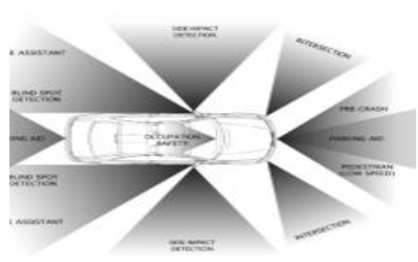
2020 Research Day

System architecture and analysis of monolithic 3D-LiDAR based on CMOS Si Photomultiplier



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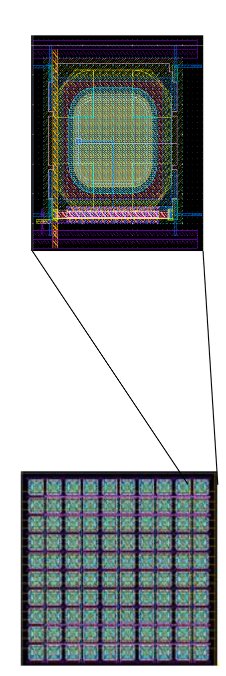
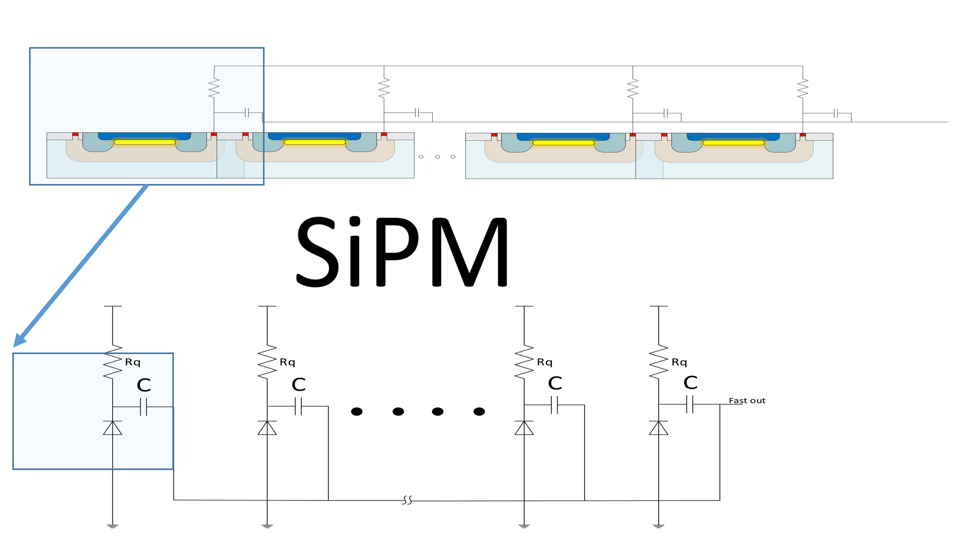
Research Motivation

- Photography is undergoing a paradigm shift to 3D Imaging
- Current 3D imaging approaches suffer from many draw-backs
- Novel devices and circuit designs implemented in CMOS technology are required to make 3D imaging a common-day reality
- Novel CMOS SPADs (Single Photon Avalanche Diode) arrays integrated into Si-Photomultipliers (SiPM) offer new opportunities by combining unprecedented performance in terms of photon counting as well as photon timing
- The key to a breakthrough in 3D imaging is understanding the physics of CMOS devices and the electro-optical requirements as well as ability to propose novel CMOS mixed design circuit implementation of new concepts
- The combination of new CMOS mixed circuit design architecture, CMOS physics and Electro-optics is where our strength, interest and unique capabilities can be best expressed

SiPM - Si Photomultiplier

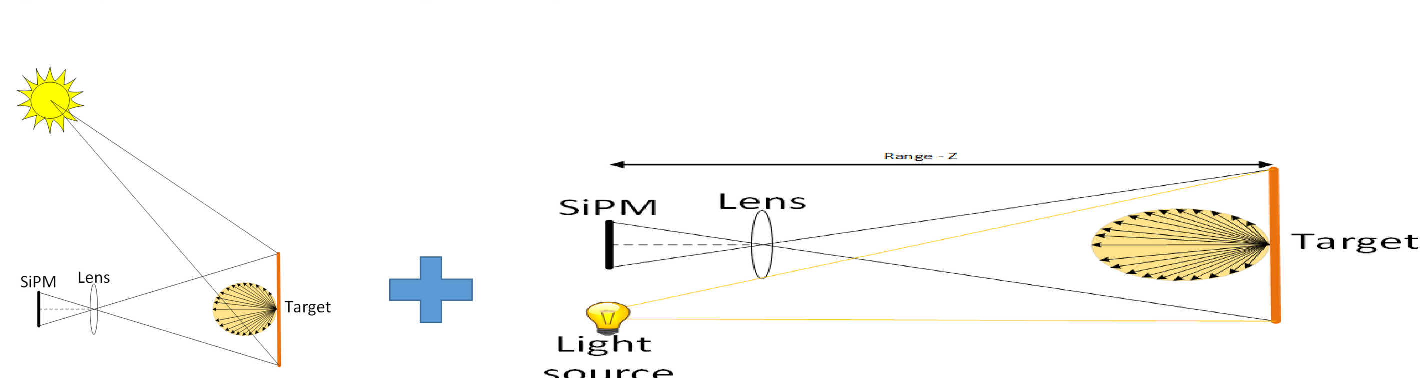
- Array of mosaic sub-pixels SPADs electrically connected in parallel but responding individually at the speed of a single sub-pixel
- Each sub-pixel includes only a SPAD and quenching resistor
- Allows scaling down of sub-pixels
- Mixed design external output circuitry allows high fill factor
- Measures packets of photons – not limited by dead-time
- Allows simultaneously photons counting/photon timing
- The most sensitive as well as fast solid state sensor





The limitation of Time-of-Flight

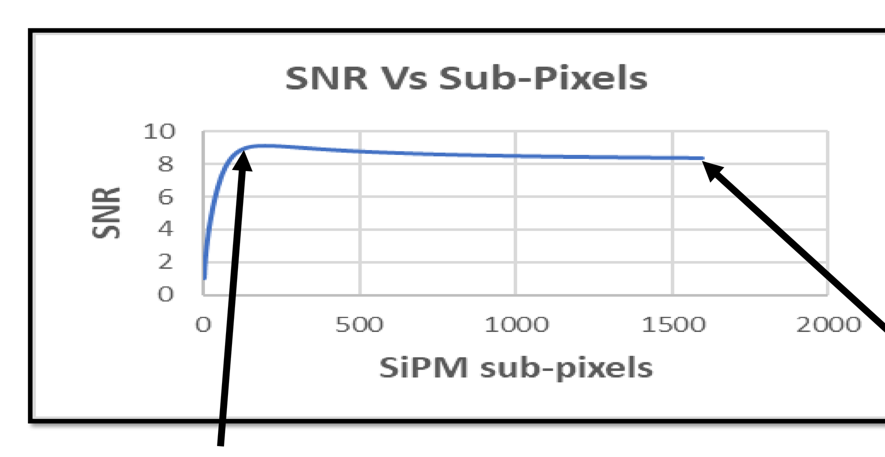
- The reflected radiation of the sun from the target provides background radiation
- Background photons contributed by the sun are just like signal photons, but are unwanted signals
- Since the background photon flux is typically high, $\sim 10^{12}[\mathrm{ph}/sec]$, even with the narrow band filter operating at an optimal wavelength, the signal and background fluxes are typically of the same order of magnitude
- The detector readout signal is a train of randomly distributed pulses corresponding to the detection of individual photons
- A signal photon and a background photon cannot be differentiated



How many SiPM sub-pixels are required?

- **In order to detect n random photons simultaneously, how many sub-pixels of SPADS are required?**
- **<u>This is a key issue not reported before</u>**
- We evaluate the exact probability density for detection of a packet of random $\boldsymbol{n}$ photons, obeying Poisson Statistics, with a SiPM with $\boldsymbol{m}$ sub-pixels (of SPADs)

OPTIMIZING THE DESIGN OF SiPM ILLUSTRATED FOR ~700 PHOTONS



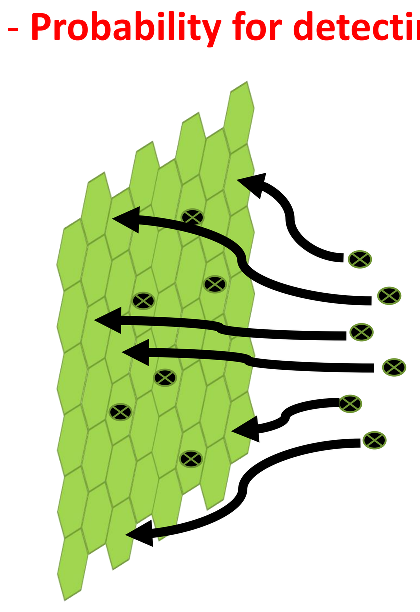
$$\frac{\partial SNR_{fire}(m_{pixel})}{\partial m_{pixel}} = \frac{\partial}{\partial m_{pixel}}\left\{\frac{\bar{m}_{pixel,SG}(m_{pixel})}{\sqrt{\bar{m}_{pixel}(m_{pixel})}}\right\} = 0$$

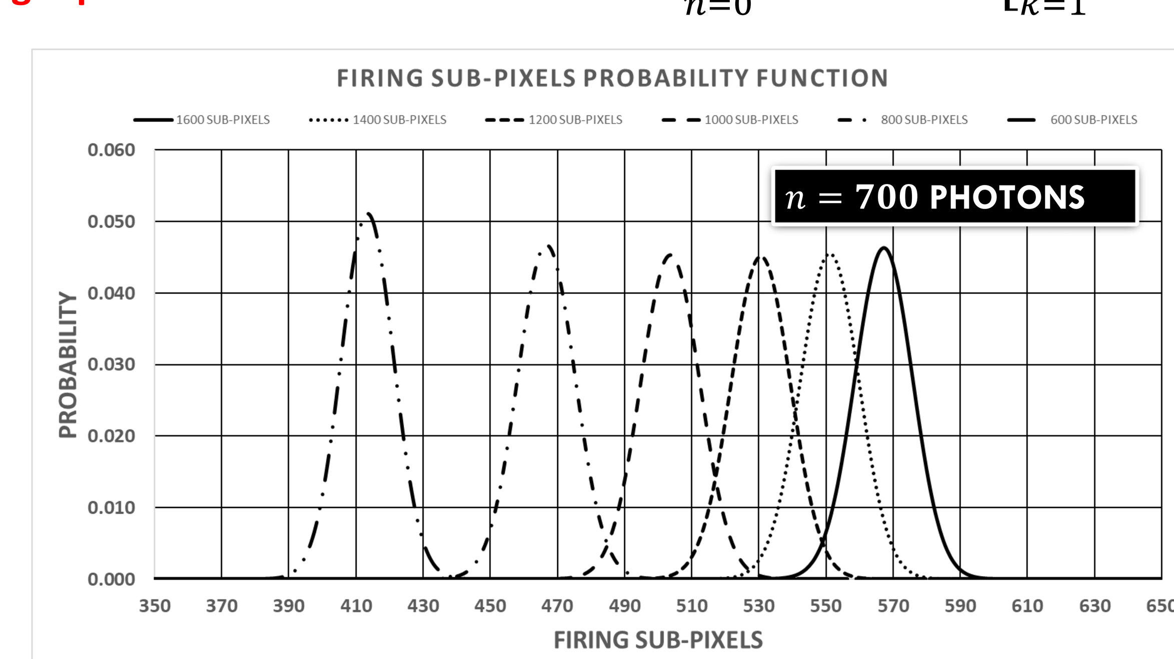
$$\lim_{m_{pixel}\to\infty} SNR_{fire}(m_{pixel}) \equiv SNR_{optical}$$

Conditional Probability density function

- $\boldsymbol{n} \sim Poisson(\lambda)$ photons randomly strike the SiPM matrix
- array consists of $\boldsymbol{m}$ identical sub-pixels
- **$P(A_k)$ - Probability for detecting k photons**

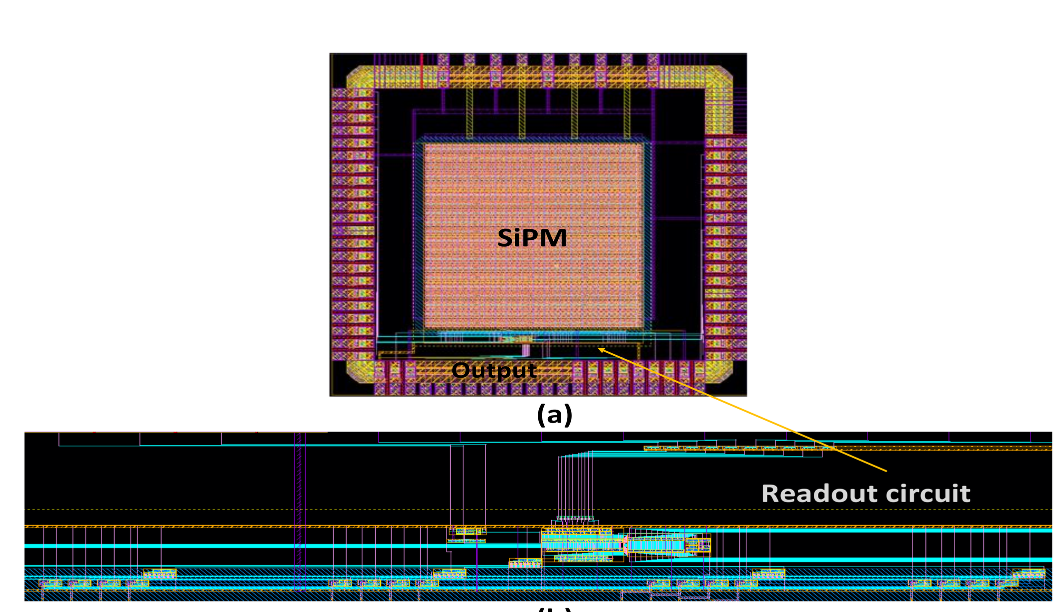
$$E\{k^l\} = \sum_{n=0}^{\infty} e^{-\lambda} \cdot \frac{(\boldsymbol{\lambda})^n}{n!} \cdot \left[\sum_{k=1}^{n} \boldsymbol{P}(\boldsymbol{A_k}|\boldsymbol{n}) \cdot k^l\right]$$

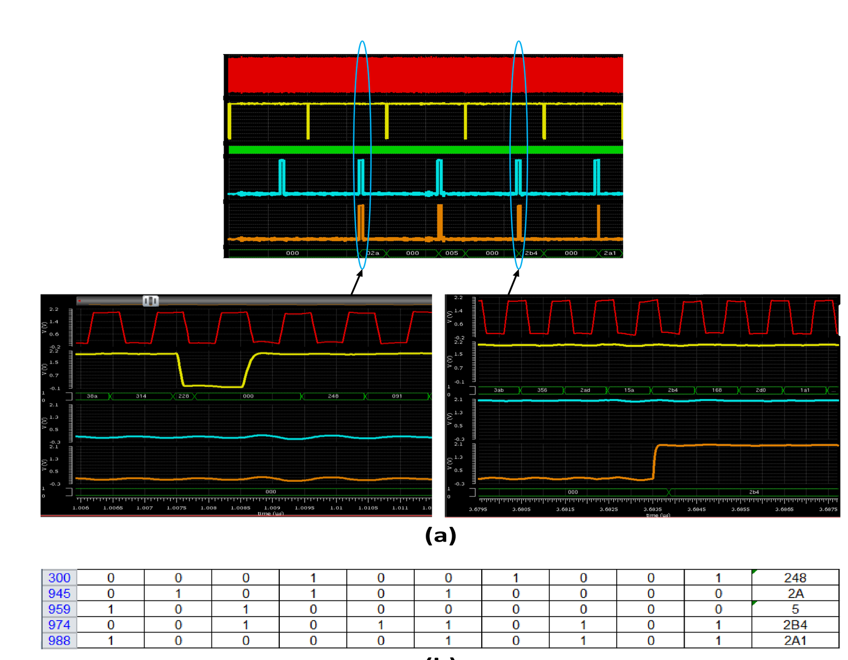




LiDAR architecture and design

- SiPM, which consists of 1600 sub-pixels N+P SPADs with NIR sensitivity (PDE=0.15)
- Each sub-pixel contains only a quenching resistor $\mathrm{R_q} = 300\mathrm{K}\Omega$ and AC coupled-capacitor $\mathrm{C_{ac}} = 16\mathrm{fF}$
- 16 sub-SiPM, each sub-SiPM contains 100 SPADs





The average value of the times is equal to $\bar{t} \equiv ToF = 666.5[ns]$the estimated range is equal to $Z_d = \frac{C_0}{2} \cdot ToF$=99.975[m].

This work was reported at:

1. A. Eshkoli, A. Nemirovsky & Y. Nemirovsky (2019). Modeling the missing part of CMOS silicon photomultiplier; the ultimate photon counting and timing sensor. SPIE defense and commercial sensing, 2019, Baltimore, Maryland, US.
2. A. Eshkoli and Y. Nemirovsky, "A stochastic approach for optimizing the required number of sub-pixels in Silicon Photomultipiler (SiPM) for optical radar applications (LiDAR), 2018 IEEE International Conference on the Science of Electrical Engineering in Israel (ICSEE), Eilat, Israel, 2018, pp. 1-4.