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From circuits to sensors
the best is yet to come!

Sara Pellegrini

Imaging Strategy Office

STMicroelectronics

How many sensors are there in an iPhone?

- MEMS sensors
  - Barometer (altitude estimation)
  - Three-axis gyroscope (combined with accelerometer to assess how you are holding the screen)
  - Accelerometer/motion sensor (screen orientation)
  - Magnetometer (compass for GPS location)
  - Moisture sensor (to sense water damage)
- Optical Sensors
  - Proximity sensor (determines how close you are to the phone)
  - Ambient light sensor (screen brightness)
  - Touch ID
  - Face ID
  - Cameras

Total of 9 type of sensors

Source: https://www.lifewire.com/sensors-that-make-iphone-so-cool-2000370

Camera sensors in iPhone

Front cameras ➔

STMicroelectronics 1.4MP

SONY 12MP

Rear cameras ➔

Telephoto camera – 12MP

Main rear camera – 48MP

Ultrawide camera – 12MP

LiDAR camera

Source: https://www.techinsights.com/blog/apple-iphone-14-image-sensor-preliminary-analysis

Sensors in iPhone

- MEMS sensors
  - Barometer (altitude estimation)
  - Three-axis gyroscope (combined with accelerometer to assess how you are holding the screen)
  - Accelerometer/motion sensor (screen orientation)
  - Magnetometer (compass for GPS location)
  - Moisture sensor (to sense water damage)
- Optical Sensors
  - Proximity sensor (determines how close you are to the phone)
  - Ambient light sensor (screen brightness + anti-flicker)
  - Touch ID
  - Face ID
  - **Cameras x 6**

Total of 14 sensors

Source: https://www.lifewire.com/sensors-that-make-iphone-so-cool-2000370

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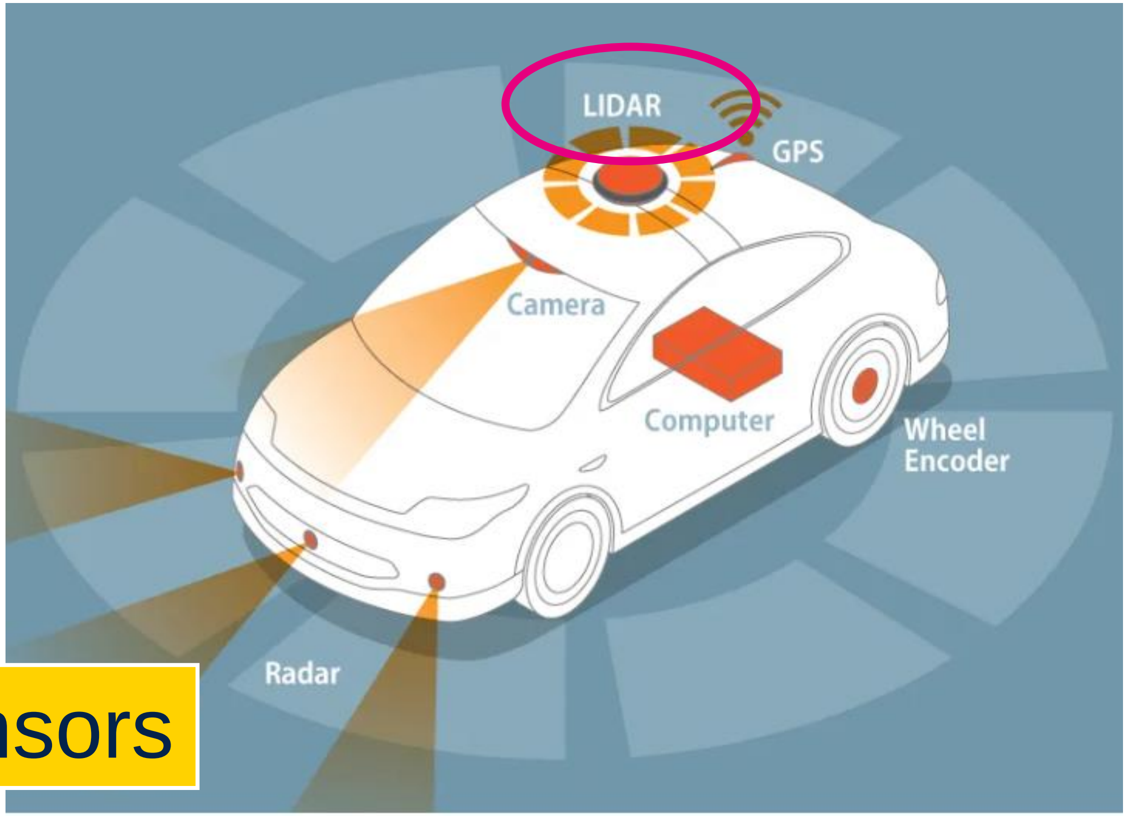
How many sensors are there in a car?

Sensor	Function
Air-flow sensor	It measures the density and volume of the air entering the combustion chamber.
Engine knock sensor	It monitors engine knocking and ensures the air-fuel mixture is ignited correctly.
Engine speed sensor	It monitors the spinning speed and position of the crankshaft.
Camshaft position sensor	It monitors the position and proper timing of the camshaft.
Manifold Absolute Pressure (MAP) sensor	Monitors engine load by measuring the difference between the manifold and outside pressure.
Throttle position sensor	Monitor the position of the throttle valve.
Voltage sensor	It manages the idling speed of the vehicle.
Oxygen sensor	It helps to measure the oxygen level present in the exhaust gases.
NOx sensor	It measures the Oxides of Nitrogen (NOx) present in the exhaust gases.
Temperature sensor	It monitors the engine temperature.
Fuel temperature sensor	It monitors the temperature of the fuel entering the engine.
Speed sensor	It measures the speed of the wheels.
Parking sensor	It recognises any obstacle present in the front or vehicle.
Rain sensor	It detects rain and sends a signal to ECU to activate the wipers.

Source: https://ackodrive.com/car-guide/different-types-of-car-sensors/

- Optical sensors for assisted driving



> 60 sensors

STMicroelectronics - 25 years of optical sensing

STMicroelectronics acquired VISION
Imaging Division Creation

1990 1999 2002 2003 2009 2012 2014 2015 2017 2018 2019 2020 2021 2022 2024

- VISION – Start-up from University of Edinburgh
- First million cameras & ISP shipped for mobile
- Camera proliferation in Nokia phones
- Several billion Cameras & ISPs shipped
- Start customer & application diversification
- Time-of-flight **ST Flight**Sense sensor ramp-up
- Mass **ST Flight**Sense pervasion in smartphones
- High volume **Global Shutter** ramp-up
- Open Market **ALS** launched
- 1Bu **ST Flight**Sense shipped worldwide
- **Open-Market** Global Shutter launch
- 1st Micro-optic production
- **High volume ALS** production
- **Automotive** Global Shutter product launch
- **Multizone ToF** Market acceleration
- Worlds 1st Metasurface in MP
- **#1 Worldwide** for in-cabin OMS/DMS global shutter
- **ST Bright**Sense Global shutter family launch

Flight Sense

ODIFF

ST FlightSense™ shipped 2 BILLION

ST BrightSense

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What is a LiDAR camera?

What is a LiDAR camera?

LiDAR = **Light** Detection and Ranging

LiDAR is similar in operation to **RA**DAR but emits pulsed laser light instead of microwaves (RAdio)

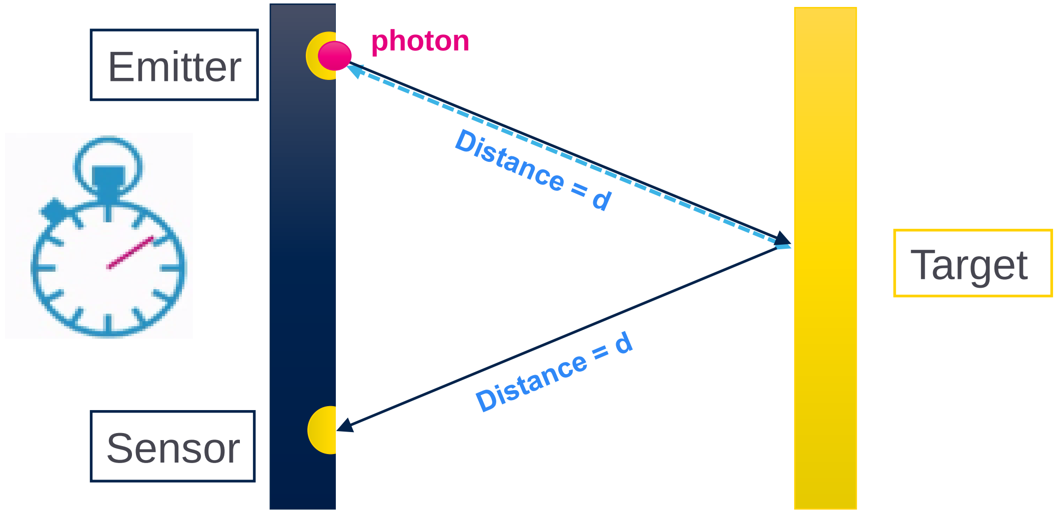
What is a LiDAR camera?

- LiDAR is a system that can measure the time **light** takes to reach a target and come back to the sensor:
- Speed of light ~ 3 x 10^8 m/s = $c = \frac{2d}{t}$

$$d = \frac{c \cdot t}{2}$$

- If d = 1m ➔ t = 6.7 ns
- Error Δd = 1mm ➔ Δt = 6.7ps

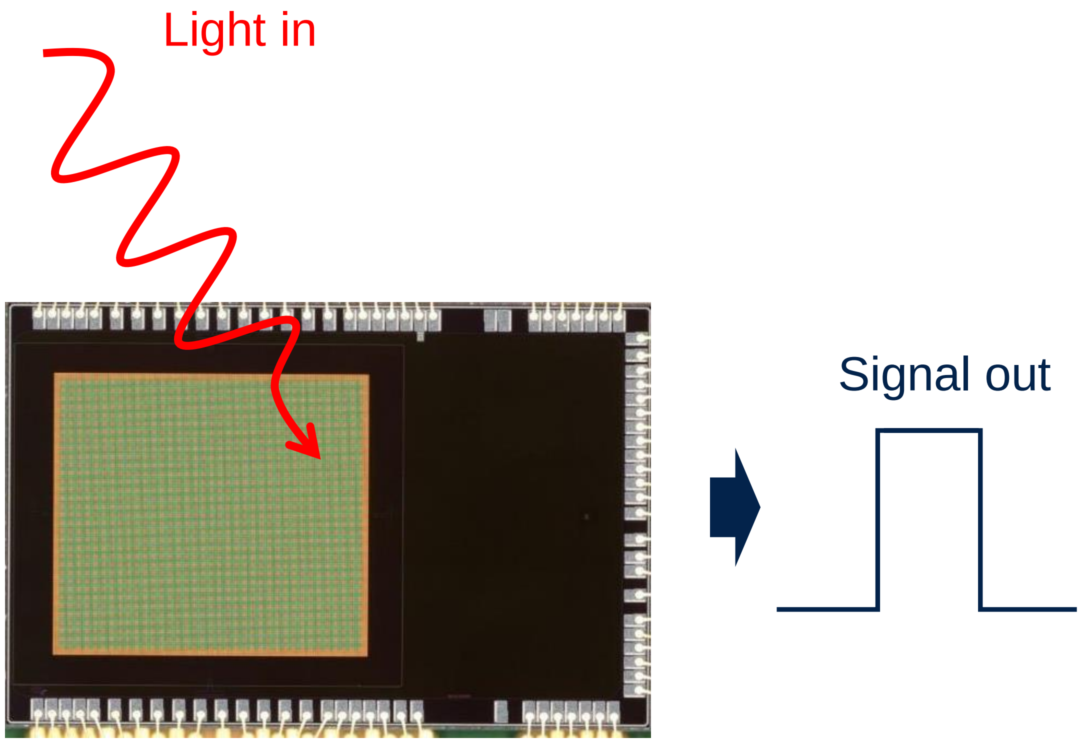
FlightSense™ Time of Flight Principle

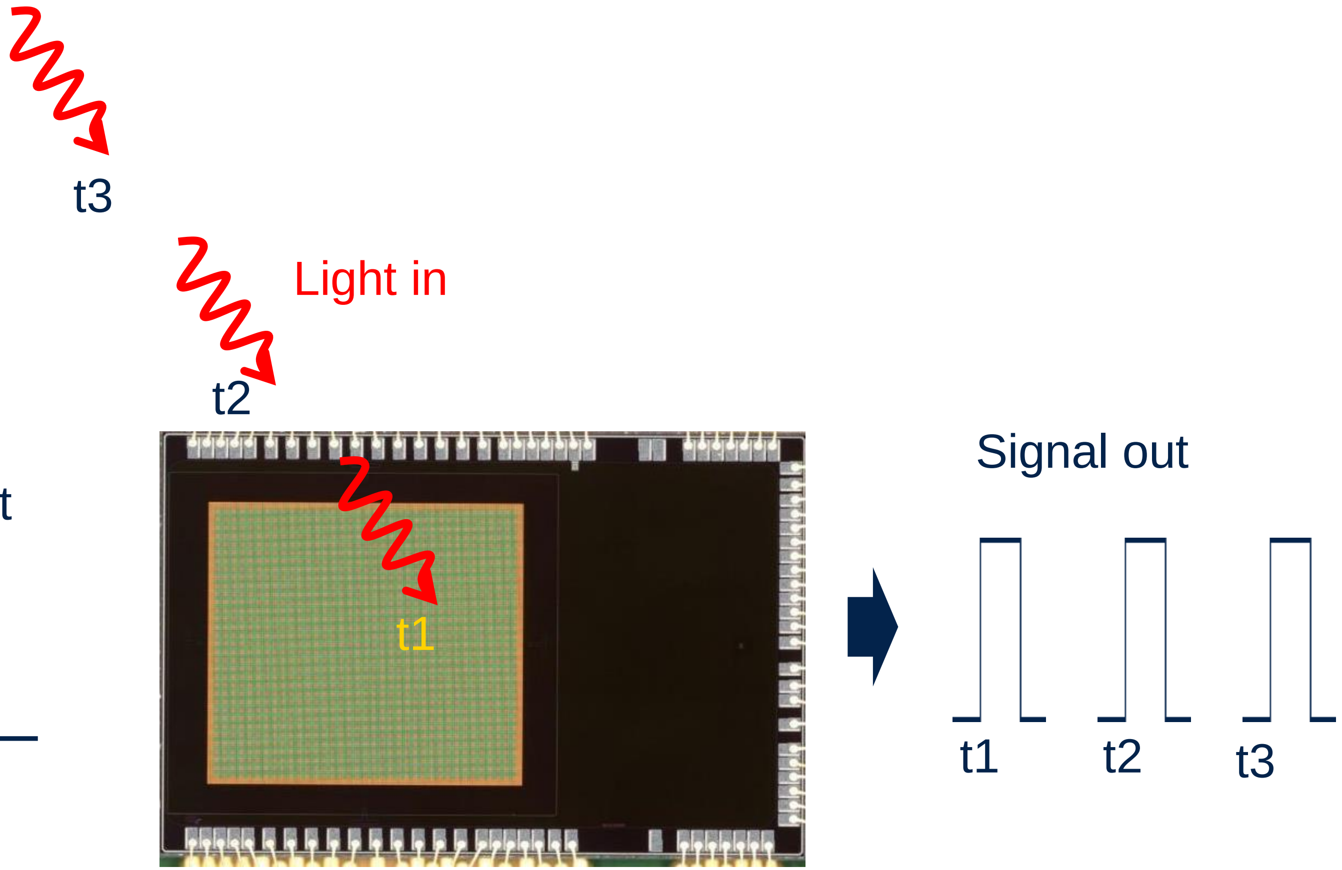


Measured distance = Photon travel time / 2 x Speed of light

LiDAR pixels' main characteristics

Sensitive to light	Capable to measure time of arrival of light





SPAD = the LiDAR pixel

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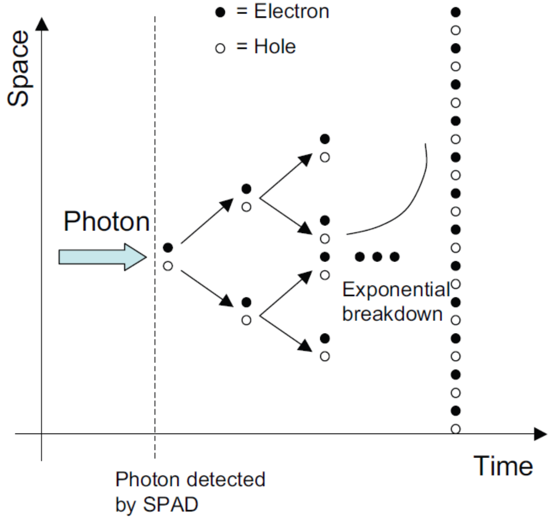
What is a SPAD?

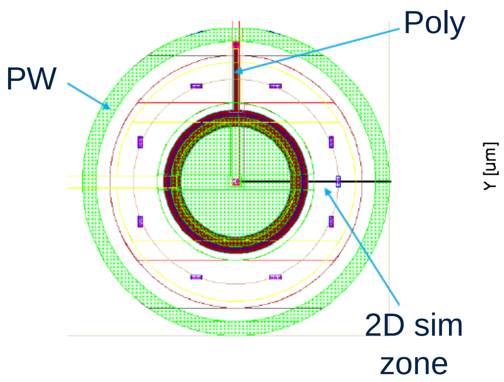
- **Single Photon Avalanche Diode**
- A SPAD **pixel** is the basic photosensitive element of a LiDAR camera
- Photodiode held in **reverse bias** beyond the breakdown voltage
- Output is digital, directly triggered by photon
  - Instantaneous response
  - Precise event counting (no readout noise)

  ➔ **150ps time resolution (rising edge average jitter)**

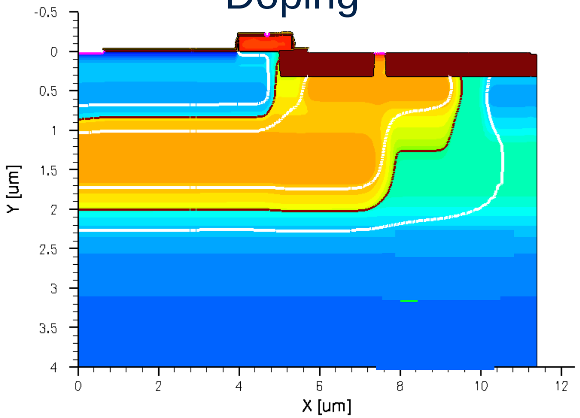
  ➔ **Enable Proximity to Long distance ranging**
- Two outputs per SPAD
  - Time arrival of photons ➔ **Distance**
  - Count arrival of photons ➔ **Signal intensity**



Layout



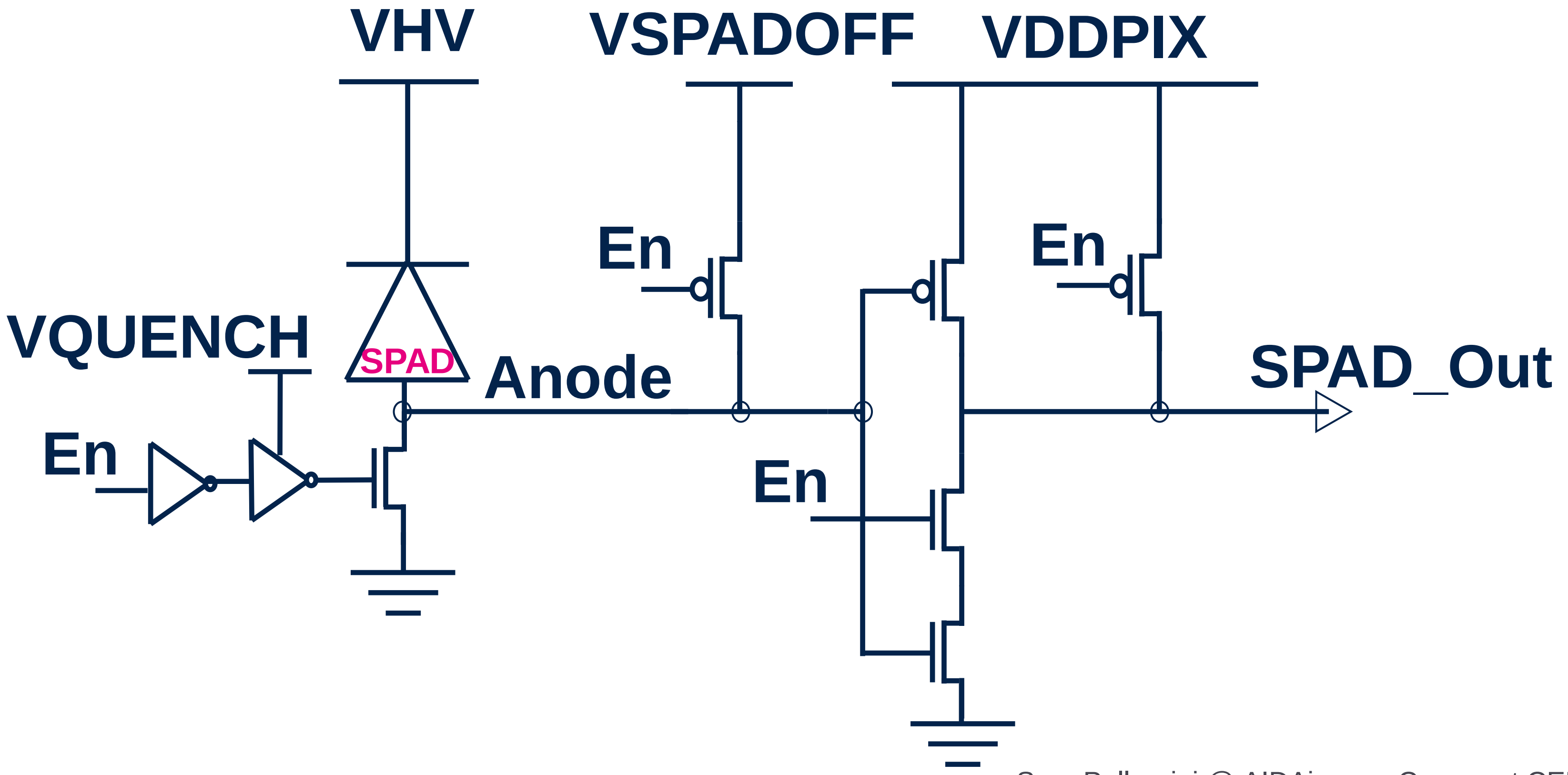
Doping



S. Pellegrini and B. Rae, “Fully industrialised single photon avalanche diodes,” SPIE Proceedings. SPIE, May 01, 2017. doi: 10.1117/12.2264364

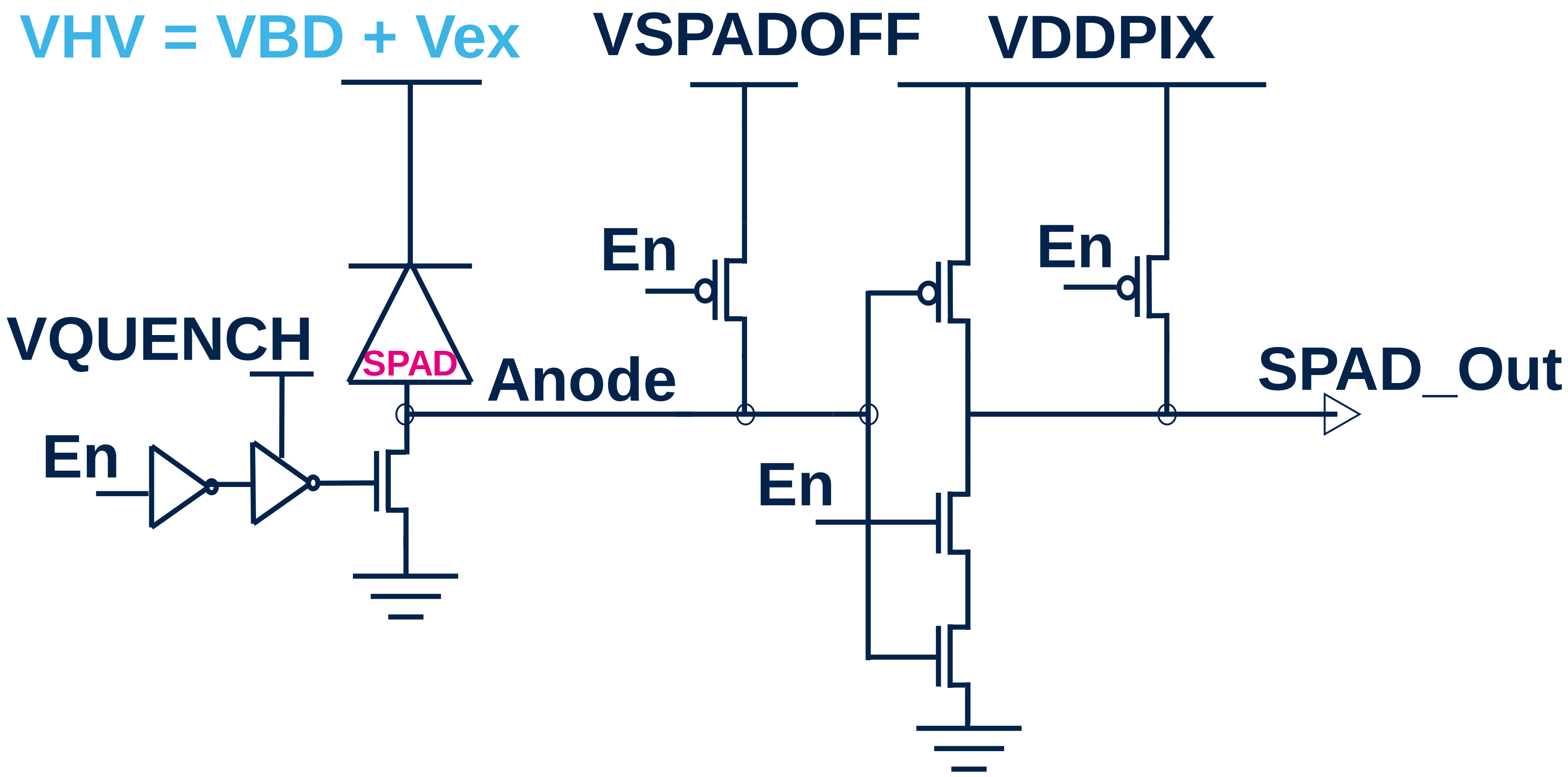
SPAD pixel quenching

- Passive quenching with disabling



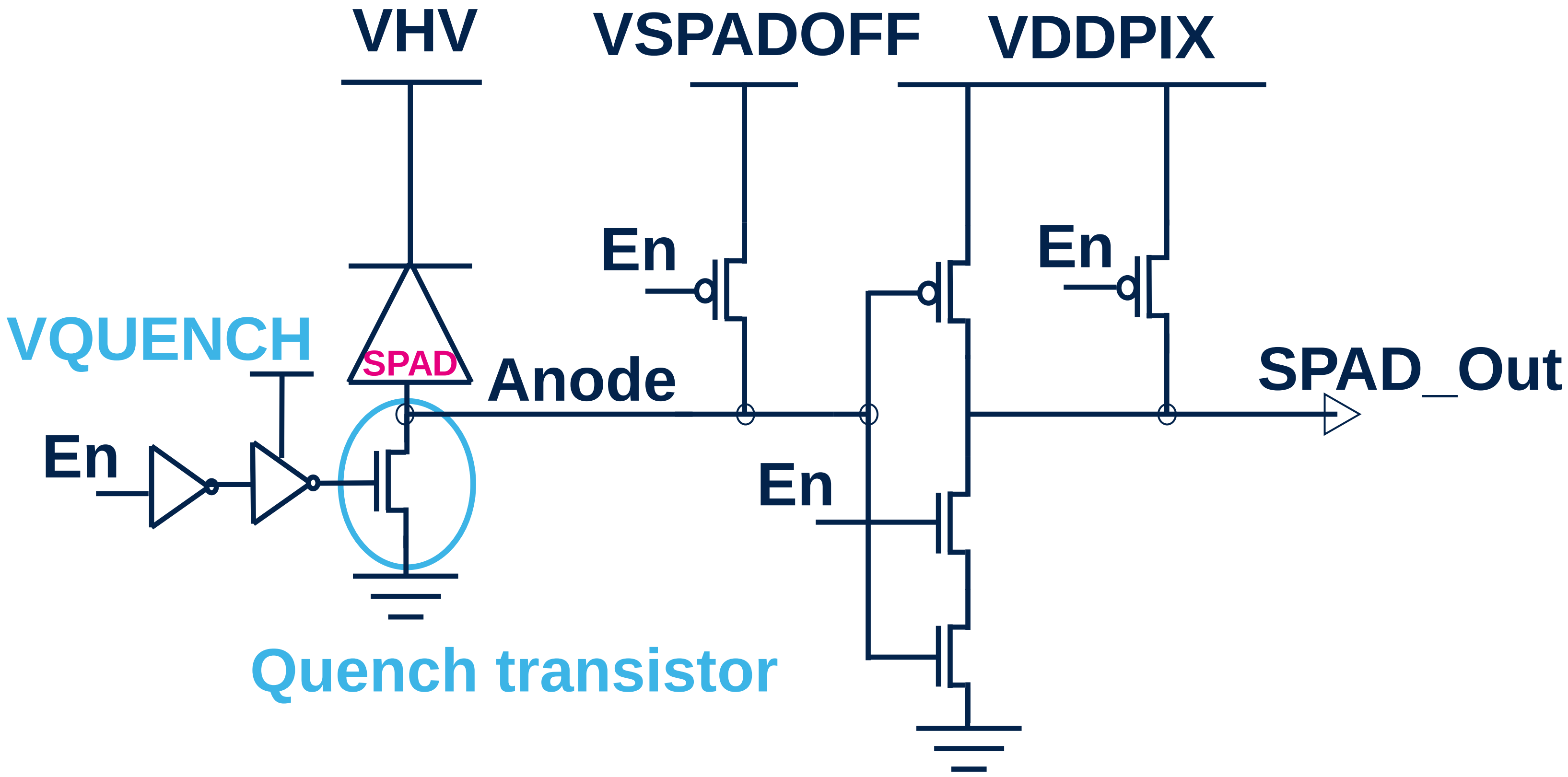
SPAD pixel quenching

- Passive quenching with disabling
  - Bias is beyond breakdown



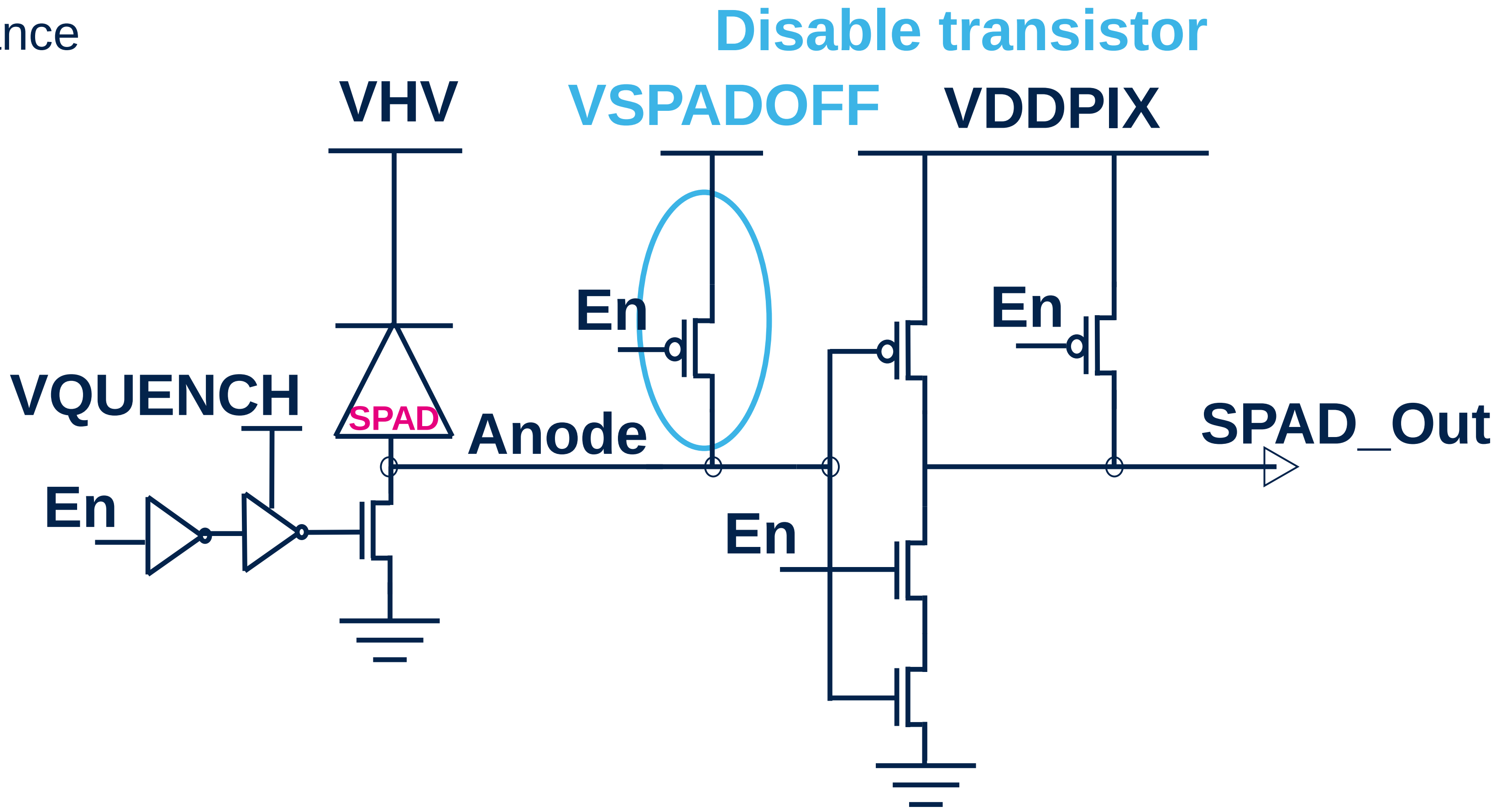
SPAD pixel quenching

- Passive quenching with disabling
  - Bias is beyond breakdown
  - Tuneable quench resistance



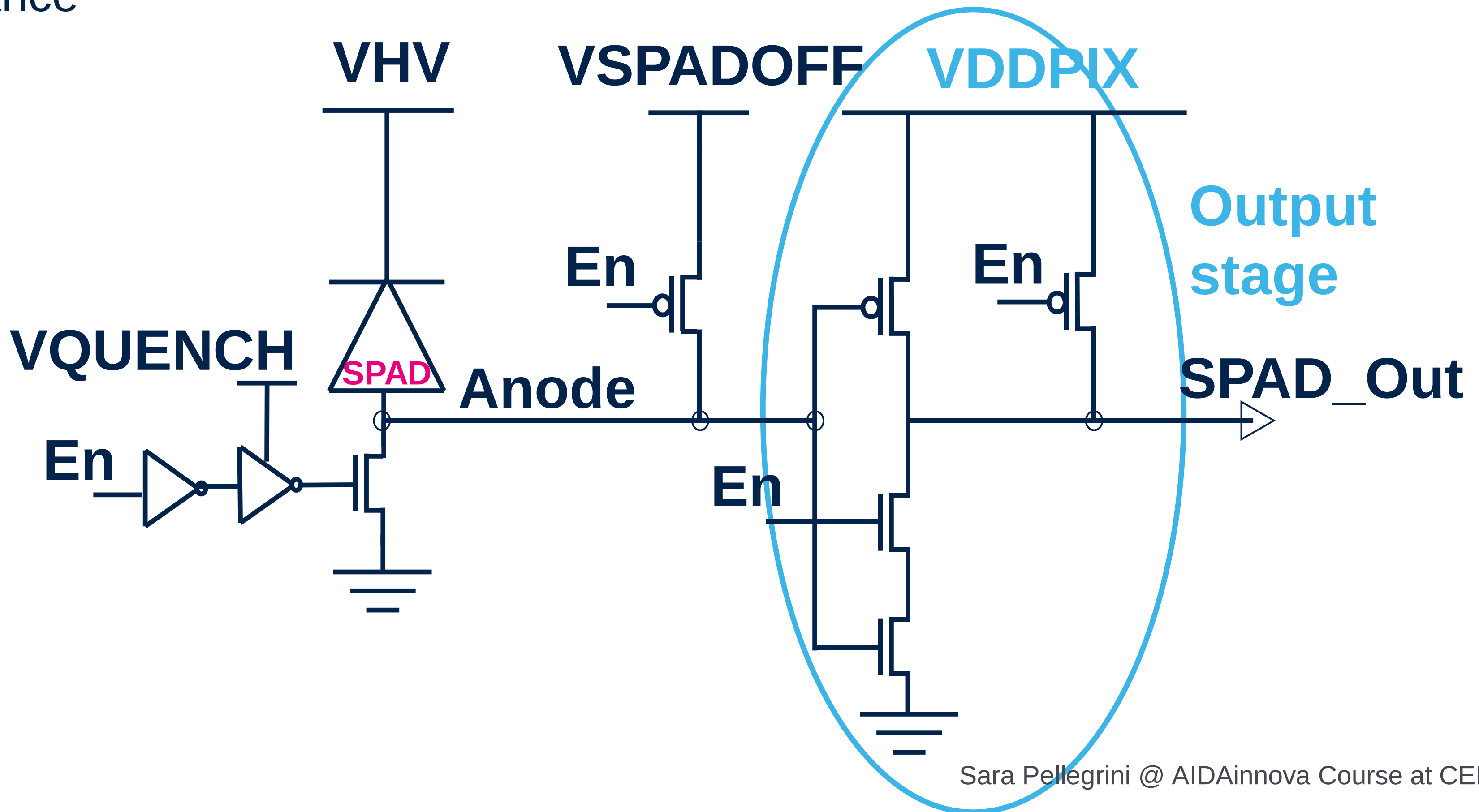
SPAD pixel quenching

- Passive quenching with disabling
  - Bias is beyond breakdown
  - Tuneable quench resistance
  - Disabling capability

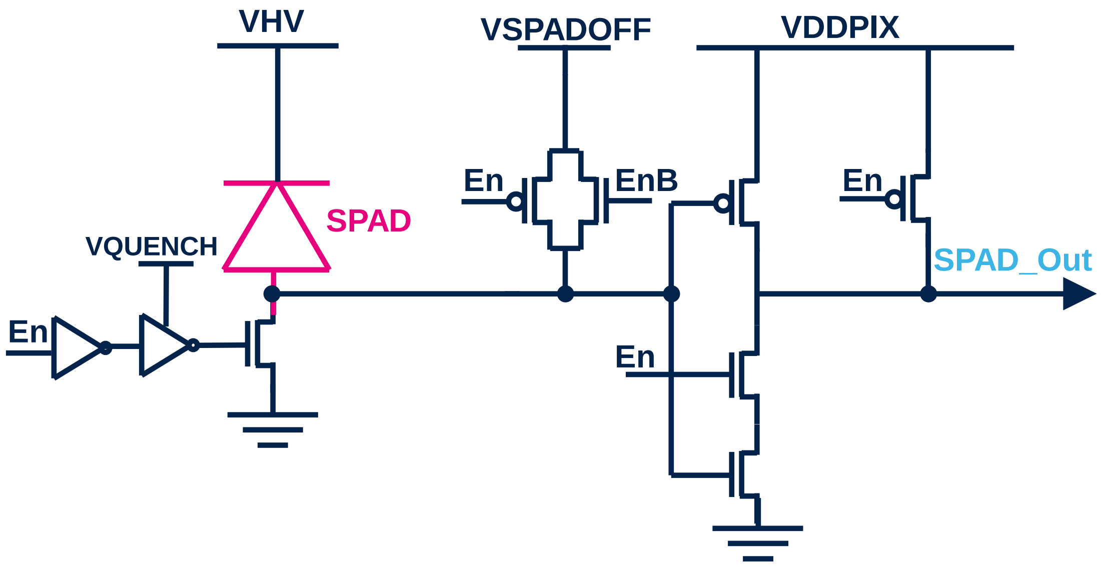


SPAD pixel quenching

- Passive quenching with disabling
  - Bias is beyond breakdown
  - Tuneable quench resistance
  - Disabling capability
  - True digital output

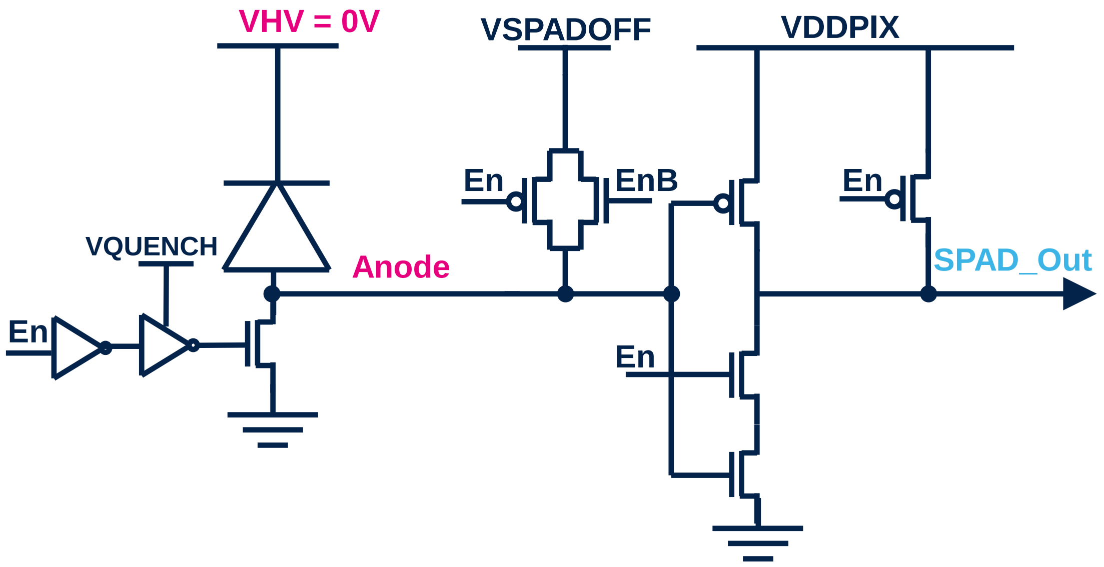


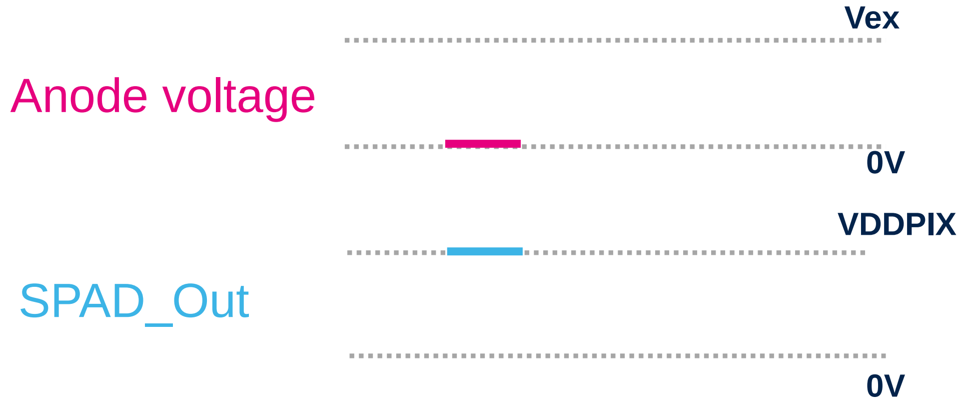
Passive Quench/Recharge Operation

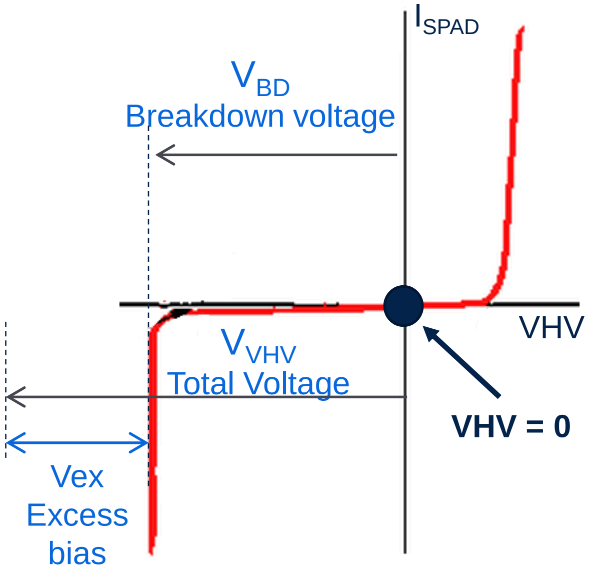


Passive Quench/Recharge Operation

No bias

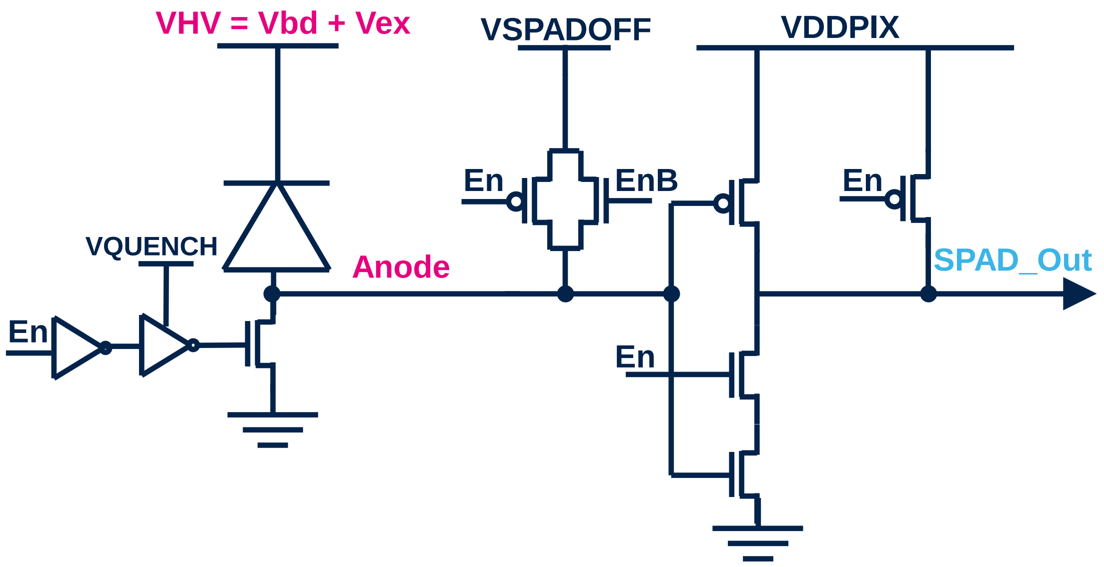


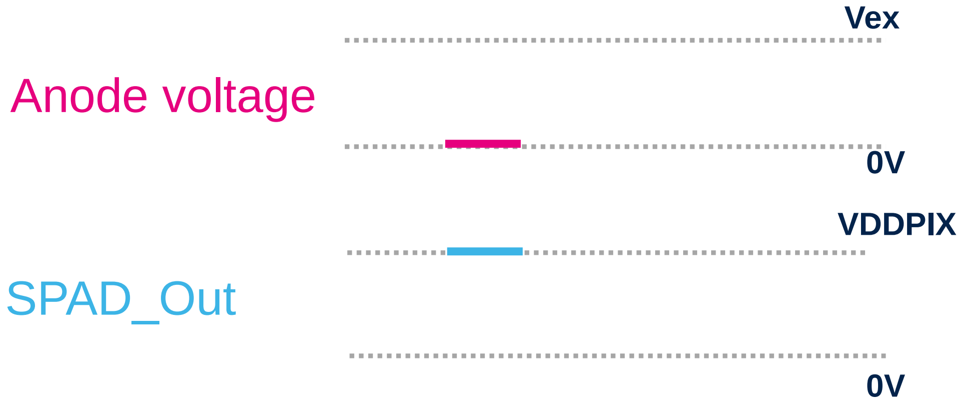


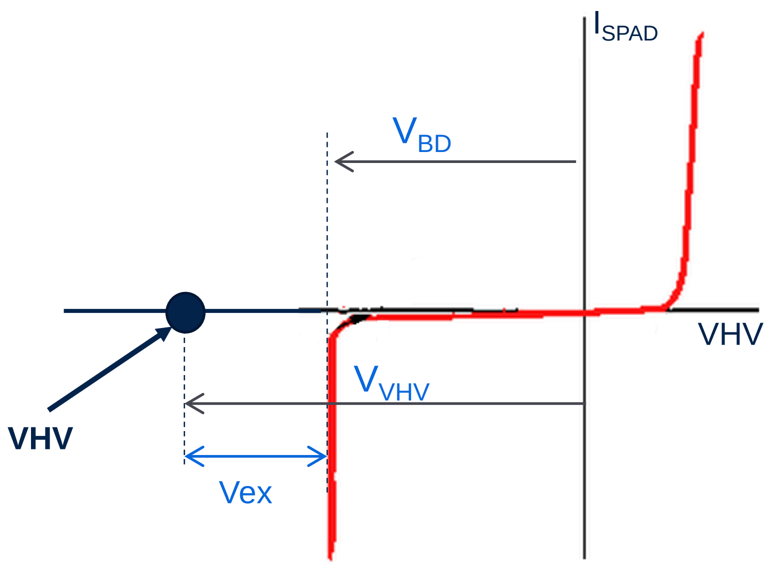


Passive Quench Pixel

High voltage bias

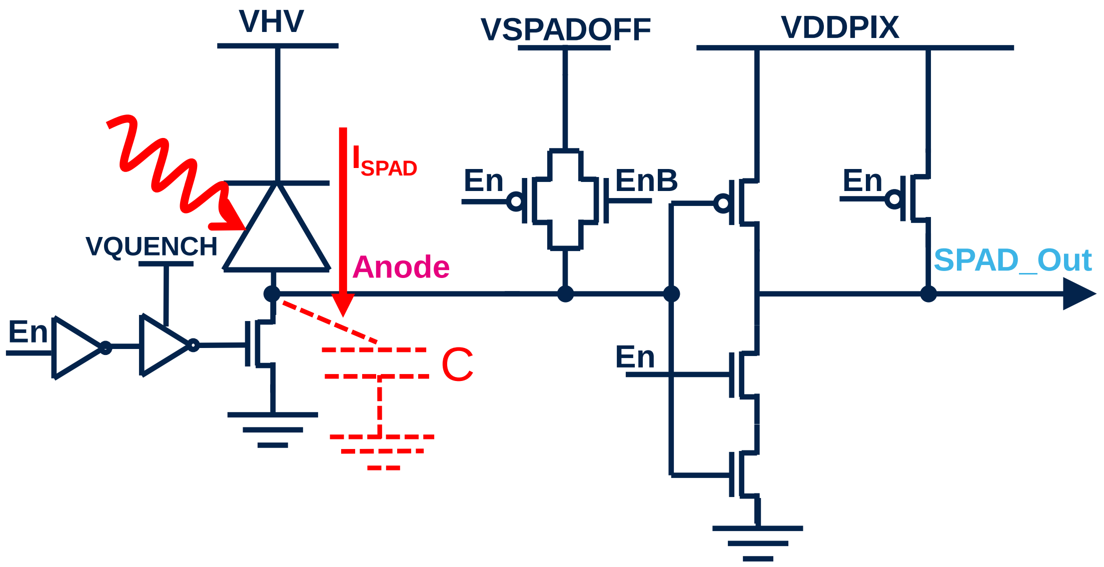


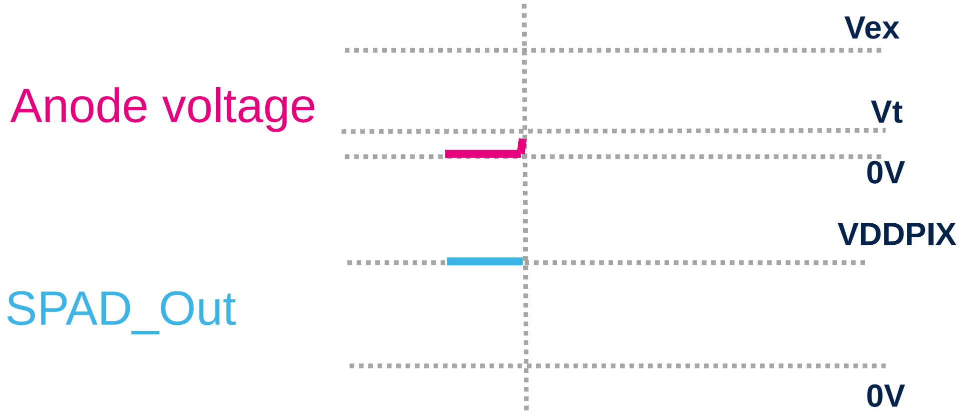


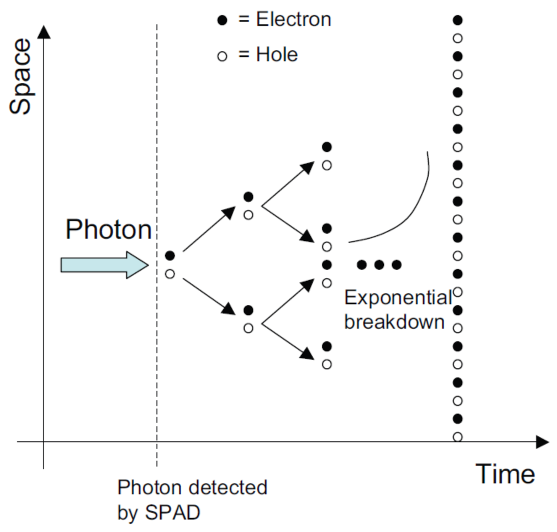


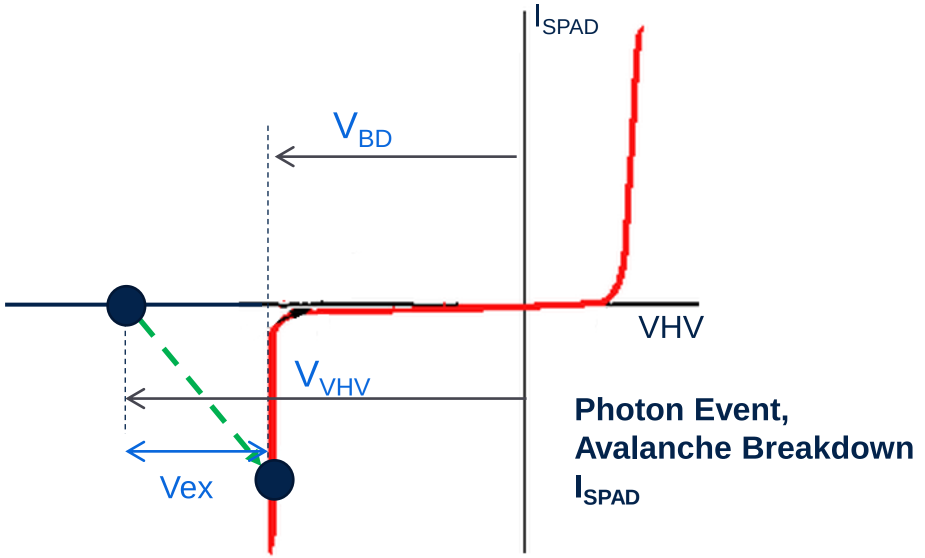
Passive Quench Pixel

Photon event



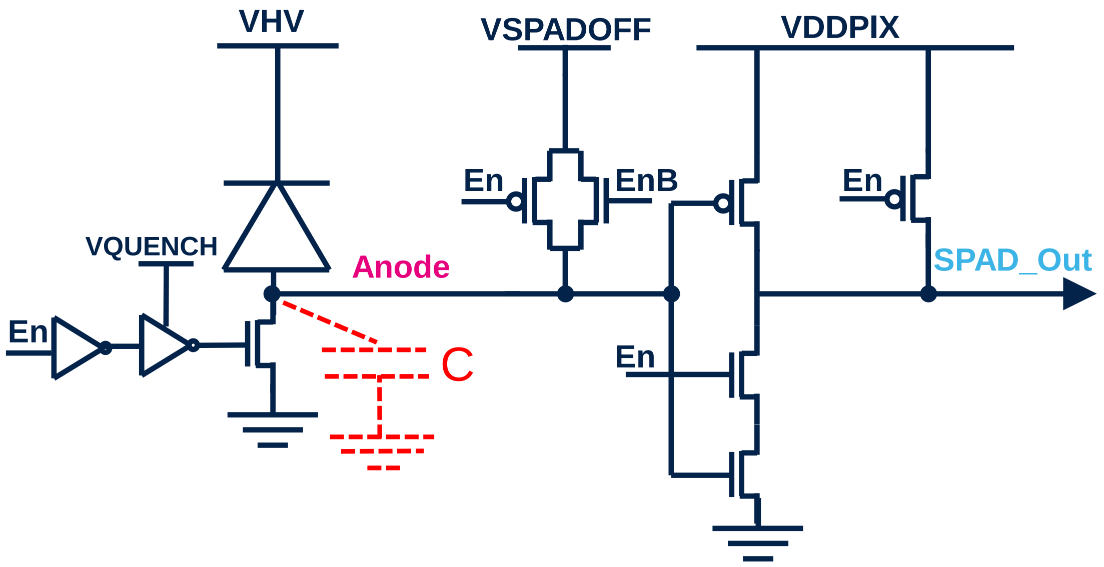


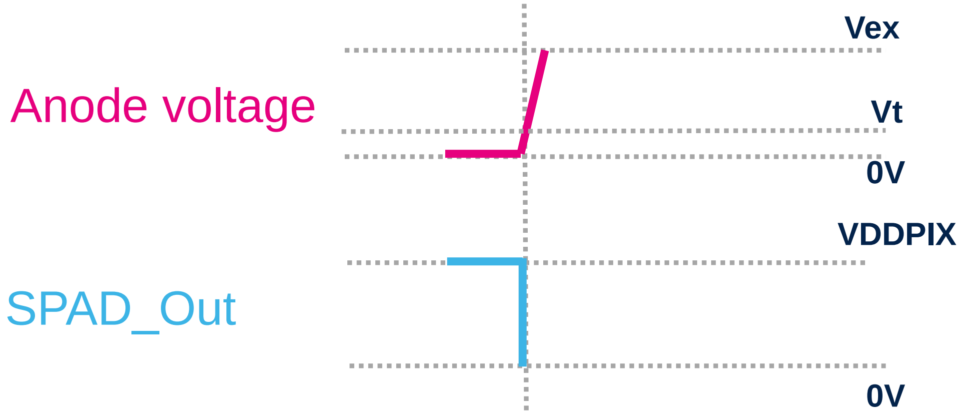


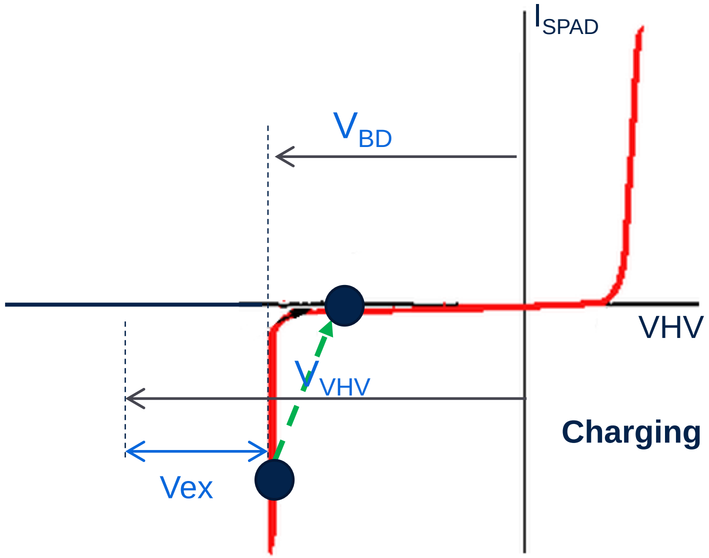


Passive Quench Pixel

Quench

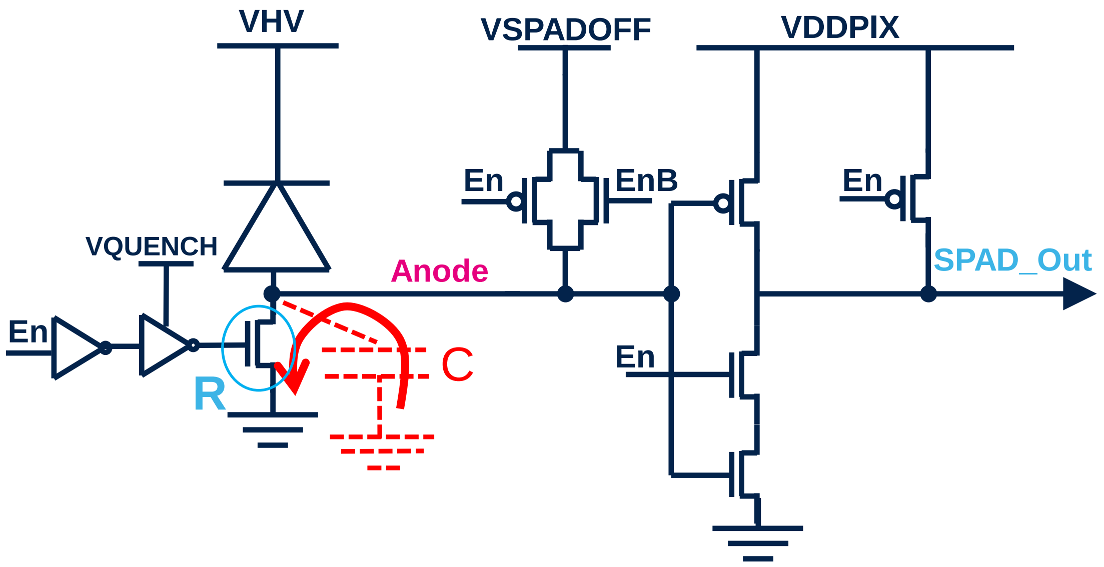


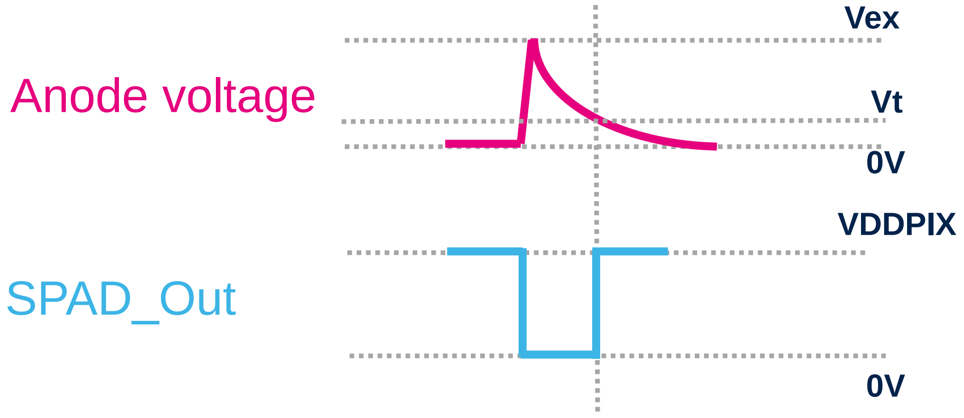


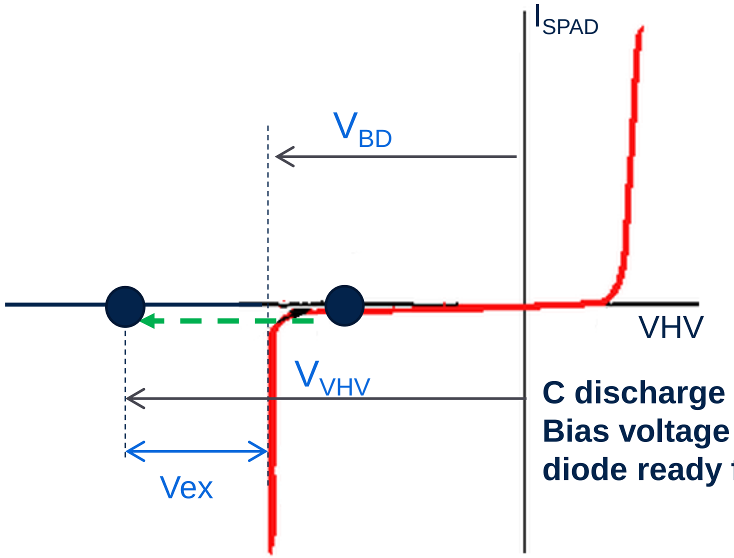


Passive Quench Pixel

Recharge







C discharge on R
Bias voltage increases – recharging diode ready for next breakdown event

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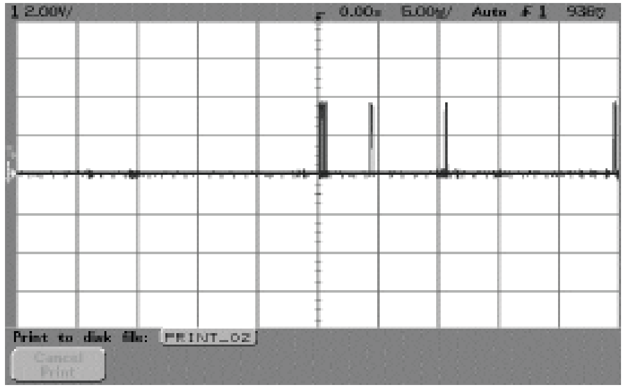
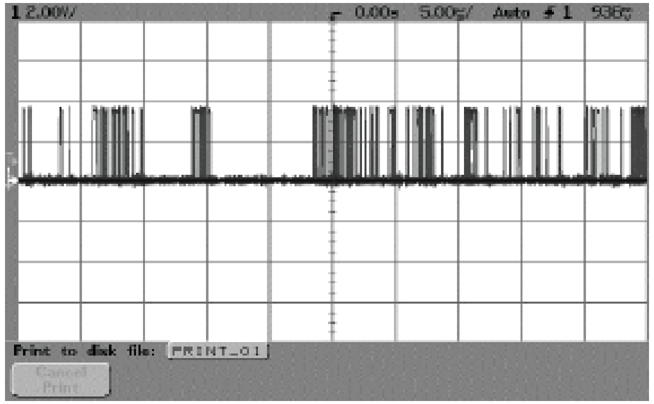
Electronics engineer ➔
Analogue circuit design
Pixel design

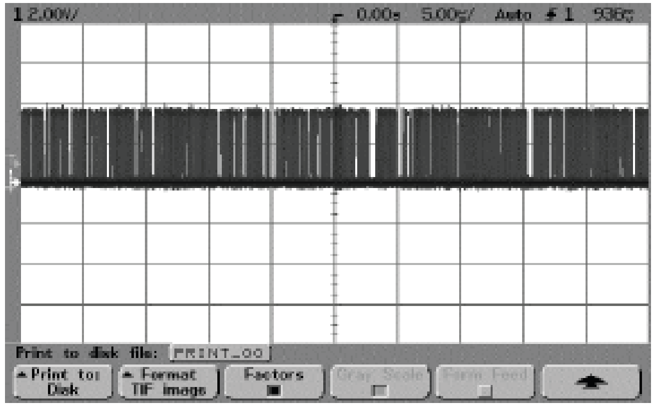
SPAD Pixel Output



Low Intensity



Medium Intensity



High Intensity

Intensity
=
counts / time

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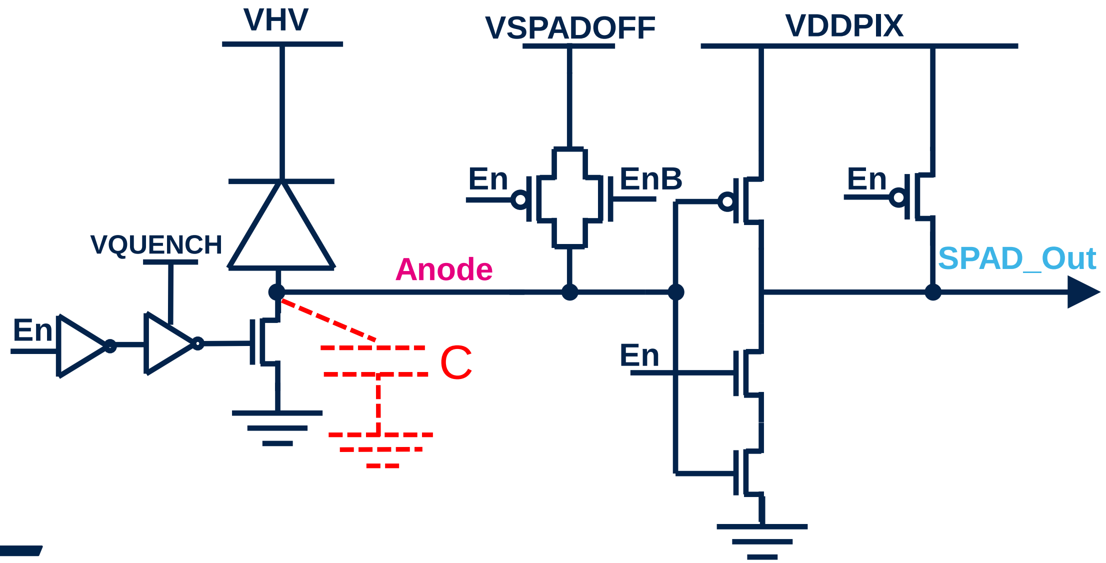
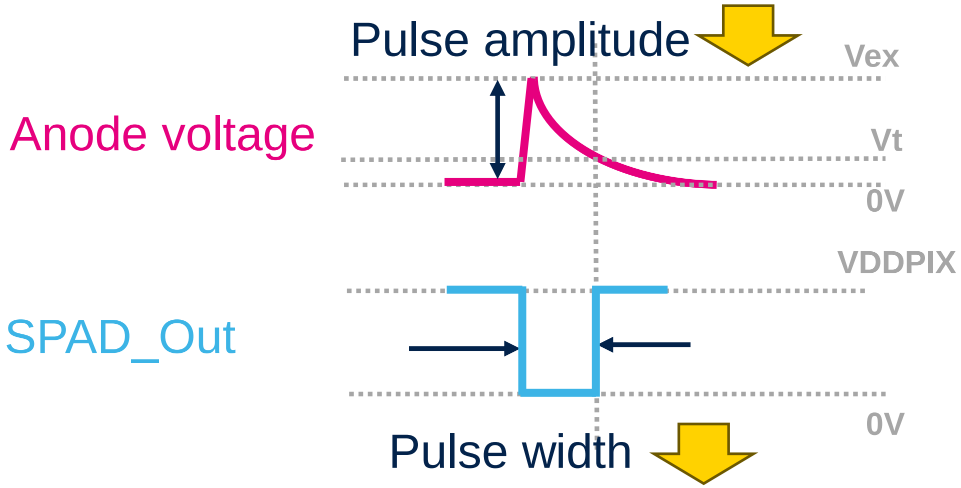
Quenching circuit optimisation

Power per pixel

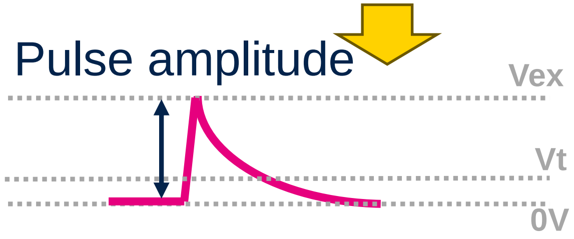
Maximum count rate



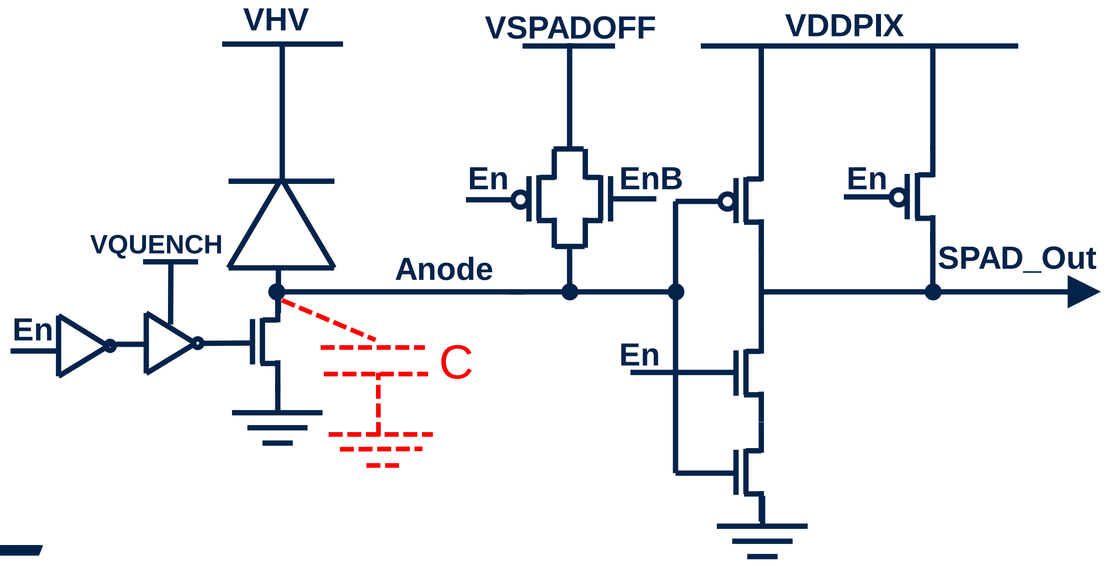


Quenching circuit optimisation

Power per pixel



I = **C** dV/dt

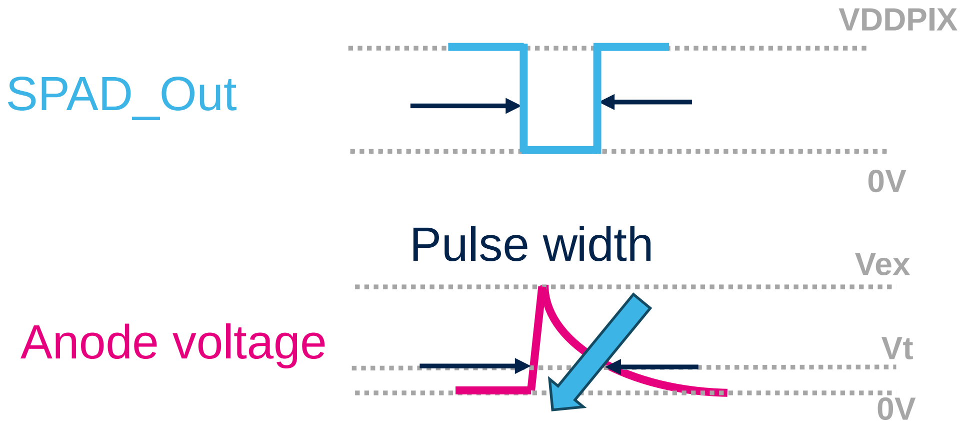


Reduce total current

Reduce **Vex**
AND / OR
Reduce **capacitance**

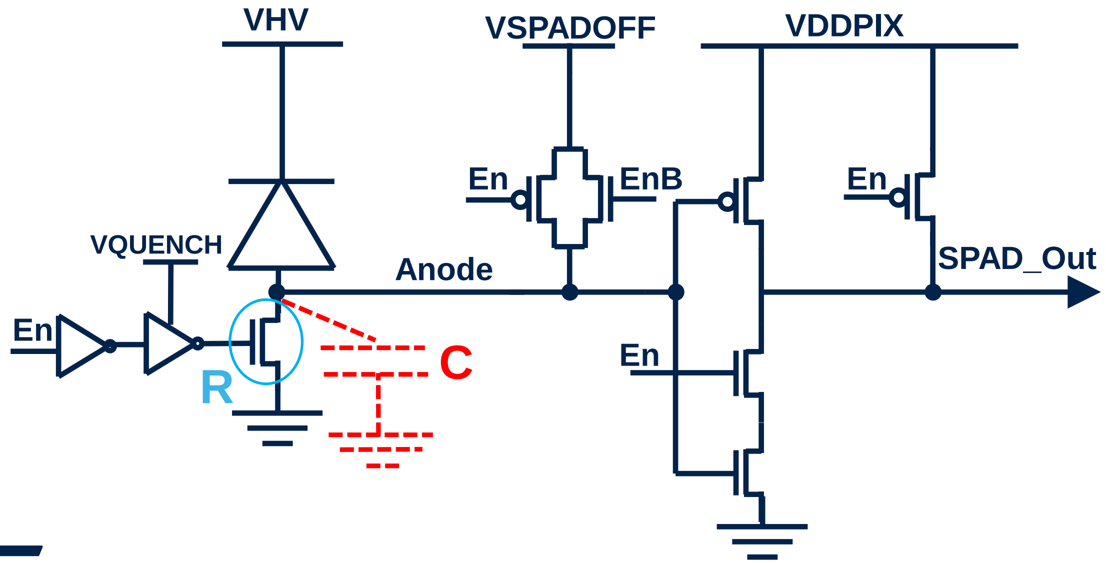
Quenching circuit optimisation

Maximum count rate



$V = V_0 e(-t/RC)$

Time constant T= RC

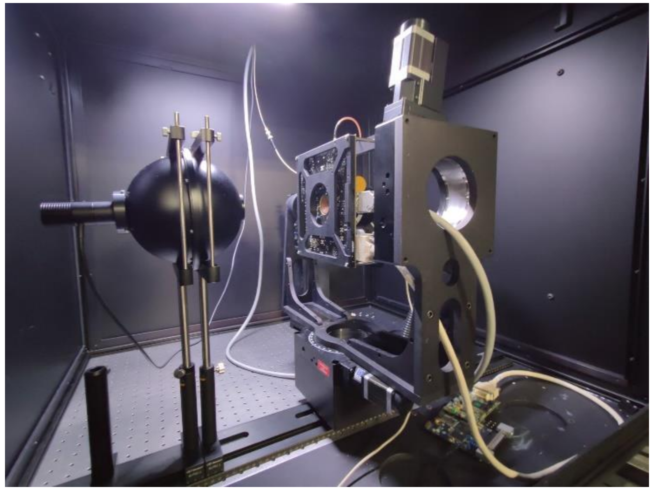


Reduce discharge time

Reduce **capacitance**
Reduce **resistance**

/!\ quenching capability

Pixel implementation flow



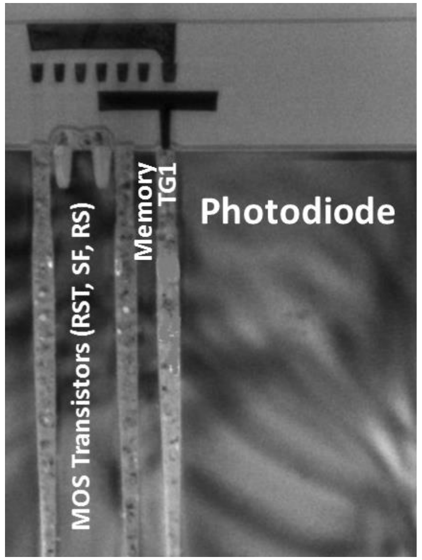
Taste it

Characterization
Electro-Optical
Characterization
Team

Take a cake order

Specifications
from customer

Electronics engineer ➔
TCAD simulations
Pixel design
Process implementation
Characterization



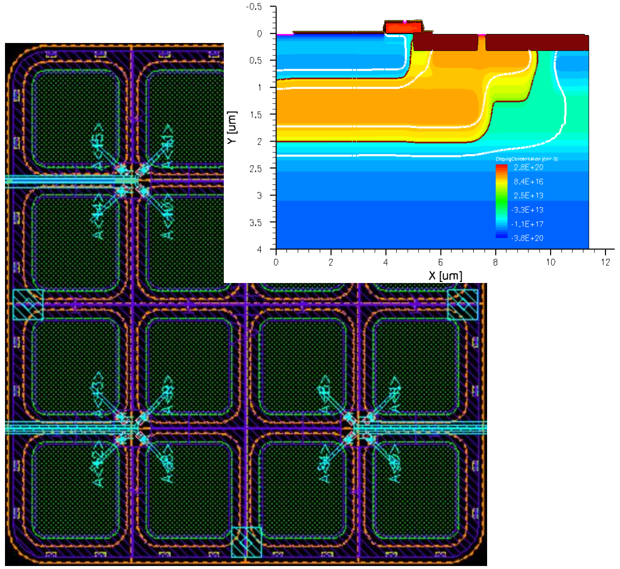
Manufacturing

Process
Integration
Team

Bake it

Layout, design
and process
definition

Pixel Design
and Simulation
Team



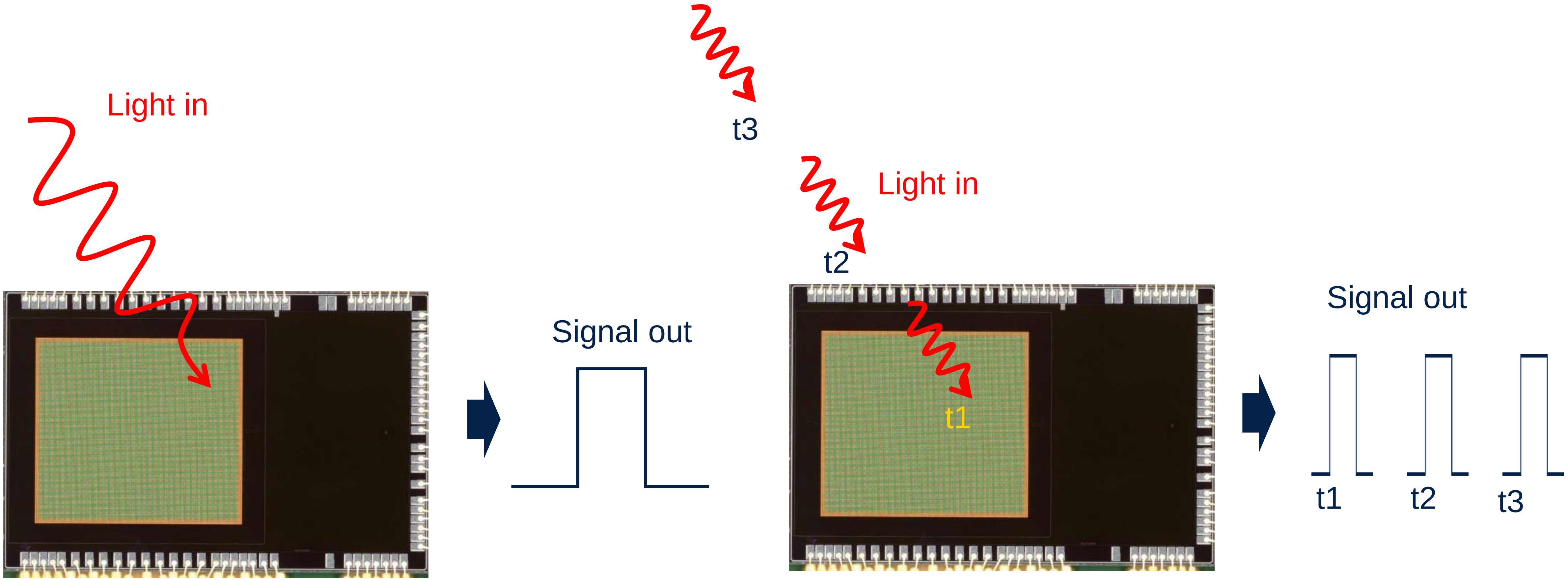
Draw its shape

Decide its ingredients

Time-of-flight sensing

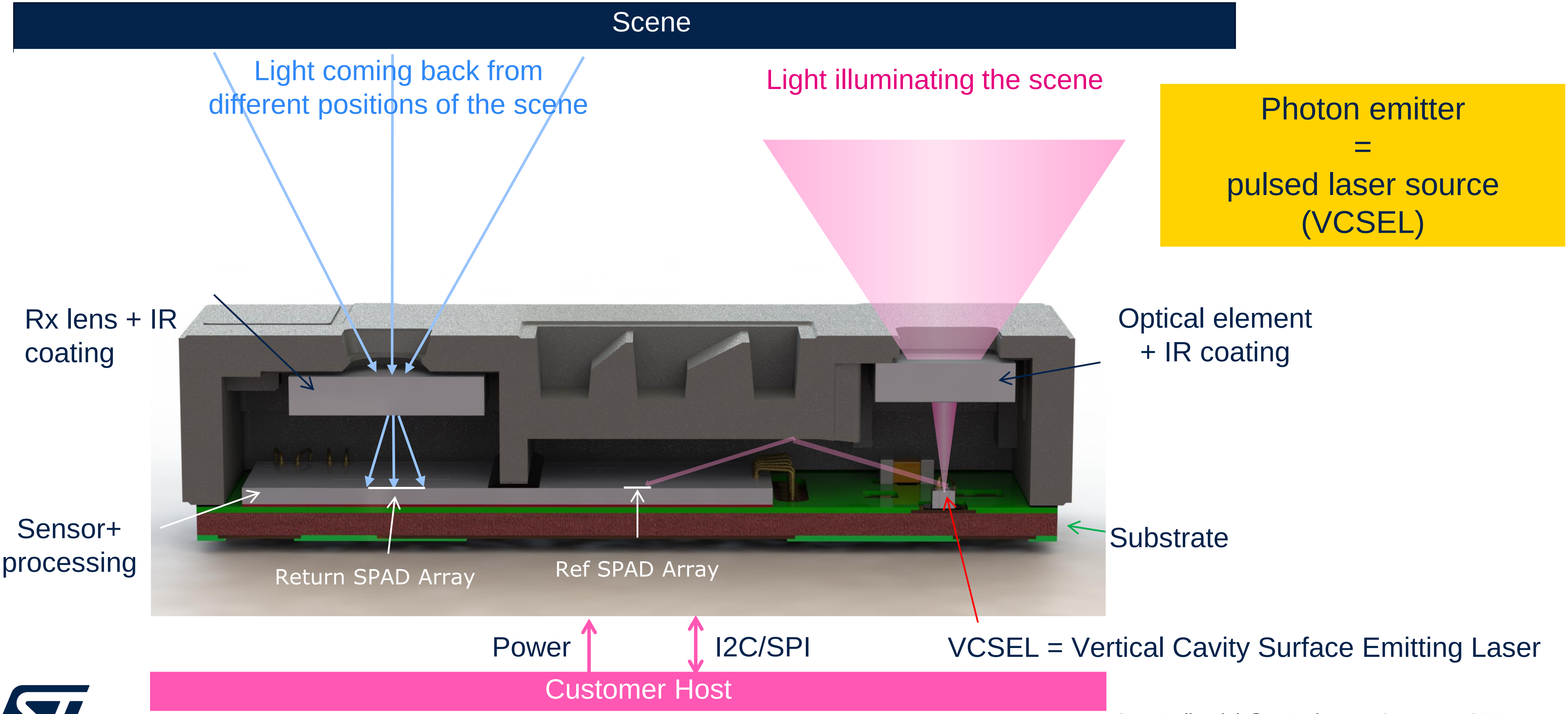
LiDAR pixels' main characteristics

Sensitive to light	Capable to measure time of arrival of light



ST VL53L5: System overview

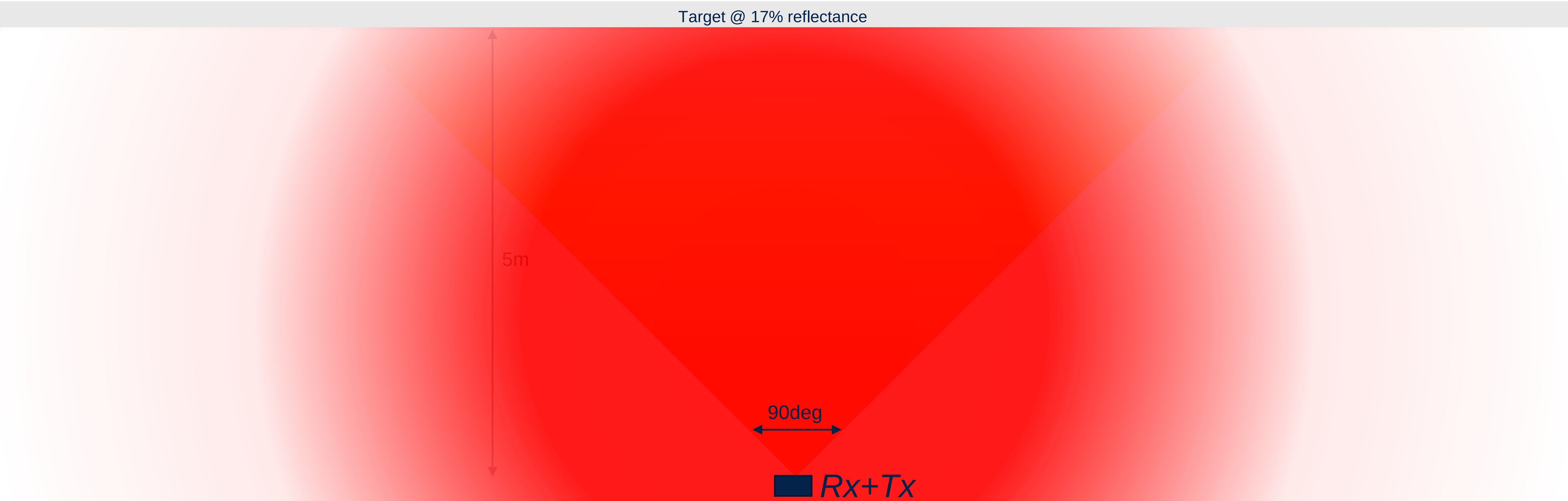
VL53L5 calculates the distance of objects by measuring the travel time of the light.



F. Martin et al., “An all-in-one 64-zone SPAD-based Direct-Time-of-Flight Ranging Sensor with Embedded Illumination,” 2021 IEEE Sensors. IEEE, Oct. 31, 2021. doi: 10.1109/sensors47087.2021.9639840

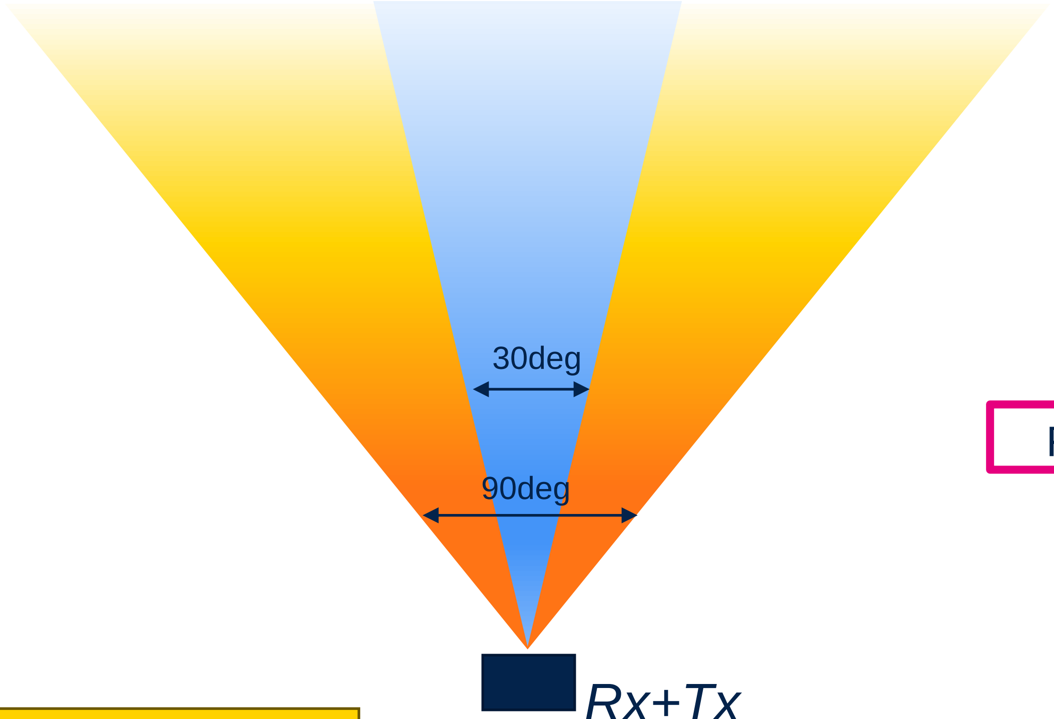
Time-of-Flight Challenge – low signal return

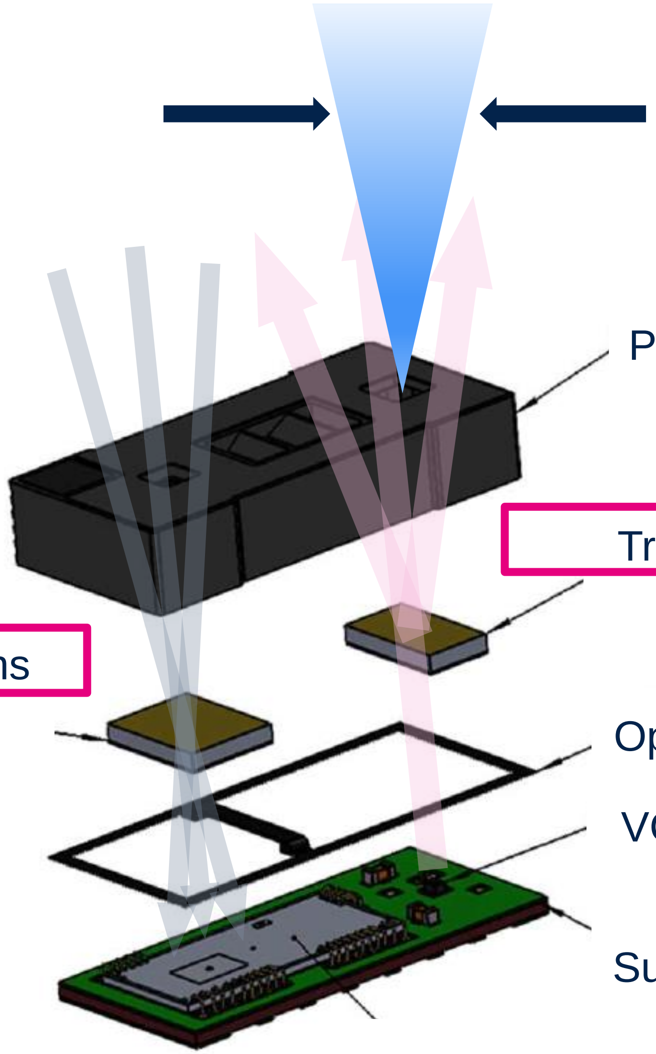
1 quadrillion (1,000,000,000,000,000) photons emitted



Only 1 signal event received!

Low Signal Return → Module & Optics





Mechanical Engineers
Optical Engineers

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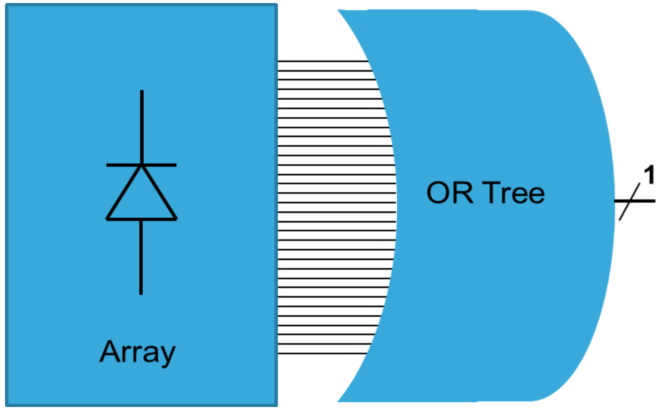
Low signal return ➔ SPAD Macro Pixel

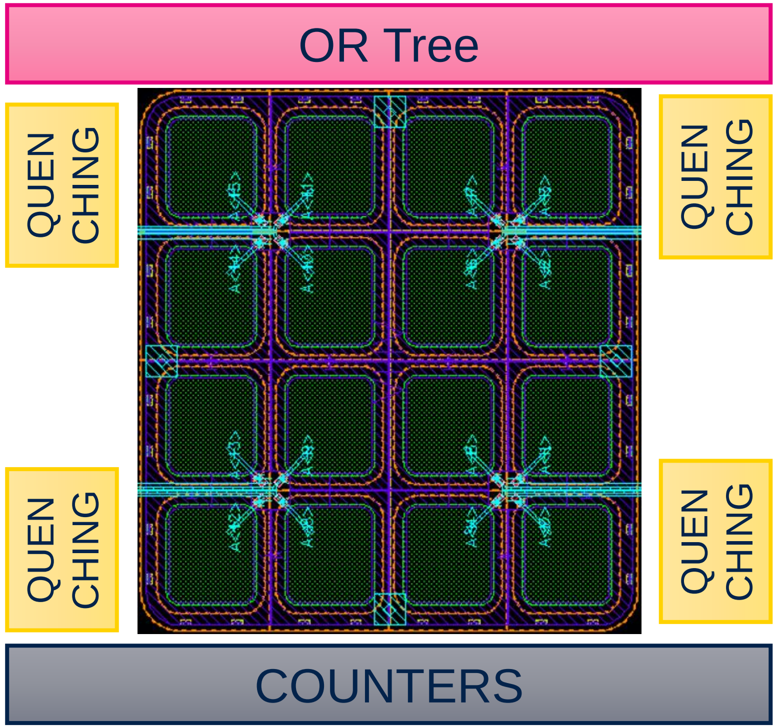
4 x 4 SPADs

- Increased sensitivity x 16

Logic

- Individual quenching and enabling
- Counters





Time-of-Flight challenges – background illumination

- Ideal situation

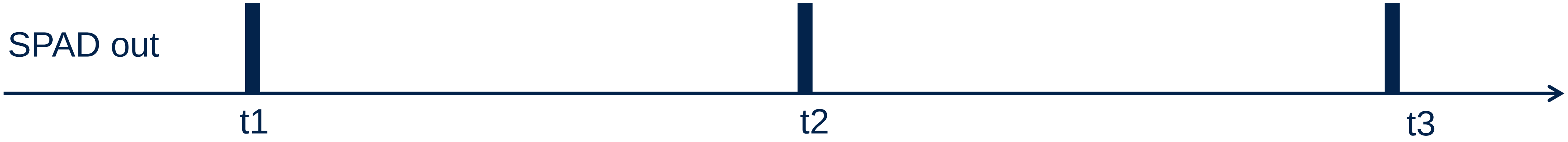
→ Dark night

- Real situation

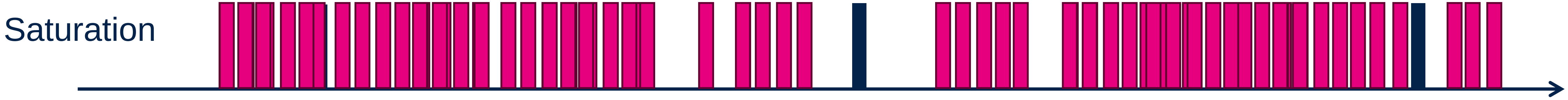
→ Bright daylight

Time-of-Flight challenges - background illumination

- Ideal case ➔ no background noise



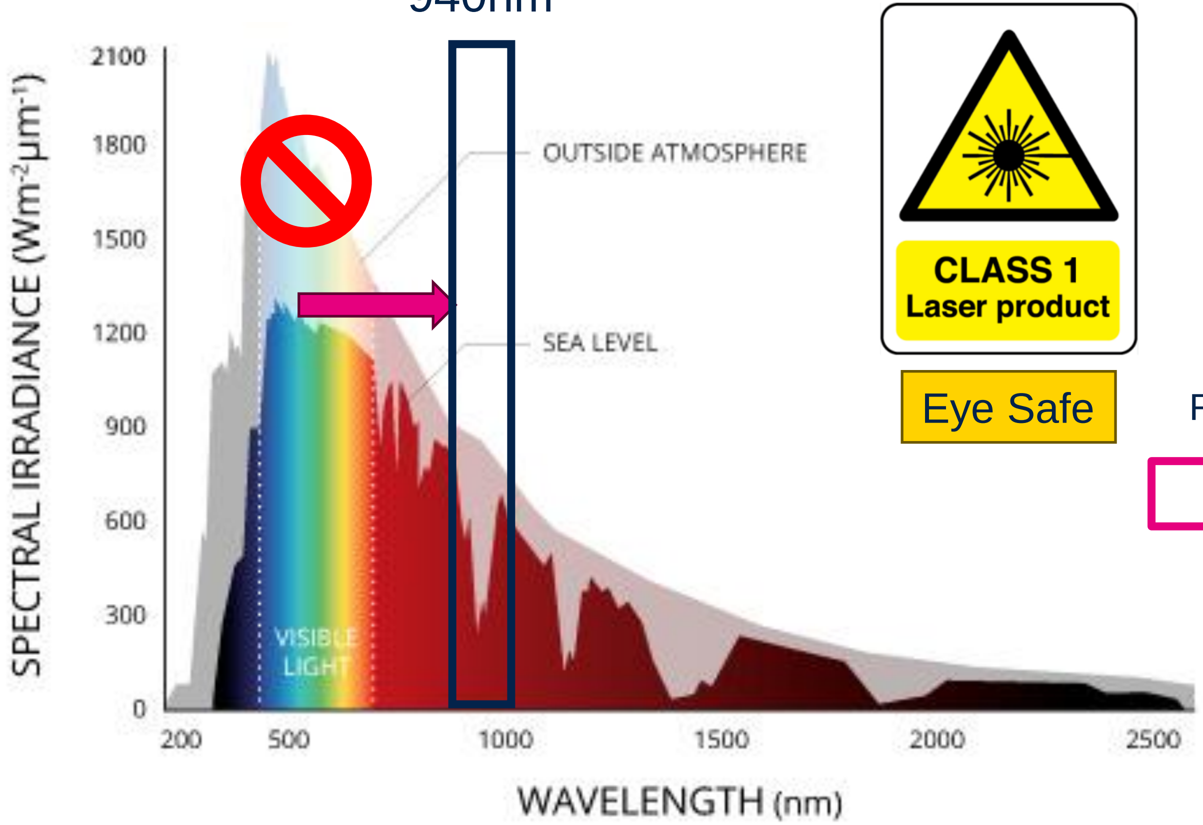
- Real case ➔ background illumination and SPAD noise



Background illumination ➔ bandpass filter

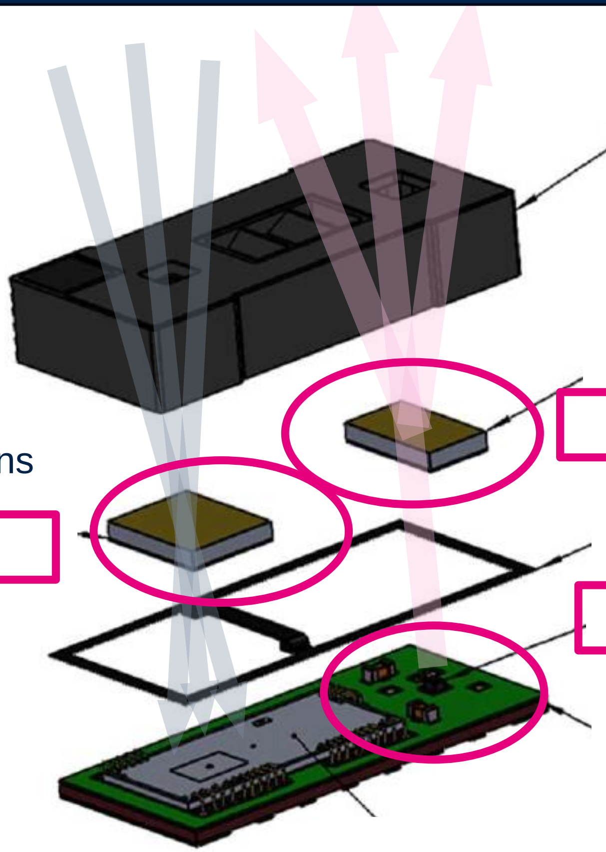
Select wavelength for low sun irradiance

940nm



Eye Safe

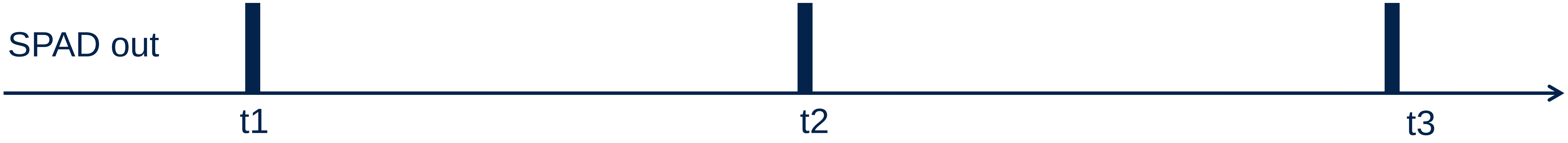
Introduce optical bandpass filters



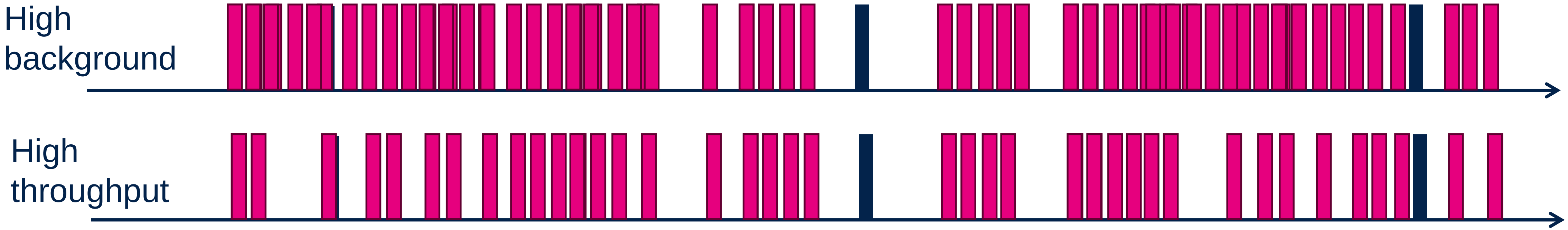
Illumination at 940 nm

Time-of-Flight challenges – background illumination

- Ideal case ➔ no background noise



- Real case ➔ background illumination and SPAD noise



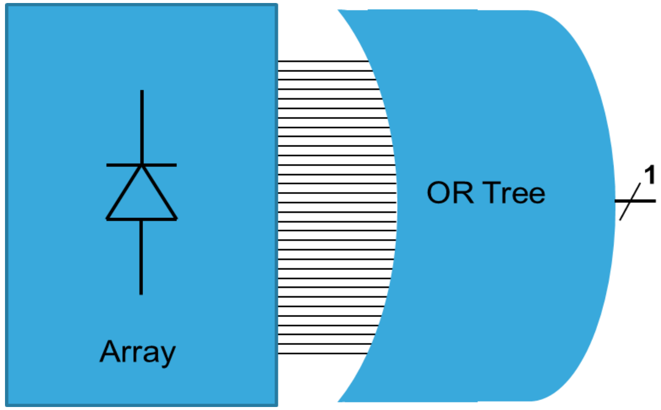
Low signal return ➔ SPAD Macro Pixel

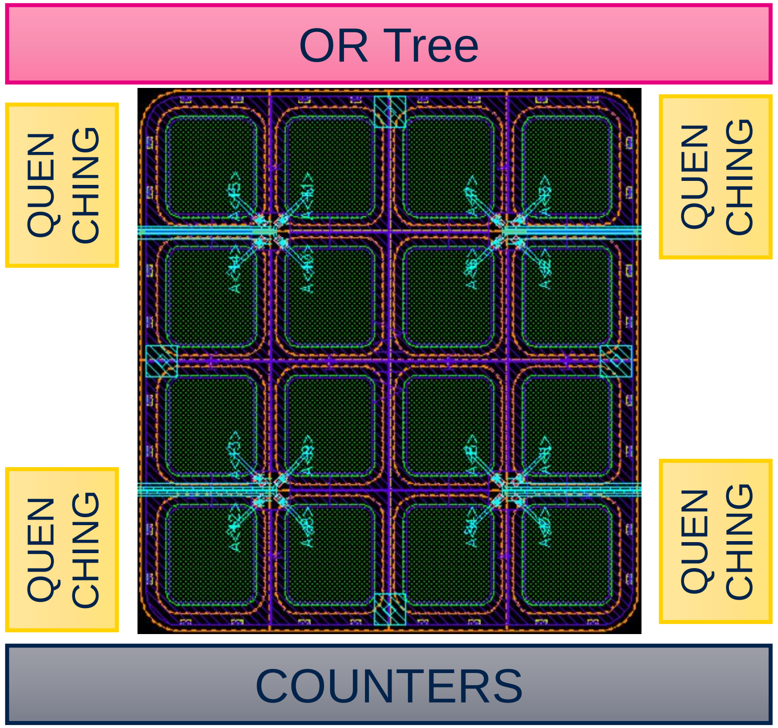
4 x 4 SPADs

- Increased sensitivity x 16

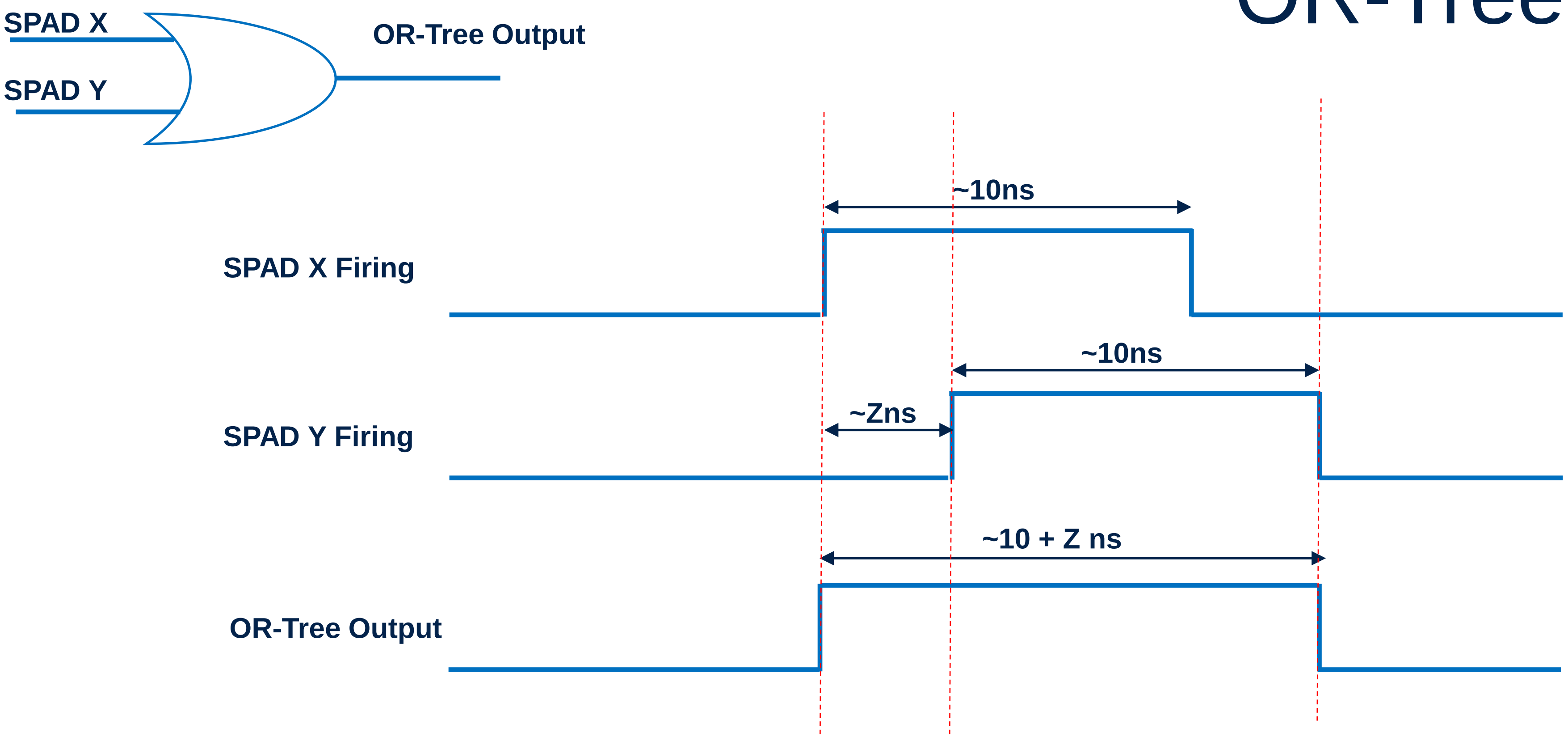
Logic

- Individual quenching and enabling
- Counters
- **OR tree**



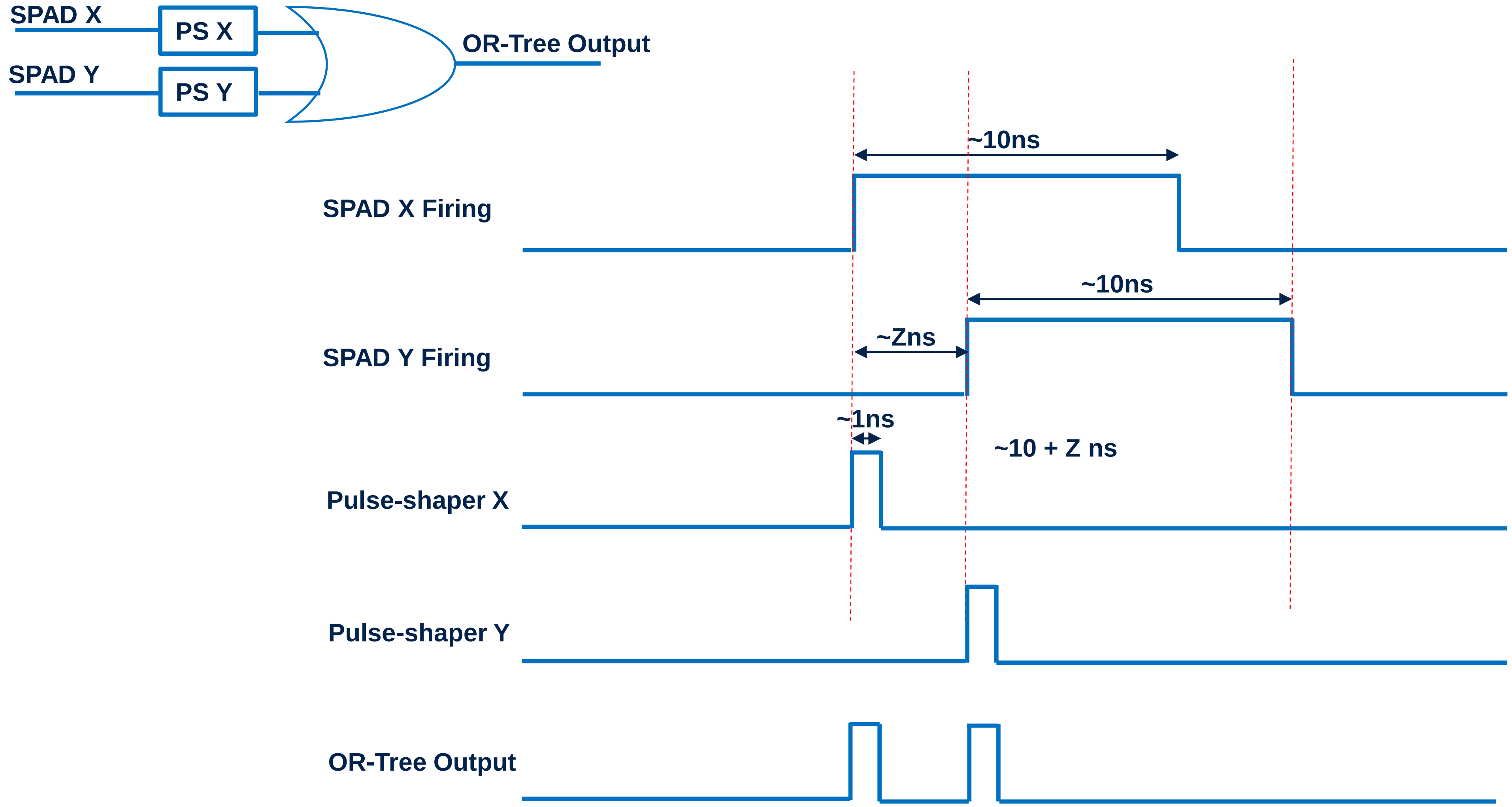


OR-Tree Congestion



- The above scenario is known as OR-tree congestion
- As the number of SPADs in the array or light levels increase chance of cross-talk increases

OR-Tree Congestion



- There is a dedicated pulse shaper per pixel
- Maximises OR-tree bandwidth

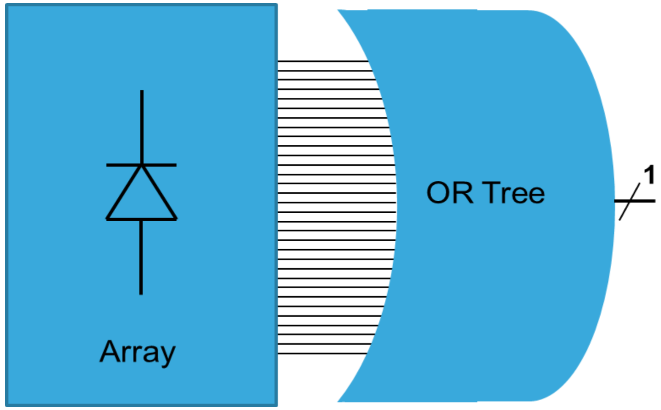
SPAD saturation → SPAD Macro Pixel

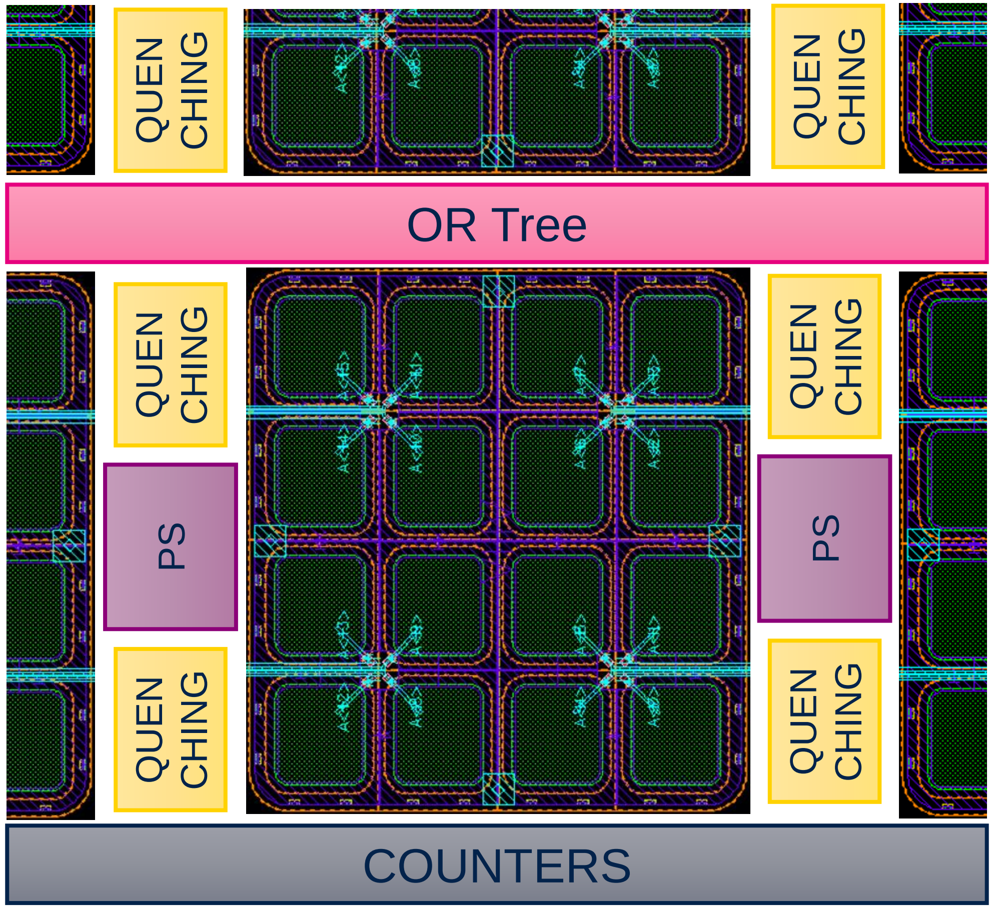
4 x 4 SPADs

- Increased sensitivity

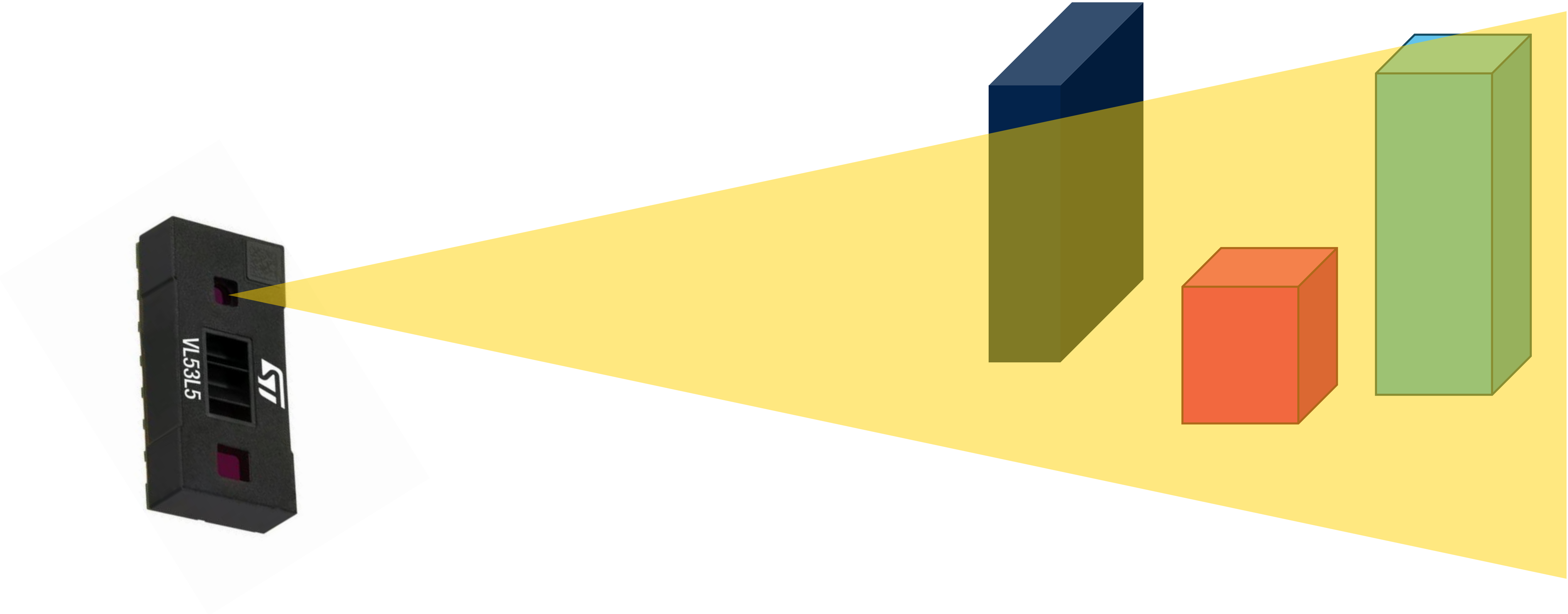
Logic

- Individual quenching and enabling
- Counters
- **Pulse shaper**
- OR tree

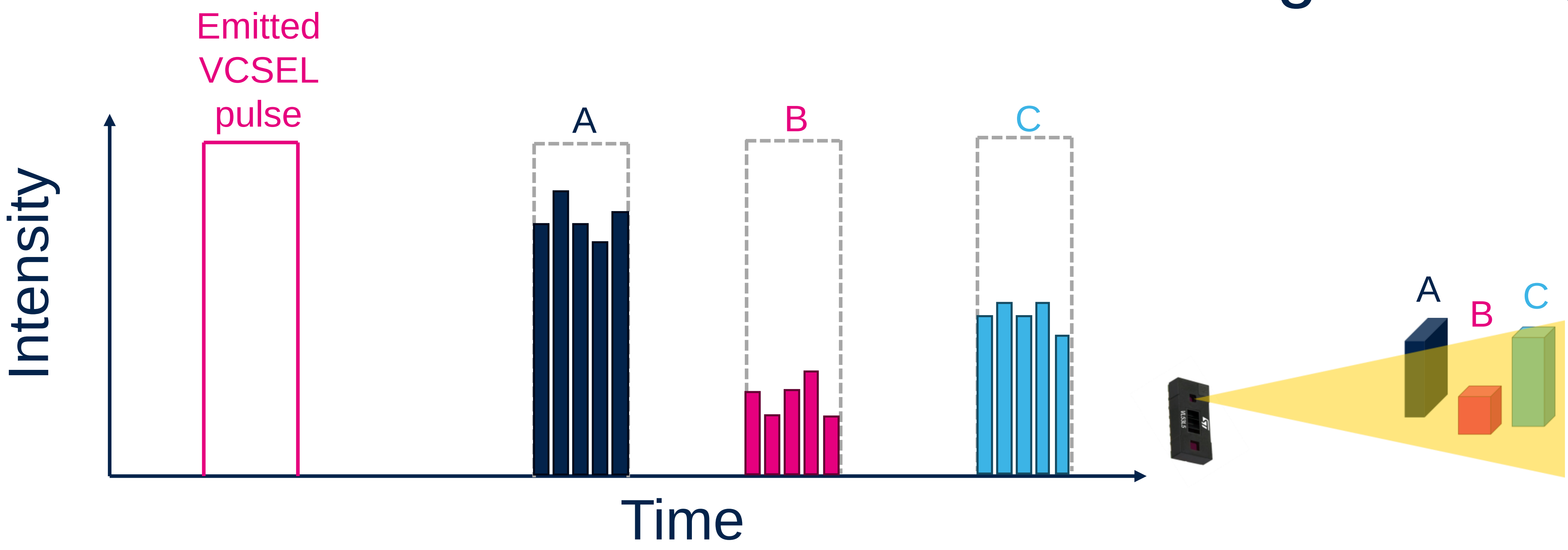




Time-of-Flight challenge – multi-object scene



Histogramming



- Each histogram bin represents a time slot
- Each peak in the histogram represents an object

- ➔ we can identify all the objects
- The cost is high amount of data and power

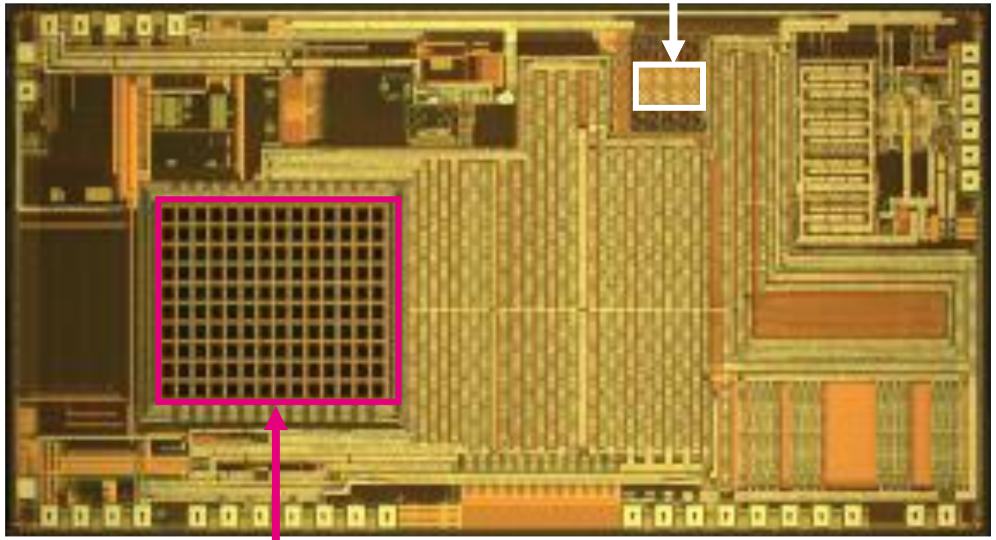
ST VL53L5: Silicon Description

VL53L5 specific silicon functionalities:

VCSEL Driver

Return and reference SPAD arrays

16 histogram parallel Readouts (64 obtained by scanning by 4)



Microcontroller

Full histogram processing

Autonomous ranging specific management

The return array zones are configurable in size and location to allow different ranging options: 4x4 or 8x8

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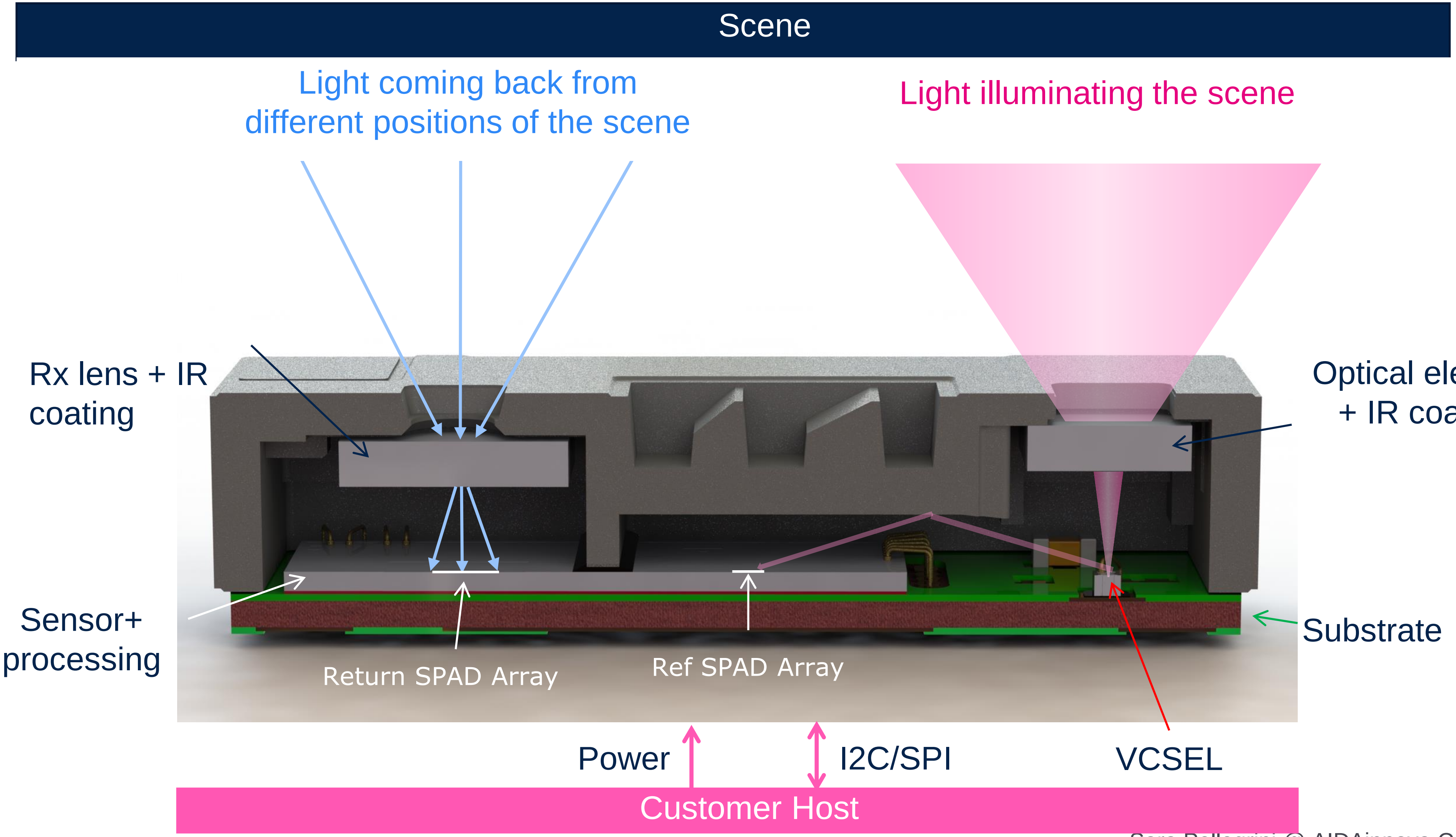
ST VL53L5: System overview

VL53L5 calculates the distance of objects by measuring the travel time of the light.



Product design flow

Pixel Develop-ment
- Pixel Design
- Pixel Characte-rization
- TCAD Simulation

Continuous

Silicon Design
- Analogue FE / BE
- Digital FE / BE
- System Archite-cture

3-6 months*

Manufacture
- Silicon Fab Production

>3 months*

AVSS, Test & Product Engineering Hardware Development
- EWS Test Develop-ment
- 2 weeks* — **Manufacture**: Module Assembly
- Final Module Test

Module R&D
- Module Design
- Optical Design

3-6 months*

Application/Validation
- SW Team
- Customer Support

Program Management, Planning & Marketing

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* All times are estimates based on monolithic technology

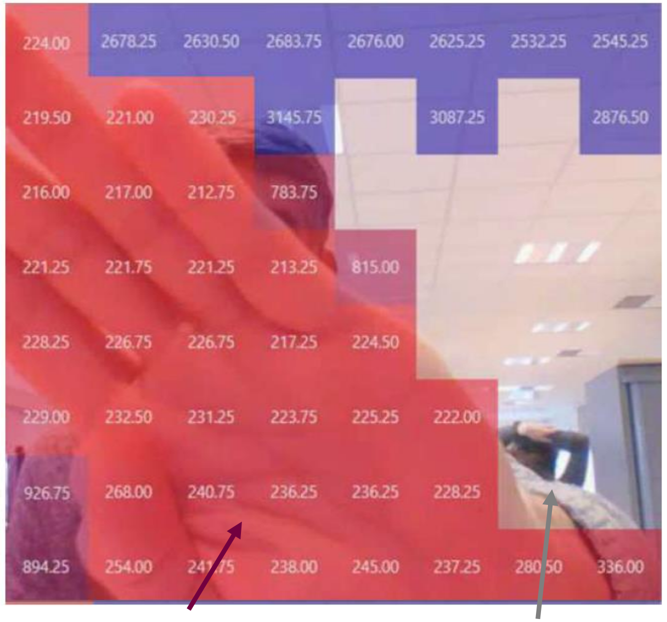
Electronics engineer ➔
Chip validation
Measurements: instrument control and data acquisition and analysis
Application engineer

VL53L5 example

A number of parameters can be made available from the VL53L5 measurements:

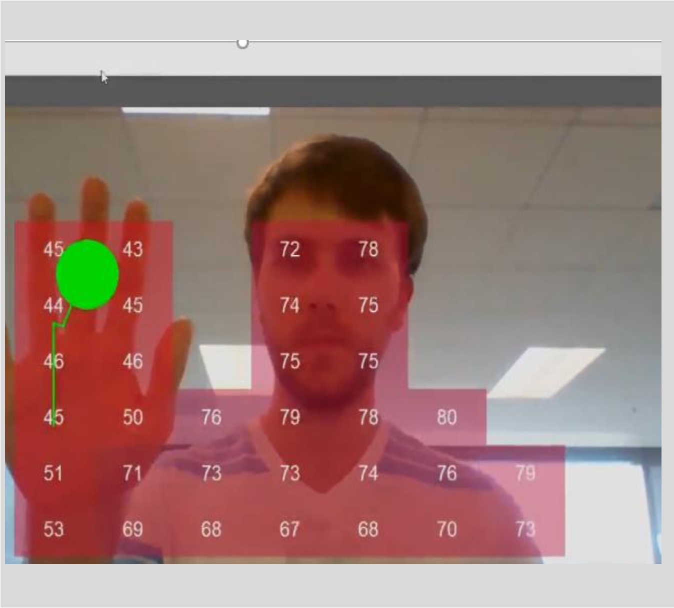
- Ranging in mm
- Target signal rate
- Ambient light rate
- Object reflectance

Scene examples, color coded: red = close, blue = far



VL53L5 Ranging results

Webcam image



Gesture detection example

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NOW 199 PHONES

And counting …

FlightSense™ Use-cases
Autofocus Assist

In 2014, FlightSense™ invented Laser Autofocus Assist, constantly improving since

2Bu shipped to-date

FlightSense™

Best DXO camera scores
Single or Dual camera assist

2019-22: Single-zone & Multizone new products & algorithms improvements extending life-time

2020-22: 0.8μ pixel CIS sensors performances prompting a revival

Reached 199 aggregated phone count, more on the way.

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Unlimited Applications

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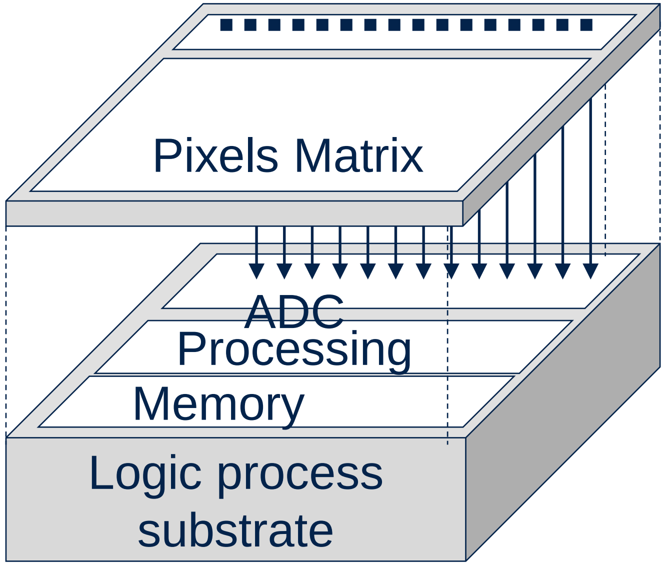
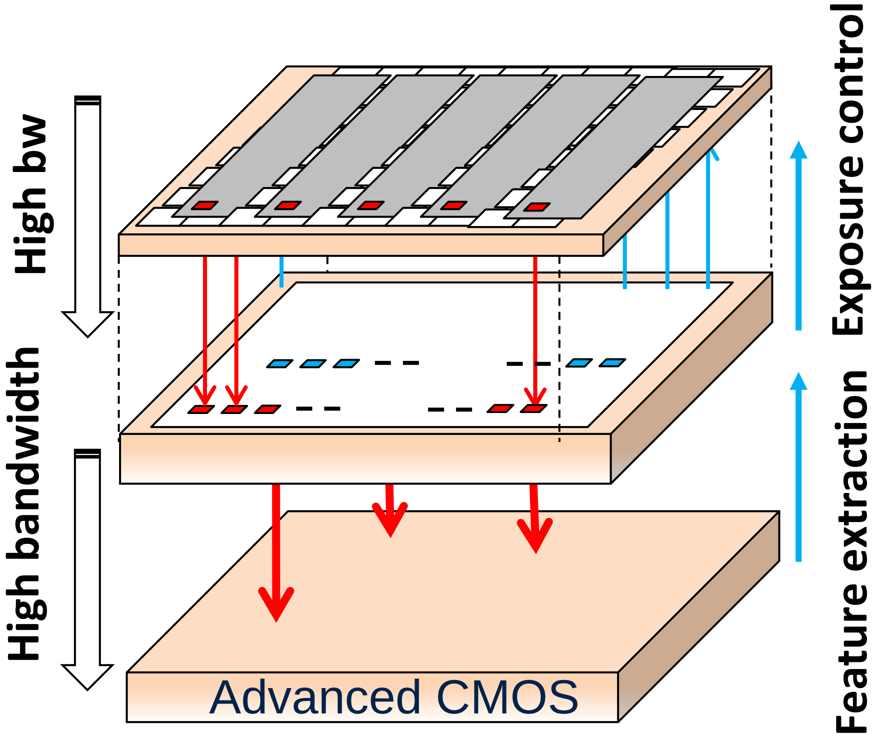
The future

What next?

3D stacking



3 layers sequential stacking



TIER 1

Light sensitive pixel area

TIER 2

MOS pixels

TIER3

Deep processing, algorithms, memories

data treatment

Optimised pixel pitch and performance +
full bottom wafer for CMOS → performance and cost effective

The future

- Nokia phone with one sensor
- iPhone with many sensors
- What's next?

Where do you fit in?

Sustainable design

- Process using less material and water
- Design solutions with enhanced performance, lower power consumption and less silicon area
- Artificial Intelligence for efficiency and security

Sustainable product

- New materials
- Reduced test time
- Optimized measurement techniques/instruments

New applications

- Augmented Reality/Virtual Reality
- Health monitoring systems

And more

- A story for you write…

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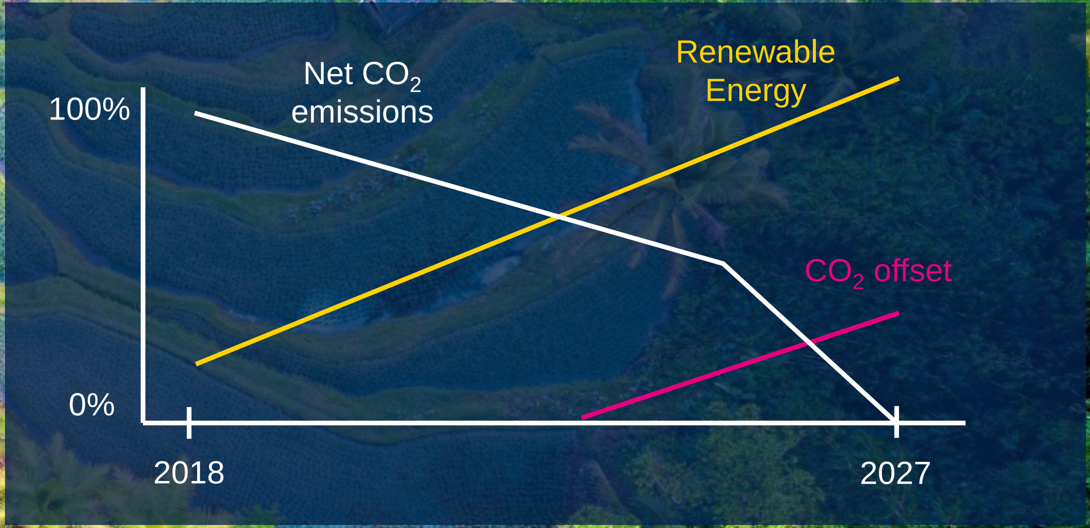
Commitment to Carbon Neutrality

ST will be Carbon Neutral by 2027

CARBON NEUTRAL

Milestones

- Compliance with the 1.5°C scenario (Paris COP21) by 2025
- Carbon neutral by 2027
- Sourcing 100% renewable energy by 2027
- Collaborative programs and partnerships for carbon neutrality throughout our ecosystems



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