Photon imaging with monolithic CMOS SPADs

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Purpose

Why a 2D array of monolithic SPADs?

Mainly for applications requiring precise information of the time of arrival of the photon. e.g.

- Photon counting
- Coincidence detection
- Time Of Flight imaging, distance ranging, approach, docking
- Fluorescence decay
- Spectroscopy
- X-ray, gamma, HE particle detection

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Purpose

Our specific goal

- to explore tunability of performance parameters
  - QE(Quantum Efficiency)
  - DCR(Dark Count Rate)
  - After pulsing time
  - In std 0.18µm technology

Outline

- Introduction: The SPAD principle
- Layout of SPAD and SPAD arrays
- Measurement results
- Conclusions

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The SPAD principle

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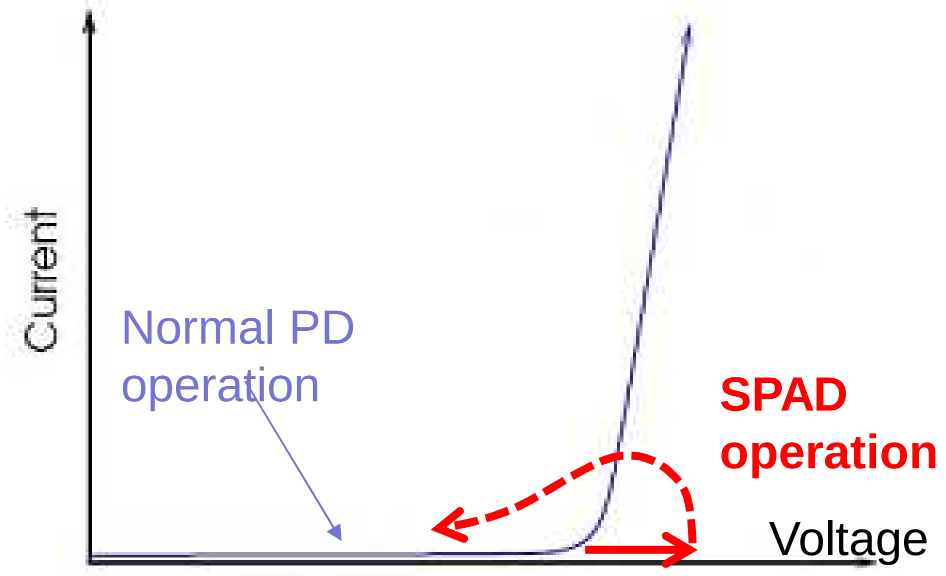
SPAD or “Geiger-Mode” APD

– Operating point beyond breakdown voltage



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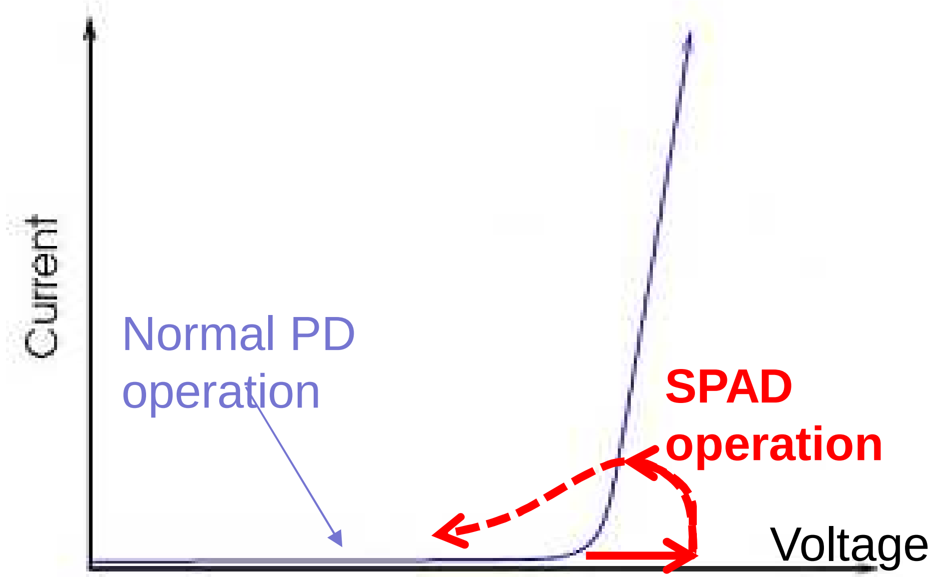
SPAD background

- Recharge (Reset):
  - Voltage beyond the breakdown value is applied and stays there until...
- Sense:
  - An electron (due to photon/dark current) causes breakdown and hence a huge current.
  - The drop in voltage is sensed with appropriate analog circuitry.
- Discharge (Quench)
  - Residual charges are drained out completely.



SPAD background

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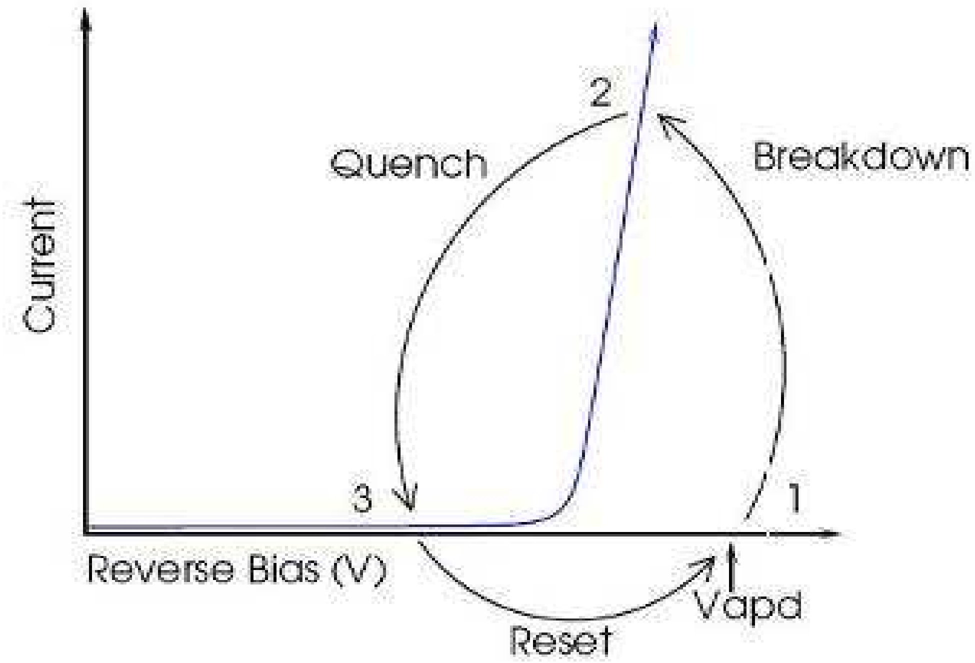
Summary



SPAD circuitry

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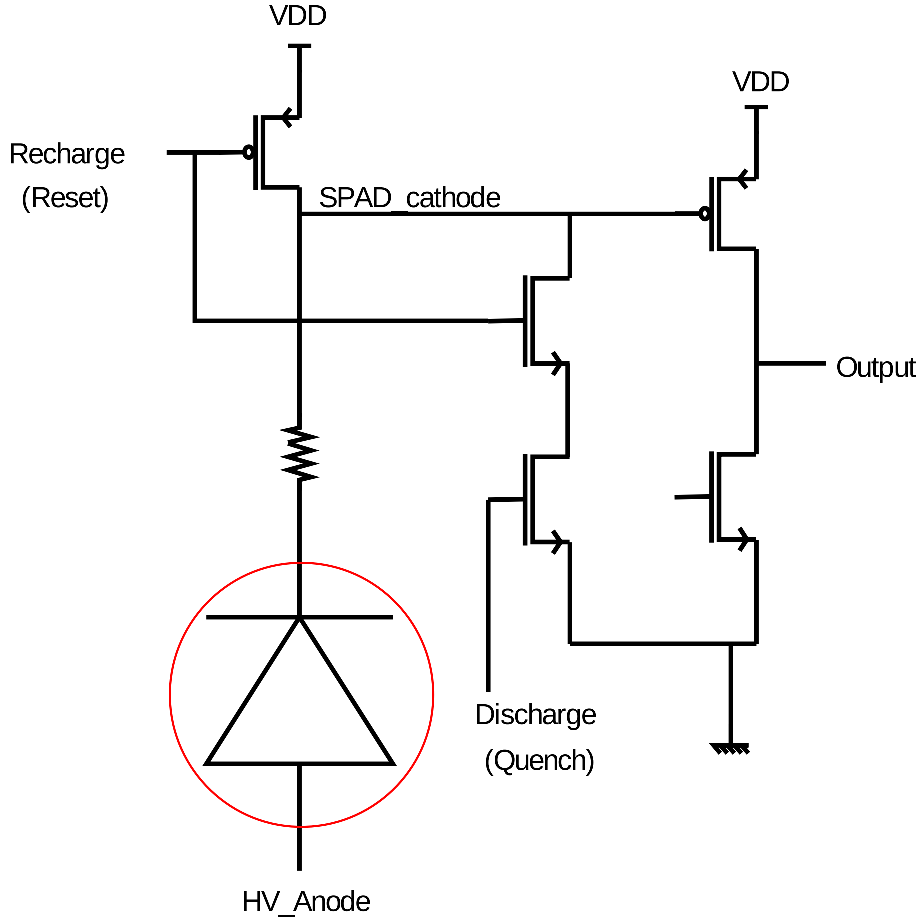

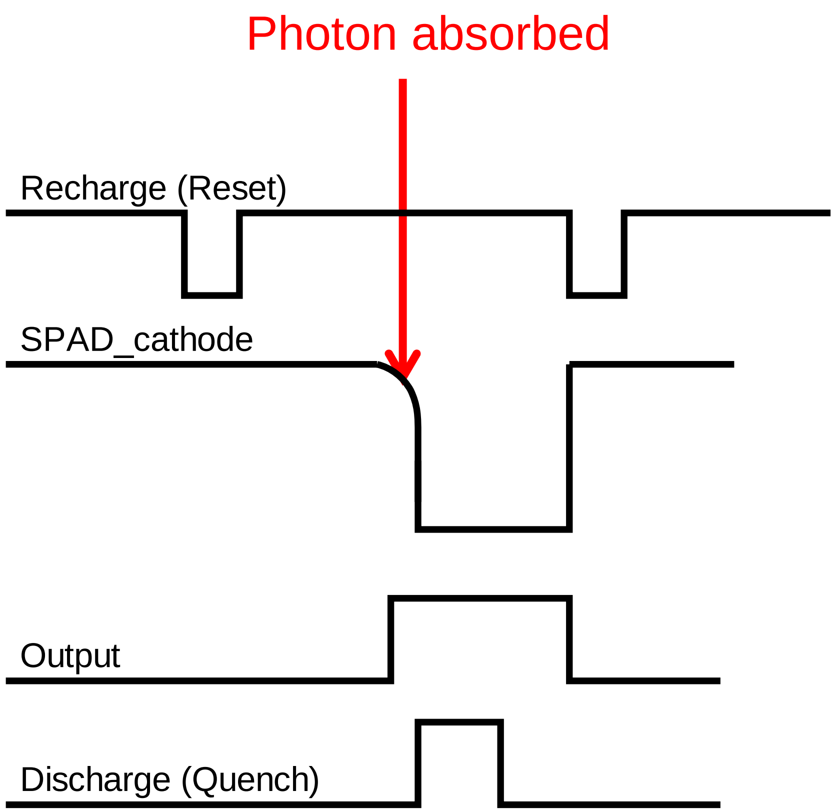

Outline

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- **Layout of SPAD and SPAD arrays**
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SPAD LAYOUT

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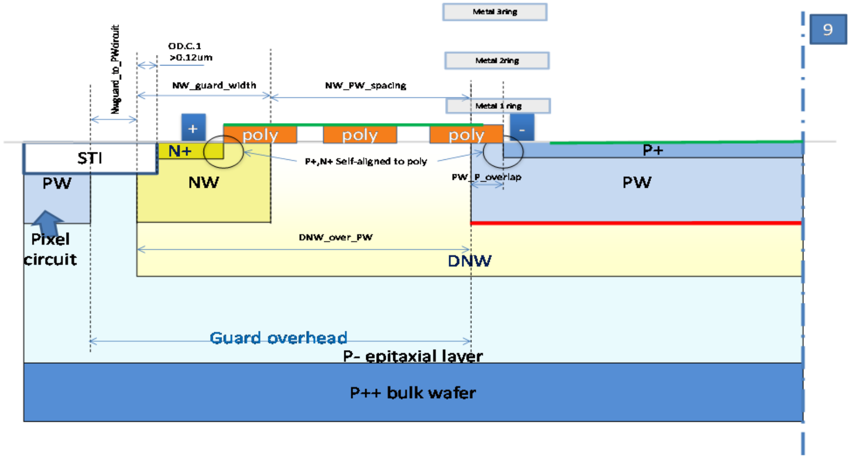
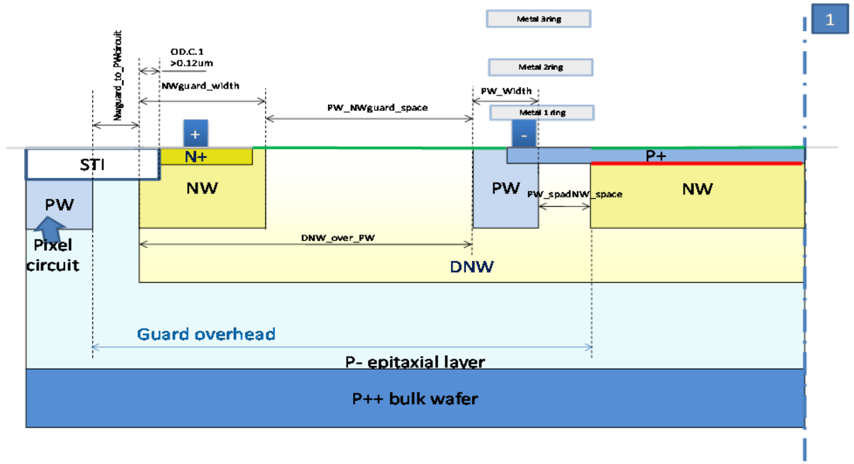
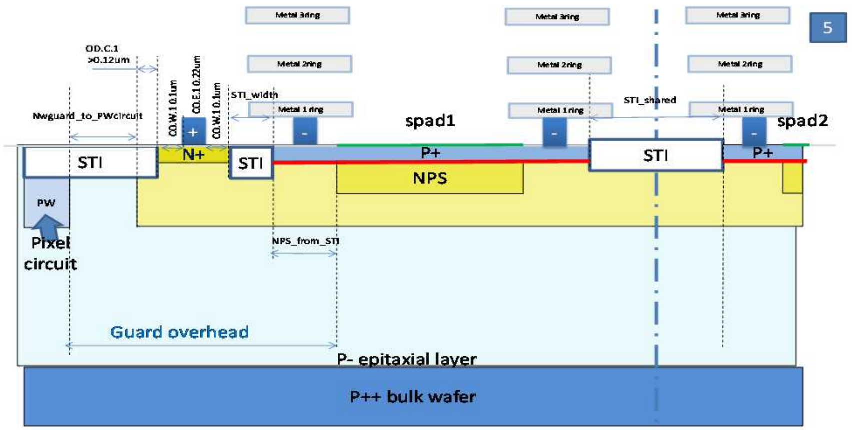
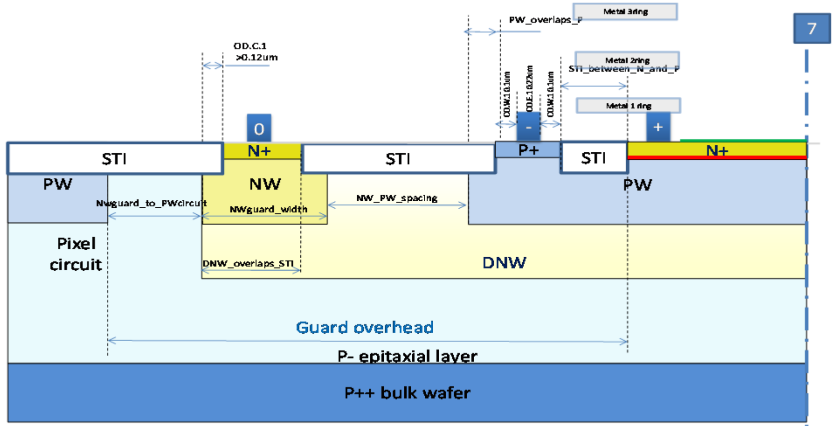
- **SPAD topologies**
  - How to use available layers in the CMOS process to create SPADs and their guard rings
- **SPAD array**
  - Create a complete 32x32 SPAD pixel image sensor
- **SPAD pixel layout**
  - Geometry, spacing, combination with in-pixel logic
- **SPAD variants**
  - 7 different topologies, 5 different guarding types, sharing or not sharing guards, cathode or anode readout, dimensions
  - In total 120 variants

SPAD topologies

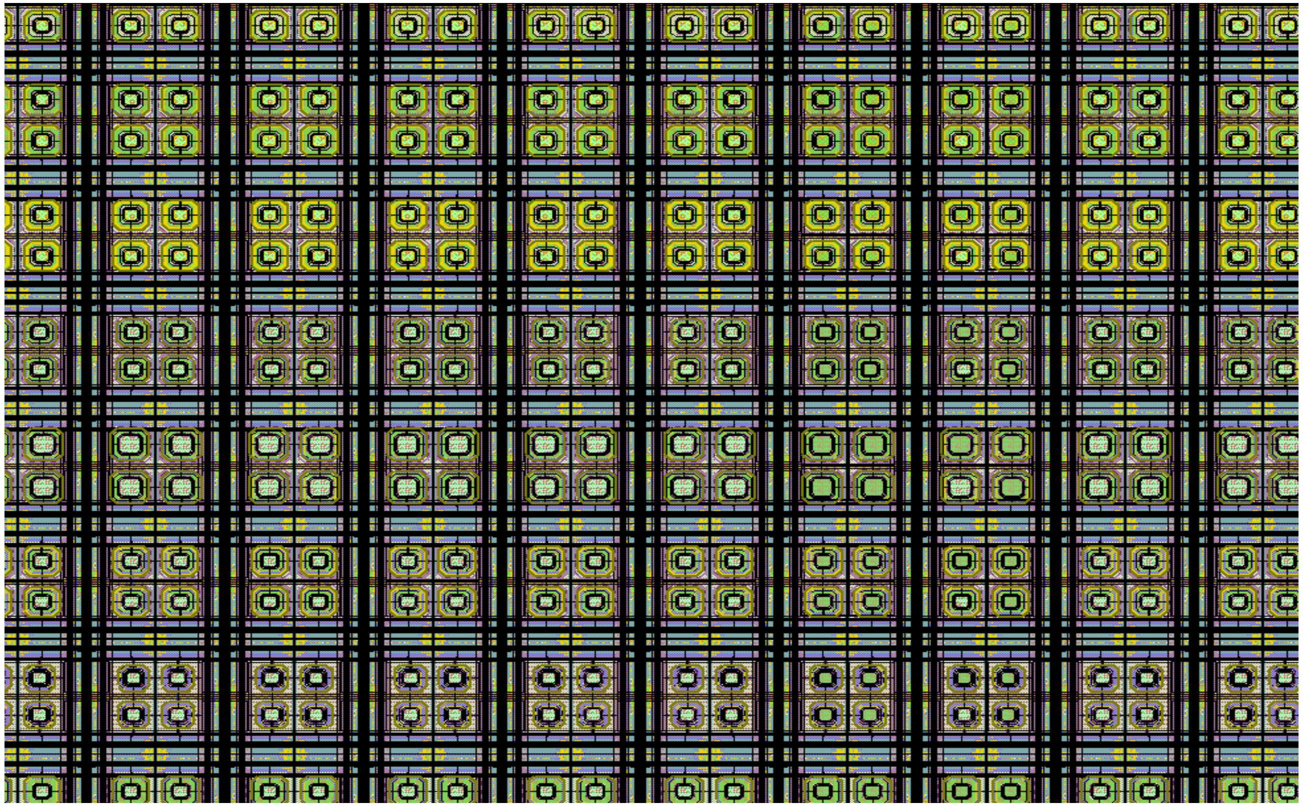








SPAD array



SPAD array prototype

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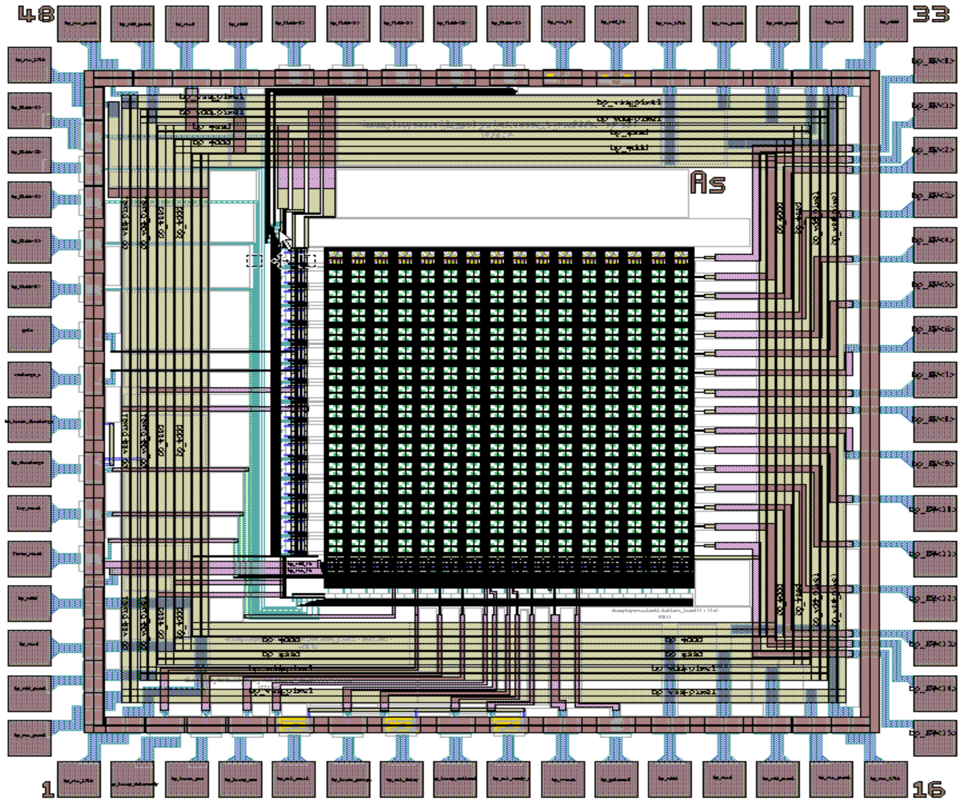
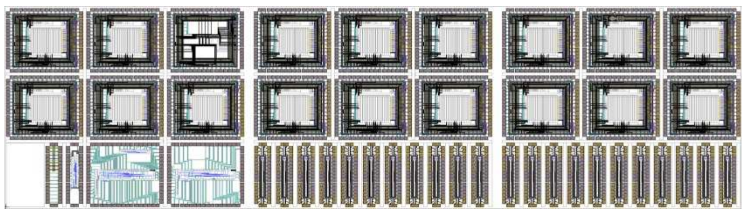
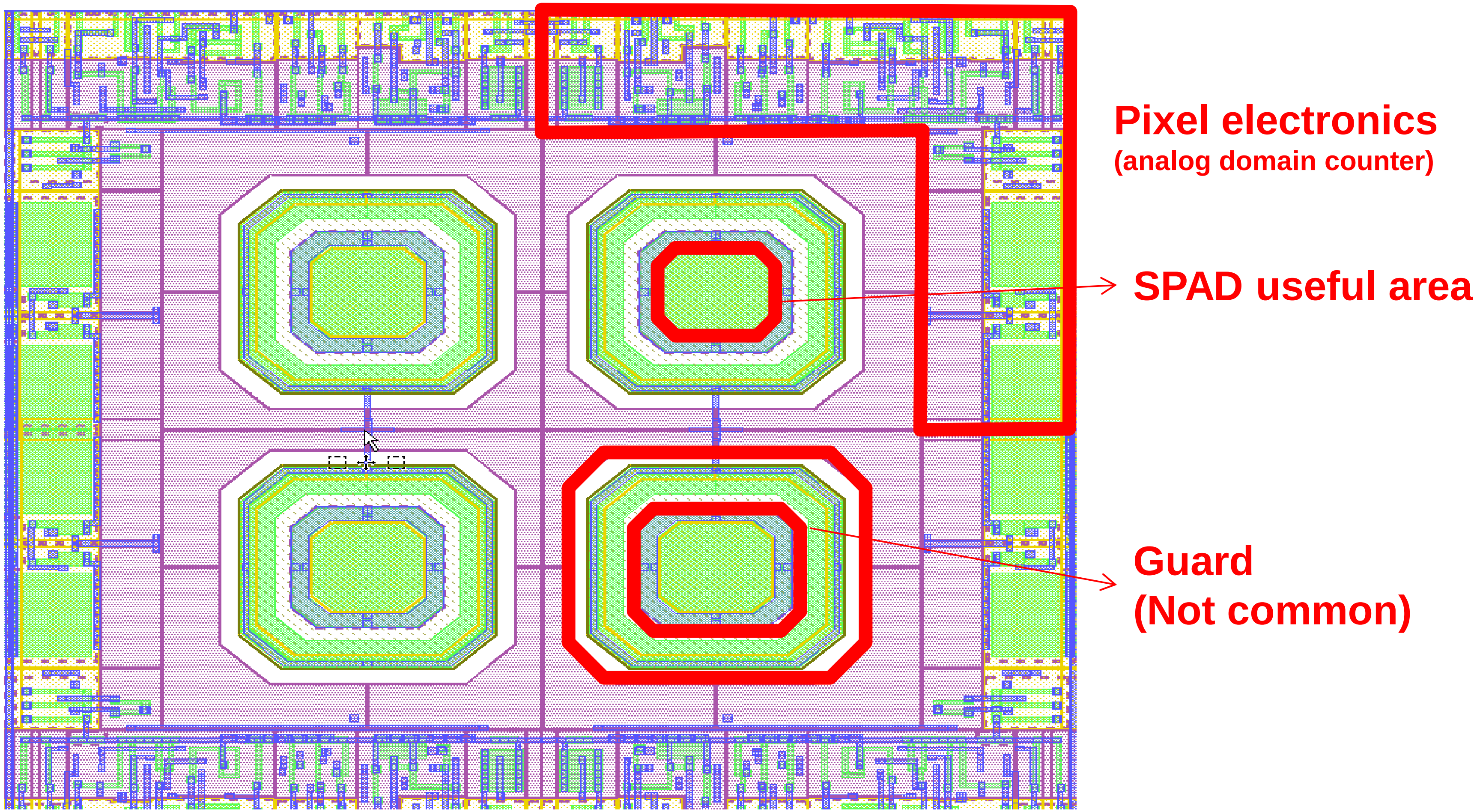


- 32x32 pixels
- 16 types (variants) per such array (frame) organized per 2 rows.
- Each 2 rows of SPADs can be independently biased
- In-pixel circuitry: reset, quench, analog domain counter, analog output, application specific operators.
- 17 such arrays ("frames") are designed with different variants pixels



SPAD 2x2 pixel layout



Layout Variants

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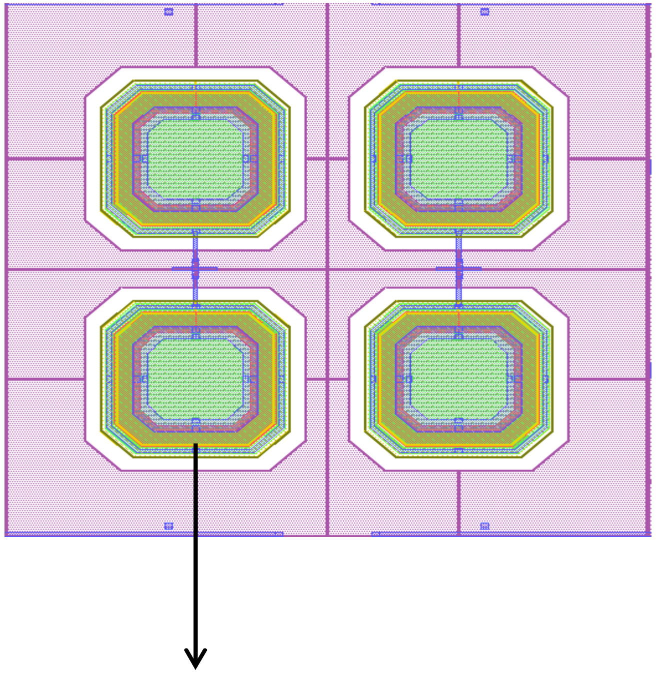
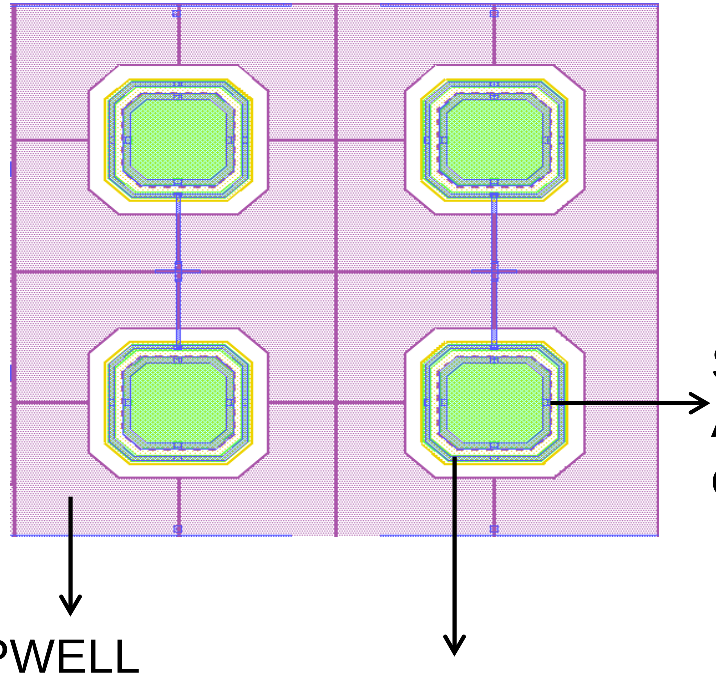
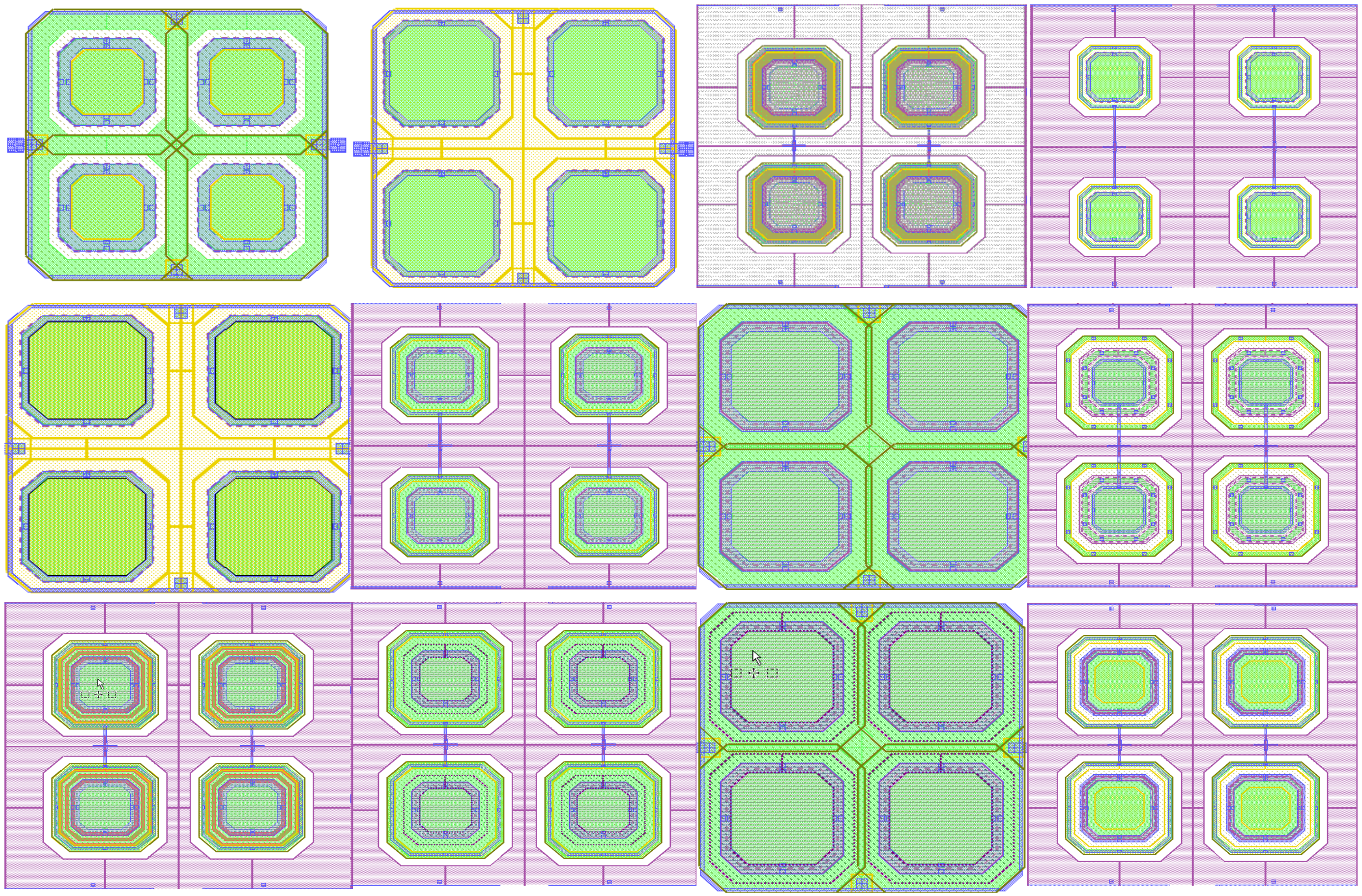




Other SPAD Variants



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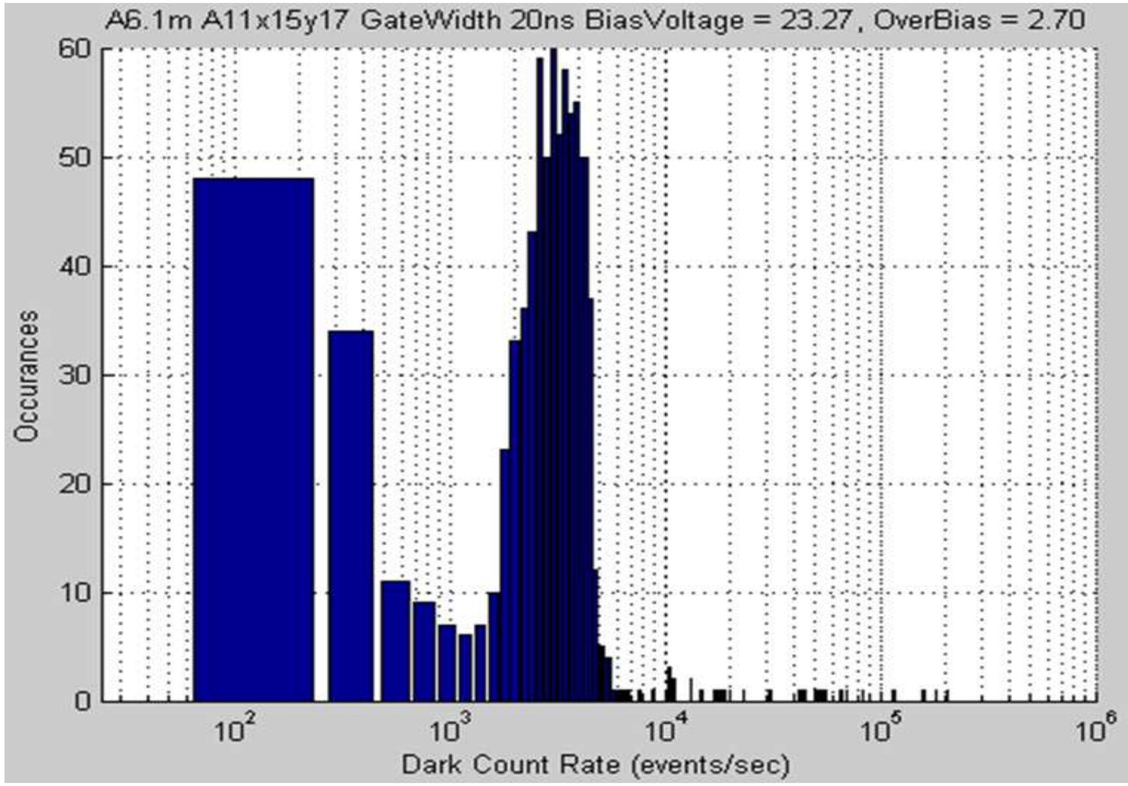
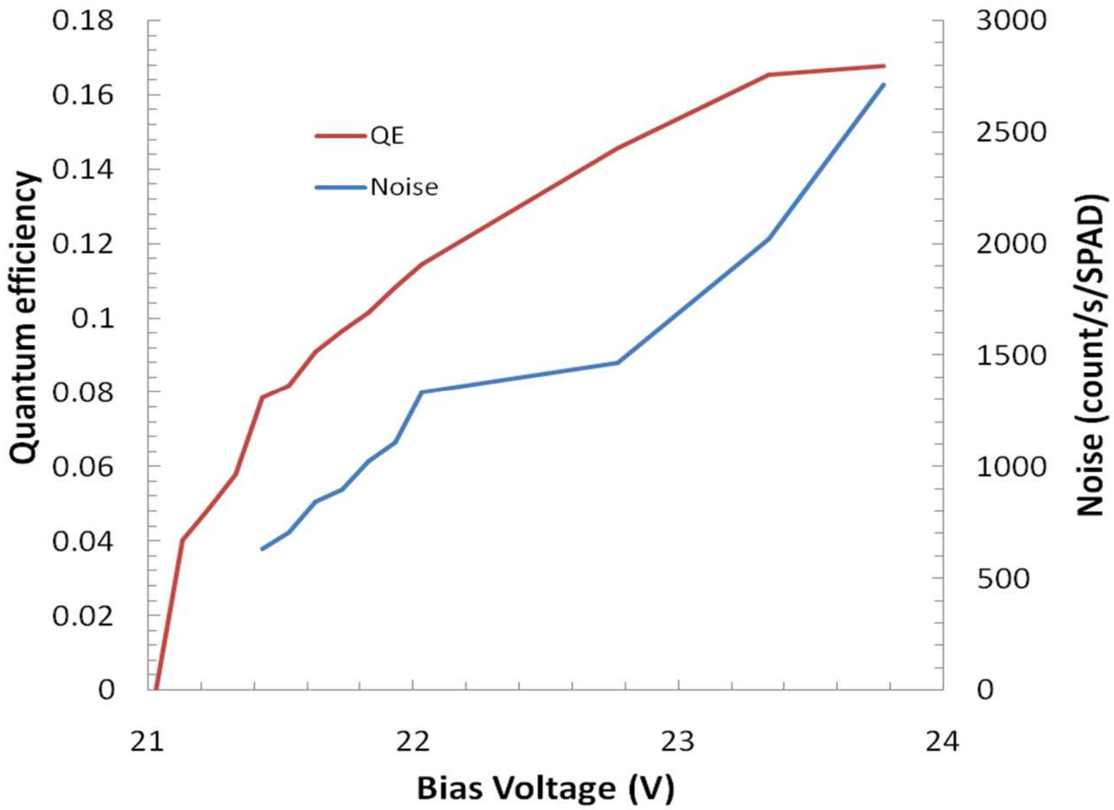
Measurement results Dark Count Rate (DCR)



QE measurement I:

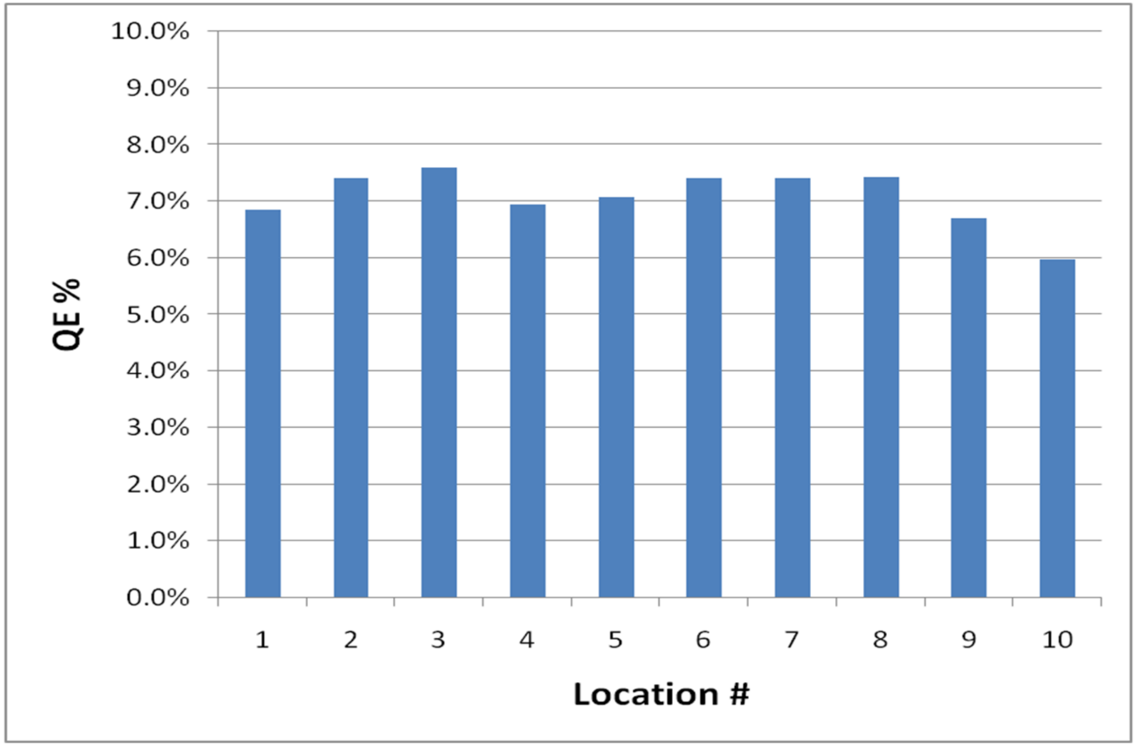
Cathode connected SPAD

- **Threshold voltage: 21.1 V**
- **Over bias up to 2.74 V in the measurement**
- **Max QE is >16%**
- **Noise = dark count rate**
- **660 nm laser**



QE at different locations

10 same pixels in the frame



QE mean = 6.7%
QE STDEV = 0.49%

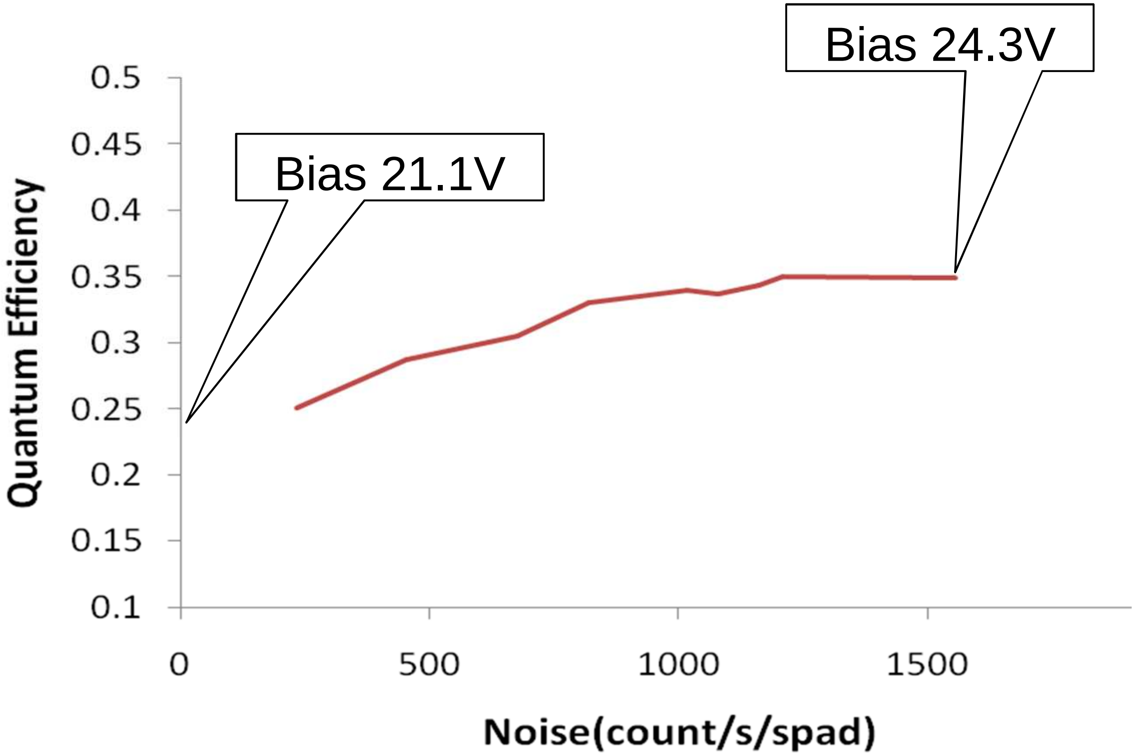
The variation is quite low:
STDEV/mean = 6.8%

Bias Voltage 21.43 V
(Threshold voltage 21.1 V)

QE measurement II:

Anode connected deep-junction SPAD

- **Threshold voltage: 21.1 V**
- **Over bias up to 3.2 V in the measurement**
- **Max QE is 34.9%**
- **Noise = dark count rate**
- **660 nm laser**



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conclusions

- **Photon Conversion Efficiency (~QE)**
  - deep junctions, not shallow
  - Deep well, deep and low doped epi layers
- **Within the constraints of the CMOS technology**
  - design rules, available layers and implants
- **It is possible to tune SPADs for a wide range of specifications using a standard CMOS technology**
- **It is found that available layers in the CMOS process can be used far outside their electrical specs.**

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Thank you