An All Pixel PDAF CMOS Image Sensor with 0.64μm×1.28μm Photodiode Separated by Self-aligned In-pixel Deep Trench Isolation for High AF Performance

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Abstract

We present a CMOS image sensor (CIS) with phase detection auto-focus (PDAF) in all pixels. The size of photodiode (PD) is 0.64μm by 1.28μm, the smallest ever reported and two PDs compose a single pixel. Inter PD isolation was fabricated by deep trench isolation (DTI) process in order to obtain an accurate AF performance. The layout and depth of DTI was optimized in order to eliminate side effects and maximize the performance even at extremely low light condition up to 1lux. In particular the AF performance remains comparable to that of 0.70μm dual PD CIS. By using our unique technology, it seems plausible to scale further down the size of pixels in dual PD CIS without sacrificing AF performance.

Introduction

As the demand for higher resolution and faster AF function is rapidly increasing [1, 2], we have seen the emergence of 1.0μm pixel and dual PD CIS with 0.70μm by 1.4μm PDs under mass production. The dual PD CIS, a CIS equipped with PDAF in all pixels by having two fully functioning PDs in each pixel, offers the ultimate solution for AF performance [3, 4]. However the pixel pitch is inevitably $\sqrt{2}$ times bigger than the corresponding size of conventional single PD CIS. In order to meet the demands, we discuss an improved pixel structure with which we fabricated a dual PD CIS consists of 0.64μm by 1.28μm PD. The size corresponds to the pixel pitch of 0.9μm which makes our sensor the smallest dual PD CIS ever reported. In-pixel DTI was used to provide a physical separation between two PDs for high AF performance.

Dual PD CIS and Pixel Structure

The key elements for AF performance are the number of AF pixels, AF separation ratio [4] and AF sensitivity. Among them, the density of AF pixel is the most important elements [5]. Fig. 1 compares the conventional metal shield PDAF and dual PD CIS. The defective PDAF pixels from the conventional PDAF are absent in dual PD CIS where the normal pixels also act as PDAF pixels simultaneously which makes the dual PD CIS defect-free. The major obstacle of developing a smaller dual PD CIS is a separation between two PDs by which the AF sensitivity ratio is determined. Therefore we developed a process with in-pixel DTI separation which is essential for pixel scaling down.

We compare the cross-sectional pixel structure in Fig. 2. The sensor was fabricated by a conventional BSI process using DTI [6] and the self-aligned in-pixel DTI was incorporated during inter-pixel DTI process. While DTI is already prevalent in CISs for mobile applications, the in-pixel DTI forces the process quite complicated when combined with inter-pixel DTI. In order to reduce side effects that affect optical and dark performances, the size and depth of the DTIs was optimized very carefully in addition to meticulous fabrication of passivation and anti-reflection layers. Fig. 3 shows VSEM image of the inter-pixel and in-pixel DTI.

Results and Discussion

A. AF Performance. The AF performance between the conventional PDAF and dual PD CIS is compared in Fig. 4 by measuring the repeatability of the PDAF which can be regarded as an error while performing AF. One can readily observe that dual PD CIS has huge advantage over our conventional discrete PDAF sensor and the gap becomes even larger as the environment gets dimmer to 1lux. This fact proves that the dual PD CIS is an ultimate AF solution, in particular at extremely low light condition, such as indoor scenes. Fig. 4 also shows a comparison between 0.70μm and 0.64μm dual PD CIS. The AF performance is practically equivalent and the typical performance degradation by the pixel scaling down is inconspicuous. Fig. 5 shows the comparison between AF cross points at the horizontal edge of the image for RGB colors. The cross points which is a reference point for AF are not aligned with each other in junction separated dual PDs while it is perfectly aligned at the same CRA by optimized DTI separation. Therefore we find that the in-pixel DTI separation is crucial to keep the AF performance from degradation as the pixel scales down.

B. Optical Performance: Fig. 6 (a) shows the normalized QE spectrum comparison between 0.70μm and 0.64μm dual PD CISs. The normalized QE curves are similar to each other which indicate no apparent loss of optical performances that might arise from the in-pixel DTI implementation at smaller size of pixels. Fig. 6 (b) shows a comparison of angular response. While there is a slight difference of angular response beyond incident angle of 15 degree due to a smaller size of pixel, the angular response below 15 degree, which dominates the AF performance with typical F-number around 2.0, are surprisingly similar between 0.70μm and 0.64μm PDs with the help of DTI separation.

C. Additional benefits: The in-pixel DTI separation has several additional benefits. By acting as a total reflection plane, DTI increases the effective depth of silicon, therefore sensitivity of Red and Green light is gained as one can see from Fig. 7. The total sensitivity increases by almost 7% which results in the increase of SNR up to 0.3dB. Fig. 8 shows the simulation result of AF sensitivity ratio as the pixel scales down further down to 0.56μm PD. It might be extremely difficult to fabricate the photo diode of 0.56μm. However, we expect the loss of AF performance can be minimized by applying in-pixel DTI process and it will be the essential process for smaller dual PD CIS.

Conclusion

We developed a world's smallest dual PD CIS with 0.64μm by 1.28μm PD using in-pixel DTI separation. The AF performance remains excellent even after the pixel size scaled down and other performances remain competitive. In-pixel DTI technique provides the possibility of further scaled down dual PD CIS.

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References

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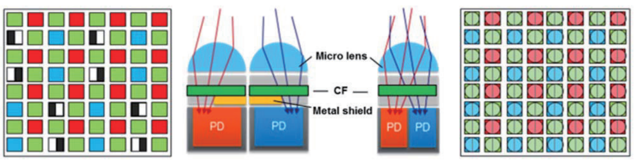
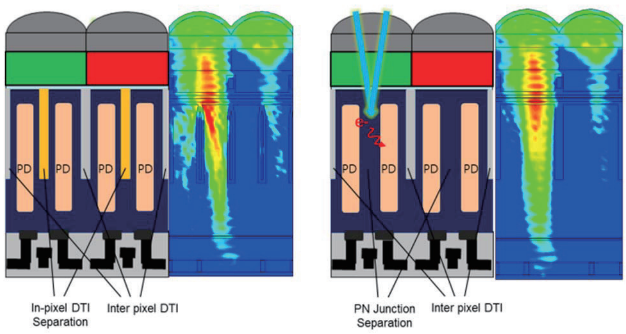


(a) (b)

Figure 1. Schematic diagram of (a) conventional discrete PDAF CIS and (b) all pixel dual PD CIS.



(a) (b)

Figure 2. Schematic diagram and optical simulation of PD to PD separation by (a) in-pixel DTI and (b) PN junction.

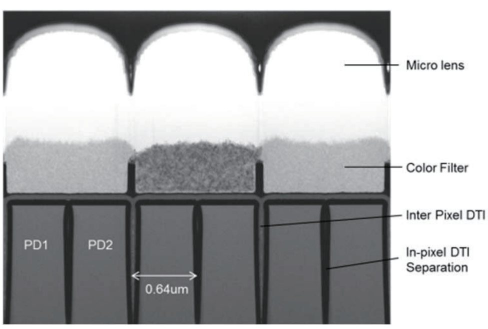


Figure 3. VSEM image of the sensor with in-pixel DTI separation.

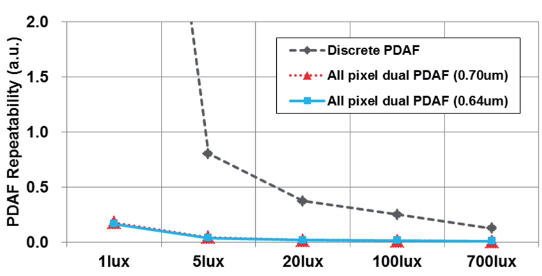
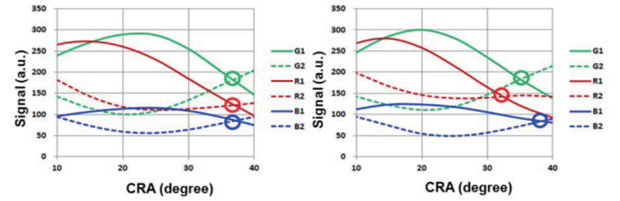
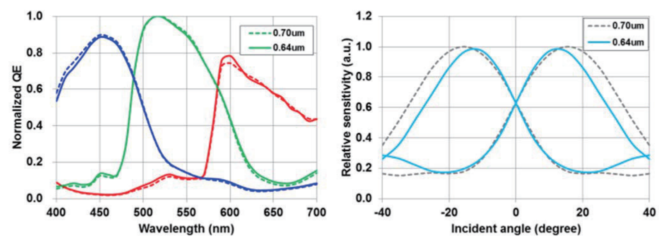


Figure 4. PDAF repeatability of conventional discrete PDAF and dual PD CIS. Lower repeatability represents better AF performance.



(a) (b)

Figure 5. AF cross point measured at horizontal edge of image with (a) in-pixel DTI separation (b) PN junction separation where solid line and dotted line represent left and right signal respectively.



(a) (b)

Figure 6. Comparison between 0.70μm and 0.64μm dual PDCIS with (a) normalized QE and (b) AF angular response.

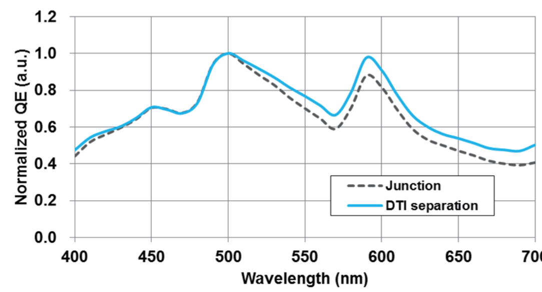


Figure 7. Comparison of QE summation. DTI separation increases the sensitivity.

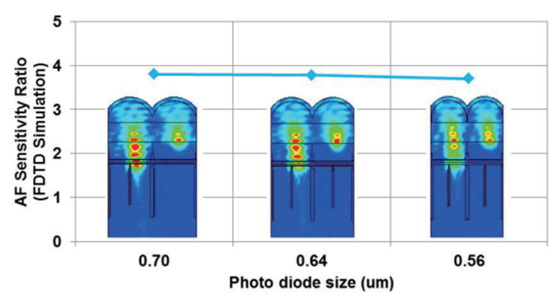


Figure 8. FDTD simulation result of AF sensitivity ratio as the pixel scales down.

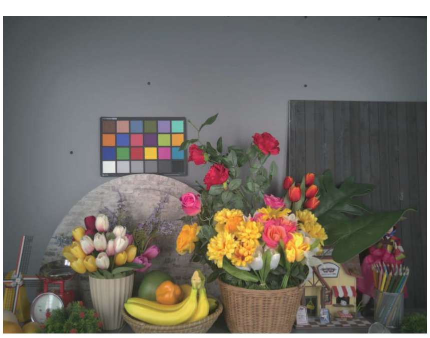


Figure 9. Sample photograph taken by our sensor (12mega pixel).