Silicon Metalenses towards a fully Silicon integrated SWIR sensing

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Most Silicon based depth and lidar sensors rely on near-infrared (NIR 750-900nm) sources to produce depth images as Silicon CMOS sensors can achieve a high quantum efficiency for an unbeatable cost at such wavelengths [1]. Some automotive LIDAR is using 900nm to 1400nm illuminations with InGaAs sensors with small advantages compared to NIR [2]. Advances in short wave infrared (SWIR) sensor technologies, such as Silicon-Germanium sensors [3], changes this paradigm and opens a new window for groundbreaking sensor designs, as SWIR can push the wavelength above retinal hazard area (>1400nm), allowing for much higher eye safety, due to the low penetration of those wavelengths through the eye lens (IEC 60825-1 Edition 3.0 2014-05, ANSI Standard Z136.1)[4]. Here, we propose to use a Silicon Metalens flat optics and build upon our stacked sensor technologies [5] to obtain a fully Silicon integrated stacked sensor at SWIR wavelengths. We will discuss the design of the stacked sensor and focus on the Silicon Metalens for multiple use-cases. We will show numerical simulations of the optical stack for eye-tracking application or wide-angle time of flight (TOF) and how we can obtain very compact form factor modules. Finally, we will demonstrate the results of our Silicon metalens prototype at 1550nm.

SWIR wavelengths are specifically interesting for sensing technologies such as TOF or eye-tracking. Firstly, the solar spectrum exhibits a dip around 1380nm: there is no solar background illumination, which leads to less shot-noise on the sensor and much higher signal to noise ratio for outdoor applications. In addition, SWIR wavelengths are much safer for the eye, opening new possibilities for eye-tracking whether it is for extended reality application or driver monitoring in automotive. Finally, at SWIR wavelengths Silicon becomes completely transparent with a high index of refraction (n=3.5), allowing for a simpler manufacturing process of BSI sensors, as back thinning is no longer required. Here, we leverage this property by designing a lens made of a single Si wafer with the metalens technology.

Figure 1 shows our proposed stacked sensor. It is made of an optional aperture wafer (glass or other low index material) and an eventual bandpass filter layer. Interestingly, glass with an index around 1.5 can play the role of a low index material in this case, as Silicon has a much higher optical index, close to 3.5 at SWIR wavelengths. Hence, we can use a first spacer made of glass or any other low index material. Using a simple Silicon spacer is also possible at the cost of a thicker design but allows easier wafer bonding between the different layers. The second layer is a Silicon Metalens, directly patterned on a Silicon wafer. Then, we use another spacer: it can be a glass wafer if we need a compact low index material, a Silicon Spacer wafer, or simply an unpolished backside illuminated sensor. Photons are collected on a SWIR sensor such as a SiGe sensor. The latter is directly placed upon a ROIC ASIC wafer on top of a reconfigurable chip, such as a Reconfigurable Instruction Cell Array (RICA) [5]. The advantage of processing at the edge is significant for low-power applications [6] and programmability can enable a broad range of image processing algorithms fast and efficiently. The multiple wafers are stacked with wafer-bonded technology to get a fully monolithic Silicon camera.

As examples of possible applications, we discuss a 2.5 µm pixel pitch eye-tracker sensor for mixed-reality glasses or headset and an iTOF sensor with 5 µ m pixel pitch. The latter needs a larger pixel pitch to accommodate several taps for the several depth sensing channels. SiGe sensors with such pixel pitches are easily obtainable with current technologies. Figure 2 shows Zemax ray-tracing simulations of the optical stacks of such an eye-tracker (a,b and c) and a iTOF sensor (d, e, and f). Fig.2a) and d) show the layout of the devices for incident field angle of 0, 10, 20, 30, 40 and 45 degrees. Fig.2.b) and e) show the spot diagrams for the two systems which are close to the diffraction limit. Finally, Fig.2c) and f) show the MTF of the optical systems up to their Nyquist frequency. The two examples exhibit high MTF of 55 % at Nyquist/2 for the eye-tracker over 70% for the iTOF sensor. Table 1 summarizes the different key parameters of a 400x400 pixels eye-tracker and a 1920x1080 pixels iTOF sensor with a silicon metalens.

The metalens phase law can be optimized using Ray-tracing software such as Zemax [7]. As a conventional lens can be optimized using aspherical terms, we propose to model it by the sum of the hyperbolic phase-law and aspherical terms:

$OPD(r) = a_0\left(\sqrt{r^2 + f^2} - f\right) + \sum_{m=2}^{10} a_m r^m$ (1)

where *r* is the radial position on the metalens normalized by the metalens radius and *f* the focal length. a_0 is a term controlling the ratio of the hyperbolic phase law with respect to the aspherical terms. It can also be used to conveniently adapt to different material. Basically, a hyperbolic metalens would have a_0 equals to the index of the material. For instance, to design a metalens focusing a normally incident beam into air, $a_0=1$, into glass $a_0=1.5$ and into Silicon $a_0=3.5$. Its sign becomes negative to model diverging lenses.

Figure 3 shows our Metalens prototype. It is made in a 500 µm thick Silicon wafer in which are etched 1200nm-long nanopillars. Those nanopillars are placed along a hexagonal unit cell with a lattice constant of 500nm. An electronic microscope image of our metalens is Shown on Fig.3a). A picture of the Metalens is shown in Fig.3b). By locally controlling the nanopillars diameters (varying between 100nm and 400nm), we can tune the phase shift the light undergoes while traversing the structure to realize a lens. Figure 3c) shows an image of a USAF target taken with our metalens prototype and an off-the shelf SWIR sensor (InGaAs) at a 1550 nm wavelength.

Those first results prove the feasibility of a fully silicon manufacturable camera based on a SWIR metalens, opening the way for a new generation of programmable smart cameras, from eye-tracking for mixed reality or driver monitoring to depth sensing for automotive or security applications. Our next step consists in switching from a R&D prototype made with e-beam lithography to an industrial process involving UV lithography to obtain a complete monolithic silicon camera fully manufacturable in a regular CMOS fab that requires no further packaging.

[1] E. Marti, M. A. de Miguel, F. Garcia and J. Perez, "A Review of Sensor Technologies for Perception in Automated Driving",*IEEE Intelligent Transportation Systems Magazine, 2019,14, 4,*94-108..
[2] Nicolas Pinchon et al., et al. "All weather vision for automotive safety: which spectral band?", *AMAA 2018, Advanced Microsystems for Automotive Applications*, 2018, 3-15.
[3] N. Na *et al*., "High-Performance Germanium-an-Silicon Lock-in Pixels for Indirect Time-of-Flight Applications," *2018 IEEE International Electron Devices Meeting (IEDM)*, 2018, 32.4.1-32.4.4.
[4] https://ohsonline.com/articles/2014/08/01/laser-safety_0.aspx
[5] B. C. Hseih et al., "A 3D Stacked Programmable Image Processing Engine in a 40nm Logic Process with a Detector Array in a 45nm CMOS Image Sensor Technologies", *International Image Sensor Workshop*, 2017.
[6] Jorge Gomez and al., "Distributed On-Sensor Compute System for AR/VR Devices: A Semi-Analytical Simulation Framework for Power Estimation", *2022 tinyML Research Symposium*.
[7] A. Arbabi et al. "Miniature optical planar camera based on a wide-angle metasurface doublet corrected for monochromatic aberrations", *Nature Communications*, 2016, 7.
[8] M Shalaginov et al. "Single-Element Diffraction-Limited Fisheye Metalens", Nano Letters, 2020, 20, 10, 7429-7437.
[9] Engelberg J, et al. "Near-IR wide-field-of-view Huygens metalens for outdoor imaging applications", *Nanophotonics,* 2020, 9, 361–370.

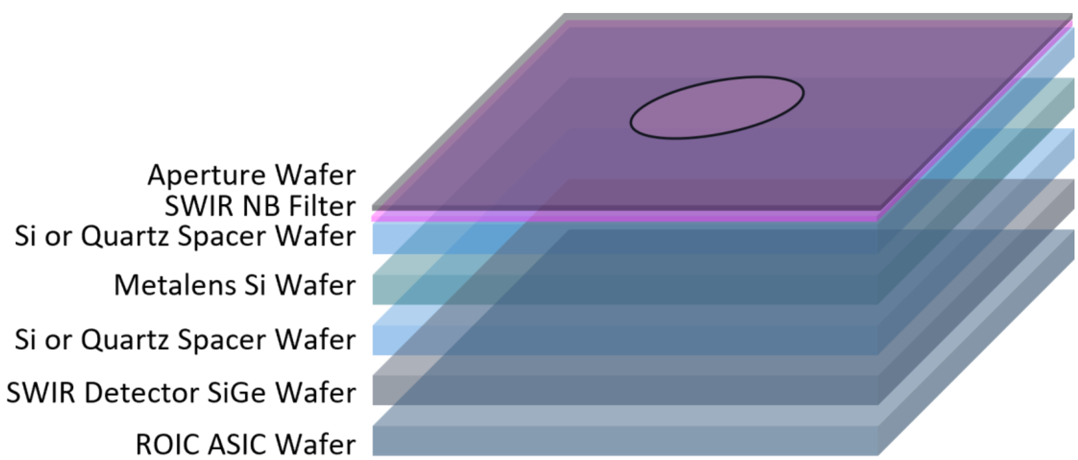

Figure 1. Stacked Silicon camera sketch.

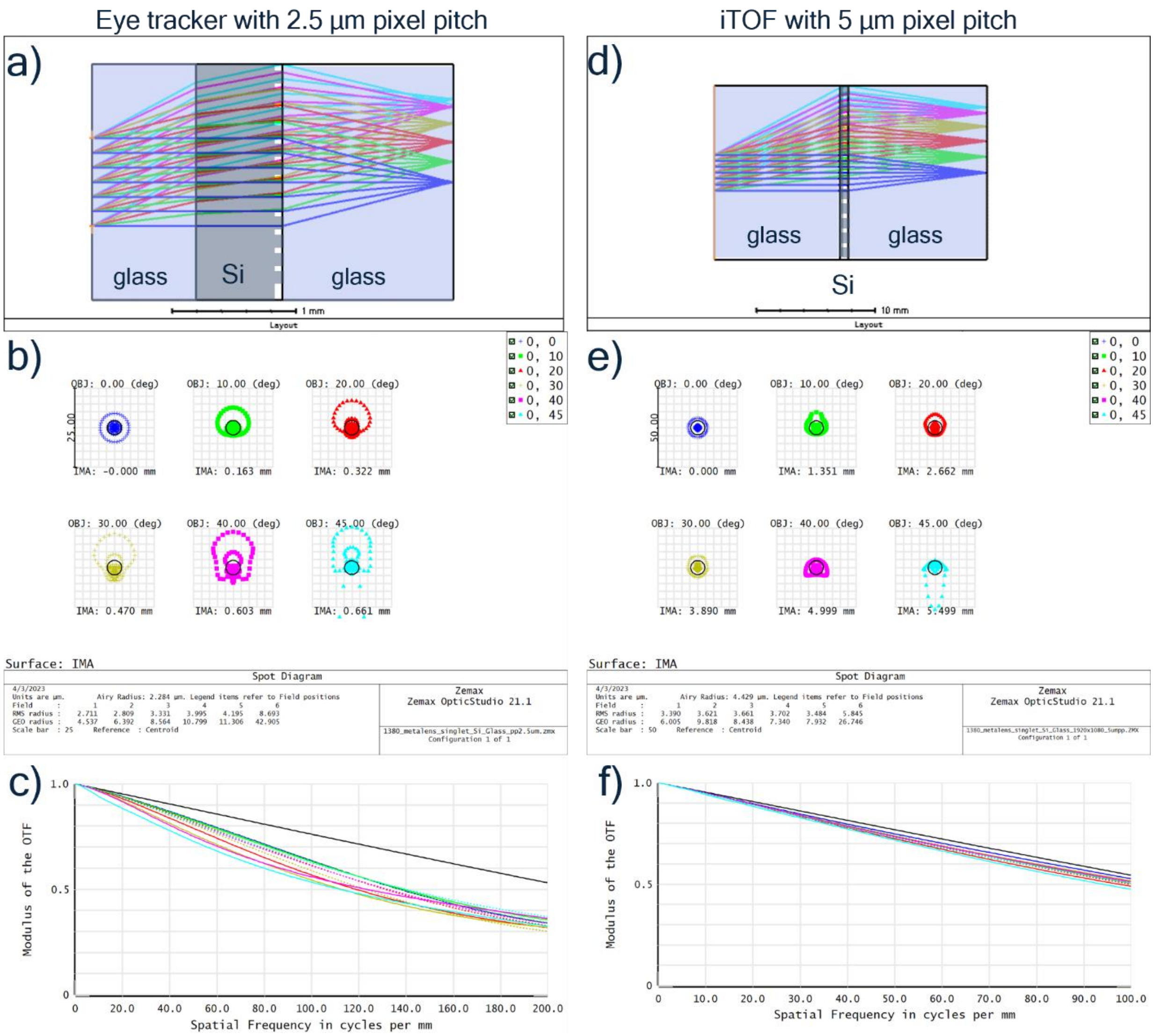

Figure 2. Ray tracing (Zemax) simulations of an eye-tracker and iTOF sensors.

	Eye-tracker	iTOF
Resolution	400x400	1920x1080
Pixel pitch	2.5 µm	5 µm
z height	2.9 mm	23 mm
FOV	90°	90°
EFL	0.9 mm	7.65 mm
Aperture Ø	0.35 mm	3 mm
F#	2.6	2.55
MTF @ Ny/2	55%	70%

Table 1. KPI comparisons of two SWIR sensors for eye-tracking and indirect Time Of Flight (iTOF).

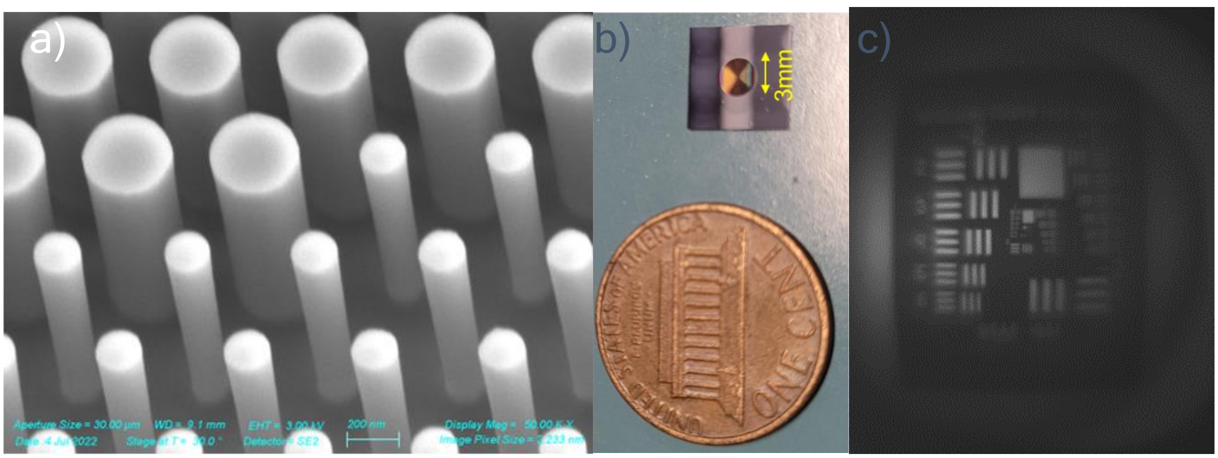

Figure 3. a) Electronic microscope image of zoom of the 1550nm Silicon metalens. b) Picture of the 3mm diameter metalens. c) Image recordeed at 1550nm using a SWIR InGaAs sensor.