A Novel method to test and optimize the periphery crosstalk in CMOS image sensor

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Abstract For the purpose of reducing the peripheral crosstalk occur in the edge pixel, we illustrated a method to test and quantify the intensity of this crosstalk, and setup a model combining the opposite incident light and color construction. With the aid of the method and model, we conducted many experiments to analyze and compare the improvement measures, finding that the increase of pixel edge to package edge distance, sealing glass thinning and black photoresist coating around edge are all effective to reduce the peripheral crosstalk. Moreover, considering the effect and cost, the sealing glass thinning is the relatively best measure.

key words: periphery crosstalk, channel color difference, sealing glass thinning, black photoresist

Classification: Integrated circuits

1. Introduction

With the benefits in process cost and readout speed, the CMOS image sensor (CIS) has been used more and more widely. And in order to meet the requirement in high resolution, the size and interval distance of each pixel in CIS has been designed to decrease down to 1 μm, even to sub-1μm, which take the risk of increasing crosstalk.

Crosstalk means that the photon injects not only to the certain target pixel but also to the adjacent pixels, which cause the uncorrected photon-to-electron transfer. The slant on the adjacent microlens and color filter, the reflection from the peripheral metal shields, and the photon diffuse through the substrate can cause the crosstalk, as shown in Fig. 1. The crosstalk in CIS would reduce the effective resolution and blur the image, so it is of great significance to suppress crosstalk. Many researches has been conducted to reduce the crosstalk. Crosstalk is widely explained and introduced in [1,2,3], and many simulation and models [4,5,6,7] are established to analyze the crosstalk. There are also many specific optimization measures In the pixel structure, including shifted microlens [8] and zero gap microlens [9], plasmonic color filter [10,11,12,13] and lensed color filter [14], optimized light guidance structure [15,16]. As for the process development, deep p-well around photodiode [17], deep trench isolation (DTI) [18] including frontside-illumination DTI [19], backside-illumination [20] and capacitor DTI [21], air-gap guard ring [22,23,24,25], anti-reflection film coating [26] and buried shield metal [27] are all applied to optimize the crosstalk behavior respectively. PMOS structure [28] also make sense due to its limit in diffusion. Besides, linear deblurring [29] and crosstalk compensation algorithm [30] are adopted to improve image quality.

However, the crosstalk that exists in the periphery when intense light slants, can also be called periphery crosstalk, has drawn little attention. Although the periphery crosstalk occurs not often, it can make obvious bad influence on the image quality, like Fig. 2. shows. The periphery crosstalk also has the characteristic that the light color will be changed in the digital output, which making the periphery crosstalk nonnegligible.

Aimed at analyzing and decreasing the periphery crosstalk, this paper illustrates some contributions shown as follow.

1) We present a method to test the periphery crosstalk. In a certain test environment, we capture and quantify the peripheral crosstalk only using the digital output of the display platform with the aid of a statistical approach.

2) We build a model to illustrate the origin of the periphery crosstalk, which is due to the reflection of the intense slant on the sealing glass sidewall. And verify the model with the method mentioned above.

3) We applied many means to optimize the periphery crosstalk, and conducted many experiments on sensors fabricated in different conditions to analyze the improvement effects, in order to find the best condition to limit the periphery crosstalk.
2. Method

The method to test peripheral crosstalk is based on the actual appearance like abnormal shine and pink, and includes three steps.

2.1 Setup a test environment
For the purpose of quantizing and analyzing the intensity of the periphery crosstalk, a stable and invariable test environment is required to exclude the influence from other parameters like light source, camera lens, sensor position and background reflection. A test platform equipped with sensor test device, tripod, light source, is set up in a darkroom. The tripod was used to fix the test device in the same location and enable the device rotation to find the worst periphery crosstalk phenomenon.

2.2 Acquire the worst peripheral crosstalk image
Use the capture software to acquire the image when worst periphery crosstalk occurs. In order to achieve an accurate capture, a statistical approach, as equation (1) is applied in the edge middle area of the full image, which is similar as the calculation to get fixed pattern noise. A large $\sigma_{PC}$ in equation (1) means a large nonuniformity and abnormal shine in the interest area, which is caused by the periphery crosstalk. So the value represent the intensity of the periphery crosstalk. Rotate the tripod platform and stop when find the largest $\sigma_{PC}$, then capture the image to acquire the worst periphery crosstalk behavior.

$$\sigma_{PC} = \sqrt{\frac{1}{XY} \sum_{x=0}^{X-1} \sum_{y=0}^{Y-1} (\bar{p}(x,y) - \bar{p})^2}$$  \hspace{1cm} (1)

2.3 Calculation on brightness and color difference
Calculate the brightness and color difference from the periphery crosstalk image. We calculate the column average brightness in the interest area and set threshold to determine the depth in pixel numbers influenced by the periphery crosstalk. As is shown in Fig.3. The x-axis means the column position coordinates from the edge to the center, and the y-axis represents the brightness. The x-coordinate of knee point, which is defined as the intersection of extension lines of edge columns curve and center columns curve, represents the pixel depth influenced by the periphery crosstalk. Moreover, to match the brightness change with behavior in visual observation and contain the color offset features, another calculation based on the difference in adjacent different channel brightness output, which we called channel color difference, as Fig.4. and Fig.5. show. This difference, especially the B+R-G color difference, takes advantage in defining the pixel depth influenced and matching the quantization result with visual observation. So we choose the B+R-G color difference as the quantization value to reflect the intensity of the peripheral crosstalk.

Fig. 1. Sketch to show the different cause in crosstalk.

Fig. 2. The image with peripheral crosstalk phenomenon

Fig. 3. Column average brightness on edge pixels
3. Model establishment and verification

Considering the color difference in the periphery crosstalk, which means the abnormal pink in the influenced area, we proposed a model that the reflection light transmit through the adjacent pixel color filter first then through the certain target pixel. Due to the different transmittance of different color filter, the uniform light injected to the pixels with different color filter would generate different amount electrons in the photodiodes, leading to the diversity in color reconstruction algorithm of digital output based on the photodiode response difference. In other words, to correctly display the color of the real scene, the parameters of the color reconstruction algorithm need to be adjusted according to the type of the color filter. When the light injected in the opposite direction, which is actually the reflection from the sealing glass sidewall, the light that punch through the wrong color filter will generate a special intensity of electrons compared to the normal one, leading to an abnormal pink phenomenon after color construction. Briefly speaking, the mismatch between the special photon response and color reconstruction algorithm result in the abnormal pink phenomenon. Moreover, in order to satisfy the limit of camera chief array angle, the color filter located in the periphery area has a shift from the center, which enhance influence of the reflection from the opposite direction, as shown in Fig.6.

In order to verify this model, we conducted test by changing the active area of pixel arrays and activating all the eight columns dummy pixels on one side (left or right, we choose left in our experiment), which has two whole columns only filled red color filters. In the theory of our model, the abnormal pink phenomenon is derived from the mismatch between the photon response and color reconstruction algorithm. So when the difference between the color filter is eliminated, the display color difference is only depended on the location in pixel array defined by color construction algorithm. And this behavior in the specific column is quietly different from the periphery crosstalk above. The test result after the activation on dummy pixels is shown in Fig.7 and Fig.8. From the figure we can see, as we expected, the value of column color difference in the left two column with only red filter are quiet smaller than other value in the periphery crosstalk area. The value of column color difference in the second column on the left is even negative due to the color construction algorithm in the second column. The test result proved the correctness of our model.
4. Experiment plan and results

Many improvement plan was analyzed in order to suppress the peripheral crosstalk, and they are shown as follow.

4.1 Improvement on the camera lens
There are many reflection and refraction in the camera lens group equipped above sensors, and the defects and deviation in lens group might lead to the opposite shift of incident light. By using the camera lens with low defects, the peripheral crosstalk would be suppressed. However, due to the difficulty to observe and check the property in camera lens group before actual use, it is not a good solution to eliminate the peripheral crosstalk in advance.

4.2 Increase in the distance between the pixel array edge and the package edge
Considering that much opposite injected slant is from the reflection of package edge, the increase of the distance mentioned above could decrease the affected pixel area, then reduce the influence of peripheral crosstalk. But this method need extra chip area on wafer to fit the chip scale package (CSP), which means a cost increase.

4.3 Sealing glass thinning
The sealing glass play the leading role in the reflection of packaging sidewall. With the method of thinning the sealing glass, the area of sidewall reflector was reduced, so as to the reflected light intensity from the package sidewall, as Fig.9 shows, and the peripheral crosstalk was suppressed consequently.

4.4 Black photoresist on sealing glass edge
As is shown in Fig.10, in order to decrease the light intensity injected to the glass side wall, a black photoresist coating around the glass edge was applied.

The photon injected on the black photoresist was absorbed, which decreased the light intensity and restrict the reflection range of the glass sidewall.

In order to analyze the improvement introduced in section 4.2, 4.3 and 4.4, we conducted many experiments. The sensors used in experiments were in different condition, and the test method was as described in the second part. Here are the results.

For different edge-to-edge distance, considering the different light sensitivity in different type of sensor, we choose the same type chip and get the different edge-to-edge distance by rotating the sensor due to the sensor internal structure. And three type of sensors were under test in order to exclude contingency and correctly analyze the influence on the distance between sensor edge and package edge. The results is shown in Fig.11. a), b) and c), and the different distance data is shown in Table.1. From these figures we can know that increasing edge-to-edge distance was surely suppress the peripheral crosstalk. And the edge-to-edge distance that could completely eliminate the peripheral crosstalk varied in different type, which cause a little difficulty in design.
Fig. 11. Channel color difference in different edge-to-edge distance

Table 1 Edge-to-Edge distance in different types and directions

| Edge difference (um) | Type1 | Type2 | Type3 |
|----------------------|-------|-------|-------|
| left                 | 320   | 321   | 403.3 |
| right                | 320   | 321   | 320.5 |
| bottom               | 335   | 434   | 276.5 |
| top                  | 867   | 914   | 698.9 |

As for methods introduced in section 4.3 and 4.4, both methods aimed at sealing glass to decrease the intensity of light injected on the package sidewall. To evaluate the effect of the methods, a thinning sealing glass, which had a thickness of 300um, and a 400um sealing glass with black photoresist around the edge, were applied on the packaging process in two different type of sensor to be compared with the effect in basic 400um thickness sealing glass. Figure a) and b) showed the result, and the figure illustrated that both thinning sealing glass and black photoresist around edge could obviously suppress the peripheral crosstalk. Besides, the thinning sealing glass method had better effect on reducing peripheral crosstalk than black photoresist around edge method. The reason could be that the block on the edge is not wide enough to effectively decrease the abnormal slant. A wider black photoresist could deeply reduce the peripheral crosstalk, but would take a risk of loss in normal incident light intensity and decreased sensitivity in edge pixels.

Fig. 12. Channel color difference in different sealing glass condition

5. Conclusion

We design a method to test and quantify the peripheral crosstalk, which is caused by the abnormal slant on the edge pixels, and setup a model combining opposite oblique light and color reconstruction to explain the abnormal pink phenomenon with specific experiments to verify it. Moreover, improvement plans were analyzed to optimize the peripheral crosstalk and many experiments were conducted based on these plans. The results showed that the improvements including increase of package edge to pixel array edge distance, thinning sealing glass, and black photoresist around the edge can all suppress the peripheral crosstalk, and the latter two take benefit from the simple process and low cost, and have potential for wide application.

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References

[1] K. Hirakawa, "Cross-talk explained," IEEE International Conference on Image Processing, (2008) 677 (DOI:
[2] I. Scherback, et al, "A comprehensive CMOS APS crosstalk study: photoresponse model, technology, and design trends," IEEE Transactions on Electron Devices, 51 (2004) 2033, (DOI: 10.1109/TED.2004.839742)

[3] Gennadiy Agranov, et al, “Crosstalk and Sub-Pixel Distribution of Sensitivity in Color CMOS Image Sensor,” Int. Image Sensor Workshop, (2001)

[4] C. Koo et al, “Improvement of crosstalk on 5M CMOS image sensor with 1.7x1.7 um2 pixels,” Proc. SPIE 6471, Ultrafast Phenomena in Semiconductors and Nanostructure Materials XI and Semiconductor Photodetectors IV, 647115 (2007), (DOI: 10.1117/12.701705)

[5] I. Djite, et al, “Theoretical Models of Modulation Transfer Function, Quantum Efficiency, and Crosstalk for CCD and CMOS Image Sensors,” IEEE Transactions on Electron Devices, 59 (2012) 729, (DOI: 10.1109/TED.2011.2176493)

[6] R. Gow, et al, “A Comprehensive Tool for Modeling CMOS Image-Sensor-Noise Performance,” IEEE Transactions on Electron Devices, 54 (2007) 1321, (DOI: 10.1109/TED.2007.896718)

[7] H. Mutoh, “3-D optical and electrical simulation for CMOS image sensors,” IEEE Transactions on Electron Devices, 50 (2003) 19, (DOI: 10.1109/TED.2002.806965)

[8] G. Agranov et al, “Crosstalk and microlens study in a color CMOS image sensor,” IEEE Transactions on Electron Devices, 50 (2003) 4, (DOI: 10.1109/TED.2002.806473)

[9] X. Jin, et al, “Sensitivity and crosstalk study of the zero gap microlens used in 3.2 µm active pixel image sensors,” Microelectronic Engineering, 87 (2010) 631, (DOI: 10.1016/j.mee.2009.08.028)

[10] Q. Chen, et al, “A CMOS Image Sensor Integrated with Plasmonic Colour Filters,” Plasmonics, 7 (2012) 695, (DOI: 10.1007/s11468-012-9360-6)

[11] S. Yokogawa, et al, “Plasmonic Color Filters for CMOS Image Sensor Applications,” Nano Lett., 8 (2012) 4349-4354, (DOI: 10.1021/nl301101z)

[12] Y. Yu, et al, “Spatial optical crosstalk in CMOS image sensors integrated with plasmonic color filters,” Optics Express, 23 (2015) 21994, (DOI: 10.1364/OE.23.021994)

[13] Q. Chen, et al., “CMOS Photodetectors Integrated With Plasmonic Color Filters,” IEEE Photonics Technology Letters, 24 (2012) 197, (DOI: 10.1109/LPT.2011.2176333)

[14] H. Kim, et al, “Development of Lensed Color Filter technology for higher SNR and lower crosstalk CMOS image sensor,” Int. Image Sensor Workshop, (2013)

[15] T. Hsu, et al, “Light guide for pixel crosstalk improvement in deep submicron CMOS image sensor,” IEEE Device Letters, 25 (2004) 22, (DOI: 10.1109/LED.2003.821597)

[16] C. Christian et al, “Optical confinement methods for continued scaling of CMOS image sensor pixels,” Optics Express, 16, (2008) 20457, (DOI: 10.1364/OE.16.020457)

[17] M. Furumiya, et al, “High-sensitivity and no-crosstalk pixel technology for embedded CMOS image sensor,” IEEE Transactions on Electron Devices, 48 (2001) 2221, (DOI: 10.1109/16.954458)

[18] B. Park, et al, “Deep Trench Isolation for Crosstalk Suppression in Active Pixel Sensors with 1.7 µm Pixel Pitch,” Japanese Journal of Applied Physics, 46 (2007) 2454, (DOI: 10.1143/JJAP.46.2454)

[19] J. Ahn, et al., “7.1 A 1/4-inch 8Mpixel CMOS image sensor with 3D backside-illuminated 1.12µm pixel with front-side deep-trench isolation and vertical transfer gate,” IEEE ISSCC Digest of Technical Papers (ISSCC), (2014) 124, (DOI: 10.1109/ISSCC.2014.6757365)

[20] Y. Kitamura, et al, "Suppression of crosstalk by using backside deep trench isolation for 1.12µm backside illuminated CMOS image sensor," International Electron Devices Meeting, (2012) 24.2.1 (DOI: 10.1109/IEDM.2012.6479093)

[21] N. Ahmed, et al, “MOS Capacitor Deep Trench Isolation for CMOS image sensors,” IEEE International Electron Devices Meeting, (2014) 4.1.1, (DOI: 10.1109/IEDM.2014.7046979)

[22] D. Youn, et al, “Air-gap guard ring for pixel sensitivity and crosstalk improvement in deep sub-micron CMOS image sensor,” IEEE International Electron Devices Meeting (2003) 16.5.1, (DOI: 10.1109/IEDM.2003.1269308)

[23] T. Hsu, et al, “A high-efficiency CMOS image sensor with air gap in situ MicroLens (AGML) fabricated by 0.18-µm CMOS technology,” IEEE Electron Device Letters, 26 (2005) 634, (DOI: 10.1109/LED.2005.854373).

[24] C. Tseng, et al, “Crosstalk improvement technology applicable to 0.14 um CMOS image sensor,” IEDM Technical Digest, (2004) 997, (DOI: 10.1109/IEDM.2004.1419356)

[25] T. Hsu, et al, “Dramatic reduction of optical crosstalk in deep-submicrometer CMOS imager with air gap guard ring,” IEEE Electron Device Letters, 25 (2004) 375 (DOI: 10.1109/LED.2004.828995)

[26] S. Wuu, et al, “A leading-edge 0.9µm pixel CMOS image sensor technology with backside illumination: Future challenges for pixel scaling,” International Electron Devices Meeting, (2010) 14.1.1, (DOI: 10.1109/IEDM.2010.5703358)

[27] T. Shinohara, et al, “Three-dimensional structures for high saturation signals and crosstalk suppression in 1.20 µm pixel back-illuminated CMOS image sensor,” IEEE International Electron Devices Meeting, (2013) 27.4.1, (DOI: 10.1109/IEDM.2013.6724704)

[28] E. Stevens, et al., “Low-Crosstalk and Low-Dark-Current CMOS Image-Sensor Technology Using a Hole-Based Detector,” IEEE ISSCC Digest of Technical Papers, (2008) 60, (DOI: 10.1109/ISSCC.2008.4523556)

[29] J. Lee, et al, “Characterization and deburring of lateral crosstalk in CMOS image sensors,” IEEE Transactions on Electron Devices, 50 (2003) 2361, (DOI: 10.1109/TED.2003.819246)

[30] W. Li, et al, “CMOS sensor cross-talk compensation for digital cameras,” IEEE Transactions on Consumer Electronics, 48 (2002) 292, (DOI: 10.1109/TCE.2002.1010134)