CF/ML Shift Optimization for Small Pixel CMOS Image Sensor through FDTD simulation

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Abstract— **Image sensor process variation may play as a more and more important role for image quality when pixel size continues shrinkage these years. Here we use FDTD simulation tool to build a model for study of relation between process tolerance and sensor optical performance. The paper discusses ML (micro lens) process overlap tolerance effect under different pixel design indexes. The 1.1um 3 mega-pixels back side illumination CMOS image sensor is as a design vehicle and CS (color shading)/CSU (color shading uniformity) are as optical performance evaluation indexes.**

Keywords—**Color shading, Color shading uniformity, SNR10, CF/ML shift, CRA**

I. Introduction

Recently, CMOS image sensors (CIS) are being widely used on Smartphone which strongly require high image resolution and quality [1]. Therefore, pixel size is shrinking continuously to meet these requirements and still keeps the same image quality as the previous pixel generation using new approaches and design concepts to overcome optical performance degradation such as backside illumination (BSI), light-guide and stacked photodiode [1-4]. However, it is inevitable to face the challenges of lower sensitivity and higher crosstalk due to optical diffraction effect especially for small pixel size less than 1.1um. In addition, the process overlay control of Microlens (ML) and color filter (CF) of small pixel significantly impacts image quality with respect to color shading, SNR10 and relative illumination (RI). Therefore, it should be probably taken into consideration while we design CF/ML shift.

Though CF/ML shift is well developed, there were only few papers [3, 5] to mention design criterion in detail. The popular criteria utilize minimum crosstalk or maximum sensitivity to determine CF/ML shift values. However, it is difficult to directly correlate with image quality only based on crosstalk or sensitivity. In this study, a new design concept of CF/ML shift by means of SNR10 criterion is proposed to improve small pixel image quality and to obtain the optimal ML process window at the same time. This concept comes from SNR10 being much better to reflect real image quality than sensitivity or crosstalk. Lumerical FDTD simulator [6] is performed to design and optimize ML/CF shift and also evaluate optical

performance, e.g. quantum efficiency spectrum (QE), crosstalk, sensitivity, and color ratio. Moreover SNR10 simulation followed Nokia and STM methodologies [7-8] and was coded by Matlab software to evaluate SNR10 performance according to simulated QE spectrum.

II. Optical Simulation Model

This study was carried out on 1.1um/3M chip fabricated by TSMC and Visera CIS technology. A 3D-FDTD model shown in Fig.1 has been built for this study. The CF/ML shift is designed to meet 25 ˚ chief-ray angle (CRA).

While plane wave with some specific incident angle, the bloch boundary condition needs to be setup and it causes the angle of incidence changes as a function of frequency, it means only central frequency fits the nominal incident angle. Fortunately broadband sources inject fields that have a constant in-plane wave vector at all frequencies, therefore we can still simulate broadband source in some nominal incident angles then interpolate the output data onto a common source angle vector. Through this method in the model, QE spectrum under various oblique incidence light and various wavelengths could be obtain.

Here, we also set up a characterization system shown in Fig.2 (a) to verify 3D simulation result. To obtain higher accuracy of measurement, the tilt and illumination uniformity must be taken care . The auto-collimated mechanism illustrated in Fig.2 (b) is used to calibrate the tilt, and the laser beam shown in Fig.2 (c) is to make sure only the central part of the collimated light beam is adopted.

Compare above mentioned simulation model and measurement system, both the simulated results of different incident angles in Fig.3 (a) and wavelengths in Fig.3 (b) are in good agreement with measured data. Fig.4 shows the simulated QE spectrum comparison between three different conditions of CF/ML shift, only ML shift and non-CF/ML shift under the oblique incident angle of 25 degrees. The CF/ML shift simulated result demonstrates 5% and 20% QE improvement at the wavelength of 540nm compared to only ML shift and non-CF/ML shift respectively. The QE improvement can also be observed at the other wavelengths like 450nm and 610nm. Fig.5(a) shows no ML/CF shift result where the energy cannot focus on Si surface and crosstalk to

neighboring pixel easily. On the other hand the energy keeps in its own pixel if the pixel has appropriate ML/CF shift like Fig.5(b).

III. Process Tolerance Study

As mentioned above, sensitivity, x-talk and SNR10 are adopted here as three optimization criteria to determine CF/ML shift value, besides color shading (CS) and color shading uniformity (CSU) are taken as two optical evaluation indexes. Fig.6 is an array schematic diagram shows different ROI position. The CS definition of R/G here is calculated from the R/G value ratio of the ROI (area of interest) and center regions of pixel array. The R/G CSU definition is R/G value difference between two relative ROI on the same line which have the same distance to the array center. The B/G CS and CSU definition are the same as well.

Fig.7 illustrates the correlation between CS and these three optimization designs. In this figures, red band represents in-line process overlay shift window for ML and CF manufacturing which shall be well controlled to meet CS uniformity requirement and obtain good image quality. However, it is often constrained by process tool limitation. Fortunately, proper optimization approach can be chosen to minimize CS variation.

From Fig.7 (a); for a certain ROI; the optimal shift value from the maximum sensitivity at 3200K light environment is around 0.2um. However, considering ML process variation, this design suffers the worst CS variation of R/G and B/G compared to other two design criteria. If crosstalk is taken as the optimized shift design criterion, the shift value plotted in Fig.7 (b) is around 0.4um, and this design can obtain the best R/G CS performance but the worst sensitivity performance about 10% less than sensitivity based design. While using this paper proposed design criterion by SNR10, Fig.7 (c) shows the optimal shift value around 0.325um and can achieve best B/G CS value and acceptable sensitivity.

Fig.8 illustrates correlation between CSU and two design indexes at a specific ROI under assumption of CSU spec is ±0.04. As shown in Fig.8(a), sensitivity criterion based shift design is safe in R/G CSU within ML process tolerance window, while SNR10 based design can only pass spec within 0.7 times of process window. It means in this specific case, if SNR10 is chosen as design index, ML process OVL window needs be tightened in order to pass R/G CSU spec. Fig.8(b) is B/G CSU correlation diagram, no matter sensitivity or SNR10 are as design criteria, current process window are far away from failure red line. Comparing Fig8(a) and Fig8(b), R/G CSU value are worse than B/G CSU value, the root cause is from Si front side structure effect while R band light passes deeper than B light in the sensor. This simulation result could be as reference for front side structure layout design thinking.

IV. Conclusion

A FDTD based model is built to study correlation between color filter process window and sensor optical performance. Through this model silicon process window could also be studied in the future.

Through this study proposed pixel design criterion by SNR10 can achieve good color shading process window, comparable sensitivity, crosstalk, and quantum efficiency. Yet in some specific case, it may need to review ML/CF process overlay window to meet color shading uniformity specification.

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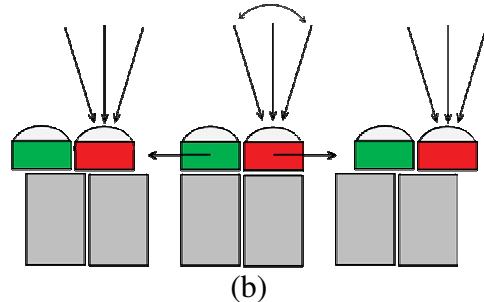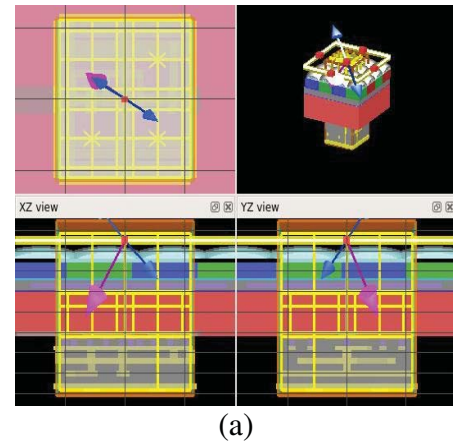[8] C. Mornet, J. Vaillant, "Evaluation of color error and noise on simulated images ", SPIE Vol. 7537, January 2010

(a)

(b)

Figure1: (a) 3D simulated structure of 1.1um BSI pixel w/i oblique incident light, (b) Optical incident model w//i ML/CF shift design
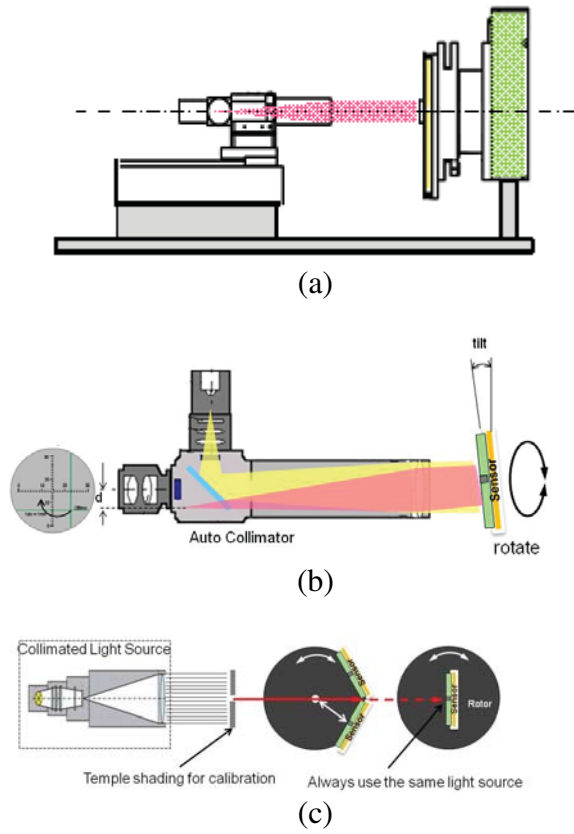
(a)

(b)

(c)

Figure2: (a) Characterization System, (b) Tilt calibration mechanism, (c) Position calibration mechanism
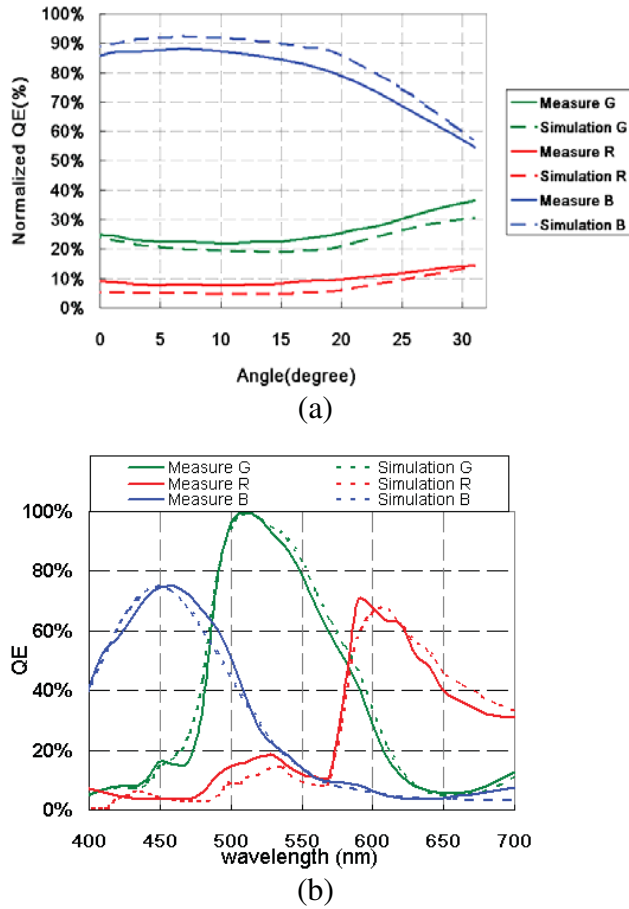

(a)

(b)

Figure3: The comparison between simulation and measurement under (a) different incident light angles and (b) different wavelengths
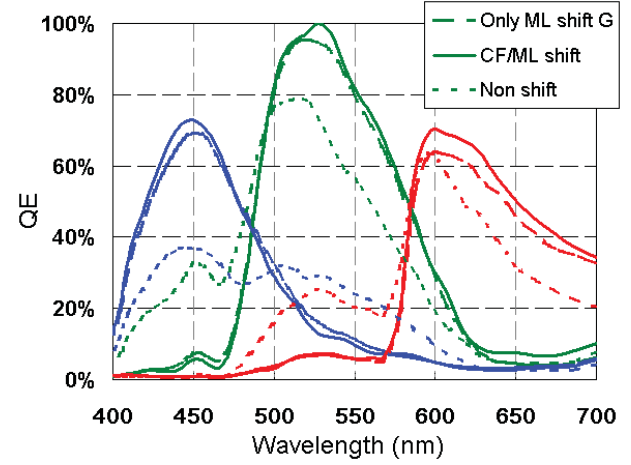

Figure4: QE spectrum under 25° incident light angle for (1) CF/ML shift, (2) Only ML shift and (3) Non-shift
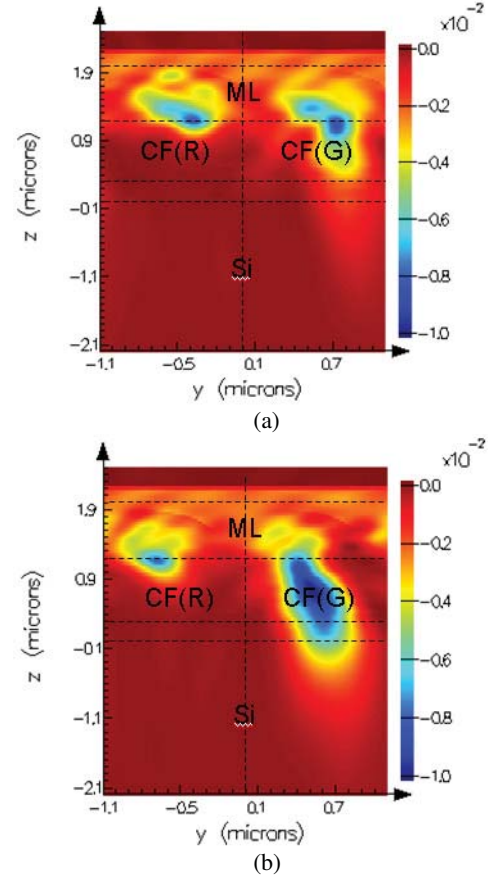

(a)

(b)

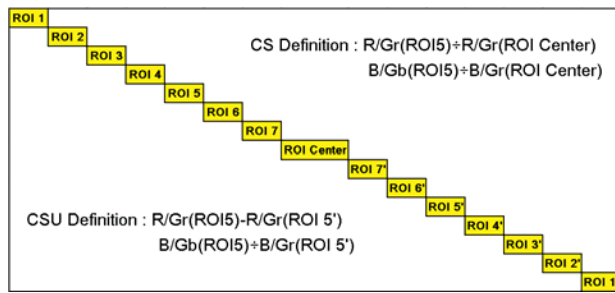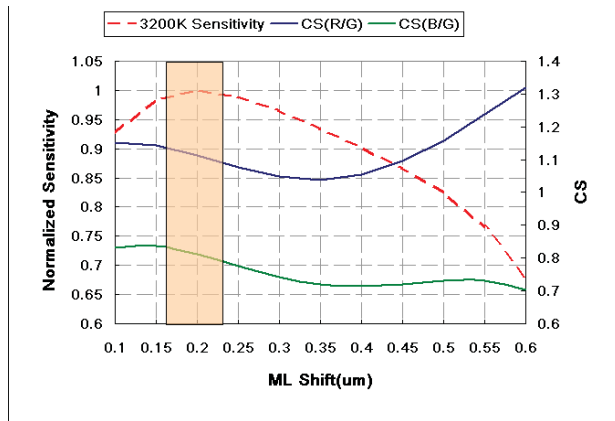Figure5 : Power result cross section (a) without ML shift (b) with optimum ML shif

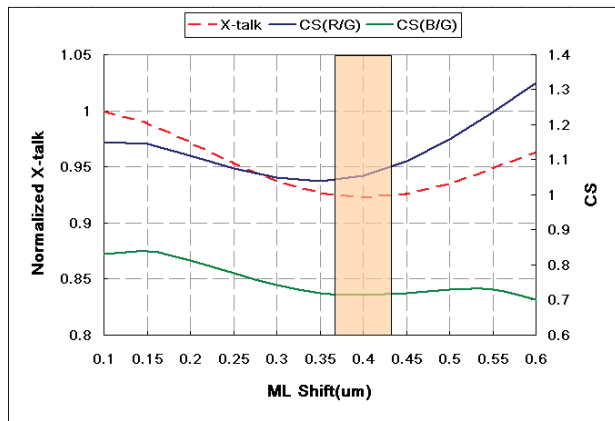Figure6 : Array schematic diagram and definition of CS/CSU

(d)

Figure7: Color shading variation within ML process window by different optimization criteria for ML shift design: (a) Sensitivity, (b) Crosstalk, (c) SNR10, and (d) 3 design index CS comparison
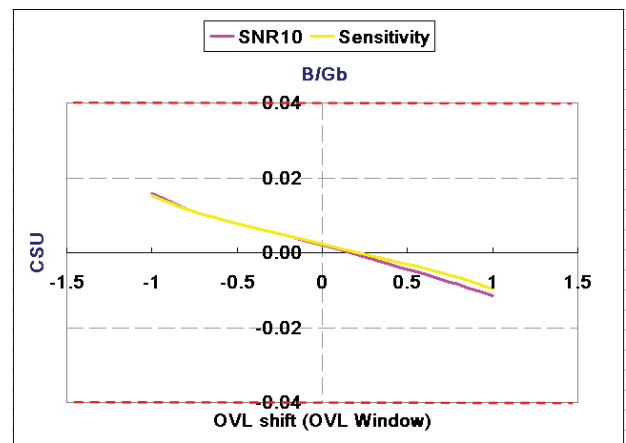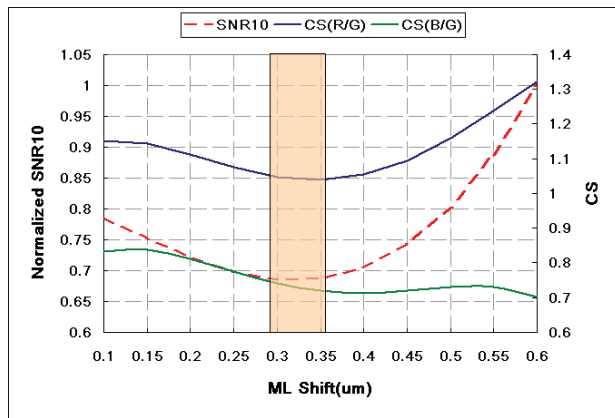

(a)

(a)

(b)

(b)
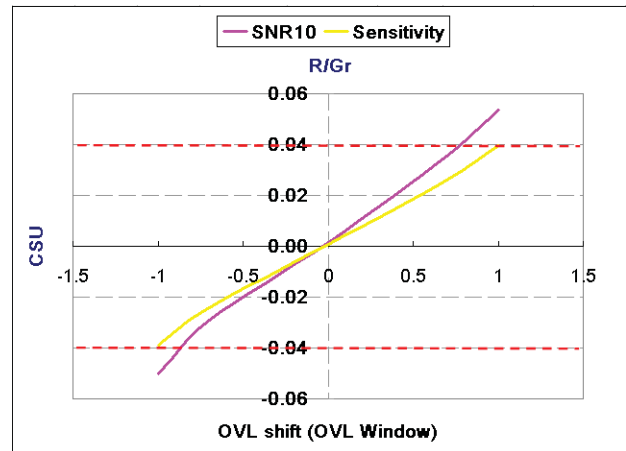
Figure8: Color shading uniformity variation within ML process window by different optimization criteria of ML shift design: (a) R/Gr CSU, (b) B/Gb CSU,

(c)