

Evolution of Optical Structure in Image Sensors

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Abstract

On-chip optics in image sensors has played an important role for image sensor pixel shrinkage and image sensor progression on the whole. There are three key functions; light collecting, color filtering and new specific functions, all of which are reviewed with their future trends. For light collecting technologies, 1.12 μm pixel FSI (front side illumination) with noble lightpipe, which is suitable for large chief ray angle lenses, is explained.

Introduction

Both image sensor innovation and market demand for such technology have been drastically advanced over the last three decades. While movie was technology driver in the 1980's and early 1990's, the market moved to digital still camera products from late 1990's to early 2000's. Thereafter, the focus has become more on mobile phone or portable devices.

Fig. 1 shows the pixel shrinkage trend and the rate of change. Both high resolution and low cost are realized. As a result, image sensors are now used for various applications, and production volumes have increased exponentially. In 2011, the smallest pixel size on market is 1.12 μm and 1.5 billion image sensors were sold. This is a very big number, around 1/5th of the global population, i.e. 7 billion.

Pixel shrinkage has been generated through fine process development and other specific image sensor technologies. Image sensors need on-chip optics in order to manage the light. The scaling rule for image sensors cannot be used so easily, since wavelength and absorption length are constant

in spite of the pixel shrinkage. When the wavelength is comparable with aperture, diffraction brings on crosstalk. Even if pixel size is around 1 μm , the photodiode depth should be larger than 3 μm to ensure red sensitivity. Then, unbalanced tall pixels should be required. Given this situation, on-chip optics technologies have evolved to realize such shrinkage capability.

On-chip optics has three key features; light collecting, color filtering, and other specific functions, such as polarization, autofocus, and coded aperture. In this paper, these technology functions are explained in detail. Together with historical review and future trends, we discuss light collection for small pixels. All image sensor makers (except Panasonic) adopt BSI (backside illumination) to small pixel image sensors because of its large aperture and small distance between microlens and silicon photodiode (1-3). Hence Panasonic has adopted the more sophisticated FSI (front side illumination), SmartFSI[®](4). Latest results for 1.12 μm pixel SmartFSI will be presented along with a comparison look at BSI.

Light Collecting

One of the most important characteristics for image sensors is sensitivity. To increase sensitivity, on-chip optics should collect and conduct light into the silicon photodiode.

On-chip optics for light collecting consists of microlens and lightpipe, together with the anti-reflection (AR) coating. AR is used at the interfaces where refraction index ratio is large, such as silicon surface and microlens surface.

Microlens was first fabricated experimentally in 1983, using resin thermal flow, as shown in Fig. 1(a) (5), and was on mass production in 1989. After that, i-line resist microlens and etching-transfer to transparent resin were developed to improve the blue transmittance. To increase effective aperture ratio, gapless microlens, inner microlens (6), and double inner microlens were developed. Inner lens is located nearby silicon, then, numerical aperture (NA) becomes larger and light collecting becomes more effective, as shown in Fig. 1(b).

Lightpipe technology was introduced to overcome the large stack height and multi-layer reflection (7). After the wiring process, lightpipe is formed by etching the entire dielectric stack above the photodiode, then coating the surface with an SiN layer (refractive index $n=2.05$), and filling with organic material ($n=1.6$), as shown in Fig. 1(c).

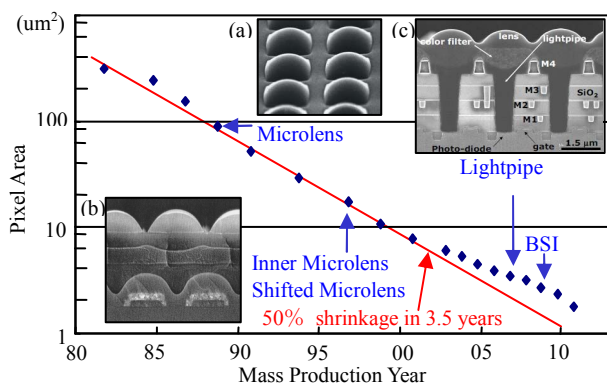


Fig. 1. Pixel shrinkage trend and on-chip optics technologies.
(a) microlens (5), (b) inner microlens (6), (c) lightpipe (7).

BSI is currently the main stream technology for small pixel size CMOS image sensors, where pixel size is less than 1.5 μm (1-3). BSI was already mentioned by Boyle and Smith for their opaque aluminum gate CCD in 1970 (8). For astronomical-use and scientific-use CCD image sensors, where pixel size is larger than 10 μm , have used BSI technology since 1980's. Since 2009, BSI has been adopted by consumer movie CMOS image sensor. Thereafter, it has been a widespread introduction to compact digital still cameras and mobile phones.

BSI has key advantages; firstly, is a large aperture size, secondly is small stack height, and thirdly is flexible wiring design, as shown in Fig. 2(a). Its disadvantage though is crosstalk. Large chief ray angle (CRA) lenses are needed to realize thin cameras. This means, oblique light fraction becomes large and crosstalk occurs especially at image area peripheral. To reduce crosstalk, shifted technology and grid-like metal photoshield are used. These technologies are effective to some extent. There is a trade-off between the crosstalk and the sensitivity for oblique incident light. If the metal photoshield width is larger and photodiode thickness

is smaller, the crosstalk becomes smaller but the sensitivity becomes smaller.

To resolve this trade-off, SmartFSI is introduced, as shown in Fig. 2(b) (4). The most important feature is the powerful lightpipe; firstly, the color filter becomes a lightpipe to use low refractive index separation wall. Secondly, the lower or original lightpipe becomes more powerful due to the high refractive index SiN used on lightpipe core. Thirdly, shift ratios for microlens, color filter lightpipe and lower lightpipe can be set separately to realize "bended" lightpipe. This feature is effective especially for oblique incident light. Another important feature is that fine process technology is adopted for backend; 65nm process and 45nm process, which are both used for 1.43 μm pixel and 1.12 μm pixel, respectively. This ensures a sufficient lower lightpipe diameter and photodiode aperture. The other feature is small stack height, which is realized by adopting low-k for interlayer insulator and limiting the wiring on image area to 2 layers.

Fig. 3 shows the light intensity distribution for 30° off-axis incident light at both (a) BSI and (b) SmartFSI by 3D FDTD

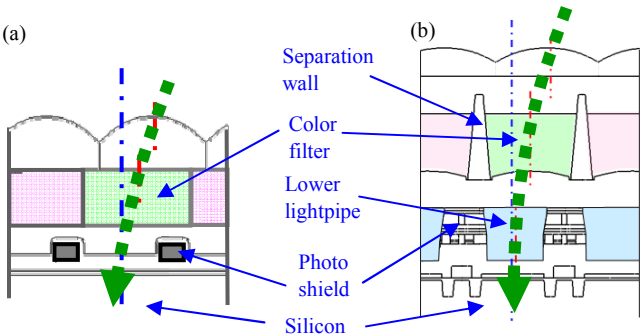


Fig. 2. On-chip optics structures for image area peripheral pixels.
(a) BSI (Backside illumination), (b) SmartFSI

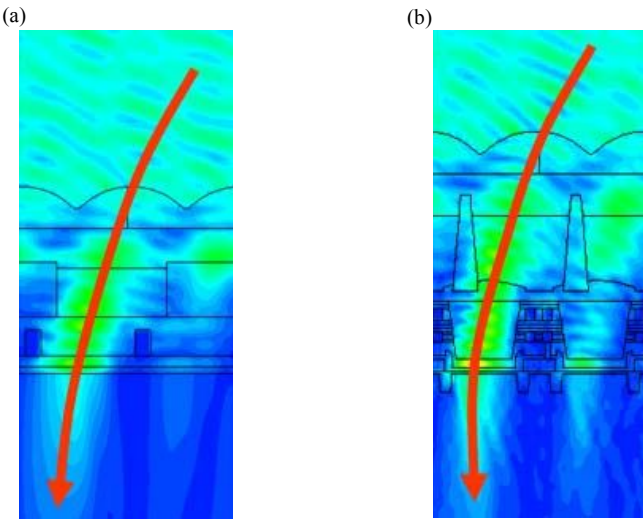


Fig. 3. Light intensity distribution for image area peripheral pixel by 3D FDTD. (a) BSI, (b) SmartFSI, Incident angle: 30°, Wavelength: 520nm.

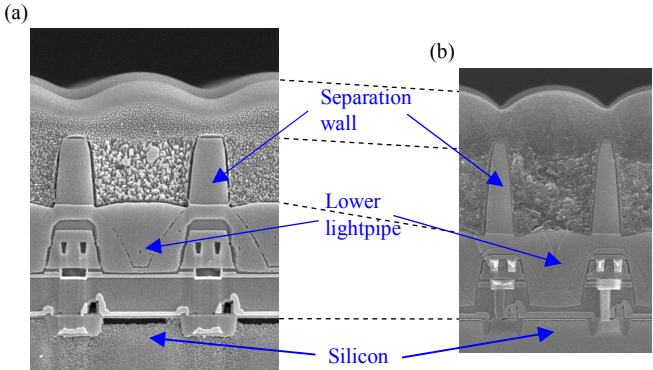


Fig. 4. SmartFSI Cross-sectional SEM images.
(a) 1.43 μm pixel, (b) 1.12 μm pixel.

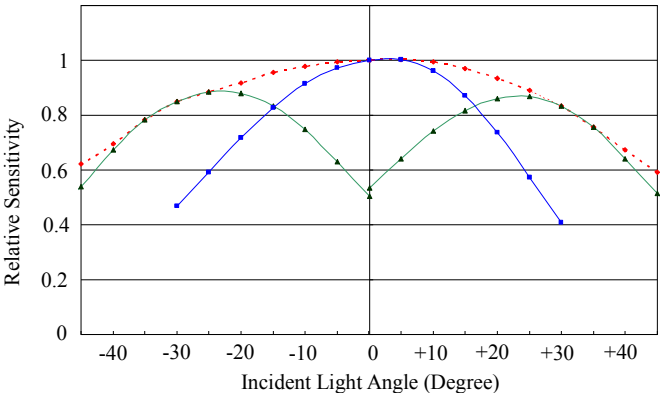


Fig. 5. Incident light angle response of 1.12 μm pixel.
—: Image area center (0°), —: Image area peripheral ($\pm 30^\circ$),
---: Envelope curve of various image area positions.

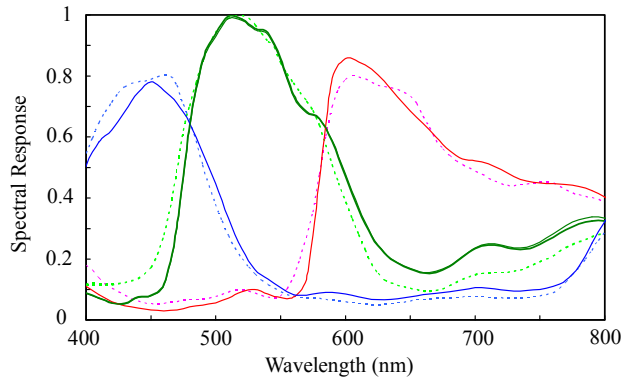


Fig. 6. Spectral response.
Solid line: 1.12um pixel, dashed line: 1.43um pixel.

Table.1. Measured characteristics of 1.43 um and 1.12 um SmartFSI.

Pixel Size	um	1.43	1.12
Saturation	ele	6130	5500
Unit Area Green Sensitivity	ele/lx/s/um ²	3010	3190
White Spot Pixels in Dark ¹⁾	/Mpix	20	24
Dark Current per Pixel @60°C	ele/s	10	7
Read-out Noise	ele	1.9	1.0

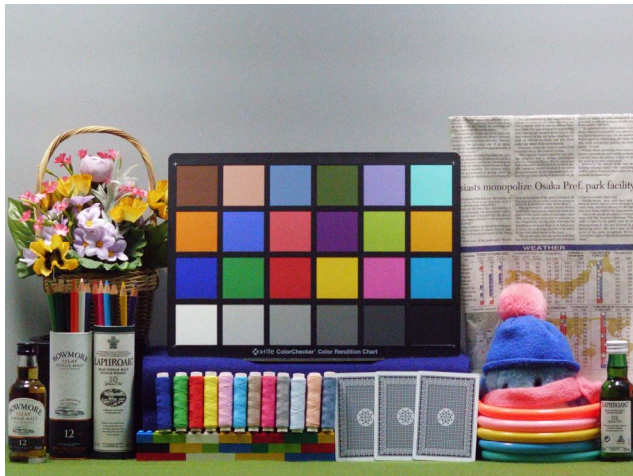


Fig. 7. Reproduce image of 1.12 um pixel SmartFSI.
Pixel number: 4208x3152, ISO: 1600,
Illumination: 35lx (D50), Aperture : F4, Expsure time : 60ms.

(finite difference time domain). With BSI, although shifted microlens and color filter, low stack height, large aperture and grid-like metal photoshield are adopted, the ray travels on an angle in silicon. It generates crosstalk. With SamrtFSI, the oblique incident light is turned into a normal direction by the bended lightpipe. It is the one of the key features that allows the ray to travel within the silicon in the normal direction.

The SmartFSI performances of successful scaling down from 1.43 um pixel (4) to 1.12um pixel are explained further.

SEM cross sectional views are shown in Fig. 4. The bottom of the lower lightpipe is nearer to the silicon surface, and the separation wall is higher, which make the bended lightpipe more powerful. Fig. 5 shows the relative sensitivity of oblique incidence. Blue solid line is for the image area center and green solid lines are for image area peripheral of 30°. Red dashed line denotes envelop curve of various image area positions. Since the decrease at 40° is less than 35%, even 40° CRA lens can be used. According to the spectral responses, crosstalk for short wavelength becomes smaller, as shown in Fig.6. Fig. 7 shows the reproduced image taken under ISO 1600. The measured characteristics are compared to 1.43 um pixel ones in Table 1. Dark current and white spot are as small as 1.43 um pixel, which are better compared with BSI, because BSI suffers from dark current on both surfaces. It can be concluded that SmartFSI is scaled down successfully.

Color Filtering

Mosaic color filter array is an important component to provide single-chip color cameras. Color filter array was fabricated on glass substrate and pasted on an image sensor until mid-1980's. Although the alignment was a troublesome process, mainly due to bad yield for color filter arrays and image sensors, it has a positive factor that a good filter array could be pasted on a good image sensor.

On-chip color filter array was experimentally fabricated in 1980 (9), and mass produced from mid-1980's. The early-stage on-chip color filters were made by staining gelatin or casein layer with dyes. Although dyes have various colors, it is difficult to control the staining process and maintain reproducibility. Color fading is also a drawback especially for security application.

To realize simple and reproducibility, pigment dispersant photoresists were developed in 1997. Since then, they have been used for almost all color image sensors.

The pixel shrinkage needs the reduction in color filter thickness maintaining color reproducibility. It becomes difficult to keep photolithography function because the photosensitizing agent decreases, if colorant cannot be reduced (10). When SmartFSI is adopted, the situation is improved; the color filter thickness reduction is not required so much because color filter forms a lightpipe. Patterning the color filter becomes easier since the separation walls define the color filter pattern.

An alternative approach to conduct the pixel shrinkage is color selective photoconductors. Fig. 8 shows examples of spectrum responses, where organic photoconductors are used (11). Color crosstalk can therefore be suppressed during this scheme.

New Specific Functions

Since image sensor application is widespread, various specific functions are required from on-chip optics, as

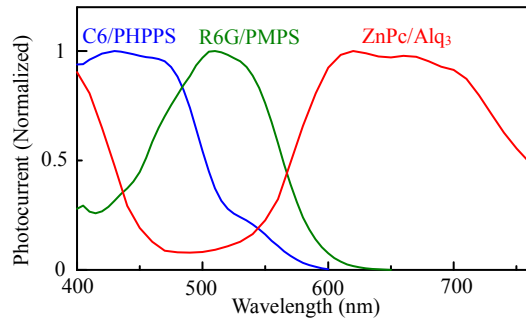


Fig. 8. Spectral response of organic photoconductors (11).
 Blue: Coumarin 6 (C6)-doped poly (m-hexoxyphenyl) phenylsilane (PHPPS),
 Green: Rhodamine 6G (R6G)-doped polymethylphenylsilane (PMPS),
 Red: Zinc phthalocyanine (ZnPc) / tris-8-hydroxyquinoline aluminum (Alq₃).

explained below.

Polarization image sensors need polarizers, which are metal stripes above photodiodes, as shown in Fig. 9 (12, 13). Smaller line and space gives better extinction ratio.

Focal plane phase detection autofocus (AF) is realized for digital still cameras to embed pairs of phase detection pixels into the pixel array, as shown in Fig. 10. One pixel of the pair has left-half aperture masked, while the other has right-half aperture masked. Then, the pair delivers out-of-phase measurement.

Single lens plenoptic cameras for computational photography need peculiarly designed microlens array and coded apertures, which are preferably monolithic. After processing planoptic image data, refocusing, 3D, super-resolution and so forth can be obtained (14).

Conclusion

On-chip optics in image sensors has three key functions; light collecting, color filtering and new specific functions. SmartFSI technology can be successfully scaled down to 1.12 μm pixel. Unlike BSI, its bended lightpipe feature provides a large angular response, whereby 40° CRA lens can be used, thus following thin cameras to be produced. Although wafer level camera is becoming an important technology, here, pixel-wise optics is focused.

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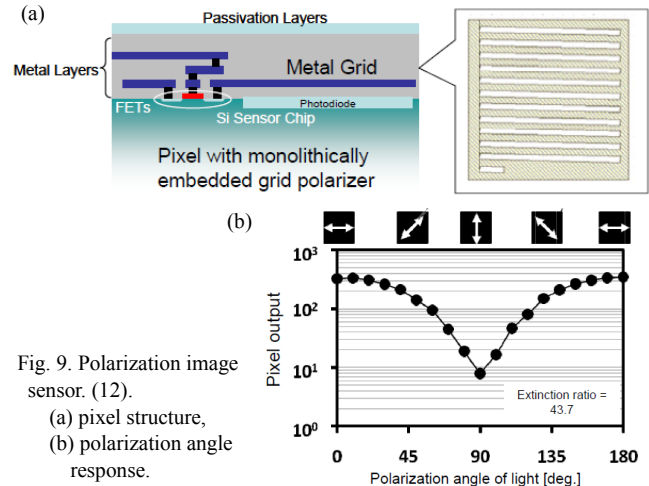


Fig. 9. Polarization image sensor (12).
 (a) pixel structure,
 (b) polarization angle response.

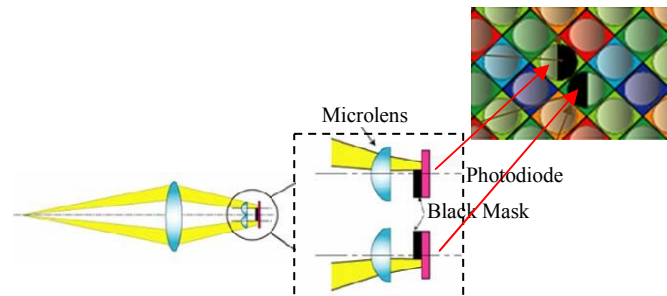


Fig.10. Built-in phase detection pixels for autofocus.
 (Courtesy of Fujifilm)

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* SmartFSI is a trademark of Panasonic Corporation.