Changing the way we count photons

"Impact and challenges of micro-optics for SPAD detectors"

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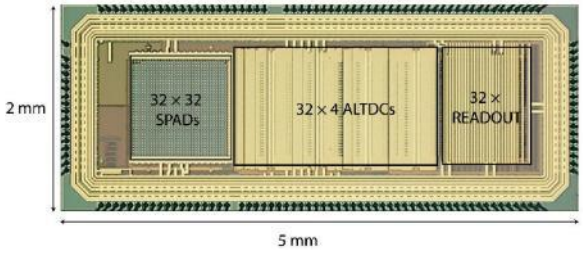
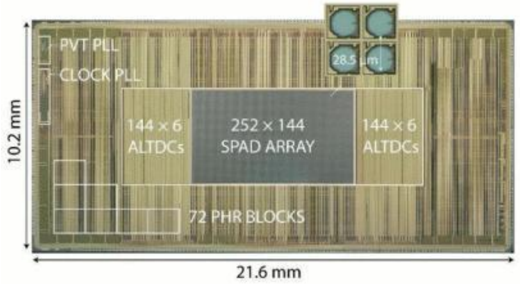
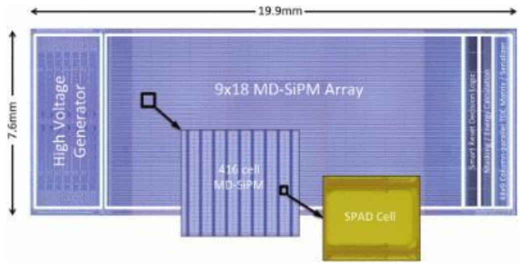
Company introduction

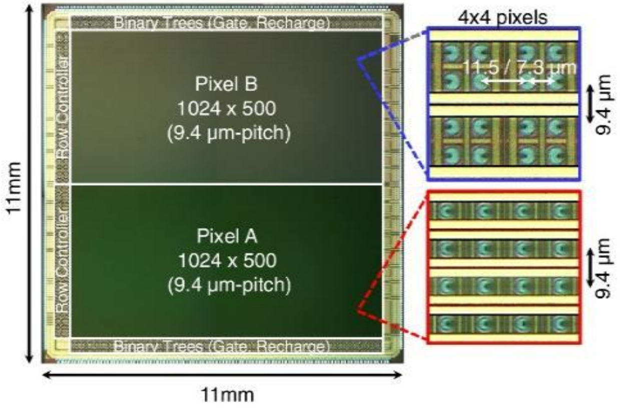
Company roots

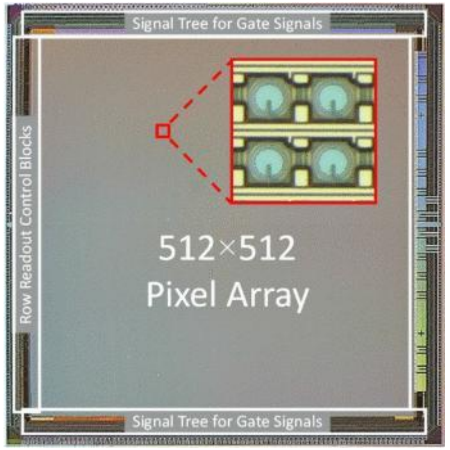
- SPADs developed at TU Delft and EPFL since 2004 by co-founders Claudio Bruschini and Edoardo Charbon
- Technology transferred from EPFL + PIT's own sensors
- Application specific detectors





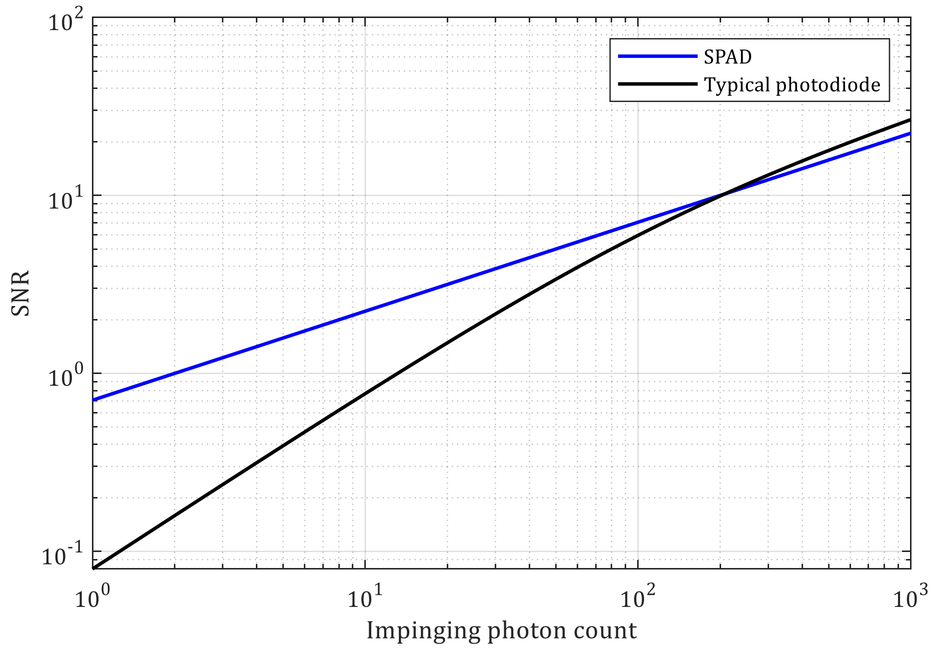


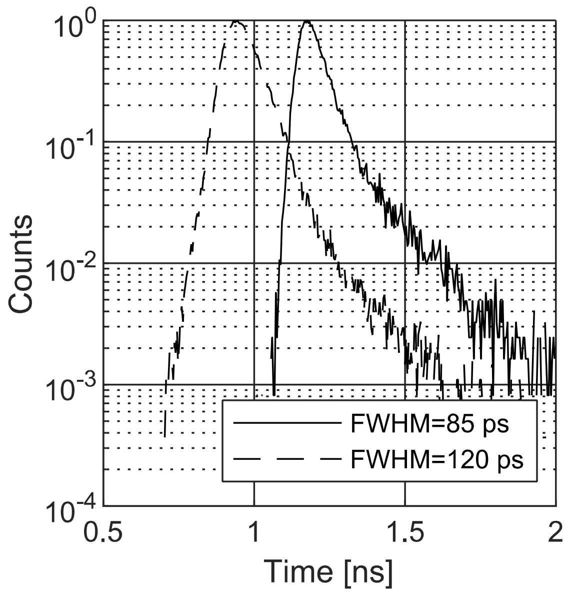




Why SPAD arrays?

- SPADs have exceptionally **high readability of low light signals** (quantified in a high signal-to-noise ratio)
- SPAD have extremely **precise timing** (quantified in a low standard deviation)

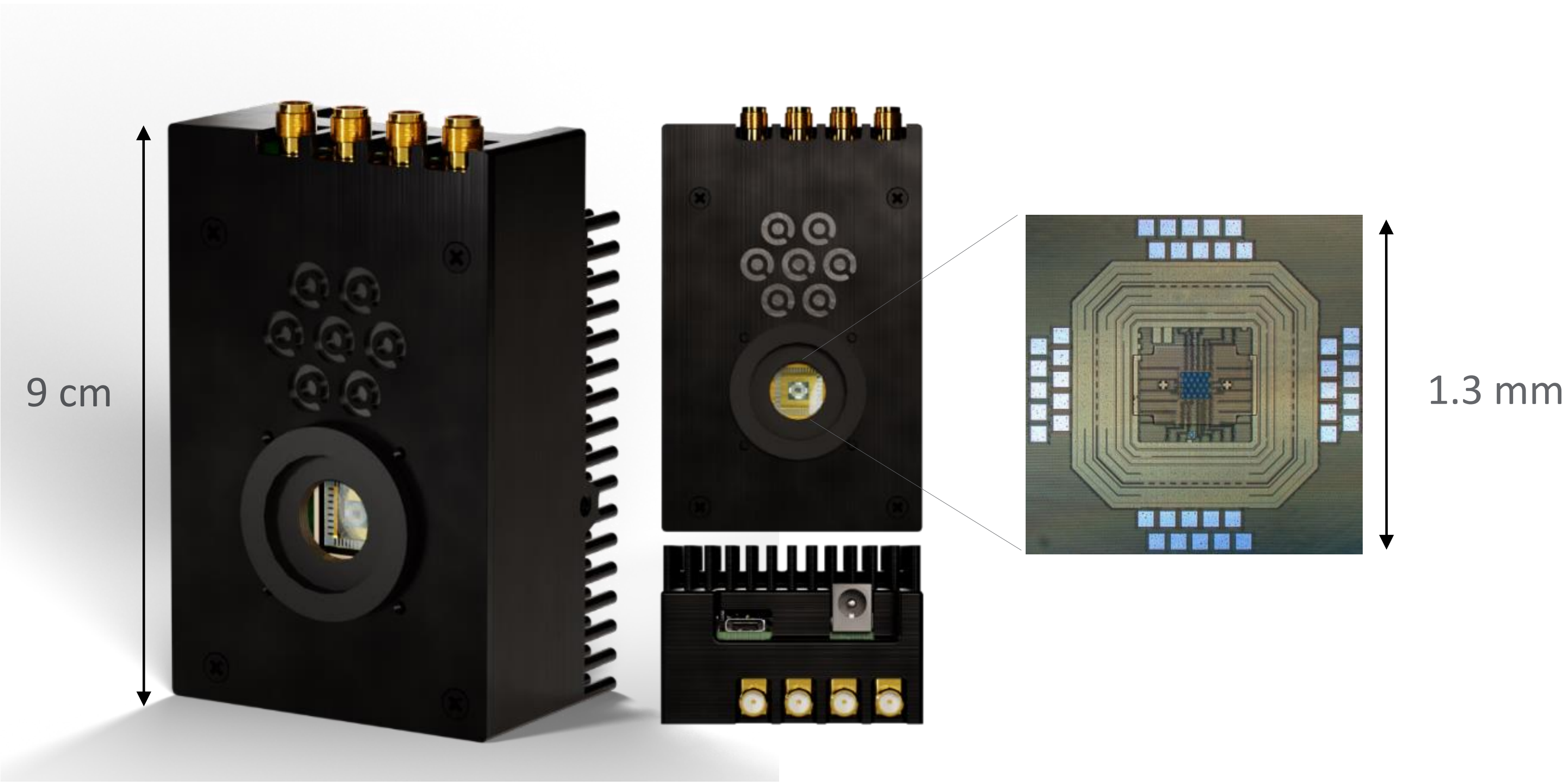




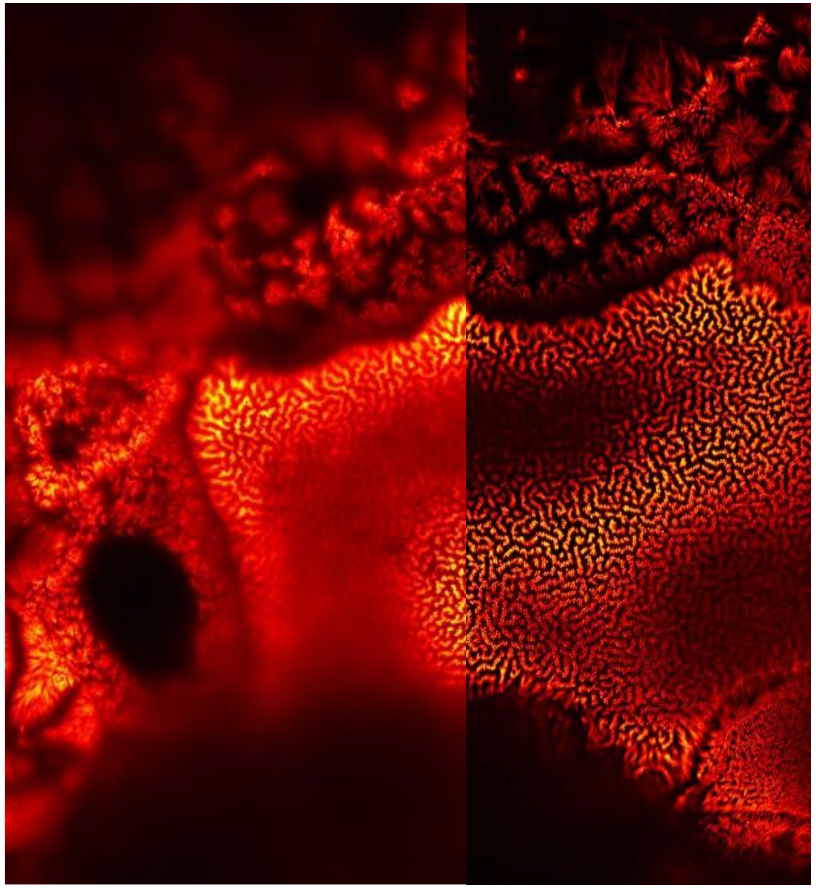
Commercialized products

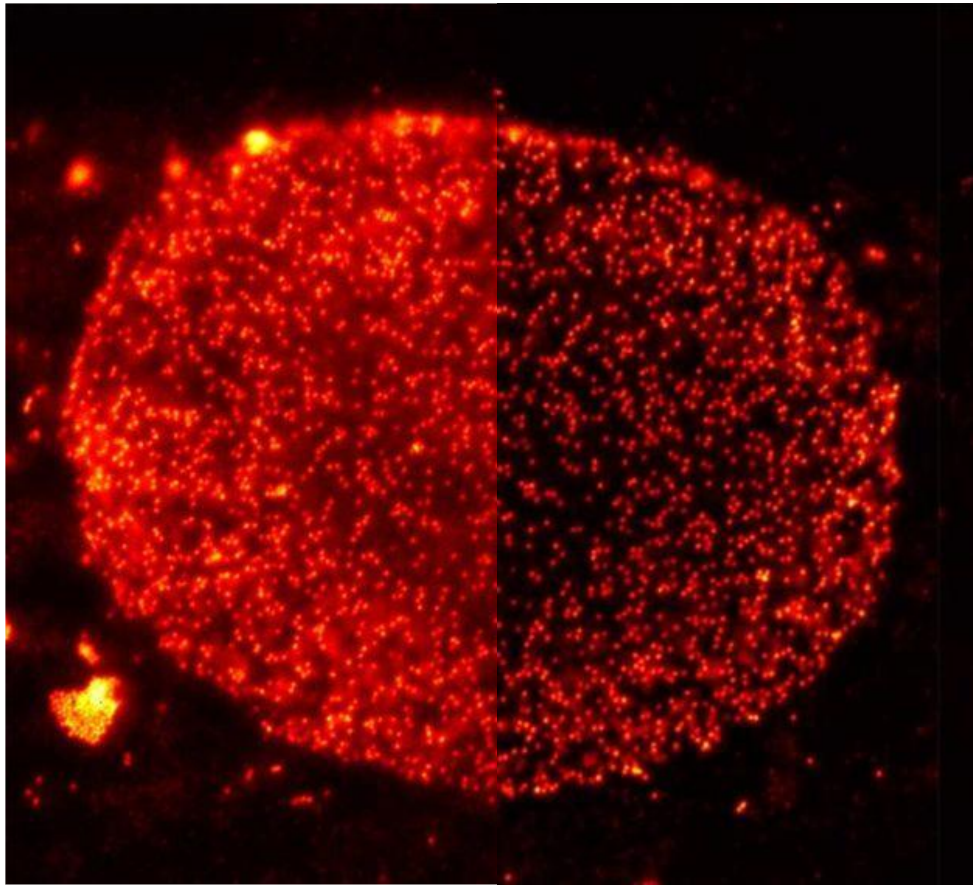
SPAD23

- 23 SPAD pixels array
- Wide detection spectrum
- Low dark noise
- Picosecond time tagging



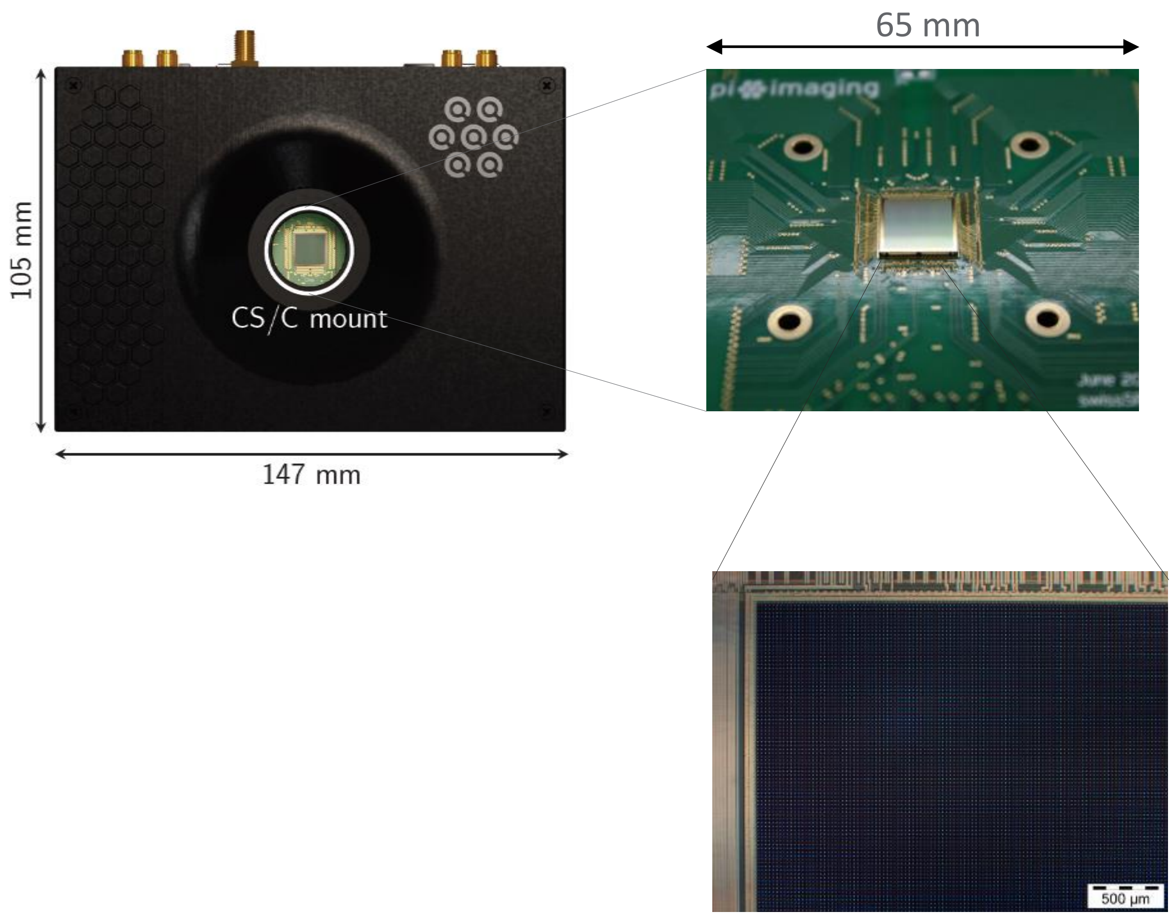
Super-resolution microscopy with SPAD23



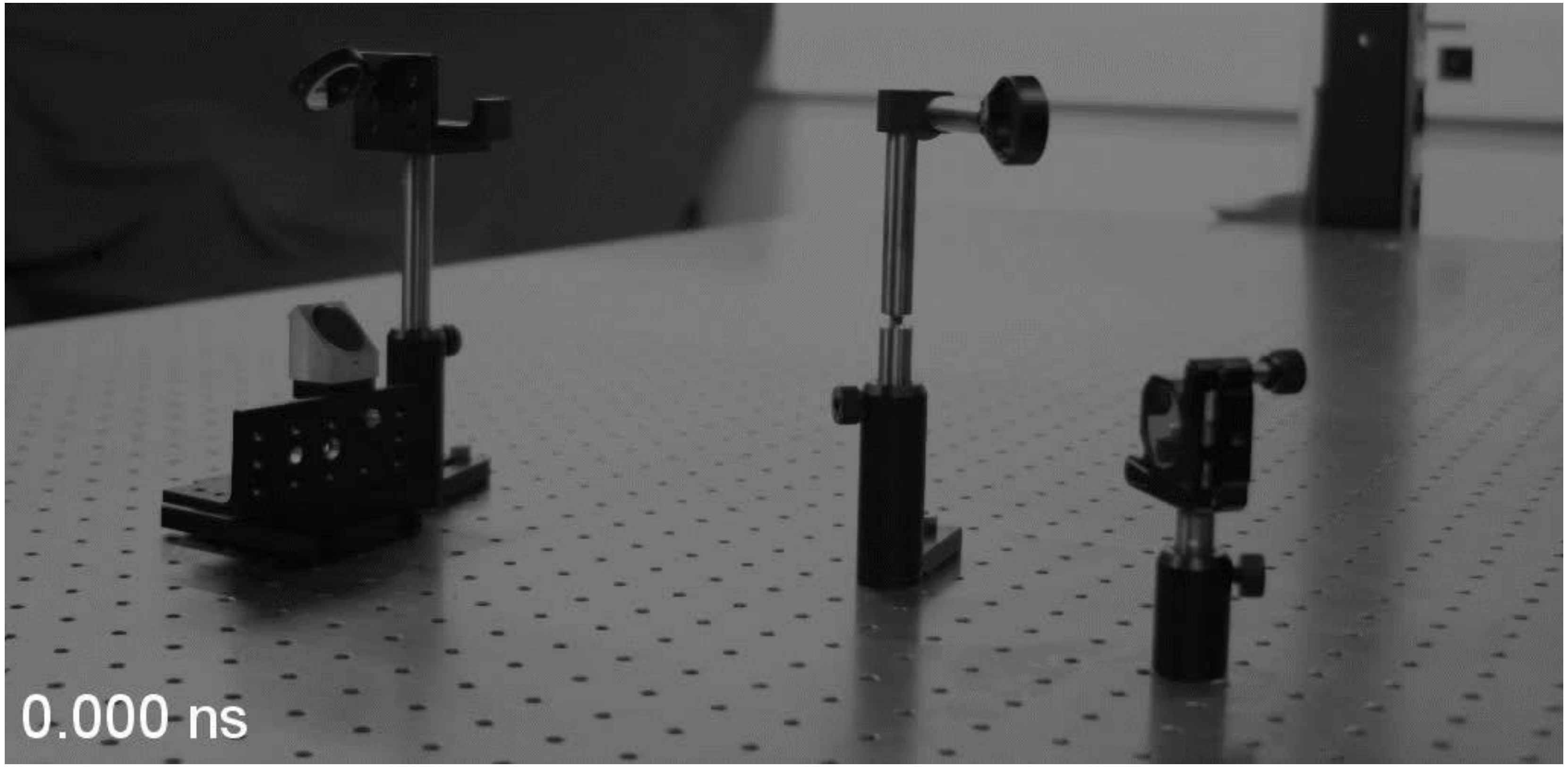


SPAD512^2

- 512x512 SPAD pixels
- Photon-counting up to 100’000 fps
- Picosecond time-gating
- Low dark noise
- No readout noise



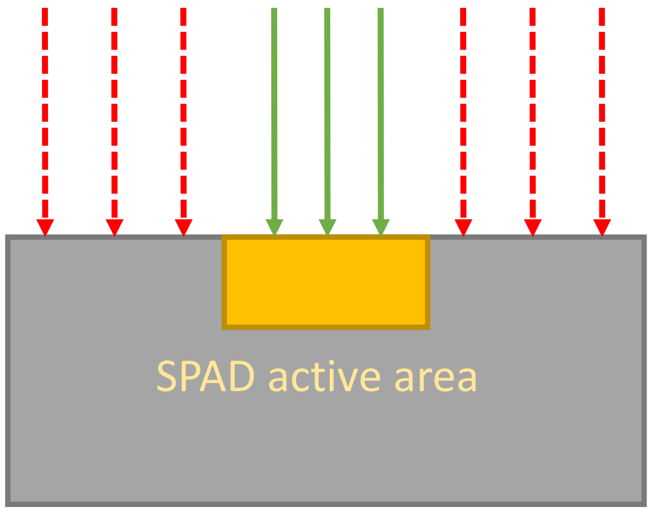
High-speed imaging with SPAD512^2



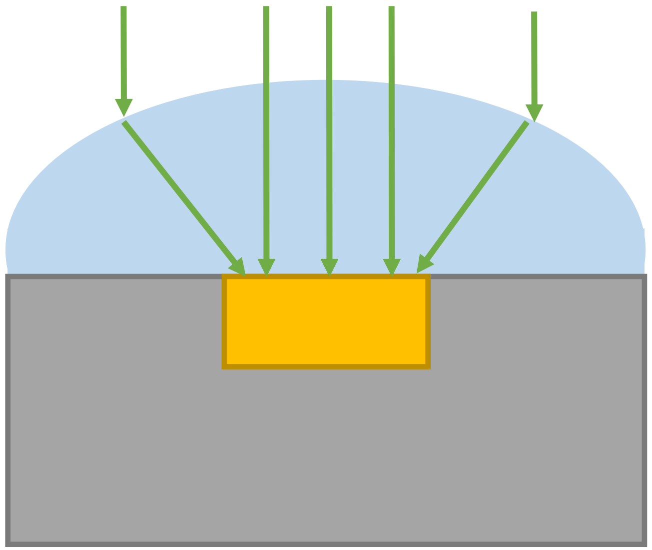
Micro-optics for SPAD detectors

Why micro-optics on SPADs?

- Main challenge: SPAD pixels contain embedded electronics
- The active area is therefore small, typical fill factors are between 10 and 25%
- Micro-lenses focus the light on the active area, sensitivity is greatly improved

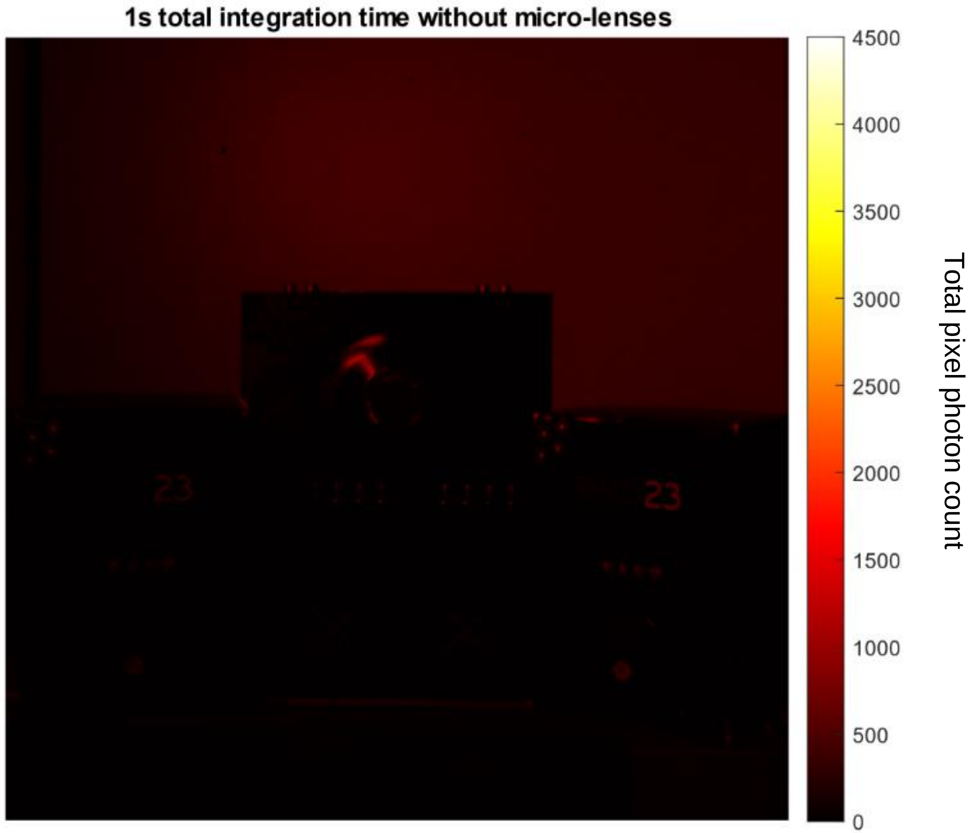


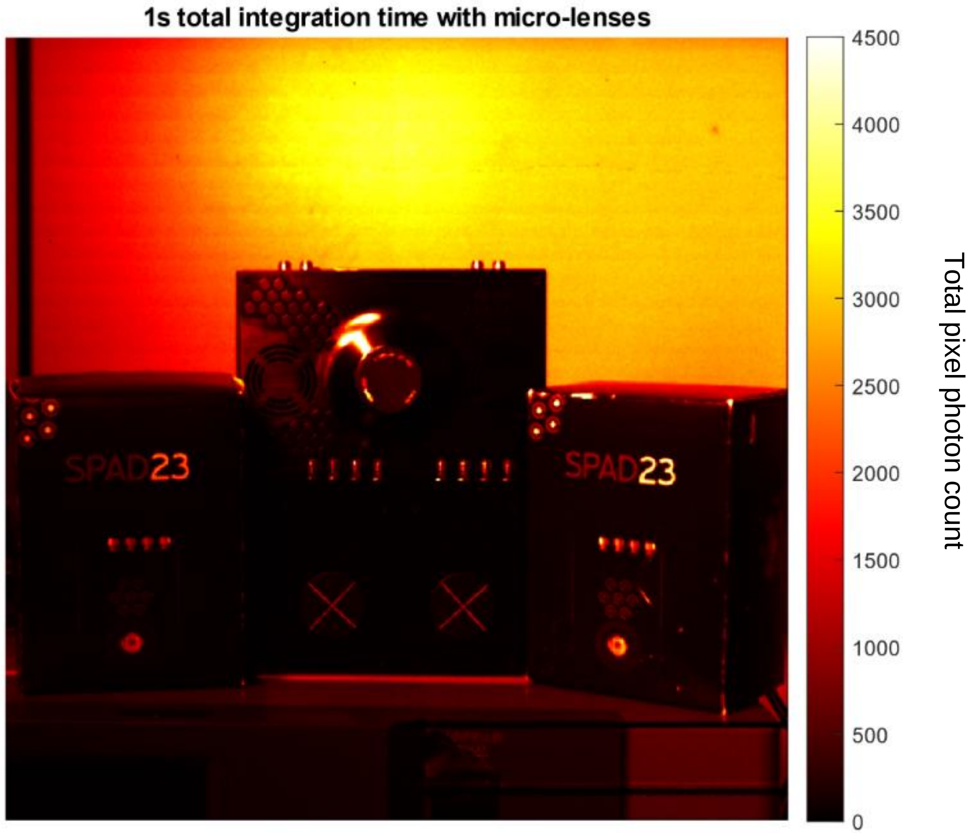
Without micro-optics: up to 90% of the photons are lost



With micro-optics: up to **8x** more photons can be captured

Why micro-optics on SPADs?



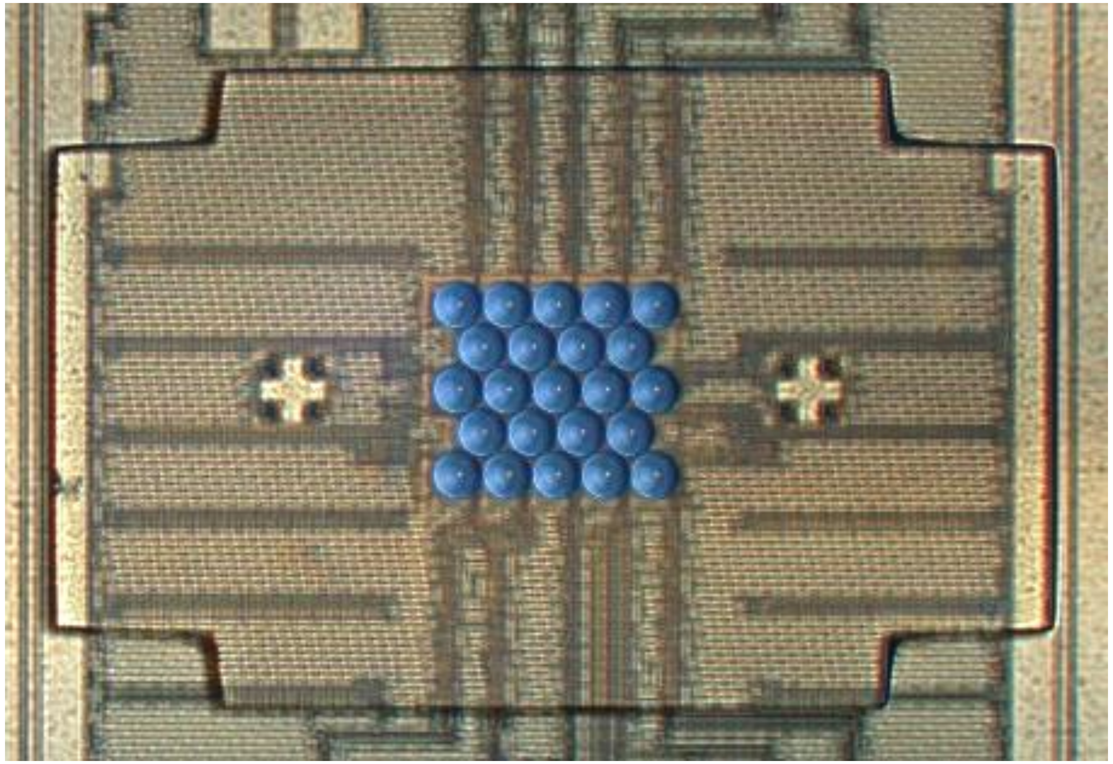


Micro-optics fabrication flow

Mould creation → Mould replication → Micro-lenses imprinting

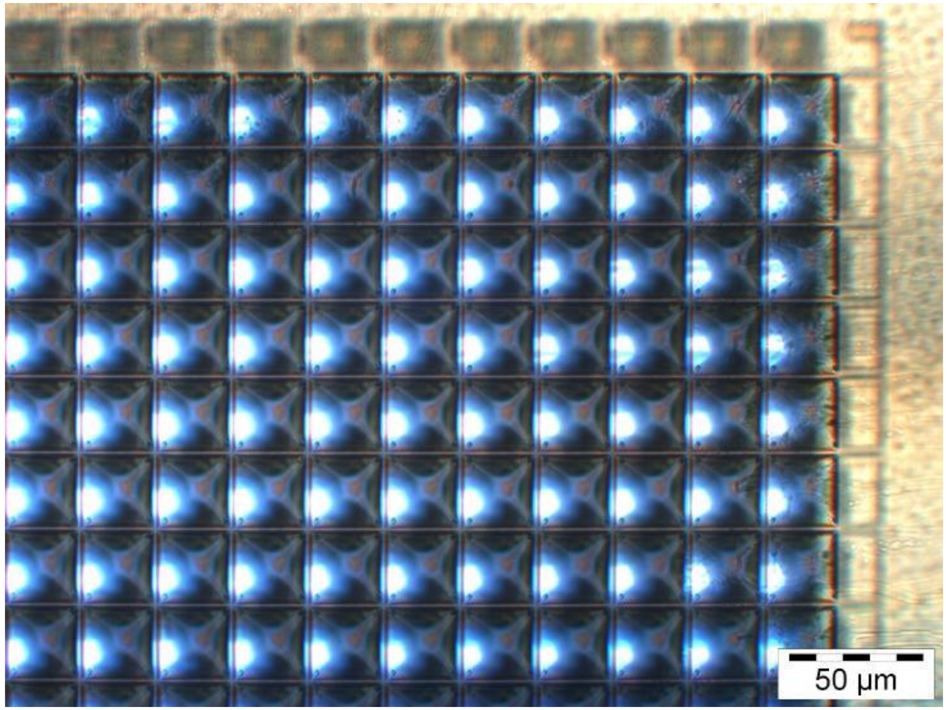
Mould fabrication: PR reflow

- First moulds have been created with photoresist reflow process
- Well established process
- Lens quality and uniformity over the array is very good
- Micro-lenses shape is limited



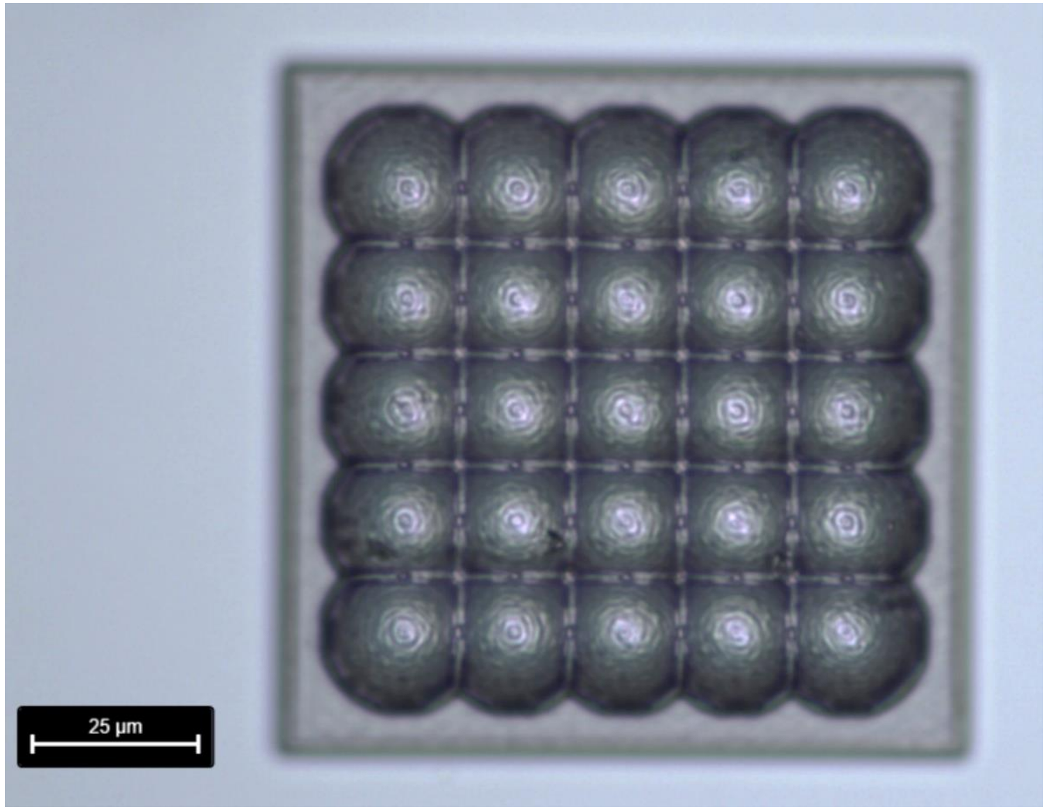
Mould fabrication: PR reflow limitations

- Reflow works well with circular lens but leaves gap between the them
- Square lenses are another problem as they get distorted after reflow
- With this technology, we can increase the light collection by 4.5x

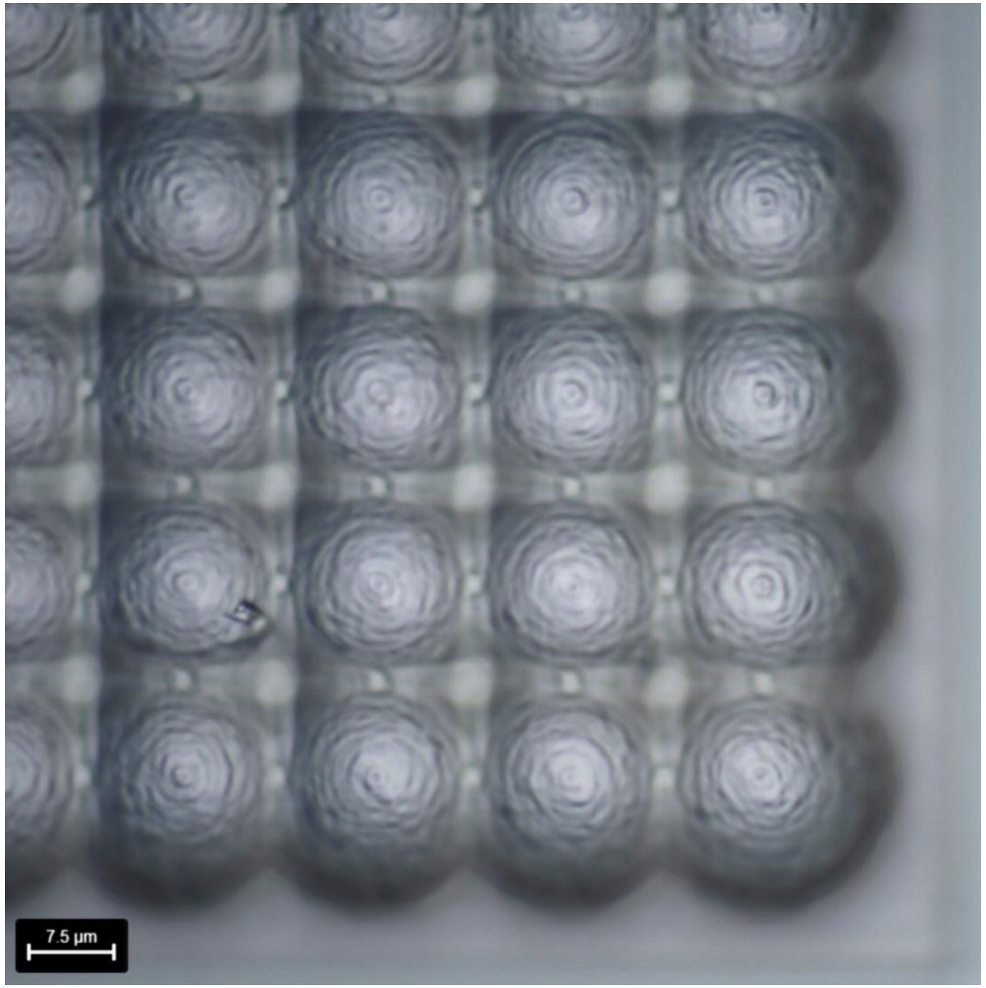


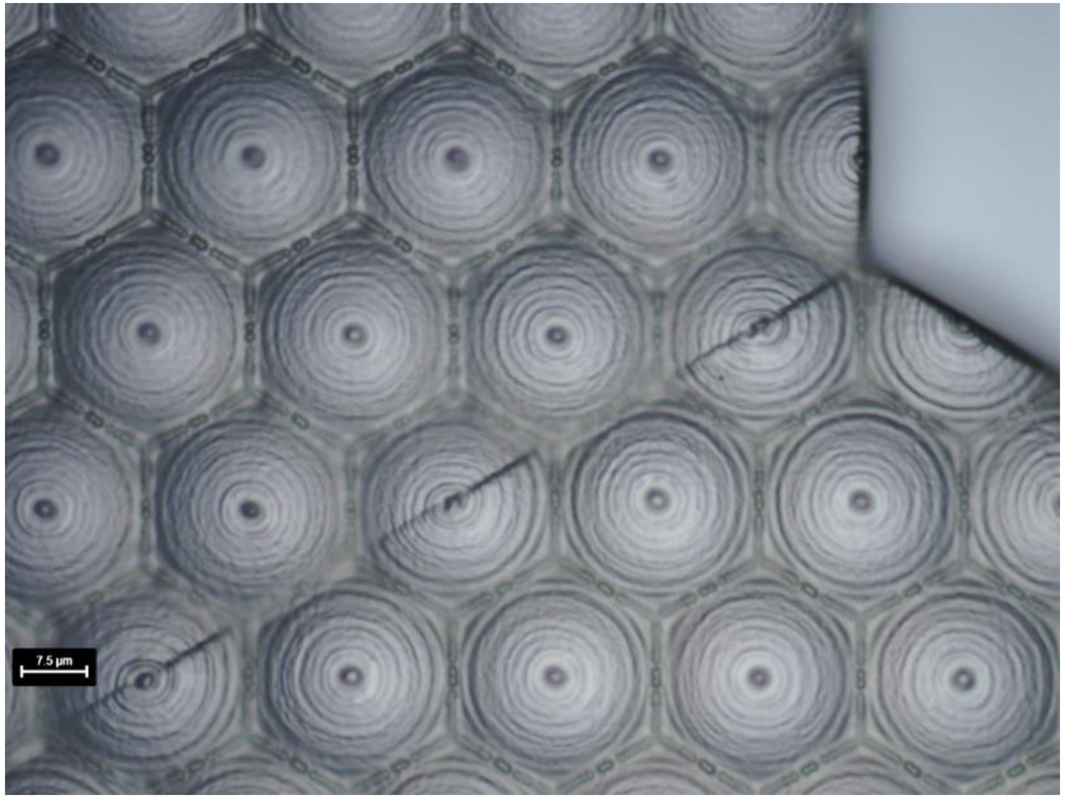
Mould fabrication: 2PP lithography

- Second mould was created using additive manufacturing
- This allowed for relatively quick micro-lenses parameters experimentation
- Freedom of the lens shape and dimensions



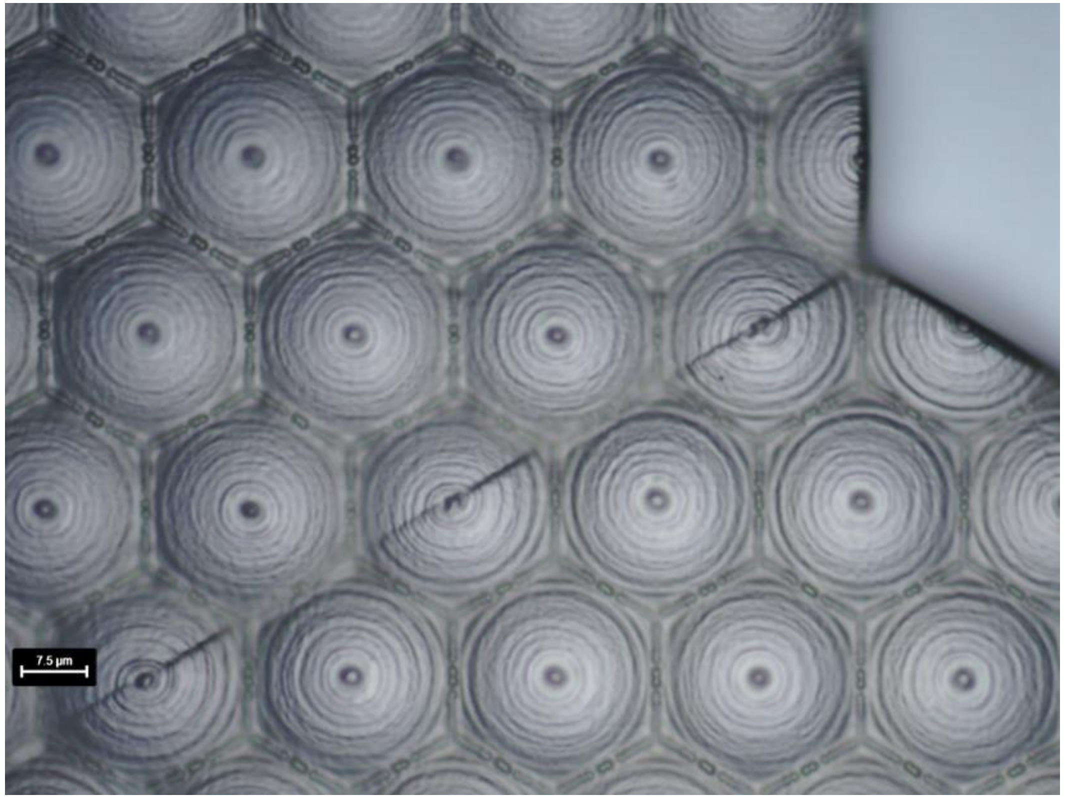
Mould fabrication: 2PP lithography





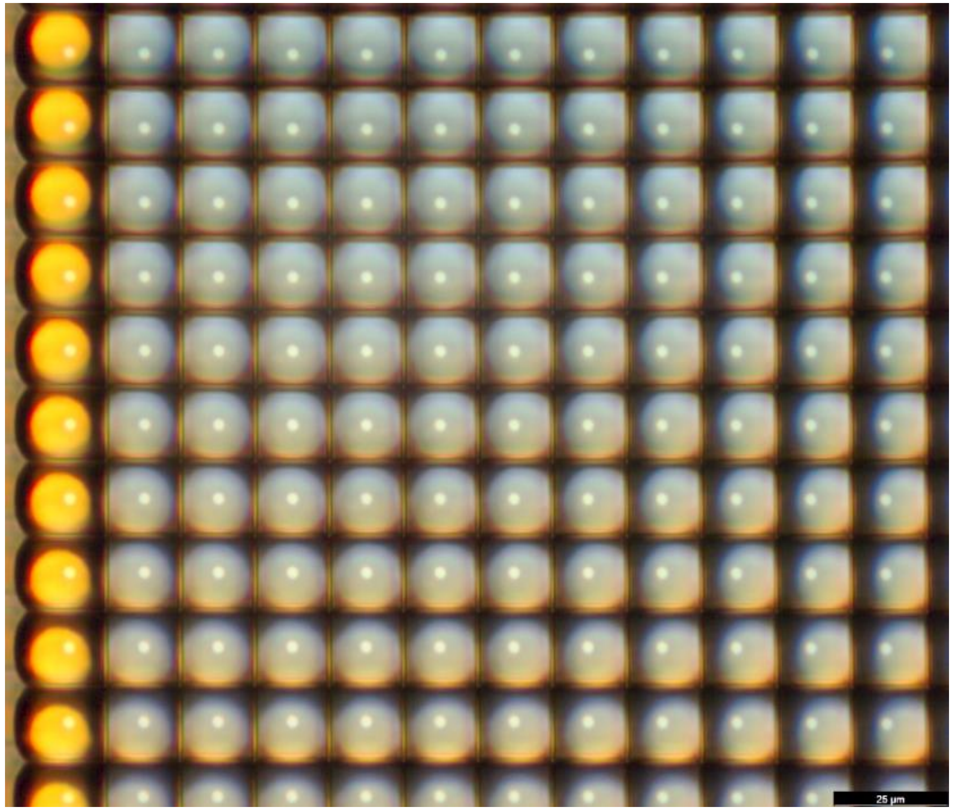
Mould fabrication: 2PP lithography limitations

- Gapless micro-lenses can be fabricated but quality is coarse
- Stitching creates artifacts
- Overall, the sensitivity was improved 10% compared to PR reflow approach
- The uniformity over the array was however reduced



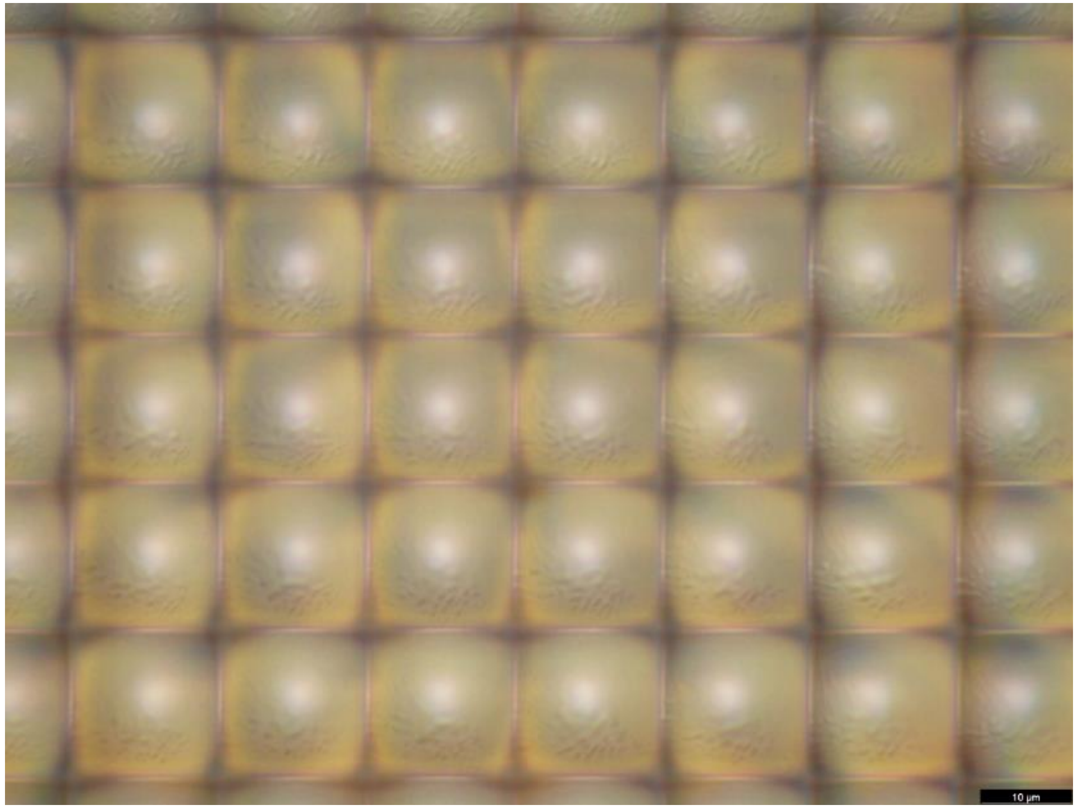
Mould fabrication: 3rd approach

- Freedom of the lens shape and dimensions
- Gapless design is possible
- Higher throughput with high quality lenses



Mould fabrication: 3rd approach limitations

- No more stitching artifacts
- Some roughness persist (post-processing?)
- Thanks to gapless design and good quality, the sensitivity is expected to increase by 6-8x



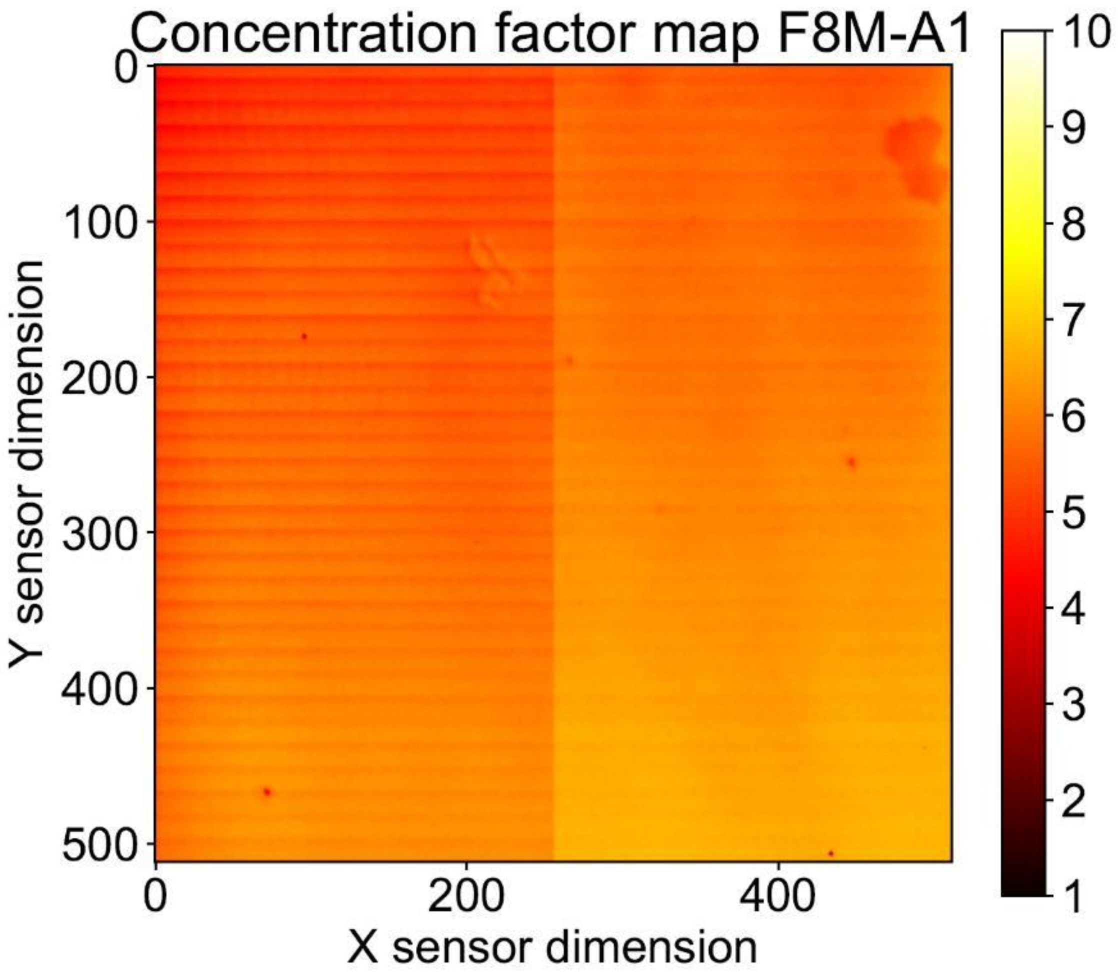
Micro-optics imprint: challenges 1

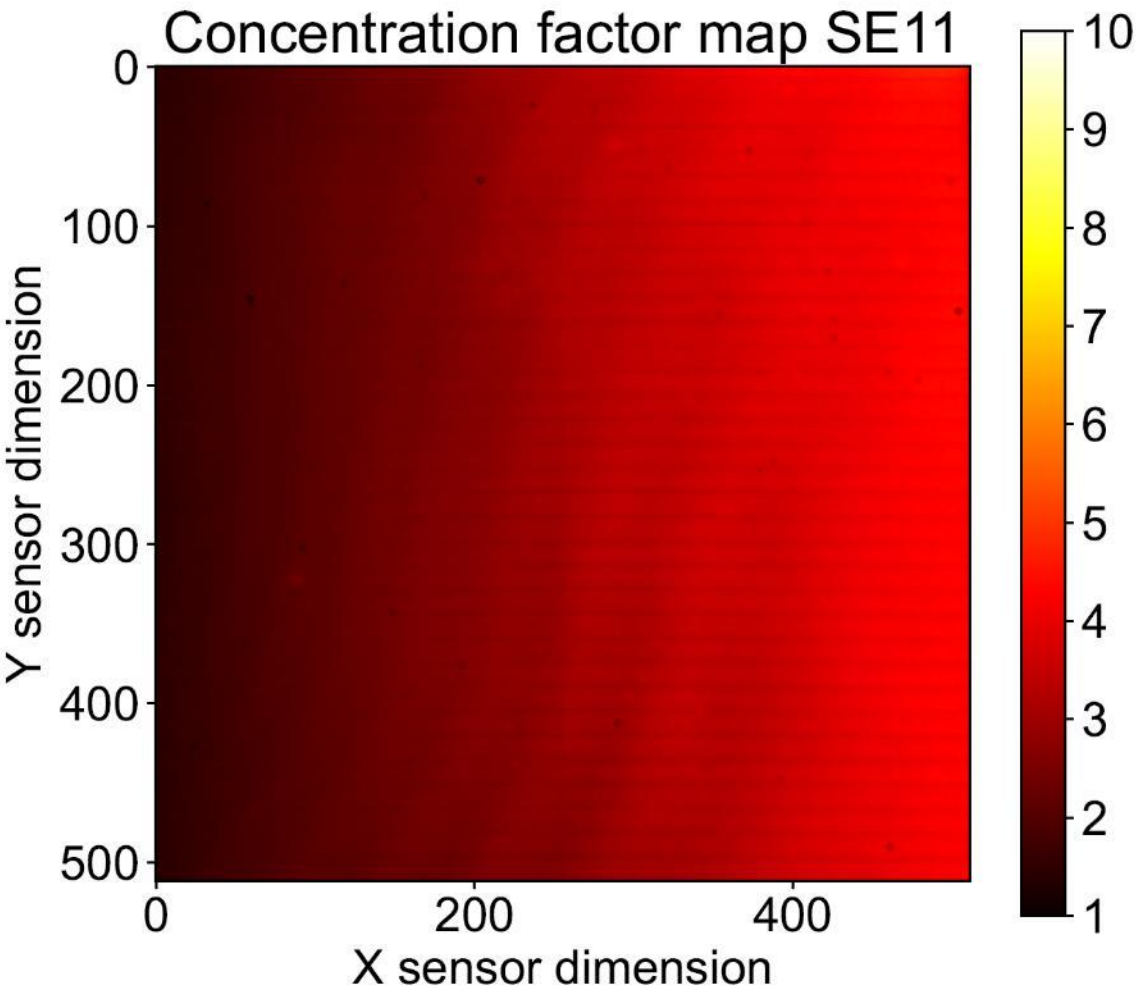
- Alignment of the mould with the SPAD pixels is critical (active area as small as 3µm)
- Distance between lens and active area is critical (“focal length”)
- This distance must be uniform across the array → undesired gradients
- Defects can occur (lens merging with PR reflow, de-moulding artifacts, etc..) and will have a big impact on image sensors

Micro-optics imprint: challenges 2

- Reticle-based imprints work well for prototyping but limit throughput
- Wafer scale imprints are investigated to increase throughput and reduce cost
- All challenges related to imprints become critical due to bigger imprinted area

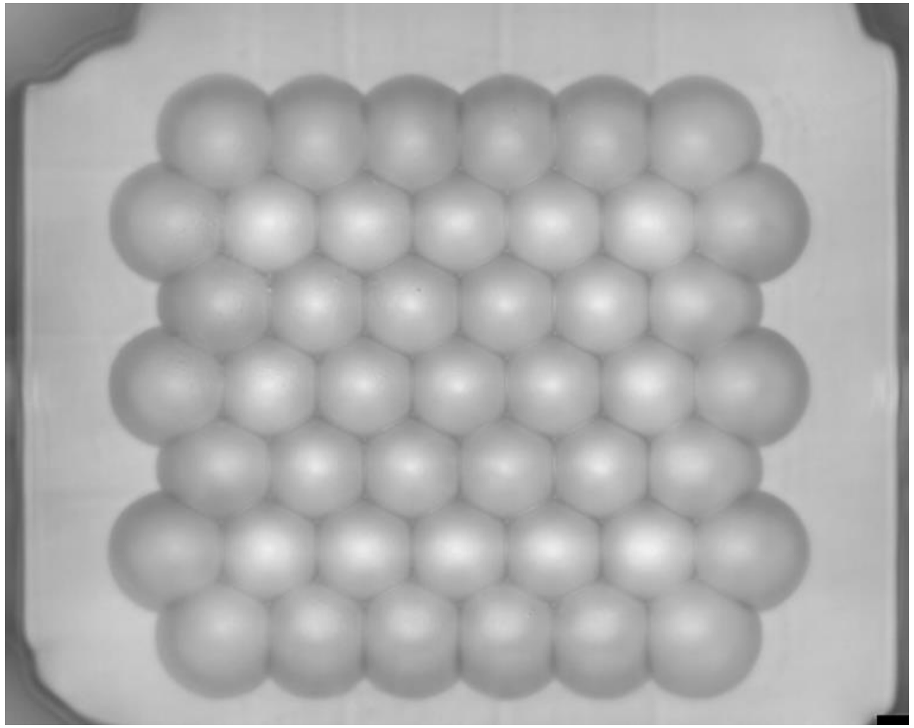
Micro-optics imprint: challenges





Conclusion

- Micro-optics are extremely important for SPAD detectors as they directly improve the sensitivity
- Optimizing the process for higher throughput, better yield and higher alignment of imprints will be the future challenge
- We hope to achieve 8x sensitivity improvement with our current flow, this will be tested soon with the real imprinted detectors



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