LightSpin Technologies, Inc.

Compound Semiconductor SPAD arrays

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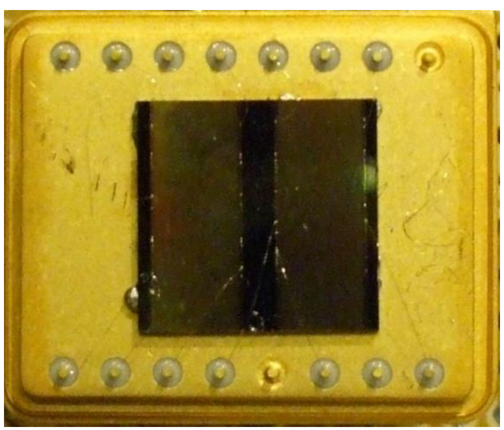
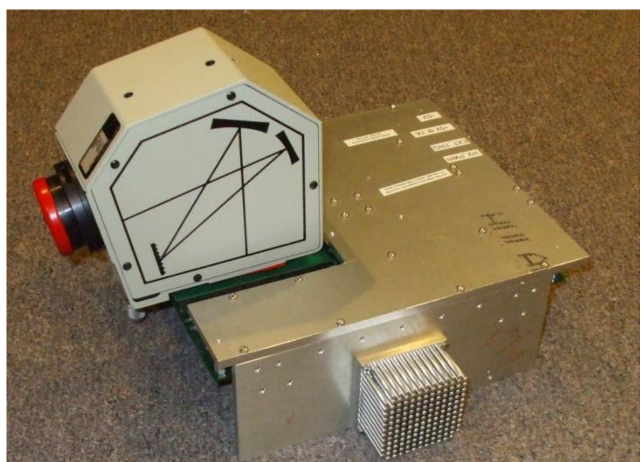
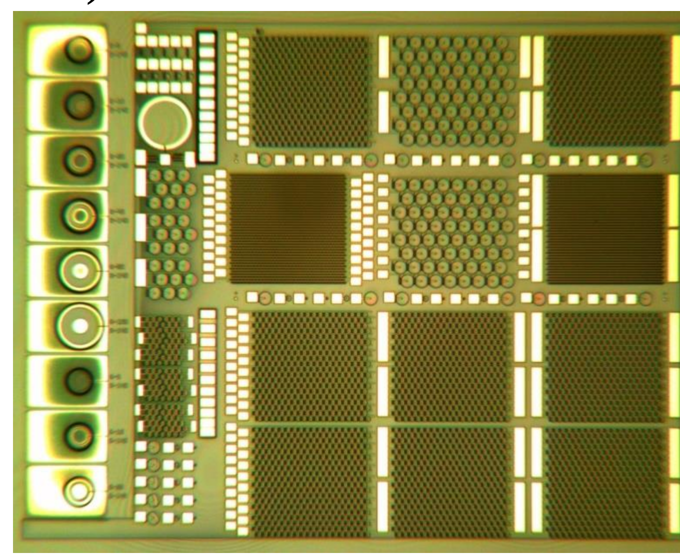
LightSpin Technologies, Inc.

- Company founded 2001
- Developing optoelectronics:
  - Highly integrated Compound semiconductors:
    - ❑Single photon detector arrays (UV-VIS-NIR)
    - ❑High gain detectors (UV-VIS-NIR-SWIR)
    - ❑Light Modulators







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Outline

- **SPAD figures of merit**
- **Quenching Circuits**
- **Experimental Data**

Why Compound Semiconductors?

- Conventional Wisdom:
  - Compound Semiconductors for NIR/SWIR → InGaAsP
  - Silicon for wavelengths < 900 nm
  - Nitrides or SiC for wavelengths < 400 nm
- Silicon?

Advantages	Disadvantages
+ lowest cost	- indirect band gap
+ highest materials quality	- avalanche characteristics?
+ high integration levels	- radiation hardness

- Need a way to compare SPAD performance across materials/device technologies

Figure of Merit: F(λ,T)

Effective dark count rate/area at 100% DE, 300K

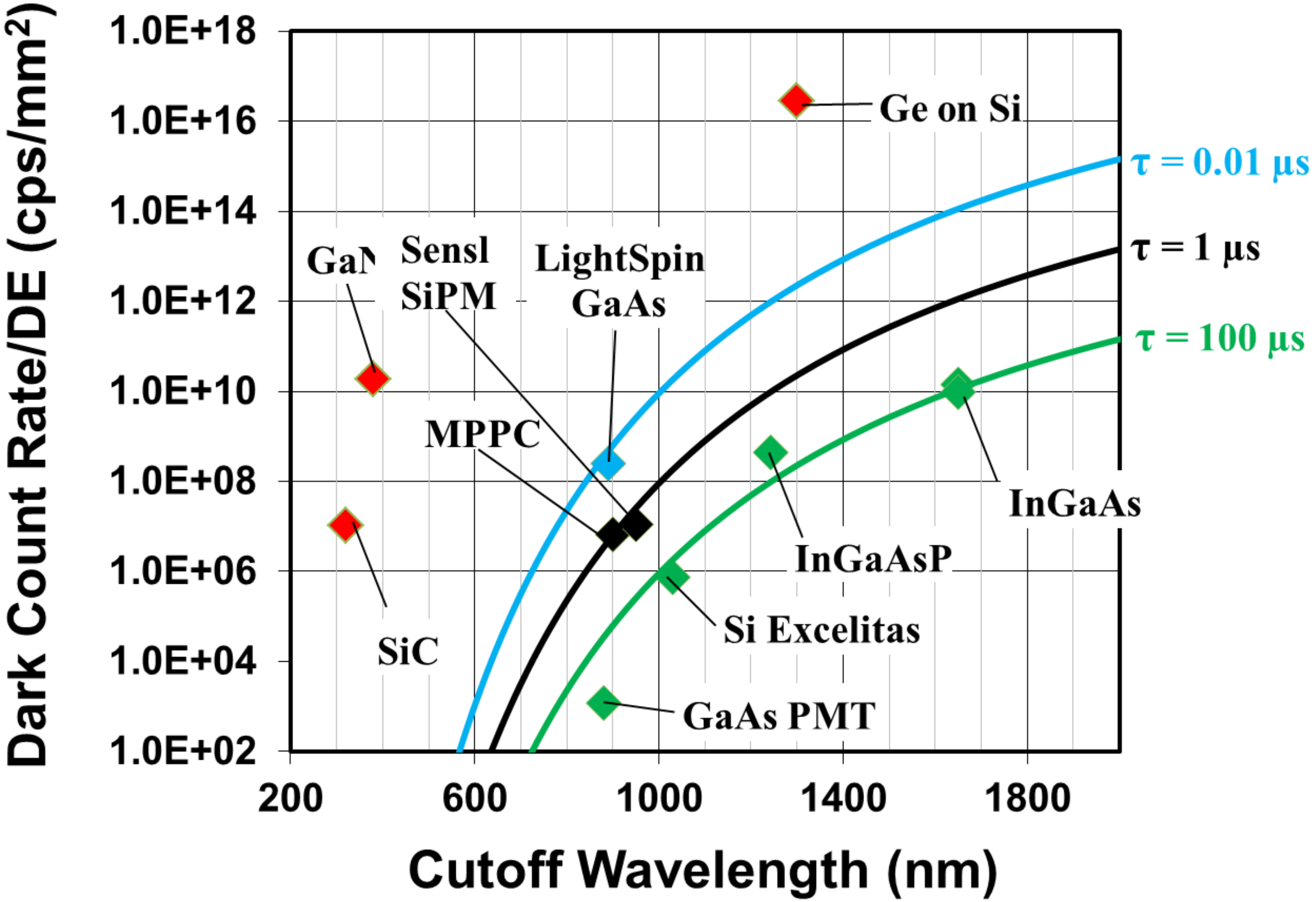

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Figure of Merit

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

- Scale Dark Count Rate to 300K
- Assume DE independent of temperature
- Provides means to compare SPADs constructed with different semiconductors
- Result is effective dark count rate at 100% detection efficiency, normalized to the detector area

SPAD Figure of Merit: F(λ,T)

- **F(λ,T) = DCR(T) / DE(λ,T) / Area**
  - λ = wavelength
  - T = operating temperature
  - DCR(T) = dark count rate at temperature T
  - DE(λ,T) = single photon detection efficiency
  - Area = area of device
- For experimental devices, F(λ,T) can be evaluated directly:
  - Depends on wavelength and temperature
  - Would like to scale to $F(\lambda,T_0)$.
- DCR(T) = can be estimated (next slide)
- Assume DE(λ,T) ≈ DE(λ):
  - Second order effects assumed negligible: band gap, after-pulsing, dead time, etc.

SPAD Figure of Merit: DCR(T)

- **DCR(T) = C × DE × G-R(T)**
  - C is a constant describing fill factor
  - G-R(T) is the thermal generation rate
- **G-R(T) ≈ (n_i / τ_{SRH}) × (Area × W)**
  - n_i is the intrinsic carrier concentration: $n_i = (N_V \times N_C)^{0.5} \times \exp\,[E_G(T) / (2 \times k_B T)]$:
    - ❑ N_V is the valence band density of states
    - ❑ N_C is the conduction band density of states
    - ❑ E_G is the band gap
    - ❑ k_B is Boltzman's constant
  - τ_{SRH} is the thermal generation lifetime
  - W is the thickness of the depletion region in the device

Experimental **F(λ,T)**

Device	Semiconductor material	Wavelength (λ_C)	DE (%)	DCR (cps)	T (K)	Area (mm^2)	F(λ_C,T=300K) cps/mm^2
PLI NFAD1[1]	InGaAs	1650	10	35	193	0.00038	1.4E10
PLI NFAD2[1]	InGaAs	1650	8	40	193	0.00080	9.6E9
Ge on Si[2]	Ge	1300	4	2.5E8	200	0.00071	2.8E16
PLI 1.064 μm array[3]	InGaAsP	1243	37.2	2000	253	0.00091	4.4E8
Excelitas Silk[4]	Si	1030	10	200	263	0.025	7.4E5
Hamamatsu MPPC[5]	Si	900	3	1E6	298	1.0	3.7E6
LightSpin GaAs PMC	GaAs	890	5	2.0E7	295	0.75	3.0E8
Hamamatsu PMT6	GaAs	880	12	125	273	19.6	1.2E3
SensL SiPM[7]	Si	800	5	1E7	294	9.0	3.8E7
LightSpin GaInP PMC	GaInP	635	30	1.3E7	295	1.5	7.1E7
GaN[8]	GaN	380	9	1E6	300	0.000624	1.8E10
4H-SiC[9]	4H-SiC	320	10	5E4	300	0.049	1.0E7

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7. M series: http://www.sensl.com/downloads/ds/DS-MicroMseries.pdf
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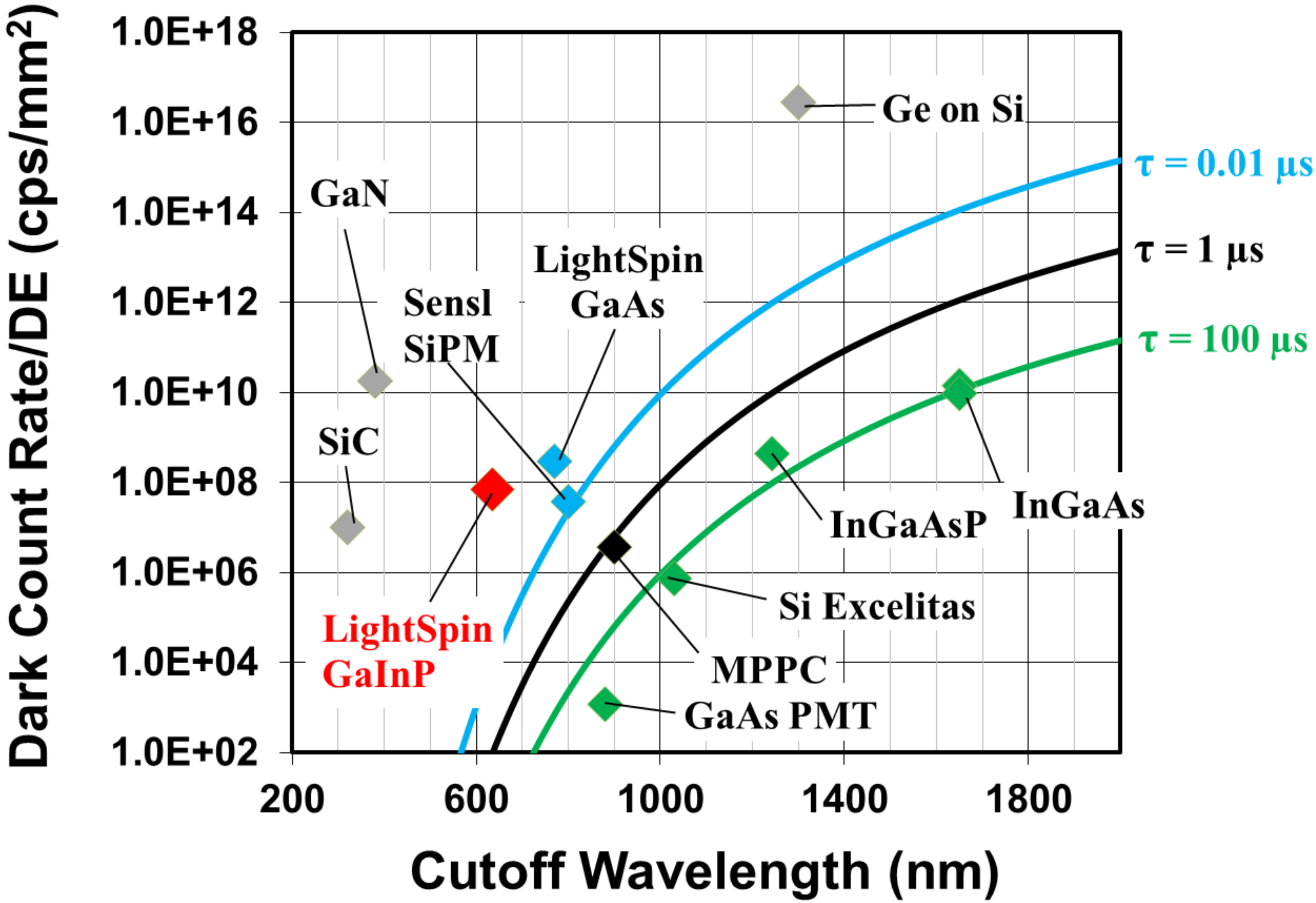
Figure of Merit



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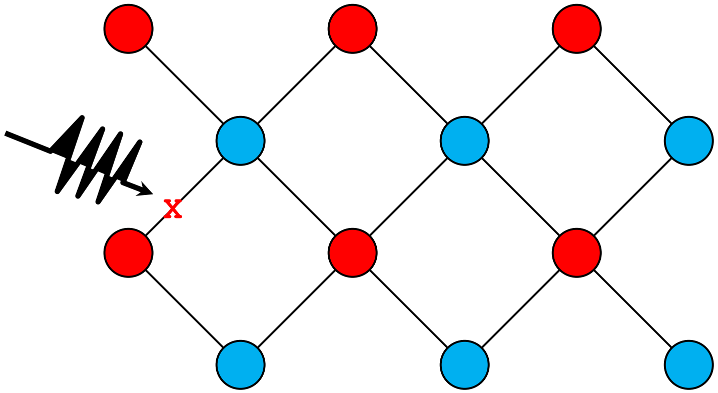
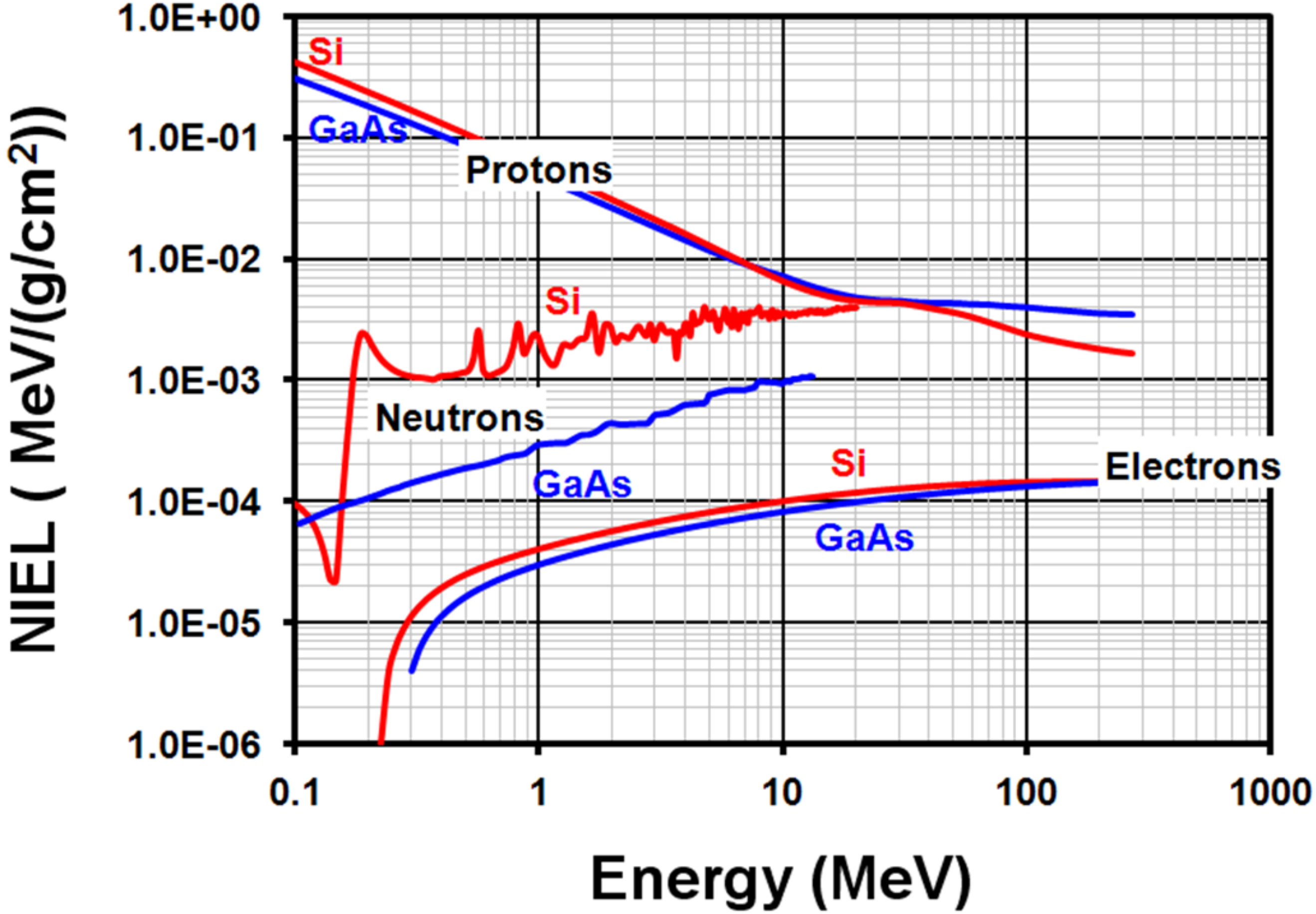
Radiation Hardness?

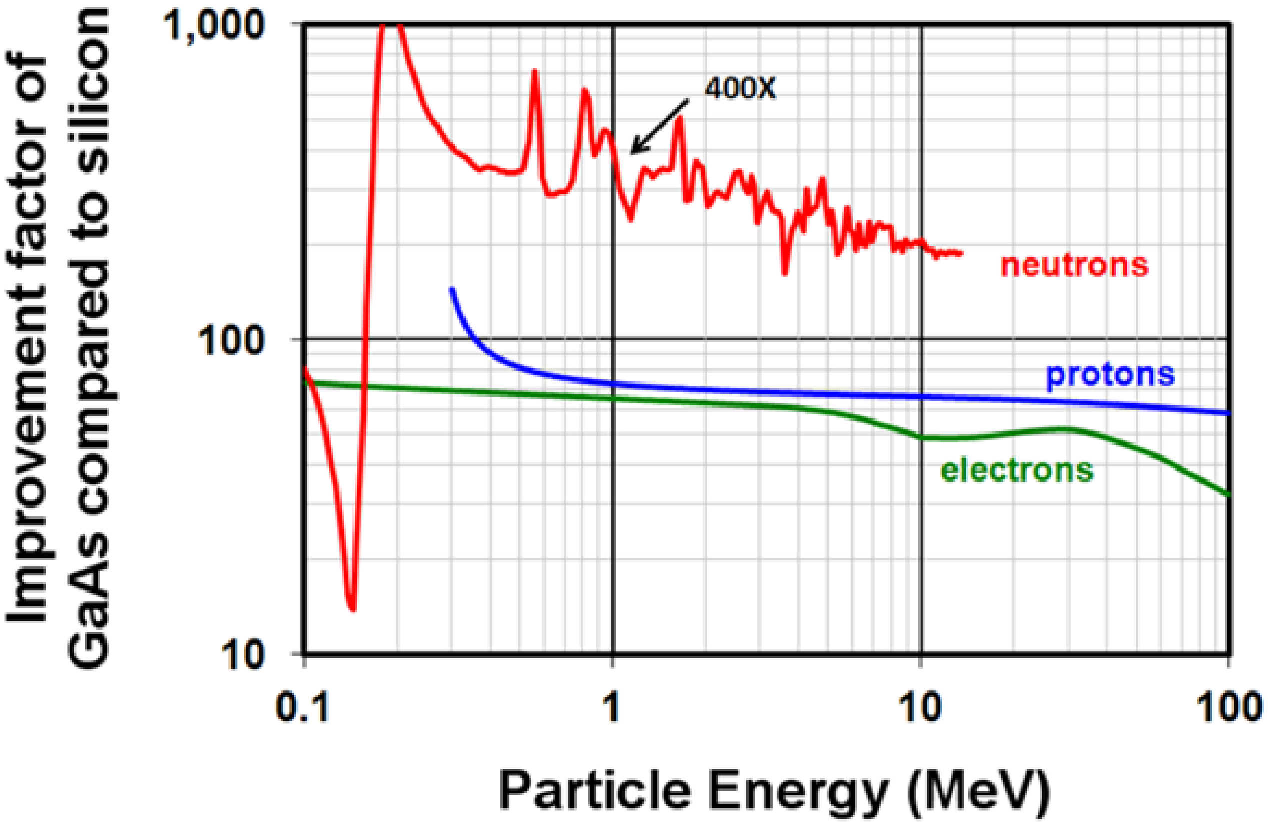


- $\tau_{SRH(\Phi)} = 1/(K \times \Phi)$
- $G\text{-}R\ (\Phi) = n_i / \tau_{SRH(\Phi)} \times (\text{Area} \times \text{W}) = n_i \times K \times \Phi \times (\text{Area} \times \text{W})$
- Where:
  - K is the lifetime radiation damage factor
  - Φ is the radiation flux

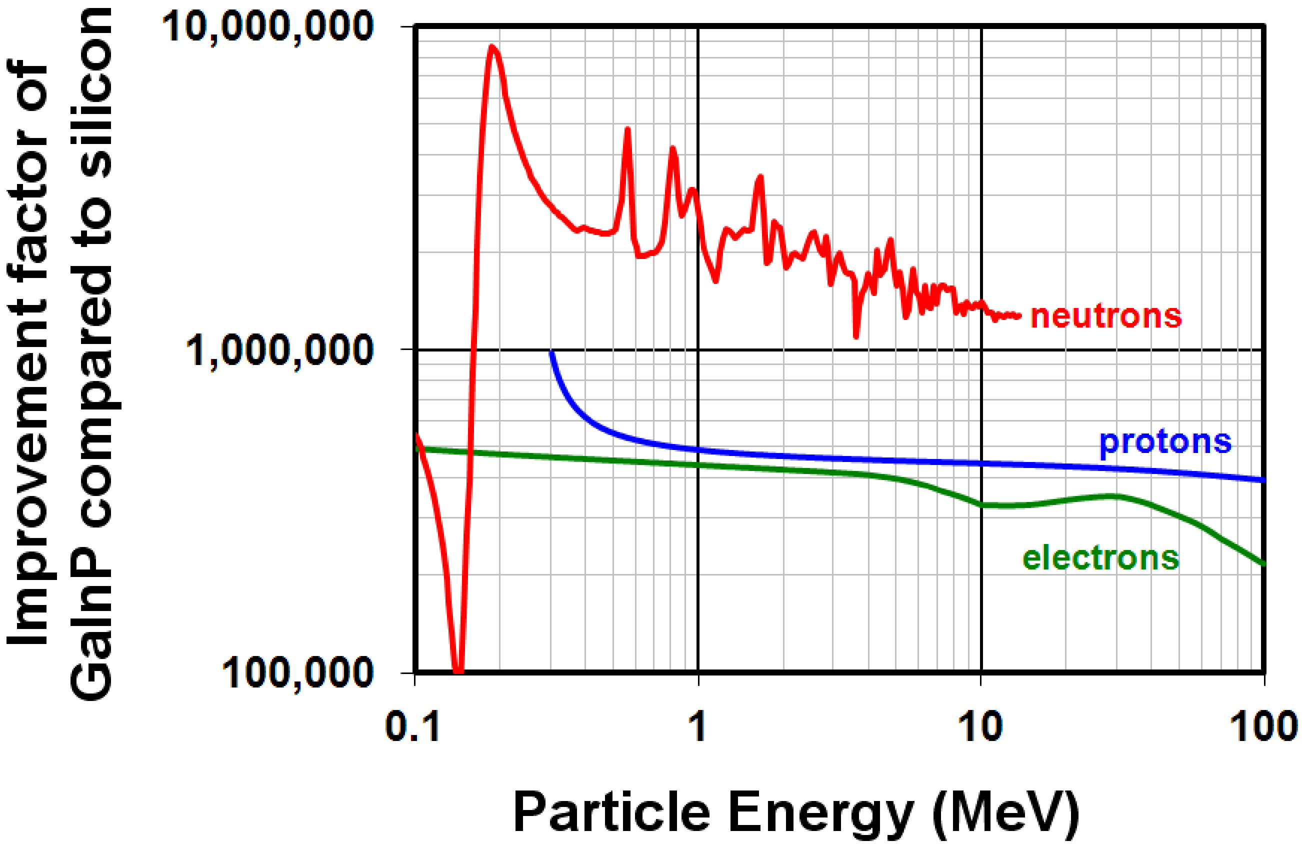
Non-Ionizing Energy Loss



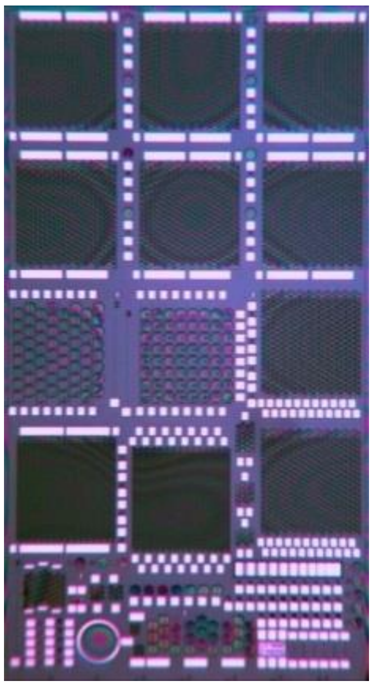
Radiation Hardness GaAs vs. silicon

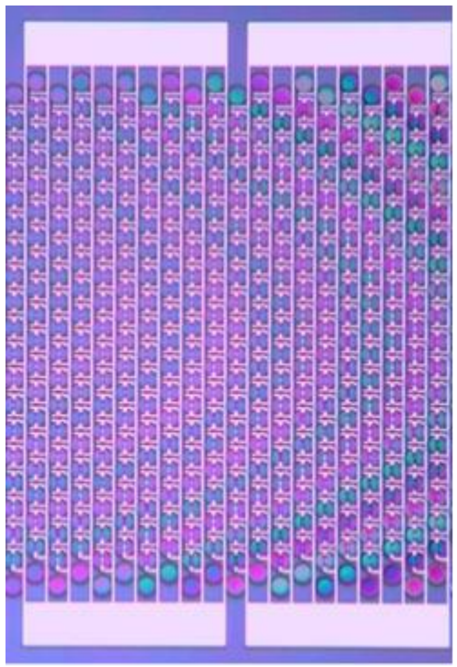


Radiation Hardness GaInP vs. silicon



Experimental Results: GaAs Photomultiplier Chips™



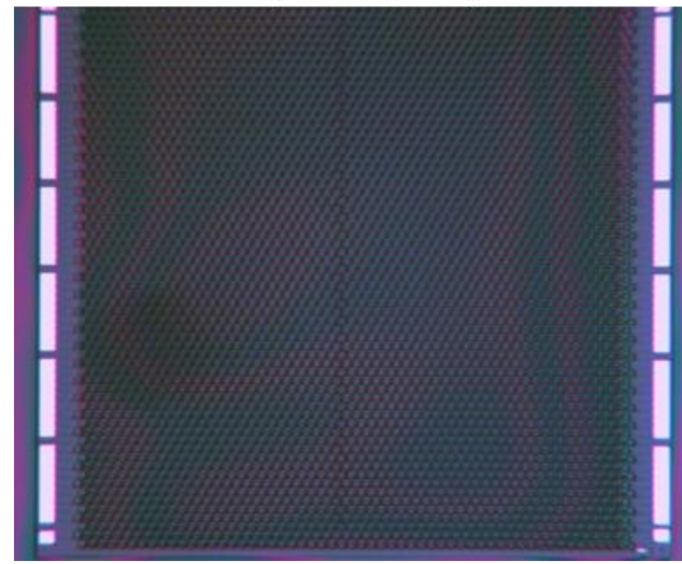


1 mm

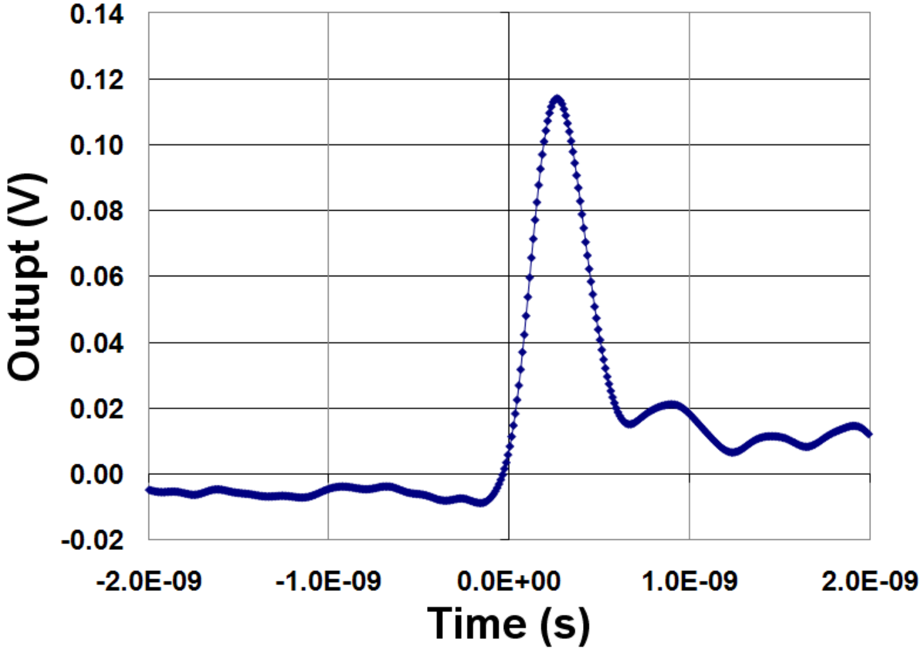
← 1 mm →

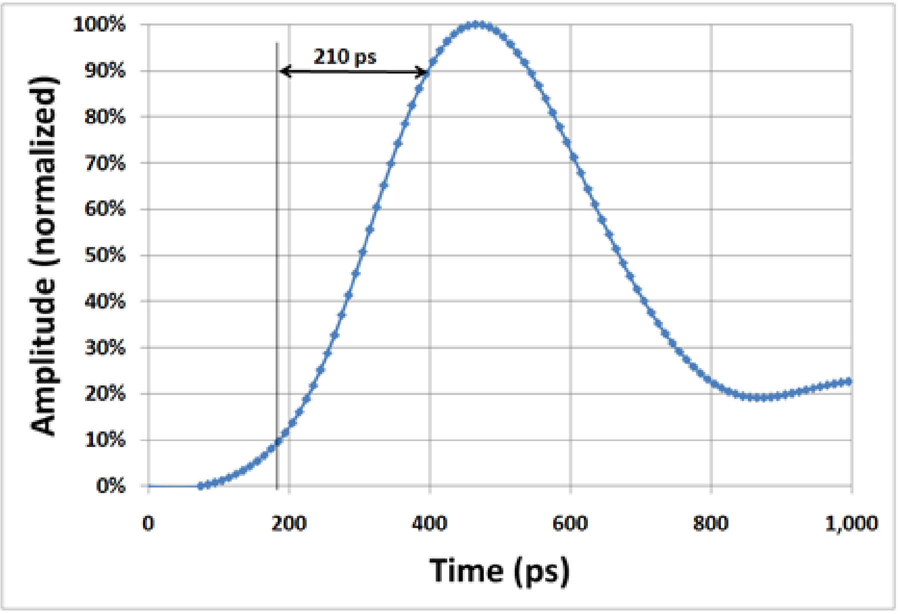
3 mm × 3 mm die

← 3 mm →



Single GaAs SPADs: fast passive quench





- Measurement bandwidth limited (2 – 2.5 GHz): estimate actual rise time is 97 – 140 psec

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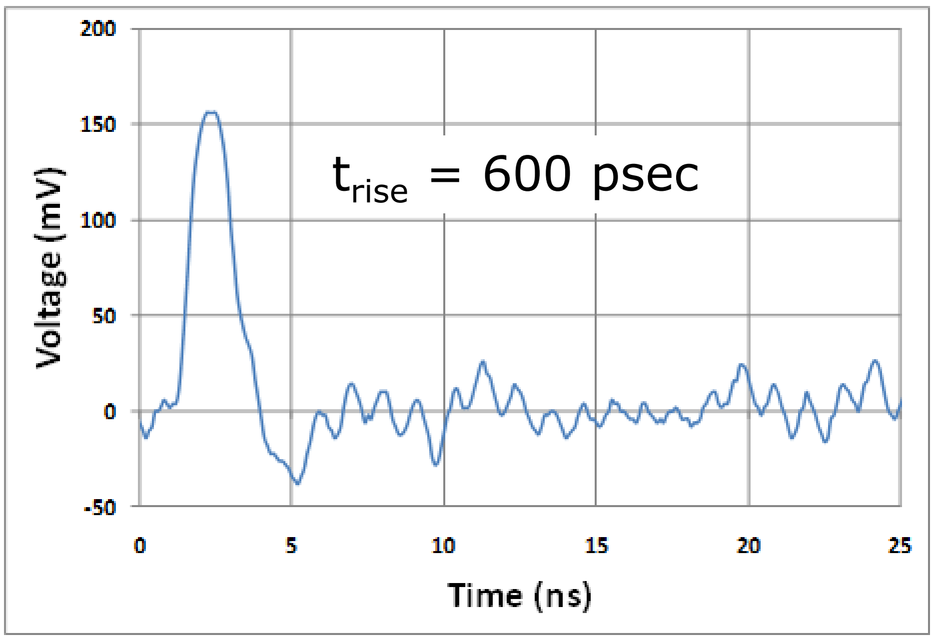
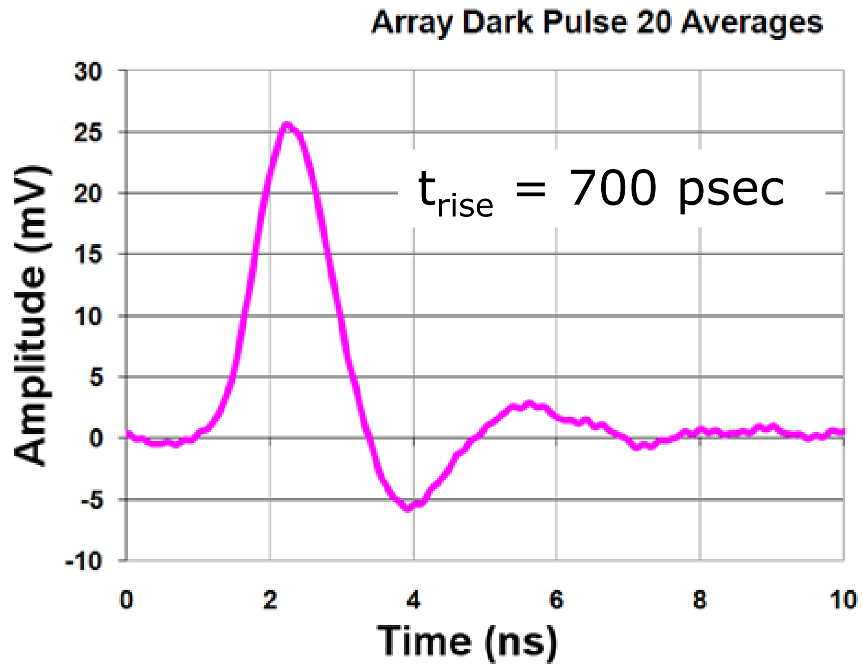
GaAs Photomultiplier Chip™

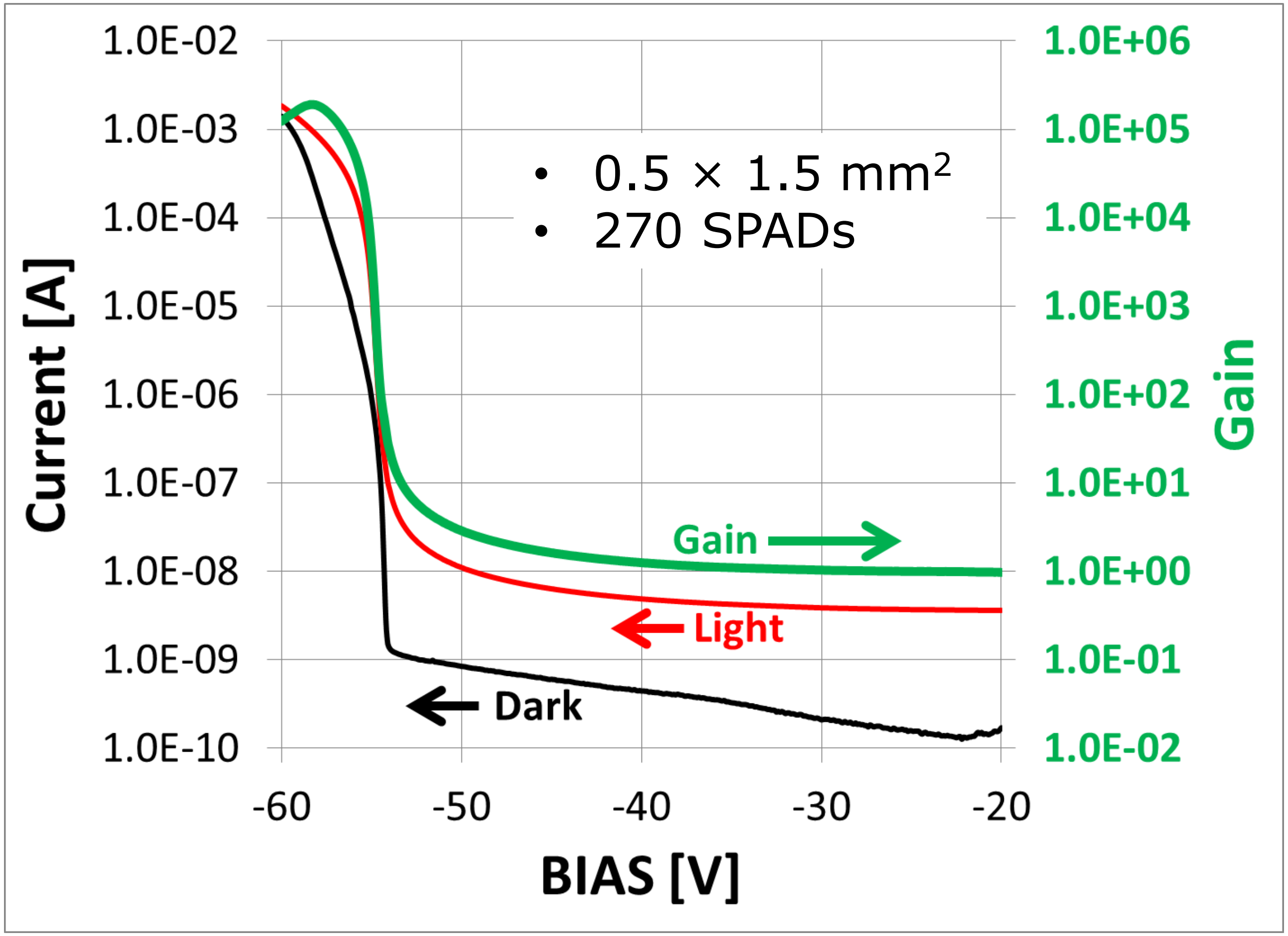
Packaged 1.0 mm × 1.0 mm array



Probed 0.5 mm × 1.0 mm array



I-V curves



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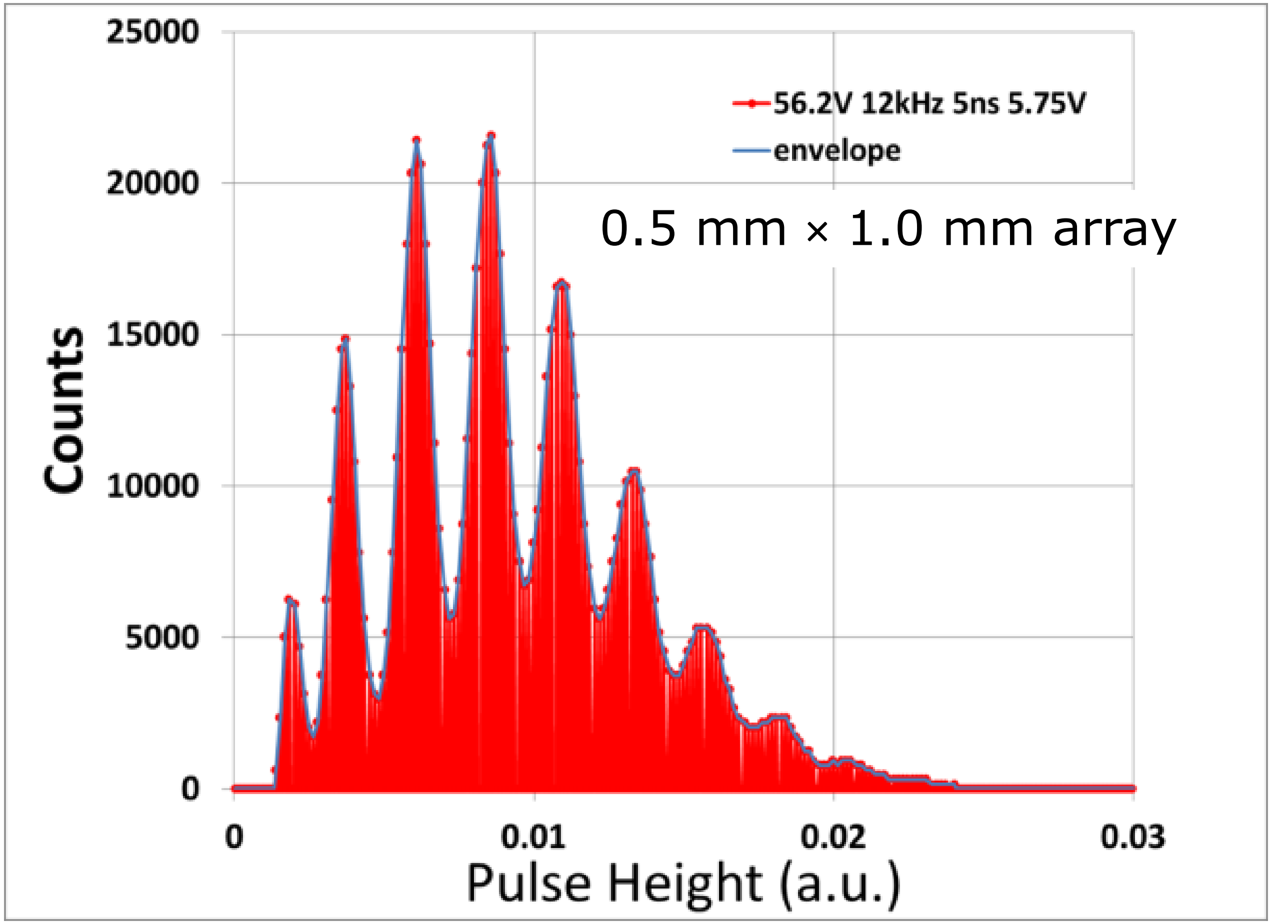
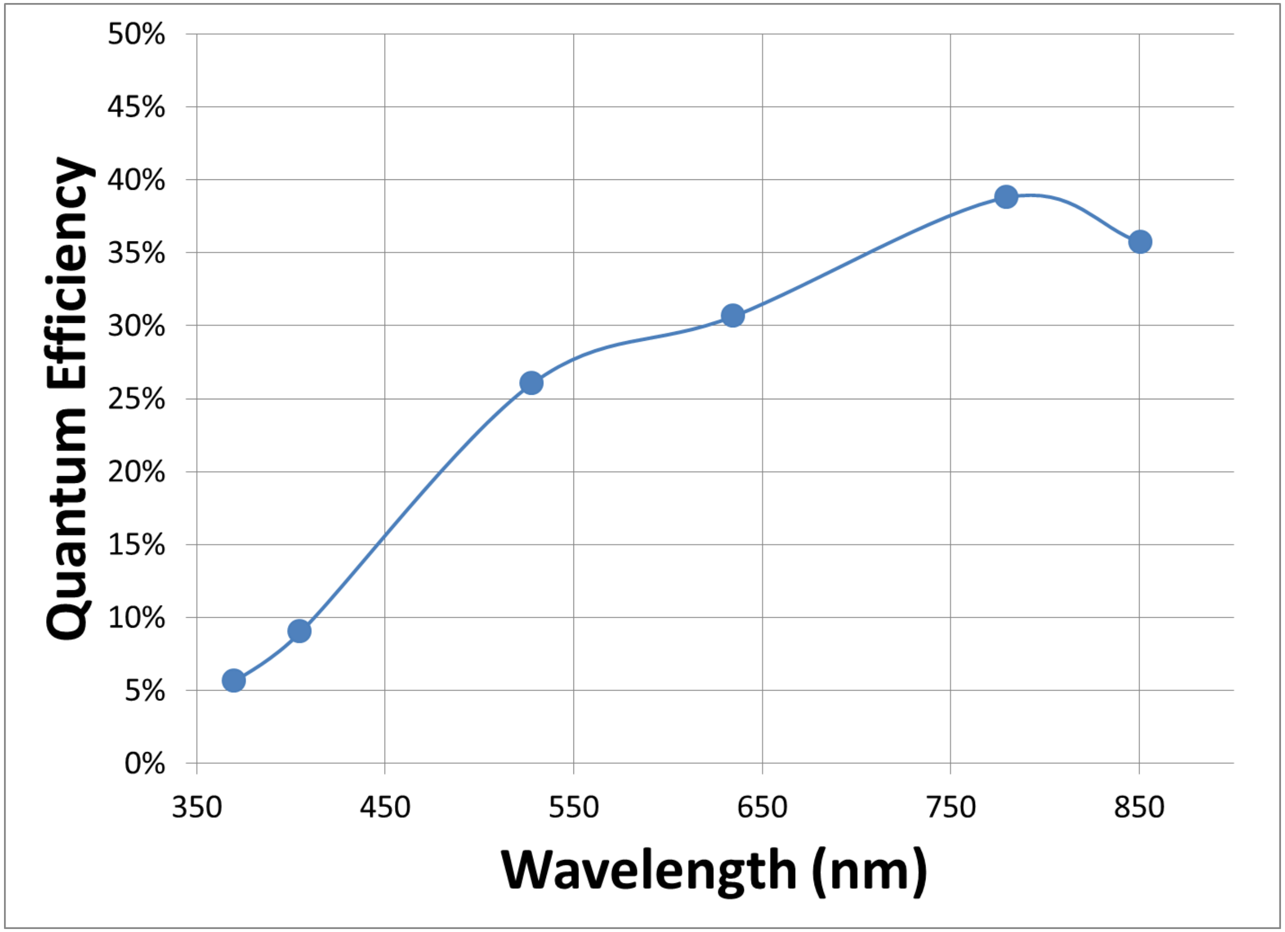
Photon Number resolving



Quantum Efficiency



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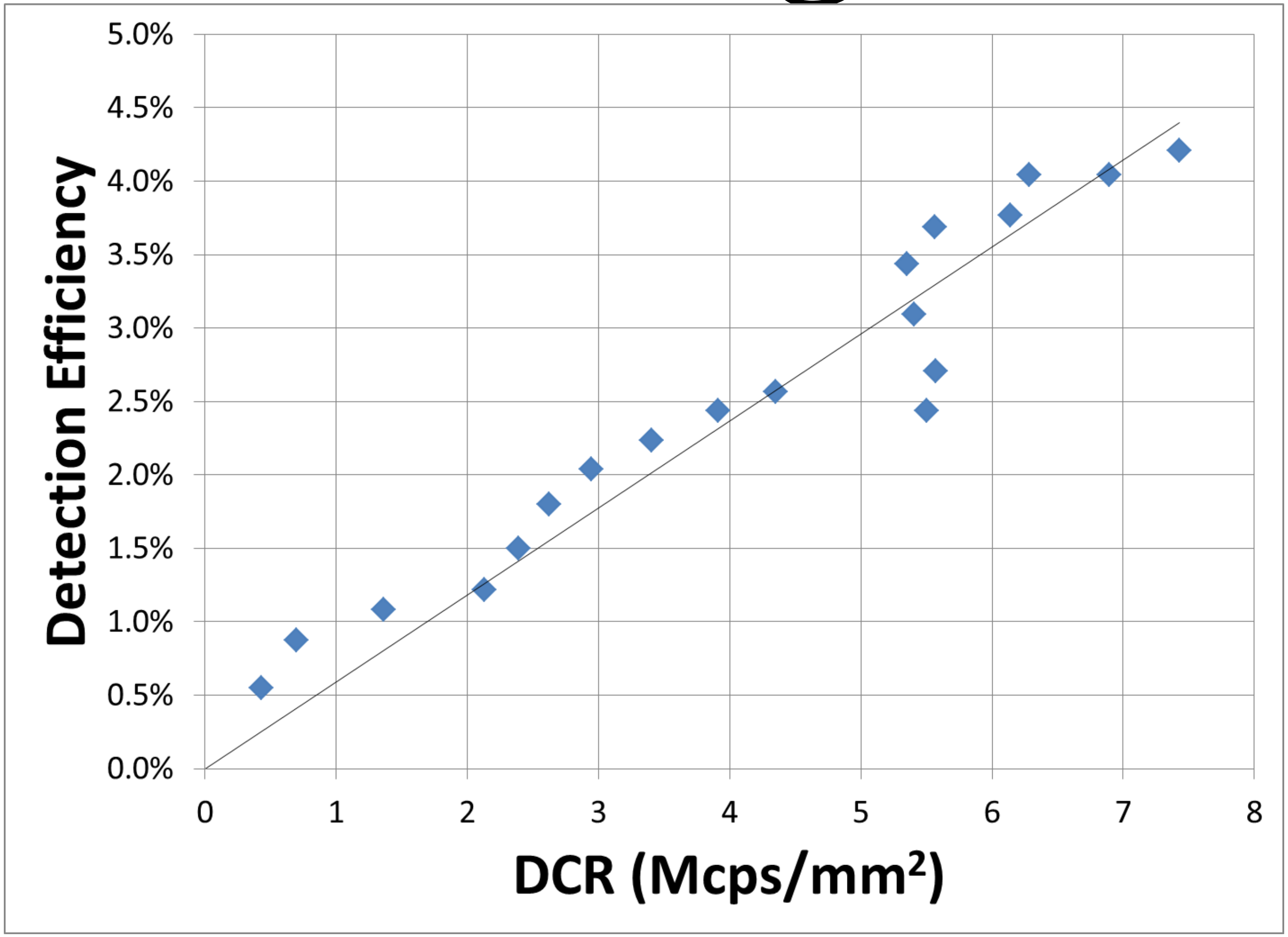
DE vs. DCR @ 770 nm



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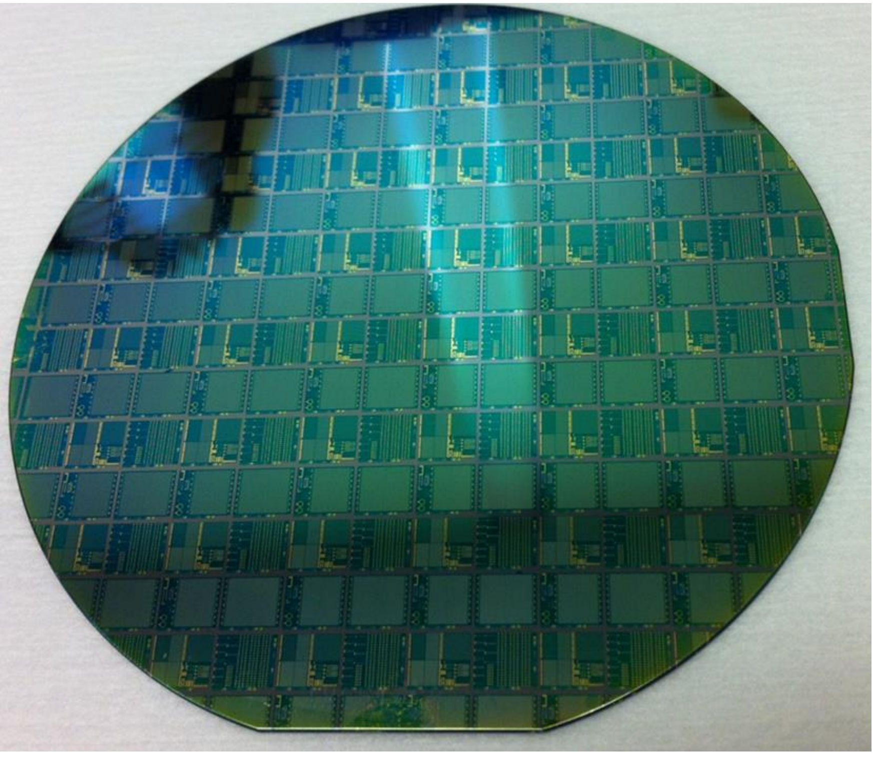
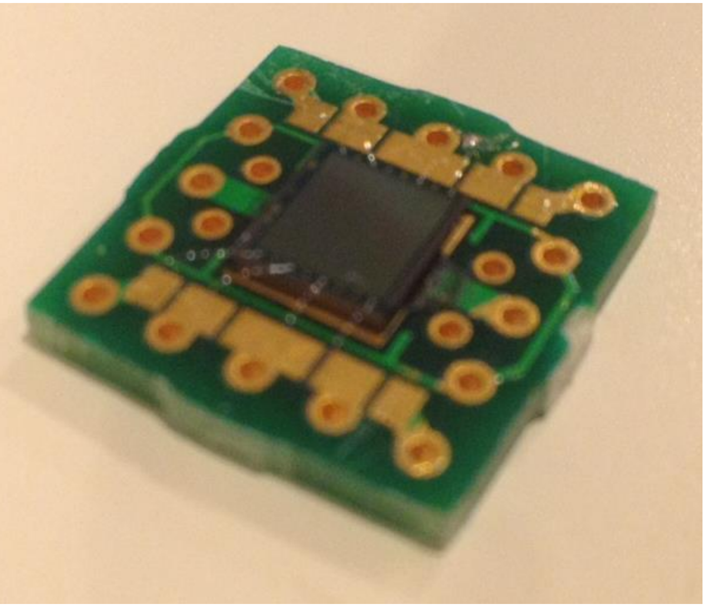
Experimental Results: GaInP Photomultiplier Chips™

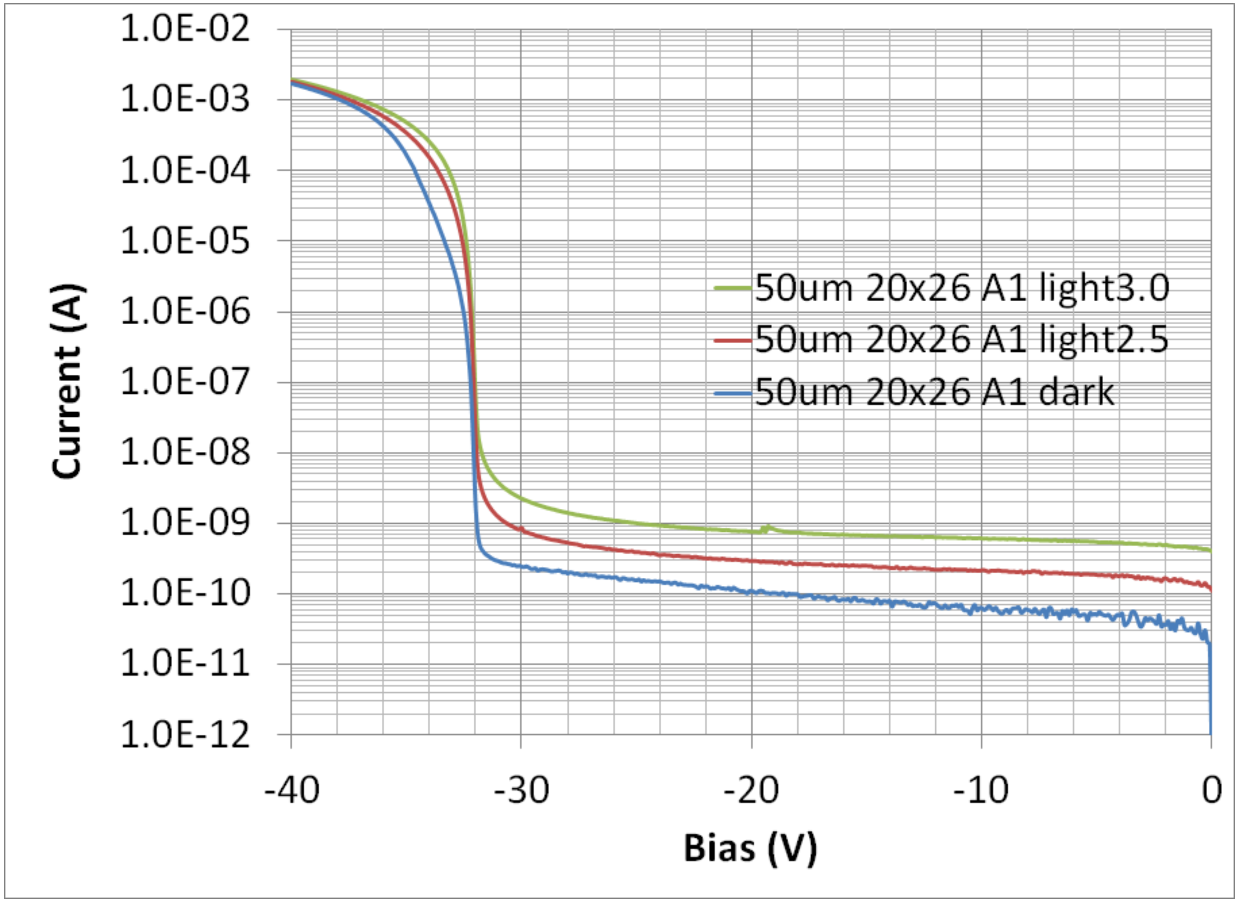


75 mm wafer



4 mm x 4 mm PMC™

GaInP I-V



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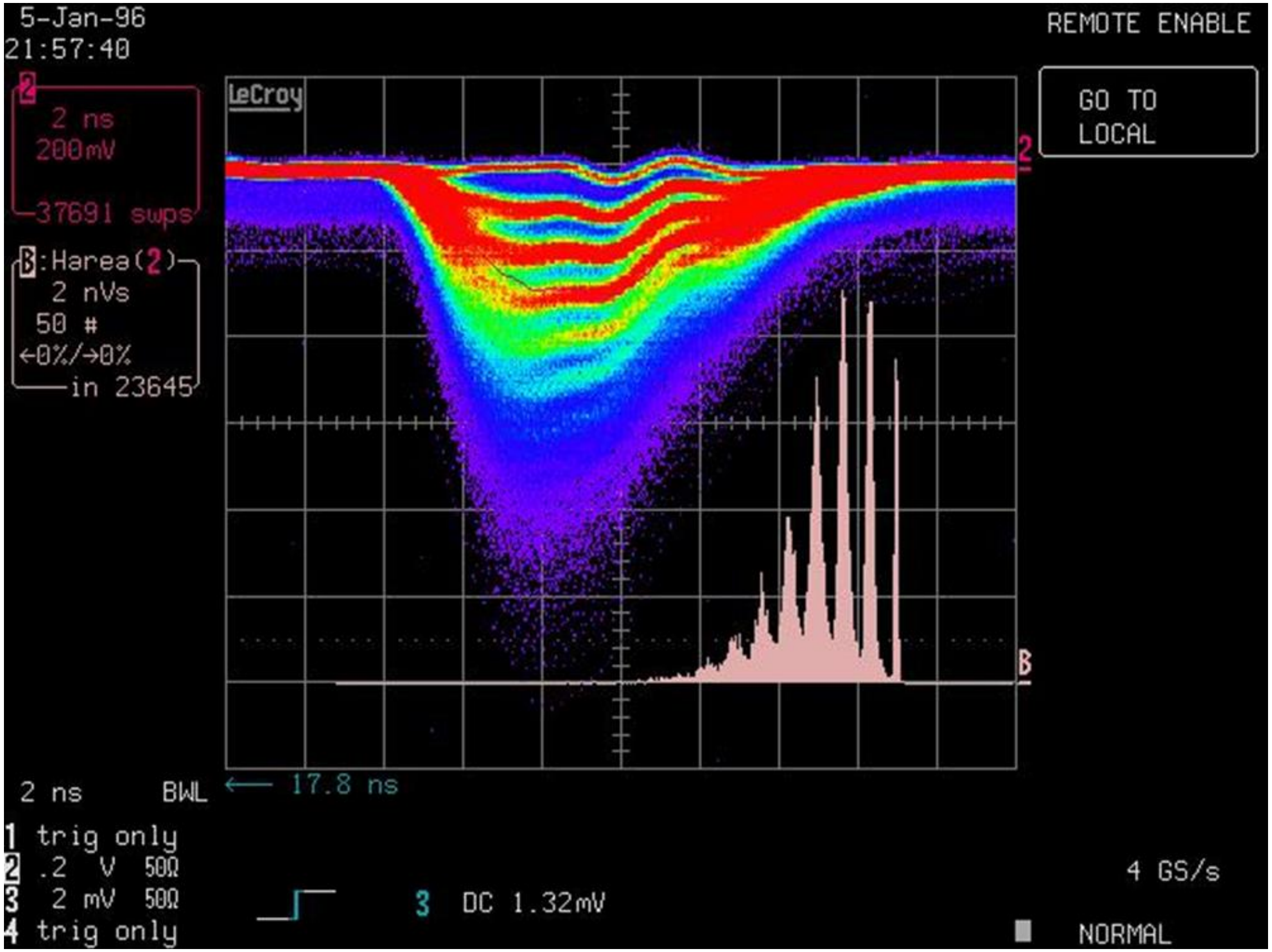
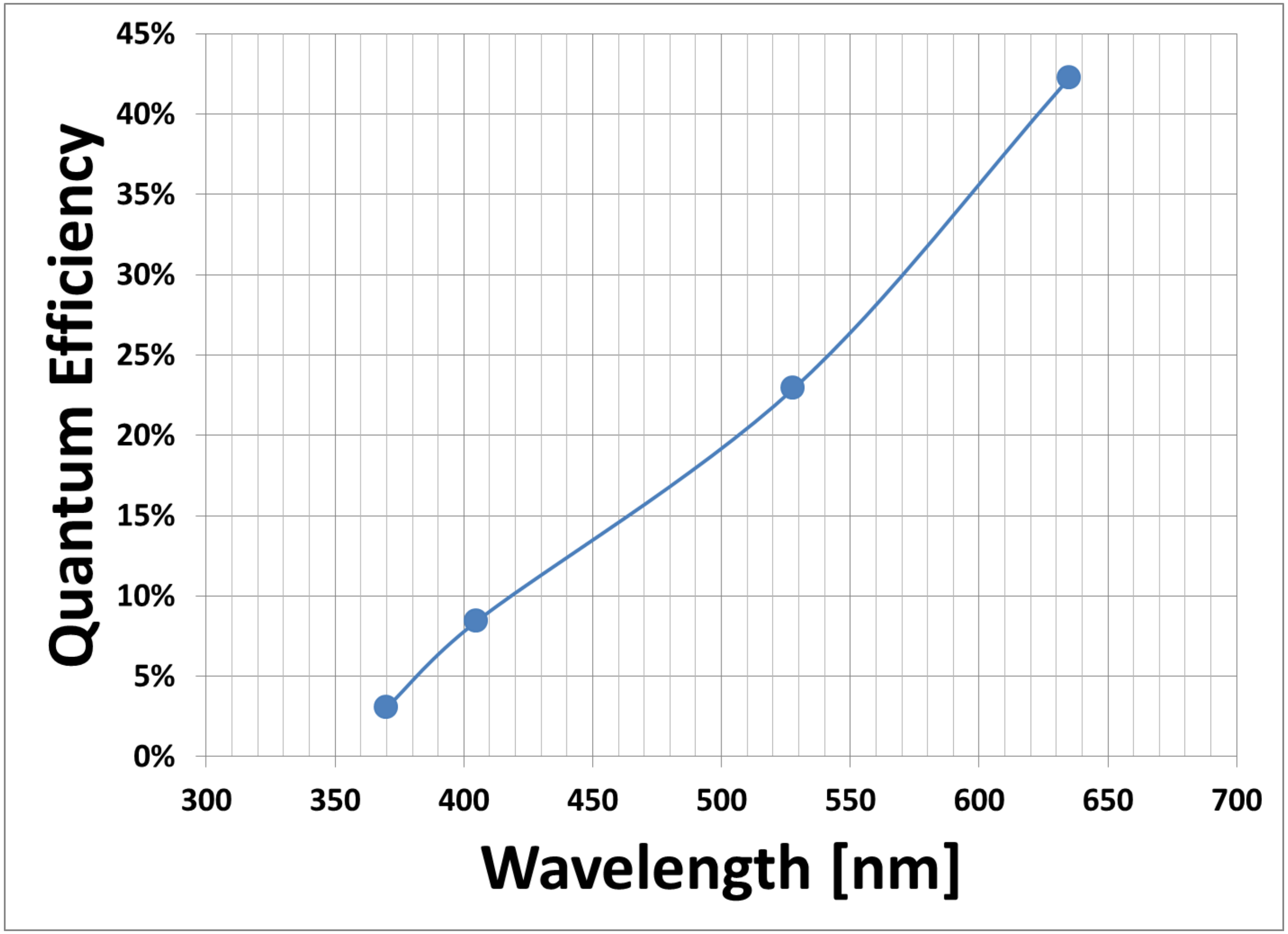
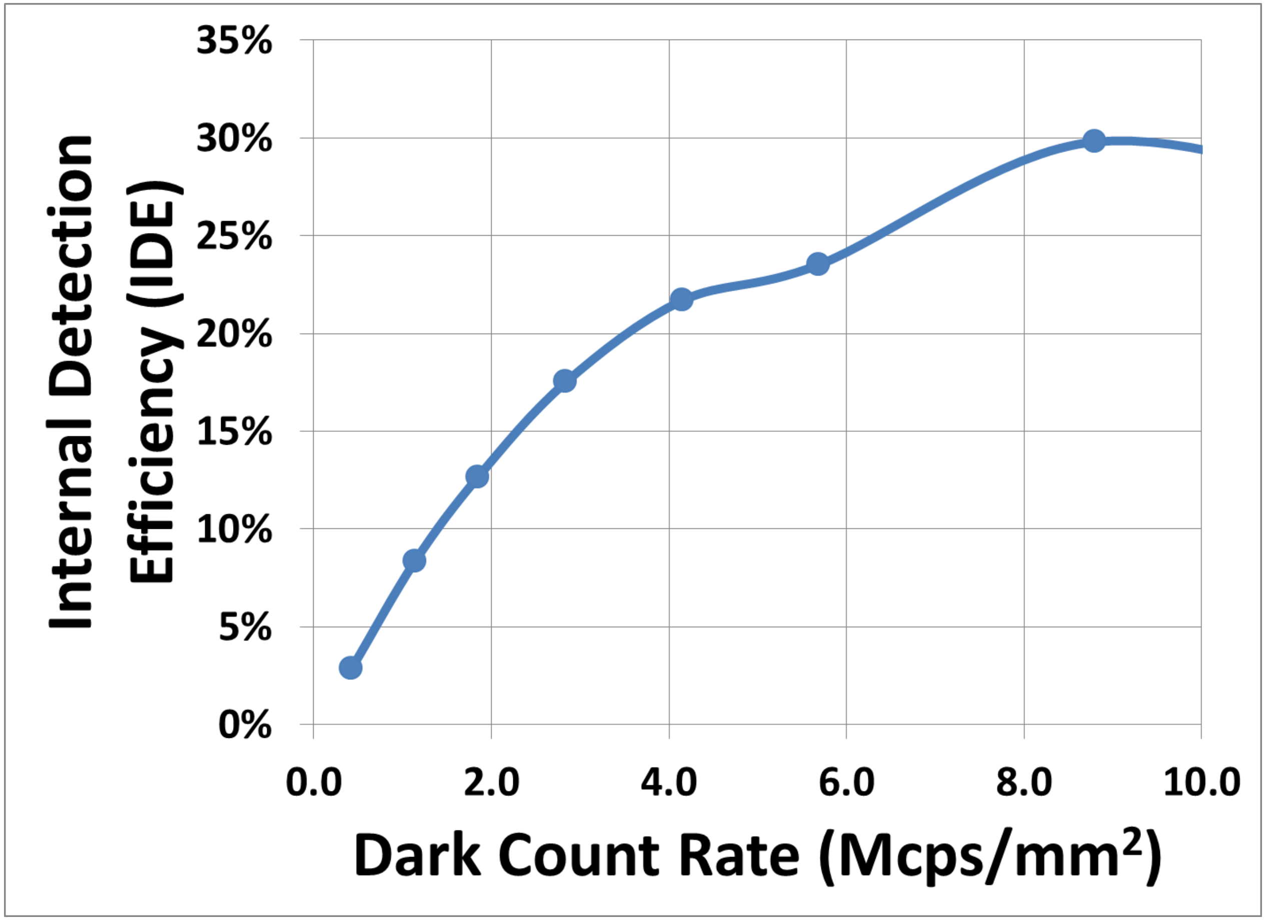
GaInP Results



Quantum Efficiency



Detection Efficiency vs. DCR



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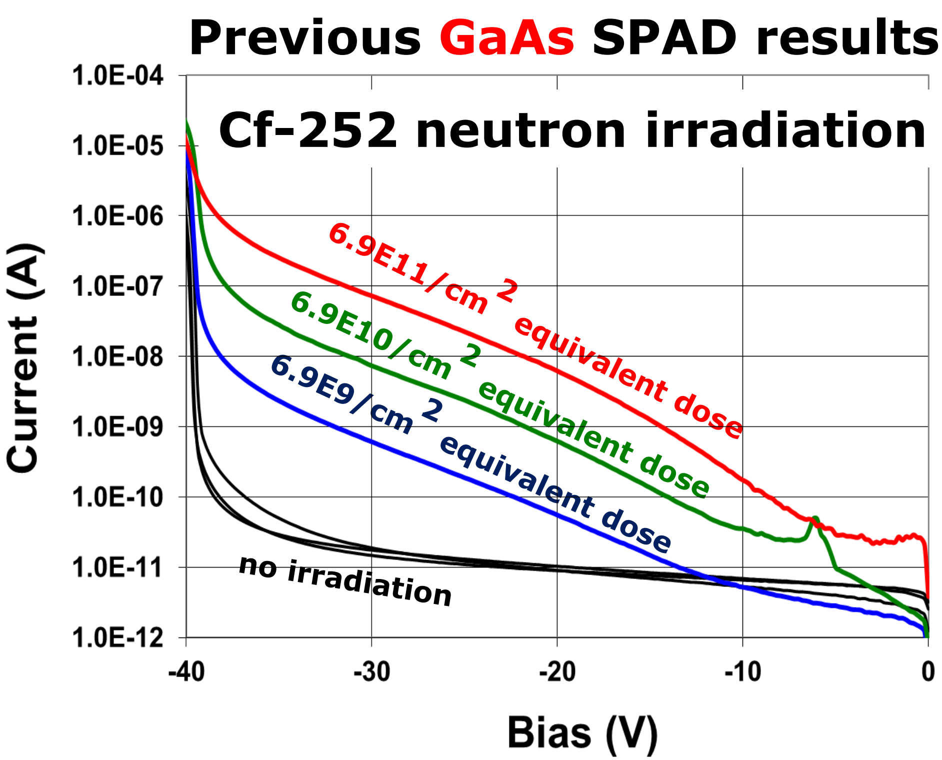
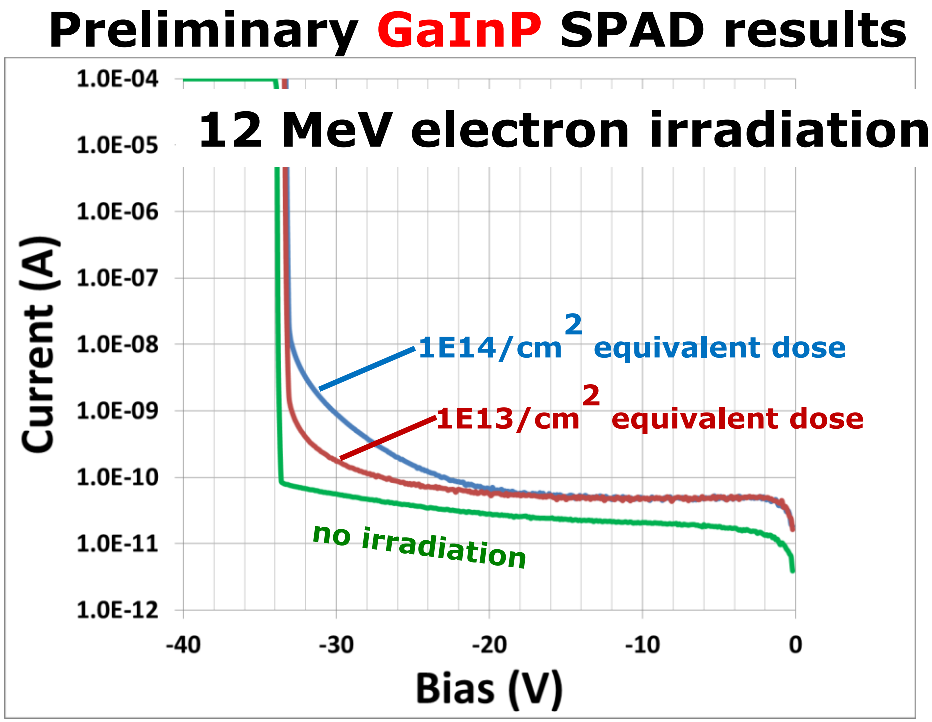
Preliminary Radiation Hardness





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Summary

- FOM: Dark count rate at 100% detection efficiency, 300K
  - DCR/DE gives the estimated dark count rate at 100% DE
  - Scale by n_i(300K) / n_i(T) to adjust for measurement temperature
- GaAs and GaInP Photomultiplier Chips™ projected to exhibit similar FOM to silicon
  - Measured devices are about 10X higher dark count rates
  - Demonstrated photon number resolving capability at 30% DE, 9 $Mcps/mm^2$
  - Demonstrated sub nanosecond rise/fall times with fast passive quenching
  - Wider band gap semiconductors have the potential to exhibit very low dark count rates and substantially improved radiation hardness

Next Generation GaInP