Pixel performance enhancement by integrated diffractive optics

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1. Introduction

Optical interfaces such as color filters or (micro-)lenses are required to enhance the performance of most imagers. In particular, micro-lenses are used to increase the effective quantum efficiency of front side illuminated imagers (by focusing the light into the sensitive part of the pixel), and to reduce the pixel-to-pixel cross-talk in backside illuminated imagers (Figure 1).

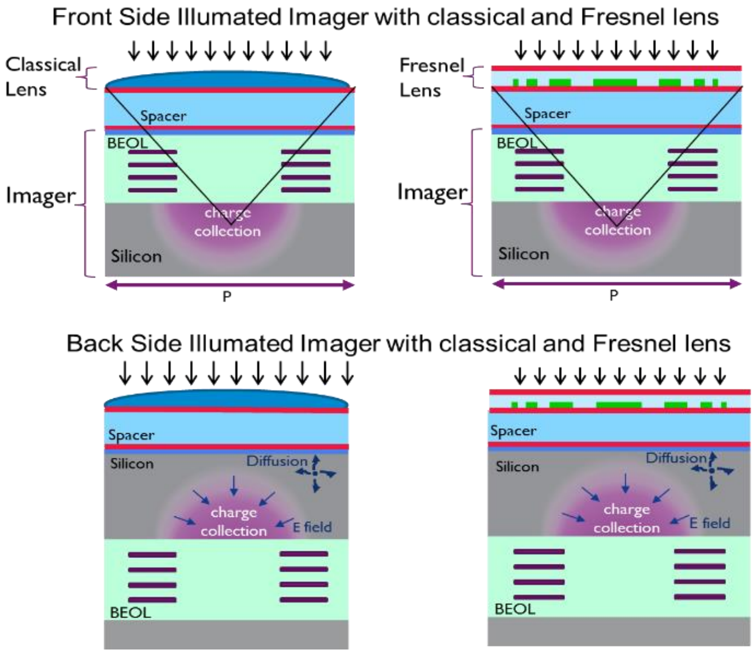

Figure 1: Front Side and Back Side Illuminated pixel cross-section with classical and Fresnel micro-lenses.

These micro-lenses can be integrated at individual pixel level using micro-electronics lens material deposition and patterning technologies, with the current state-of-the-art process flow based on a polymer lens material and thermal reflow. This process however presents several shortcomings. For large pixel sizes, the shape of the resulting lens is suboptimal (Figure 2), and leads to poor optical efficiency. Moreover, for space applications, the use of polymers can lead to outgassing issues.

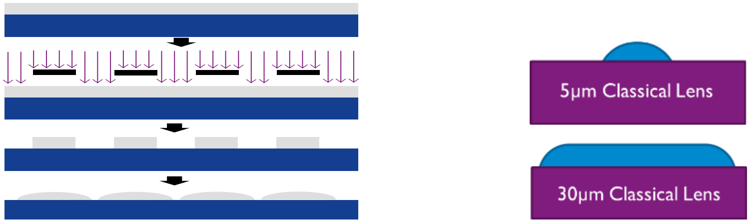

Figure 2: Process flow for classical micro-lenses and their shape for pixels with 5μm and 30μm pitch.

In order to solve these problems, imec recently started to develop planar micro-lenses at pixel level using diffraction optics similar to Fresnel lenses.

2. From Classical Lenses to Fresnel Lens

Typical ***classical lenses*** focus light by introducing non-uniform phase-shifts to incident light waves. Their faces are designed so as to equalize optical path lengths between their focal points. To use the vocabulary of transformation optics, lenses fold space so that Fermat's principle, while apparently violated, remains unviolated [1]. Key for the function of such lenses is thus their production using a transparent material presenting a refractive index contrast with the background material in which the light beams otherwise propagate. The smaller the focal distance is, the smaller the curvature radius of the lens is and, as a result, the thicker the lens is, the higher the protrusion of the lens away from its image plane is and finally the heavier the lens is. In the early 19th century, Fresnel lenses have been introduced in lighthouses where these new low weight, with low protrusion lenses with small focal distance were requested. Historically, Fresnel lenses were proposed to be produced by grinding pieces of spherical lenses and complemented with linear prisms as shown in Figure 3.

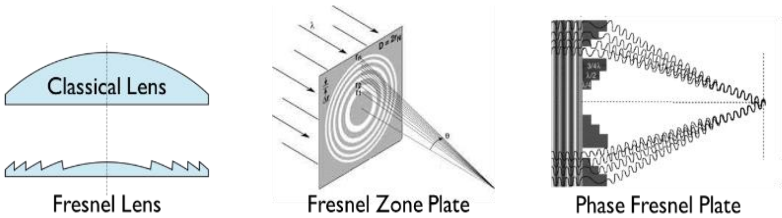

Figure 3. Concepts of classical lens, Fresnel lens, Fresnel Zone plate and Phase Fresnel Plate. [4-5]

The first Fresnel Lens using diffractive optics is the ***Fresnel zone plate*** [2]. Following Huyghens' principle, a plane wave incident on a thin transparency can be decomposed in a uniform distribution of sources in the plane of the transparency. If the transparency presents opaque regions, interferences will occur that can be used to define an effective lens with a focal point where constructive interference will boost the light intensity. This lens optimally focuses half of the light flux intensity. The other half is lost (reflected). It is however important to note that the opposite, or dual, of the Fresnel zone plate is another valid zone plate defining the same focal point. Combining both zone plates and compensating for their relative phase shift through a uniform offset, yields thus a novel brighter lens, i.e. a ***Phase Fresnel Plate***. While the previous zone plates selected transmission zones with uniform intensity or correction zones with uniform phase shifts, a classical Fresnel lens applies a continuous optimal phase-shift along the radius of the lens in order to have all incident beams to contribute in phase to the image plane. Once more, this distributed phase shift can be realized varying the thickness of a lens material. This segment-continuous evolution of the transparency can be approached using a staircase-approximation, more appropriate for CMOS-fab mass-production.

This Fresnel lens enables optical performance similar to those offered by classical lenses, but achieves this in a much smaller height. Therefore it is more suitable for planar wafer level processing which is typically handling layer thickness of a few micron only. Moreover, with one process flow different lenses can be designed. e.g. it is possible to develop a single process and adapt the design for different pixel pitches. This approach uses advanced lithography and allows miniaturization and integration of micro-lenses into more complex optical stacks, e.g. also containing optical filters or waveguides, and therefore permits to combine various optical features in a single process flow.

3. Design of Phase Fresnel lens for 5x5µm² FSI pixel

In this work we compare the optical performance of a 5x5µm² pixel without any lens, with a classical micro-lens and with an optimized Fresnel lens, by computing the optical absorption of visible light (400nm-700nm) in the diode region, when a plane wave light source illuminates the imager with perpendicular (normal) incidence (Figure 4). The calculations were performed with the optical simulation software Lumerical, which is based on the Finite Difference Time Domain (FDTD) method. The performance of the pixel without any lens and with a classical lens is depicted on Figure 5. For this 5x5µm² pixel size the classical lens is quasi spherical, and leads to an increased optical absorption by a factor 3 compared to the imager without lenses. The oscillations of the absorption with respect to the wavelength are due to the reflections of the incident light in the back-end-of-line (BEOL) dielectrics of CMOS.

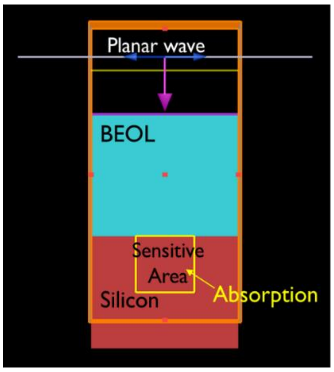

Figure 4 : Simulation Model.

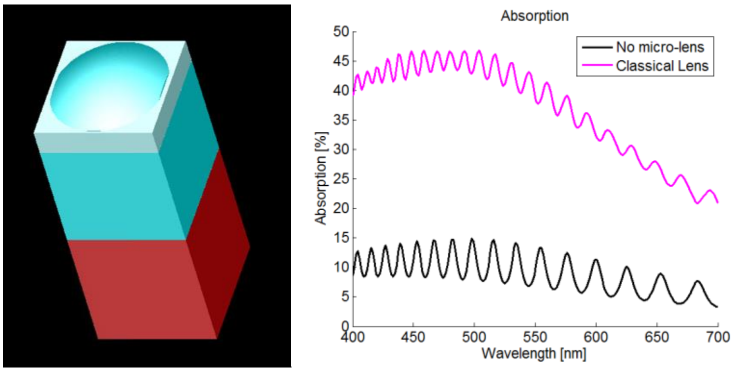

Figure 5: Simulation of the effect of an ideal spherical classical lens.

The performance of the optimized Fresnel Phase Plate solution is summarized in Figure 6. Several characteristic parameters [3] were considered and carefully optimized to obtain the final design: the focal point (i.e., the diode region), the central design wavelength, the number of levels (layers), the materials, ... In addition, for the 5x5µm pixel, the target wavelength range limits the number of "rings" to a few, which makes the design challenging. After optimization, the central design wavelength is chosen as 600nm, the focal distance 5µm, and the materials used, i.e. Silicon Nitride embedded in Silicon Oxide. Numerical simulations show that choosing 2 "staircase" levels is a good compromise between performances and process complexity, and Table 1 demonstrates that the performance of this optimized Phase Fresnel Plate matches the performance of the classical lens over the whole target wavelength range, but with a much lower height then a classical micro-lens.

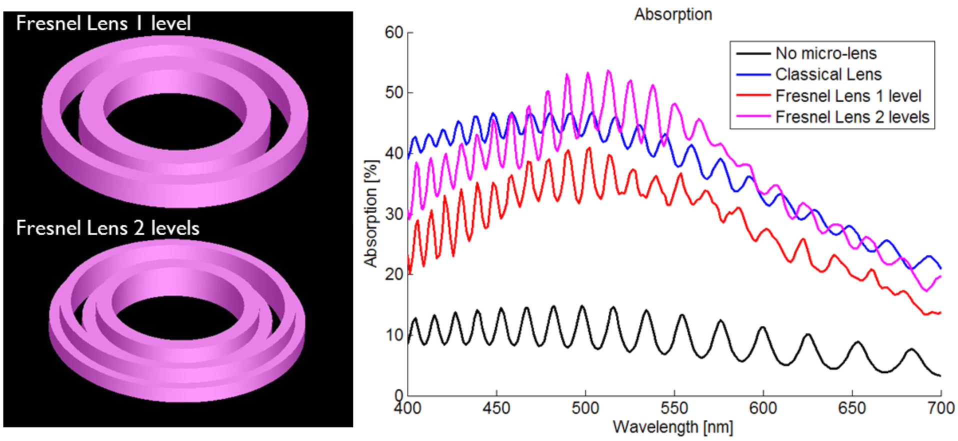

Figure 6 : Simulation of the absorption with a Fresnel Lens with 1 (top) and 2 (bottom) levels and comparison with the classical lens and the pixel.

Absorption	400nm	500nm	700nm	Mean Enhancement
No micro-lens	10%	11.5%	5.8%	1
Micro-lens	40%	42%	20%	3.7
Fresnel 1 level	25%	35%	17%	2.8
Fresnel 2 levels	35%	48%	20%	**3.7**

Table 1: Comparison of the performance of the imager alone, the classical lens and the Fresnel lens (with 1 and 2 levels). The Fresnel lens with 2 levels shows similar mean enhancement as the classical lens.

Finally, Figure 7 shows that comparable focusing performance can be obtained in an even simpler process flow implementing metamaterial design approaches. Indeed, we replace a phase level of the

Fresnel phase plate by a well-defined etch pattern density distributed in 2D with almost no performance penalty, thereby reducing the process complexity. Figure 8 shows pictures of recently processed test structures of Fresnel lens with 2 levels and meta-material lens with 1 level.

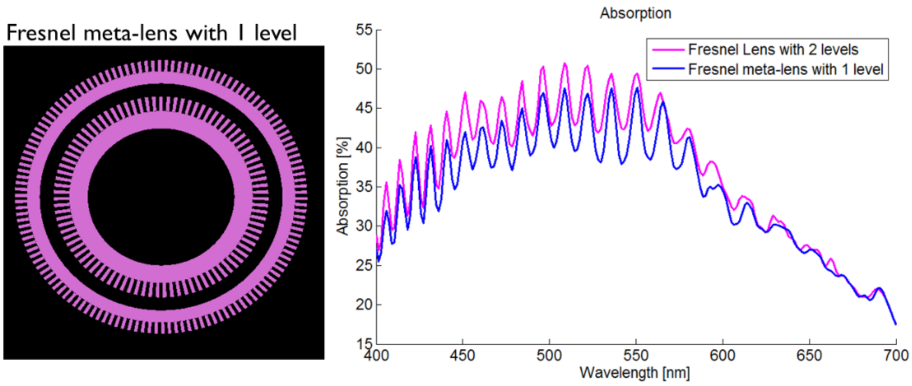

Figure 7: Simulation showing a Meta-material lens design with 1 level can equal the performance of classical Fresnel lenses with 2 levels.

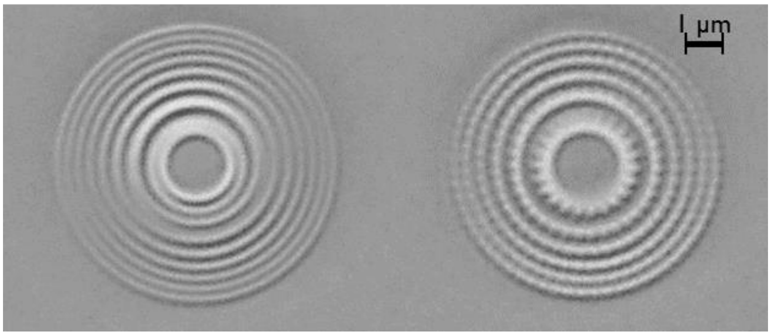

Figure 8: Top view picture of a fabricated classical Fresnel lenses with 2 levels on the left and a Meta-material lens with 1 level.

4. Conclusions

This paper presents the benefits of introducing high quality cleanroom-grade diffractive elements at the pixel level in imagers. These components offer the perspective of complex high-performance light management at the pixel-level, e.g. focusing, optical axis tilt, color or polarization filtering. All these techniques are key enablers for emerging applications, such as light-field cameras, polarization diversity sensing and LiDAR.

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