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Can Science Save the Earth? –

Optical sensing/fast acquisition systems for LIDAR mapping/telemetry

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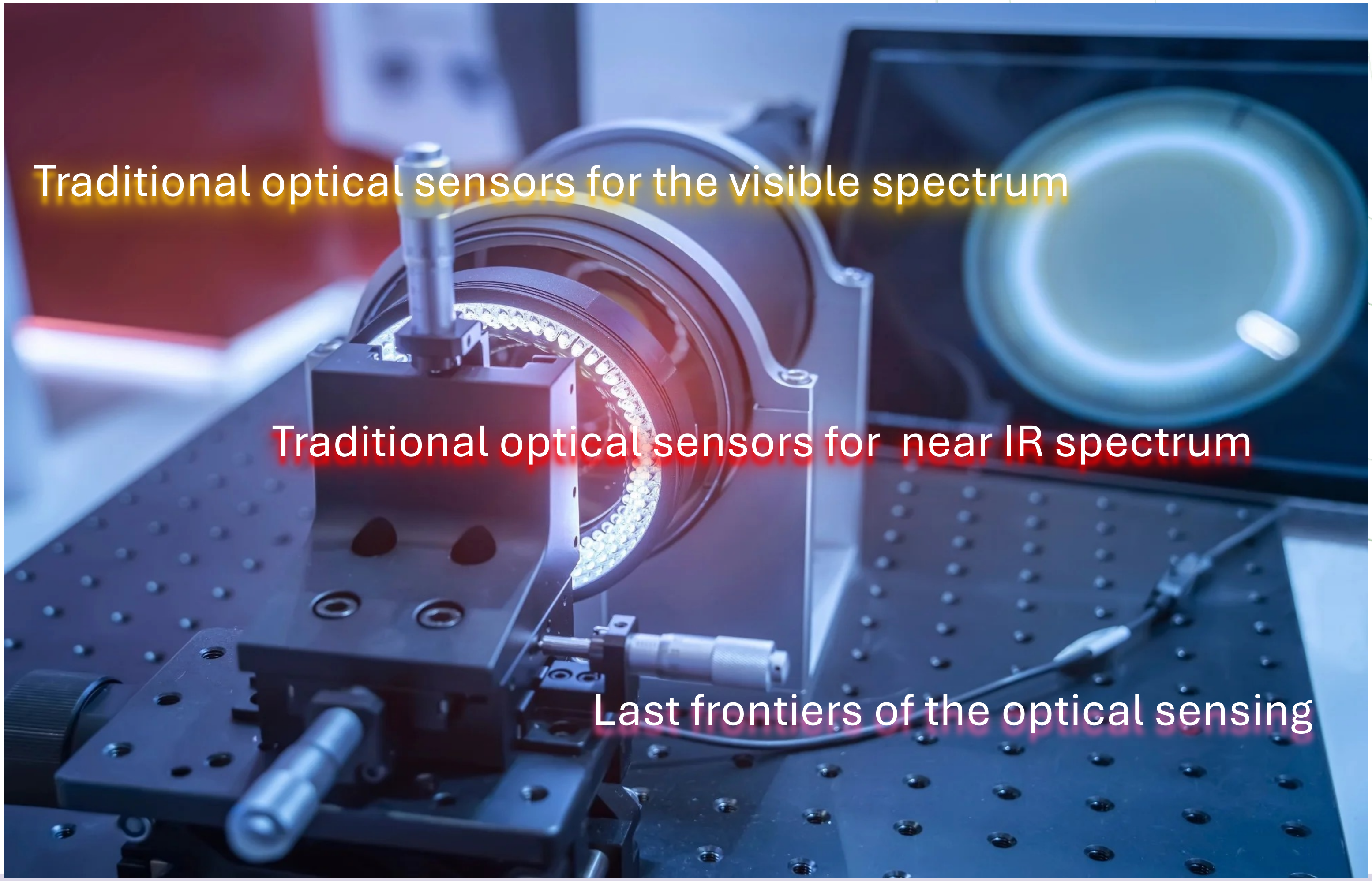
Optical sensing/fast acquisition systems



Traditional optical sensors for the visible spectrum

Traditional optical sensors for near IR spectrum

Last frontiers of the optical sensing

Optical sensing/fast acquisition systems

Optical sensors are a broad class of device for detecting light intensity

- They produce an electrical output (detection)
- The simplest component only notify when ambient light levels rise above or fall below a prescribed level (PD)
- Some devices show an highly sensitivity for detecting single photons (photonic sensors)
- Among these devices a few are able to give signal with just one photon (single photon detection)

Optical sensing/fast acquisition systems

Photonic sensors play a vital role in the modern world

- Utilize single photon to detect, measure, and analyze different parameters such as light intensity, wavelength, phase, and polarization

Integrated photonics is a specialized field within optics and photonics

- Miniaturizing and combining optical components and systems onto a single chip or substrate
- Manipulating light at micro- and nano-scales, resulting in compact and efficient photonic circuits
- Integrating multiple optical functionalities onto a single chip

Optical sensing/fast acquisition systems

Integrated photonics provides several benefits

- Reduced size, weight, power consumption, and cost in contrast to traditional optical setups

- Allow advancements in:
  - high-speed data transmission
  - Telecommunications
  - data communications
  - Sensing
  - Imaging
  - quantum information processing
  - biomedical imaging
  - next-generation computing architectures

- The origins of photonic sensors trace back to the early 20th century. A pivotal moment emerged in the 1950s and 1960s with the development of **fiber optics**, a breakthrough enabling the transmission of light through slender glass fibers across extensive distances

Optical sensing/fast acquisition systems

Photonic sensors encompasses a diverse range of technologies classified **into four general types** based on their design, platform and applications

I) **Optical Fiber-Based Sensors**: These sensors utilize optical fibers as the core component for detecting changes in various parameters like temperature, pressure, or chemical composition. The principle involves modulation of light signals propagating through the fiber, which can be altered by external influences, allowing for precise measurements

II) **Integrated Photonic Sensors**: This category involves sensors that integrate photonic components on a single chip. By leveraging advanced nanofabrication techniques, these sensors can achieve high sensitivity and compactness. Integrated photonic sensors are often used in applications requiring miniaturization and enhanced performance

III) **Wearable Sensors**: These are photonic sensors designed to be integrated into wearable devices, such as smart clothing or health monitoring gadgets

IV) **Metasurface (MS)-Based Sensors**: MSs are artificially engineered surfaces composed of subwavelength structures that can manipulate light in unique ways. MS-based sensors utilize electrical output

Optical sensing/fast acquisition systems

Beyond technological innovations, emerging applications are driving demand for photonic sensors across a myriad of sectors

- Autonomous vehicles
- Robotics
- Augmented reality
- Smart infrastructure
- LiDAR sensors for high-resolution 3D mapping (automotive industry)

Optical sensing/fast acquisition systems

Integrated photonic sensors have recently experienced remarkable advancements, they still face several obstacles

- Sensitivity limitations in some spectral ranges remain a critical challenge, particularly in detecting weak signals
- Small signal amplification
- Dark noise reduction
- Temperature sensitivity (gain & noise)

Optical sensing/fast acquisition systems

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Hamamatsu Photonics

Based in Japan, is a renowned manufacturer of photomultiplier tubes and photodiodes used in several fields of investigation

HAMAMATSU
PHOTON IS OUR BUSINESS

Excelitas

Based in Pittsburgh, USA, is a provider of advanced photonic technologies

excelitas®

Optical sensing/fast acquisition systems

Single-photon detectors can be divided into the following groups:

- Vacuum based: photomultiplier tubes (PMTs), micro-channel plates (MCPs), etc.

- Solid-state: electron-multiplying CCD (EMCCDs), single photon avalanche diodes (SPADs), SPAD array, silicon photomultipliers (SiPMs), etc.

- Cryogenic-temperature based: superconducting nanowire single-photon detectors (SNSPDs), etc.

Optical sensing/fast acquisition systems

Working principles of PMTs

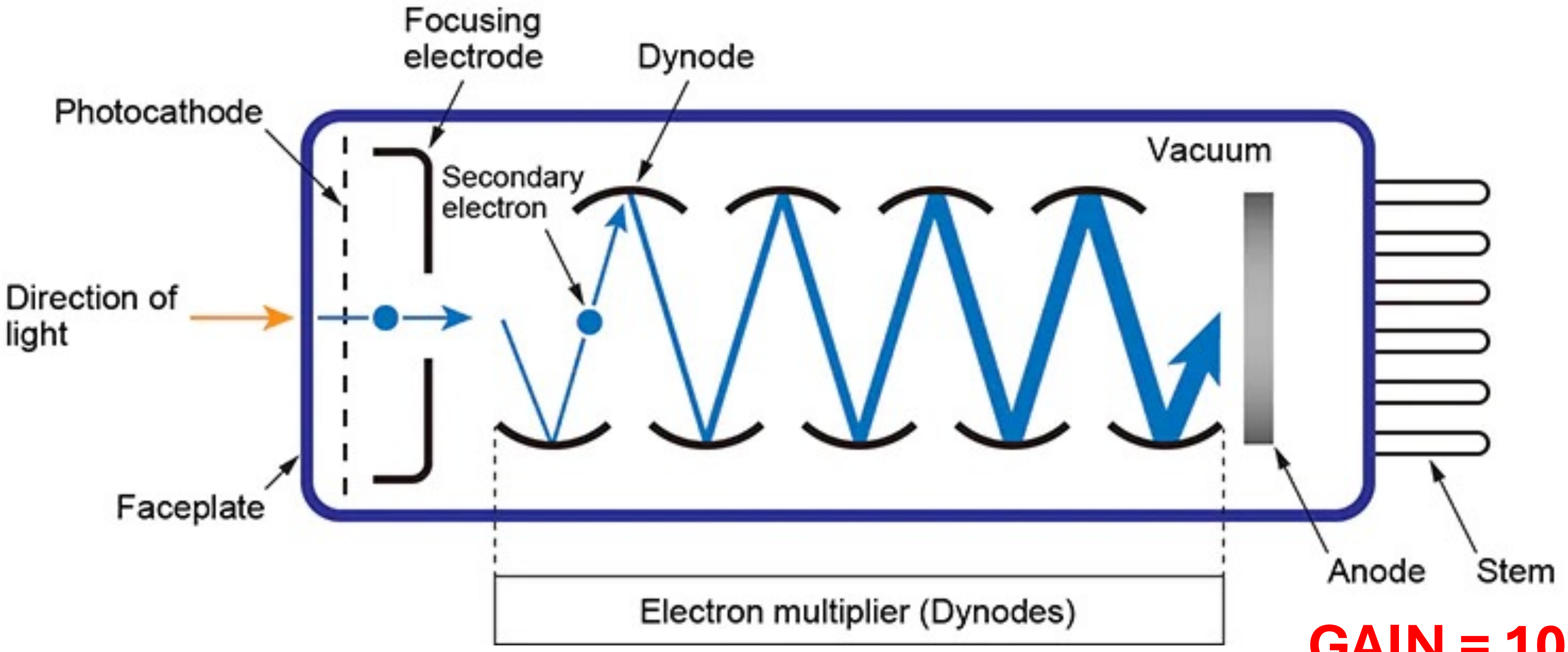
The PMTs are vacuum tube detectors capable of detecting light in the ultraviolet to near-infrared range of the electromagnetic spectrum.

They consist of

- Photocathode
- Glass housing which acts as a vacuum tube
- Several dynodes and an anode

When a photon strikes the photocathode material, electrons are ejected due to the photoelectric effect. These electrons then collide to a series of dynodes which multiply them to a level (~10^9 electrons) where a detectable signal can be retrieved from the anode. The dynodes need to be biased to a voltage of ~1kV.

Optical sensing/fast acquisition systems



GAIN = 10^6

Optical sensing/fast acquisition systems

Working principles of SPADs

The SPAD is a semiconductor device capable of detecting from ionizing radiation to infrared rays in the electromagnetic spectrum.

It operates in inverse bias mode, above the breakdown voltage and exploits the photon-triggered avalanche current to detect an incident radiation.

The SPADs can be divided in **two main categories**

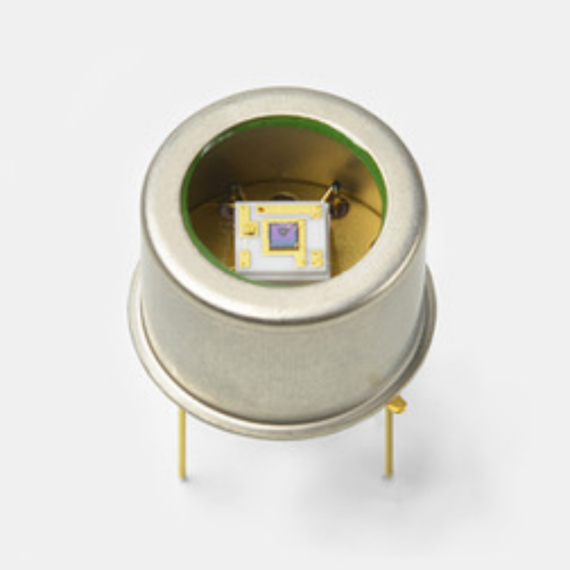
- **Thin-junction SPAD** which has a breakdown voltage from 10 to 50V, an active area from 50 to 150μm and a photon efficiency of up to 45% on the visible range (single photon detection)

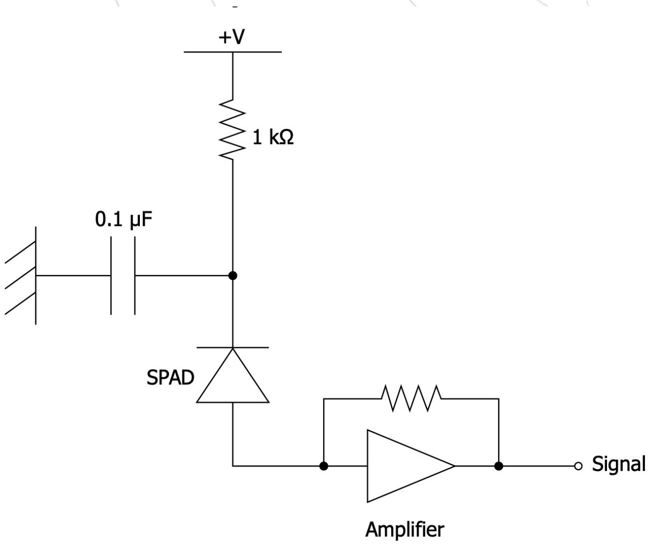
- **Thick-junction SPAD** which has a breakdown voltage from 200 to 500V, a wider active area of 100 to 500μm and efficiency of over 50% on the visible spectrum (analog detection)

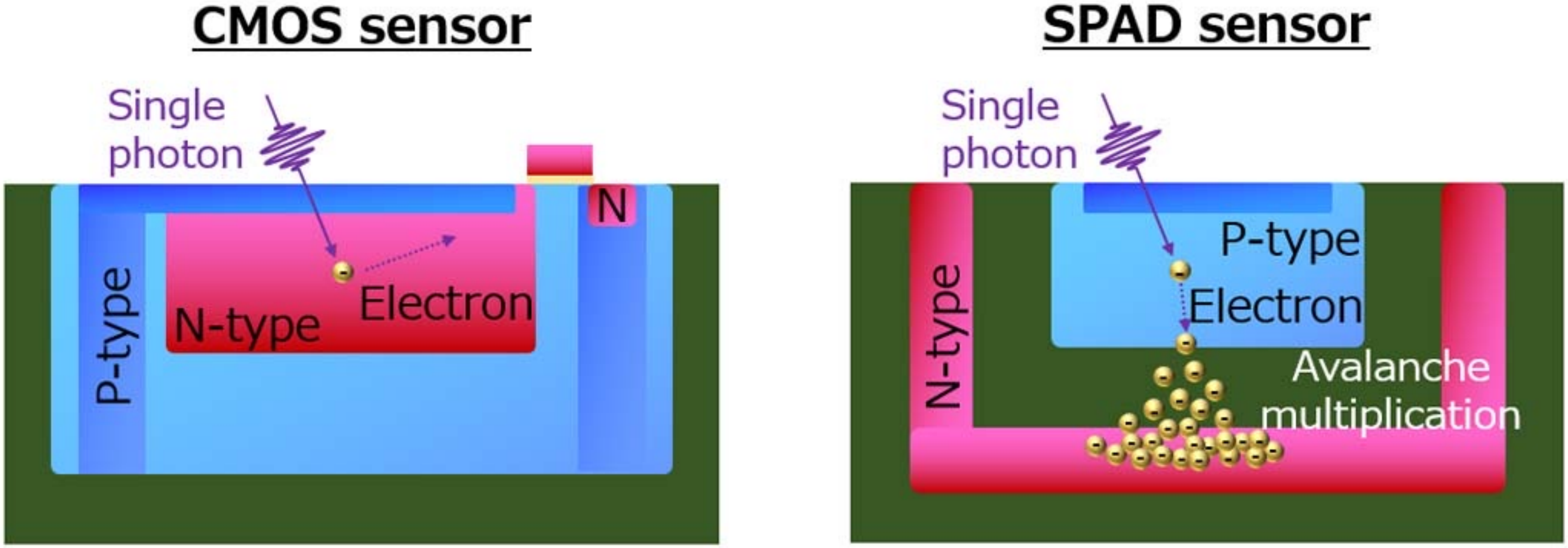
Optical sensing/fast acquisition systems

	PD	APD	MPPC	PMT
Gain	1	10^2	to 10^6	to 10^7
Quantum efficiency	Highest	High	Medium	Low
Operation voltage	5 V	100 to 500 V	30 to 60 V	800 to 1000 V
Large area	No	No	Medium	yes
Multi channel with narrow gap	Yes	Yes	Yes	No
Readout circuit	Complex	Complex	Simple	Simple
Noise	Low	Middle	Middle	Low
Uniformity	Excellent	Good	Excellent	Good
Energy resolution	High	Medium	High	High
Temperature sensitivity	Low	High	Medium	Low
Ambient light immunity	Yes	Yes	Yes	No
Magnetic resist	Yes	Yes	Yes	No
Compact & Weight	Yes	Yes	Yes	No

SPAD sensor - evolution of the CMOS-PMT technology







Multiplication gain: approx. 1x

Multiplication gain: approx. 1,000,000x

P-type semiconductor: Intrinsic semiconductor doped with boron (B) or other elements
N-type semiconductor: Intrinsic semiconductor doped with phosphorous (P), arsenic (As) or other elements

Optical sensing/fast acquisition systems

Specific parameters identifying SPAD performance 1/2

- Photon detection efficiency (PDE), i.e., the ability to detect photons. This is the ratio between the number of detected photons and the photons arriving at the detector. PDE is calculated as the product of: (i) the quantum efficiency (QE) and (ii) the avalanche triggering probability (PT)

- The noise, typically divided into “primary” noise and correlated noise.
  - The primary noise represents all the avalanche pulses due to thermally generated carriers (or generated by tunneling or field-assisted thermal generation). The dark count rate (DCR) is typically in the order of 10–1000 counts per second.

  - The correlated noise is represented by the afterpulsing. During the avalanche, a large amount of carriers flows through the depleted region and some of them can be trapped in deep-levels (traps), being subsequently released with a delay, causing retriggering of another spurious avalanche, not related to photon absorption but to a previous avalanche, thus “correlated noise.”

Optical sensing/fast acquisition systems

Specific parameters identifying SPAD performance 2/2

- The dead-time is the time interval after an avalanche, where the SPAD is not sensitive to another photon. This interval is necessary to recharge the SPAD and to let the traps to release the carriers without triggering a spurious avalanche. This is typically in the order of tens of nanosecond. Differently from active quenching, with passive quenching, the recharge is exponential, and thus it is not easy to identify a precise dead-time. The recharge time-constant can be used as a parameter

- The time resolution of the SPAD, i.e., the ability of precise time-tag the photon arrival time, is another important parameter. The “timing jitter” or “single-photon time resolution” (SPTR) quantifies the time spread between the photon arrival and the pulse detection by the front-end electronics. This spread is due to the different absorption position and the statistical avalanche buildup time. It is in the order of a few tens of

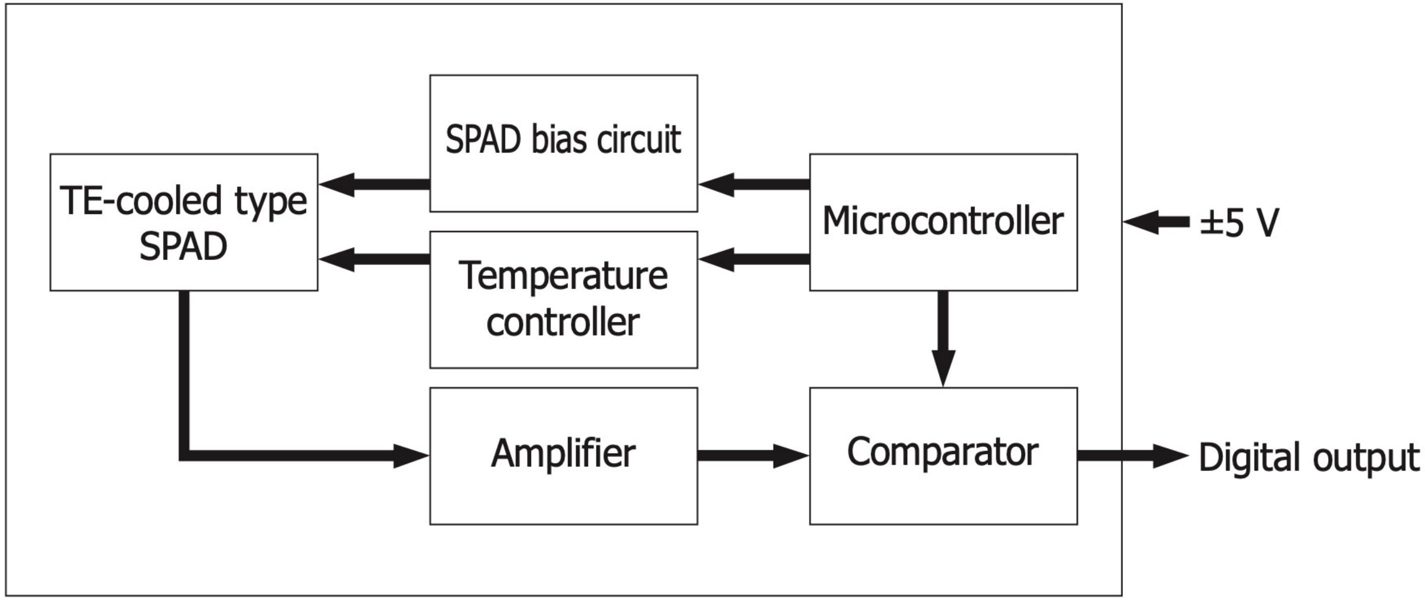
Optical sensing/fast acquisition systems

Single SPAD sensor module

Sensor diameter 200 um

Optical sensing/fast acquisition systems

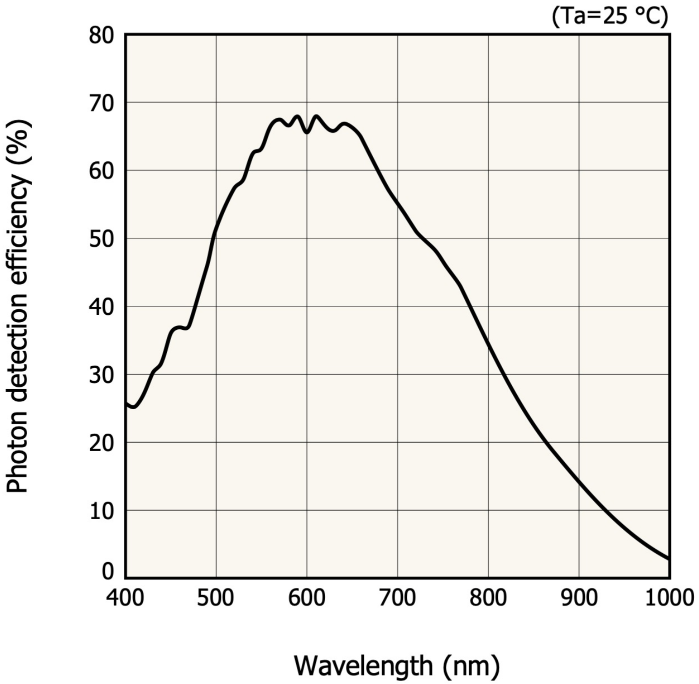
SPAD module

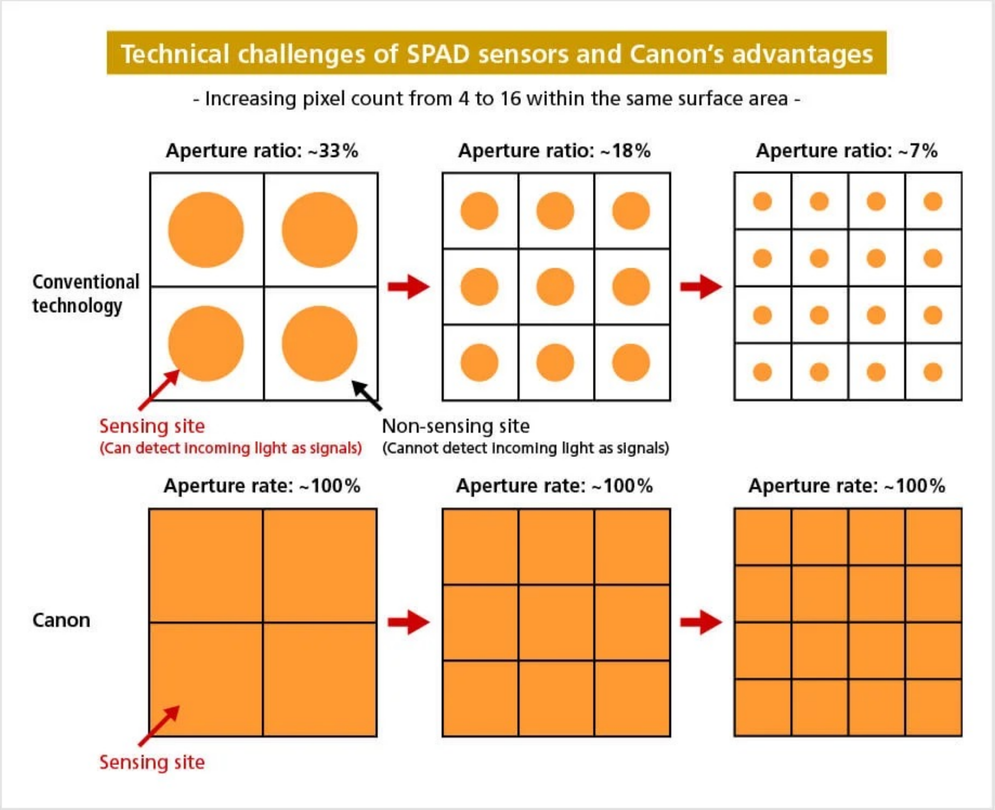


Optical sensing/fast acquisition systems

SPAD ARRAY sensor

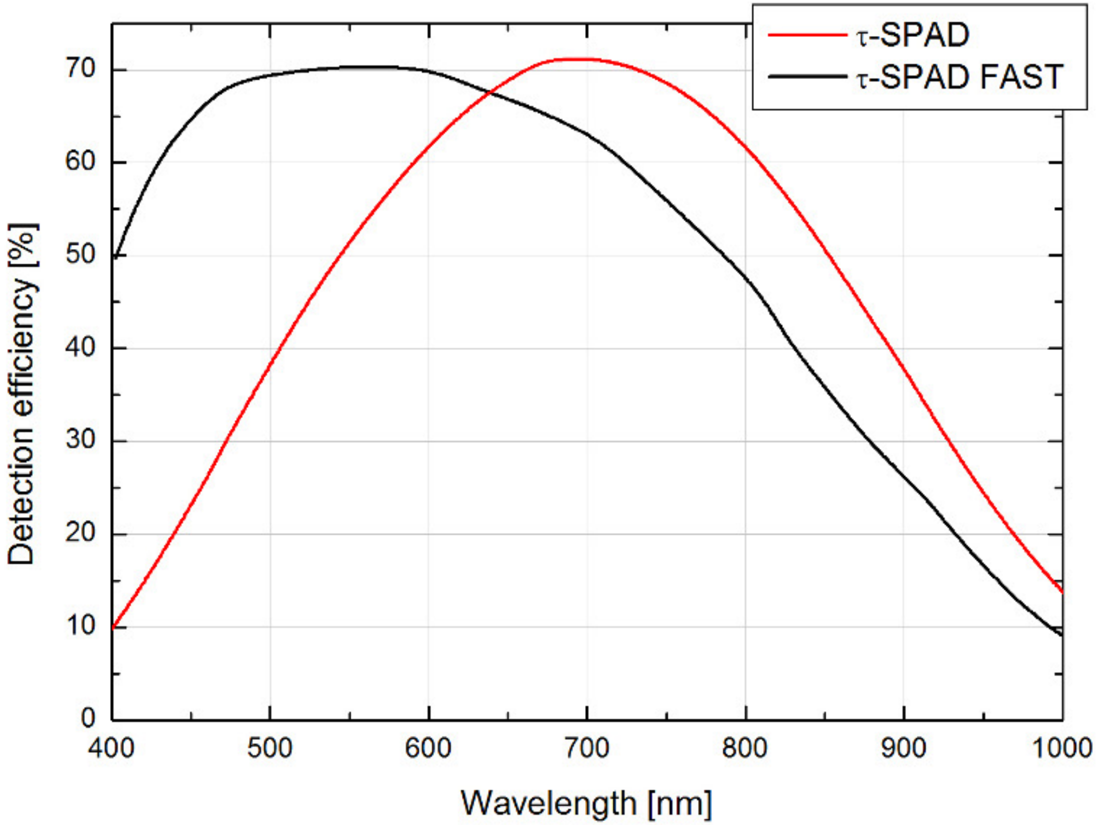
Sensor diameter from 10s to 100s um





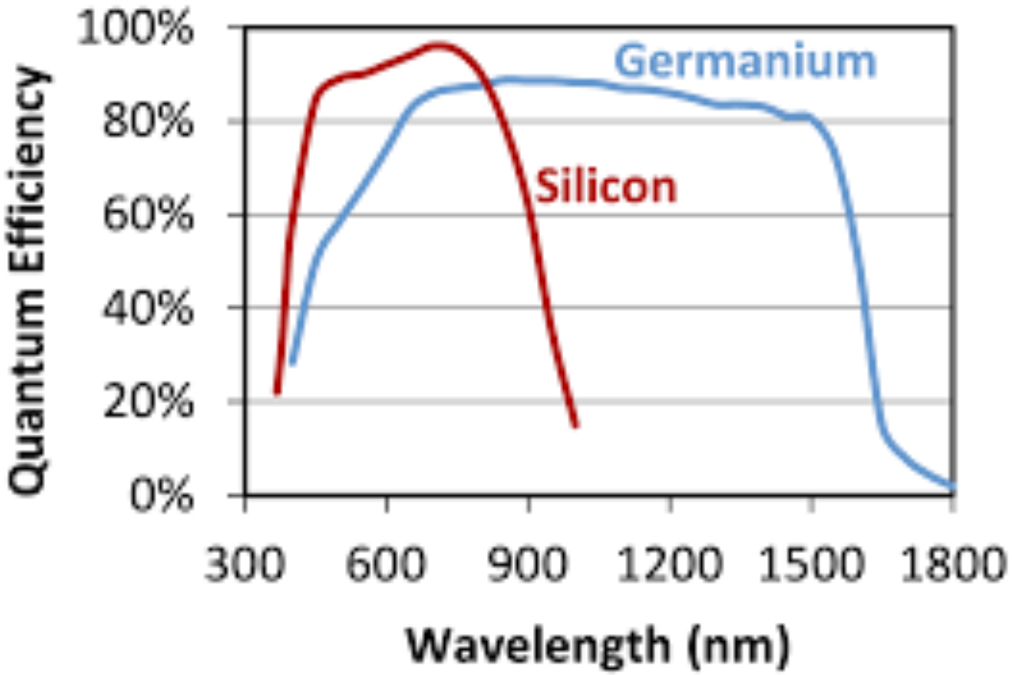
Optical sensing/fast acquisition systems

HIGH QUANTUM EFFICIENCY OVER VISIBLE AND NIR SPECTRUM

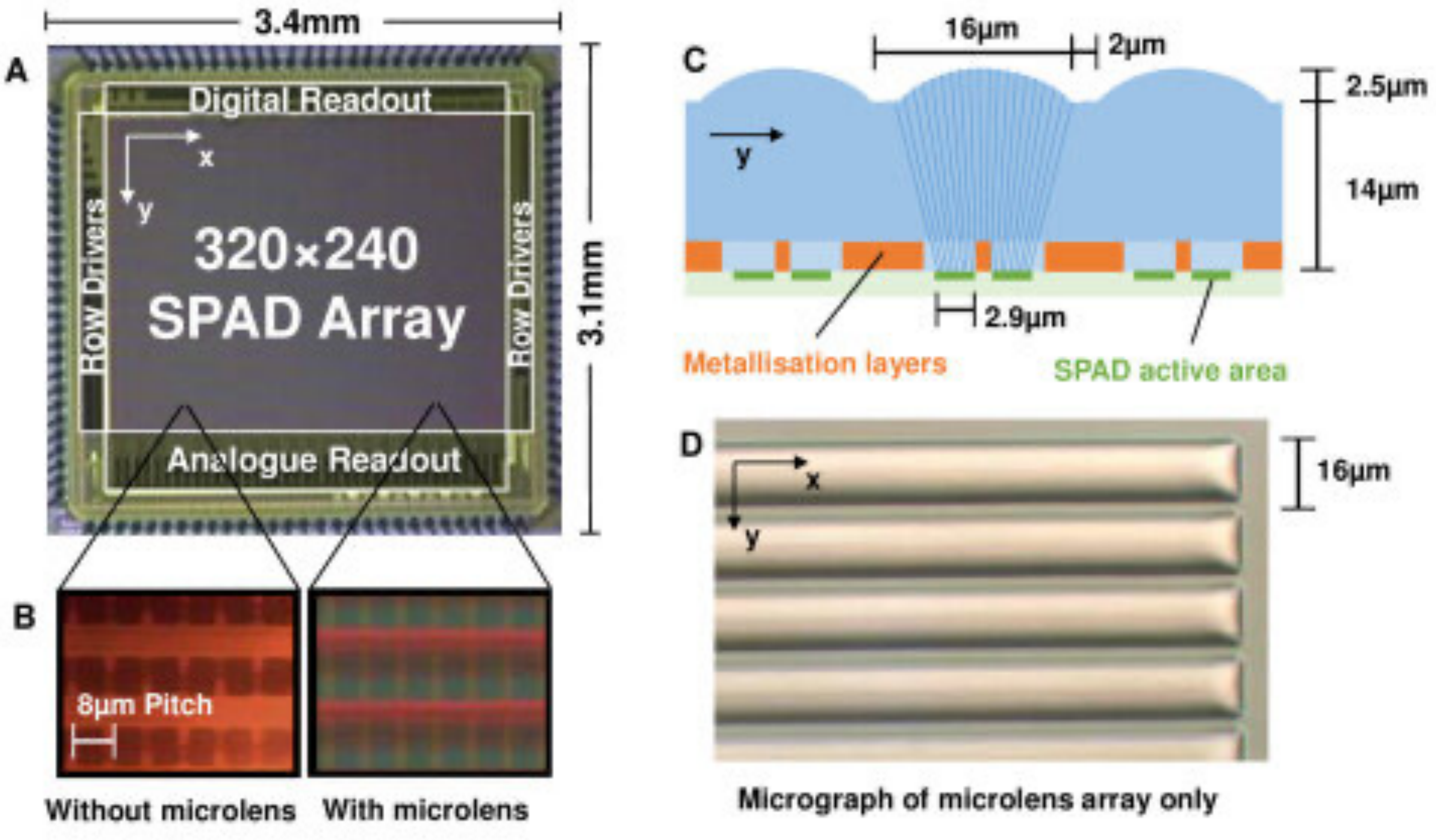


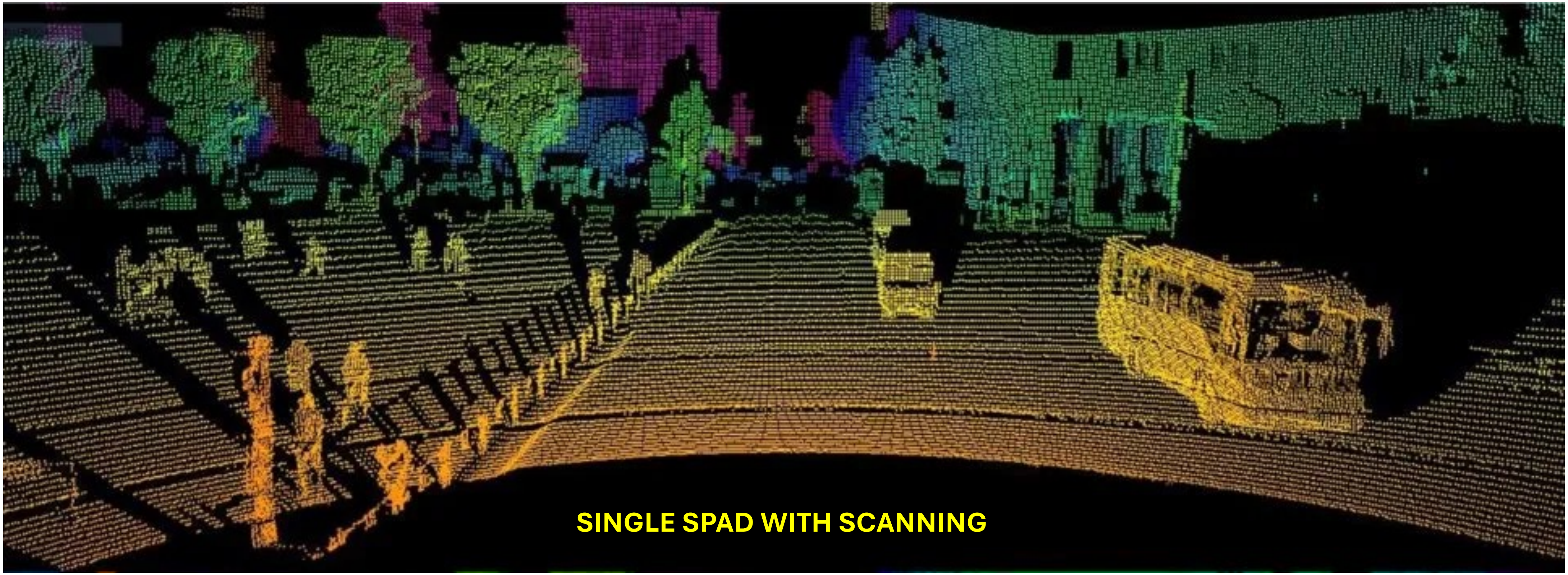
Optical sensing/fast acquisition systems

Si vs InGas Q.E.



Optical sensing/fast acquisition systems





SINGLE SPAD WITH SCANNING

SPAD ARRAY WITHOUT SCANNING

Optical sensing/fast acquisition systems

SPAD ARRAY

- A SPAD array, or Single-Photon Avalanche Diode array, is a highly sensitive optical sensor designed to detect and count and time the arrival of single photons.

MPPC - SiPMT

- MPPC (Multi-Pixel Photon Counter) is configured with a plurality of pixels, in which several SPADs are arranged in plural numbers and electrically connected in parallel.

Optical sensing/fast acquisition systems

Optical sensing/fast acquisition systems

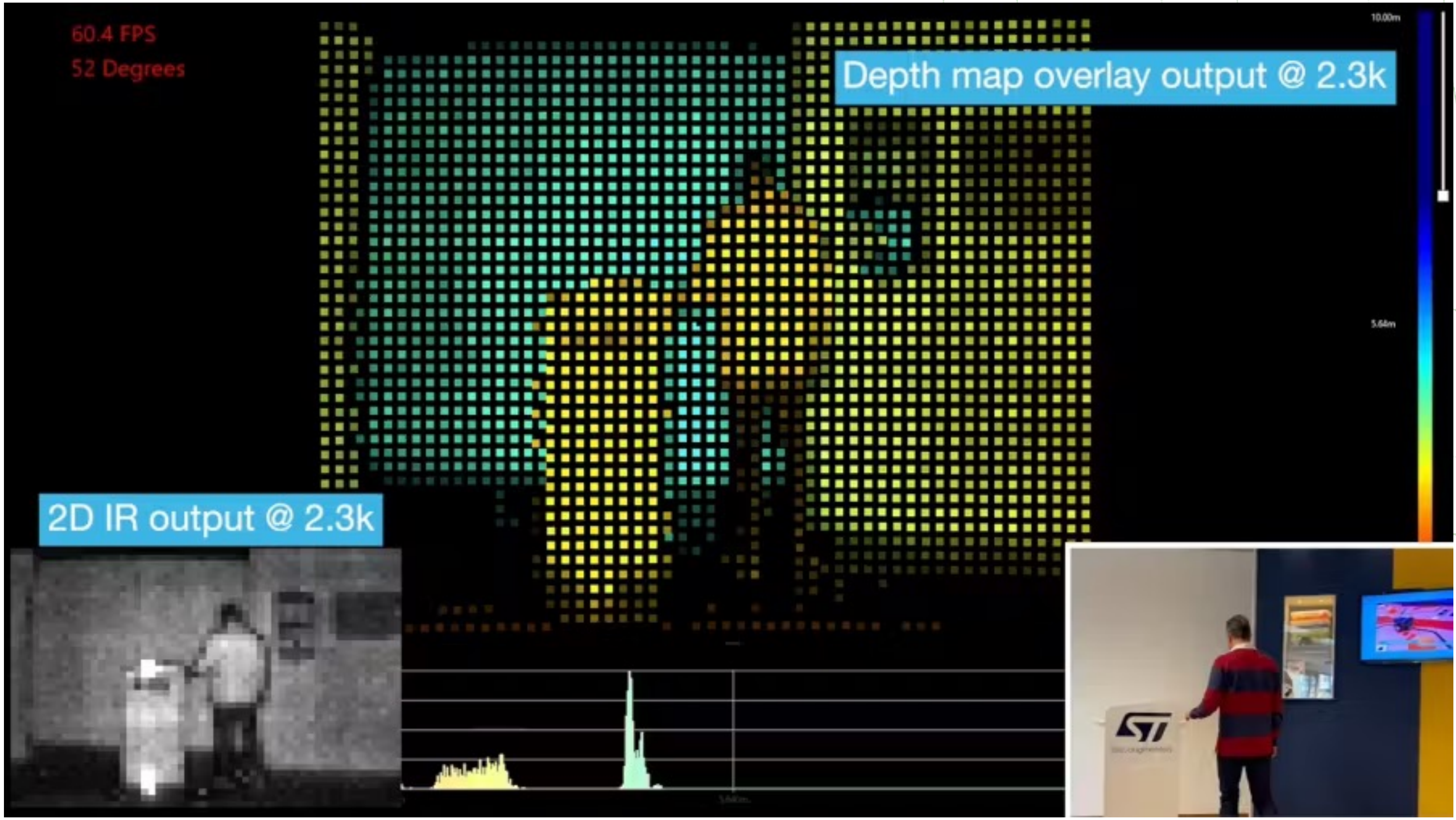
An integrated miniaturized 3D LIDAR from STMicroelectronics

Size: 12.8 x 6.1 x 4.6 mm

The **VL53L9CA** is a state of the art, dToF 3D lidar module with resolution of up to 2.3k zones

- SPAD array (54 x 42 pixels)
- 60 Hz frame rate
- Range 5 cm -10 m
- Postprocessing SoC
- 2D & 3D IR images
- Two VCSEL emitters
- Infrared filters
- Metasurface optical elements (MOE)
- 71° FOV

Optical sensing/fast acquisition systems



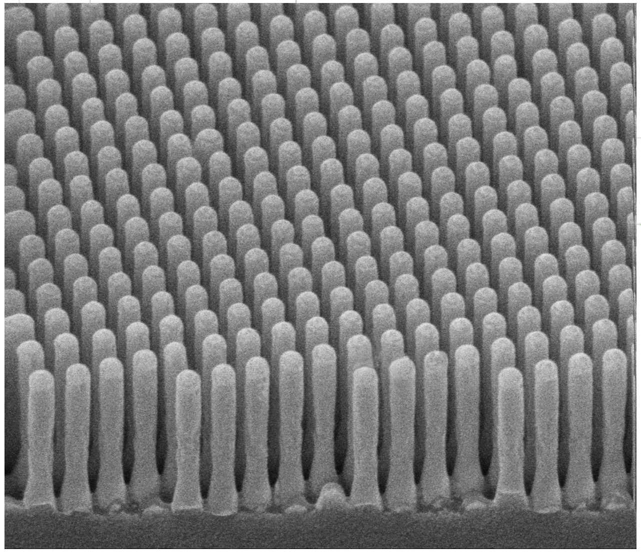
Optical sensing/fast acquisition systems

MOE are a radical new flat lens technology that disrupts conventional optics

What is the difference between a refractive lens and a metalens?

- Classical lenses operate by refractive index of the medium (Glass or other materials) (Fresnel lenses for flatness)

- Metalenses operate by diffraction of the light using implemented nanostructures smaller than the wavelength of light (Flat optics)
  Limited to mm2 size!!!



Optical sensing/fast acquisition systems

Superconducting nanowire single-photon detector (SNSPD or SSPD)

The SNSPD consists of a thin (≈ 5 nm) and narrow (≈ 100 nm) superconducting nanowire. The length is typically hundreds of micrometers, and the nanowire is patterned in a compact meander geometry to create a square or circular pixel with high detection efficiency.

The nanowire is cooled well below its superconducting critical temperature (2K) and biased with a DC current that is close to but less than the superconducting critical current of the nanowire.

A photon incident on the nanowire breaks Cooper pairs and reduces the local critical current below that of the bias current. This results in the formation of a localized non-superconducting region, or hotspot, with finite electrical resistance. Resulting in a measurable voltage pulse

Optical sensing/fast acquisition systems

SNSPD represents very best in single-photon detection, with ultra-stable performance

- Near-ideal detection efficiency (> 95%)
- NIR sensitivity up to 2 um
- Highly precise timing
- Low noise
- Fiber connections
- Mix and match up to 16 detectors
- Ultra-compact cryostatic systems

Optical sensing/fast acquisition systems

Time-correlated single photon counting (LIDAR Digital Acquisition)

TCSPC is a technique in the DIGITAL DOMAIN to reconstruct the temporal shape of faint light signal based on:

- Detection of single photons of periodic light signals (atmospheric echoes)
- Each measurement starts with the arrival of a pulse from the reference signal (START) and stops with the arrival of the signal related to the photon detection (STOP).
- Measuring their detection times
- Building a histogram with specific width timing (binning, i.e. time/range resolution)
- After several detections, the histogram represents the waveforms of detected optical signal (average)

The assumption of TCSPC is that the light signal intensity is low enough so that the probability of having one photon at the detector in each cycle is much less than one, i.e. **the probability to have more than one photon is negligible**. This is to avoid distortion because the TCSPC system can detect only one event per cycle.

Optical sensing/fast acquisition systems

What Is ADC Converter (Analog-to-Digital Converter)?

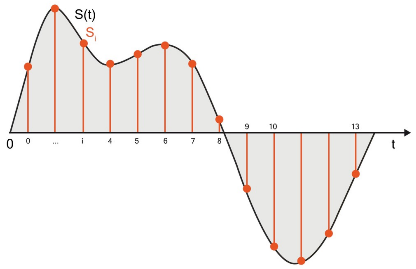
**ADC converts information
from ANALOG domain to DIGITAL domain**

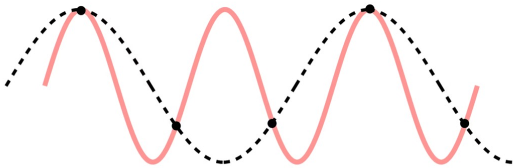
The main purpose of the A/D converters within a data acquisition system is to convert conditioned analog signals into a stream of digital data so that the data acquisition system can process them for display, storage, and analysis.

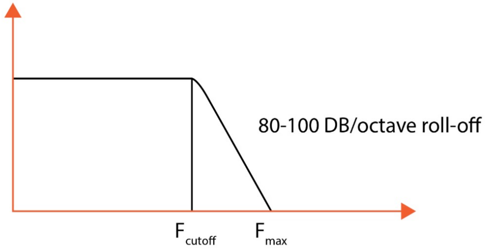
Optical sensing/fast acquisition systems

Key ADC features and capabilities

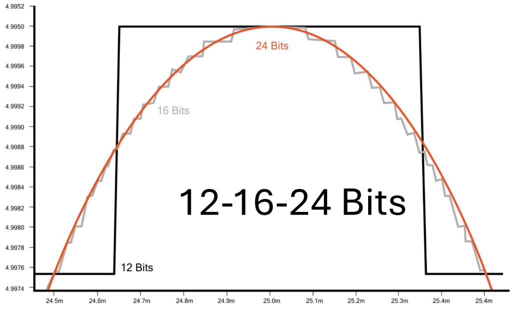
- **Sample rate -** how fast can an ADC convert analog to digital (Aliasing issue is important !! Anti-aliasing filter))







- **Bit resolution -** with how much precision can an ADC convert analog to digital



12-16-24 Bits

Optical sensing/fast acquisition systems

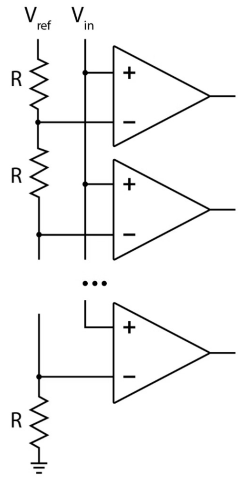
Five major types of ADC Converter

- Successive Approximation (SAR) ADC
- Delta-sigma (ΔΣ) ADC
- Dual Slope ADC
- Pipelined ADC
- Flash ADC

ADC TYPE	PROS	CONS	MAX RESOLUTION	MAX SAMPLE RATE
Dual Slope	Inexpensive	Low speed	20 bits	100 Hz
Flash	Very fast	Low bit resolution	12 bits	10 GHz
Pipeline	Very fast	Limited resolution	16 bits	1 GHz
SAR	Good speed/resolution ratio	No inherent anti-aliasing protection	18 bits	10 MHz
Delta-sigma (ΔΣ)	High dynamic performance, inherent anti-aliasing protection	Hysteresis on unnatural signals	32 bits	1 MHz

Optical sensing/fast acquisition systems

Flash ADCs



Flash ADC diagram

Flash ADC converts are used in digital oscilloscopes

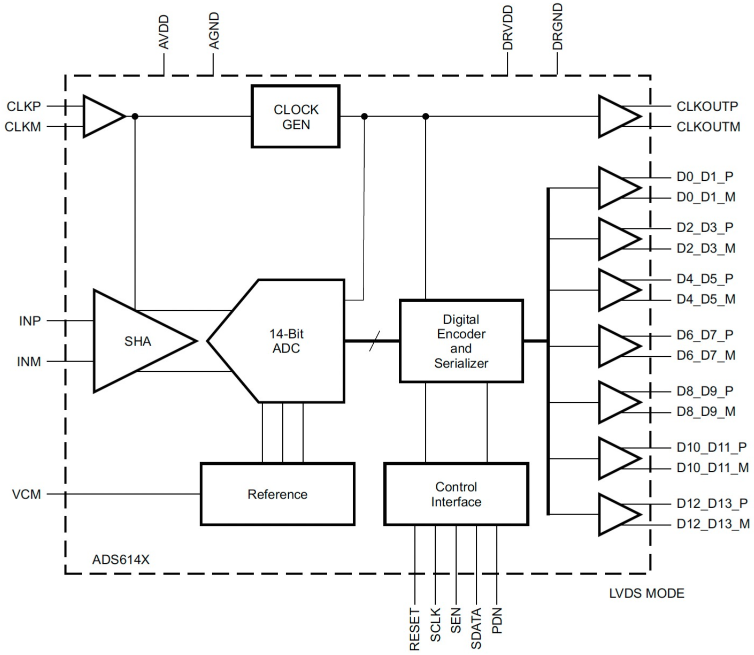
Flash ADCs are **fast and operate virtually without latency**, which is why they are the architecture of choice when the highest possible sample rates are needed.

They convert analog to digital signals by comparing them with known reference **values**.

The more resolution we want, the bigger and more power-hungry the Flash ADC becomes - and the sample rate has to be reduced (**heat dissipation issue on the microchip**).

Optical sensing/fast acquisition systems

An example: ALA analog acquisition solution



A/D converter from TEXAS Instruments

125 MS/s
14 bit
Parallel data output
ENOB from Texas = 11.9

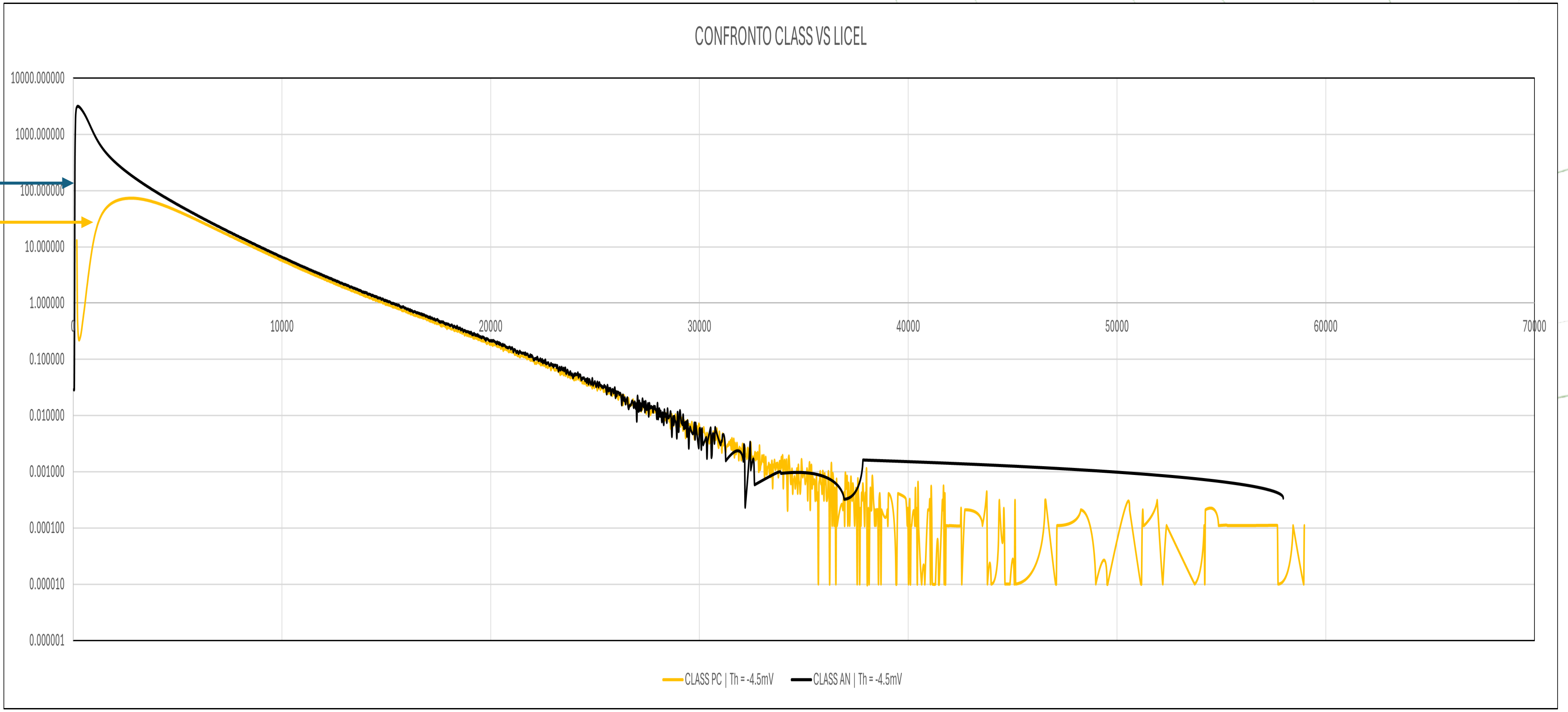
The ENOB describes the effective resolution of a real converter in terms of the number of bits an ideal converter with the same resolution would have

Optical sensing/fast acquisition systems

Digital/analog acquisition

ANALOG

DIGITAL



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