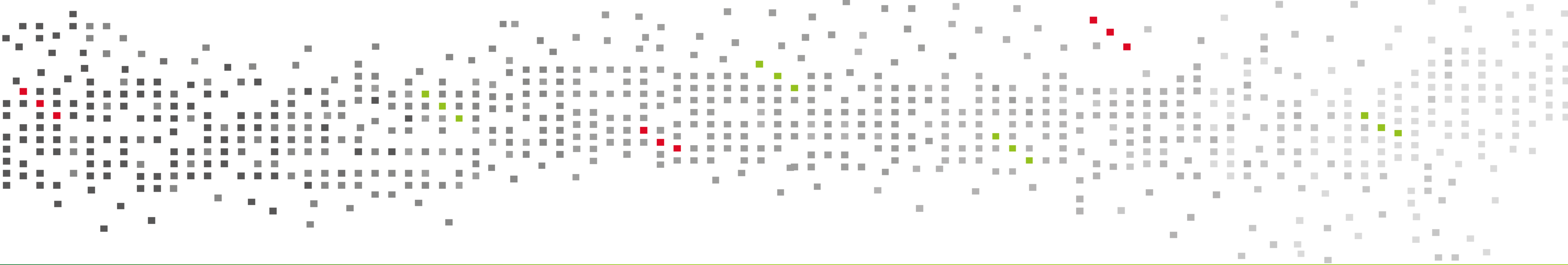

PLANAR MICROLENSES FOR SPAD SENSORS

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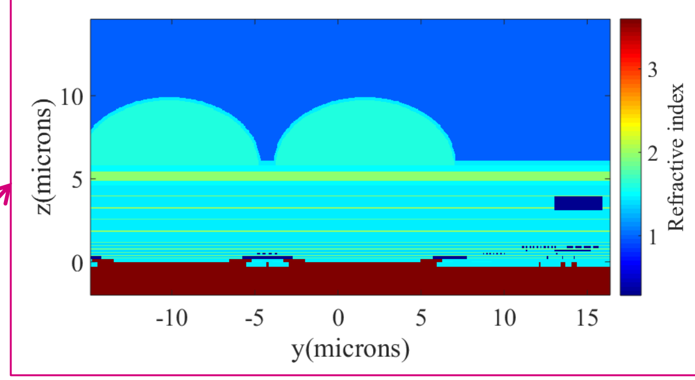
OUTLINE

- **Introduction**
  - SPAD array and melted microlens
  - Towards planar microlenses
- **Planar microlenses**
  - Theory basics
  - Process
  - Simulations
  - Characterization results
- **Conclusion**

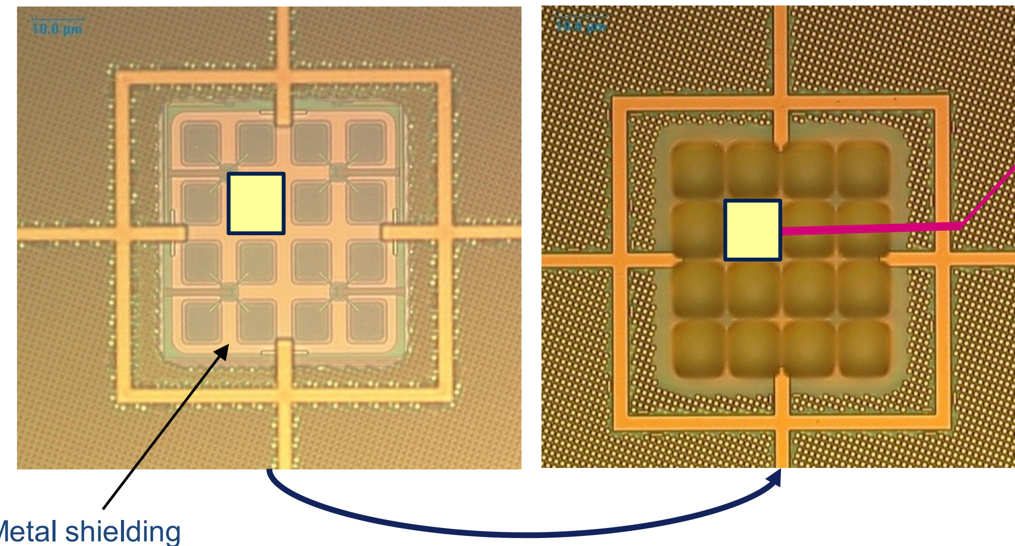
INTRODUCTION

- **SPAD array with standard melted microlens**
  - 4x4 SPADs pixels 10.18 µm pitch to form a macropixel
  - STMicroelectronics C40 CMOS technology



Cross-section of 2 SPAD pixels with melted microlens [3]

Macropixel without microlens (ff_O ~ 40%) Macropixel with melted microlens



Light-collecting surface

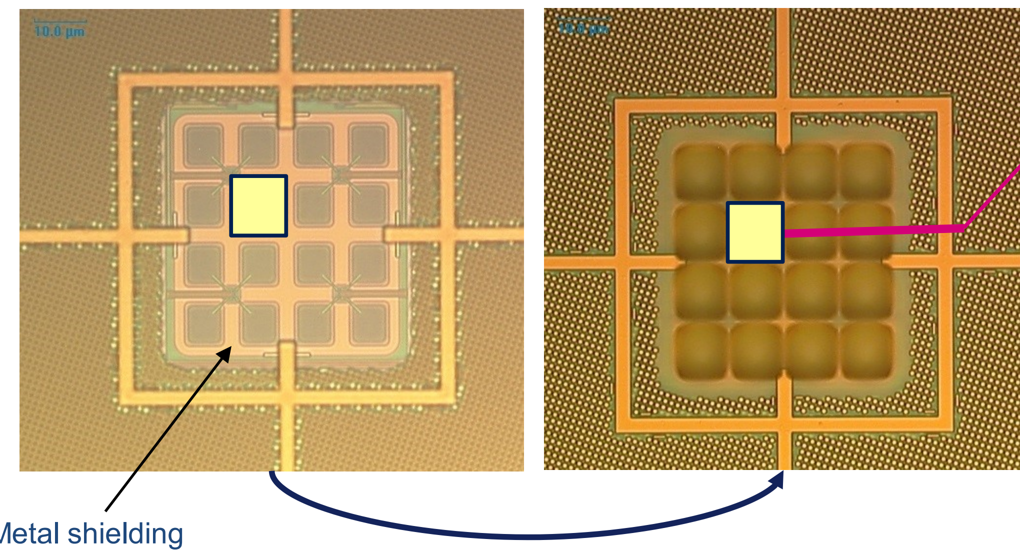
Pixel surface

[1] G. Intermite et al, Enhancing the Fill-Factor of CMOS SPAD Arrays Using Microlens Integration, Proceedings of SPIE, Vol. 9504 (2015).
[2] S. Pellegrini, International SPAD Sensor Workshop (2018).
[3] High-Performance Nanophotonic Simulation Software, http://www.lumerical.com/.

INTRODUCTION

- **SPAD array with standard melted microlens**
  - 4x4 SPADs pixels 10.18 µm pitch to form a macropixel
  - STMicroelectronics C40 CMOS technology

Macropixel without microlens (ff_O ~ 40%)   Macropixel with melted microlens

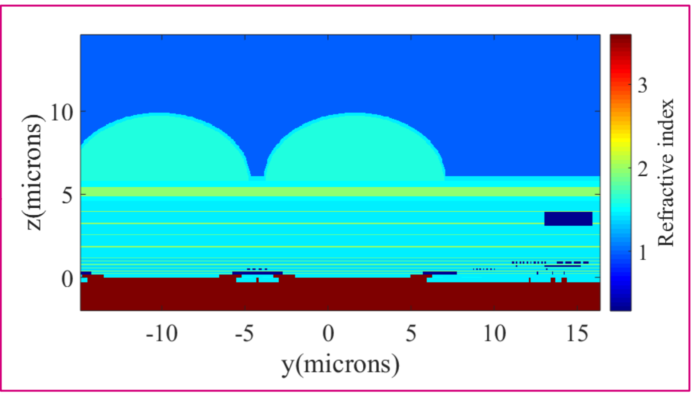


Metal shielding

Fill-factor +30% [2]

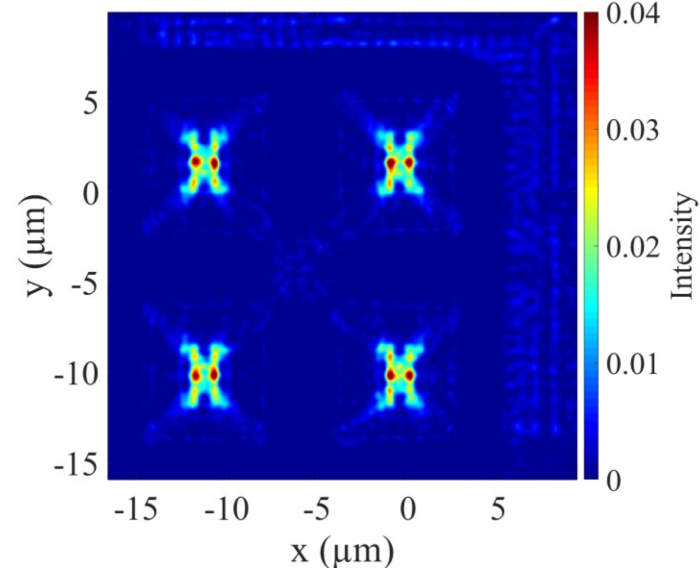
Light-collecting surface

Pixel surface



Cross-section of 2 SPAD pixels with melted microlens [3]

FDTD calculation of light intensity at Si entrance [3]



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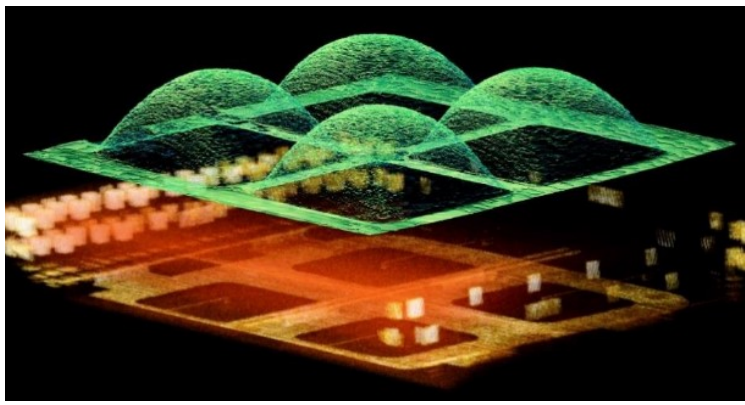
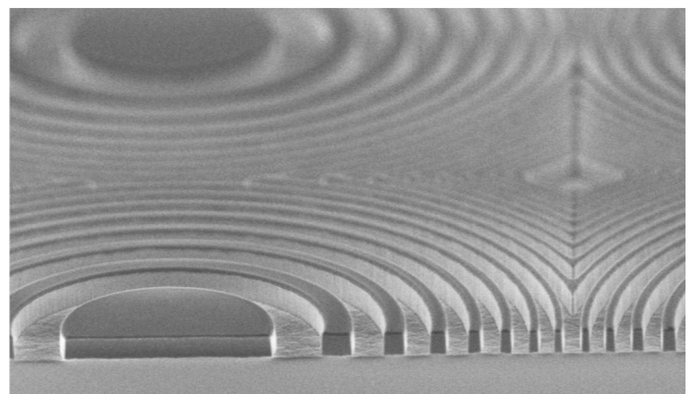
TOWARD PLANAR MICROLENSES

- Melted microlens
  - Adapted process for 10 µm pitch max
  - « Thick » layer (few µm) dedicated to large pitch
  - Topography, « dome » shape
  - Shape irregularity due to variability of reflow process
  - Delicate process with reliability concerns
  - Sensitive to temperature



S. Pellegrini, ISSW2018

- Planar microlens
  - Shaped by design (mask)
  - « Thin » layer (<1 µm)
  - Planar surface
  - Gapless possibilities
  - Classical lithography steps (litho-etch)
  - Materials robust to reliability testing



THEORY BASICS

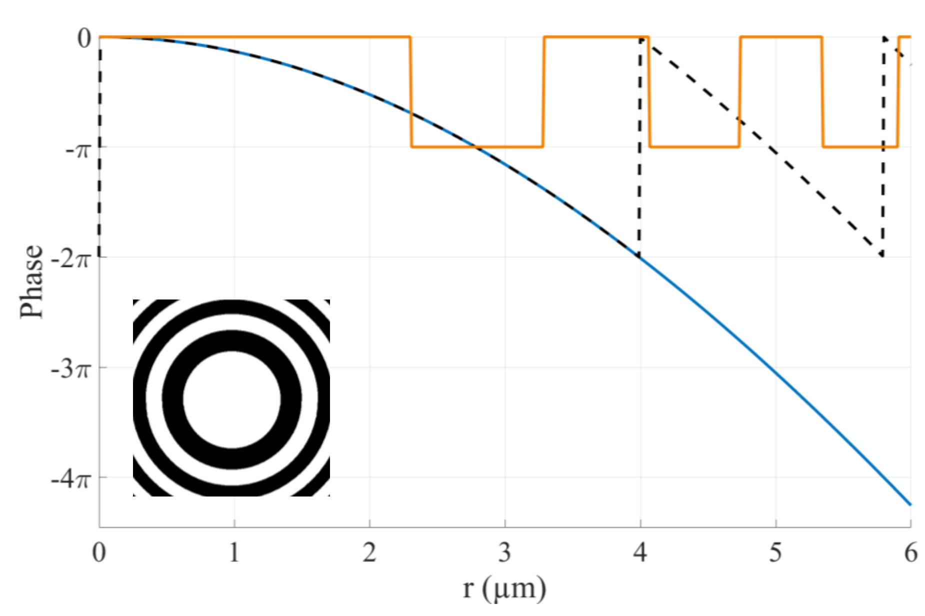
Arbitrary profile

Phase modulo 2π

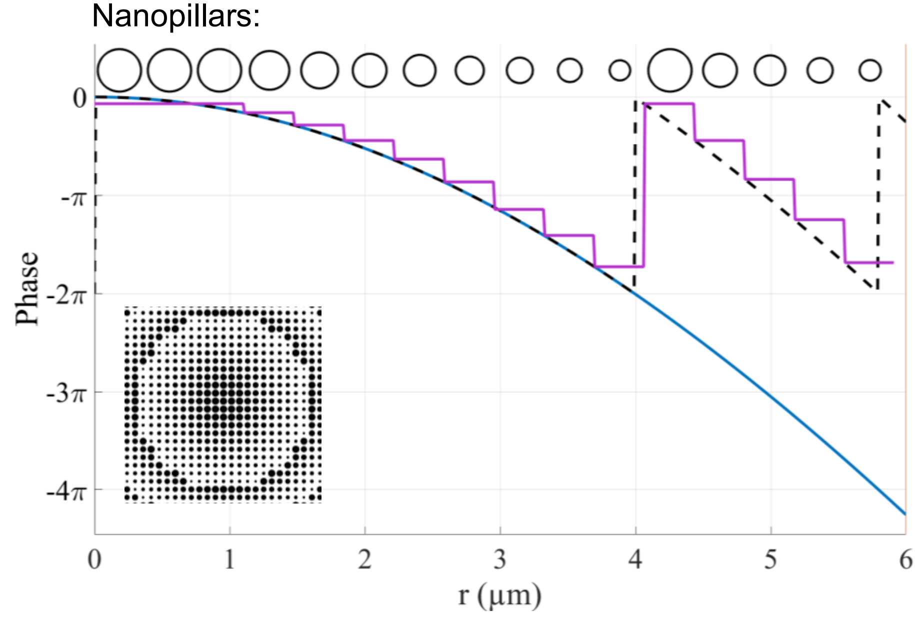
FZP phase profile

Meta phase profile

Fresnel Zone Plate



Metamicrolens



With Plan convex profile

f = 8 μm
λ = 940 nm
Normal incidence
n_{spacer}= 1,45

Binary phase, 0 – π
Radius of the k_{th} ring:

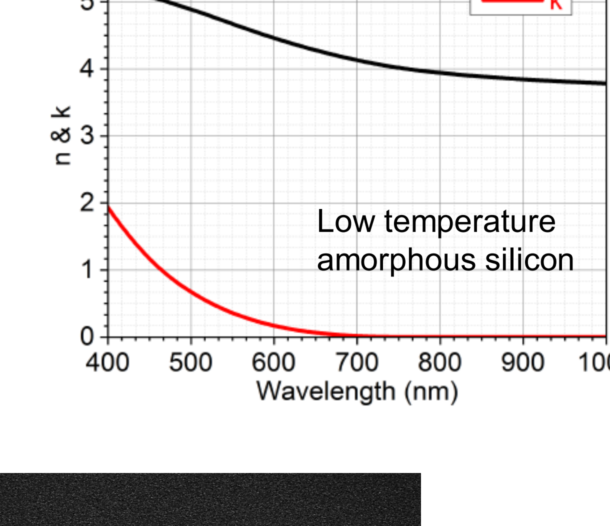
$$R_k = \sqrt{\frac{k\lambda}{n}\left(f + \frac{k\lambda}{4n}\right)}$$

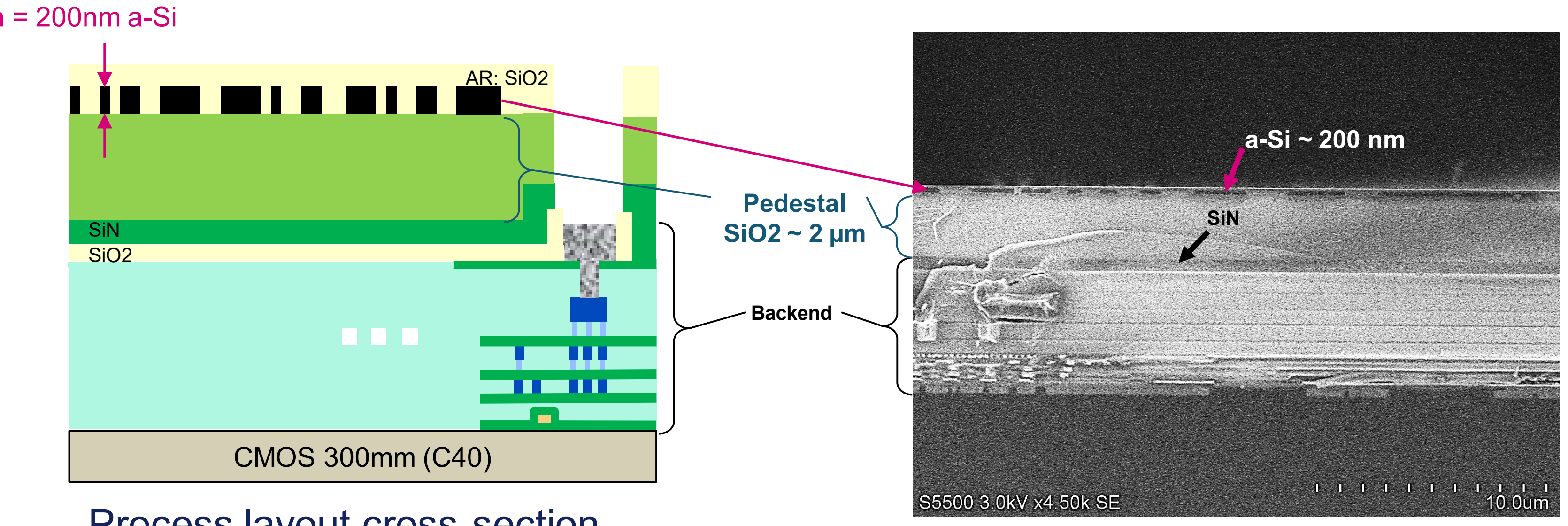
Phase gradient, 0 – 2π
Phase at position r :

$$\varphi(r) = \left[\frac{2\pi}{\lambda}\left(\sqrt{(r^2 + f^2)} - f\right)\right] mod(2\pi)$$

PROCESS

- **Process materials**
  - Silicon oxide spacer (2 µm to 10 µm) adjusted to focal distance and pixel size.
  - Amorphous silicon, high index (3.8) for phase shift transparent at λ > 800 nm
  - Stress minimization of the full stack (mainly aSi)
  - Silicon oxide as antireflective coating
  - Final planarisation



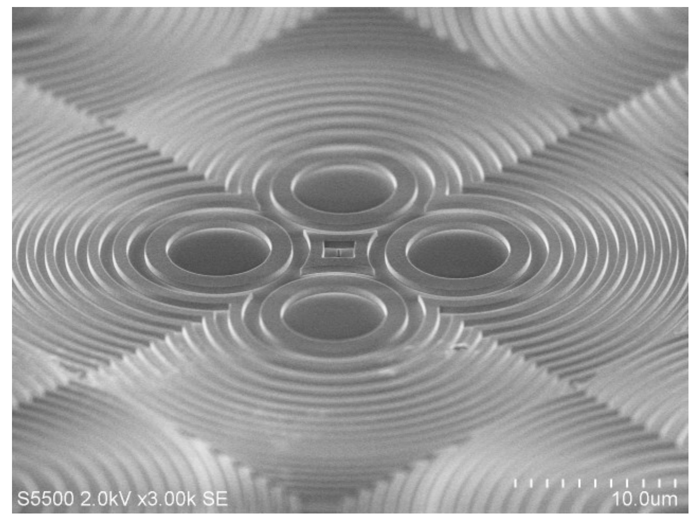


Process layout cross-section

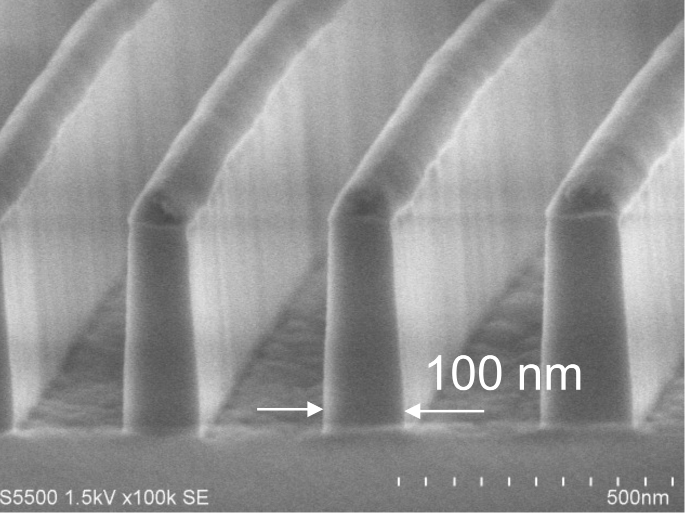
MEB cross-section

PROCESS

- **Patterning control**
  - Deep UV scanner with optical proximity correction (OPC)
  - Down to 100 nm structures, up to 500 nm tall
  - (Quasi) Vertical etch optimization with resist and SiO_2 hard mask
  - High aspect ratio filling with SiO_2 (Anti reflective coating)



Artistic view of Quad SPAD µlenses



SEM cross section before resist mask removal

LAYOUT AND SIMULATION

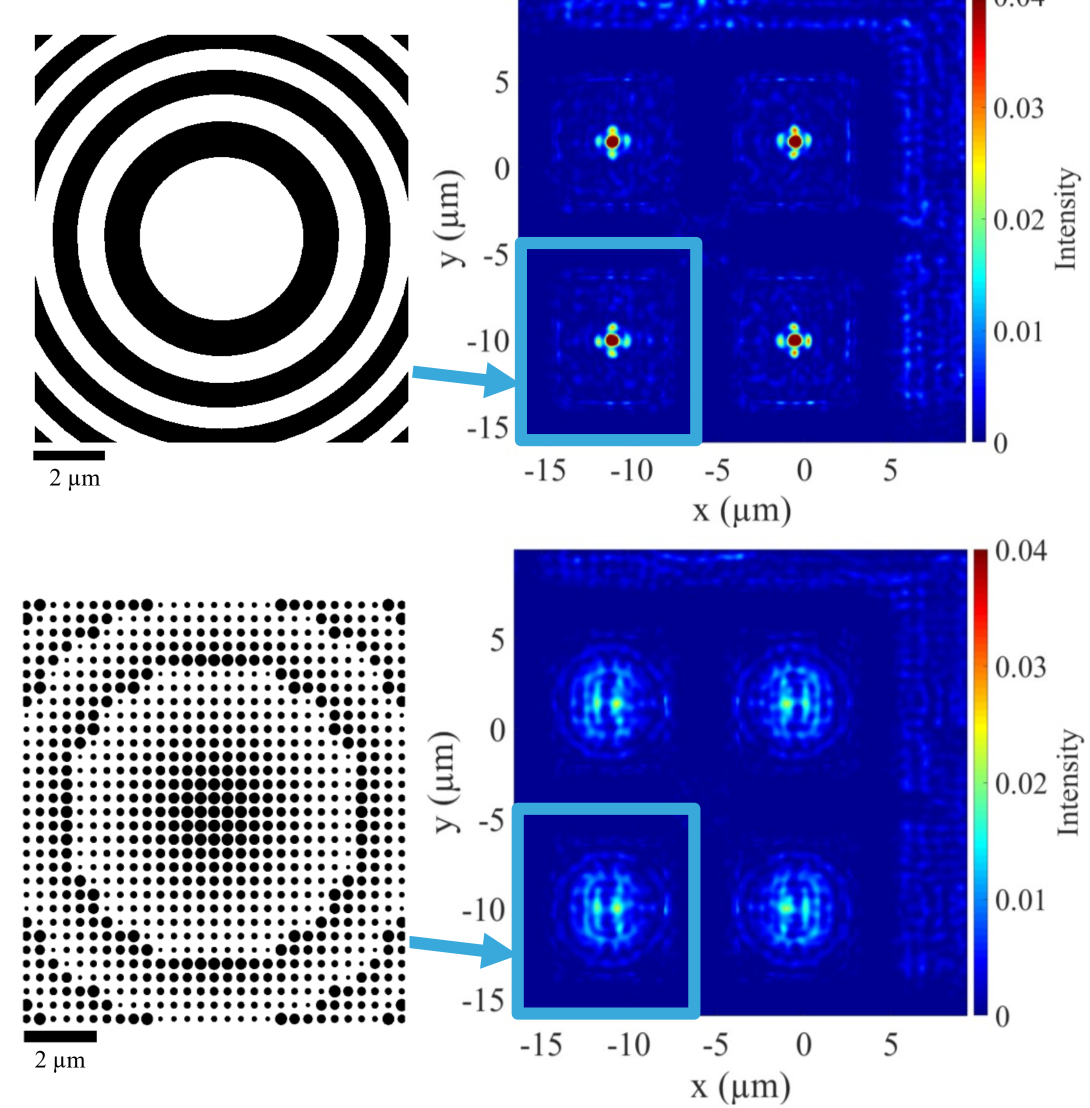
- **FZP microlens**

  Only h, f optimization parameters with process constraints

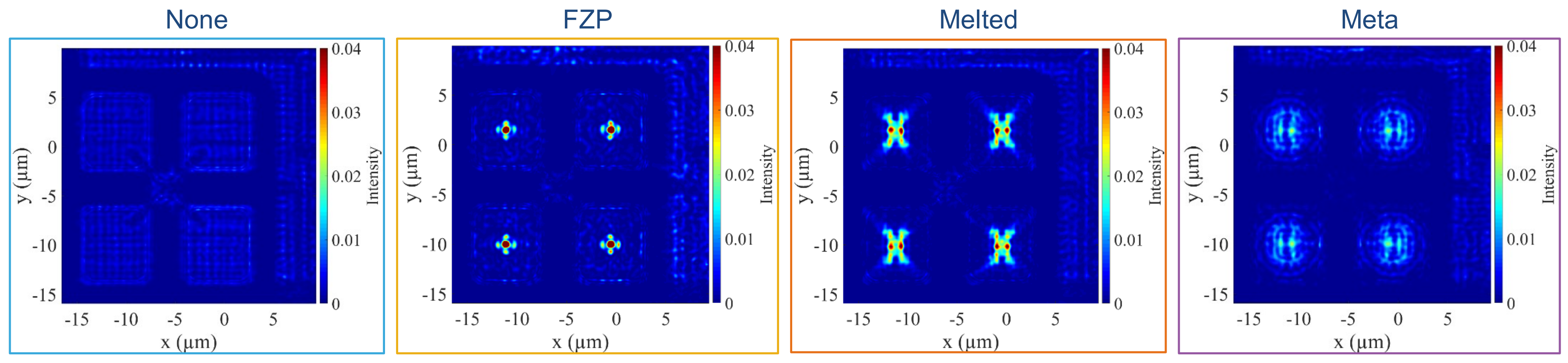
  Key parameters:
  f = 8 µm
  h = 200 nm
  AR = 150 nm

- **Metamicrolens**
  - Choice of pitch (process)
  - Define library of pillars with 0 to 2π phase shift
  - Optimization on h, f, pillars/pitch

  Key parameters:
  f = 8 µm
  h = 500 nm
  pitch = 370 nm
  Phase : 0 to 2π



SIMULATED PERFORMANCES



Microlens type	None	FZP	Melted	Meta
Simulated PDE (%)	2,2 ± 0,2	2,6 ± 0,1	3,4 ± 0,2	4,1 ± 0,1
Average gain	–	x 1,2	x 1,5	x1,8

PDE: Photon Detection Efficiency on pixel pitch

Maximum gain $(ff_O=40\%) = S_{pixel} / S_{SPAD\ metal\ Shield}$ = **x 2,5**

CHARACTERIZATION RESULTS

Statistical distribution

Distribution: 0, 1, 2, 3, 4, 5, 6

PDE (%): 1.0, 1.4, 2, 2.5, 2.7, 3, 3.5

Microlens: None, Melted, FZP

X 1,4

X 1,9

λ = 940 ± 5 nm
Open at *f/2*

Statistics:
Melted: 18 816 pixels
No lens: 5632 pixels
FZP : 2816 Pixels

No microlens

FZP microlens

Melted microlens

CHARACTERIZATION RESULTS

Statistical distribution

Distribution (y-axis: 0–6); PDE (%) (x-axis: 1.0, 1.4, 2, 2.5, 2.7, 3, 3.5)

Microlens: None, Melted, FZP

X 1,4

X 1,9

λ = 940 ± 5 nm
Open at *f/2*

Statistics:
Melted: 18 816 pixels
No lens: 5632 pixels
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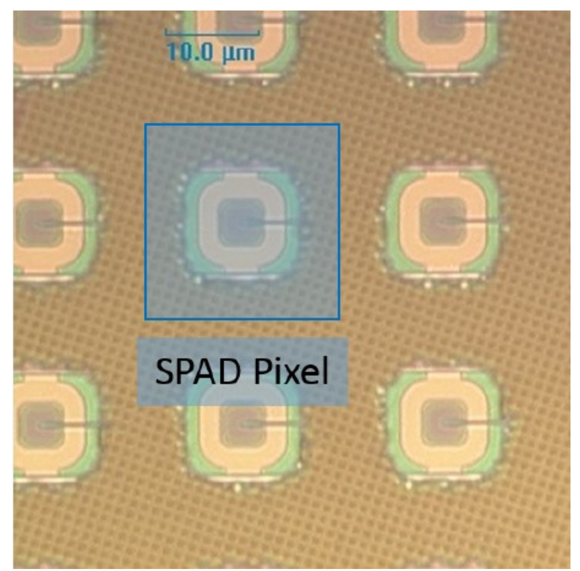
No microlens

FZP microlens

Melted microlens

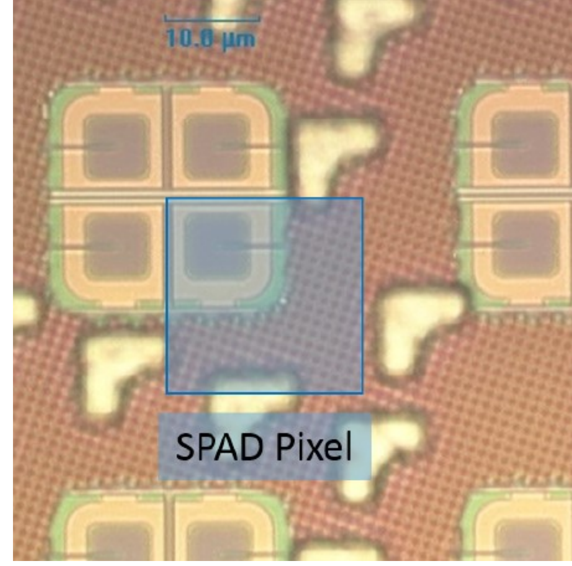
PREVIOUS RESULTS ON LARGE PITCH ARRAYS

- **Tested SPAD arrays**
  - Isolated SPADs 21.6 µm pitch and Quad SPAD (2x2 SPAD) pixels
  - Large Microlens on total pitch not available in reflow process
  - Off axis optical center



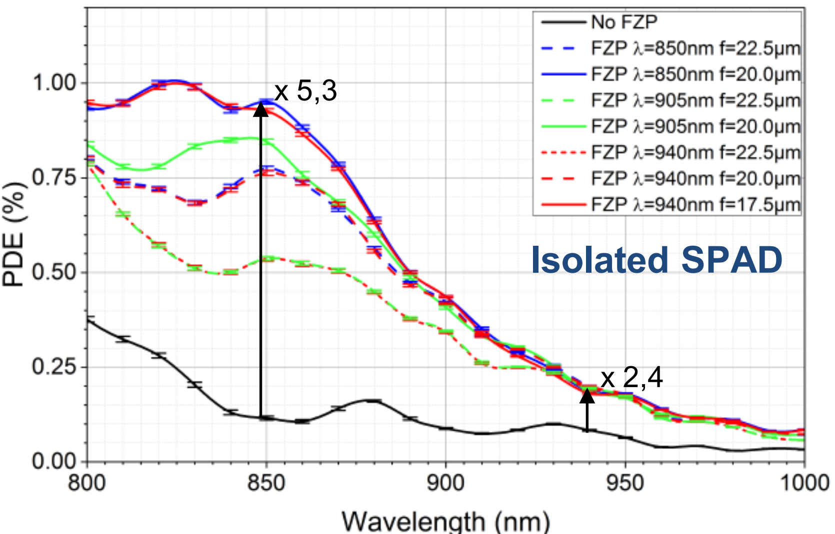
Isolated SPAD

21.6 µm pitch, 5% ff_o
4.7 µm metal shield opening



Quad SPAD

2x2 SPAD macropixel
21.6 µm pitch, 12% ff_o
7.5 µm metal shield opening



FZP µlens	Gain @ 940 nm	S_{pixel}^{*}/S_{SPAD}
Isolated SPAD	x 2,4 ±0,1	21
Quad SPAD	x 1,7 ±0,1	8

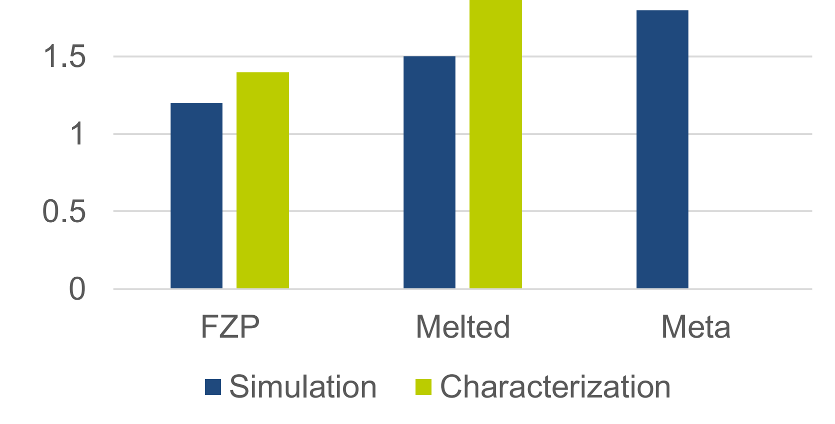
*Presence of metals in light path

CONCLUSION

- **Planar microlens**
  - Some process and stability advantages
  - Predictive simulations : Require a tight description of stack materials and layout (f/2 aperture, neighborhood to be included)
  - Arbitrary lens shape
  - Low limit ~5 µm pitch, large pitch must be confirmed
  - 940 nm much more difficult than 850 nm wavelength

- **FZP microlens**
  - Gain lower than melted microlens
  - Process successfully developed

- **Metamicrolens**
  - Gain should be close to melted microlens
  - Process under development



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