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Abstract

In this work, a unified model, based on a thorough analysis of experimental data, is developed for the overall Modulation Transfer Function (MTF) estimation for CMOS image sensors. The model covers the physical diffusion effect together with the impact of the pixel active area geometrical shape. Comparison of both, our predicted results and the MTF calculated from the Point Spread Function (PSF) measurements of an actual pixel array gives excellent agreement. The results indicate that for any potential active area shape, a reliable estimate of image performance is possible, so the trade off between the conflicting requirements, such as signal-to-noise ratio (SNR) and MTF could be compared per each pixel design.

I. Introduction

In CMOS Active Pixel Sensor (APS) arrays, the pixel area is constructed of two functional parts (see for example, Fig. 1). The first part, that has a certain geometrical shape, is the sensing element itself, which usually consists of a photodiode or a photogate [1, 2, 3, 4, 5, 6] in a silicon substrate. The second part is the control circuitry required for readout of the acquired charge. The ratio between the active area and the total pixel area is referred as the Fill Factor (FF), which in APS is less than 100 percent (in contrast to CCDs where the FF can approach 100%). Since the fill factor influences the signal and SNR, it is preferred to keep it as high as possible. Fig. 1 describes an L-shaped active area pixel, which is most commonly used.

Imagers lose resolution as the result of the photocarrier diffusion process within the substrate. Solid-state imager MTF has been an ongoing subject of research [7, 8, 9, 10, 11, 12, 13, 14]. This current work is a continuation of the formerly presented analytical analysis, which shows that the active area shape contributes significantly to the behavior of the overall MTF of a CMOS Active Pixel Sensor (APS) [15]. Here we present a more comprehensive model, which takes into account the effect of the minority carrier diffusion together with

the effect of the pixel active area shape. This is especially important for APS design, where the fill factor is always less than 100%.

II. Experimental Details and The Unified Model Description

Our model is based on the measurements of sensitivity variation on a subpixel scale, for the various APSs. These measurements were reported in [15]. The resulting PSF as a function of the spot position provides a map of the pixel response (see Fig. 2). The value at each point represents the electrical outcome of the three-dimensional photocarrier diffusion from this point to the depletion. Thus, the 2D signal map plane we get in the experiment can be generally considered as a “diffusion map” of the 3D diffusion in the device. Based on the solution of the steady-state one-dimensional transport equation of excess minority carriers in the semiconductor, we fit the PSF data acquired from actual pixel scanning. Note that without the generality limitation, in this work we demonstrate, as an example, only the results for an L-shaped active area pixel (see Fig. 2). The model used for fitting, is

$$y = y_0 + \frac{A}{W\sqrt{\pi/2}} \exp\left[-\frac{2(x-x_c)^2}{W^2} - 1\right] \quad (1)$$

where x_c - is the center, W - the width, A - the area. From the generalization of the fitting results for all pixels, we derive the common functional dependence, with common parameters that describe the diffusion process in the array and extract the characteristic diffusion length - L_{eff} (see Fig. 3).

$$W = 2\sqrt{2D_n\tau}, \Rightarrow L_{eff} = \sqrt{D_n\tau} \quad (2)$$

A unified numerical model including both the effect of photocarrier diffusion within the substrate and the effect of the pixel sampling aperture shape and size is worked out, based on the analysis of the experimental data and the actual layout of the pixel array. The model empirically produces the PSF of the pixel. We use the extracted parameters for the

creation of a 2D symmetrical kernel matrix (there is no diffusion direction priority within the uniform silicon substrate). The convolution of this matrix with the one representing the pure geometrical active area shape produces the desired unified PSF model. The dimensions of the kernel matrix are important. Fig. 4 explains the choice of the kernel matrix dimensions. It could be seen that at the points corresponding to the kernel dimension, i.e. points 7~9, the mean and standard deviation functions obtained from the comparison between modeled and actually scanned PSF reach an extremum. These matrix dimensions (both) equal the physical pixel size in our representation. Thus, we conclude that the diffusion primarily occurs within the pixel, i.e., $L_{eff} \approx 24.4 \mu m$. Note that the parameter value obtained here directly from our model is the same as the one previously obtained analytically by fitting.

III. Results and Discussions

To compare the PSF and the MTF of a practical square, rectangular and an “L” active area shaped pixels, two-dimensional MTF of these structures for a specific design were calculated, simulated, and compared with the measurements. The measurements currently used for the analysis are from an HP 1.2 μ process chip as described in [15]. We calculated the PSF map for the proposed unified model and present here the comparison results: Fig. 5a represents the difference between the actually measured and pure geometrical PSFs for a given pixel, while Fig. 5b is the comparison between the actually measured PSF and the PSF obtained from our unified model, with the diffusion effects. Figure 6 shows two MTF plots, calculated from the PSF via the 2D Fourier transform: the left one represents the measured, while the right one represents the modeled PSF. From this experimental comparison, it seems that our model gives an excellent estimation for the CMOS APS imager. The comparison of the extracted diffusion length values, presented in Table 1, gives a confirmation for the universality of the described method. The same model can be used for any process design.

As was already shown, the active area shape contributes significantly to the behavior of the overall MTF [15]. However, there is essential difference between the actual and geometrical MTFs (up to 20% in some cases). Our unified model gives better agreement between the modeled PSF/MTF for a certain active area shape, and the actual measurements. One still can see (Fig. 5)

some difference between the PSF matrices, the one actually scanned, and the one modeled (~4% in a few pixels). However, these differences are confined by the background level, and in average are calculated to be less than 1%. Those distinctions occur due to other factors in the design and process, such as optical crosstalk [16]. Optical crosstalk results from the interference in the oxide level, especially between metal lines, and had an effect on the overall MTF [7,8,9]. This would have more effect as the pixel size scales in multi-level metal processes [17].

Table 1
Parameters Comparison

Diffusion Length	Obtained Value
Extracted by function fit	$\sim 24 \mu m$
Extracted from kernel optimization	$\sim 24.4 \mu m$
Calculated: $L_{eff} = \sqrt{D_n \tau}$, ($D_n = 37.5 \text{ cm}^2/\text{sec}$ (300K) [2], $\tau = 20 \text{ p sec}$ [5])	$\sim 27 \mu m$

IV. Summary

In this work, analysis of experimental data of subpixel scanning sensitivity maps for pixel arrays with a different active area shape was performed. Based on this analysis a unified model for estimating the MTF of a CMOS-APS solid-state image sensor was developed. This model includes the effects of the photocarrier diffusion within the substrate in addition to the effects of the pixel sampling aperture shape and size. Minority-carrier diffusion length, characteristic for the process, was extracted for various active area pixels via several different ways. The agreement between the values obtained by the model and other methods verifies the usefulness of the model. Comparison of both, the simulation results and the MTF calculated from the Point Spread Function measurements of the actual pixels confirms that the active area shape in aggregation with the minority charge carrier diffusion effect are the two determining factors which affect the overall MTF behavior. The results also indicate that for any potential pixel active area shape, a reliable estimate of the degradation of image performance is possible, so that the tradeoff between conflicting requirements, such as signal-

to-noise ratio (SNR) and MTF, could be compared per each pixel design for better overall sensor performance. The proposed model is general in nature. However, evolving technologies will cause other effects like wave-guides etc., to become stronger, and have more influence.

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References

- [1] E. G. Fossum, "CMOS Image Sensors: Electronic Camera on A Chip," *IEEE Trans. Electron Devices*, vol. 44, pp. 1689-1698, Oct 1997.
- [2] P. Bhattacharya, "Semiconductor Optoelectronic Devices," Prentice Hall, 1993.
- [3] N. S. Kopeika, "A System Engineering Approach to Imaging," SPIE Press, 1998.
- [4] K. M. Kramer, W. N. Hitchon, "Semiconductor Devices A Simulation Approach," Prentice Hall, 1997.
- [5] S. M. Sze, "Physics of Semiconductor Devices," New York, J. Wiley and Sons, 1981.
- [6] T. Spirig, "Smart CCD/CMOS based image sensor with programmable real time temporal, and spatial convolution capabilities for application in machine vision and optical metrology," ETH, Dissertation #11993, Switzerland.
- [7] T. O. Körner and R. Gull, "Combined Optical/Electric simulation of CCD Cell structures by Means of the Finite-Difference Time-Domain Method," *IEEE Trans. Electron Devices*, vol. 47, ED-5, pp. 931-938, May. 2000.
- [8] J. P. Lavine, E. A. Trabka, B. C. Burkey, T. J. Tredwell, E. T. Nelson, C. N. Anagnosopoulos, "Steady-State Photocurrent Collection in Silicon Imaging Devices," *IEEE Trans. Electron Devices*, vol. 30, ED-9, pp. 1123-1134, Sept. 1983.
- [9] E. G. Stevens, "A unified Model of Carrier Diffusion and Sampling Aperture Effects on MTF in Solid-State Image Sensors," *IEEE Trans. Electron Devices*, vol. 39, ED-11, pp. 2621-2623, 1992.
- [10] D. H. Seib, "Carrier Diffusion degradation of modulation Transfer Function in Charge Coupled Imagers," *IEEE Trans. Electron Devices*, vol. 21, ED-3, pp. 210-217, 1974.
- [11] E. G. Stevens, J. P. Lavine, "An Analytical, Aperture and Two-Layer Diffusion MTF and Quantum Efficiency Model for Solid-State Image Sensors," *IEEE Trans. Electron Devices*, vol. 41, ED-10, pp. 1753-1760, 1994.
- [12] J. P. Lavine, W. Chang, C.N. Anagnosopoulos, B. C. Burkey and E. T. Nelson, "Monte Carlo Simulation of the Photoelectron Crosstalk in Silicon Imaging Devices," *IEEE Trans. Electron Devices*, vol. 32, ED-10, pp. 2087-2091, 1985.
- [13] D. Kavaldjiev, Z. Ninkov, "Subpixel Sensitivity Map for a Charge Coupled Device sensor," *Optical Engineering*, vol. 37, no. 3, pp. 948-954, Mar. 1998.
- [14] S. G. Chamberlain and D. H. Harper, "MTF Simulation Including Transmittance Effects of CCD," *IEEE Trans. Electron Devices*, vol. 25, ED-2, pp. 145-154, 1978.
- [15] O. Yadid-Pecht, "The Geometrical Modulation Transfer Function (MTF)- for different pixel active area shapes," *Optical Engineering*, vol. 39, no. 4, pp. 859-865, 2000.
- [16] D. Ramey, J. T. Boyd, "Computer Simulation of Optical Crosstalk in Linear Imaging Arrays," *J. Quant. Electron*, vol. 17, pp. 553-556, Apr. 1981.

- [17] H. Wong, "Technology and device Scaling Considerations for CMOS Imagers," *IEEE Trans. Electron Devices*, vol. 43, ED-12, pp. 2131-2142, Dec. 1996.

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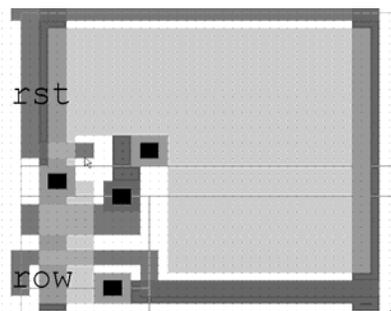


Fig 1. Layout description of an "L" shaped active area pixel design. Reprinted from O. Yadid-Pecht, "The Geometrical Modulation Transfer Function (MTF)- for different pixel active area shapes," *Optical Engineering*, vol. 39, no. 4, pp. 859-865, 2000.

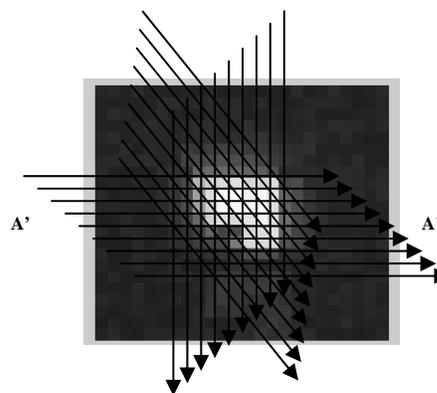


Fig. 2. Plot of the actual measured PSF for the "L" shaped pixel design (after [15]). Cross-sections used for fitting are located along the arrows, normal to the layout surface. Here, and in the following images, the lighter the area - the stronger the pixel response.

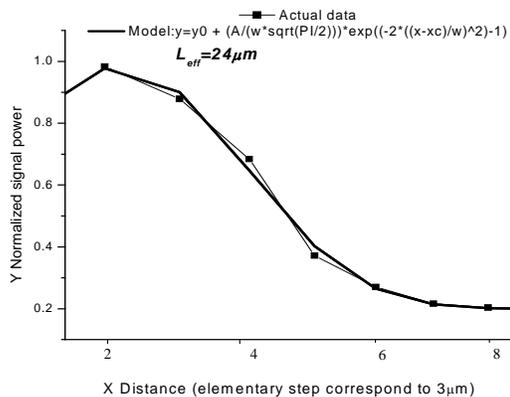


Fig. 3. Functional analysis of the obtained Point Spread Function. The example corresponds to A'-A'' cross-section on Fig. 2.

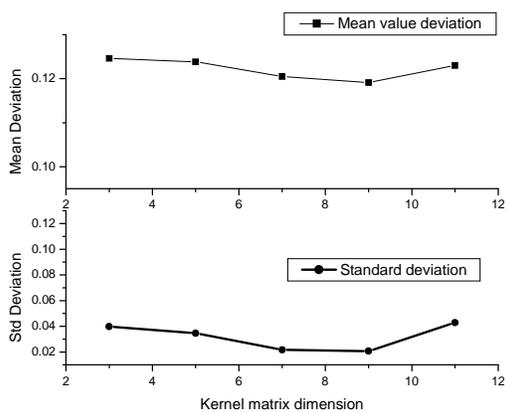


Fig. 4. Mean and standard deviation dependence on the kernel matrix dimensions.

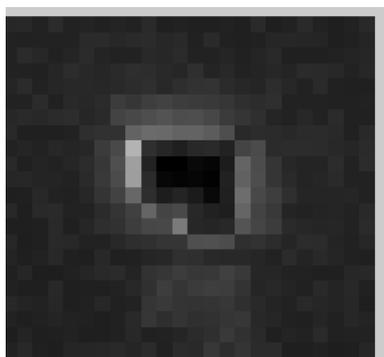


Fig. 5a. The difference between the pure geometrical PSF and the PSF obtained by scanning the "L" shaped pixel design. Maximum difference ~20% of maximum pixel response.

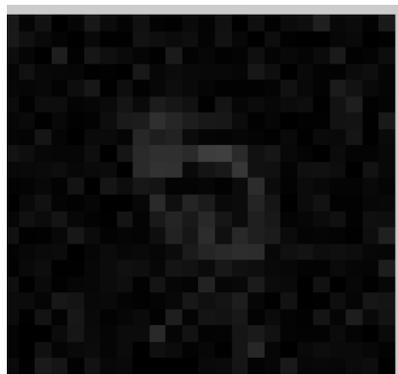


Fig. 5b. The difference between the unified model PSF and the PSF obtained by scanning the "L" shaped pixel design. Maximum difference ~3.8% of maximum pixel response.

