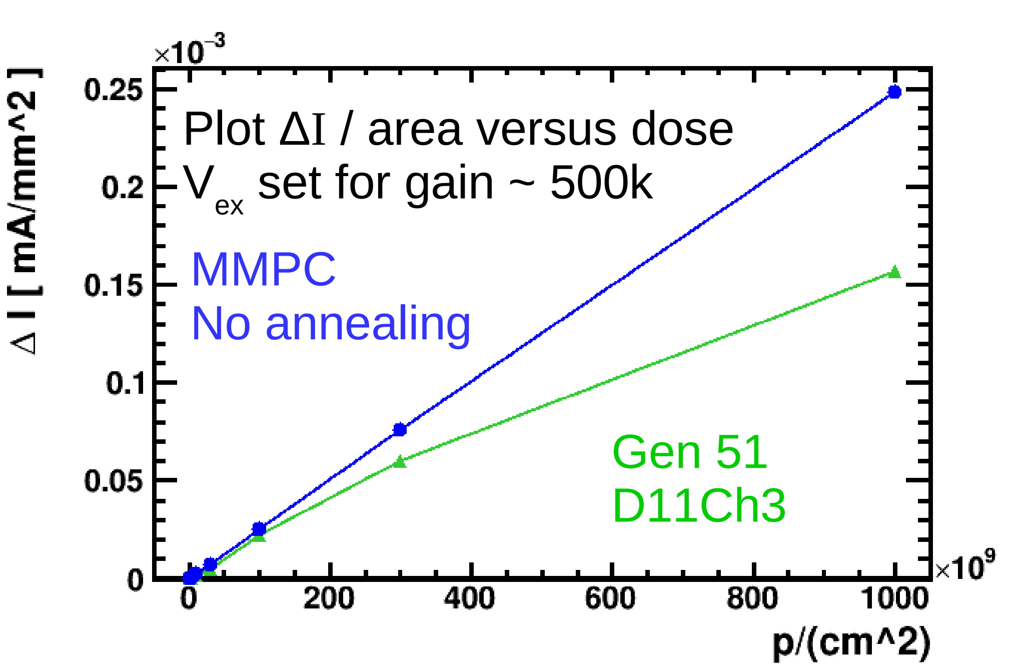


Plot increase in I_{dark} vs proton fluence









Similar results for Si and GaInP G5.1

Compare theoretical potential for GaInP

Figure of Merit: $F(\lambda,T_0) = DCR(T_0) / DE(\lambda) / Area \propto 1/\tau_{SRH}$

Result is effective dark count at 100% detection efficiency, normalized to detector area, measured at T_0=300K

Silicon has best FOM.
Si/InGaAs close to ideal - GaAs good (τ = 3.9 nsec)
But, semiconductors with band gap > 1.5 eV should be better.

Why not demonstrated?

- Low quality semiconductors … τ < 1 nsec
- Perimeter generation → surface defects
- After pulsing
- ~~Tunneling*~~, Trap assisted tunneling (~defect density)

* suppressed with larger band gaps

Expect GaInP/SiC to have tremendous room for improvement, therefore better FOM, but not demonstrated.
Maturity of processing?

[Ref: Harmon1, Harmon2]

Summary I

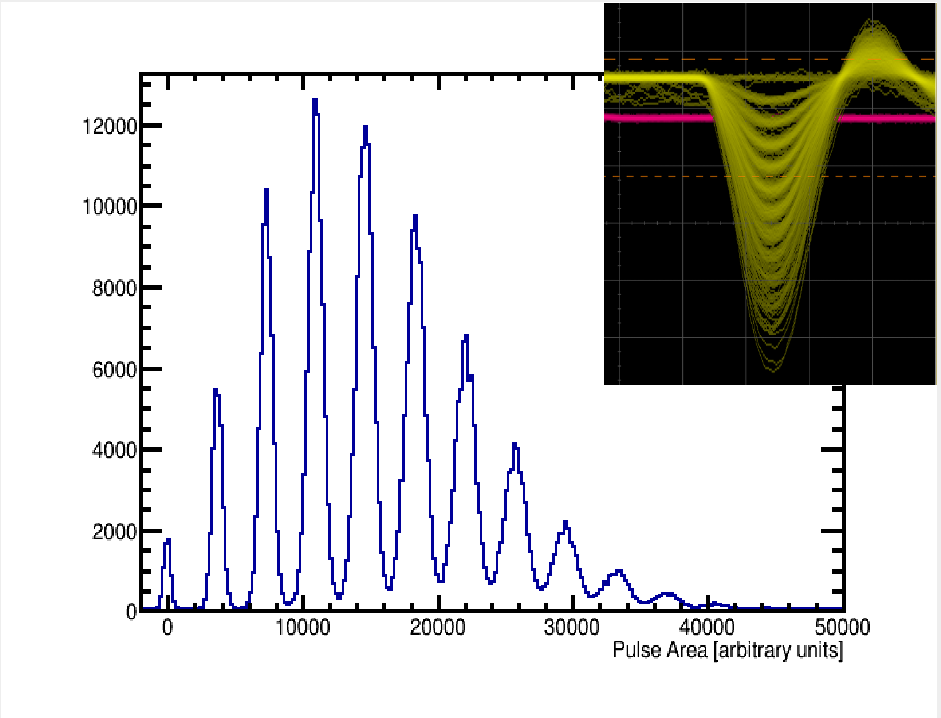
A variety of epitaxy, array structures, surface treatments, Rq implementations have been adjusted over several propotype generations.

Optimizations have incrementally improved

- DCR
- surface leakage current
- pulse shape and recovery times, ...

Preliminary results on newest GaInP SPAD arrays show encouraging progress on device performance

These latest samples provide further proof of principle that high performance detectors can be constructed using GaInP.



Summary II

More to do on characterizing devices and studying radiation damage effects, eg

- Temperature dependence of DCR (thermal vs trap assisted tunneling)
- Study DCR vs dose (try to measure K-factor for damage, compare to theory)

GaInP devices are still in prototype phase, how close can theoretical performance characteristics be approached?

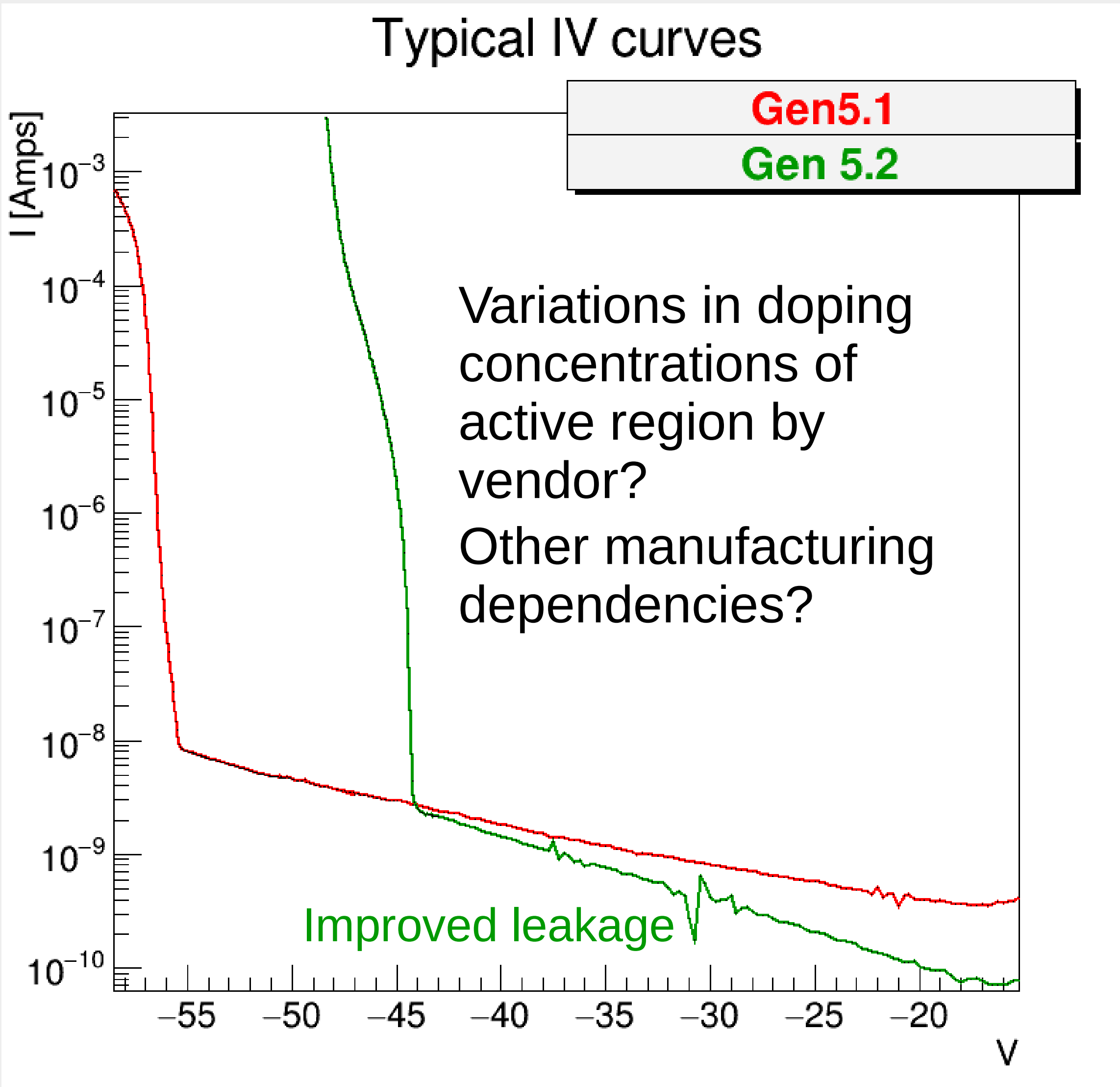
- Engineering vs physics: low hanging fruit for engineering solutions? Eg how much can radiation performance be improved by top surface passivation?

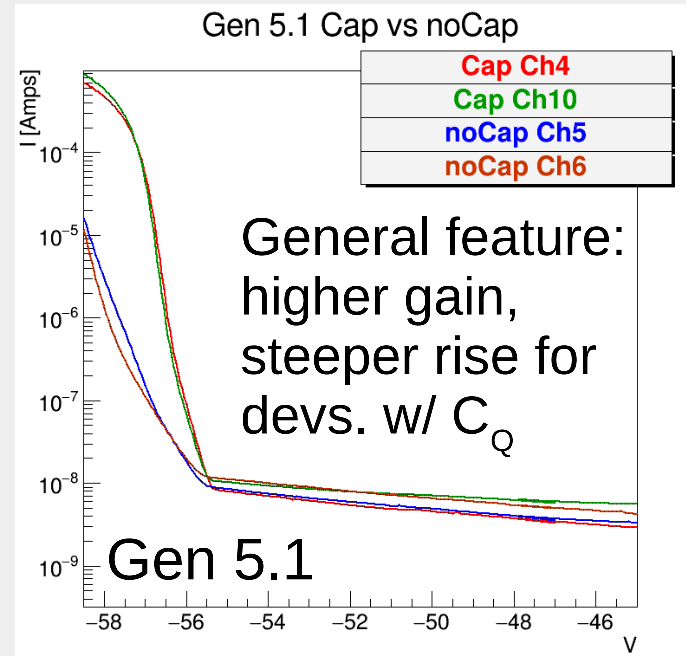
Gen 6 due by end of year, with improved window layer (improved blue QE), improved quench resistors, more optimized processing and test structures.

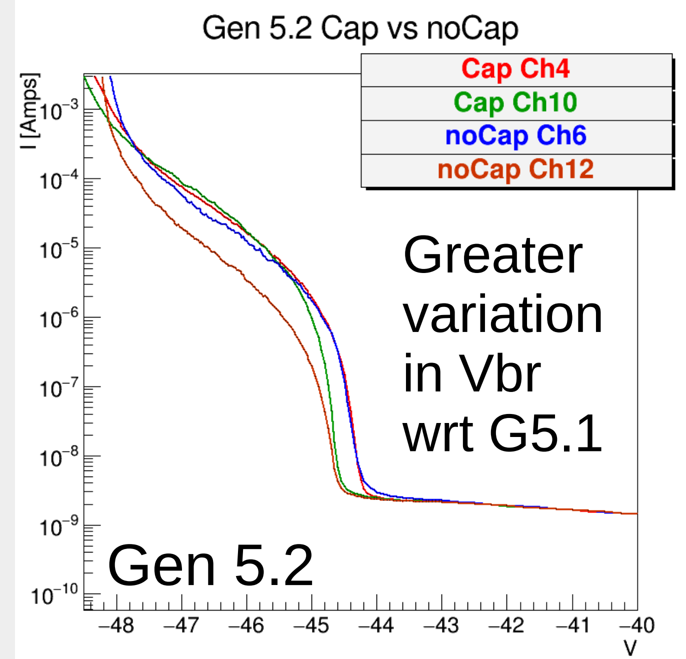
Thanks

Additional slides

Breakdown Characteristics

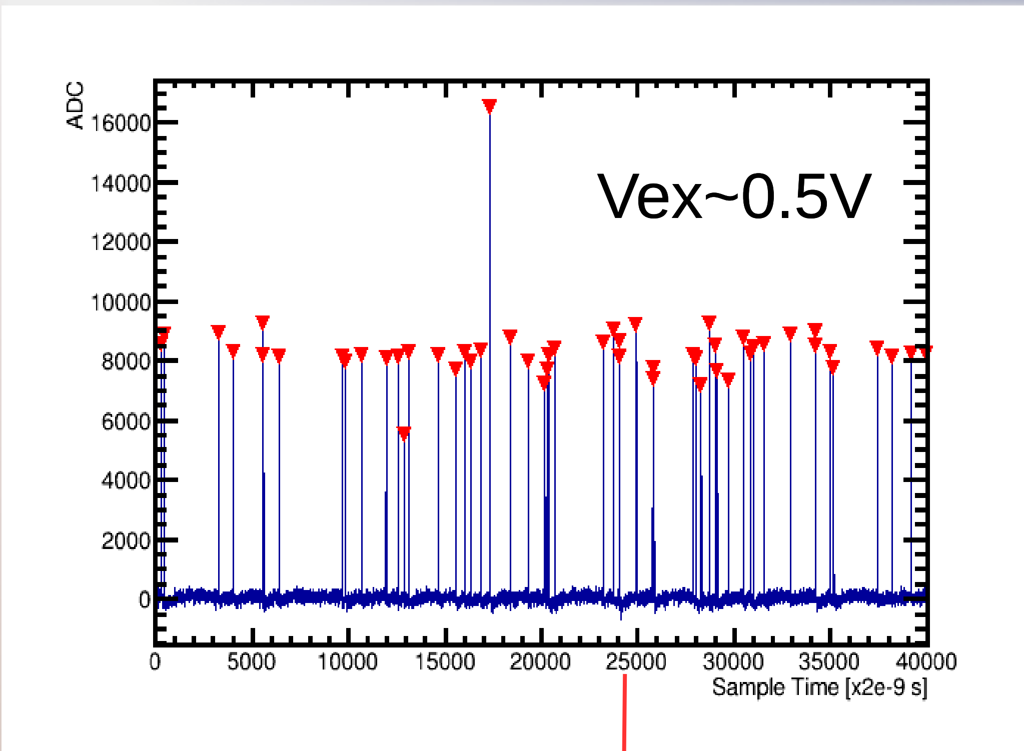


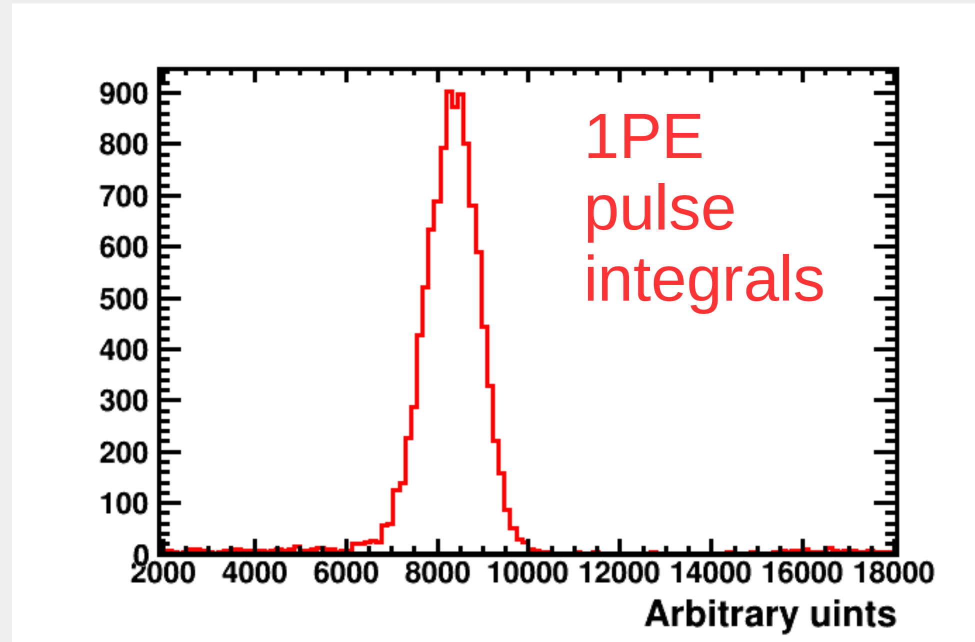


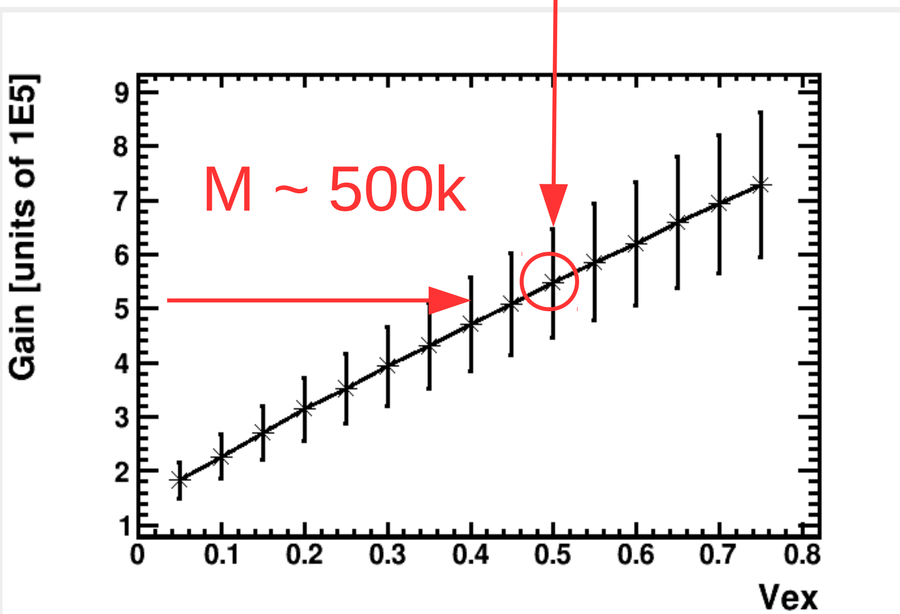


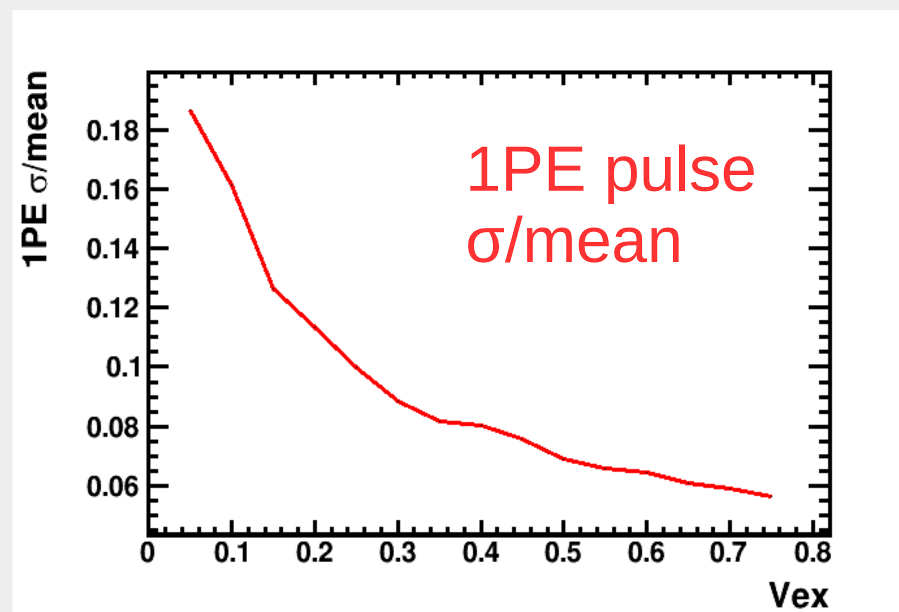
Gen 5.1
D14 Ch 4
23 C

Dark Pulse Spectrum



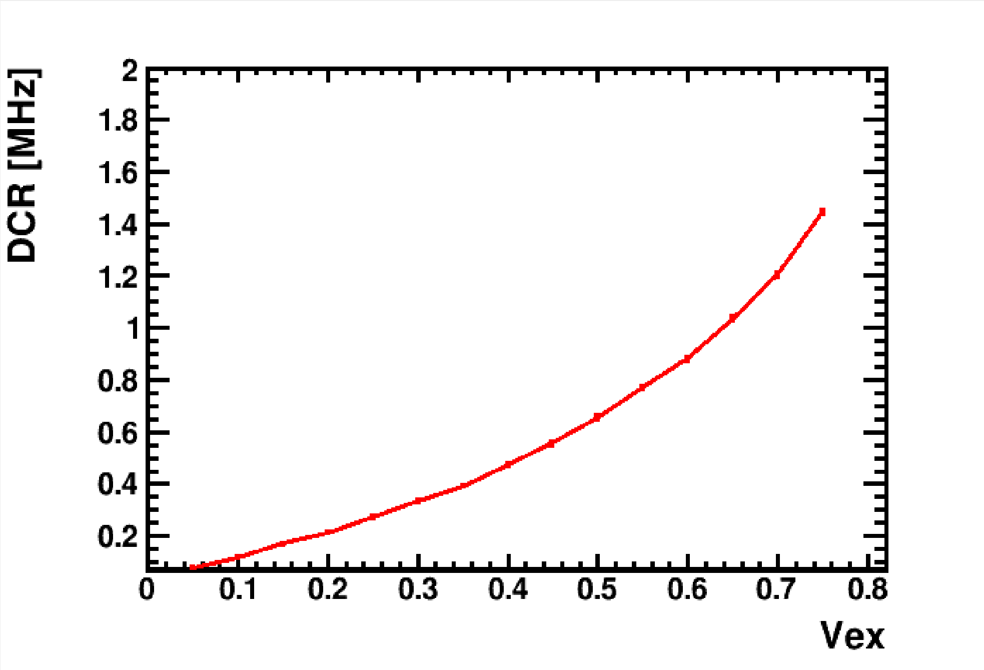






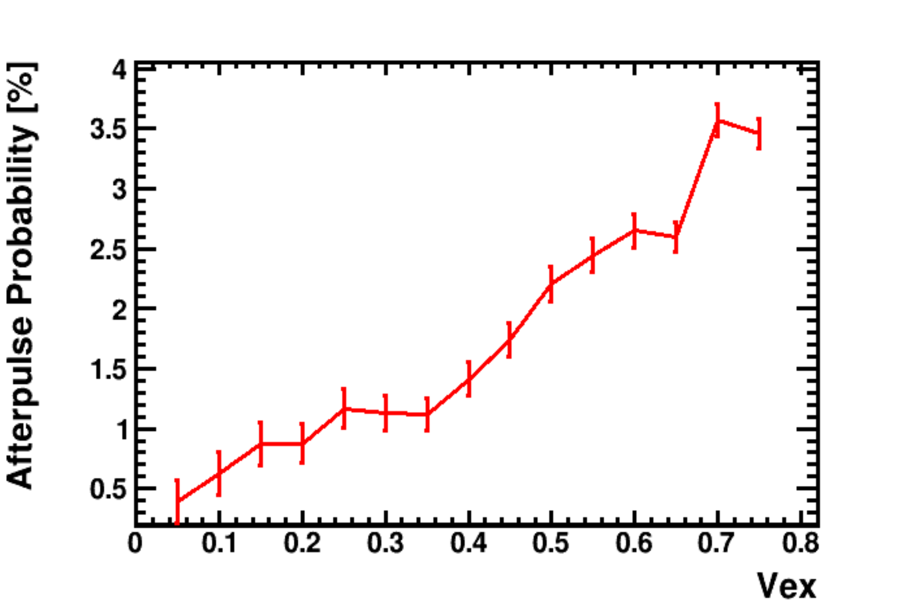
Gen 5.1
D14 Ch 4
23 C

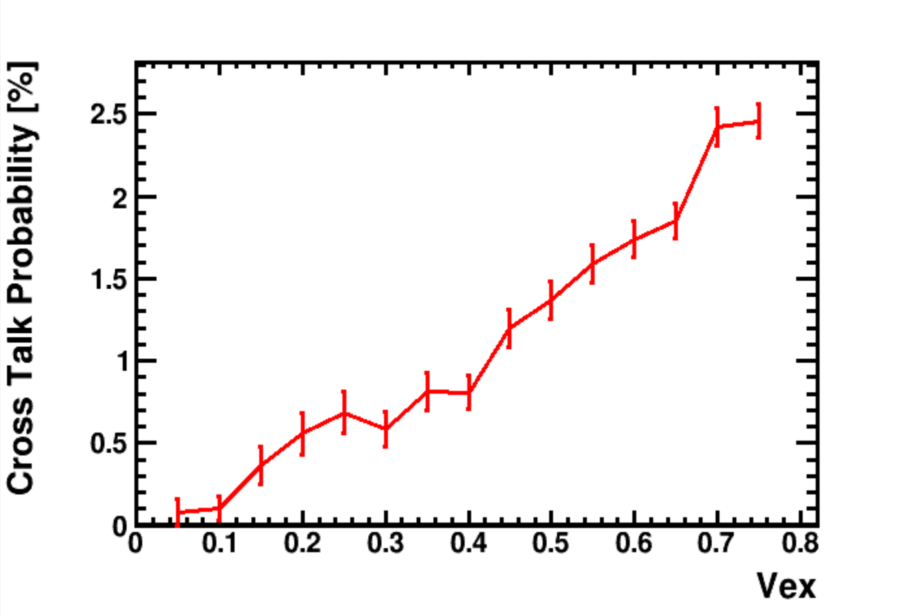
Dark Pulse Spectrum



DCR ~ 0.4 MHz/mm^2 @ 0.5 Vex

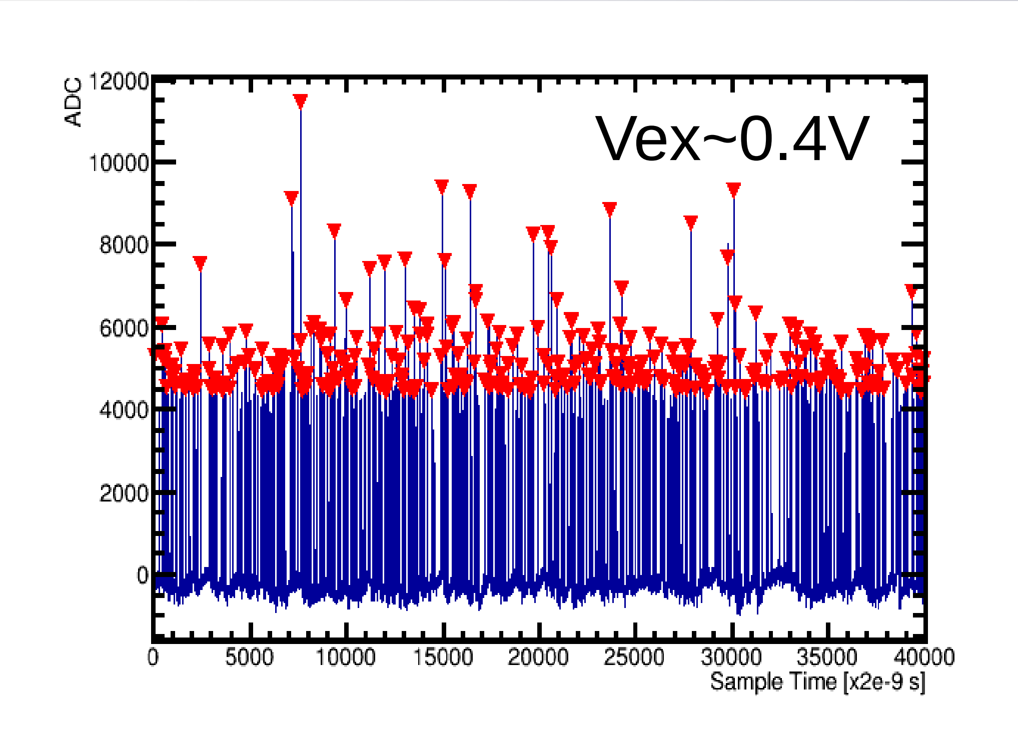
Percent level afterpulsing and cross talk probability

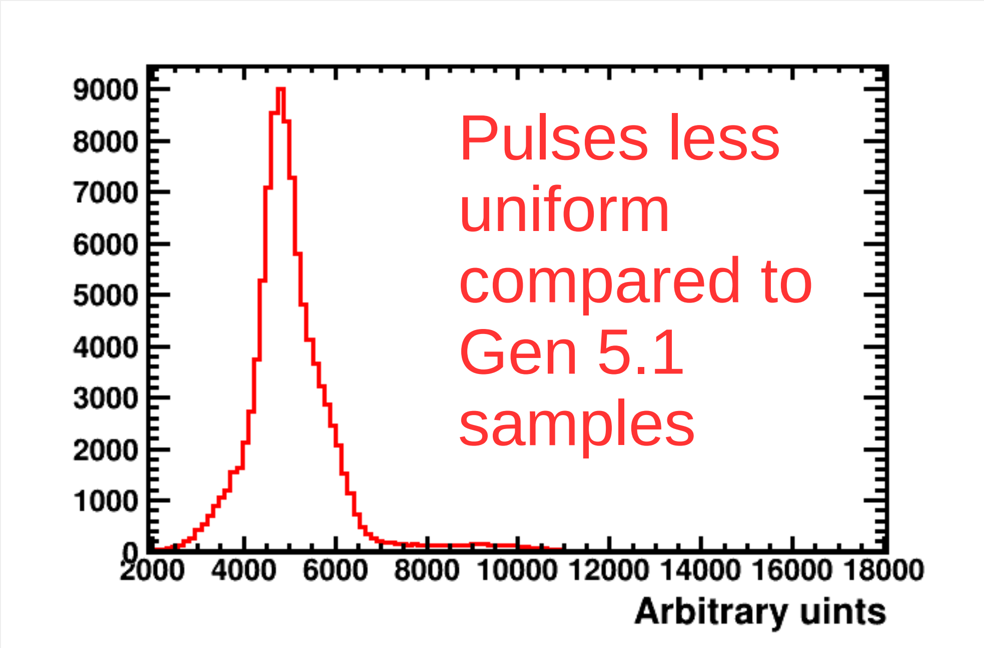


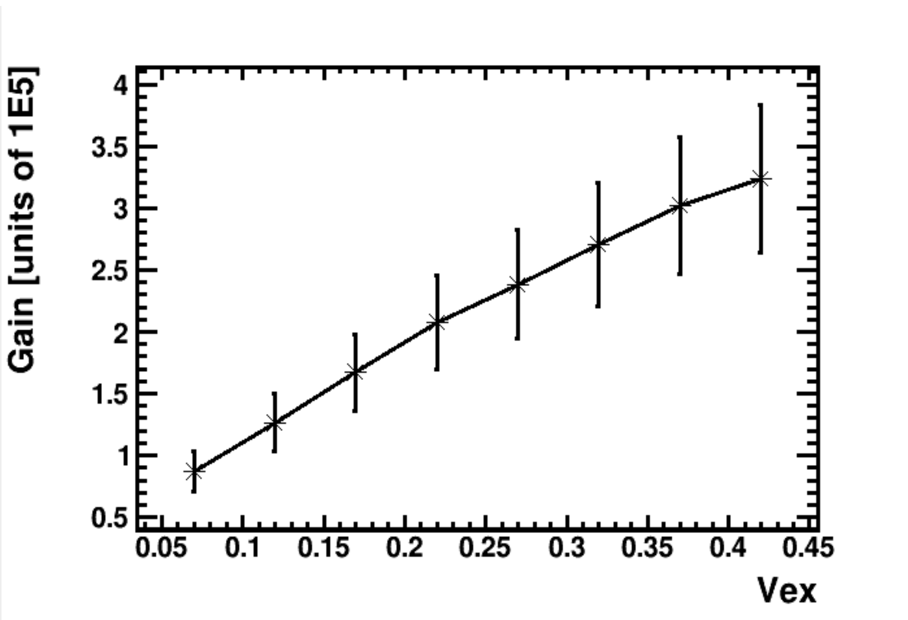


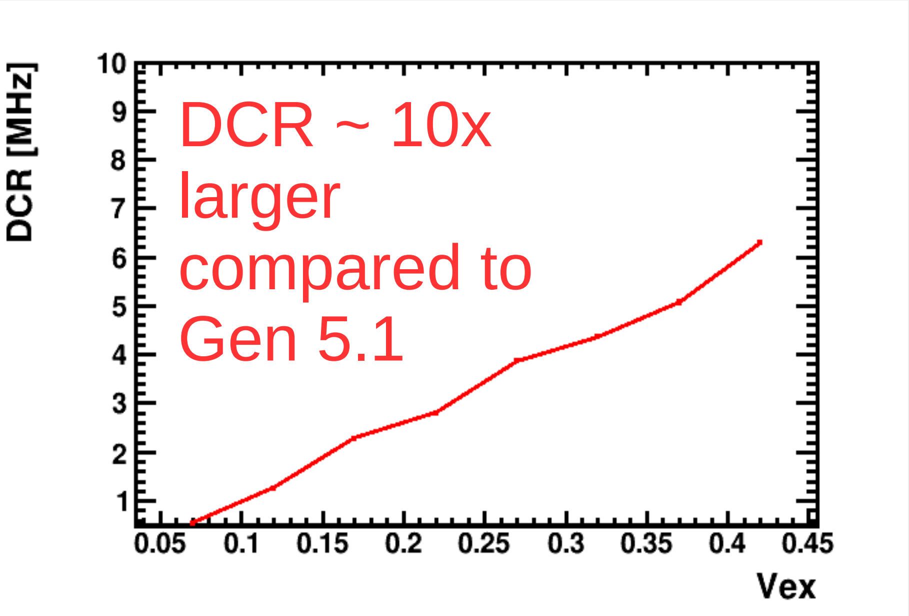
Gen 5.2
D8 Ch 3
23 C

Dark Pulse Spectrum

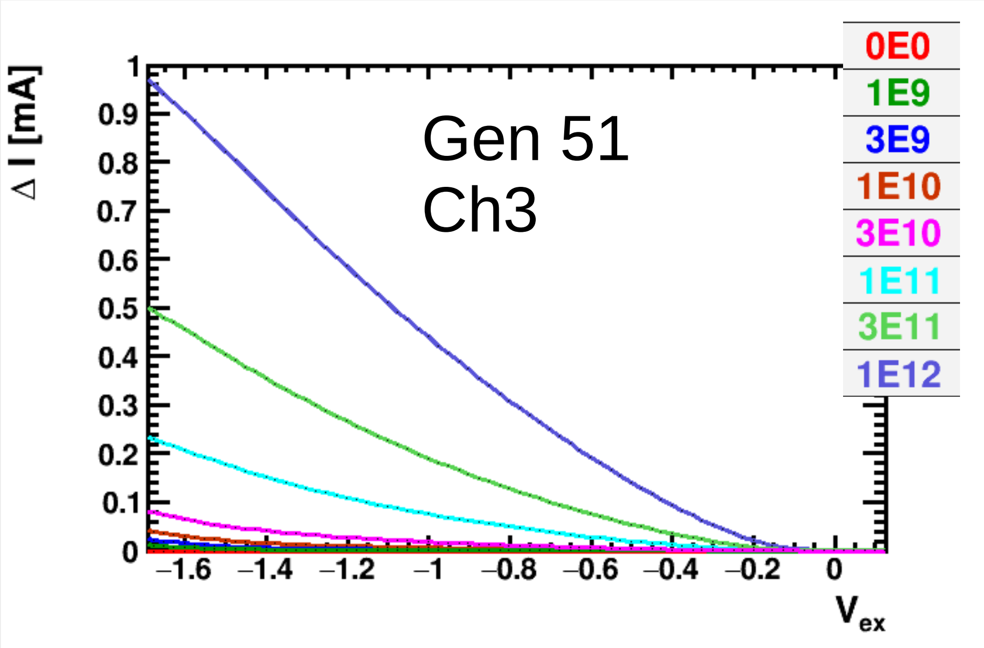


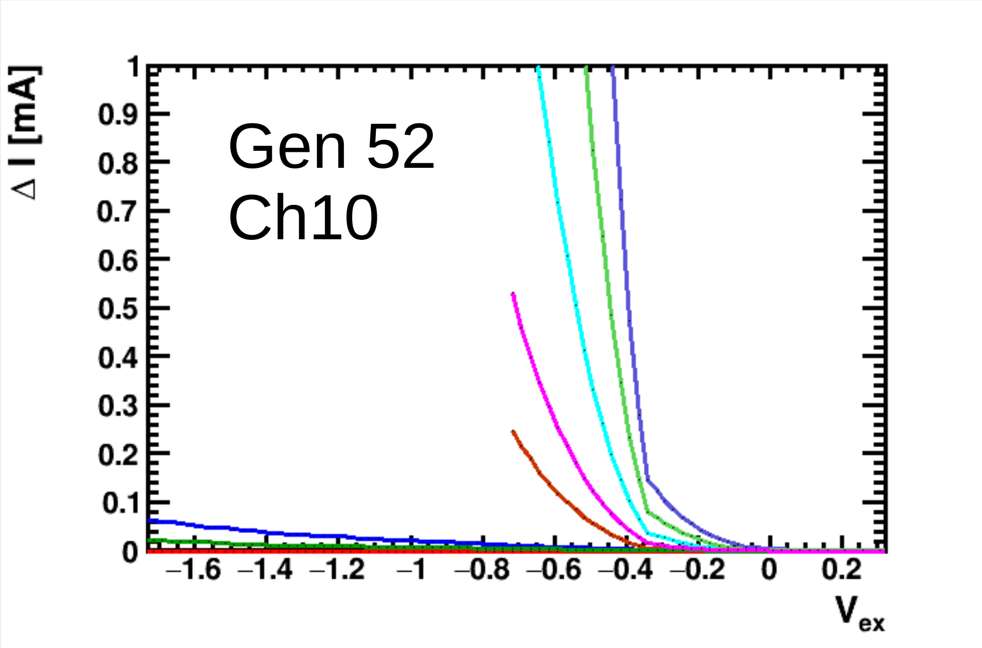


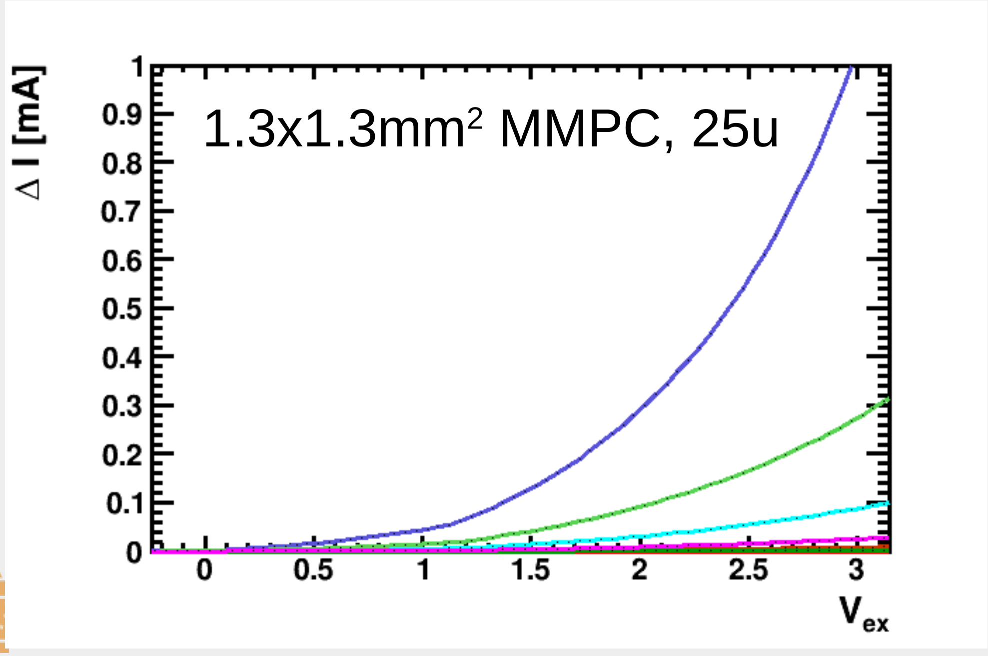




Plot increase in I_{dark} vs proton fluence

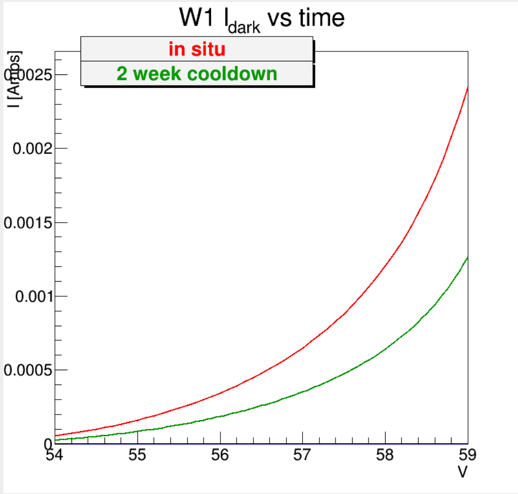






Comments:

- In situ measuremetns, not annealed
- Expect no annealing in GaInP
- Si ~ 2x drop in 2 weeks
- Vop for MMPC Vex ~ 3–5V
- Vop for GaInP Vex ~ 0.5–1V

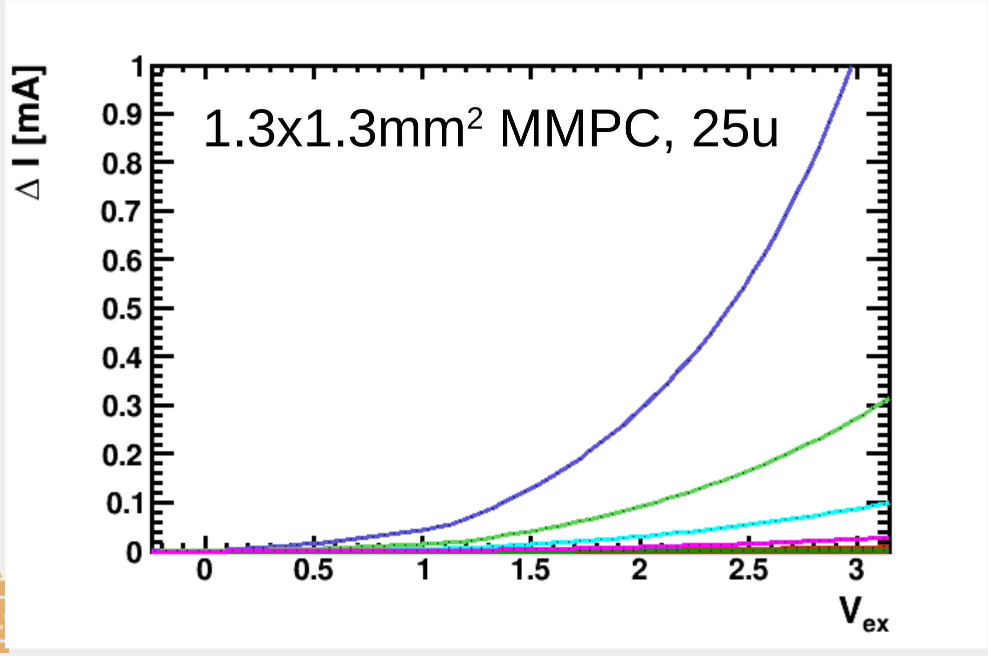


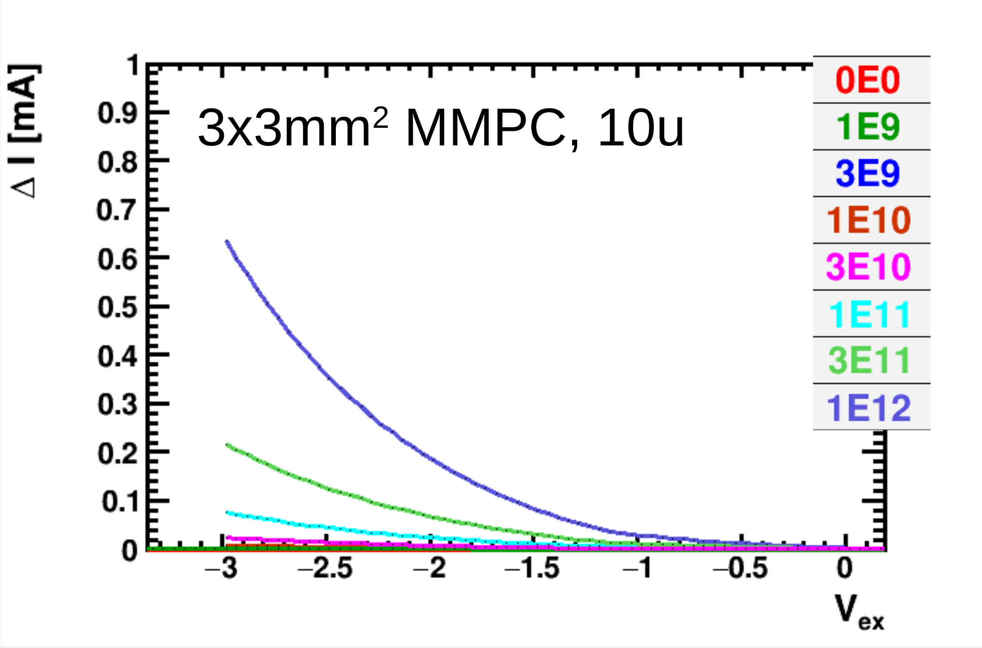
Plot increase in I_{dark} vs proton fluence

Effect of pixel size is as expected

10u devices show decreased I_{dark} rates wrt 25u

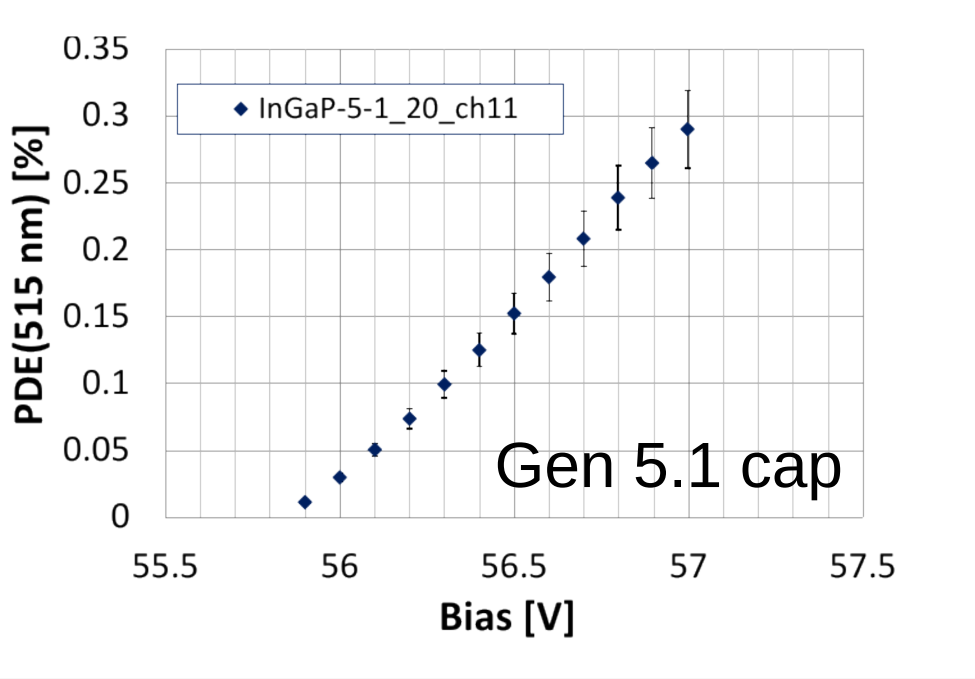
Note: 5x larger area for 10u device as well

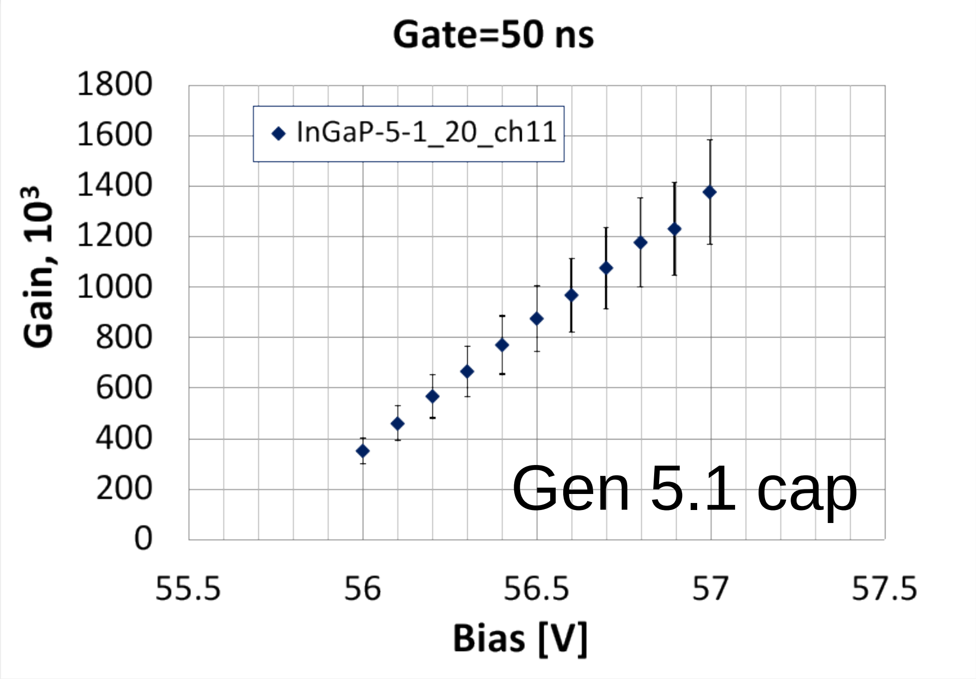


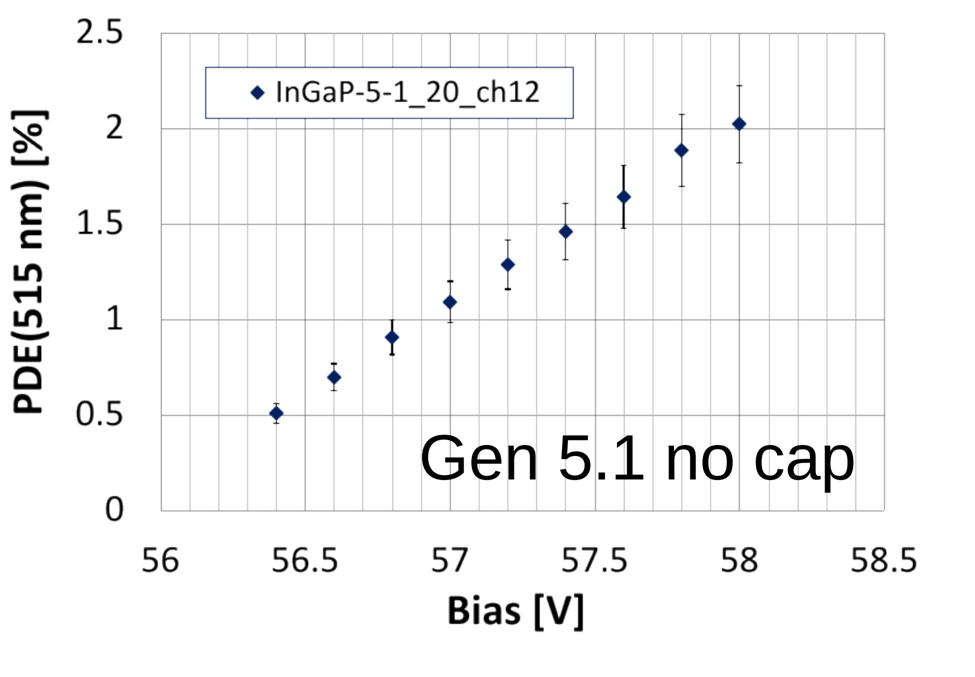


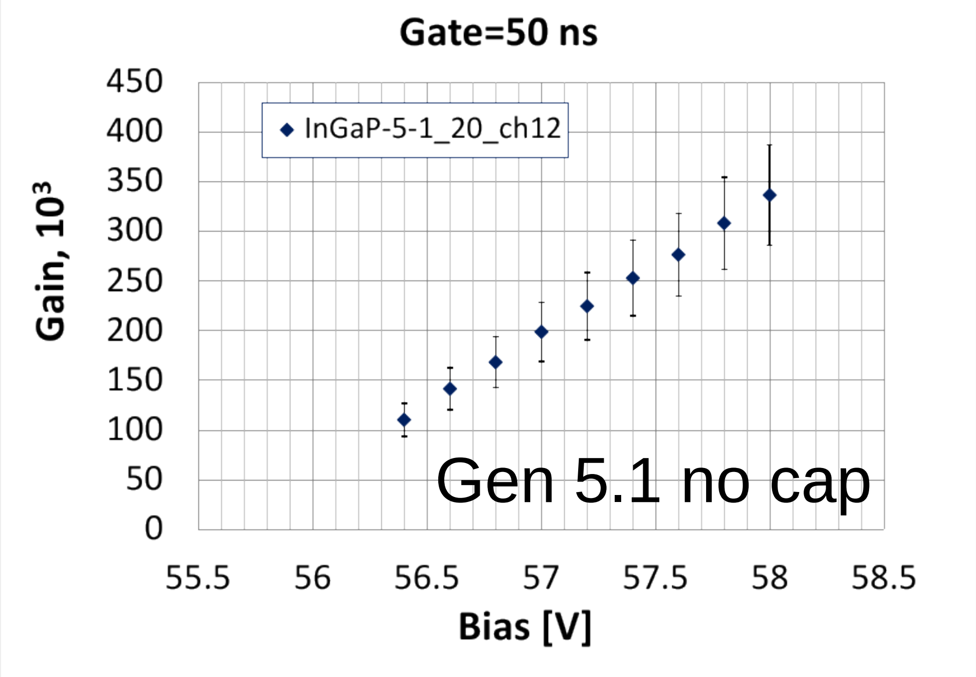
Bob Hirosky, UNIVERSITY of VIRGINIA

Gen 5.1 PDE@515nm and gain at larger bias



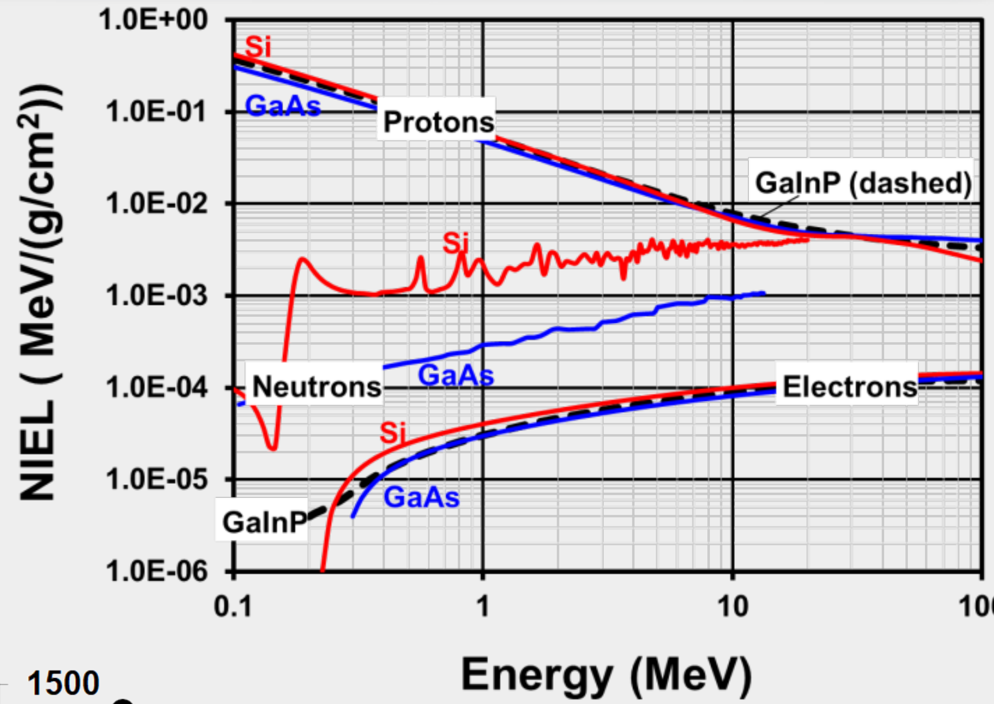


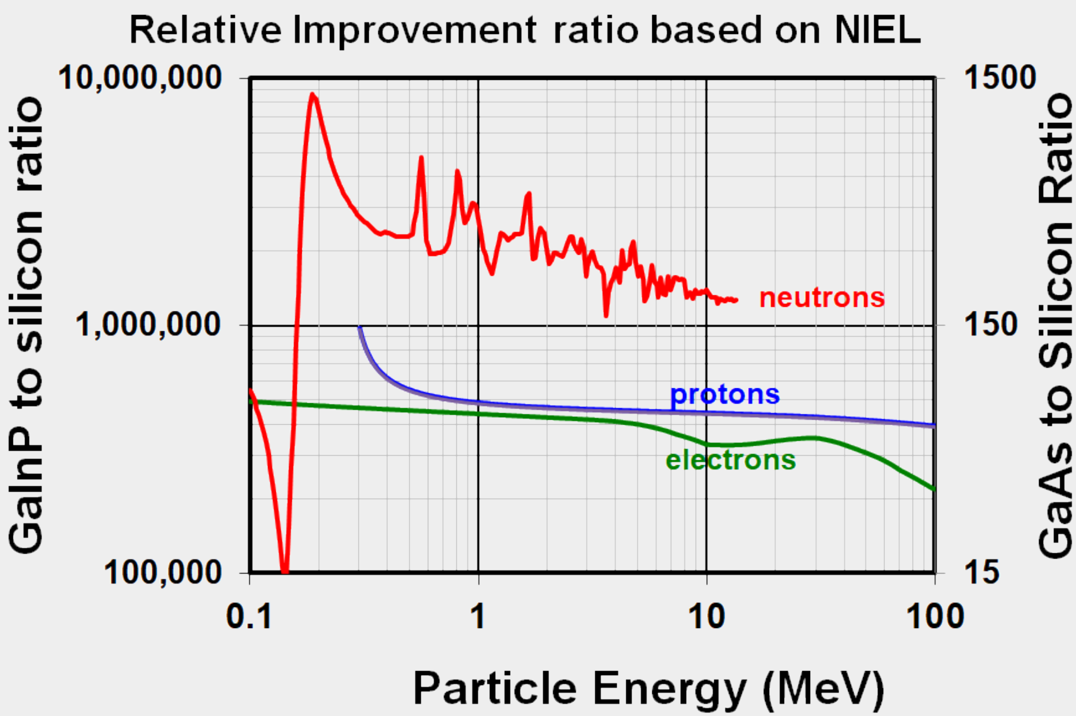




NEIL and relative G(Φ)

Expectations for relative improvement in radiation-induced bulk damage effects for GaInP





Practical:
building devices / tuning designs required!

Figure of merit to compare SPAD performance across materials/device technologies

- $F(\lambda,T_0) = DCR(T_0) / DE(\lambda) / Area$
  - **Result is effective dark count at 100% detection efficiency, normalized to detector area, measured at T_0=300K**
  - Assume $DE(\lambda,T) \approx DE(\lambda)$
    2nd order effects assumed negligible: band gap, after-pulsing, dead time, etc.

- $DCR(T) = C \times DE \times G\text{-}R(T)$
  - C is a constant describing fill factor
  - G-R(T) is the thermal generation rate

- $G\text{-}R(T) \approx (n_i / \tau_{SRH}) \times (Area \times W)$
  - n_i is the intrinsic carrier concentration
  - τ_{SRH} is the thermal generation lifetime
  - W is the thickness of the depletion region
  - Use to estimate τ_{SRH} from DCR

[Ref: Harmon1, Harmon2]

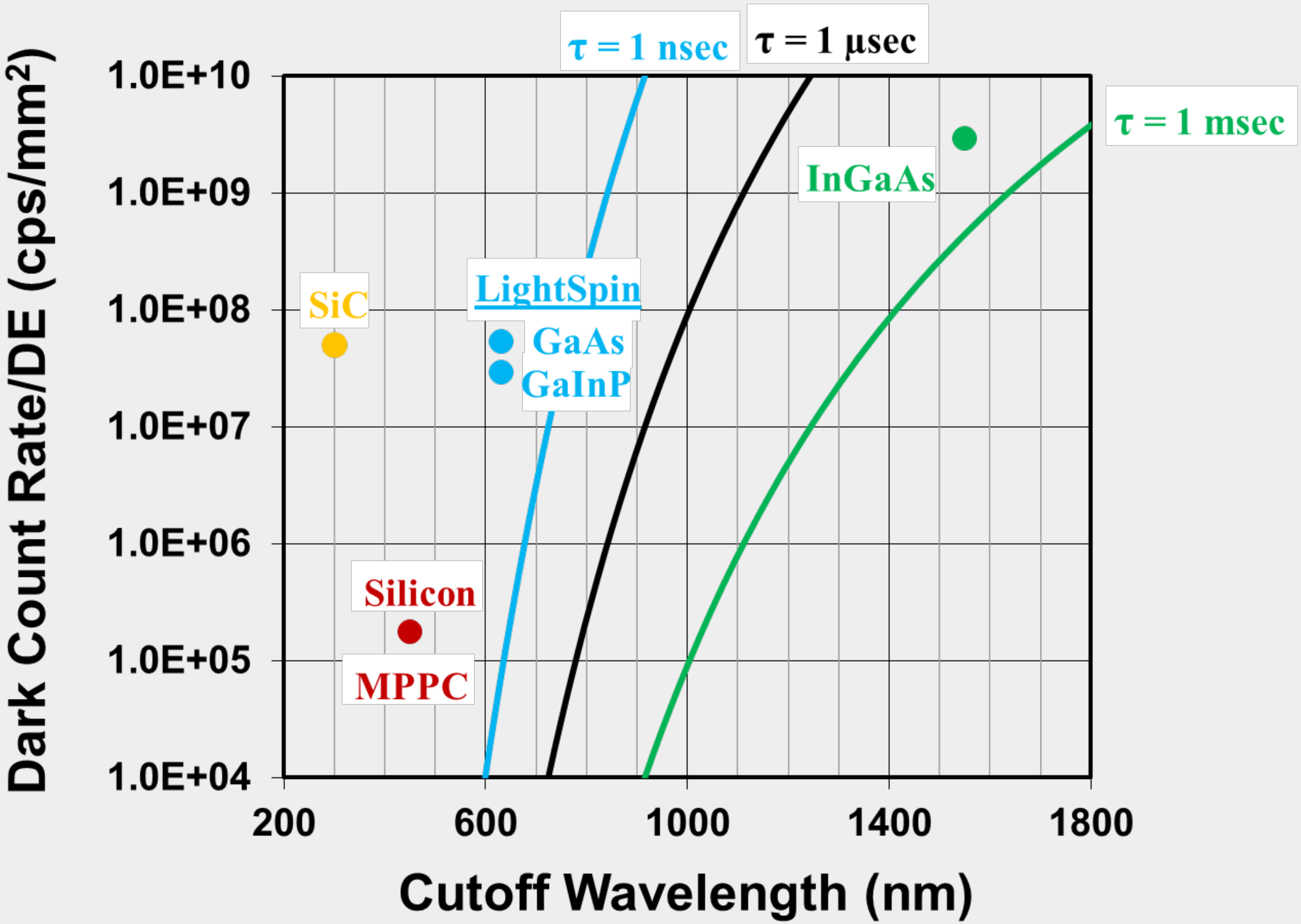
Experimental FOM

$$F(\lambda,T_0) = DCR(T_0) / DE(\lambda) / Area$$

Material	Wavelength (nm)	DCR (Mcps)	Temperature (K)	DE (%)	Area (mm^2)	FOM ($Mcps/mm^2$)
InGaAs	1550	0.040	290	2.8	4.9E-4	2900
Silicon	450	1.6	298	25	36	0.18
GaAs[1]	630	2.0	297	5	0.75	533
GaInP	630	13.2	298	30	1.5	29
4-HSiC	300	1.0	298	8	0.25	50

[1] Harmon, E. S., Naydenkov, M., and Hyland, J. T. "Compound Semiconductor SPAD arrays," Proc. SPIE v. 9113, paper 911305 (2014).
[2] Warburton, R.E., Itzler, M.A., and Buller, G.S., "Improved free-running InGaAs/InP single-photon avalanche diode detectors operating at room temperature", Electronics Letters v. 45(19) Pp. 996 – 997 (2009)
[3] Hamamatsu data sheet MPPC model S13360-6025: http://www.hamamatsu.com/resources/pdf/ssd/mppc_kapd0004e.pdf
[4] Harmon, E. S., Hyland, J. T., Naydenkov, M., "Compound Semiconductor SPAD Arrays," New Developments in Photodetection, Tours, France, July 4, 2014, http://ndip.in2p3.fr/ndip14/AGENDA/AGENDA-by-DAY/Presentations/5Friday/AM/ID34711_Harmon.pdf
[5] Soloviev, S. Dolinsky, S. Palit, S., Zhu, X., and Sandvik, P. "Silicon Carbide Solid-State Photomultiplier for UV light detection", Proc. SPIE v 9113, paper 911305 (2014)

FOM for state-of-the-art



State-of-the-art and theory

Material	FOM Mcps/ mm²	Temperature (K)	$n_i(T)$	τ	Potential gains?	Comment
InGaAs	2900	290	5.2e11	180 μsec	< 10×	Already optimized
Silicon	0.18	298	7.4e9	42 msec	< 10×	Already optimized
GaAs	533	297	1.9e6	3.6 nsec	> 10×	Some improvement available
GaInP	29	298	210	7 psec	> 10,000×	Significant optimization available
SiC	50	298	6e-9	1e-22 sec	>1E10	Unphysical τ – dominated by surface effects?