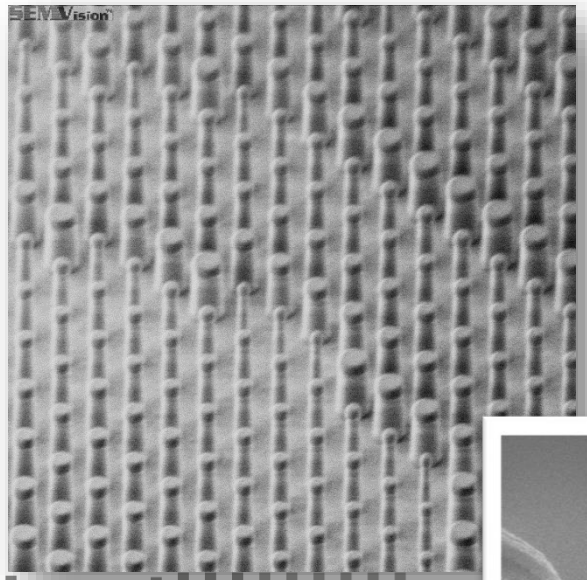
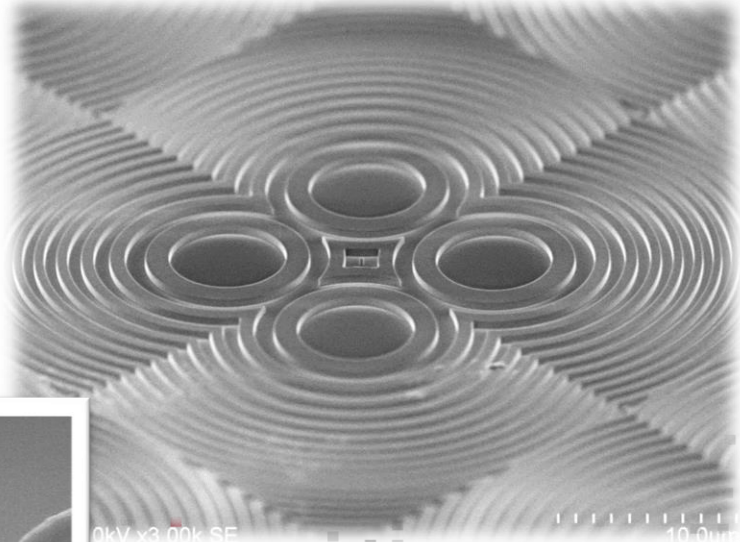
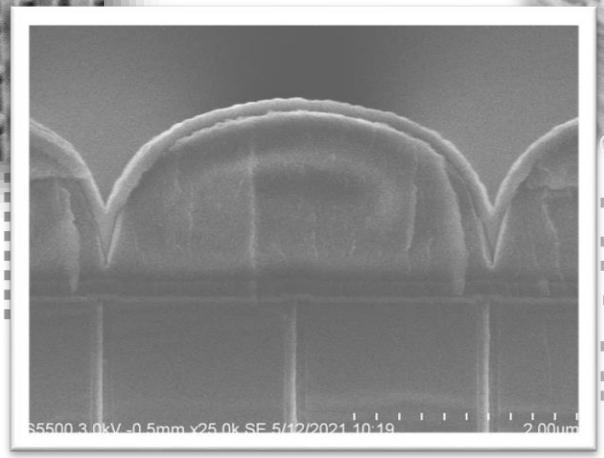






CMOS Image Sensor development in LETI: Optics at pixel level… (and a bit more)

Labex Focus | J. Vaillant - G. Chataignier | 21/06/2022

Agenda

- Who we are?
- Constraints we have
- Optics at pixel level
- Other developments: pixel architecture & process

Laboratoire d'imagerie sur silicium: who we are?

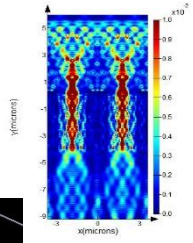
22 permanents
1 fixed term contract
4 PhD students

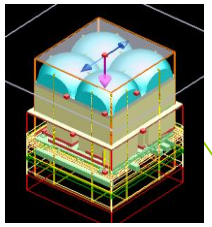
57 patents in portfolio
25 publications since 2018

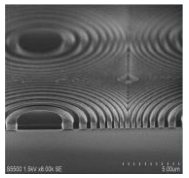
Development of Si based detectors and integrated optics for 2D and 3D imaging, meeting the needs of our industrial partners:

- Photodetection/pixel : SPAD, lock-in pixels, Global Shutter, …
- Pixel level optics: microlens, optical filters, structuration, …

Characterization & instrumentation

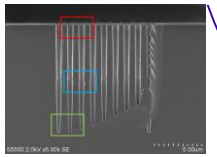


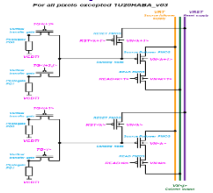




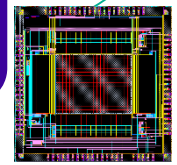
Process integration & device expertise

Simulations: Optics & TCAD





Design & pixel layout



Agenda

- Who we are?
- **Constraints we have**
- Optics at pixel level
- Other developments: pixel architecture & process

Constraints

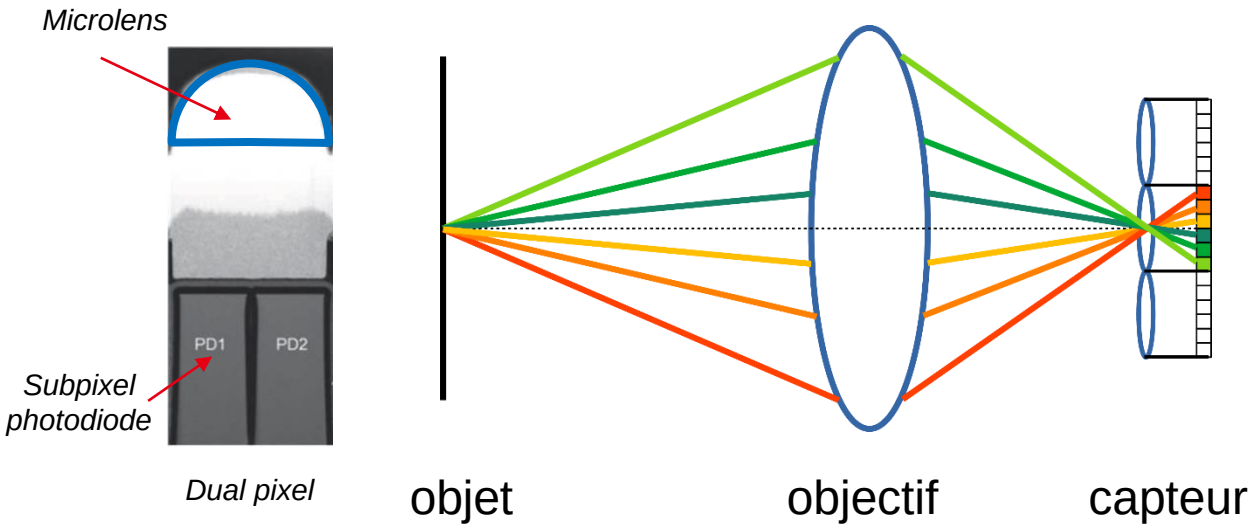
- **300mm wafer level process**
  - No single die
  - No 200mm wafer or below
- **Materials are, almost, limited to CMOS compatibility**
  - Intensive use of SiO2, SiN, amorphous Si
  - Metals: mainly W, Cu
  - More “exotic” oxides or metals may be used, depending on tools capabilities
- **We are dependent of CMOS image sensor foundry for the imager fabrication**

Agenda

- Who we are?
- Constraints we have
- **Optics at pixel level**
  - Quad-pixel
  - Diffractive & refractive microlenses
  - Interference filters
- Other developments: pixel architecture & process

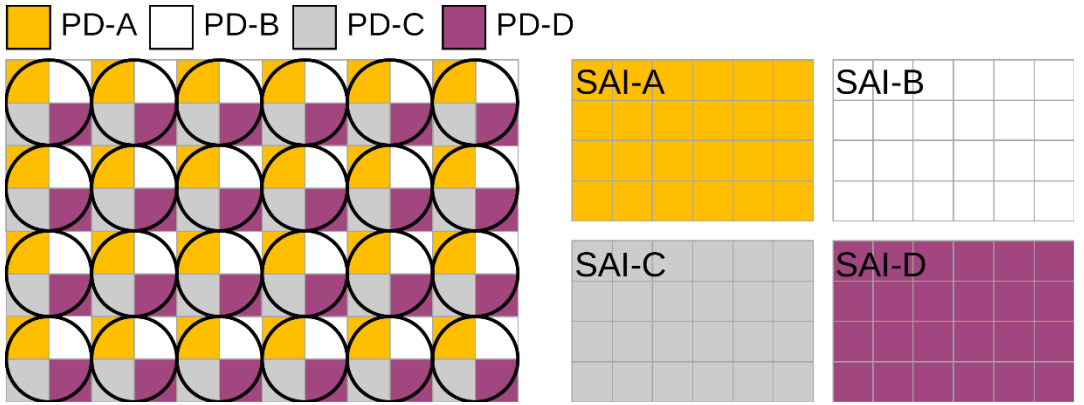
Plenoptic sensors and quad-pixel

- **Principle of plenoptic sensors**
  - Multiple pixels under a microlens
  - 2x1 : «dual pixel» / 2x2 : «quad pixel» / 3x3 : «nona pixel» etc…
  - Enables spatial and angular sampling of rays



Principle (colors denote the angle of incidence)

- **Sub Aperture Images (SAI)**
  - Images produces by pixels having the same position under a microlens
  - Example on a quad-pixel :



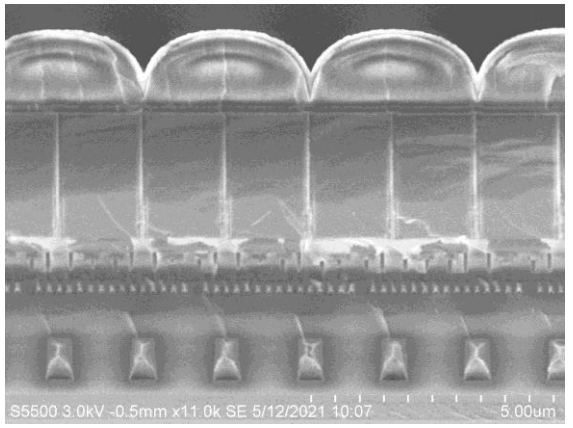
Quad-pixel development in Leti – Proof of concept

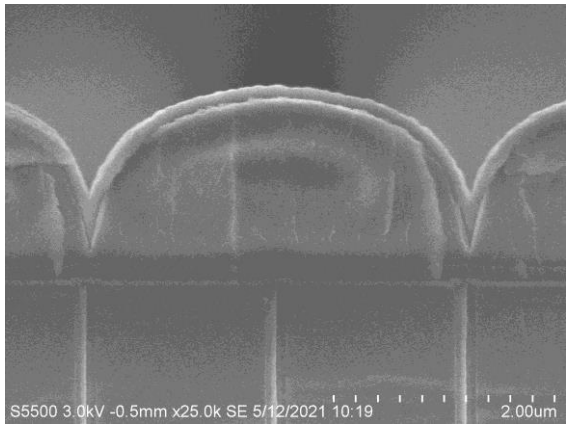
- **Proof of concept (v1 in 2021)**
  - Based on 1.75µm pixel => 3.5µm Quad-pixel
  - BSI technology
  - 998x852 image sensor (dev. test vehicle from ST)
  - Different areas (µlens positioning)
    - Imaging (centered µlens)
    - Linear CRA
    - Constant CRA / blocks (1-30)

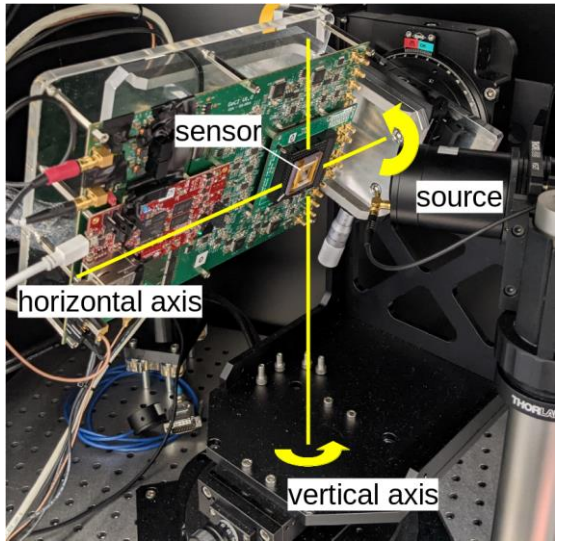
- **Optical test benches:**
  - Angle characterization
  - Imaging / dataset

- **PoC v2 in progress**
  - To be characterized by the end of 2022

Microlenses of 1st prototype





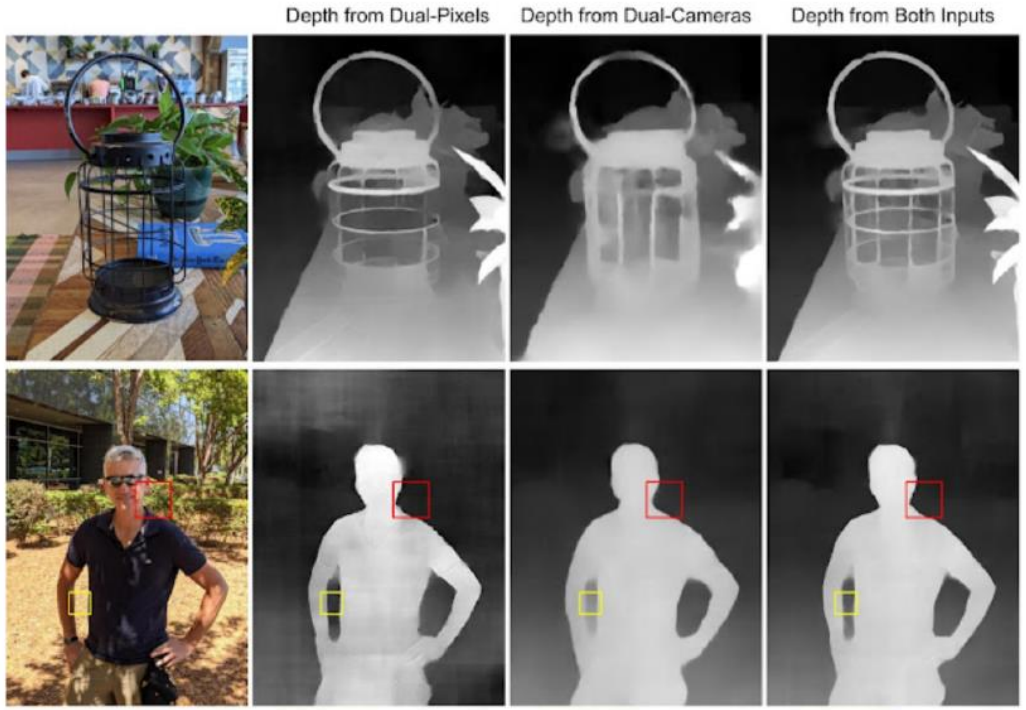


Testbench

Quad-pixel development in Leti – Image processing SoA

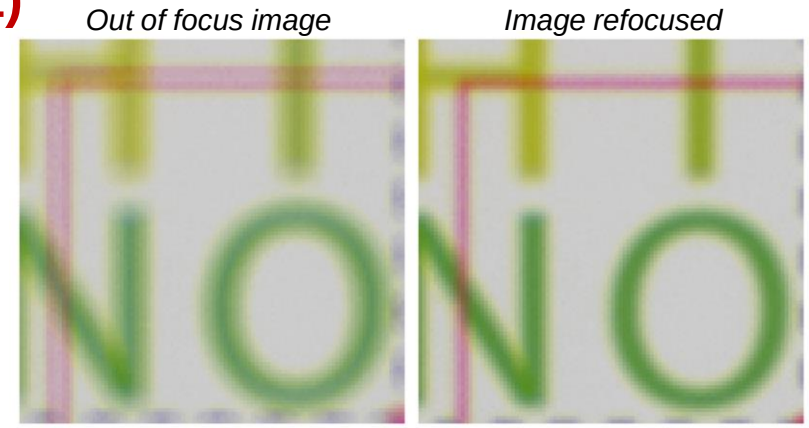
- **Autofocus**
  - Reflex & mirrorless, smartphones
  - Canon, Samsung, Sony 2x2OCL (IMX766), Omnivison QPD (OV50A), Hynix (A4C)
- **New capabilities in image processing**
  - Mainly Google teams, with a lot of deep learning:
    - Refocusing, passive depth estimation, reflection removal, defocus debluring

Depth map example (Google blog)

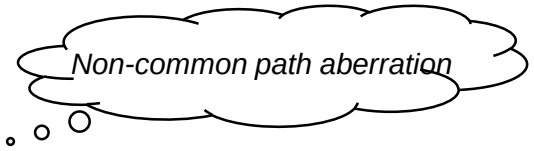


Quad-pixel development in Leti – Image processing (1)

- **DoF extension / refocusing**
  - Global shift of sub-aperture images



Refocusing example



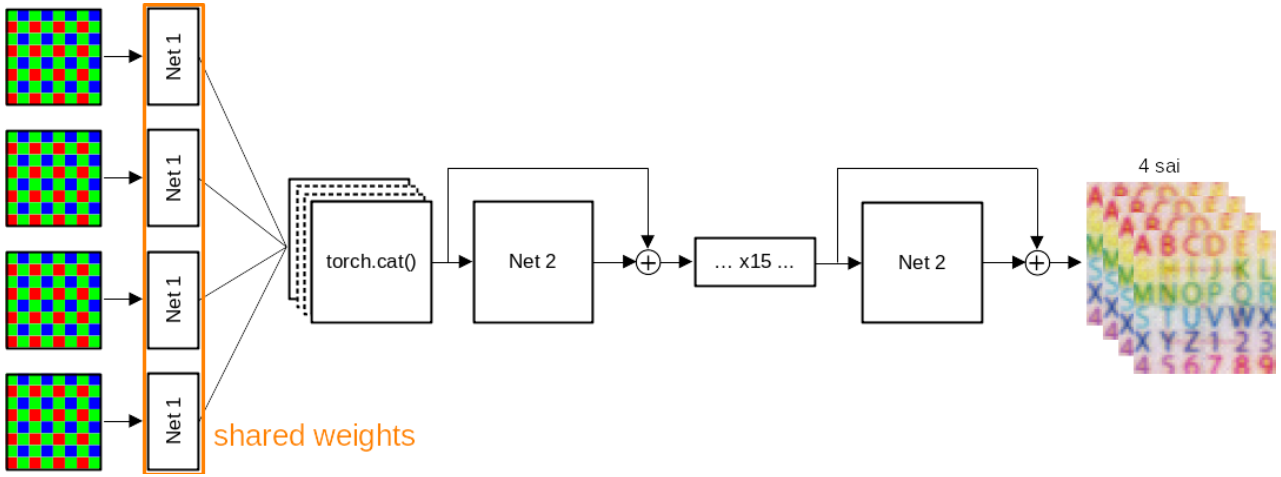
- **Main lens aberrations correction**
  - Some correction is possible via the light field capture
  - classic algorithm based on block matching
    1. In focus texture (usually noise)
    2. Estimation of disparities
    3. Local shifts (resampling) → correction

Non corrected
0,07

Corrected
0,088

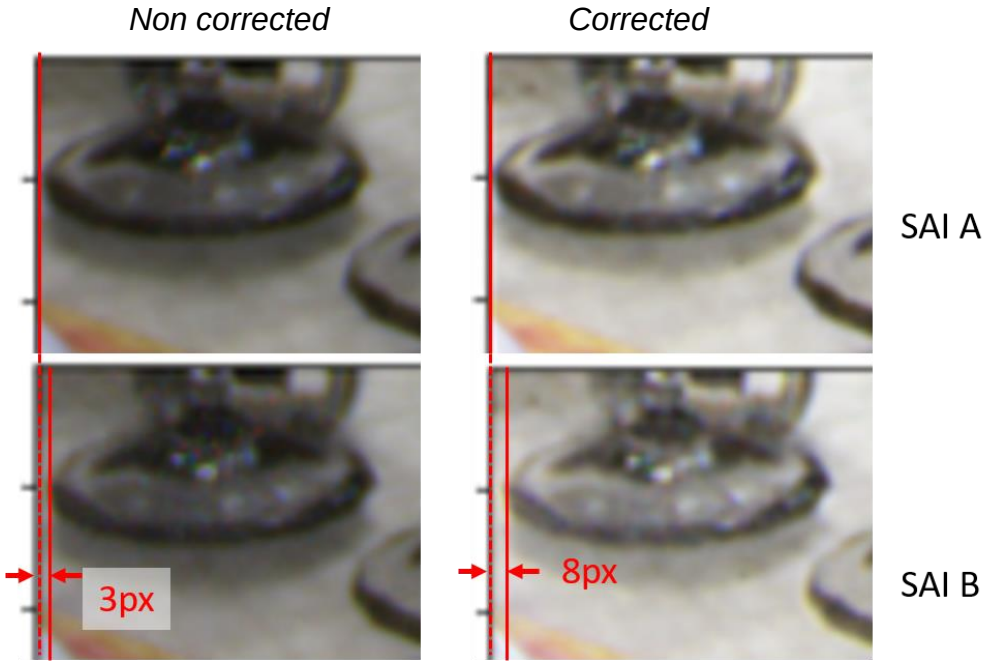
Quad-pixel development in Leti – Image processing (2)

- **Color demosaicing of sub-aperture image cube**



	Syu – 670k param. (dB)	Verma – 714k param. (dB)	QP_net – 485k param(dB)
No refocus	36	37,7	**37,8**
Refocus at +1 pixel	38,9	40,8	**40,9**

- **Pixel crosstalk correction**
  - Crosstalk between SAIs caused by µlens diffraction
  - Interest:
    - Help disparity estimation
    - 1st step in image processing
  - Problem:
    - Necessity of a diffraction-free dataset
    - Only possible in simulation



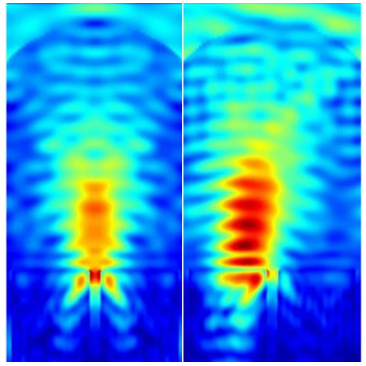
Quad-pixel development in Leti – Image simulation

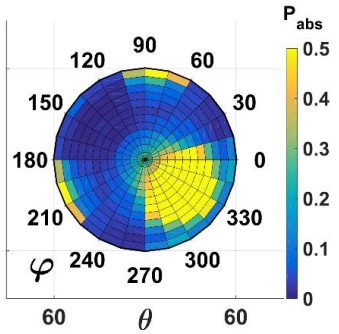
- **Synthetic images**
  - Need to simulate the main lens and its aberrations / Depth of Focus → Ray tracing
  - Need to simulate pixel level optics and diffraction → Electromagnetic simulation

Ray tracer

Photorealistic image *Ground truth depth*

FDTD





Agenda

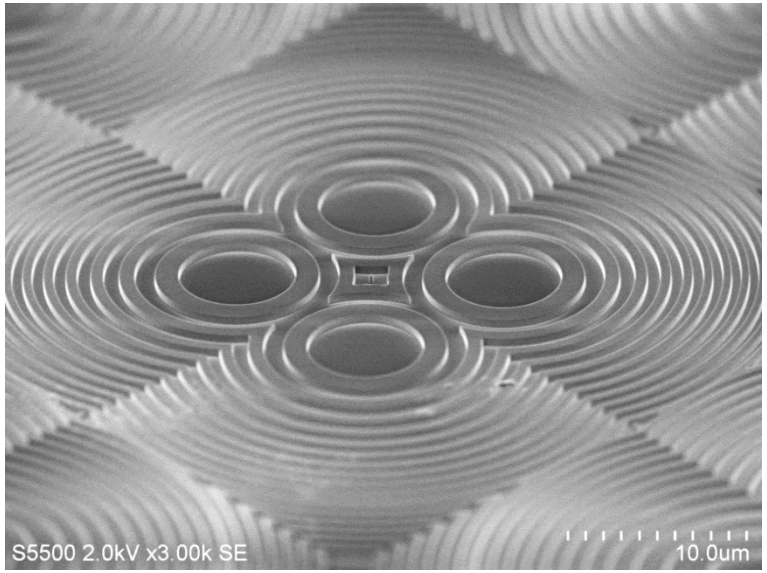
- Who we are?
- Constraints we have
- **Optics at pixel level**
  - Quad-pixel
  - Diffractive & refractive microlenses
  - Interference filters
- Other developments: pixel architecture & process

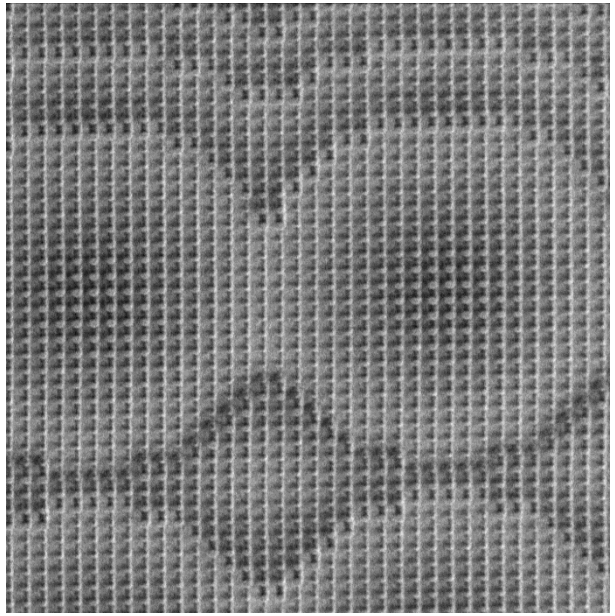
Diffractive microlens

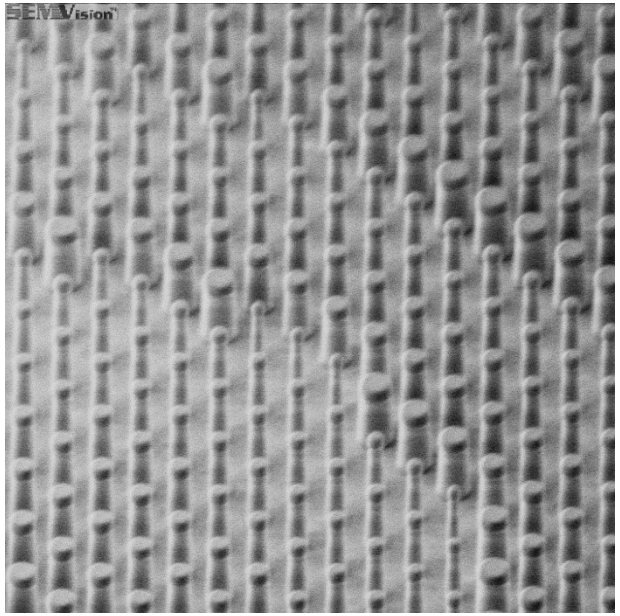
- **Currently based on amorphous silicon**
  ⇒ Efficient in NIR range (>800nm)

- **Phase Fresnel Zone Plate**

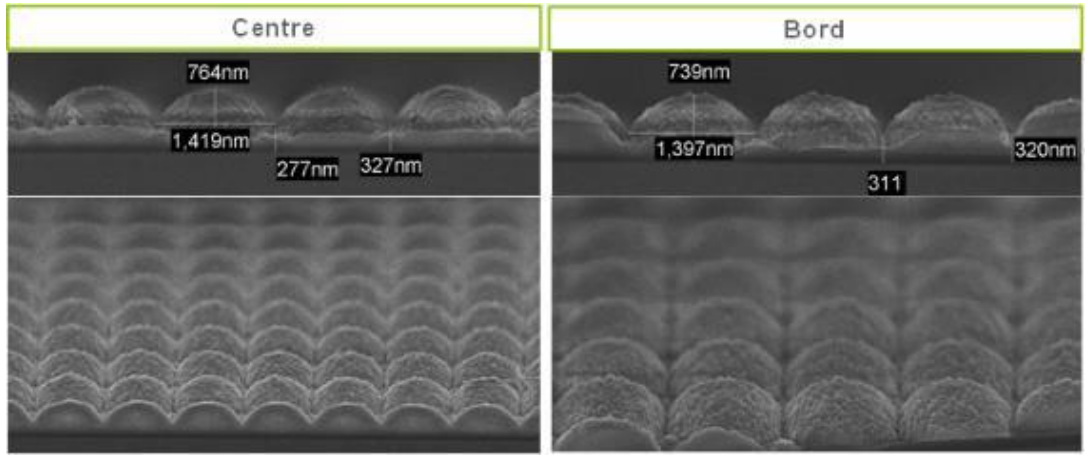
- **Metasurfaces**
  - Deep-subwavelength structures used to tune the wavefront
  - min size / min space ~80nm





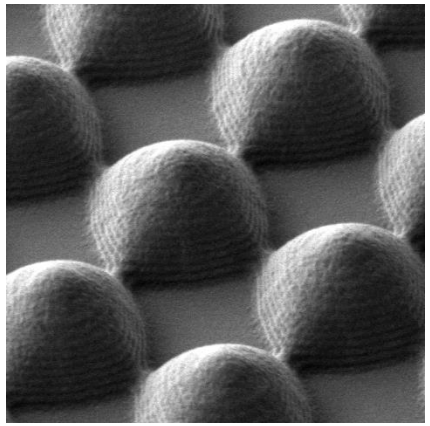


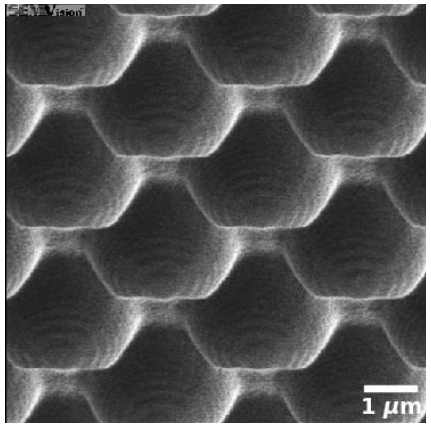
Refractive microlens

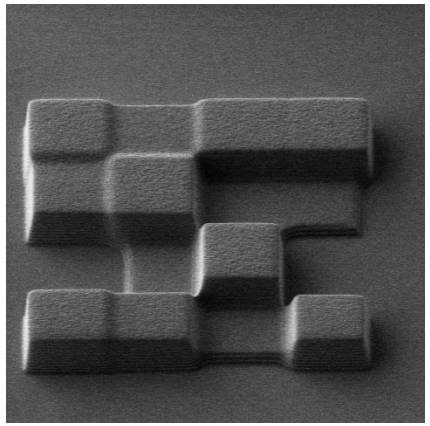


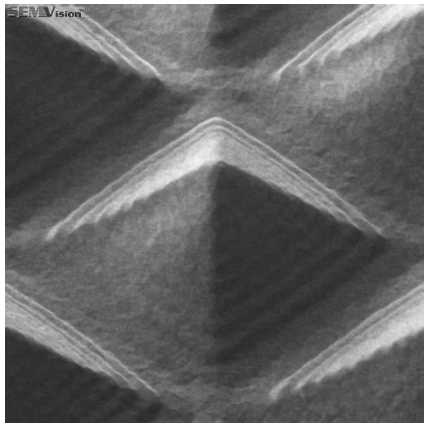
- **Generated using lithography:**
  - high positioning accuracy (typ. 10-20nm)

- **Microlens 3D shape:**
  - Reflow option: centro-symmetric shape
  - Grayscale lithography: shape defined by mask, off-axis and unconventional shape achievable (pyramid, staircase, …)









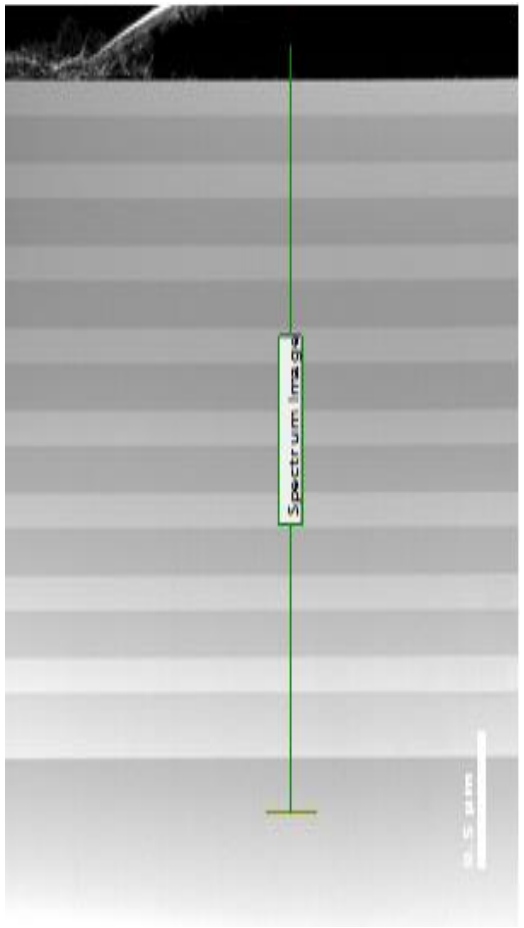
- **Material**
  - Can be used “as made”, or transferred into another material (resin, silicon oxide, silicon nitride, amorphous silicon, …)

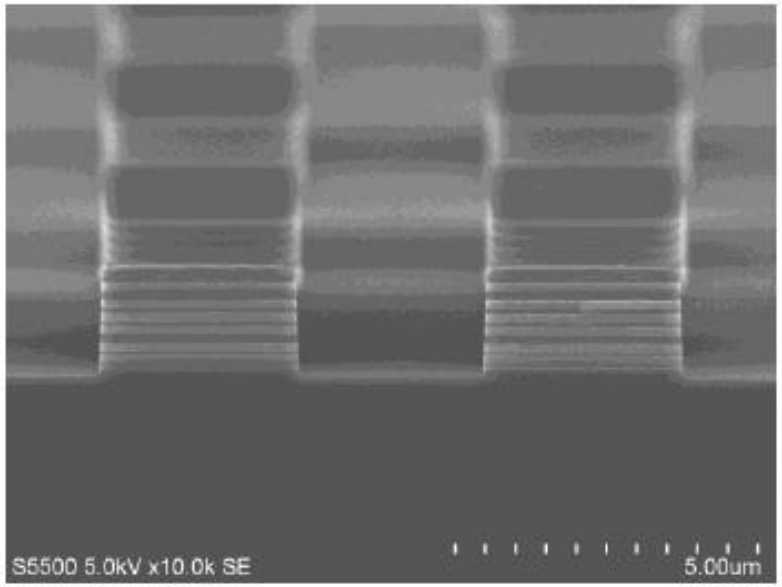
Agenda

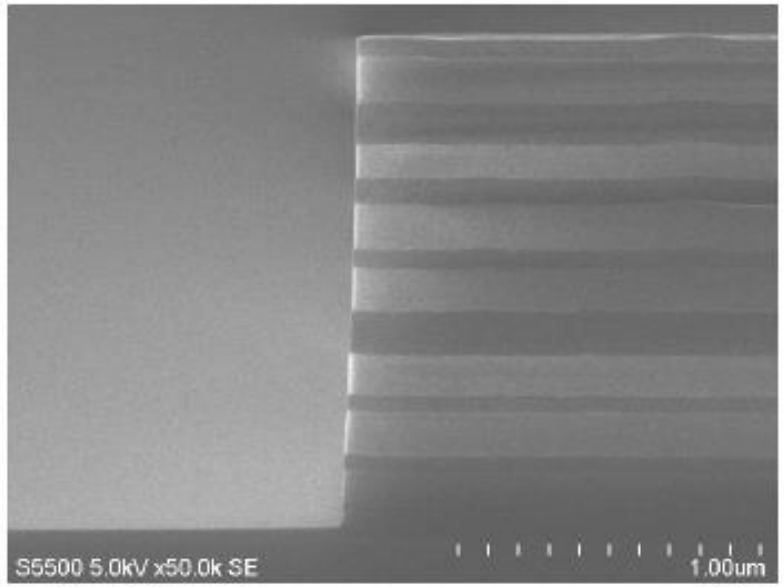
- Who we are?
- Constraints we have
- **Optics at pixel level**
  - Quad-pixel
  - Diffractive & refractive microlenses
  - Interference filters
- Other developments: pixel architecture & process

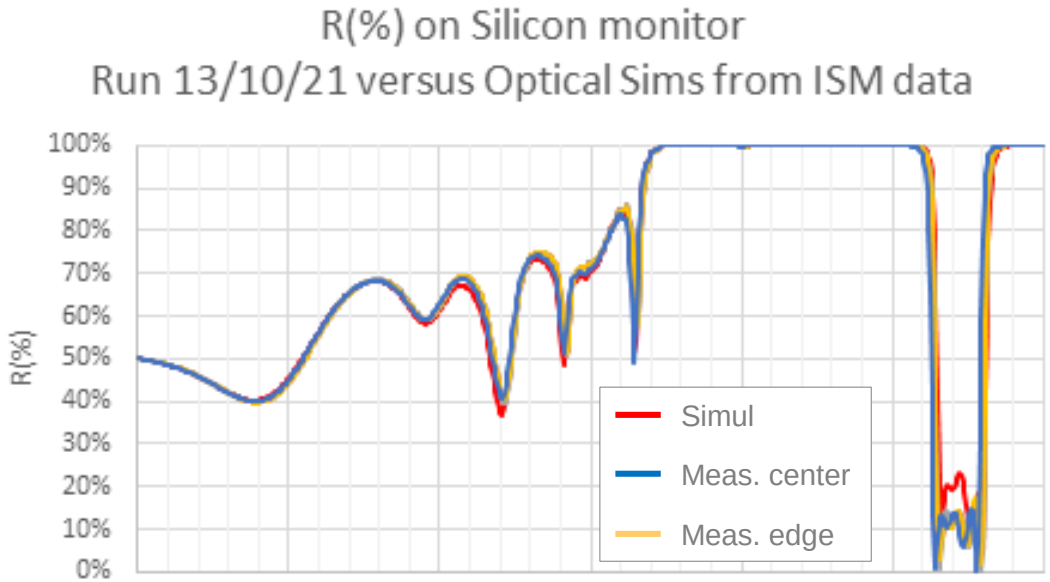
Interference filters

- Processed at wafer level
- Can be pixellized
- IR-Cut filters, bandpass filters







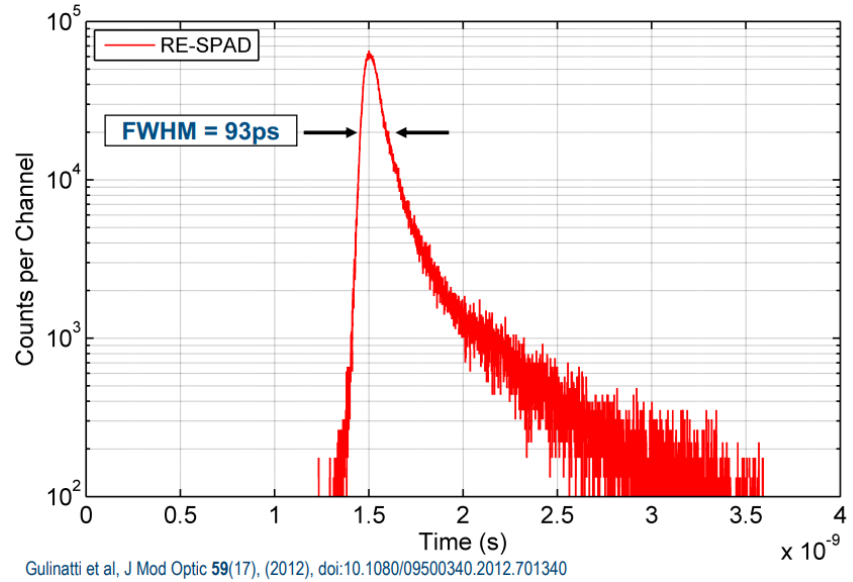


Agenda

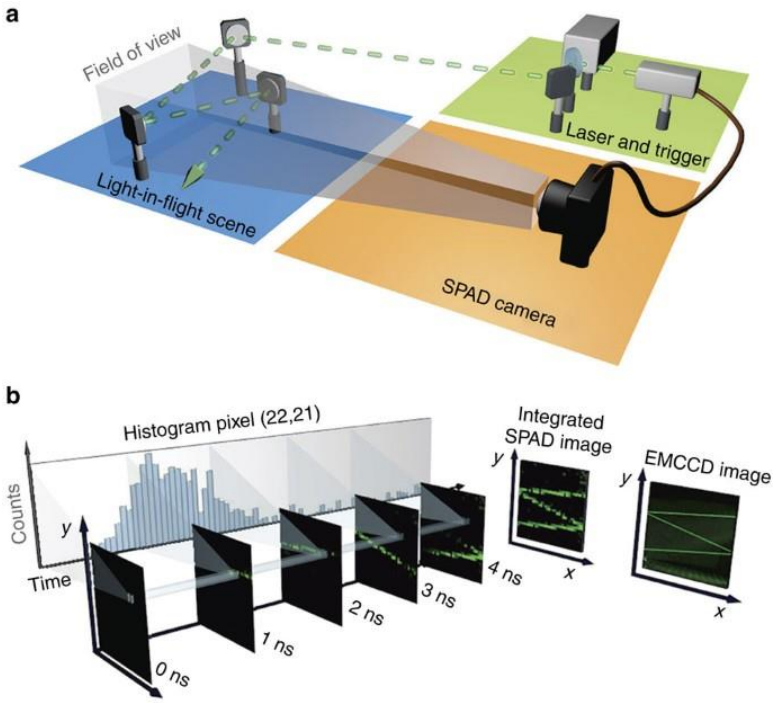
- Who we are?
- Constraints we have
- Optics at pixel level
- **Other developments: pixel architecture & process**

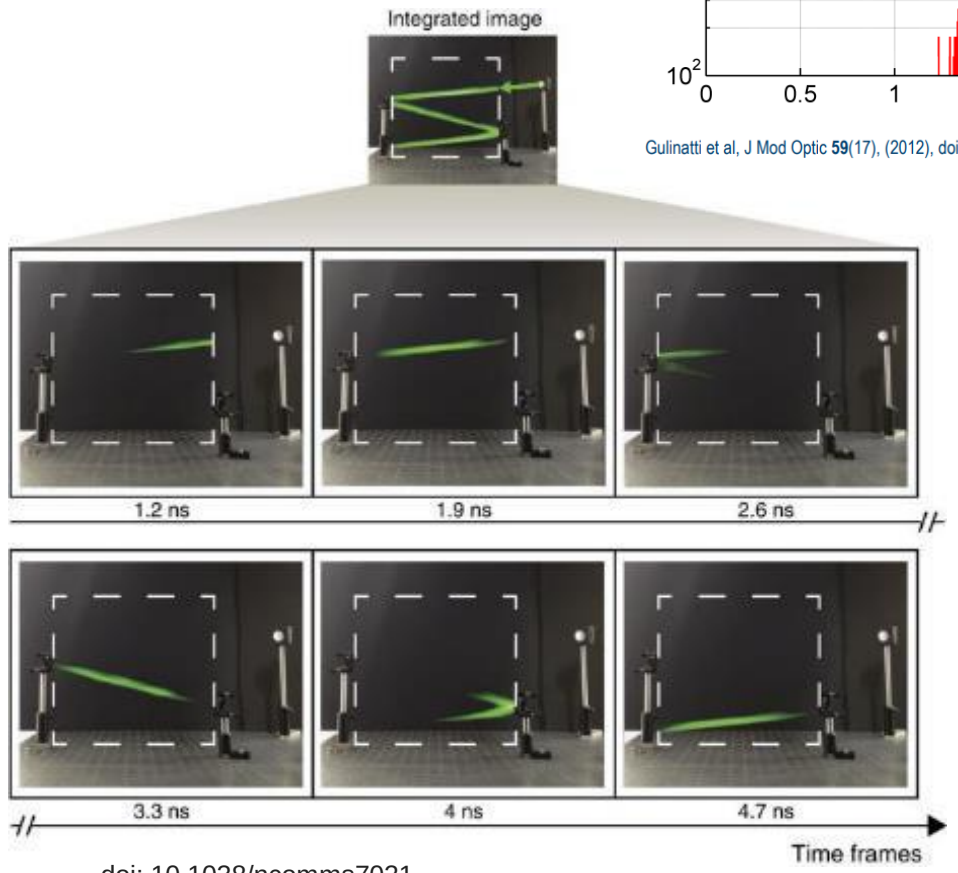
Unconventional pixel of interest?

- **SPAD (Single Photon Avalanche diode)**
  - Avalanche photodiode in Geiger mode
  - Precise datation of photon time of arrival (~100ps)



Gulinatti et al, J Mod Optic **59**(17), (2012), doi:10.1080/09500340.2012.701340

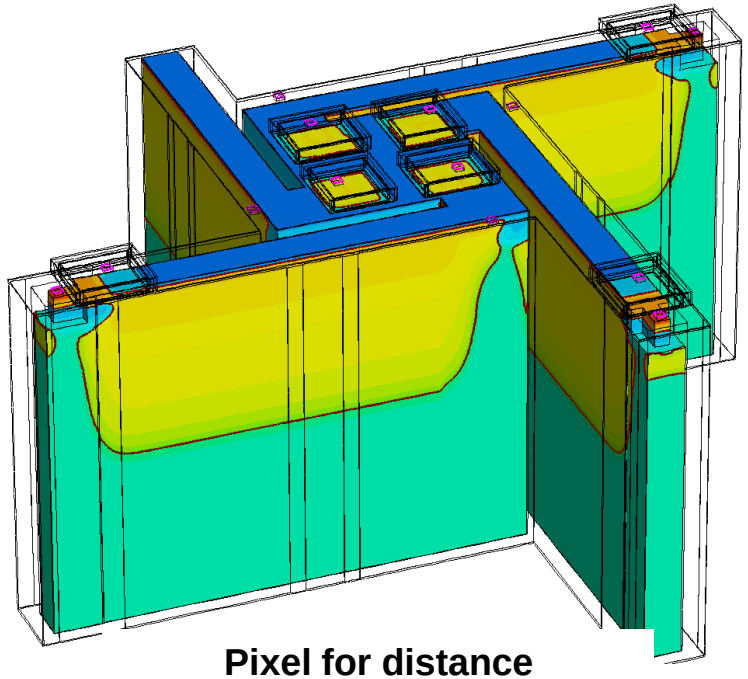




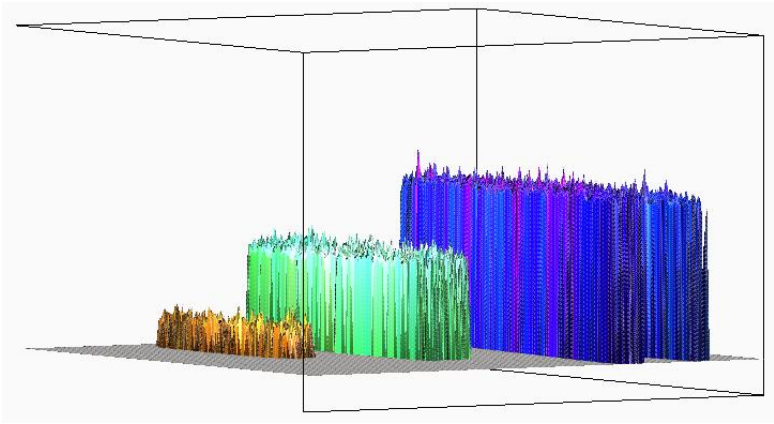
doi: 10.1038/ncomms7021

Unconventional pixel of interest?

- **Lock-in pixels: optical demodulator**
  - Charges transferred and integrated on in-pixel memory
  - Working frequency several 10's of MHz
  - Used for 3D measurement using indirect Time-of-Flight

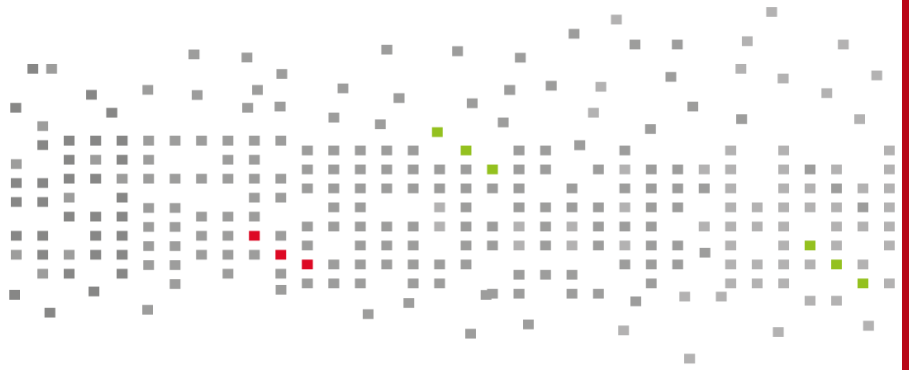


Pixel for distance measurement (iTOF)



Thank you for your attention

Any questions?



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