RMD

Solid-state Detectors

Instrument Research & Development

From CMOS APDs, GPDs and SSPMs to LAAPDs and PSAPDs

Radiation Monitoring Devices, Inc.

44 Hunt St.; Watertown, MA

James F. Christian, C.J. Stapels, E.B. Johnson, R. Sia, M. McClish, P. Dokhale, K.S. Shah, M.R. Squillante (RMD)

F. Augustine, P. Barton, & D. Wehe

Light 07: Workshop on the Latest Developments of Photon Detectors; Ringberg Castle, Tegernsee, Germany; Sept. 23-28, 2007

CMOS Detectors

optical photons, & scintillation

- CMOS APD Pixels
- CMOS GPD Pixels
- CMOS SSPM Detectors
- Applications:
  - Dosimeter-on-a-chip
  - PET

- ➢ APD: below breakdown – proportional
- ➢ GPD: above breakdown - Geiger
- ➢ CMOS Ubiquitous: basis of all digital ICs – integrated chips (readout)

CMOS APD Pixels

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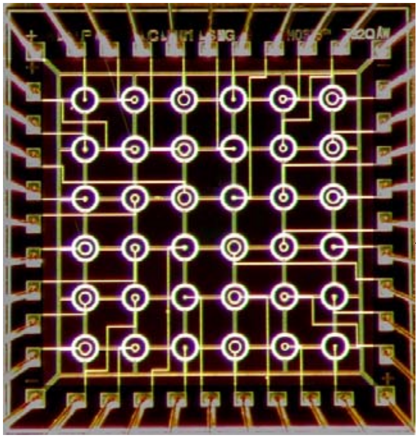
- Internal gain reduces readout noise contribution from integrated preamplifier

2.2 mm

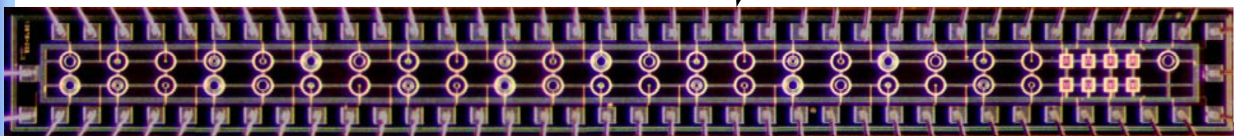


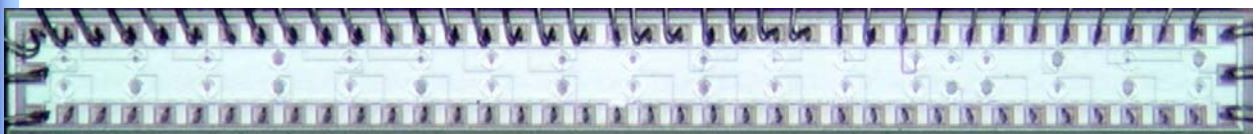
- Explore different CMOS technologies & different designs

AMIS CMOS Process

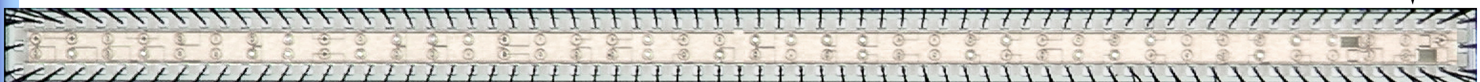
AMS CMOS Process

8mm x 0.6mm



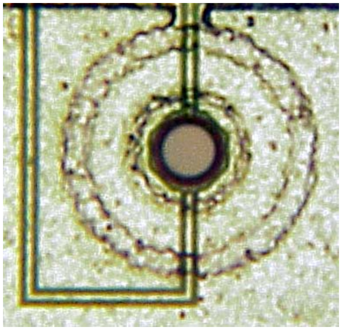


16mm x 0.6mm



CMOS APDs

Pixel Design 12



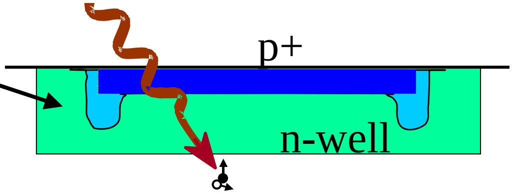
Performance

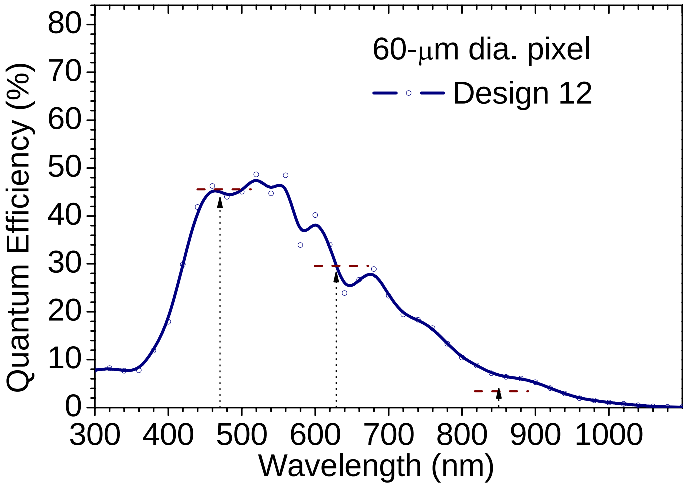
- Quantum Efficiency (QE)
- Gain & excess noise
- Uniformity (small pixel effect)
- Dark current and capacitance: 300μm x 300μm
  - Important for integrated preamplifier
    - 1.5 pA bulk, 0.15 pA Ohmic
    - ~20 pF

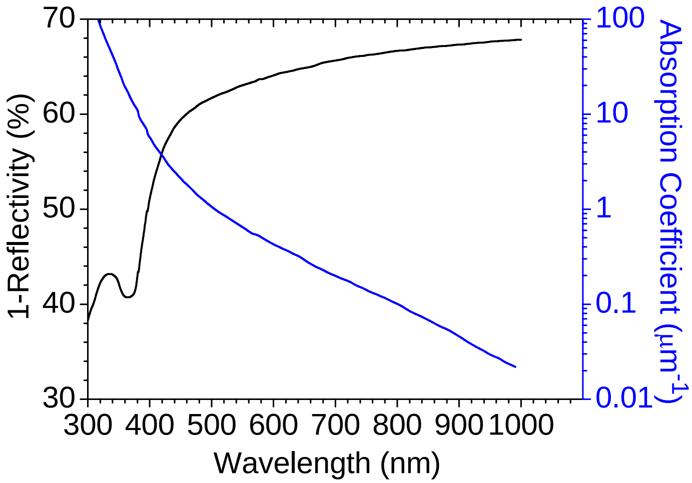
Pixel Design 12: Besse *et al.* (2003)
Stapels *et al.* (2006)

QE vs. Wavelength

CMOS Pixel:
(Design 12)







A.S. Grove 1967

- Good Spectral Response
  - Blue: Increased reflection and surface recombination
  - Red: Reduced absorption by thin pixel

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CMOS APD Characterization

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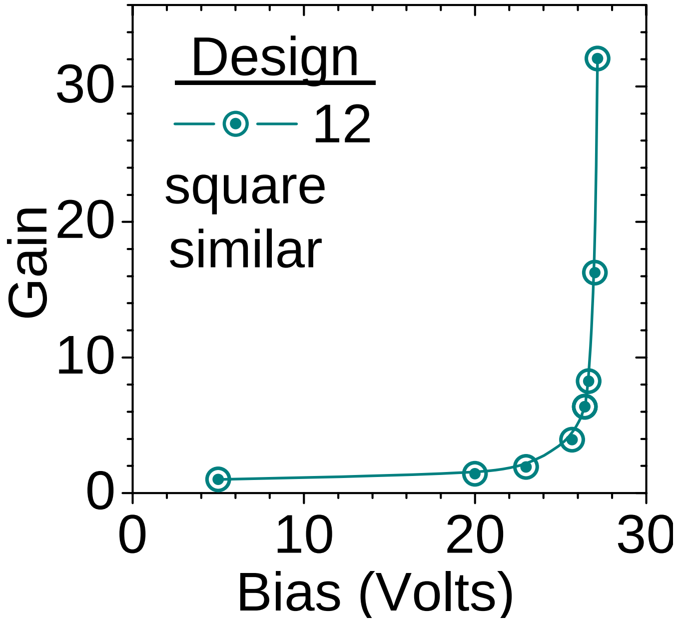
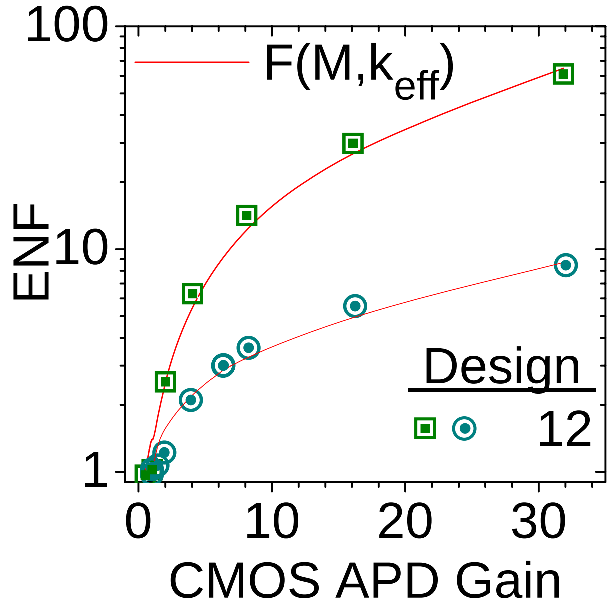
30-μm round & square CMOS APD pixels





$$F = k_{eff}\overline{G} + (1 - k_{eff})\left(2 - \frac{1}{\overline{G}}\right)$$

- Gains > 30 (632-nm photons)
- ENF of round better than square (small pixel, edge effect)
- k_{eff} = ~0.2

➢ Useful gain ~4

➢ Extracts signals from noise floor

CMOS APDs for SPECT Camera

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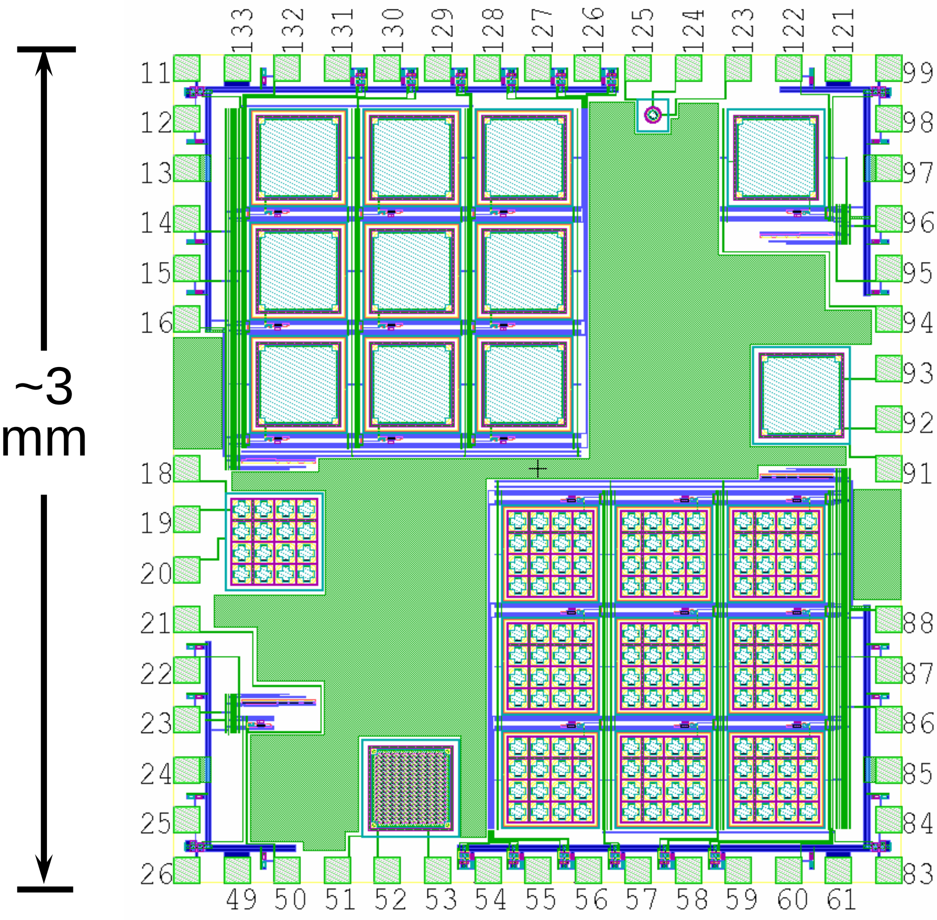
- Integrated preamplifiers for each pixel
- Better Performance from larger pixels:



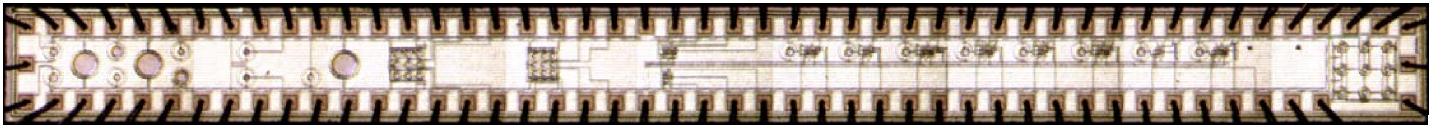
Less edge effects

300µm x 300µm pixels

Submitted Design

CMOS GPDs

Pixel Design 12



Pixel operated above breakdown

- Count (digitize) optical photons
- Geiger tube - Passive vs. Active Quenching

Performance

- Detection Efficiency
- Selection of Quenching resistor
- Dark Count Rate
- After Pulsing (multiplier in t – excess noise)
- Dynamic Range (improved w/ AQ)

GPD DE

(*Cova et al.*)

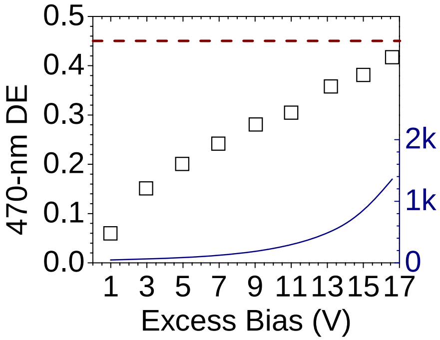
$$DE(\lambda, V_x) = QE(\lambda)\, P_g(V_x)$$

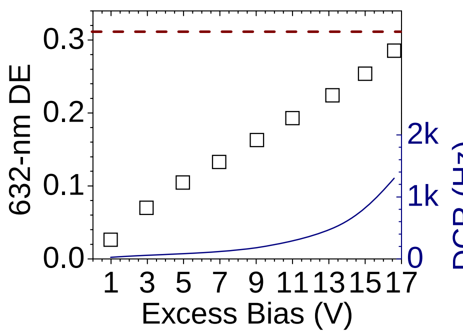
P_g – Geiger Probability,
V_x – Excess Bias

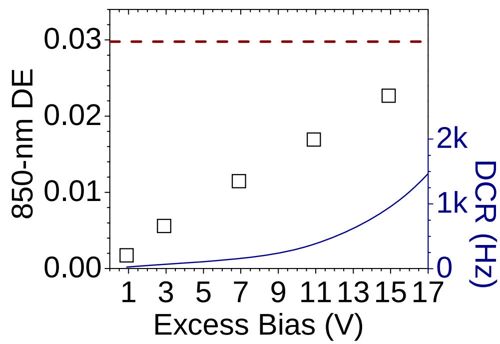
$$\langle DE \rangle = QE(\lambda) \times \int_0^{\Delta V_a} P_g(V_x) \times P_{V_x}\, dV_x$$

P_{Vx} – Excess Bias Distribution

Low count rate limit: $\langle V_x \rangle \sim V_x;\quad P_g \sim \alpha\, V_x$







$$\langle DE \rangle \sim QE(\lambda) \times \alpha \langle V_x \rangle$$

$\alpha \sim$ 5% per V excess

- High count rates: $\langle V_x \rangle < V_x$ “saturation effect”

Selection of Q Resistor

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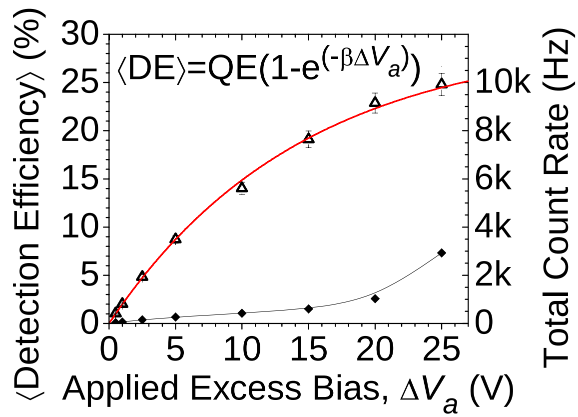
<u>Saturation Effects:</u> $\langle V_x \rangle \neq V_x$;

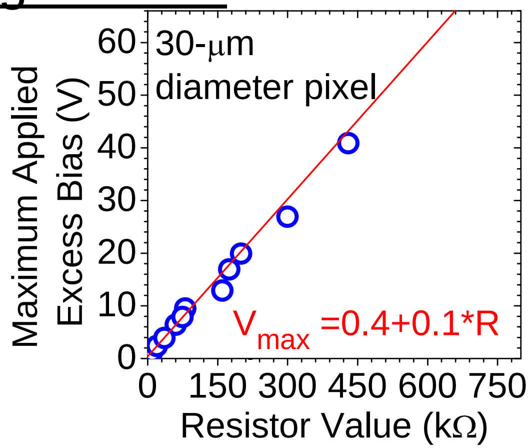
$$\langle DE \rangle \sim QE \times \alpha \left(1 - e^{-\frac{\beta \tau_{RC}(\Delta V_a)}{\tau_{cps}(\Delta V_a)}} \right)$$

- High Q-resistor→long recharge:
  - Count rate (thermal) affects $\langle DE \rangle$



<u>Passive quenching (PQ) failure at high biases</u>

- Low Q-resistor→Limit Max. Operating Bias
  - Limits Max operating bias & DE
  - Quenching time →∞
  - Smaller pixels, lower Vmax @ R-Quench, but faster recharge



- Best Q-resistor depends on count rate (DCR)
  - Valid for SSPM design

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Active Quenching

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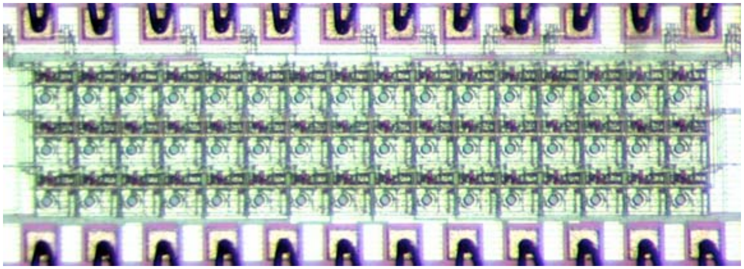
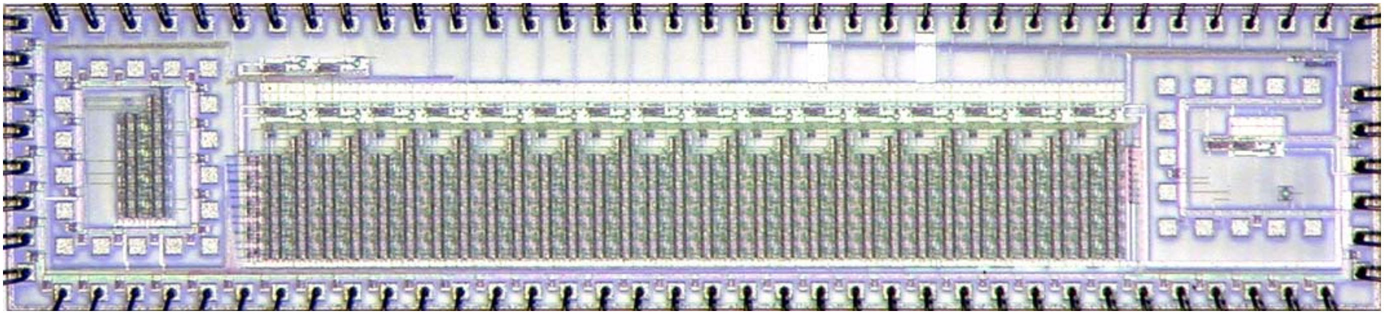
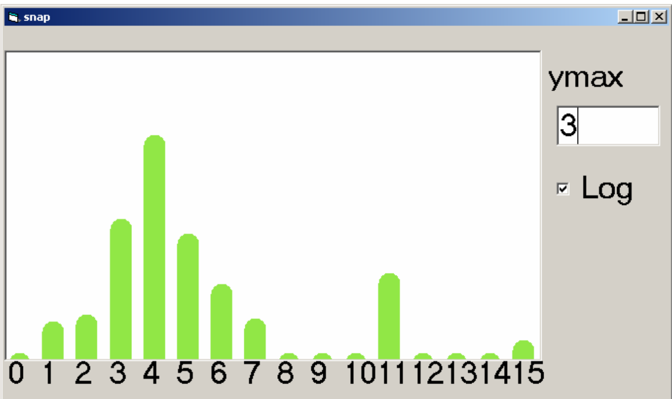


3x16 pixels, 30-μm dia. on 150-μm pitch





1x16, 30-μm dia. pixels, up/down counters & RAM

Real-time readout through USB

- Active Quenching improves performance, but trade-offs

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After Pulsing

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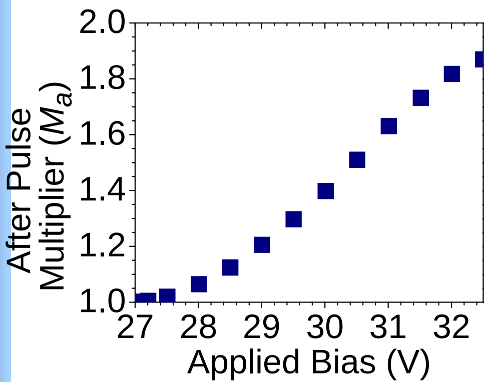
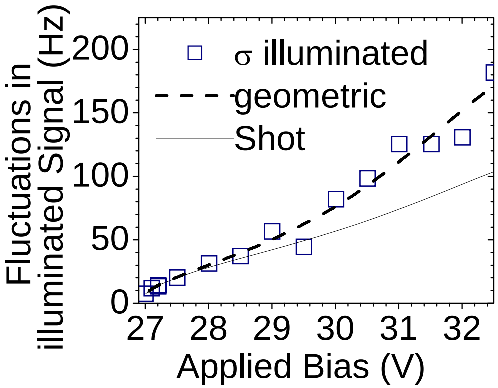
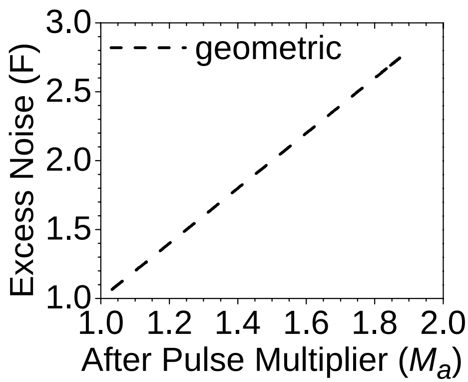
- Delayed release from traps charge → After pulsing
- Multiplier, M_a, ($\overline{n}_{ttl}$=M_a*$\overline{n}_d$) & Excess Noise, F (σ^2=F*I_{in})
- M_a depends on PQ configuration (no short-lived)







geometric (probability distribution):

$$\sigma^2 = M_a^2 \sigma_d^2 + \overline{n}_d \sigma_{Ma}^2 = \overline{n}_{ttl} \left(2M_a - 1\right)$$

- ➢ Easily calculate σ estimates from n_{ttl} and M_a
- ➢ After pulsing F on SNR: equiv. to decrease in DE by F
  - For same SNR, increase collection/integration time by F

CMOS SSPMs
Arrays of GPD Pixels

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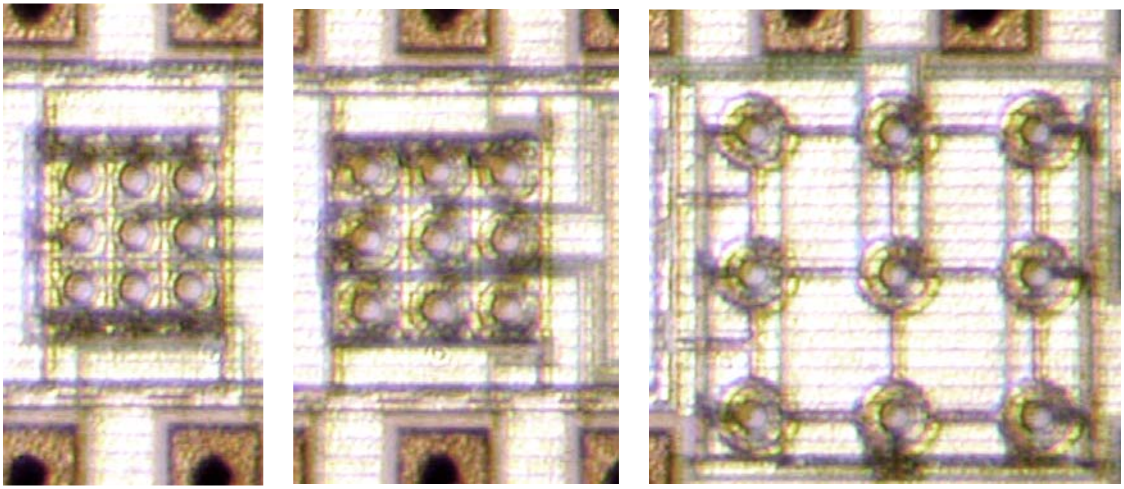
Performance

- DE = fill factor*DE_{GPD}
- Gain, & Dark (thermal) Count Rate (DCR)
- Temperature dependence of breakdown V
- Excess noise & Energy resolution
- Cross talk (optical) analogous to After Pulsing



30μm dia.

pitch:
60μm
80μm
150μm.

CMOS SSPM Prototype

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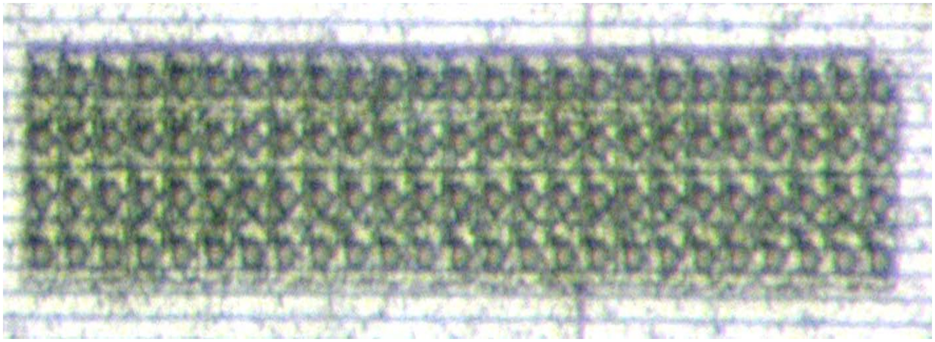
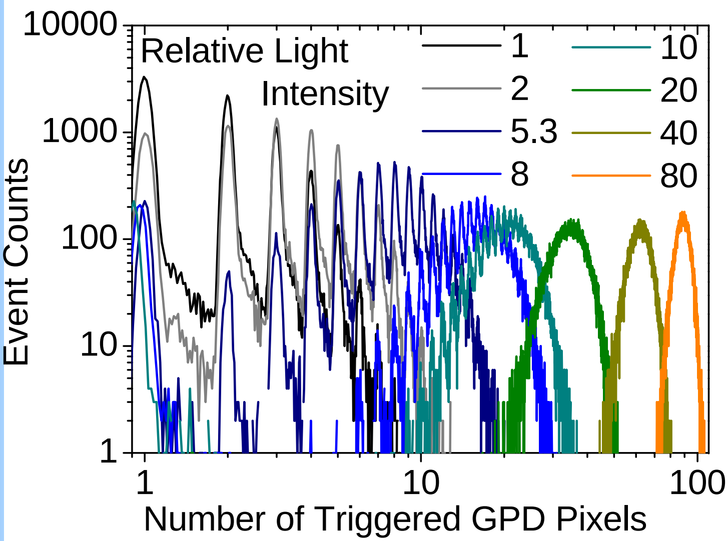
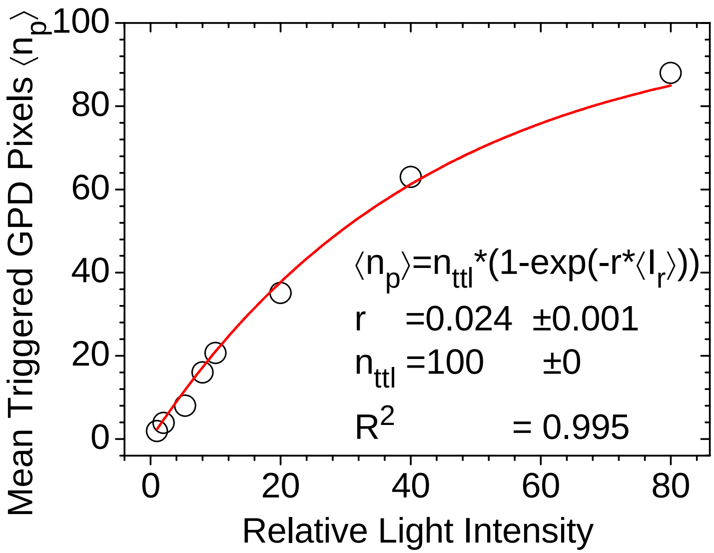


4 x 25, 20-µm dia. CMOS GPD pixel array, 43-µm pitch

- Signal from pulsed diode laser





- ➢ Increased intensity triggers more GPD pixels
- ➢ Energy calibration

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SSPM Performance Considerations

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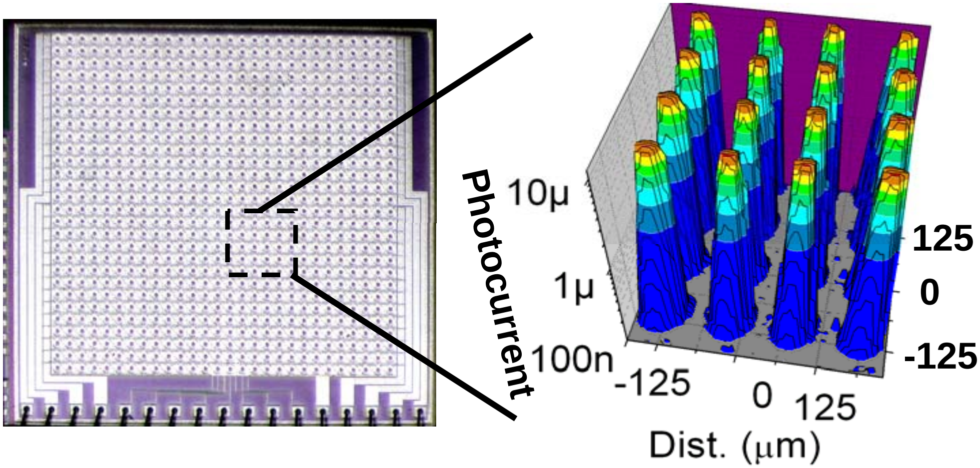

Early Prototype

- 28 x 28 (784) 30μm dia., SSPM quad.
- 7% fill factor (100μm pitch)

- Gain: $N_{pix} \times q = N_{pix} \times C_{jn} \times V_x$
- Dark Signal: $R_N = \dfrac{\exp(-\mu)\mu^N}{N!t}; \quad \mu = t \times \langle DCR \rangle$ uncorrelated
- Temperature Dependences:
  - Gain (fixed applied bias): $N_{pix} \times C_{jn} \times 0.025\text{V}/\,^\circ\text{C} \times \Delta\text{T}$
  - DE (fixed applied bias): QE $\times\ 0.05\text{V}^{-1} \times 0.025\text{V}/\,^\circ\text{C} \times \Delta\text{T}$
  - Pixel DCR: ~doubles every 8° C (small affect on R_N)

➢ T-dependence of Gain largest

- Control applied bias for constant V_x

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High-Density SSPM

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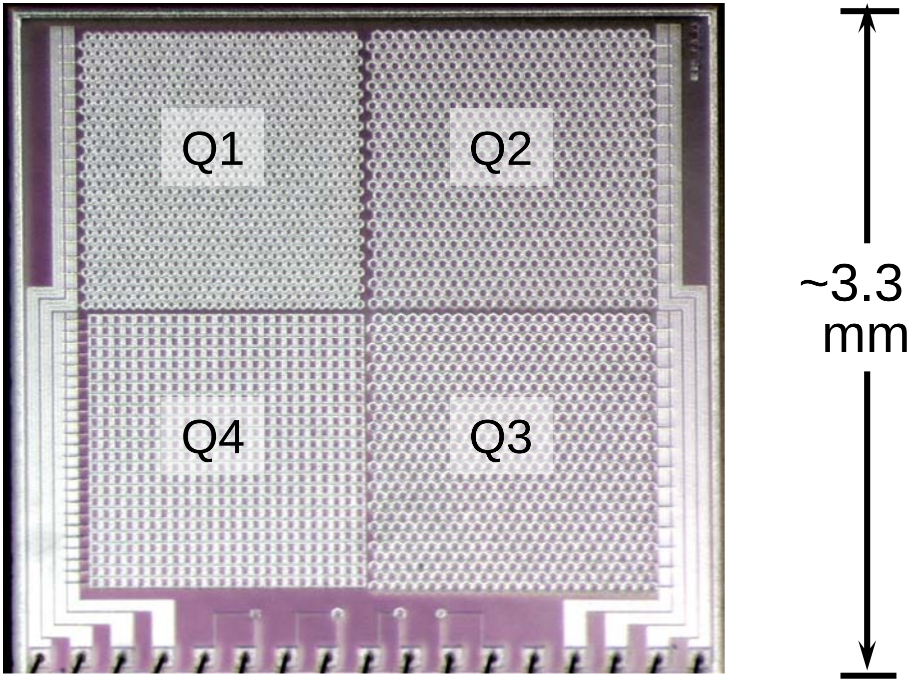
<u>Q1: Type 12</u>
Fill Factor = 19%
1020 pixels

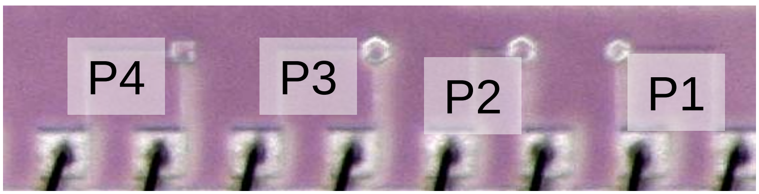
<u>Q2: Type 12</u>
Fill Factor = 29%
700 pixels

<u>Q3: Type 4</u>
Fill Factor = 29%
700 pixels

<u>Q4: Type 12</u>
Fill Factor = 29%
576 pixels

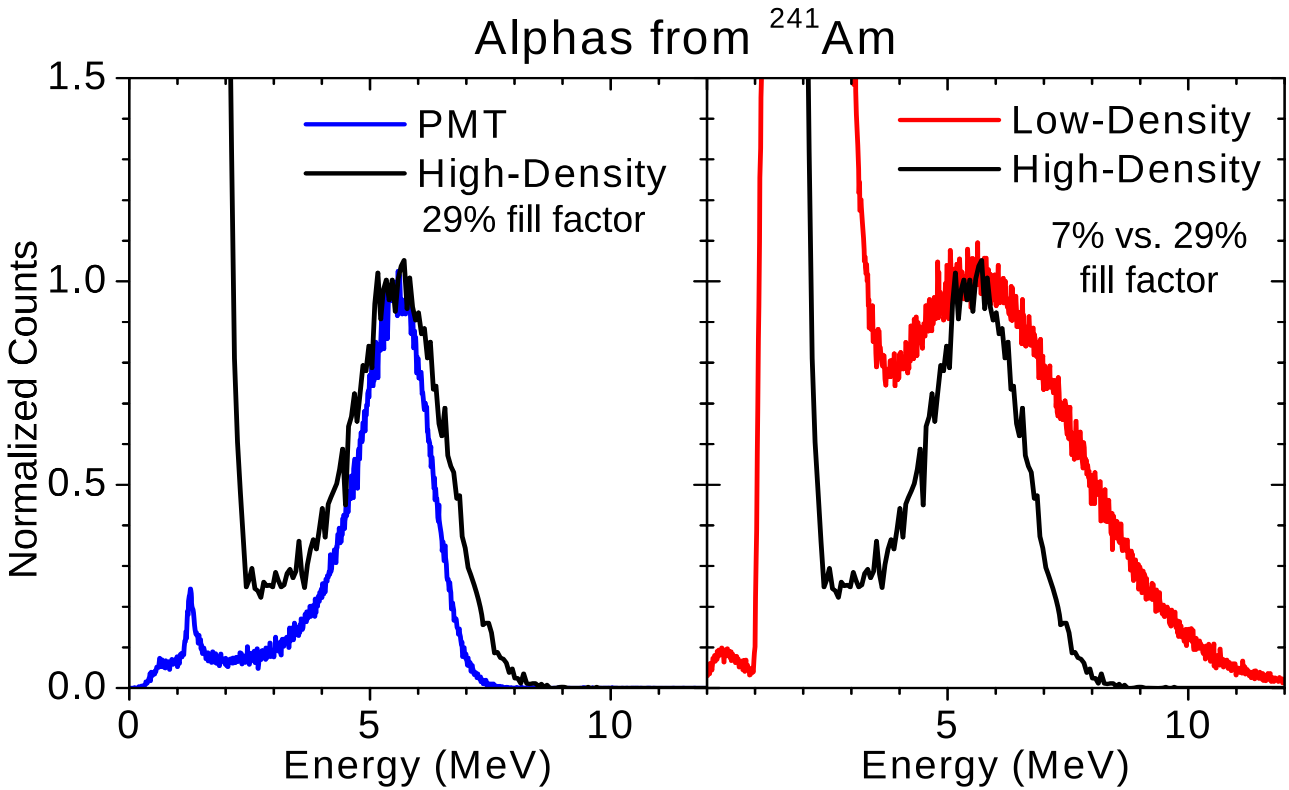


- P1: Q1 pixels (12) P2: Q2 pixels (12)
- P3: Q3 pixels (4) P4: Hyper-dense square pixel (12)



- ➢ Better fill factor, better SSPM DE

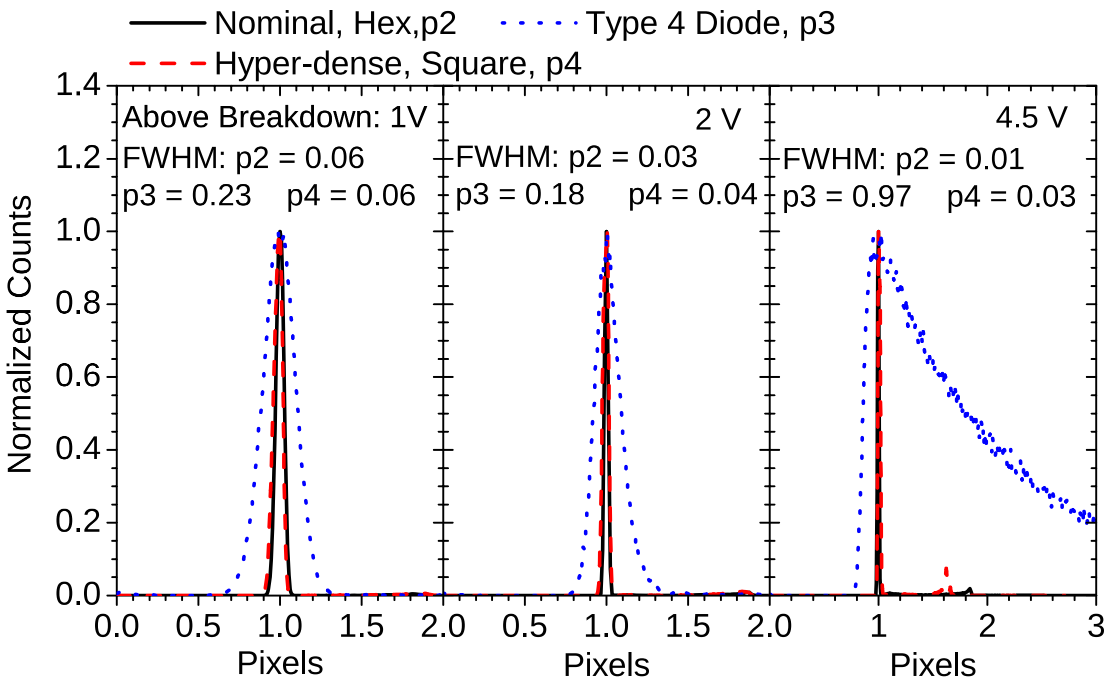
Energy Resolution



- Alpha particles illuminating plastic scintillator (bc430)
- SSPM DE (& fill factor) limit energy resolution
- Equivalent performance to PMTs.

SSPM Excess Noise

& selection of operating bias

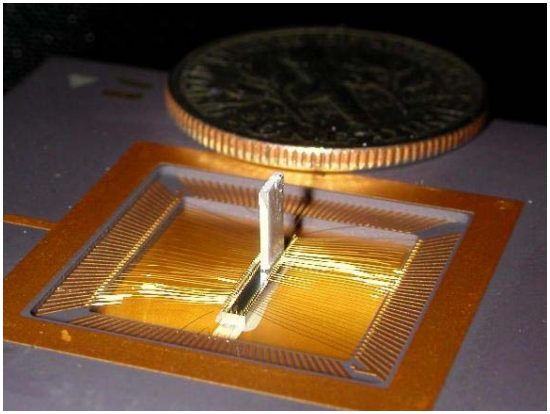


$$\left(\frac{\sigma_E}{E}\right) \approx \sqrt{\frac{F}{N} + \sigma_{scint}^2} \approx \sqrt{\frac{F}{DE \times N_{photons}} + \sigma_{scint}^2}$$

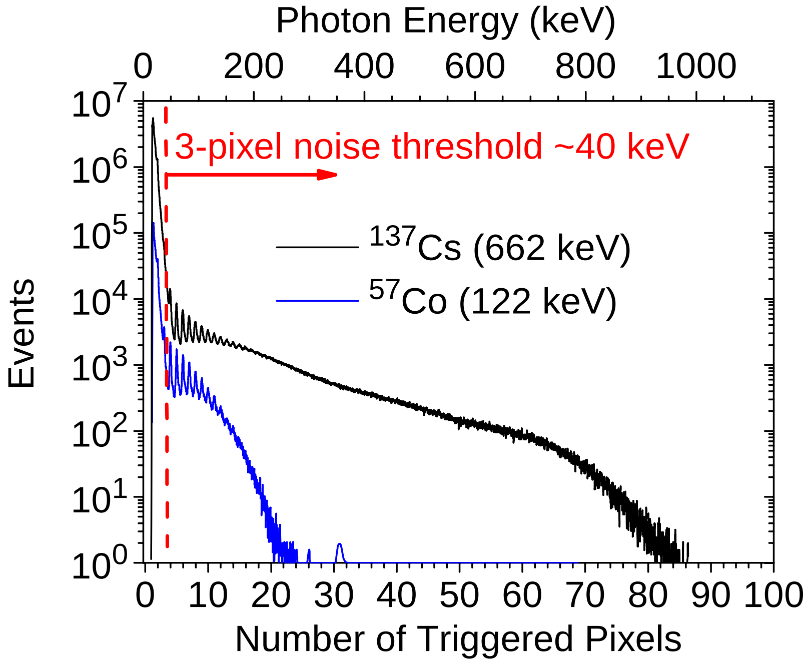
- Number of triggered pixels often dominates σ_E
- SSPM excess noise:
  - F = $\sigma_{pixel}^2 + 1$
  - F >2 to appreciably affect σ_E

σ_{pixel} = single pixel resolution
σ_{scint} = scintillator resolution

CMOS SSPM Prototype Dosimeter



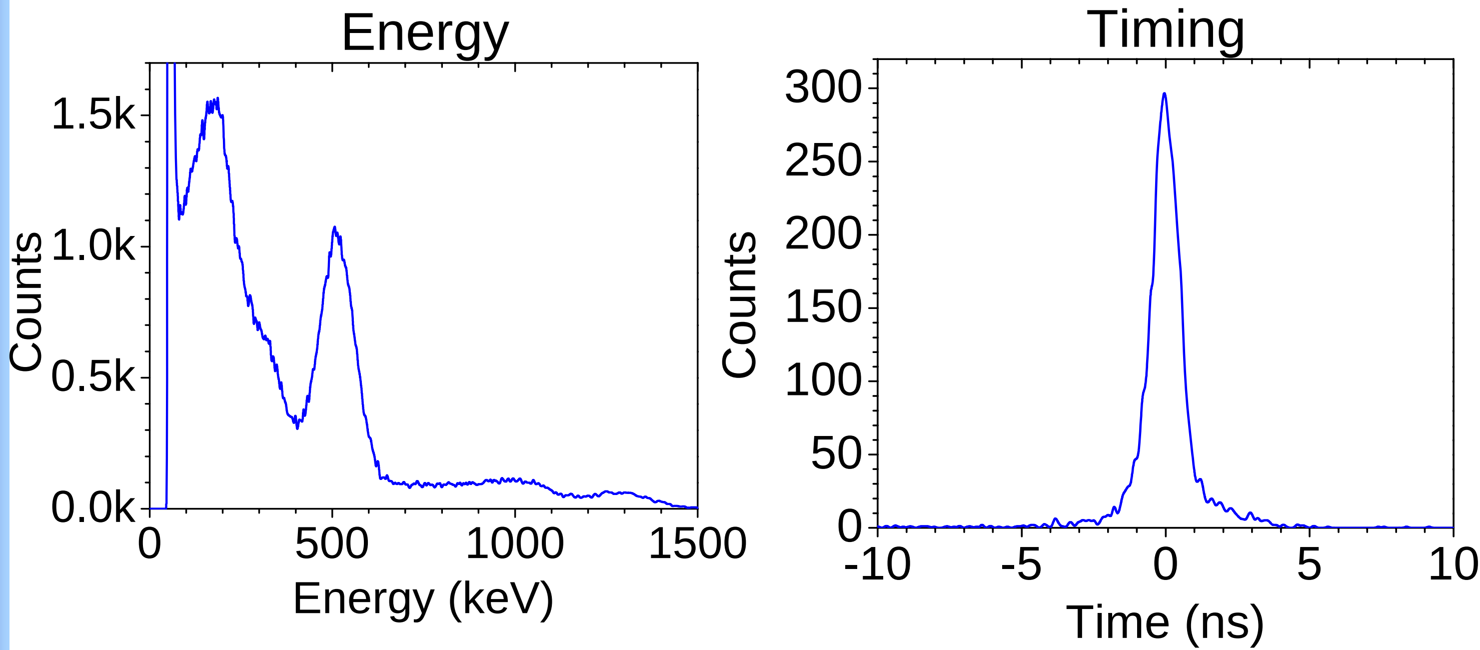
- 100-pixel SSPM & LSO crystal



- Easily differentiates between low & high-energy events
- Low optical coupling combined with DE and fill factor is sampling the tail of the energy spectrum
- Small LSO crystal

CMOS SSPMs for PET

1.5mmx1.5mmx3mm LYSO crystal
on quad-2 of high-density SSPM



- Energy resolution at 511keV ~16%
- Coincidence timing ~0.9 ns
- Promising: 1.5mmx1.5mm SSPM cells

The End

- Compact photodetector for dosimeter
- Neutron Detection & γ-ray Spectroscopy
- Arrays for imaging:
  - Position-sensitive SSPMs
- Integrated Active Quenching & Digital readouts

➢ DE & F useful for optimizing performance

Acknowledgements: NASA, DTRA, DOE, & NIH