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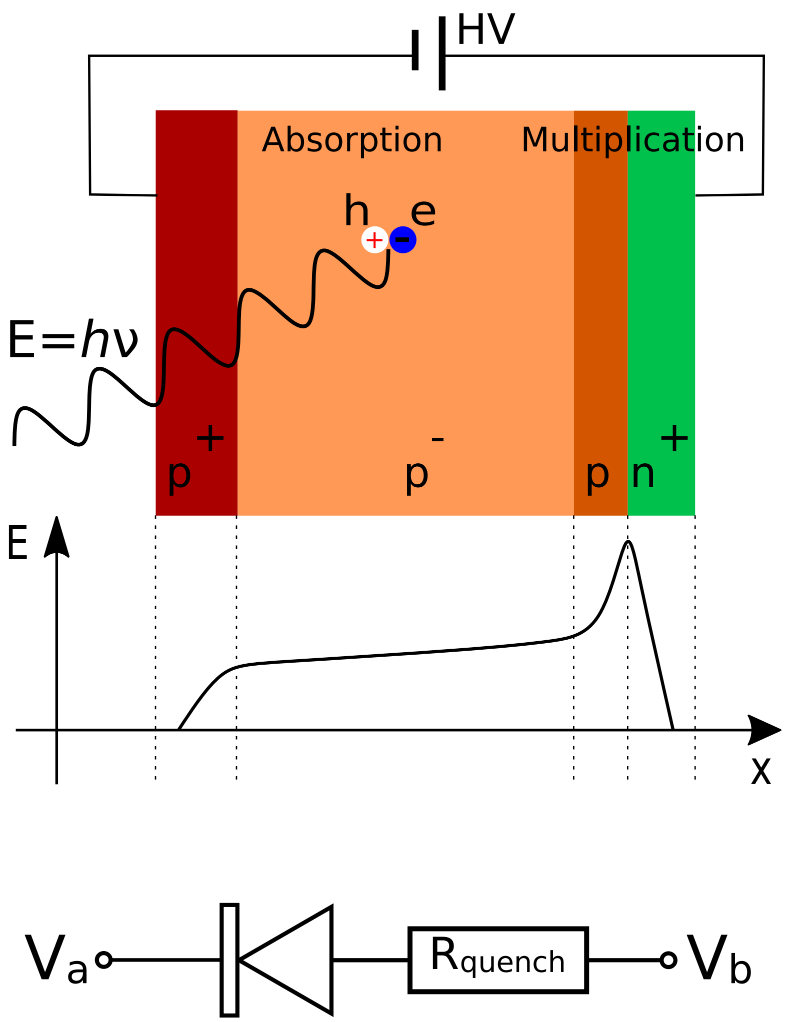
ZUKUNFT SEIT 1386

Schaltungstechnik und Simulation

CMOS based SPAD Arrays

Michael Keller – Heidelberg University
27.09.2019, Bergen, Lecture week on “Imaging with particles”

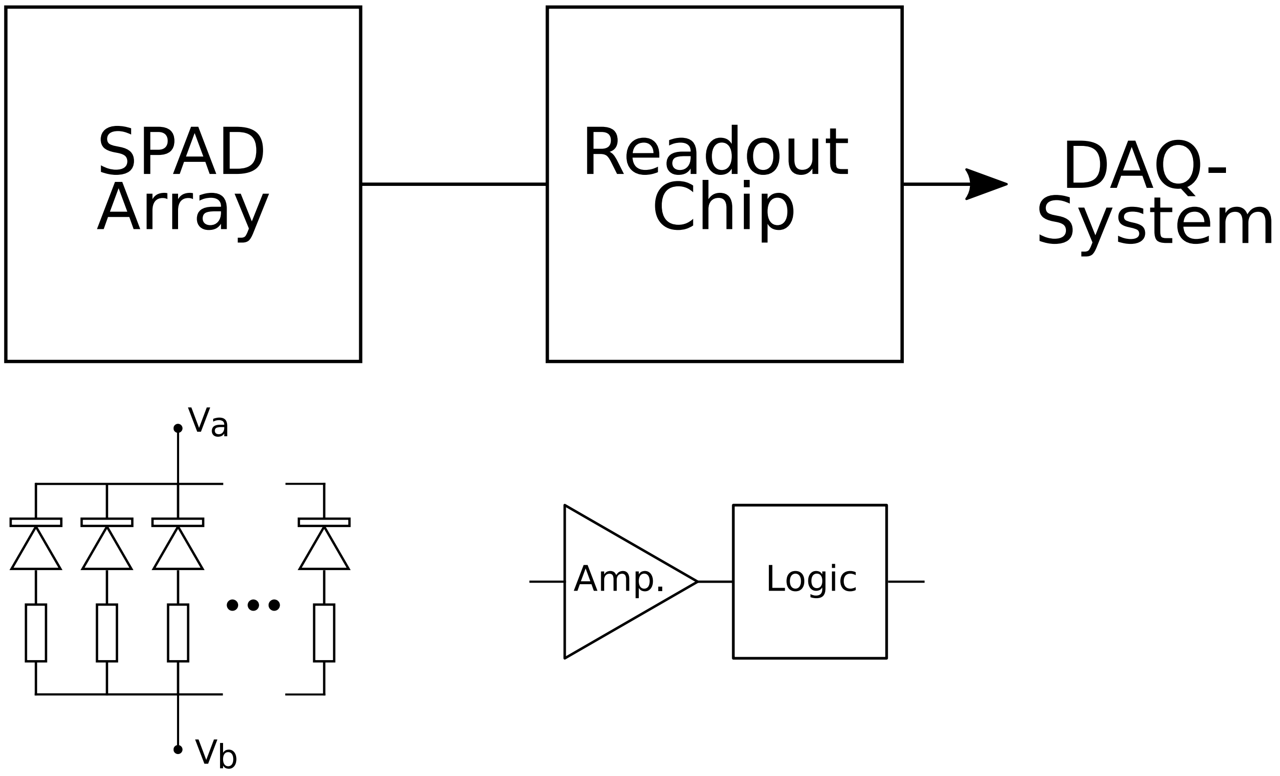
Single Photon Avalanche Diode



- Sensitive to single photons in the visible range of light
- Good quantum efficiency (~ 50% @ 450nm)
- Excellent timing resolution (O ~ 100ps)
- Micro structured on silicon → combine several SPADs to arrays

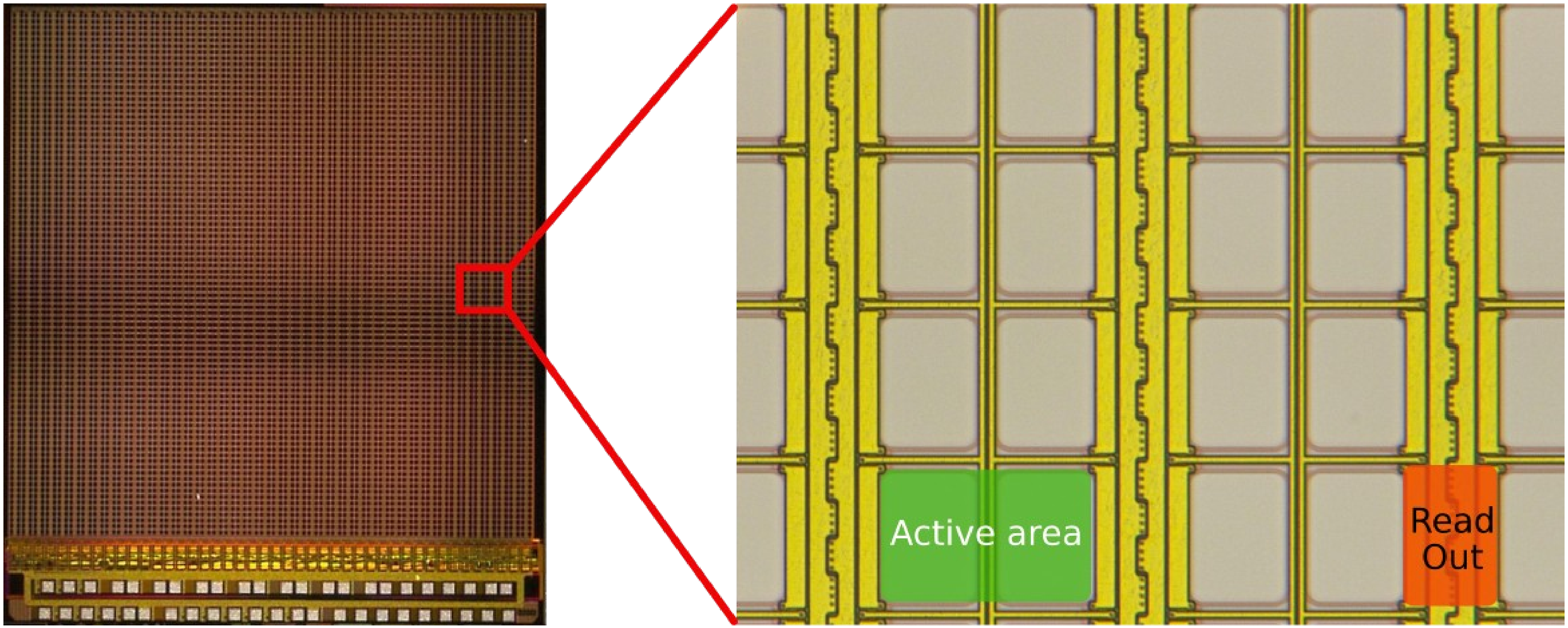
SiPM: Silicon Photon Multiplier

- SPADs and the dedicated readout logic are on independent chips
  - SPADs are connected in parallel → combined signal is readout



CMOS based SPAD Arrays

- Technology allows to mix SPADs and active MOS devices
  - SPADs and readout combined on a single chip



CMOS SPADs vs. SiPMs

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- Drawbacks of CMOS SPADs:
  - Dark count rate (DCR) is worse due to more complex processing or not yet fully optimized SPAD design
  - Fill factor is decreased due to electronics in cells (70% or more is possible)

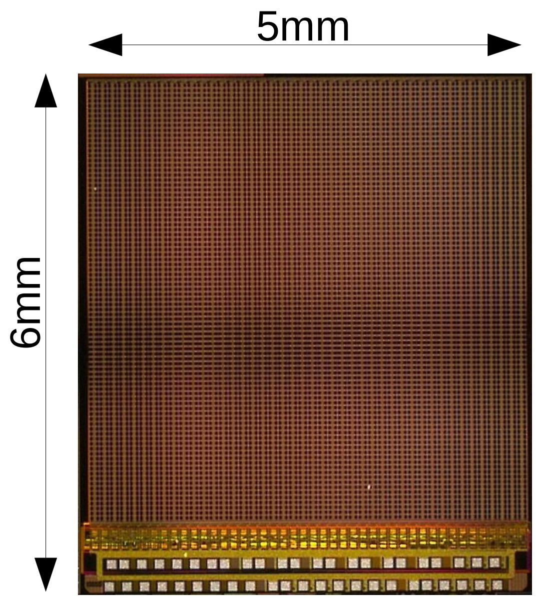
- Advantages of CMOS SPADs:
  - Light detection and tailor made readout on a single chip
    → Simple mechanics, lower cost (suitable for mass production)
  - Each SPAD is read out individual
    → Single photon detection is simple (no amplifier needed)
    → Low power readout
    → Spacial resolution down to SPAD level
  - Bad SPADs can be turned off to reduce overall noise (Trade-off between active area and noise)

Present sensor

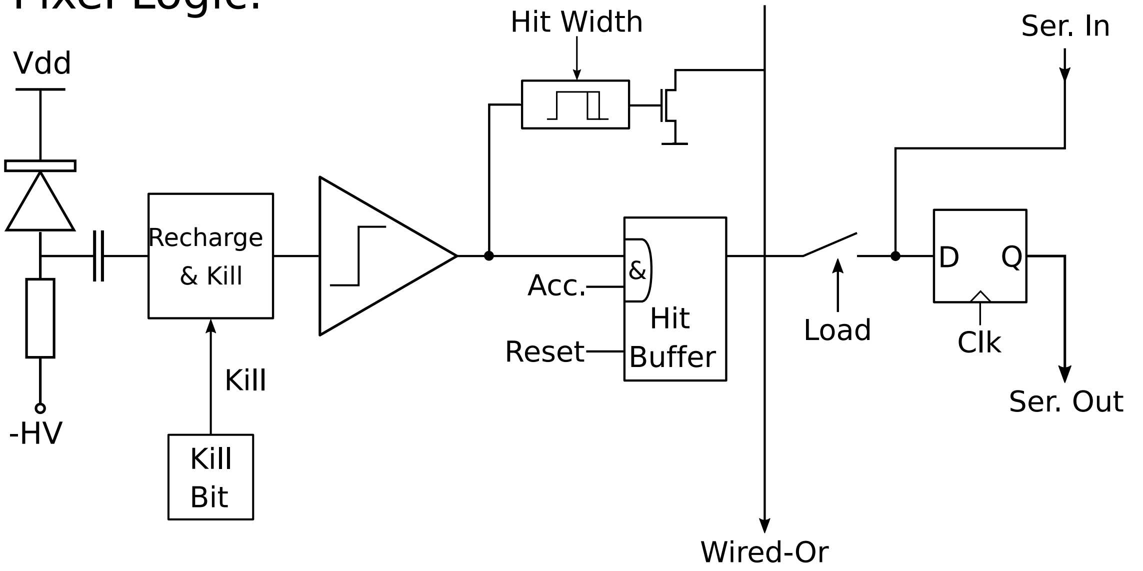
IDP2 Chip:

- 88 x 88 = 7744 pixels
- Pixel Size: 56 x 56 µm²
- Fill factor ~ 55% → 12mm² active area

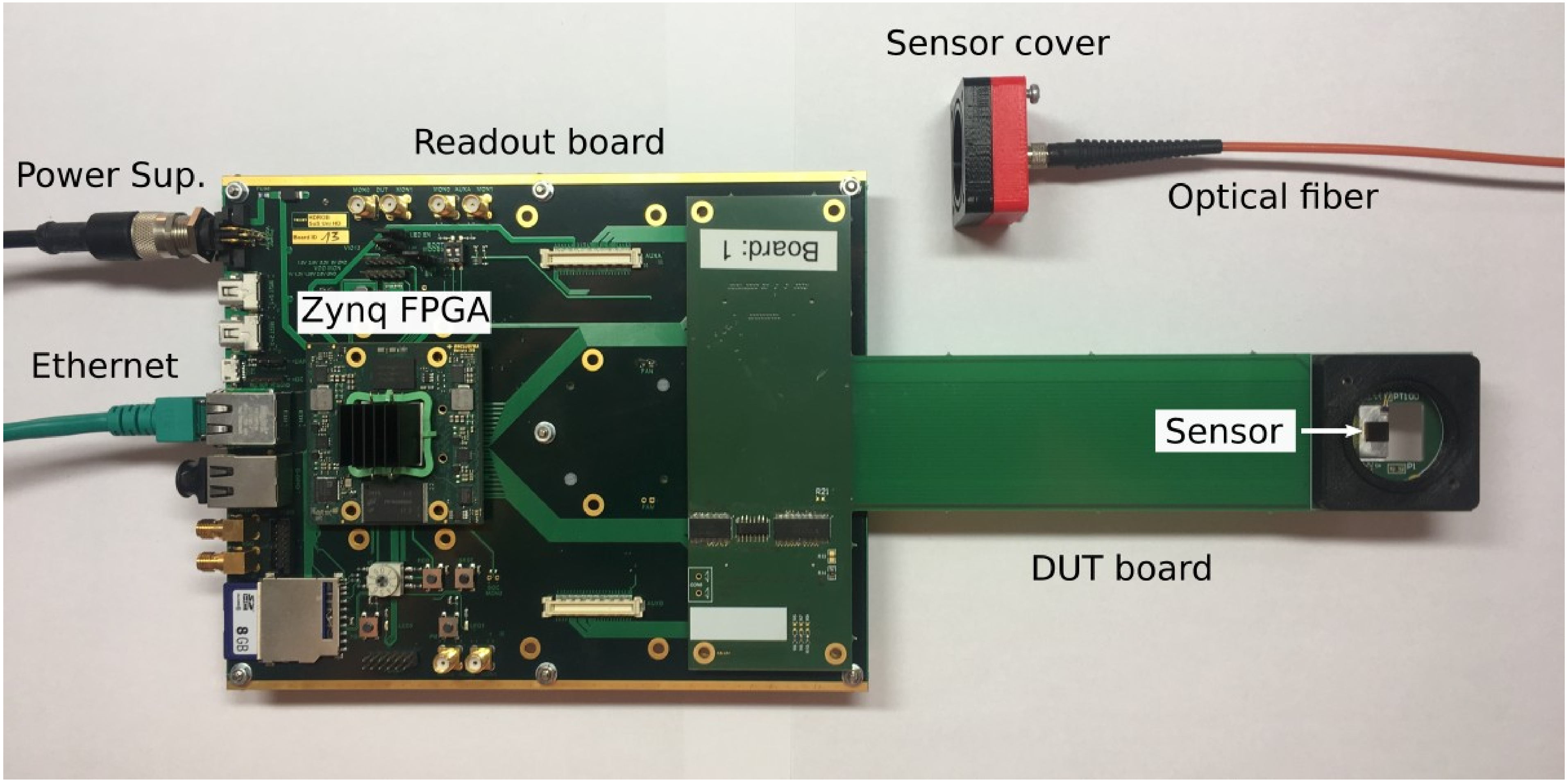
- Only digital output signals
- Full frame readout:
  2D binary images are recorded
- Frame rates up to 400kHz
- Fast hit wired-or for triggering:
  FWHM ~120 ps



Pixel Logic:



Measurement setup



Simple mechanics, only supply voltage as analogue bias. FPGA for data collection.

IDP2: Application so far...

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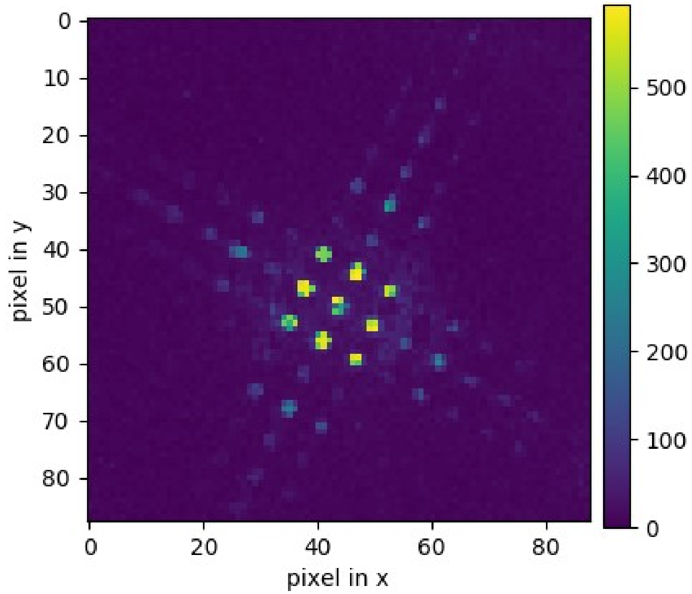
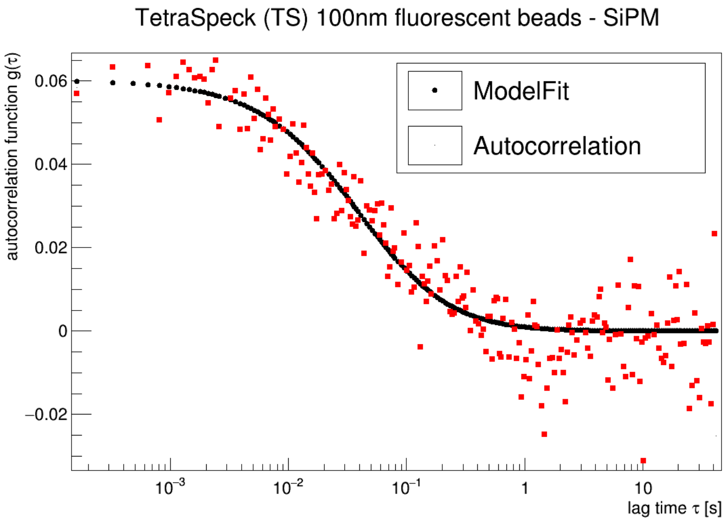
Single photon inteference:

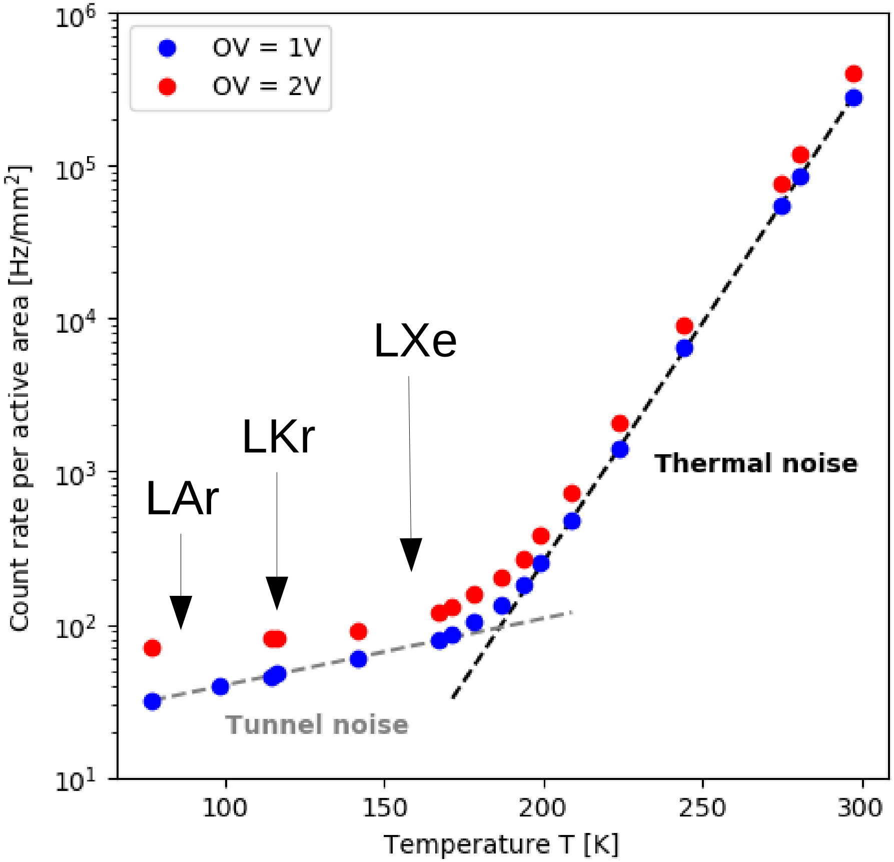


Florescence Correlation Spectroscopy:



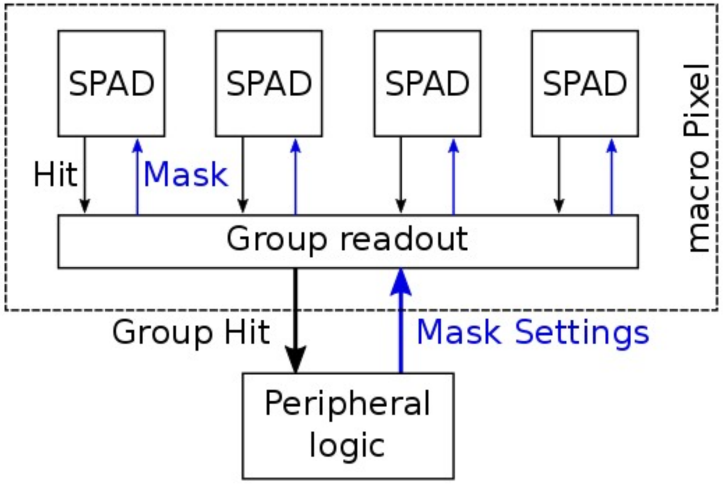
CMOS SPADs for
rare event searches
with liquid noble gases?

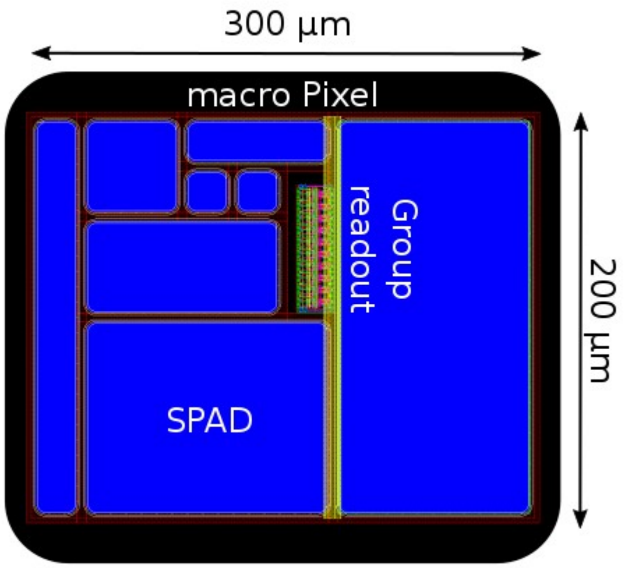
DCR vs. Temperature



- Thermal noise is dominant until 180K
- For lower temperatures tunnelling noise is the main noise source
- SPADs are in the low-noise regime for all liquid noble gases
- For OV = 1V noise is well below 100 Hz/mm²

Low photon flux detector

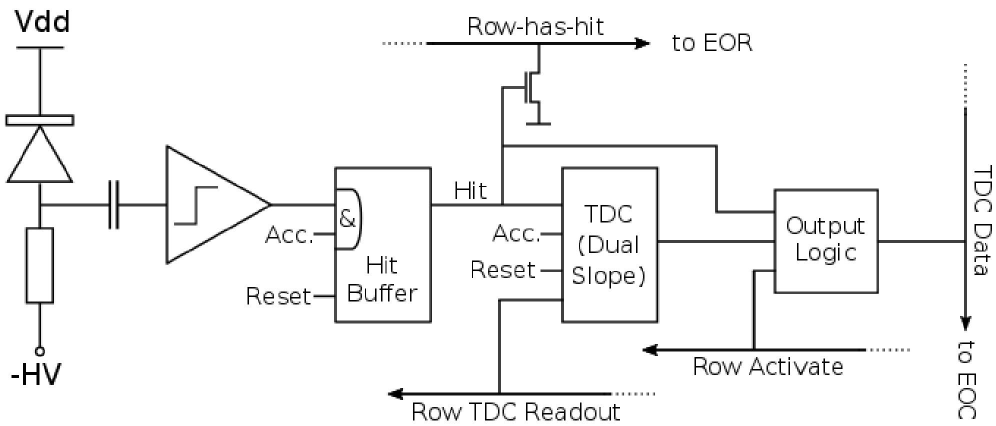


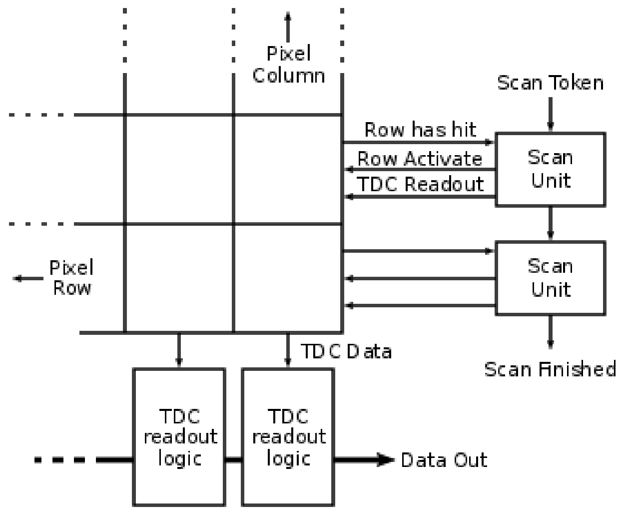


- High fill factor ~80%: SPADs grouped to macro pixel
- Mask bit for each SPAD cell to keep noise low.
- Low Power: Datadriven readout, no static DC current.
- Different SPAD geometries to optimize fill factor vs DCR ratio
- Cost estimation for mass production: ~10€/cm²
- Application: Rare event searches with liquid noble gases

Time-of-Flight camera

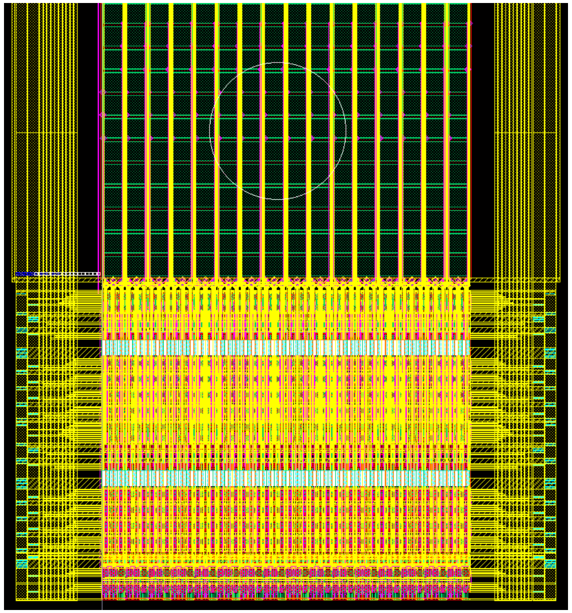
Pixel Logic:

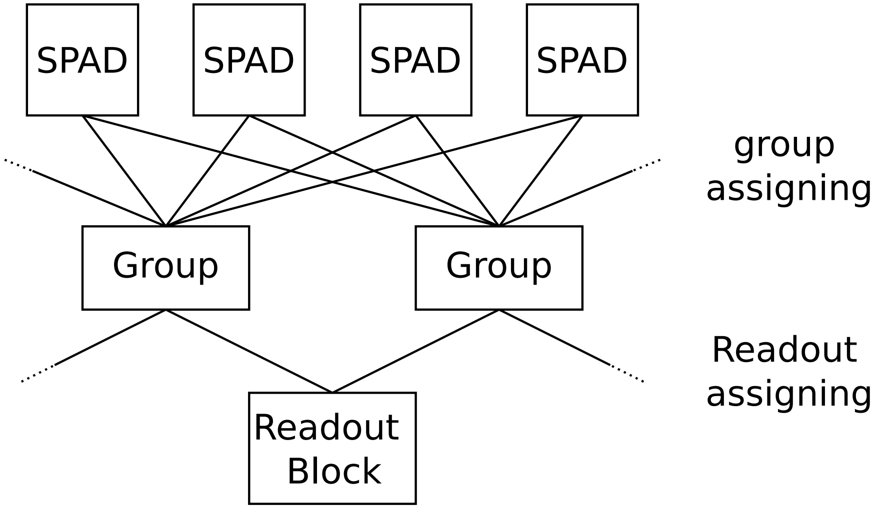




- Measures timing of an inivitual photons of instantaneous burst of many
- Dual Slope Time to digital converter (TDC) with time resolution FWHM ~ 100ps
- Timing relative to a start signal
- Full frame readout: Row wise with zero suppressed row select logic
- Application: ToF camera, LIDAR, fluorescence lifetime imagine

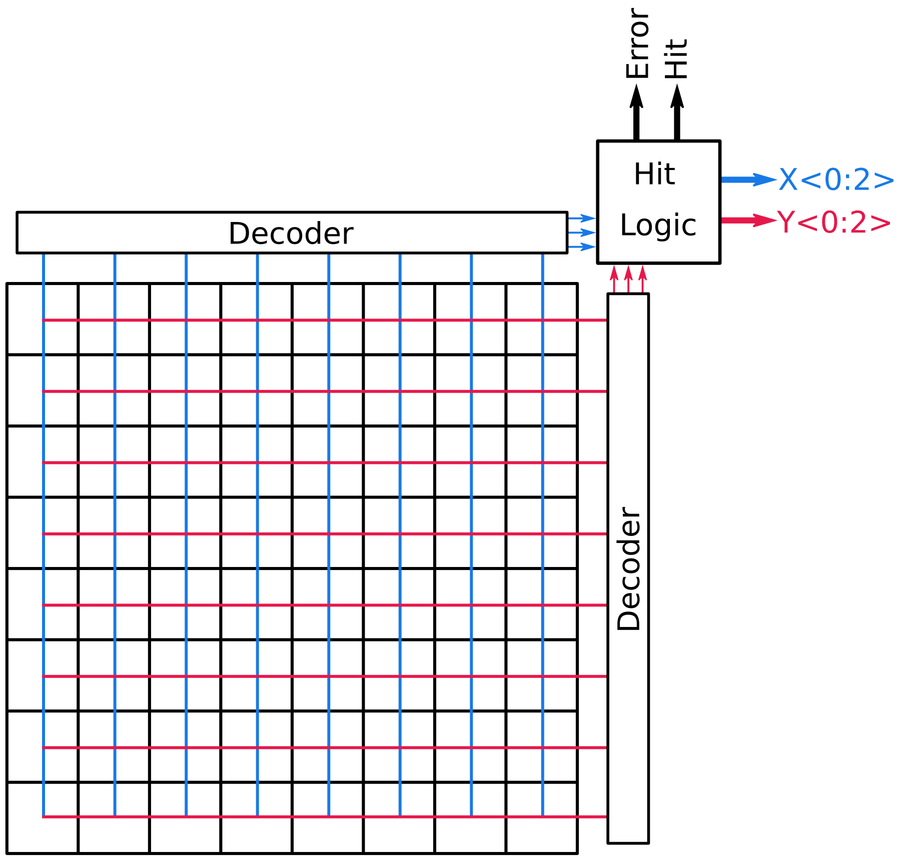
Optical fibre readout





- Measures timing (~100ps) and amplitude of a photon cluster emitted by an optical fibre
- Several pixels are assigned to a group readout structure
- Pixel assinging is freely programmable → good alignment to optical fibre
- Application: Readout of optical fibre or cell tracing in biology

XY-Readout



- Photon hit is converted in binary decoded x and y address of respective pixel
- Double hits not allowed → can be vetoed with error flag
- Very simple architecture
- Higher rates: divide in several quadrants → also done in upcoming submission
- Application: Low photon flux experiments, particle tracking

Summary

CMOS based SPAD arrays are power full but rather unknown detector technology for single photons in the visible range of light:

- Simple system: Detection and readout combined on one chip
- Tailor made readout architecture, designed for application (submission of our new designs in next few weeks!)
- Spatial resolution down to the SPAD level and excellent timing resolution (from SPAD, expect < 1ns)
- Low power single photon detection (NO amp needed!)
- Low cost and simple mechanics