Crosstalk and Sub-Pixel Distribution of Sensitivity in Color CMOS Image Sensor.

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Abstract

The paper describes results of micro-lens (μ-lens) scan experiments and crosstalk investigations in color CMOS image sensor with active pixel structure [1]. The investigation of optical and electrical cross-talk was made on 7.8 and 5.6 μm pixels by using samples with continuos shift of color filter (CF) and μ-lens across the array. As a result of this investigation the distribution of sensitivity inside pixel has been determined. By using minimum crosstalk criteria the optimum parameters of μ-lens manufacturing process and optimum position of μ-lens was determined. The paper presents color maps of pixel sensitivity and crosstalk criteria as well as snapshots illustrating sensitivity distribution and collection area. The paper presents spectral characteristics measured at different f/# as well. The quantitative analysis of spectral responses allowed determining the contribution of each component to the overall crosstalk.

1. Introduction

Crosstalk in an image sensor array degrades the spatial resolution, reduces overall sensitivity, makes poor color separation, and leads to additional noise in the image after color correction procedure. We will consider crosstalk in CMOS image sensors as consisting of three main components:

- Spectral crosstalk. This component is due to imperfect color filters passing through some amount of unwanted light of other colors.
- Optical spatial crosstalk. The main reason for this component of crosstalk is that color filters are located at some distance from the pixel surface due to metal and insulation layers. The light coming at angles other than orthogonal passes through a filter and can partially be absorbed by the adjacent pixel rather than one below. Depending on the f/# of the lens, this portion of the light absorbed by neighboring pixel can vary significantly and can be big enough for low f/#. μ-Lenses located on the top of color filters reduce this component of crosstalk significantly when appropriate form of μ-lenses and optimum position of them are chosen.
- Electrical crosstalk. This component of cross-talk results from photo-generated carriers having the possibility to move to neighboring charge accumulation sites. In comparison to the previous two components, this crosstalk occurs in both monochrome and color image sensors. The quantity of the carriers that can be accumulated by the neighboring pixel and the corresponding crosstalk strongly depends on the pixel structure, collection area, and distribution of sensitivity inside a pixel.

To optimize the position and manufacturing process of μ-lenses, we developed special samples of photosensitive arrays having continuous 2-dimential shift of μ-lenses/CF across the array. Section 2 describes the details and results of these experiments. Section 3 presents spectral responses of sensors with 7.8 and 5.6 μm pixel size after optimizing of μ-lenses. The analyses of spectral characteristics measured at different f/# allowed us to determine the contribution of each component to the overall crosstalk.

2. μ-Lens scan experiment

The center of μ-lens is always aligned together with the center of CF (Bayer pattern: R, G1, G2, B). The edges of μ-lens and CF are aligned with the vertical/horizontal polysilicon and metal lines, so that the leakage light will be blocked. However, there are still certain range that the center of μ-lens can be moved around to find the optimal position for the best sensor performance in sensitivity and crosstalk. Typically, the position can be decided by selecting the best result from several sub-arrays which have different positions proposed by estimation following theoretical or empirical rules. But this method can not find the optimal position.

The excellent way to find the optimal position for the center of μ-lens/CF is the following. The pitch of the μ-lens/CF is made a little larger or smaller than the pitch of the pixel. For example, if the pixel pitch is 7.8 μm, the pitch of μ-lens and CF can be 7.82 μm. In this case the center of μ-lens will move 0.02 μm for each row and column. For the CIF format sensor, the total difference between pixel array and μ-lens array will be 7.04 μm (H) and 5.76 μm (V). That will cover most of the sensitive area of the pixel. Based on the results for the crosstalk and sensitivity, the optimal position can be calculated from the coordinates of the best pixel.

We illuminated above described array by uniform light with spectral range corresponding to spectral response of different color's pixels. Distribution of sensitivity inside pixel as well as crosstalk to neighborhood pixels can be clearly seen from the images received under such kind of illumination. As an example, Figure 1 presents the "color plane separated" snapshot received from the array under green light illumination (lmax=550 nm, FWHM=40 nm). Keeping in mind that different pixels in the array correspond to different position of μ-lens in relation to the pixel structure, the image from G1 or G2 pixels (2^{nd} and 3^{rd} quarters) corresponds to the distribution of sensitivity in the pixel. On the other hand images from R and B pixels (1^{st} and 4^{th} quarters) represent crosstalk between pixels. We decided to optimize μ-lens/CF from crosstalk consideration because the extra crosstalk drastically reduce a quality of color image and increase a noise on the image after color correction procedure. We tried to find the position and process parameters of μ-lenses corresponding to the minimum of crosstalk rather than maximum of sensitivity.

All investigations were made on 7.8 and 5.6-μm pixels utilizing 0.35 μm UMC CMOS process. Figures 2 and 3 present 3-dimentional plots and color maps of crosstalk criteria and sensitivity vs. μ-lens position for 256×256 array with pixel size 7.8 μm. The coordinates of the pixel with minimum crosstalk criteria give us the optimal position of μ-lens and CF. The value of crosstalk criteria in the optimal position can be used for optimization of process parameters affecting on the curvature of μ-lenses (melt temperature and thickness). As can be seen from the plots:

- distribution of crosstalk criteria differs from distribution of sensitivity;
- crosstalk criteria allows to locate optimal position of μ-lenses with high accuracy;
- position of μ-lens with minimum crosstalk is closed to the position providing maximum of sensitivity, but doesn't match it.

The experiment described above allowed us to find the optimal position of μ-lens for the case, when the principle ray of accident light is normal to the photosensitive array. In some applications when output pupil and focal length are small enough in comparing to the array, one can be experiencing in the "non-telecentric" problems. The principal ray of the light comes to the periphery of the sensor at some angle. The angle increases with increasing of distance from the center of the array. That can cause a non-uniformity of signals and increasing of crosstalk followed by color shift and white balance distortion in the image. The problem can be fixed by adjusting of μ-lens position to the angle of non-telecentric light. Optimal position of μ-lens at every angle can be determined by using the same technique and illuminating the array by plane wave light coming on the sensor at this angle. By using dependence of optimal position vs. angle of non-telecentric light the array can be optimized to the specified lens.

As another very helpful result of these experiments we were able to observe the distribution of sensitivity inside pixel as well as regions shadowed by pixel structure components. That allowed us to determine the collection area for generated carriers, and to estimate the pixel fill factor. Figure 4 shows the collection area of generated carriers for 7.8 μm and 5.6 μm pixel. The value of effective fill factor estimated from distribution of sensitivity is 60 % for 7.8 μm pixel and 55 % for 5.6 μm pixel.

3. Spectral response and color crosstalk components

To investigate the contribution of each component to the overall crosstalk we measured spectral responses at different f/# of incoming light [2]. Sensors after optimization of μ-lenses have been used for these experiments. Comparison with transmission of color filters allowed us to separate optical spatial and electrical components of crosstalk, and to estimate their contribution to the overall crosstalk. For the quantitative analysis we used a simple model calculating overlaps between spectral responses of different color pixels (see Figure 5). It good correlates with color correction matrix used in color correction procedure.

Spectral responses at different f/# for CIF sensor with 7.8 μm pixel size and for VGA sensor with 5.6 μm pixel size are shown in the Figure 6. Color overlaps are presented in the Figure 7. Contributions of optical and electrical components to the overall crosstalk are:

- 34 % and 35 % for 7.8 μm pixel;
- 31 % and 33 % for 5.6 μm pixel.

Reducing of epi-layer thickness and optimization of both CMOS process and pixel design are required for electrical crosstalk improvement.

Decreasing of metal/insulation layers thickness is helpful for spatial optical crosstalk reduction.

4. Conclusion

Optimization of μ-lenses can significantly reduce both electrical and optical spatial crosstalk in CMOS image sensors. The excellent way to do such optimization is using of special arrays with continuous shift of μ-lenses. While different kind of illumination and minimum crosstalk criteria are used, this method allows:

- to find the optimal position of μ-lenses/CF for applications with telecentric imaging lens, and to determine the optimal parameters of μ-lens manufacturing process;
- to implement the variable position of μ-lenses/CF for applications with non-telecentric imaging lens, when μ-lens/CF position varies depending on the coordinate of the pixel and parameters of the imaging lens.
- to investigate the pixel structure and collection area of generated carriers.

Finally, after optimization of μ-lenses/CF, the contribution of optical spatial and electrical components to the overall crosstalk was estimated as 34 % and 35 % for pixel 7.8 μm correspondingly. For pixel 5.6 μm their contributions are 31 % and 33 % correspondingly.

Acknowledgment

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References

[1] E.R .Fossum, Trans. ED, ED 44, 1997, pp.1689-1698.

[2] G. Waligorski et al. IEEE Workshop on CCD and Advanced Image Sensors, 1999, pp.239-241.

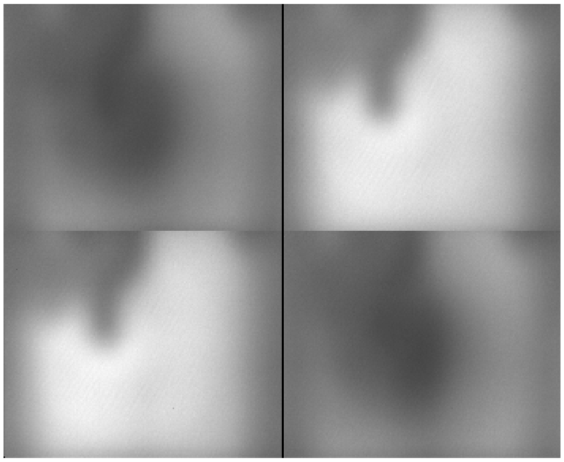


Figure 1. Image under green light illumination. "Color separated" view. G1 and G2 pixels – 2nd and 3rd quarters, R and B pixels – 1st and 4th quarters.

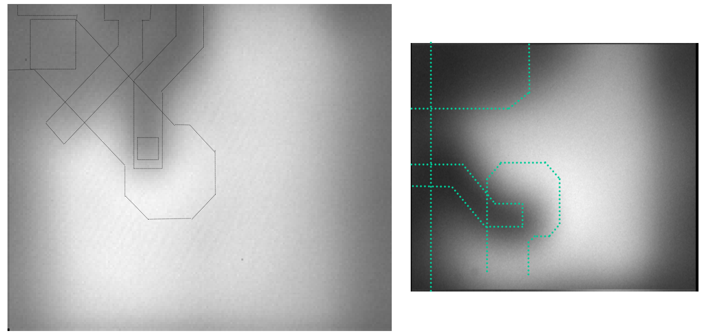


Figure 4. Collection area of photogenerated carriers for 7.8 μm and 5.6 μm photodiode pixel.

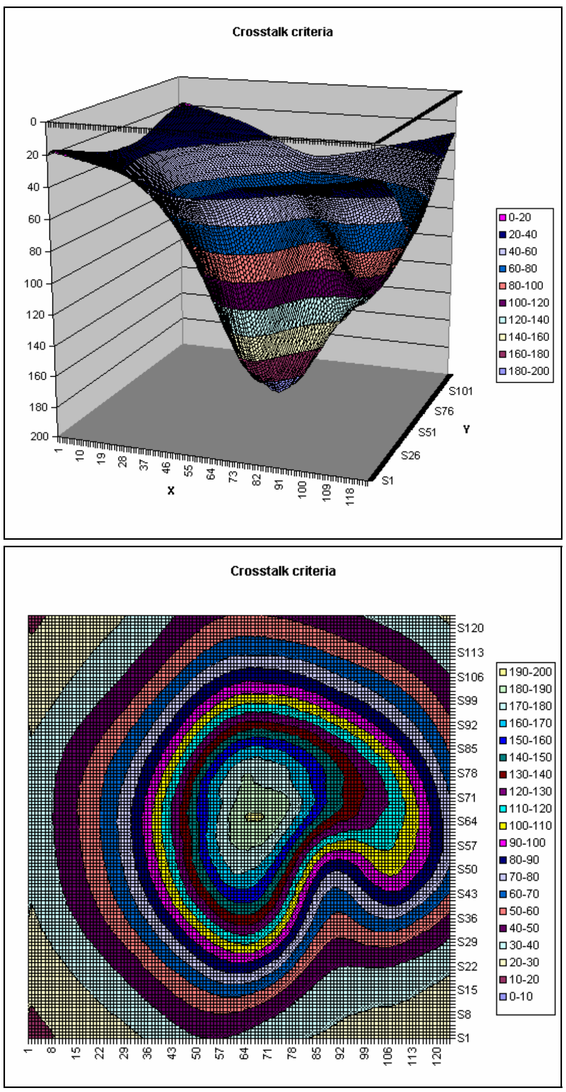


Figure 2. Crosstalk criteria vs. μ-lens position for 7.8 μm photodiode pixel. (central part of the pixel –5.1*5.1 μm) Maximum value corresponds to the minimum of crosstalk

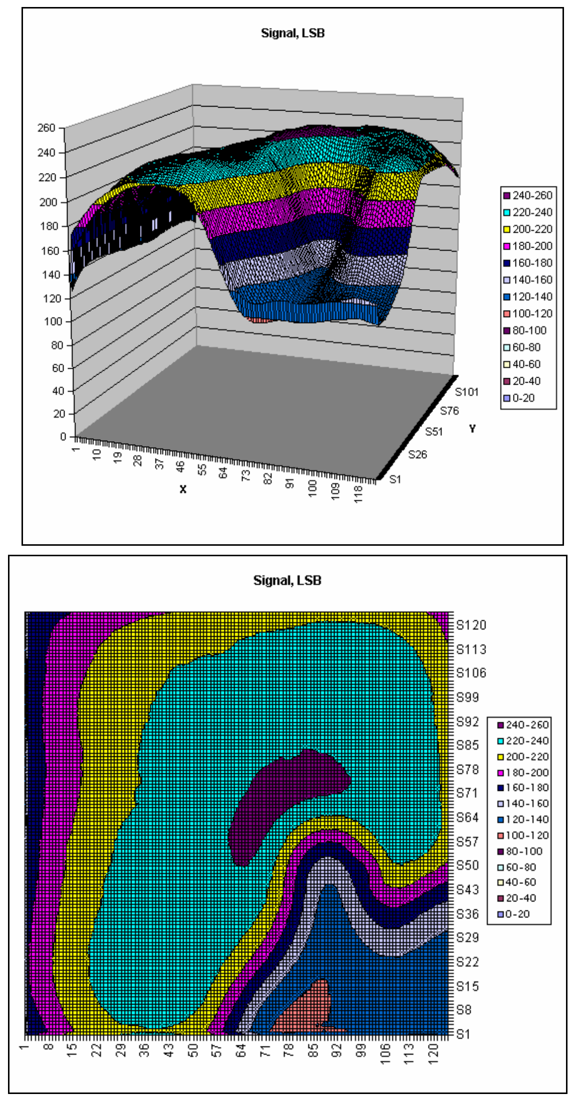
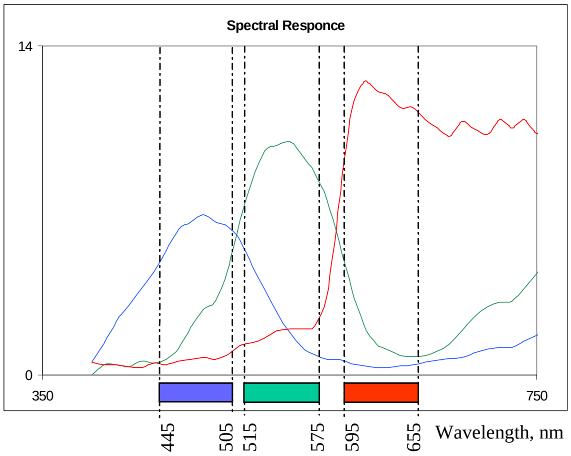


Figure 3. Sub-pixel distribution of sensitivity for 7.8 μm photodiode pixel (central part of the pixel –5.1*5.1 μm)



$$\int_{515}^{575} R_{blue}\cdot d\lambda \Big/ \int_{515}^{575} R_{green}\cdot d\lambda$$

$$\int_{595}^{655} R_{green}\cdot d\lambda \Big/ \int_{595}^{655} R_{red}\cdot d\lambda$$

$$\int_{445}^{505} R_{green}\cdot d\lambda \Big/ \int_{445}^{505} R_{blue}\cdot d\lambda$$

$$\int_{595}^{655} R_{blue}\cdot d\lambda \Big/ \int_{595}^{655} R_{red}\cdot d\lambda$$

Color cross-talk (%)	/ Blue 445-505 nm	/ Green 515-575 nm	/ Red 595-655 nm
Blue		39	13
Green	47		32
Red	18	27	

$$\int_{445}^{505} R_{red}\cdot d\lambda \Big/ \int_{445}^{505} R_{blue}\cdot d\lambda$$

$$\int_{515}^{575} R_{red}\cdot d\lambda \Big/ \int_{515}^{575} R_{green}\cdot d\lambda$$

Figure 5. Basic formulas for quantitative evaluation of color crosstalk

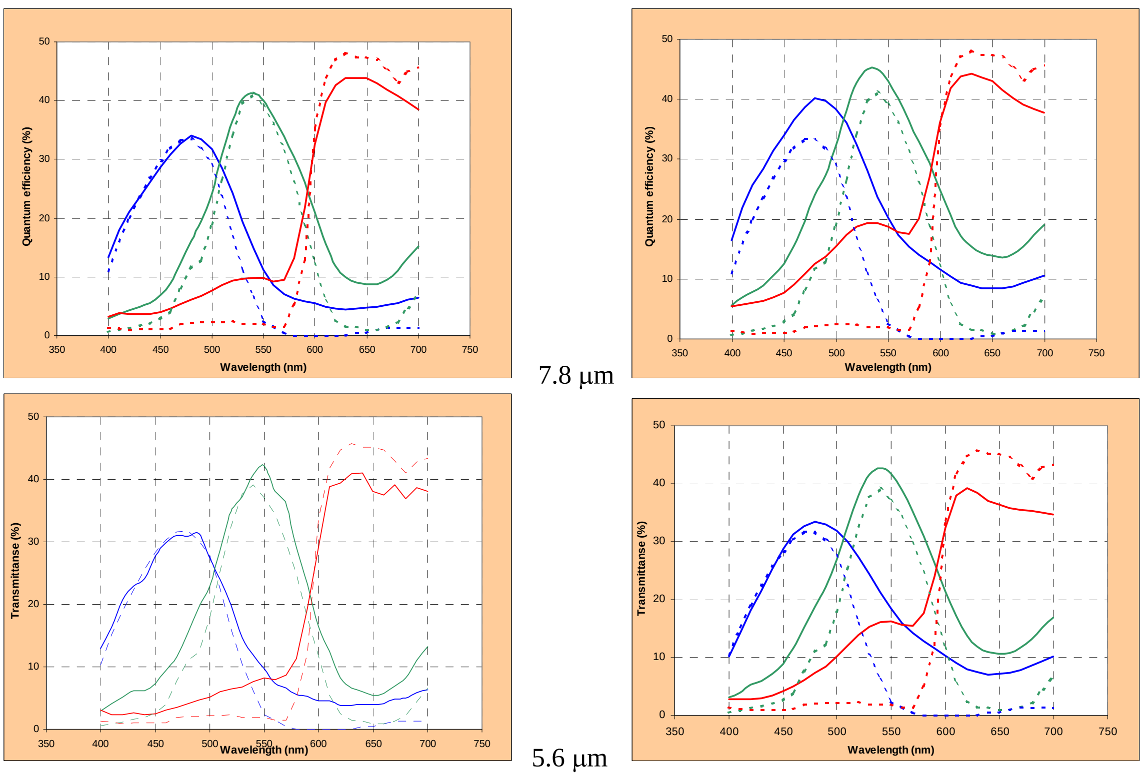


Figure 6. Spectral response of 7.8 µm (top) and 5.6 µm (bottom) pixels at different f#. Dash lines – color filters (convolution with monochrome response). Solid lines – sensor at f/5 (left) and f/1 (right)

CF	/Blue	/Green	/Red
Blue		17	0
Green	32		9
Red	19	5	

f/5	/Blue	/Green	/Red
Blue		37	12
Green	46		28
Red	20	25	

f/1	/Blue	/Green	/Red
Blue		54	23
Green	58		38
Red	31	44	

CF	/Blue	/Green	/Red
Blue		17	0
Green	32		9
Red	19	5	

f/5	/Blue	/Green	/Red
Blue		30	11
Green	50		29
Red	20	20	

f/1	/Blue	/Green	/Red
Blue		51	22
Green	55		42
Red	22	39	

Figure 7. Color's overlap illustraiting crosstalk for 7.8 µm (top) and 5.6 µm (bottom) pixel. Left – color filters (spectral crosstalk). Meadle – Sensors at f/5 (spectral + electrical crosstalk). Right – Sensors at f/1 (spectral + electrical + spatial optical crosstalk).