A Smart Dual Pixel Technology for Accurate and All-Directional Auto Focus in CMOS Image Sensors

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Abstract—We developed a dual pixel with accurate and all-directional auto-focus (AF) performance in CMOS image sensor (CIS). The optimized in-pixel deep trench isolation (DTI) provided accurate AF data and good image quality in the entire image area and over whole visible wavelength range. Furthermore, the horizontal-vertical (HV) dual pixel with the slanted in-pixel DTI enabled the acquisition of all-directional AF information by the conventional dual pixel readout method. These technologies were demonstrated in 1.4μm dual pixel and will be applied to the further shrunken pixels.

I. Introduction

The higher resolution and new functions are the increasing demands in the recent mobile CMOS image sensor [1-4]. AF is one of the essential function, and the AF separation ratio, pixel density, and sensitivity are the major factors to enhance the AF performance. The phase detection auto focus (PDAF) with sparse pattern such as metal-shield or 2x1 micro-lens (ML) has been used. In recent years, the all dual pixel and the all 2x2 ML pixel with no defects and excellent low-light AF performance tend to be employed in flagship cameras (Fig.1) [5-8]. Compared to 2x2 ML pixel, dual pixel has superior image qualities when it comes to the channel difference in full resolution, full well capacity and readout noise in 4sum mode (Table 1).

The key technology of dual pixel is the separation between two photodiodes (PDs), and two structures have been developed for dual pixel separation so far. One is the electrical isolation by PN junction in the deep silicon, and the other is the physical isolation by in-pixel DTI (Fig.2). In this paper, we discussed two isolation structures in terms of AF accuracy and image qualities. Also, we proposed the new structure to provide all-directional AF information like 2x2 ML pixel. The optimized in-pixel DTI and HV (horizontal and vertical) dual pixel technologies were successfully demonstrated in 1.4μm pixels.

II. Dual Pixel with In-pixel DTI

A. Auto Focus Accuracy of Dual Pixel

According to the light absorption nature in silicon, the short wavelength light is mostly absorbed from the surface of silicon and the long wavelength light can penetrate the deep silicon region. Their skin depth corresponds to about 0.4, 1.7, and 3.8μm at 450, 540, and 650nm, respectively (Fig. 3a). When the light is incident in the image edge obliquely, the light is divided into left and right photodiodes. For the electrical isolation structure, the amount of optical power varies according to the wavelength due to the difference of absorption depth. However, for the physical isolation structure, the amount of optical power can be separated evenly regardless of wavelengths (Fig. 3b & 3c). Fig. 4 shows the simulated quantum efficiency curves of left and right PDs at image edge. For the electrical isolation by PN junction, when the left and right signals are matched by the green signal, the blue signal of left PD becomes higher than that of right PD, the red signal becomes vice versa. However, for the physical isolation by in-pixel DTI, the left and right signals are evenly separated for all colors.

Due to the physical phenomena mentioned above, the electrical isolation by PN junction cannot provide accurate AF for all colors at the edge of image, while the physical isolation with in-pixel DTI has no difference of AF cross-point between colors at the edge of image. Therefore, only physical isolation can deliver accurate AF characteristics in the entire image area over whole visible wavelength range. As shown in the experiments results, PN junction separation has a huge chief ray angle (CRA) mismatch among colors (~7deg), but the in-pixel DTI has well matched AF cross-point at image edge for all colors.

B. Image Quality of Dual Pixel

In general, the micro-lens is designed in a shifted placement according to CRA and is optimized to deliver an accurate AF data (AF CRA matching). In this case, it is difficult to optimize sensitivity in the image edge area, simultaneously. However, with shrink design of in-pixel DTI according to CRA, all pixels have little sensitivity loss in the entire image area as well as exact AF CRA matching. In other words, the shift ratio of in-pixel DTI could be chosen considering both AF performance and image quality and this is another advantage of physical separation of dual PDs.

However, in-pixel DTI causes the optical crosstalk to adjacent pixels and deteriorate color signal to noise ratio (SNR) with high color correction matrix (CCM) gain. To reduce the optical crosstalk, the in-pixel DTI should be shallower (Fig. 6). When the depth of in-pixel DTI is from

1.6μm to 0.5μm, the optical crosstalk induced by in-pixel DTI is reduced by around 1.9%, and the AF separation ratio is a little decreased in 0.15. With the fabricated shallower in-pixel DTI (Fig. 7), the crosstalk and CCM gain were reduced, similar to the case of PN junction while the AF characteristics (separation ratio, cross-point) were maintained similar to deeper in-pixel DTI.

III. Dual Pixel with All-Directional AF

A. Concept of HV Dual Pixel

Although the conventional dual pixel provides accurate AF data and little sacrifice of image qualities, only horizontal AF operation is possible and vertical AF data is not available. However, using the physical separation, if the in-pixel DTI is placed at an angle between two photodiodes, AF information of vertical direction as well as horizontal direction can be obtained (Fig.9).

The HV dual pixel consists of a pair of the slanted in-pixel DTIs in opposite directions. The acquisition method of horizontal and vertical phases from a pair of pixels is shown in Fig. 10. The slash pixel has left/top and right/bottom AF information, and the backslash pixel has right/top and left/bottom AF information. The above four data can be readout with the existing dual pixel method and readout noise is maintained same. The final AF data of left, right, top, and bottom can be obtained by the calculation from these four signals.

By changing the slanted angle of the in-pixel DTI, horizontal AF and vertical AF performances can be adjusted. Theoretically, horizontal and vertical AF portions are cos θ and sin θ, respectively (Fig. 11). In our experiment, it was designed at 35deg to increase horizontal AF performance.

B. Experimental Results of HV Dual Pixel

The HV dual pixel was demonstrated in the 1.4μm tetra cell and Fig. 12 shows the top view image of the HV dual pixel with the slanted angle of 35deg. In Fig. 13, the angular responses of conventional dual pixel and HV dual pixels were measured and compared. HV dual pixel has the phase information of vertical direction as well as horizontal direction and horizontal separation ratio is higher than others because the slanted angle is 35deg. On the other hand, conventional dual pixel has no vertical component but higher horizontal AF separation ratio. Spectral responses of image pixel were also compared and HV dual pixel had a little higher sensitivity and lower crosstalk. The triangular shape of DTI effectively increases depth of light absorption in silicon and decreases the optical crosstalk with better total internal reflection of DTI. Fig. 14 shows the test results of disparity in module AF operation. HV dual pixel can detect not only horizontal AF but also vertical AF phase while the conventional dual pixel has only horizontal disparity. Here, horizontal and vertical components correspond the cos 35deg and sin 35deg of the value of conventional dual pixel.

We summarized the overall pixel characteristics of the HV dual pixel with an angle of 35deg and compared with the conventional dual pixel (Table 2). Electrical characteristics such as full well capacity and image lag are measured with similar level to conventional dual pixel. Even though some part of the slanted in-pixel DTI was placed inside the photodiode, white spot and dark current are also similar. For optical characteristics, sensitivity increased by 3% and crosstalk decreased by 0.2% in HV dual pixel. Photo response non-uniformity (PRNU) was also maintained low. AF contrast was divided into H and V by the slanted angle of in-pixel DTI but each values were a little deviated from the ideal case due to the electrical crosstalk between two PDs. The horizontal AF contrast of 3.6 (ideal 3.7) and the vertical AF contrast of 2.3 (ideal 2.6) were obtained. In overall, the proposed HV dual pixel was successfully demonstrated.

IV. Conclusion

AF is the most important function in the recent CIS and various types of pixel structure such as metal shield, 2x1 ML, 2x2 ML, and dual pixel have been developed. Among them, dual pixel is one of the most appropriate structure when it comes to AF performance and image quality. In order to obtain both AF accuracy and good image qualities, in-pixel DTI was developed and optimized by CRA shift and shallow depth. In addition, with an angle of slanted in-pixel DTI, HV dual pixel can provide all directional AF using the conventional dual pixel readout method. Our technology was demonstrated in 1.4μm dual pixels and will be applied to the further shrunken pixels.

References

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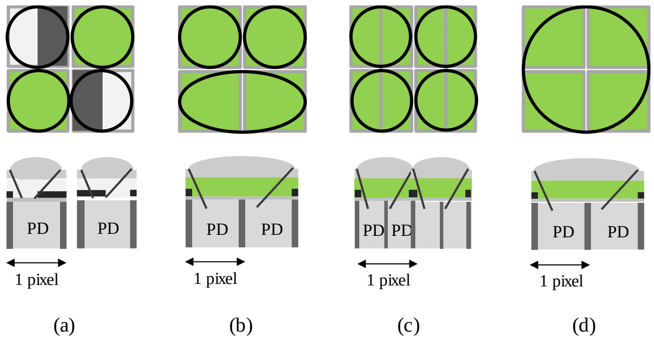

Fig. 1. Various PDAF pixels (a) sparse metal-shield, (b) sparse 2x1 ML, (c) all dual pixel, and (d) all 2x2 ML pixel.

Items	All dual pixel (AF contrast + other mismatches = a)		All 2x2 ML pixel (AF contrast + other mismatches = b)	
	full	4sum	full	4sum
Full Well Capacity	A	4A	<A	A (1+2/b+1/b^2)
Sensitivity	B	4B	B	4B
Channel diff.	Small	-	Large ($\propto$ b)	-
Readout noise	C	C	C	2C
Auto Focus	Horizontal	Horizontal	Horizontal & Vertical	Horizontal & Vertical

Table 1. Comparison between dual pixel and 2x2ML pixel in terms of image qualities and AF performances

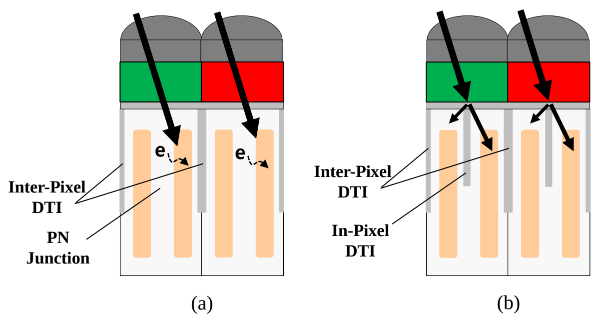

Fig. 2. Two types of dual pixel isolation, (a) electrical isolation by PN junction (b) physical isolation by in-pixel DTI

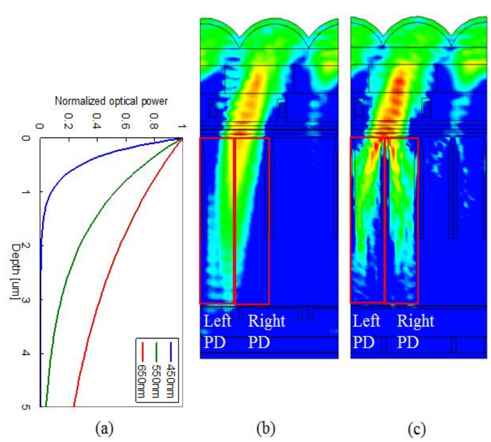

Fig. 3. (a) Light absorption properties of silicon, beam profile images with FDTD optic simulation in (b) junction isolation, (c) in-pixel DTI at wavelength of 540nm

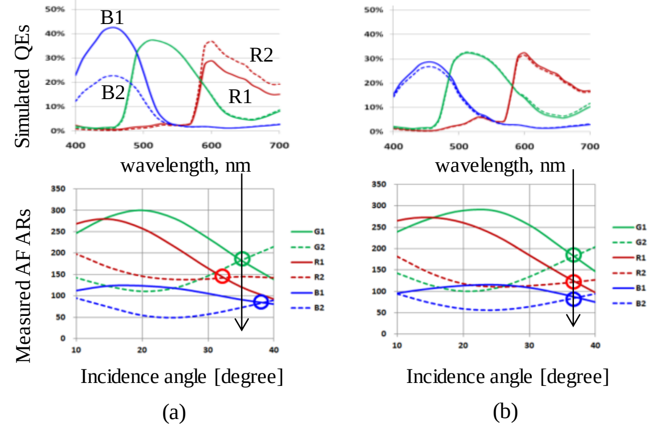

Fig. 4. Simulated QE curves and measured AF angular response at image edge, (a) electrical isolation by junction, (b) physical isolation by in-pixel DTI

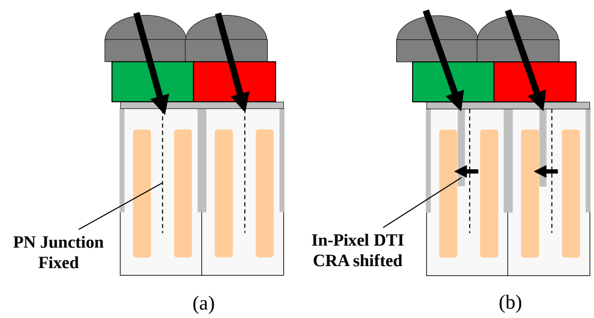

Fig. 5. (a) Fixed electrical isolation by PN junction, (b) CRA-based shrunk in-pixel DTI

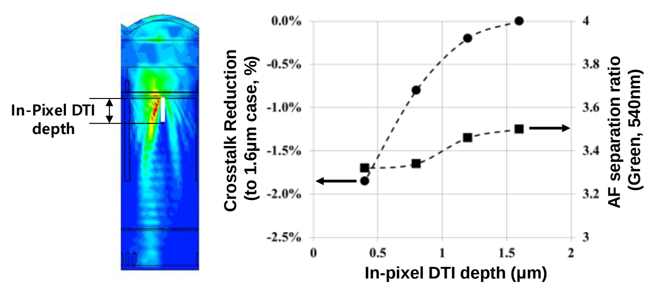

Fig. 6. Simulated optical crosstalk and AF separation ratio according to the depth of in-pixel DTI

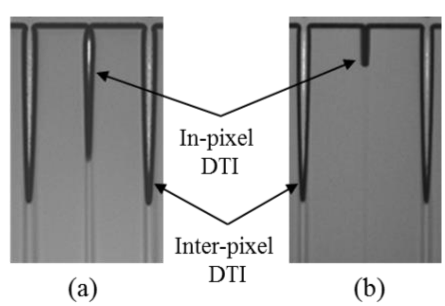

Fig. 7. In-pixel DTI structures – TEM images, (a) in-pixel DTI depth of 1.6㎛, and (b) in-pixel DTI depth of 0.5㎛

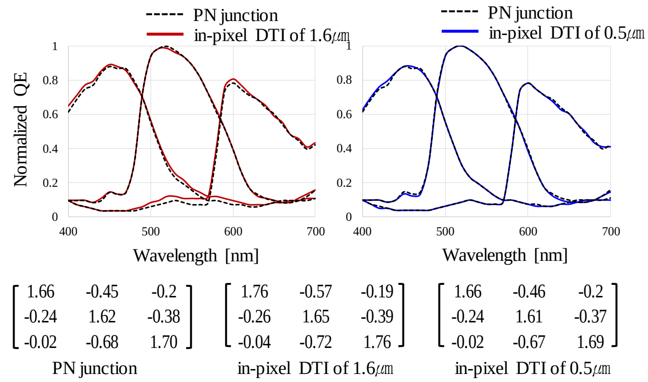

Fig. 8. Comparison of QE spectra of dual pixel according to the depth of in-pixel DTI

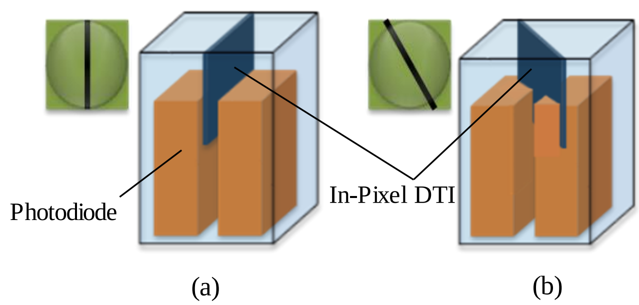

Fig. 9. (a) Conventional dual pixel, (b) proposed HV dual pixel

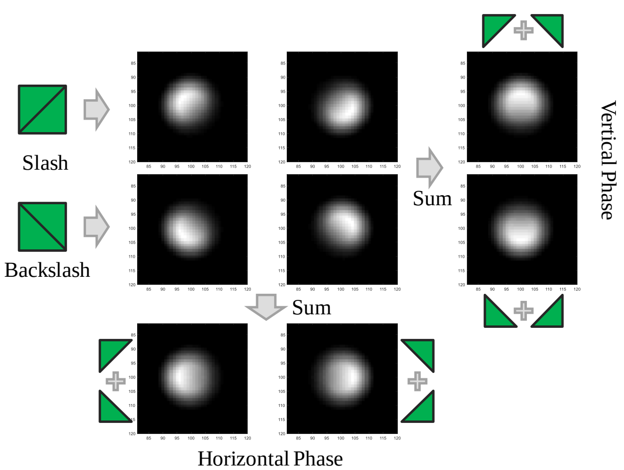

Fig. 10. Concept of HV dual pixel and calculation method of AF phase

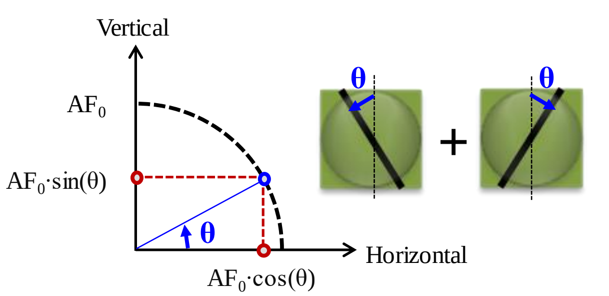

Fig. 11. Ratio of horizontal and vertical AF separation ratio according to the slanted angle of in-pixel DTI

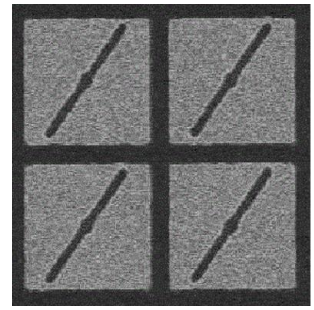

Fig. 12. Top view image of the fabricated 1.4㎛ HV dual pixel with an angle of 35deg (Tetra cell case)

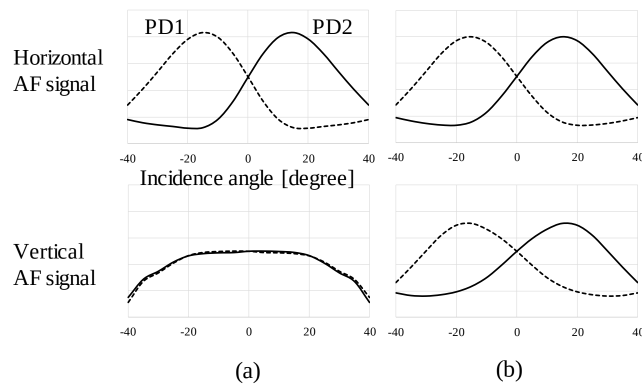

Fig. 13. Measured AF angular response of (a) conventional dual pixel, (b) HV dual pixel with an angle of 35deg

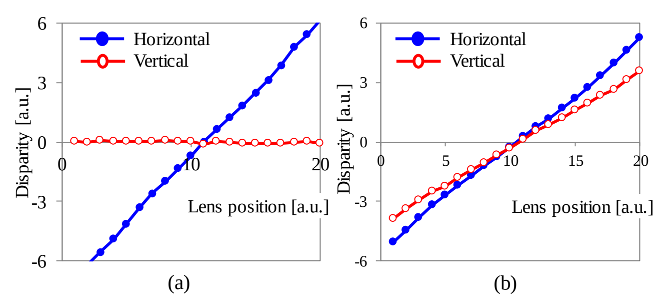

Fig. 14. Disparity results according to lens position (a) conventional dual pixel, (b) HV dual pixel with an angle of 35deg

item	unit	Conventional dual pixel	HV dual pixel (angle 35deg)
Full well capacity	e-	10,000	10,000
Image lag	e-	<1.0	<1.0
G-sensitivity	e-/lux.sec	7,000	7,200
Crosstalk	%	16.3	16.1
PRNU	%	0.8	0.8
AF contrast @H	-	4.5	3.6
AF contrast @V	-	-	2.3
White spot	ppm	93	90
Dark current	e-/s·㎛^{2}	1.0	1.0

Table 2. Comparison of overall pixel characteristics between conventional dual pixel and HV dual pixel with an angle of 35deg