



# IMMS

INSTITUT FÜR MIKROELEKTRONIK- UND  
MECHATRONIK-SYSTEME GEMEINNÜTZIGE GMBH

## Enhancing Chemiluminescence-Detection with Dark-Count Rate Optimization Strategies for SPADs in Conventional CMOS Technologies

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ISSW 2024, Trento Italy, 06.06.2024

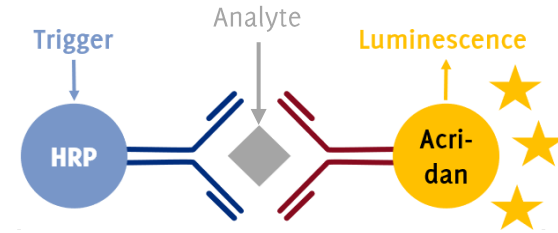
REACT-EU – Als Teil der Reaktion der Union auf die COVID-19-Pandemie finanziert.



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# Motivation: SPAD-based Chemiluminescence Detection for Point-of-Care (POC) Diagnostics

- Need for low-cost, sensitive POC devices
- Chemiluminescence offers high sensitivity for bioanalytical diagnostics but has low light intensity
  - usually a Photon Multiplier Tube (PMT) is used as a sensor
  - SPADs enable cost-effective, miniaturized detection



[https://en.wikipedia.org/wiki/File:Chemoluminescent\\_reaction.jpg](https://en.wikipedia.org/wiki/File:Chemoluminescent_reaction.jpg)



Assure Tec CLI1000: Fully Automatic Chemiluminescence Immunoassay Analyzer



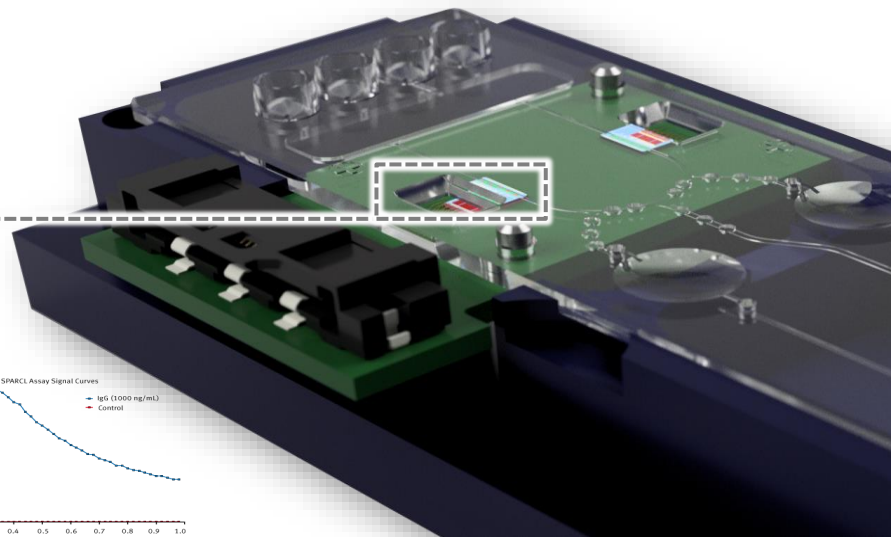
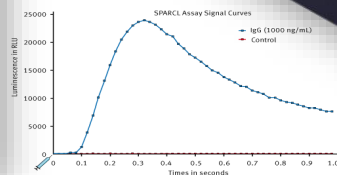
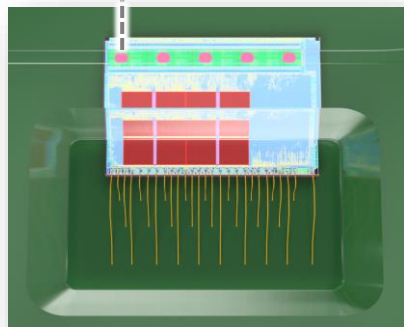
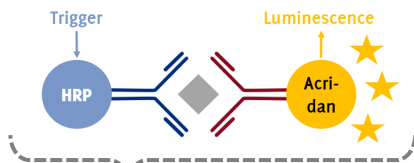
Hamamatsu Micro PMT Module H12406 (effective area 3x1mm<sup>2</sup>)

# Application & Chip Overview

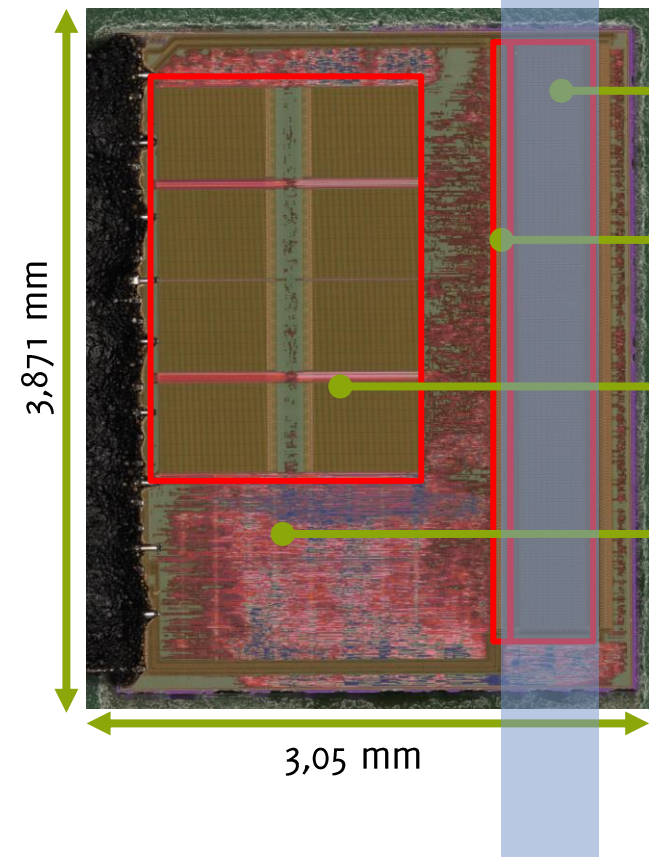
- SPAD based Line sensor IC, tailored for **in-vitro-diagnostic** chemiluminescence assays in microfluidic channels
  - SPADs offer **best SNR** for low light imaging in CMOS technologies (DCR  $\sim 1 \times 10^1$  cps/ $\mu\text{m}^2$  @25°C)
  - however dark count rate is **orders of magnitude worse than for PMTs** (DCR  $\sim 1 \times 10^{-4}$  cps/ $\mu\text{m}^2$  @25°C)



Hamamatsu Micro  
PMT Module H12406  
(DCR  $\sim 1 \times 10^{-4}$  cps/ $\mu\text{m}^2$ )



# Chip Features



High density linear SPAD array with 192 rows

- SPAD can individually be enabled/disabled

Row-wise counting of the SPAD pulses

- Adjustable measurement interval (100  $\mu$ s-100 ms)

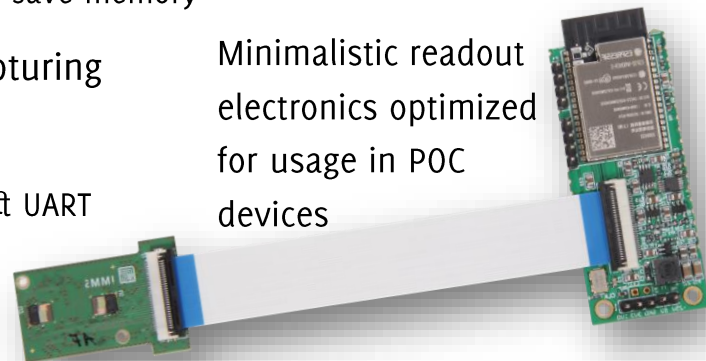
On-chip 64kB SRAM for up to 300 measured values per row

- ALU with bfloat16 encoding to save memory

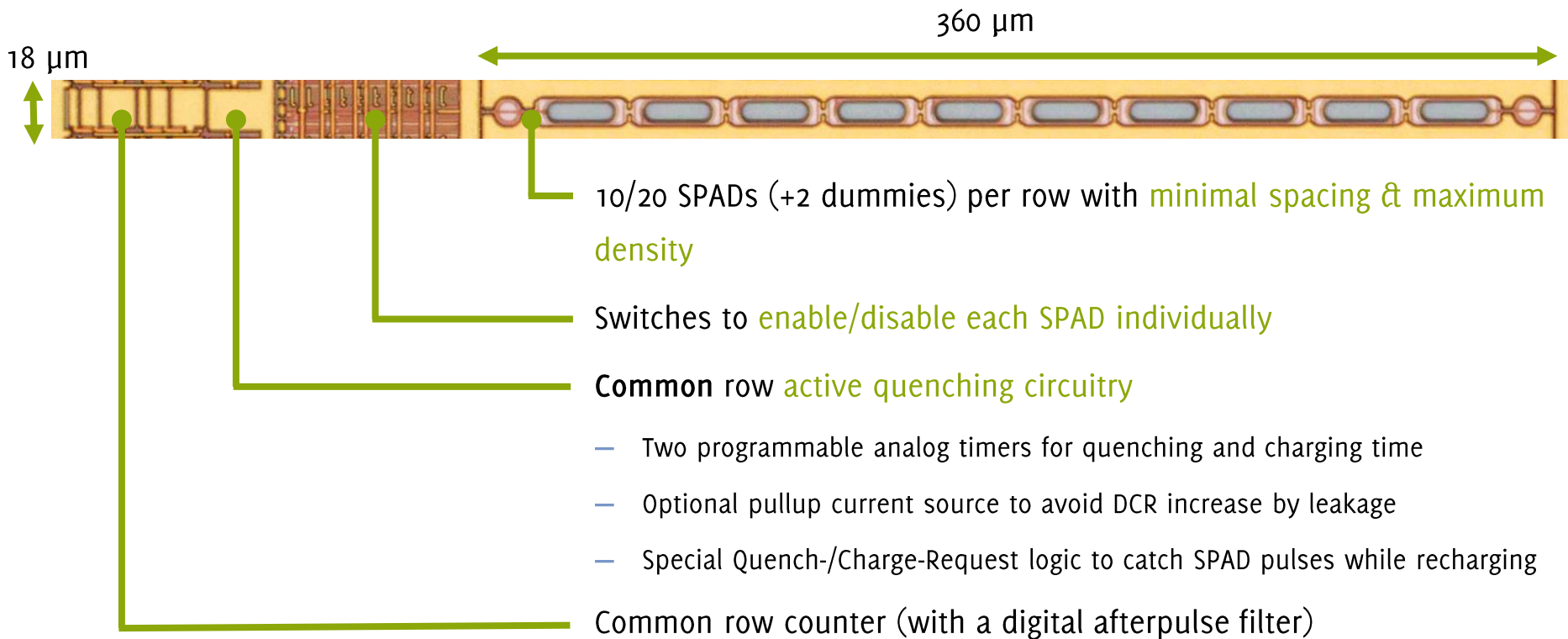
Freely configurable image capturing via programmable sequencer

- Easy interfacing via I<sup>2</sup>C, QSPI & UART

Minimalistic readout electronics optimized for usage in POC devices

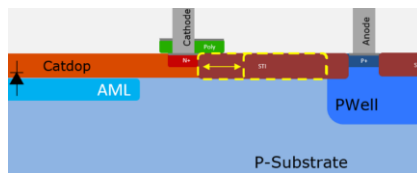


# Row layout

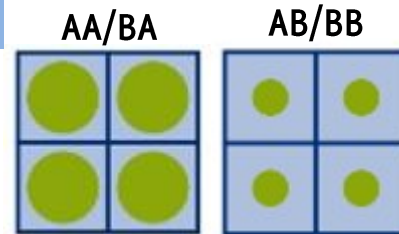


# SPAD Layout Optimization for DCR performance

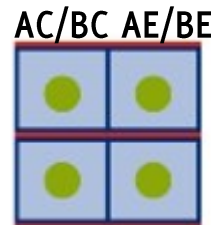
- commercial 180-nm CMOS process from X-FAB XH018
- several SPAD layout variations were investigated
  - Goal is to find the best trade-off between DCR, PDP & cross talk



Modified anode to cathode distance



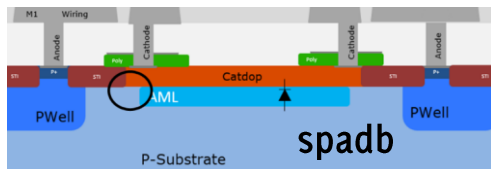
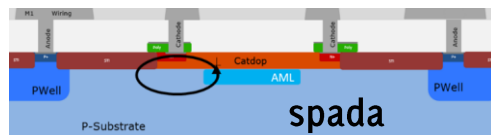
Additional guard ring



Larger sized SPADs



Two basic SPAD devices from PDK



# Hot SPAD Cut-Off Threshold – State of the art

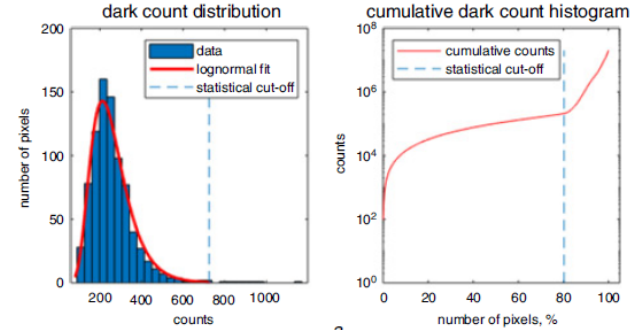
- fitting of a log normal distribution

$$\frac{1}{\sigma x \sqrt{2\pi}} \exp\left(-\frac{(\ln(x) - \mu)^2}{2\sigma^2}\right)$$

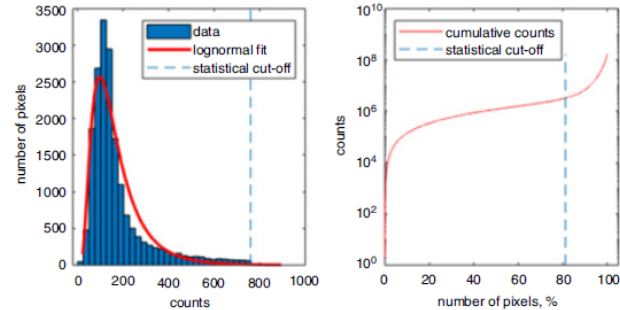
- set cut-off threshold to  $\mu + 3\sigma$
- this approach worked well for the tested SPAD arrays

- Reference:

Connolly *et al.*, “Hot pixel classification of single-photon avalanche diode detector arrays using a log-normal statistical distribution”, Electronics Letters, vol. 55, no. 18, pp. 1004–1006, Sep. 2019



a



b

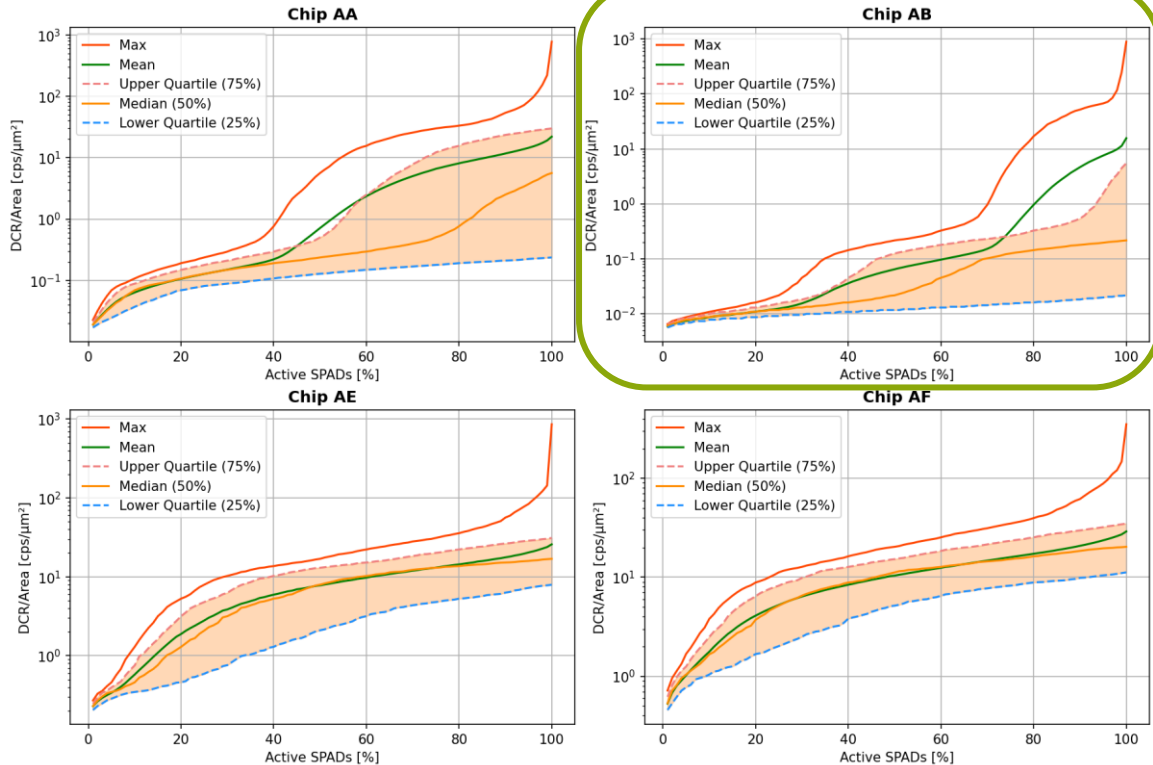
a) MF32, a 32 x 32 SPAD array

b) Qunticam, a 192 x 128 SPAD array



# DCR Statistics

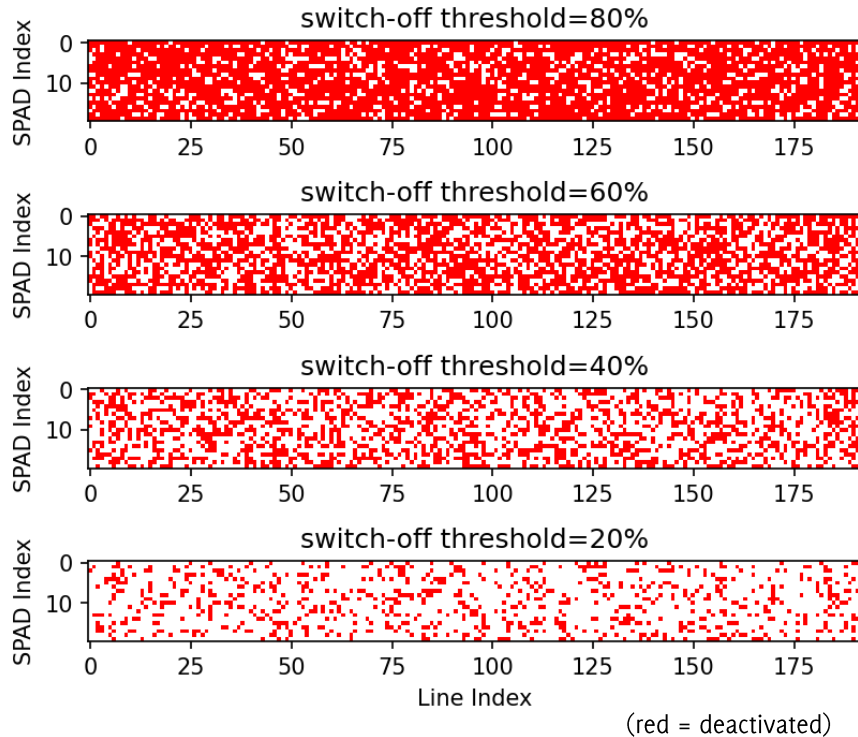
- Measured normalized DCR distribution over the percentile of active SPADs for different layout variations
- DCR varies over more than three decades for different switch-off thresholds
- SPAD types A-D exhibit distributions distinct from a log-normal distribution, unlike types E and F



all @25°C



# SPAD Deactivation Masks for different Switch-Off Thresholds



- For high switch-off thresholds maintaining adequate spatial resolution becomes crucial
- Deactivated SPADs are randomly distributed
- Sufficient spatial resolution is maintained even at high thresholds (80%)

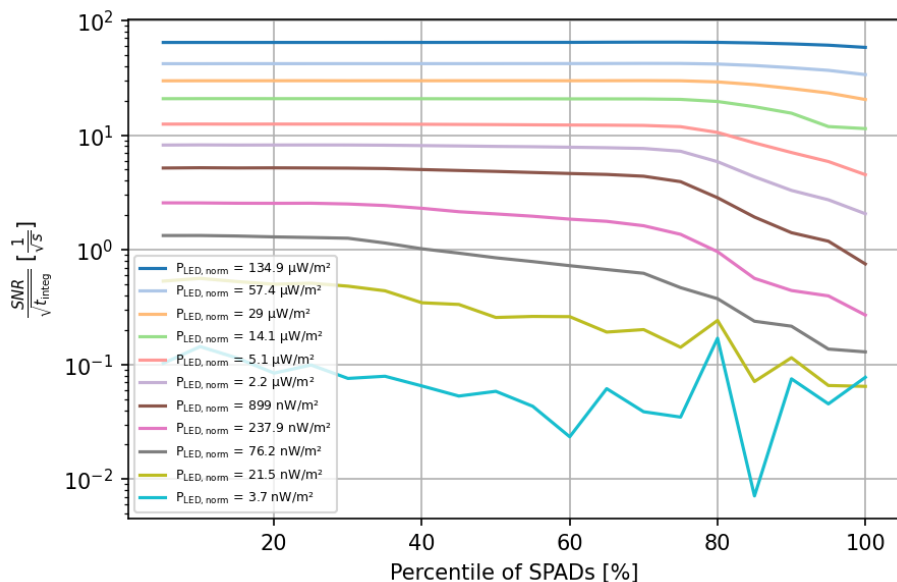
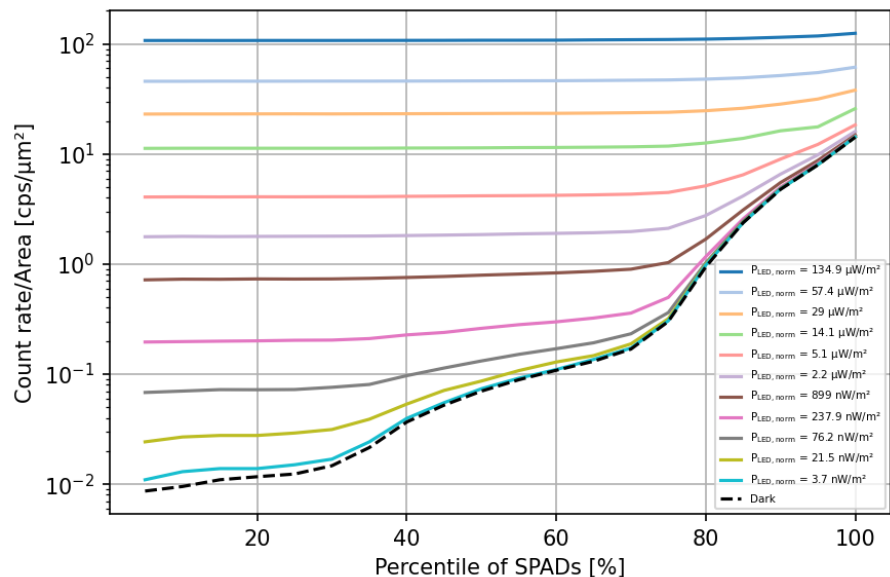
# Measurement of the Low-Light Performance and SNR Optimization

- Switch-off threshold is not critical at high illumination levels
- At very low light levels, deactivating SPADs prevents the signal from being lost in the noise

$$SNR = \frac{PDE \phi_p t}{\sqrt{(PDE \phi_p + 2DCR)t}} \quad [1]$$

$$MCR = PDE \phi_p + DCR$$

$$\frac{SNR}{\sqrt{t}} = \frac{MCR - DCR}{\sqrt{MCR + DCR}}$$

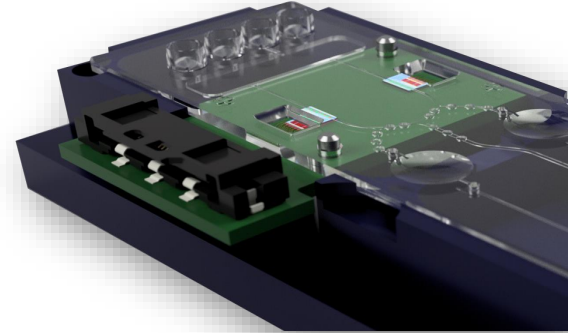


[1] <https://www.hamamatsu.com/eu/en/resources/interactive-tools/photon-counting-snr-simulator.html>

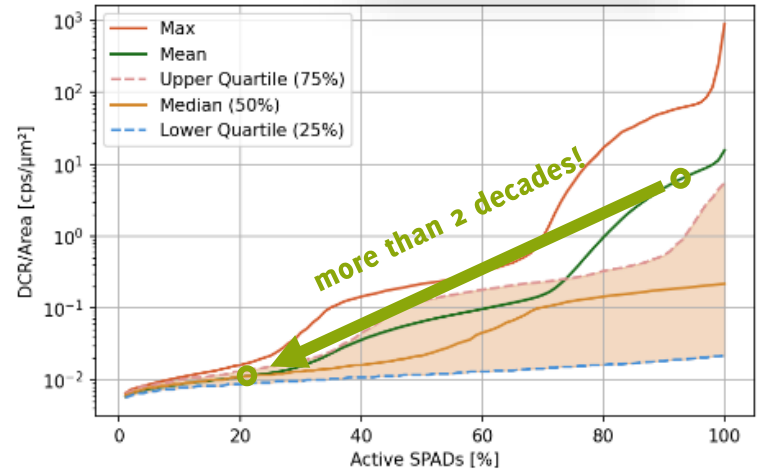
D4030AB Chip Variant

# Conclusion

- SPAD based line sensor IC, tailored for in-vitro-diagnostic chemiluminescence assays in microfluidic channels
  - Combination of SPAD device optimization, flexible sensor IC architecture, and hot-pixel calibration leads to high sensitivity and low DCR
  - Improvement of mean DCR by more than 2 decades by choosing a SPAD switch-off threshold of 80% instead of  $\sim 10\%$
  - Achieved DCR of approx.  $10^{-2}$  cps/ $\mu\text{m}^2$ , only two orders of magnitude above PMTs
- Next step: Investigate the low light performance with real chemiluminescence measurements



D4034AB



Thank you for your attention!

This work has been carried out in the project KODIAK which was funded as part of the European Union's response to the COVID-19 pandemic through the European Regional Development Fund (ERDF-OP 2014-2022) under the references 2021 FE 9127 and 2021 FE 9129.

REACT-EU – Als Teil der Reaktion der Union auf die COVID-19-Pandemie finanziert.



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