5.5 A 1/1.57-inch 50Mpixel CMOS Image Sensor with 1.0μm All-Directional Dual Pixel by 0.5μm-Pitch Full-Depth Deep-Trench Isolation Technology

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As the strong demand for higher resolution and new functionality is rapidly increasing in the mobile CMOS Image Sensor (CIS) market, we have seen the emergence of: submicron pixels, >200M pixels, fast readout, global shutter, high dynamic range, and phase-detection autofocus (PDAF) [1-3]. Among these, PDAF is an essential feature of cutting-edge CIS for accurate autofocus at extremely low-light situations, and dual-pixel technology has been widely used for AF of the entire image area [4]. To implement high pixel resolution in a limited optical size, the pixel size has continued to shrink, and the pixel structure has evolved to maintain high image quality. However, for a dual pixel, integrating two photodiodes (PDs) in one pixel by backside deep trench isolation (BDTI) has technical limitations and causes degradation of image AF performance as well as image quality.

In this paper, we present a 1.0μm (0.5μm×2) pixel whose image quality is the same as that of the single pixel. To improve full-well capacity (FWC) of PD and AF performance of the 1.0μm dual pixel without deterioration of signal linearity in high-light conditions, we propose a layout that can form an overflow path in the full-depth isolation structure. Instead of the backside BDTI process that was applied to previous generations of dual pixels [5], a frontside deep-trench isolation (FDTI) process is used [6]. The technical challenges to adopt the FDTI structure are: (1) how to place transistors in a half pitch of 1.0μm, (2) how to form an inter-PD overflow path between two adjacent PDs while maintaining perfect isolation with for signal linearity, and (3) how to reduce optical loss in the polysilicon of in-pixel DTI at the center of the pixel.

Figure 5.5.1 shows the concept of the dual pixel with FDTI structure, compared to a conventional BDTI dual pixel. The dual pixel consists of a left PD and a right PD in one pixel to output the PDAF signal, so the PD area decreases by ~20% compared with a single pixel. It should consist of PDs, Transfer Gates (TGs), a Floating Diffusion (FD), an inter-PD overflow path, and other transistors. The conventional dual pixel with BDTI structure has a shallow PD due to the limitation of the heat process that causes low FWC and high white defects. In particular, partial-depth BDTI degrades the AF contrast due to crosstalk between PDs. Limiting silicon thickness to suppress crosstalk causes low pixel sensitivity. On the other hand, a full-depth DTI structure is used in this paper to increase the silicon thickness to improve sensitivity, and the in-pixel DTI between PDs improves the AF performance by reducing inter-PD crosstalk. The area in which the PD and transistors should be located is reduced due to the in-pixel DTI area. In terms of FWC, a vertical broad PD is designed within ~0.4μm pitch silicon area and vertical TG (VTG) is also optimized with lossless charge transfer. One transistor is located per unit PD area, and four pixels share a Source Follower (SF), Reset Gate (RG) and SEL transistor.

In the dual pixel, to preserve signal linearity in a defocused scene, an overflow charge path between two PDs is essential. When the sensitivity difference between two adjacent PDs occurs due to defocus and other mismatches in the dual pixel, one PD is saturated first, and the image signal (L+R) loses linearity and its FWC is limited to 1/2(1+1/A). That is, when the AF contrast (A) is 3.5, the linear FWC is reduced from 10,000e- to 6,420e- as shown in Fig. 5.5.1. In order to resolve the FWC loss, an overflow path is formed by modifying the in-pixel DTI layout. Also, a tapered profile is introduced to simultaneously optimize the overflow barrier and optical characteristics. The overflow level is controlled by the space of the in-pixel DTI, and the bigger gap size lowers the potential.

To lower power consumption, we apply a negative substrate bias using internal power-management circuitry. Through the Negative Sub (N-Sub) scheme, a 2.2V analog and pixel supply is applied instead of 2.8V, which results in more than 20% analog power reduction without sacrificing FWC by lowering the substrate voltage of the larger PD.

In addition, the demand for AF performance is diversified, as all-directional AF, which has vertical and horizontal AF information. Since all dual pixels are fully isolated, each pixel can be rotated and placed horizontally and vertically to enable an all-directional AF, as shown in Fig. 5.5.2. Since the Horizontal-Vertical (HV) dual pixel introduced in [7] places the in-pixel DTI at an angle between the PDs, horizontal AF disparity is reduced by cosθ. The previous HV dual pixel obtains final AF information using the left/top signal of the slash pixel and right/bottom signal of the backslash pixel [7]. However, the proposed pixel can be placed and be combined in horizontal and vertical directions, and thus all-directional AF information can be obtained without a calculation from adjacent pixel data. Furthermore, we achieve the same AF contrast in horizontal and vertical directions.

Figure 5.5.3 shows the vertical structures of BDTI and FDTI dual pixels, and FWC performances of 1.0 to 1.4μm dual pixels. The 1.0μm dual pixel has an FWC of 10,000e- in one pixel, 40,000e- in a 2×2 merged pixel, which is similar performance to that of a 1.4μm dual pixel by adopting the vertically broad PD and VTG.

Figure 5.5.4 provides a comparison of quantum efficiency (QE) spectra among the various pixel sizes. QE is increased by employing partial in-pixel FDTI and thicker Si. In addition, crosstalk is also improved by full-depth FDTI [8]. Despite the dual PD structure, the sensitivity is high and similar crosstalk is achieved compared to a 1.0μm single PD. The dual pixel with BDTI structure shows a significant decrease in AF contrast as pixel pitch shrinks, but the 1.0μm FDTI dual pixel can suppress the inter-pixel and inter-PD crosstalk, and AF results are similar to 1.2μm and 1.4μm BDTI dual pixels in horizontal-only and horizontal/vertical directions, respectively. As a result, the AF performance of the proposed pixel is better than that of a conventional 1.4μm BDTI dual pixel whose size is almost double.

The pixel performance is summarized in Fig. 5.5.5. New dual pixel technology demonstrates pixel performance beyond previous-generation dual pixels. FWC of 10,000e- without image lag is measured. Optical characteristics such as sensitivity are similar to the 1.0μm single pixel, and crosstalk is better than the 1.2μm and 1.4μm BDTI dual pixels. Contrasts of 3.5 are achieved for both horizontal and vertical AF.

In summary, a 1.0μm dual pixel in 0.5μm pitch FDTI technology is developed to maintain AF, crosstalk, and FWC performance. As a result, the 1.0μm dual pixel with FDTI shows the same pixel performances as 1.2μm and 1.4μm dual pixels using a BDTI process. FWC of 10,000e- and AF contrast of 3.5 are achieved without compromising image quality measures such as signal linearity, sensitivity, and crosstalk. A novel structure with inter-PD overflow removes some of the in-pixel DTI at the center of the pixel, and signal linearity and high sensitivity are achieved.

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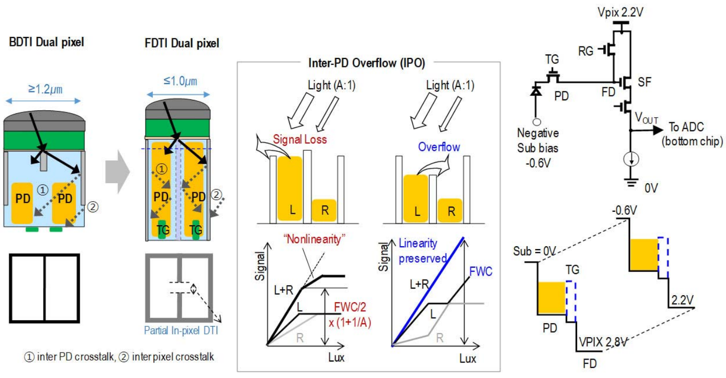


Figure 5.5.1: FDTI dual-pixel concept compared to conventional BDTI dual pixel.

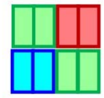
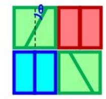
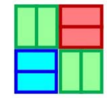
	BDTI Horizontal Dual Pixel [5]	BDTI Horizontal & Vertical Dual Pixel [7]	FDTI Horizontal & Vertical Dual Pixel
Pattern			
AF data acquisition	Left L R Right	Top: LT + RT; Left: LT+L+LB, RB+R+RT: Right; RB + LB: Bottom	Top: T; Left: L, R: Right; B: Bottom
Horizontal AF	A	B x cos θ	C
Vertical AF	0	B x sin θ	C

Figure 5.5.2: FDTI H&V dual-pixel pattern compared to BDTI dual pixel.

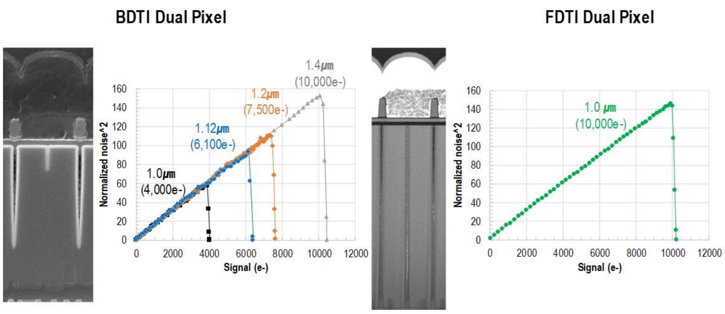


Figure 5.5.3: Comparison of pixel structure and full-well capacity.

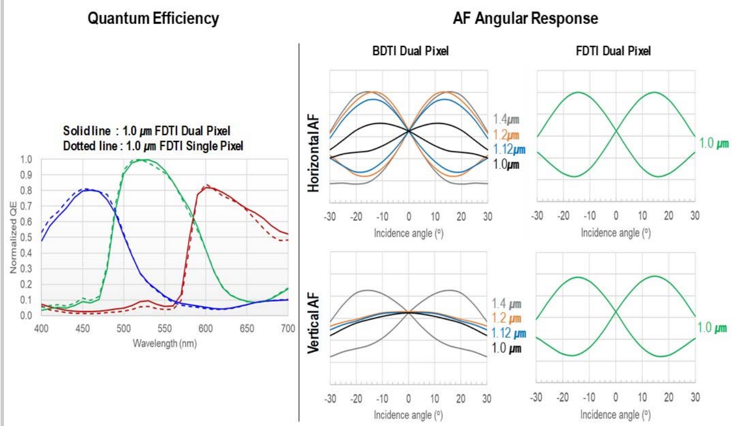


Figure 5.5.4: Comparison of quantum efficiency and AF angular response.

Items	unit	1.4μm BDTI HV dual pixel [7]	1.2μm BDTI dual pixel [5]	1.0μm FDTI single pixel	1.0μm FDTI dual pixel (This work)
Full well capacity	e-	10,000	7,500	6,400	10,000
Image lag	e-	<1.0	<1.0	<1.0	<1.0
G-sensitivity	e-/lux.sec	7000	4900	3430	3450
Crosstalk	%	16.1	19.0	14.8	15.5
Horizontal AF @ 10°	-	3.6	3.5	-	3.5
Vertical AF @ 10°	-	2.3	-	-	3.5
White spot	ppm	90	50	30	30

Figure 5.5.5: Pixel performance summary of 1.0μm HV dual pixel compared to 1.2μm dual pixel, 1.4μm HV dual pixel, and 1.0μm single pixel.

Figure 5.5.6: Sample image.

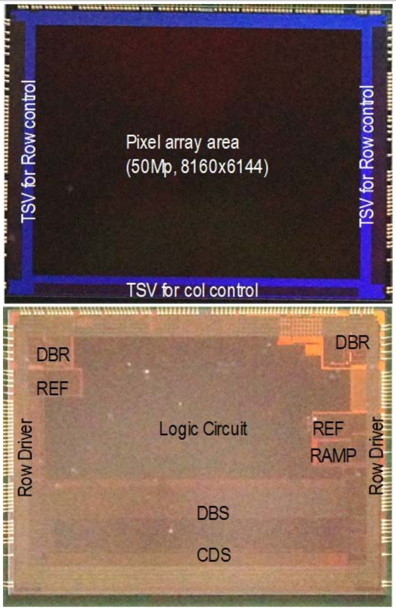


Figure 5.5.7: Chip micrographs.

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