

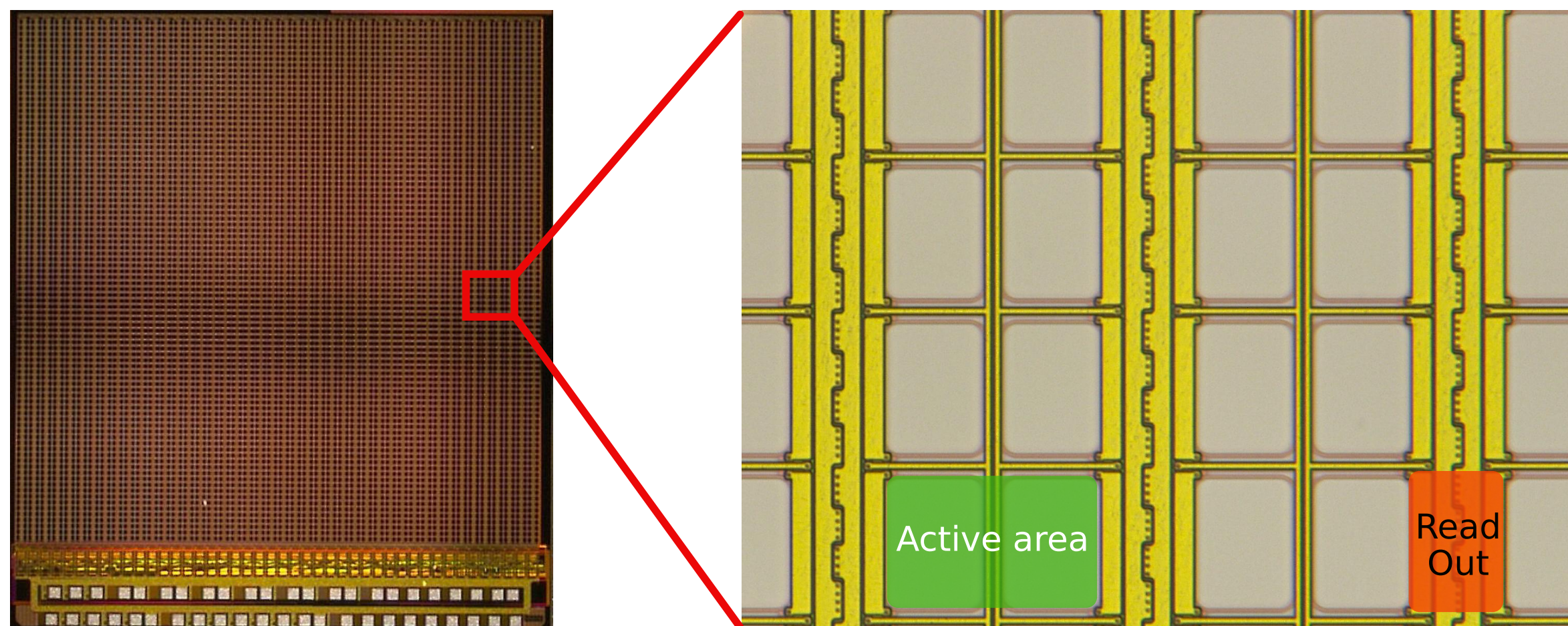
CMOS based SPAD Arrays for Detection of Rare Photon Events at Cold Temperatures

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Introduction

We have operated a 2D array of 88×88 Single Avalanche Photo Diodes (SPADs) fabricated in a CMOS technology in liquid nitrogen to evaluate its dark count rate at low temperatures. We found a rate of <20 dark counts per second and per mm^2 equivalent active area and observed an additional background at the edge of the array, which we attribute to photons emitted in the peripheral circuitry. The low dark count rate in combination with good timing information and excellent spatial resolution may lead to novel applications of such chips, like for instance search experiments using liquid Argon or Xenon. As a next step, we have therefore developed a 2D array with high fill factor and with a very low power, data-driven readout architecture.

Sensor



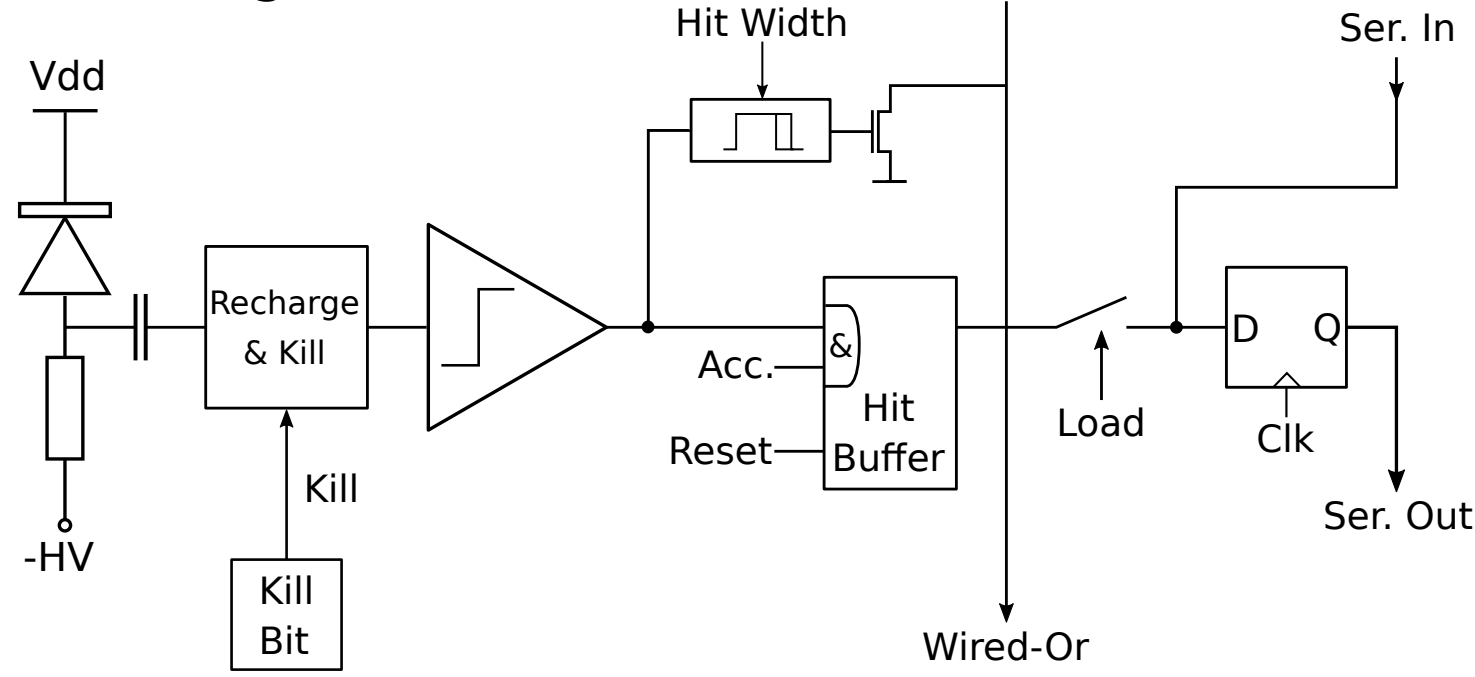
Sensor overall:

- Single Photon Avalanche Diode (SPAD) array fabricated in a CMOS technology.
- SPADs and read out on the same chip.
- 2D Array with $88 \times 88 = 7744$ pixels.
- Pixel size is $56.4 \times 56.4 \mu\text{m}^2$.
- Fill Factor: Active vs. dead area $\approx 50\%$.
- Each pixel delivers binary hit information.
- Pixel can be killed. Reduces overall noise.

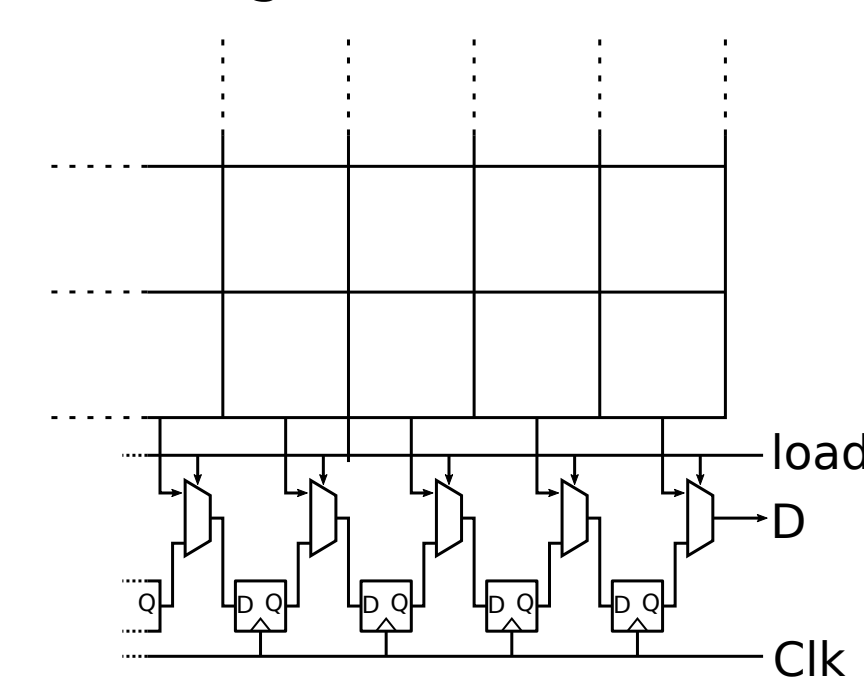
On chip readout:

- Full frame readout
- Pixels are sensitive in a defined time window and save a hit in their buffer.
- Hit data are read out with horizontal and vertical shift registers.
- Spatial information is available: 2D binary images are recorded.
- Frame rates up to 400 kfps at 200 MHz.

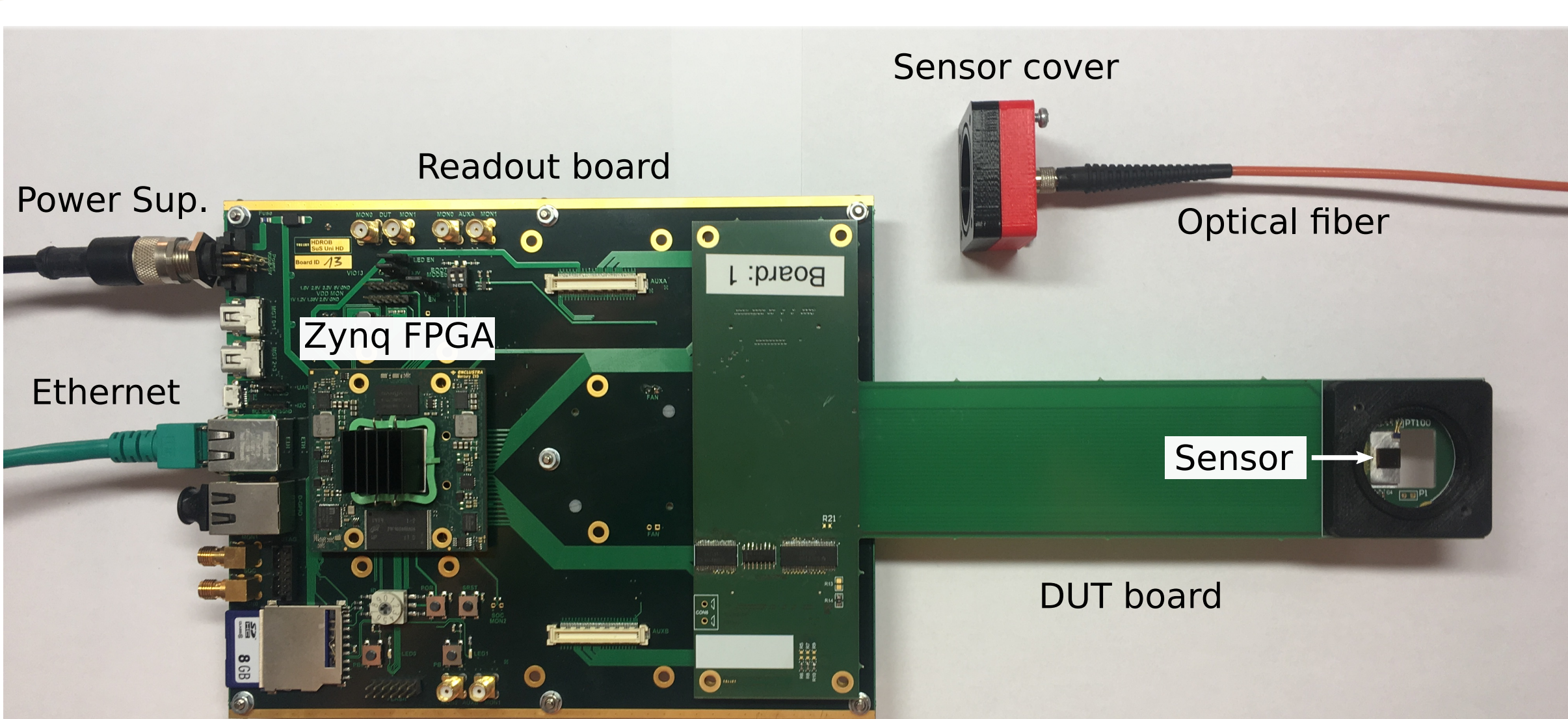
Pixel Logic:



EOC Logic:



Measurement Setup



Readout board:

- Zynq FPGA for sensor control and local data processing.
- Communication with a PC over ethernet at up to 90 MiB/s via TPC.
- Timing of readout sequence is controllable in software at runtime.

DUT Board:

- Special "T" shape to keep readout board at room temperature while sensor is immersed in liquid nitrogen.
- PT100 as wide range temperature sensor.
- Optical fiber to illuminated the cold sensor.

Results

Sensitivity Measurement:

- Pulsed low intensity laser $\lambda = 625 \text{ nm}$.
- Light evenly distributed over sensor.
- Fraction of detected hits in 20k frames.

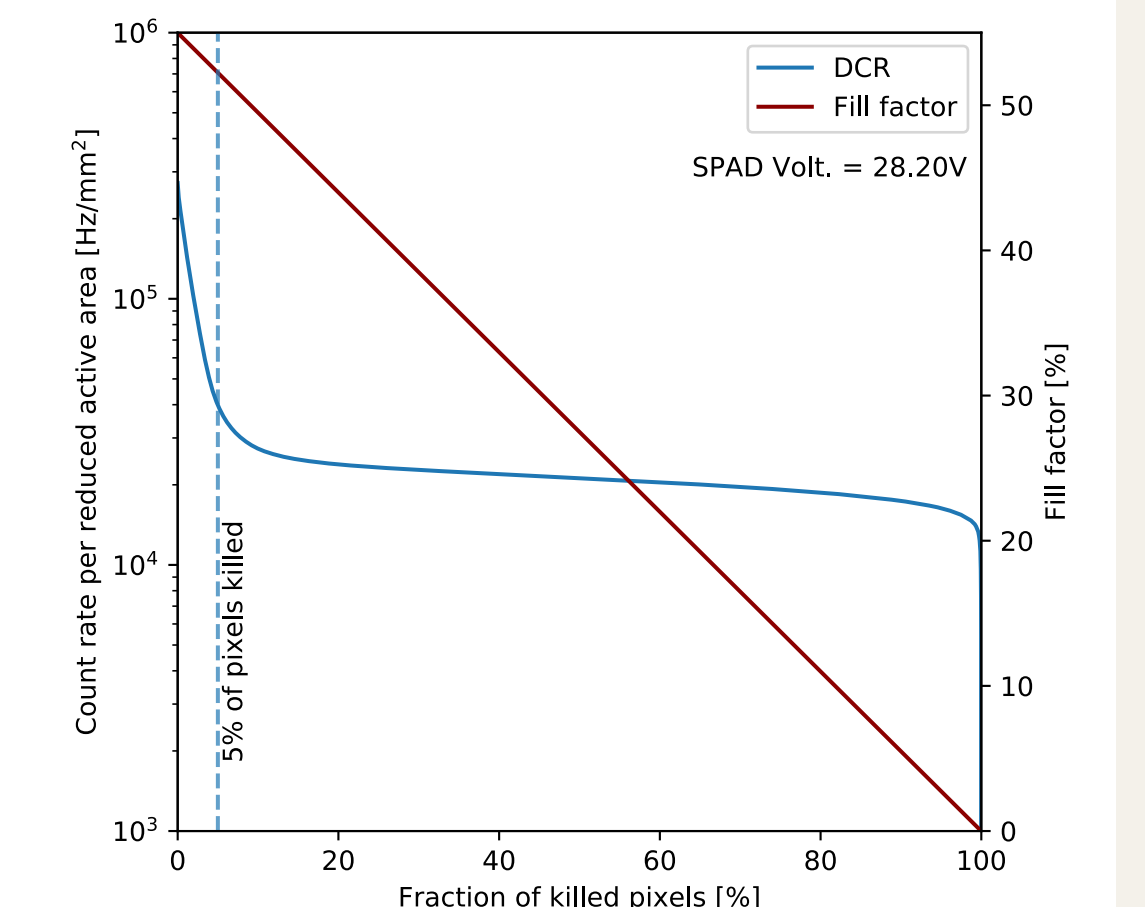
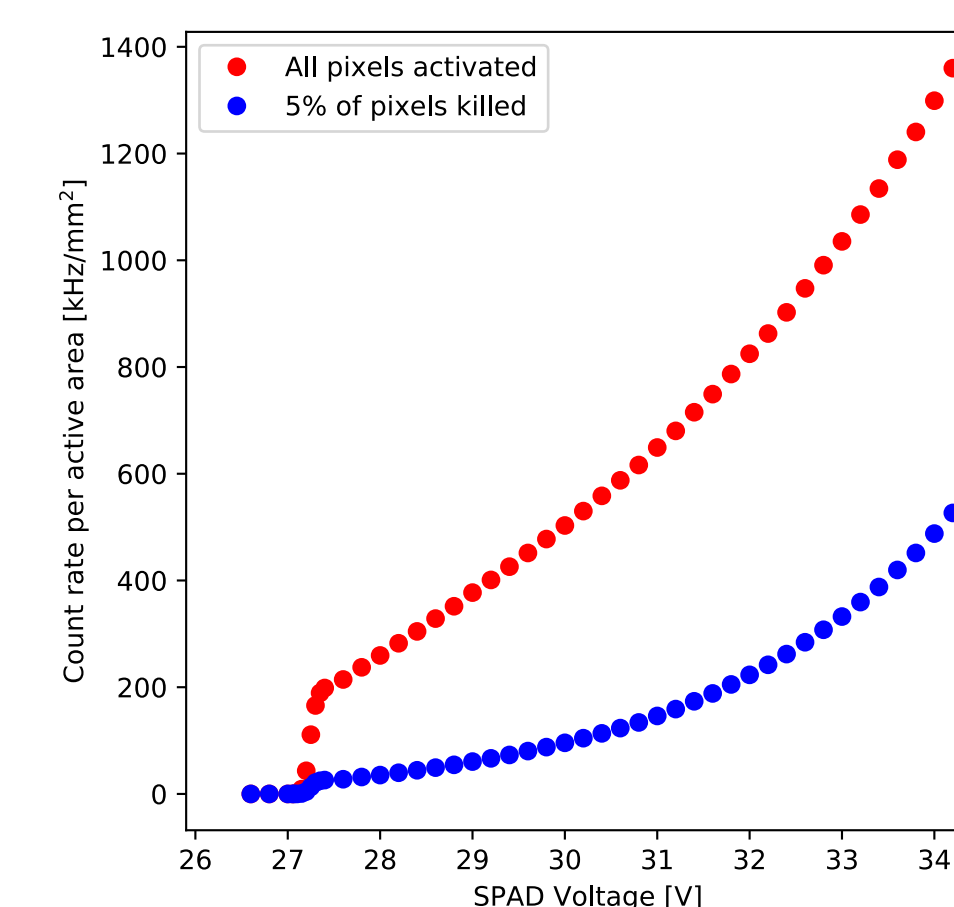
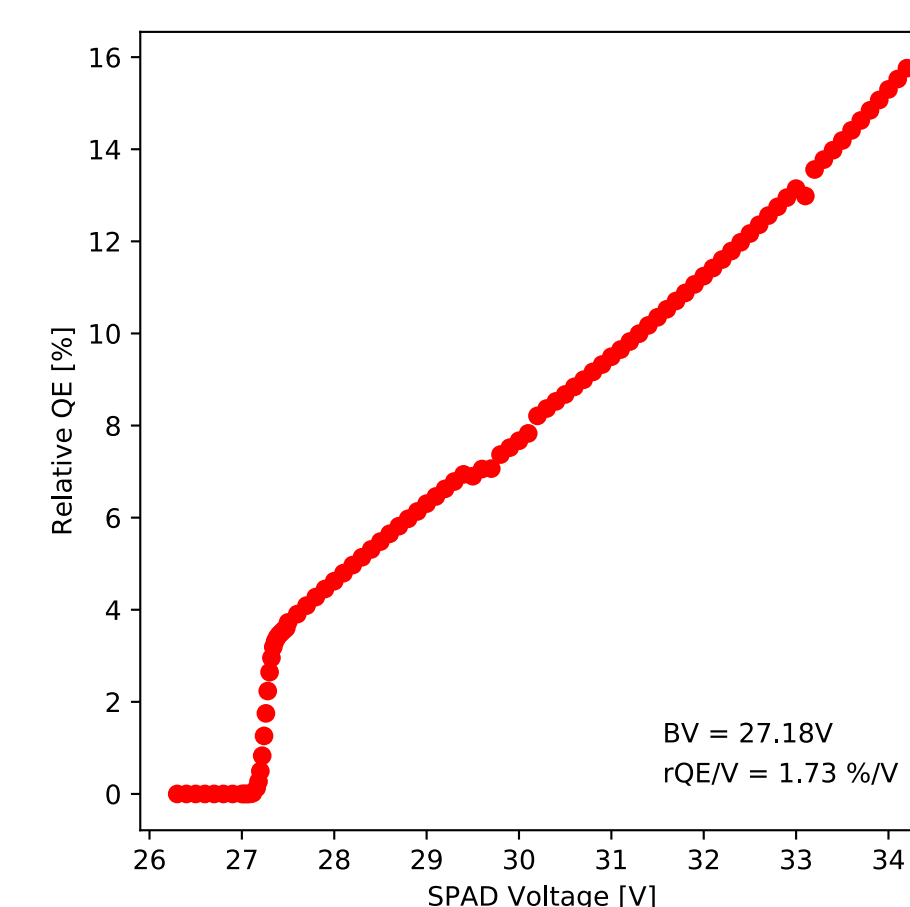
Dark Count Rate (DCR):

- Frames evaluated which were recorded in a dark environment.
- Dark count rate per active area.
- Integration Time: RT 1s, LN 100s

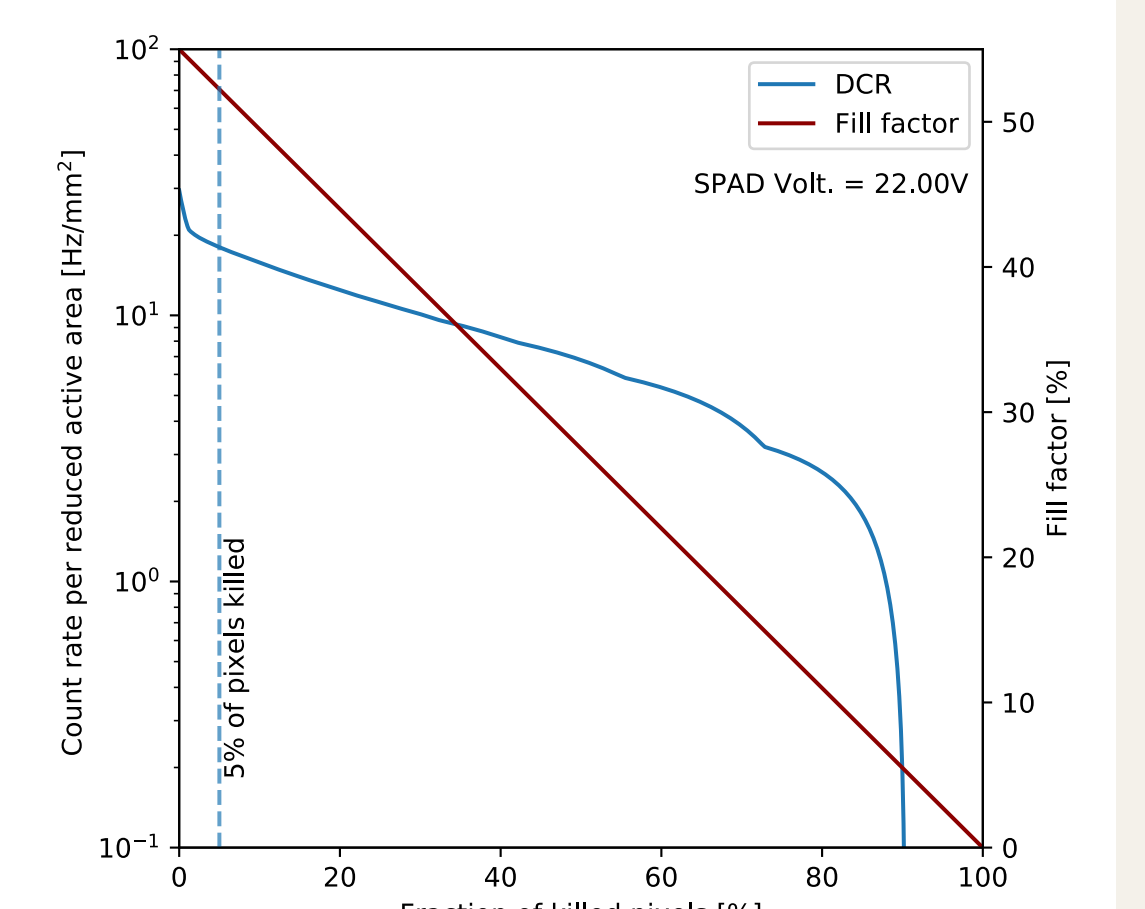
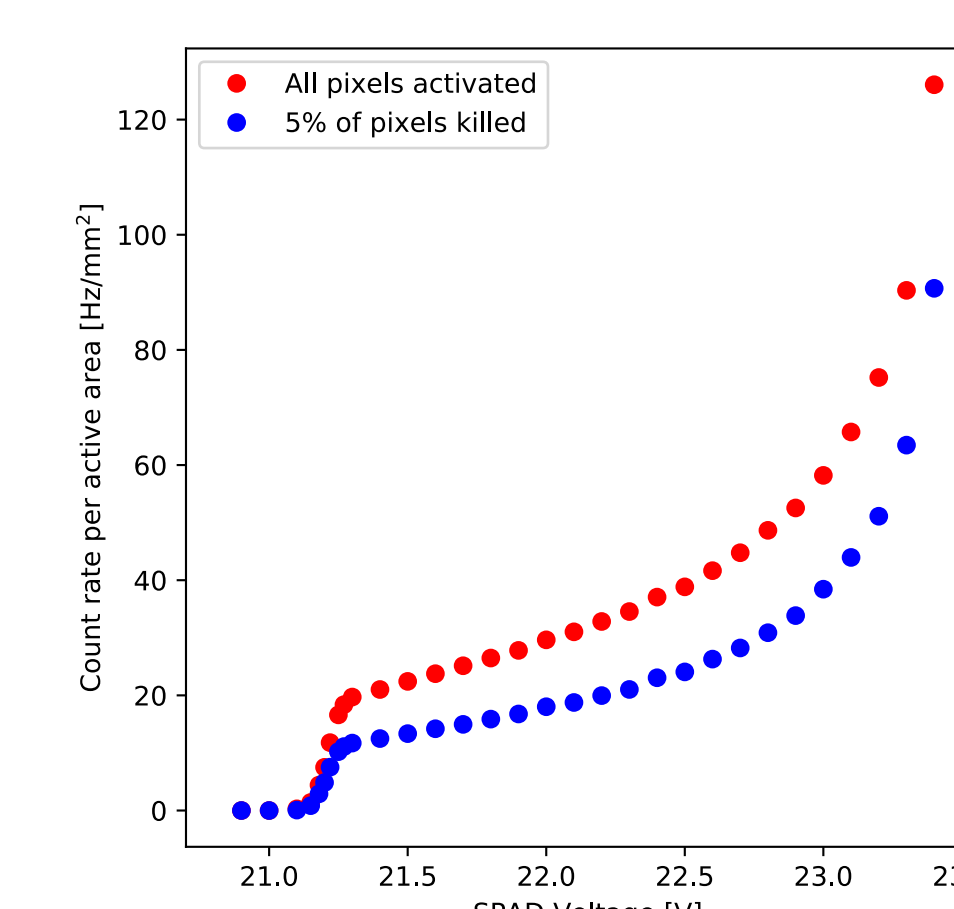
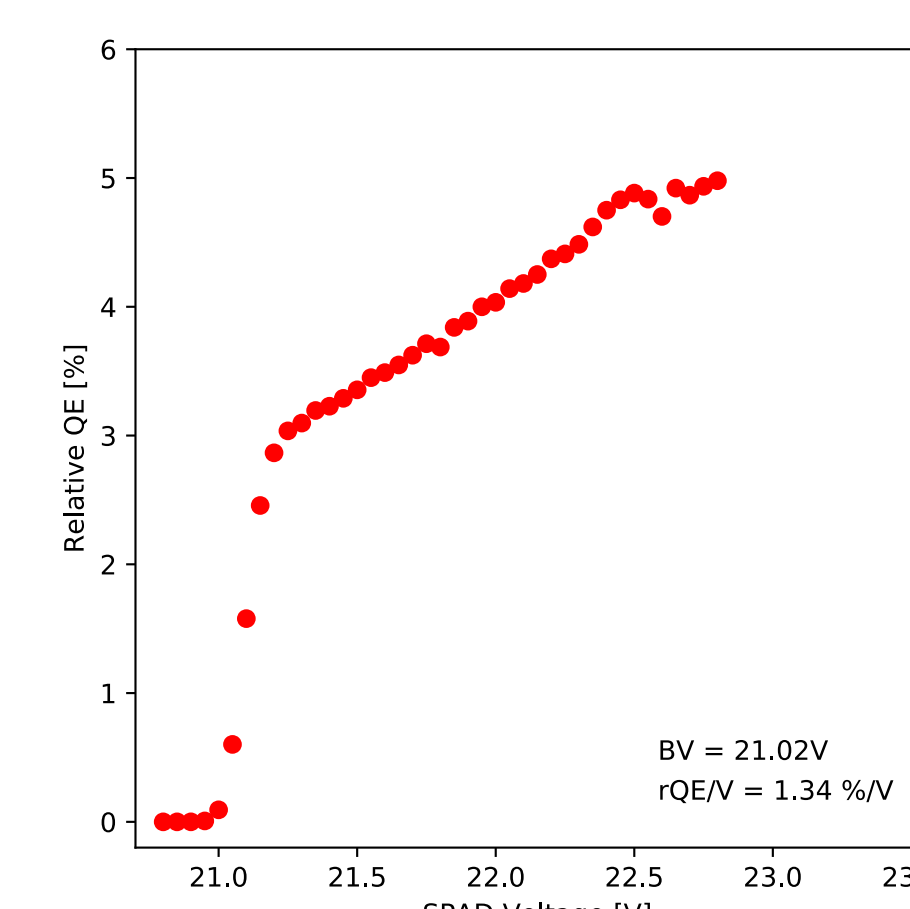
Fraction of killed pixel:

- Deactivate noisiest pixels one by one at a fixed SPAD voltage.
- Killing of pixel reduces fill factor.
- DCR per reduced active area.

Room Temperature 23°C :



Liquid Nitrogen Temperature -196°C :

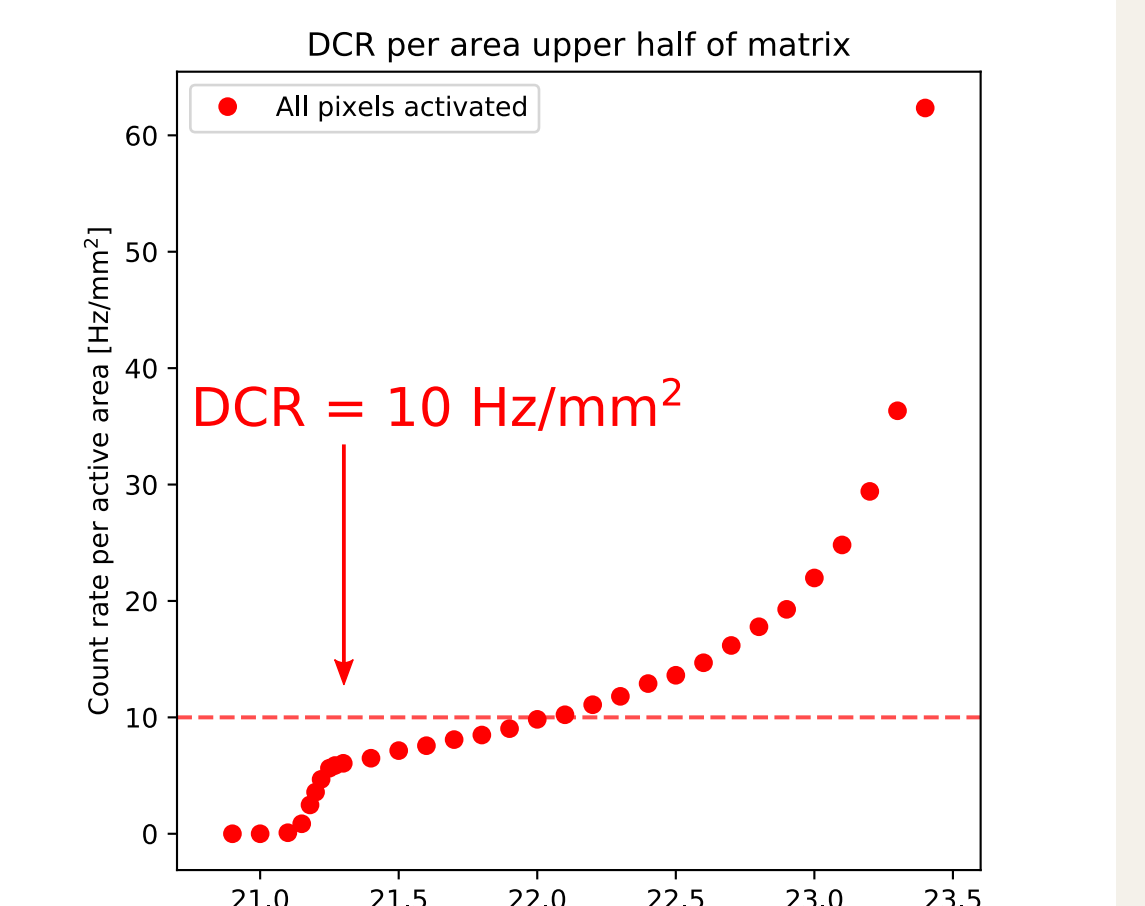
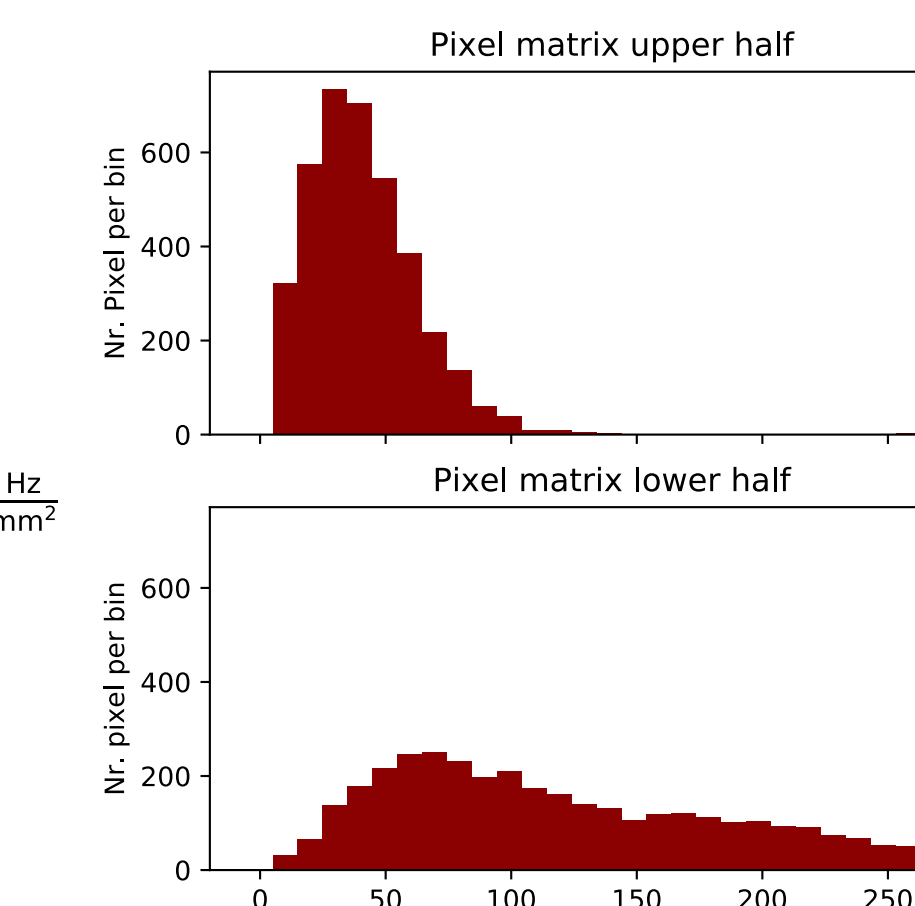
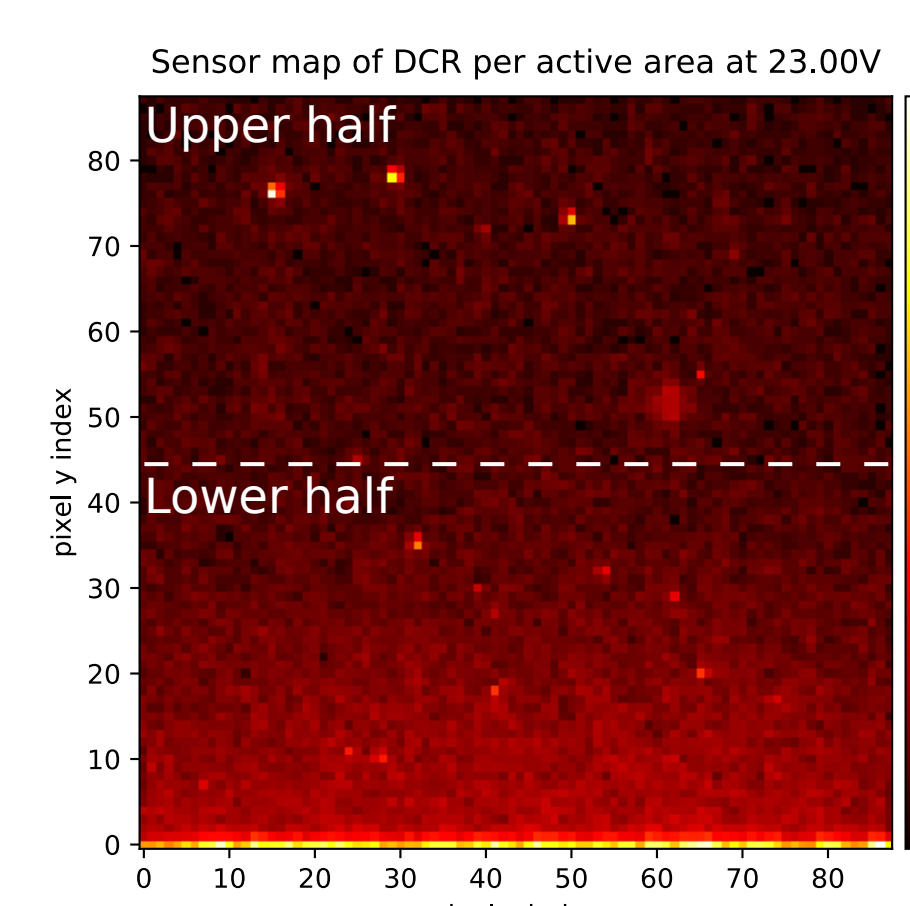


- Sensor is working at low temperatures.
- Sensitivity slightly lower.
- Breakdown voltage around 6 V lower.

- DCR about a factor of 10^4 reduced.
- Operational voltage range of SPAD decreased.
- Killing of pixels is less effective.

- Activity of hot pixels is strongly reduced.
- Gap at the end: $\sim 10\%$ of pixels had no count in 100s.

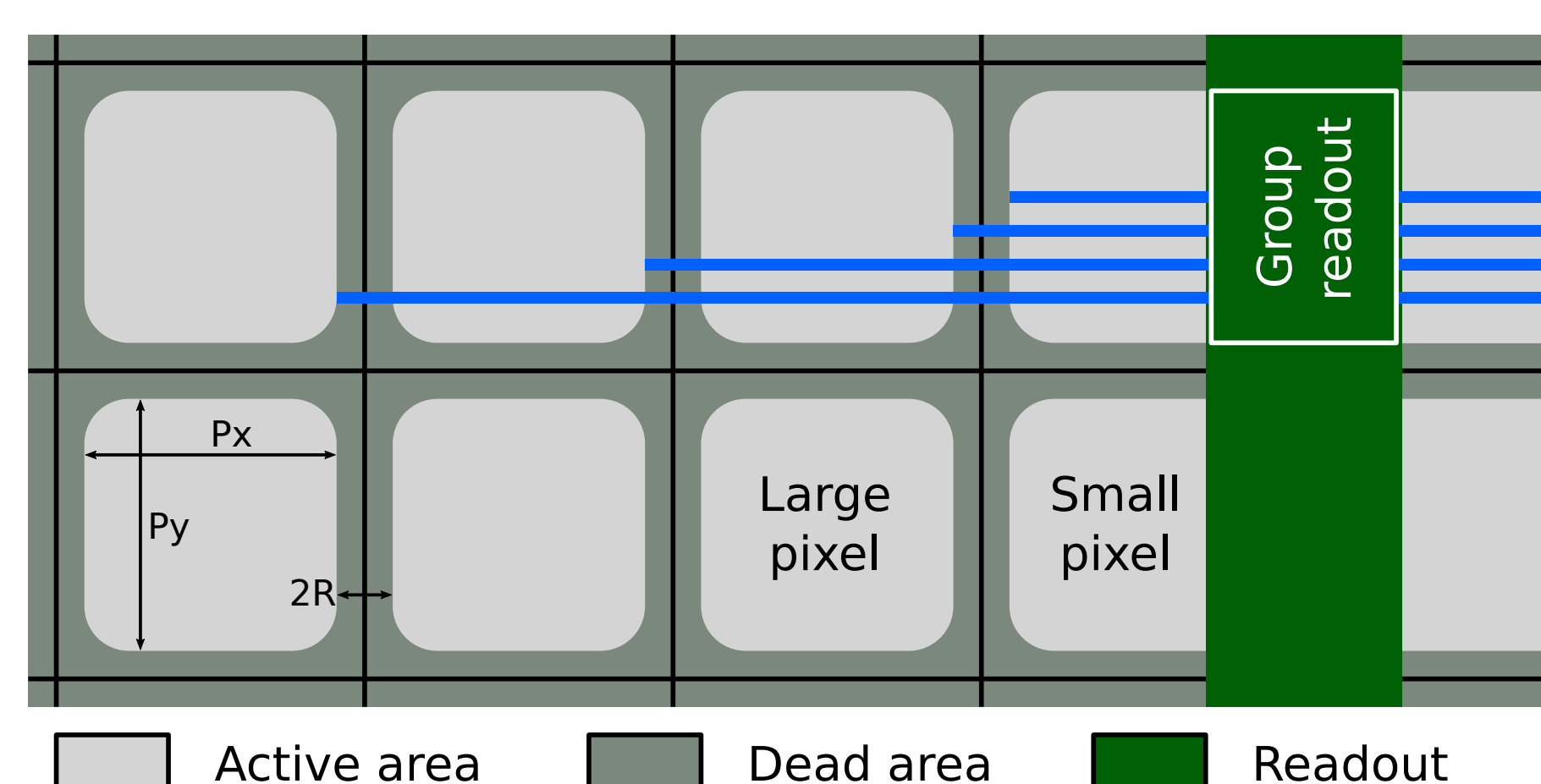
Further noise analysis:



- DCR intensity map shows that the noise level of the pixels is higher for the lower half of the matrix. Noise level rises strongly towards the lower edge of the pixel matrix.
- This additional background is suspected to be caused by light emission of MOSFETs in the peripheral readout circuit.

- Separate evaluation of the upper half of the pixel matrix.
- DCR of this part is about a factor of 2 lower than the overall DCR.

Outlook



- Possible application: Dark matter search experiment DARWIN.
- New submission in summer is planned and currently worked on.
- Other novel CMOS SPAD readout architectures will also be submitted.

- A low noise sensor with high photon detection efficiency for cold environments was developed.
- Low power and high fill factor is required.
- Data driven readout of a group of SPADs reduces power and increases fill factor.
- May increase SPAD size for higher fill factor.
- Fill factor estimation for group of 8 pixels:
 - FF of $50 \times 50 \mu\text{m}^2$ pixel area $\approx 59\%$
 - FF of $80 \times 80 \mu\text{m}^2$ pixel area $\approx 80\%$

