On-Chip Narrow Angle Filter Development

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***Abstract* — This paper presents the narrow angle optical filter developed using a new process integration to enable the thick stack and the following pad opening**

Keywords — angle filter, thick optical stack, micro-lens array, process integration

I. Introduction

Certain imaging applications require an optical filter allowing only light propagating perpendicular to the sensor to be collected by their pixels. In recent years, one outstanding application for such a filter was in fingerprint sensor located under the cell phone's OLED screen [1]. For this application such a filter replaces the system lens which is often too thick to fit in modern thin cell phones. Another application example is a compound-eye camera [2].

The challenge is to implement such a filter directly on the Silicon for both a compact and cost-effective solution. To achieve this target, the required processing steps should be compatible with standard CMOS Image Sensor (CIS) capabilities. The main performance features of such a filter are the filter width, namely how fast the response drops for impinging beam angles larger than zero, and the quantum efficiency for the light coming in the right zero angle direction.

A straightforward approach to implement such a filter is by using micro-lenses focused on small apertures in an opaque material over the photo diodes in the pixel array, as depicted in Fig. 1 [1]. Angle beams will focus away from the aperture and will be blocked. With smaller light spot and aperture, filtering of only vertically impinging beams becomes more and more efficient. However, the spot size is limited by the wave nature of the light, thus a quality filter requires large, highly curved micro-lens elevated high above the photodiode. Simple analytical expression for this dependence is

$$\Delta\phi = \left[\left(\frac{d}{f}\right)^2 + \left(\frac{\lambda}{D}\right)^2\right]^{1/2}$$

where "d" and "D" are the diameters of aperture and the micro-lens, f is the micro-lens focal length and λ is the wavelength [2]. The aperture is optimized for avoiding light penetration at high angles and is realized using a set of apertures in several layers of the CIS metal layers (Fig. 2). The thick organic optical layers add a challenge for pad opening. A new process integration was developed to enable the thick stack and the following pad opening.

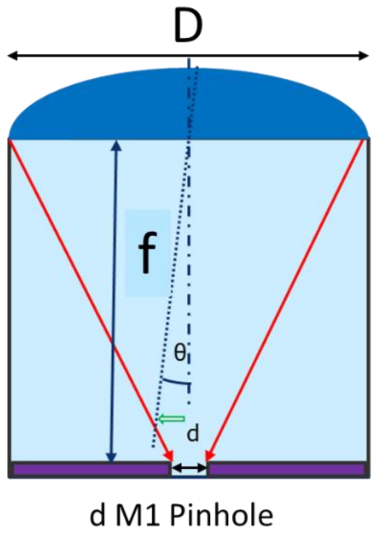

Fig. 1. – angle filter apparatus

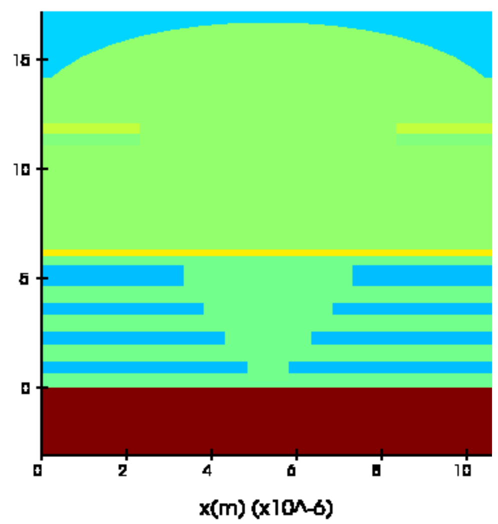

Fig. 2. – Multilayer aperture implementation by metal (blue) and color filter layers

II. Filter Design

The micro-lens design was optimized by optical simulations. An example is shown in Fig. 3. The required angular sensitivity of the filter is defined by 90% signal drop at 5-degree illumination beam tilt. To satisfy the requirement, the bottom aperture diameter d was set to 1μm, the required focal distance was 20µm, the micro-lens diameter D was checked in the range of 15-25µm and the micro-lens thickness (sag) was checked in the range of 5-9µm

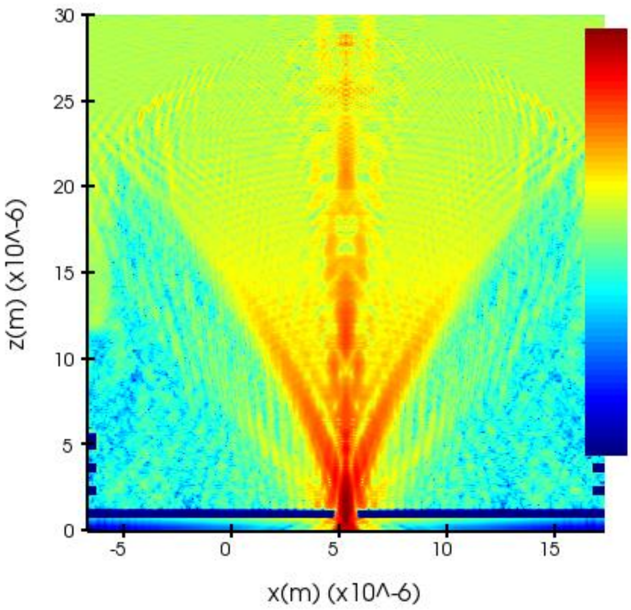

Fig. 3. – optical simulation of the structure from Fig. 2: microlens diameter is 21µm, lens sag is 7µm and predicated focal distance is 20µm

III. THICK OPTICAL STACK INTEGRATION

The conventional micro-lens integration steps are described schematically in Fig.4. The process consists of the following steps:

1. Photo-imageable CT (transparent organic layer) depositions
2. CT exposure & development
3. Micro-lens (UL) coat on CT topography
4. UL exposure + development
5. UL melt

The narrow angle filter design requires much thicker CT layer than in the conventional optical back end. The thick organic optical stack introduces aggressive topography that puts a strong limitation on photo resist coating and patterning. Micro-lens photo-resist process over thick topography (5um or thicker) causes two main problems (Fig.5):

a. Photo-resist coating thickness non-uniformity
b. Photo-lithography focus issues (leveling)

The novel integration steps are described schematically in Fig.6. This integration enables a large range of thick stacks with relatively few process steps. An elegant approach was implemented where all steps of micro-lens formation were completed before the pad-opening topography is created. The new process consists of the following steps

1. CT coating
2. Flood (no mask) UV exposure for CT material bleaching
3. Micro-lens material coating and photo-lithography over planar surface
4. UL melting
5. Thin Low Temperature Oxide (LTO) layer deposition (used as a hard mask in the flow)
6. Photo-lithography to protect the lens array area
7. LTO and thick CT layer etch

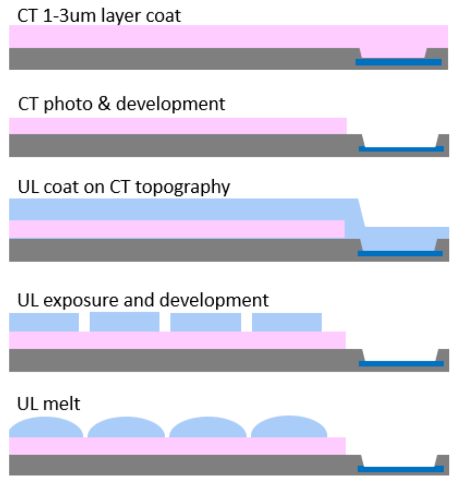

Fig. 4. – Conventional micro-lens process flow

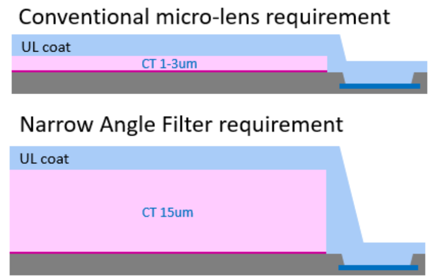

Fig. 5. – Conventional micro-lens process flow over standard and very thick topography

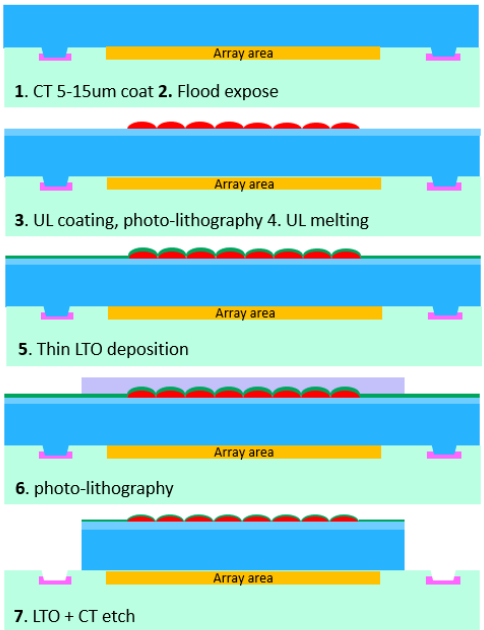

Fig. 6. – the novel process flow for thick optical layers

Cross sections of the final optical stack shown are for the array (Fig. 7), array edge and pad area (Fig. 8)

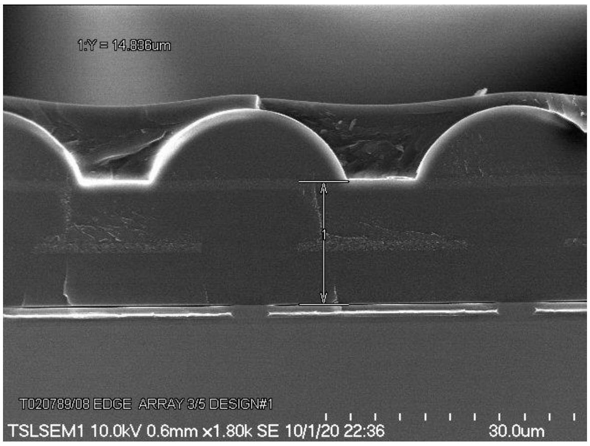

Fig. 7. – Cross section of the optical stack over the array

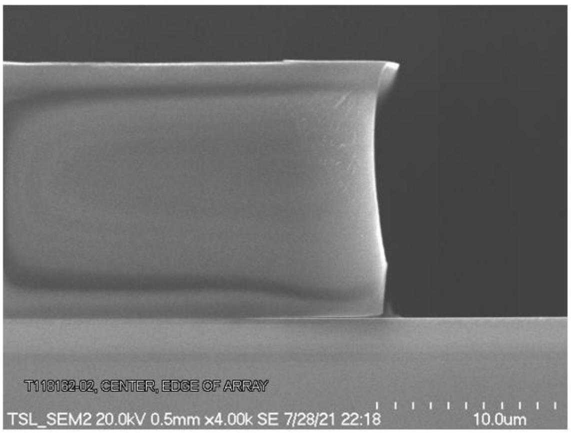

Fig. 8. – Cross section of the optical stack on array edge near the pad opening area

IV. Experimental Results

Results of empirical experiments with different apertures, lens sag, and elevation of 20µm are summarized in Table 1: Full Width Half Max (FWHM) of the filter and a stricter criterion for performance – angle where the normalized response drops to 10% of the maximum response at normal illumination.

TABLE I. Summary of 3 examples of optical stack optimization showing performance of the filter

Lens Sag [um]	Micro-lens Diameter D [um]	Metal Aperture diameter d [um]	Color aperture diameter [um]	QE	Angle of 90% drop	FWHM angle
8	21.4	1	10	9.0%	5.2	2.7
7	21.4	1	10	8.8%	5.0	2.5
6	18.3	1	9	10.9%	5.2	2.8

Angle response curves and comparison to the simulated curve are shown in Fig. 9 and Fig. 10. The experimental results show good agreement with the simulations for 90% signal drop at 5-degree illumination tilt.

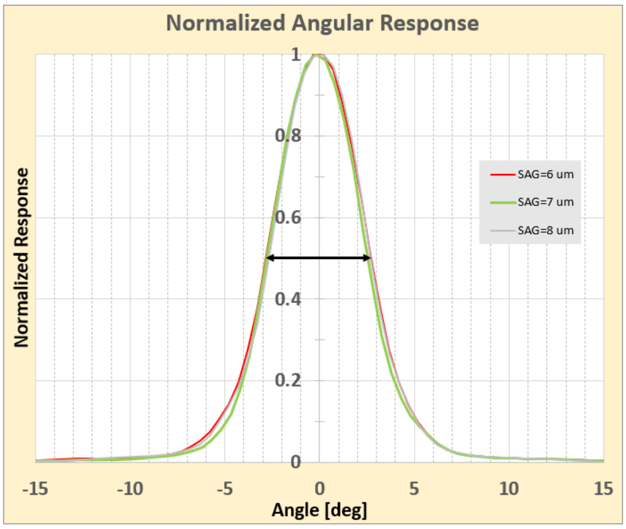

Fig. 9. – Measured filter performance, normalized response vs. impinging beam angle for the conditions from Table 1

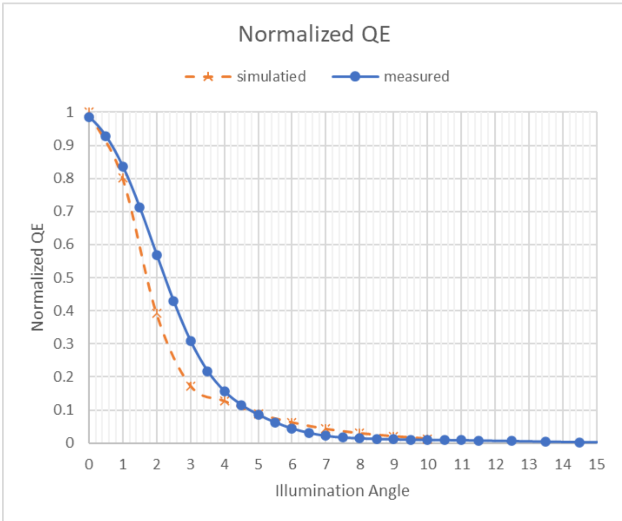

Fig. 10. – comparison of simulated filter performance to measured one for the 7 µm sag

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[2] Duparré, J., Dannberg, P., Schreiber, P., Bräuer, A., & Tünnermann, A. (2005). Thin compound-eye camera. Applied optics, 44(15), 2949-2956.