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Two Layer Image Sensor Pixel Concept for Enhanced Low Light Color Imaging

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Abstract**—**Low light applications such as security and surveillance often require object identification and target discrimination which are made much easier with color imaging. However, most low light sensors tend to be monochrome since color filters used in Color imaging reduce light sensitivity. We present a two layer pixel concept for maximizing low light sensitivity which is capable of producing color images without the use of conventional absorption filters.

I. INTRODUCTION

CMOS image sensors have seen tremendous improvement in performance especially under optimal illumination conditions. However, for low light applications, despite the emergence of technologies such as backside illumination and panchromatic filters, there is still much room left for improvement. Sensors operating in light-starved conditions typically use monochrome sensors since they collect more photons. These sensors are also able to incorporate near-infrared to further increase the collected signal. The lack of color however makes object detection and identification extremely difficult.

The use of absorption color filters is a major limiting factor to the color image sensor's low light performance. Primary color filters utilize about a third of the incident illumination whilst complementary filters transmit about two thirds. To make the most use of incident illumination, three pixel layers can be stacked vertically to sample different colors without the need for an absorption color filter as demonstrated by Foveon[1]. This is possible because light absorption in silicon is wavelength dependent. The increased complexity associated with implementing readout circuitry for each of the three junctions has limited the growth of this technology. Other challenges such as increased noise, lag and reduced fill factor have hampered the use of this concept for low light imaging.

A compromise which has been explored quite extensively is to stack two pixel layers to reduce the readout complexity and still leverage the wavelength dependent absorption for color sampling. Each pixel outputs two color samples which is insufficient for full color reproduction. Several Implementations of two layer pixels [2,3] therefore tend to use a color filter array (CFA) to vary the response of pixels in order to generate three or more color samples. It has been suggested that the use of Green and Magenta checkered filter pattern over the two layer pixels is optimum for both good color reproduction and high SNR [4]. The use of color filters however reduces the light collected by the pixels. In order to maximize the light absorption to make these two layer pixels useful for low light applications, an alternative method of color sampling is required which eliminates the losses caused by absorption color filters.

In this paper, we present an initial study of a two layer pixel which uses a dielectric reflector instead of absorptive color filters for improved low light performance. Through model simulation, we compare the color and SNR performance of the novel pixel structure to the state of the art.

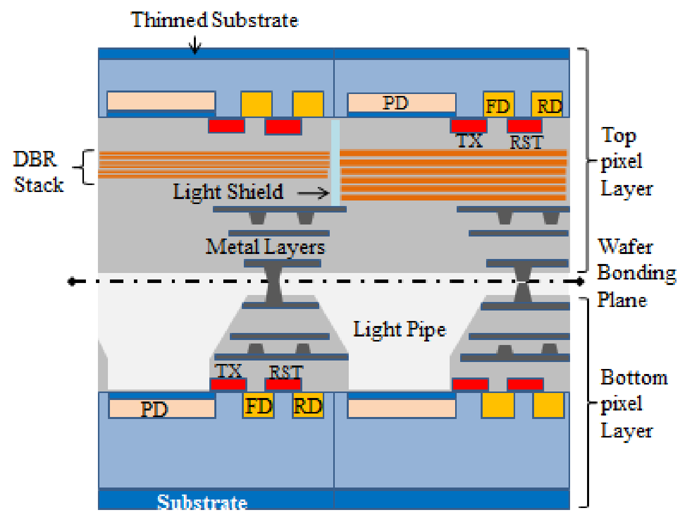

Fig.1. Conceptual Illustration of proposed two junction pixel

II. SENSOR CONCEPT

Two layer pixels have been fabricated in the past using two main methods. In the first approach, the top junction is formed by a shallow implant and the bottom junction formed by deep implantation. Alternatively, the bottom junction is implanted first, followed by epitaxial growth and then the implantation of the top junction. A deep implant is still required to make contact to the bottom junction. One drawback common to both methods is that readout of the signal from the bottom junction is typically prone to excess noise. Besides, in order to form a dielectric reflector between the top and bottom junctions, the deep implantation method cannot be used.

A very convenient method for the implementation of such a pixel structure is the use of wafer bonding. A first junction is implemented on one wafer and a second on a separate wafer [5]. In our pixel concept, a wavelength-dependent dielectric reflector stack is inserted between the top and bottom pixel layers. The dielectric reflector stack can be implemented on either the top or bottom wafer. If backside illumination is used on the top wafer, then the dielectric reflector stack can be deposited before the metal layers. Light reflected by the dielectric reflector passes back up through the top layer where it can be absorbed. To ensure that different pixels in a kernel produce different color samples, the dielectric reflector stack is tuned to reflect a different band of the visible light spectrum. Figure 1 shows two different distributed Bragg reflector (DBR) stacks over the two pixels. DBRs are formed from alternating quarter wavelength layers of high and low refractive index dielectric materials. Different thicknesses of the dielectric layers produce DBRs which reflect different wavelengths.

By incorporating one or more different DBRs in a kernel, four or more color samples can be produced. Figure 2 shows block diagrams of four-pixel kernels utilizing 2, 3 and 4 DBRs

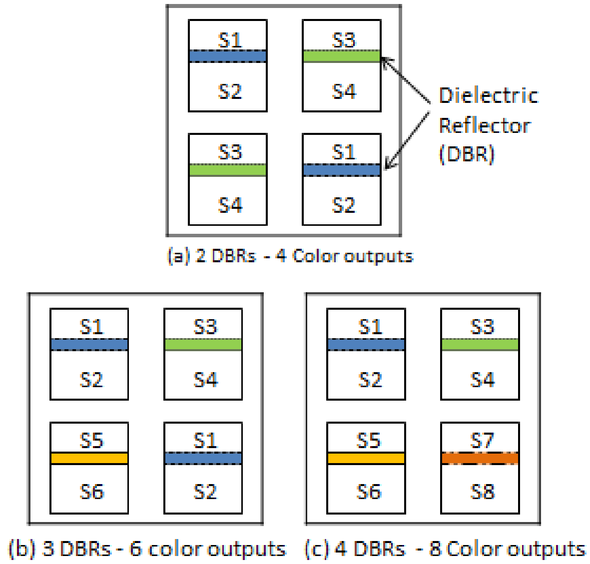

Fig.2. Different 4 pixel kernels – a, b and c produce 4, 6 and 8 color samples respectively

to produce 4, 6 and 8 color samples per kernel. Shown in figure 3 are the normalized spectral responses of two 2-Layer pixels with 2 different DBRs designed for reflection at 450nm and 650nm. D65 illuminant was used in this simulation and the spectral reflectance displayed is for the white color patch in the Macbeth color chart. Significantly different spectral responses are obtained for the top (L_1) and bottom (L_2) layers in each pixel. Also observe the spectral response for the L_1 layers in the 700-1000nm range is extremely small as a result of the large penetration depth of NIR light.

It is well known that intrinsic color separation in two and three layer pixel structures is often quite poor. When used for color reproduction, image sensors using these multilayer pixels typically require aggressive color correction for good color fidelity. Because of the high overlap in spectral responses of the different color channels, significant signal subtraction has to be done in the color correction process. The noise in the final image however is a quadratic sum of the noise in all the signals added and subtracted. Therefore the noise is amplified and SNR is decreased.

However, there is a trade-off between the color reproduction quality and the noise amplification (and by extension the SNR) of the reproduced image. For low light applications where SNR is at a premium and color accuracy isn't a priority, color correction matrices which trade color accuracy for increased SNR can be used.

An important advantage of monochrome sensors in low light conditions is the possibility of enhancing the signal by collecting light in the near infrared (NIR) region of the electromagnetic spectrum. NIR light is often considered noise in color imaging since it has no direct color information. Near infrared light reflection however provides information of the scene and so may be used to enhance the low light SNR. It is especially advantageous to utilize the NIR light since the night sky illumination spectrum has a fairly high proportion of NIR light. To augment the available lights in low light conditions for applications such as security, NIR light may also be used since it provides illumination but isn't easily visible to the eye.

III. CONCEPT SIMULATION

To test the concept described above, the performance of a two layer pixel structure with an interlayer dielectric reflector is modelled in MATLAB. We extend this model to generate an array and compare the color and visual SNR performance of our test structure to two equally sized sensor arrays: One utilizing a Bayer pattern and the other a two layer pixel structure with Green and Magenta filters (2L-GrMg).

A distributed Bragg reflector (DBR) is used as the inter-layer reflector. In our simulations, SiO_2 and Si_3N_4 are used as the low and high refractive index materials respectively. Multilayer stacks of these materials are easy to realize in standard CMOS technology. Figure 3 shows the spectral reflectance of DBRs designed for 450nm and 650nm reflection. The DBR simulations used 10 SiO_2/Si_3N_4 pairs and achieved nearly full reflection at the desired wavelengths. The resulting dielectric stack thickness is relatively low (~1.3um for 450 nm reflection and 1.9um for 650 nm).

In our simulations, the Macbeth spectral chart was used as a target to generate test images. The illumination incident on the top pixel layer was determined using the incident photon flux $\Phi(\lambda)$ in photons/um^{2}s and the target spectral reflectance $M(\lambda)$.

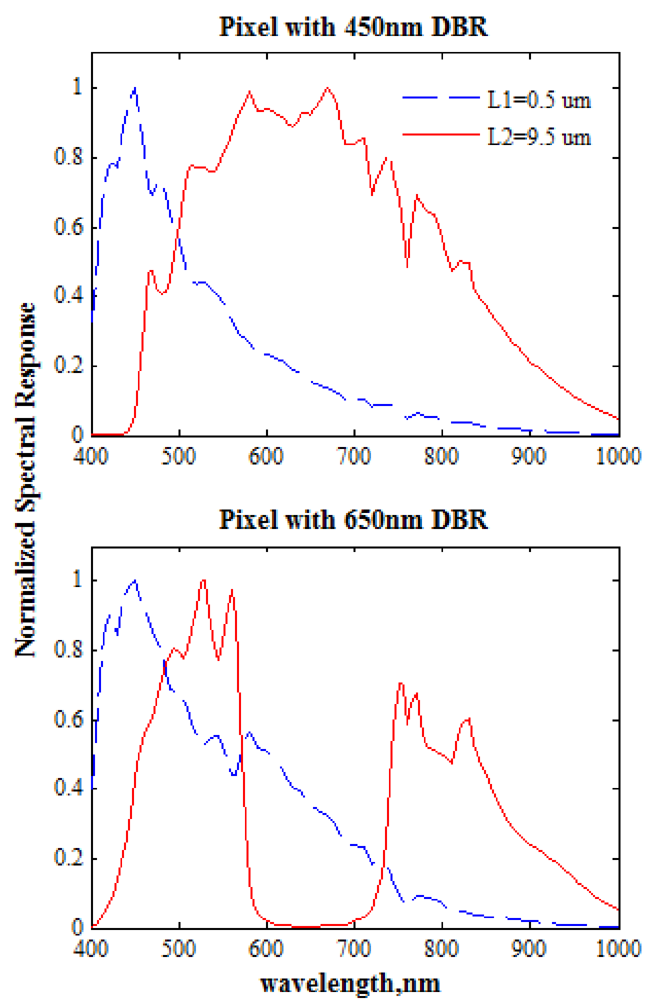

Fig.3. Normalized spectral responses of the top and bottom layers (L_1 and L_2) - D65 Illuminant used

$$\Phi_{pix}(\lambda) = k \cdot \Phi(\lambda) \cdot M(\lambda). \quad (1)$$

The parameter k accounts for the pixel parameters including size, lens F#, reflectances etc. The top pixel layer response is dependent on the light incident on the pixel, the thickness of the top pixel layer and the reflectance of the dielectric reflector.

$$S_{top}(\lambda) = \Phi_{pix}(\lambda) \cdot \left(1 - e^{-\alpha(\lambda) L_1}\right) \cdot \left(1 + R_{DBR}(\lambda) e^{-\alpha(\lambda) L_1}\right) \quad (2)$$

The parameter $\alpha(\lambda)$ and L_1 are the absorption coefficient of silicon and the top pixel layer thickness respectively. The output of the bottom pixel layer is determined by the thickness L_2 and the DBR transmittance.

$$S_{bottom}(\lambda) = \Phi_{pix}(\lambda) e^{-\alpha(\lambda) L_1} \cdot \left(1 - R_{DBR}(\lambda)\right) \cdot \left(1 - e^{-\alpha(\lambda) L_2}\right). \quad (3)$$

Test images were generated for array using the different kernels described in figure 2. The different DBR reflectances result in a variation in the output of pixels in a kernel producing different color outputs.

For the test images generated for the Bayer pattern and the 2-layer pixel sensor with green and magenta color filters, the pixel outputs for the test image are determined by $\Phi_{pix}(\lambda)$, and the color filter spectral transmittance $T_{CFA}(\lambda)$.

$$S_{CFA}(\lambda) = \Phi_{pix}(\lambda) T_{CFA}(\lambda) \cdot \left(1 - e^{-\alpha(\lambda)(L_1 + L_2)}\right). \quad (4)$$

Arrays of 240 by 360 pixel test images were created. Shot noise was added by means of the Poisson random generator in MATLAB and read noise of 2e- was used. Bilinear interpolation and white balancing were performed on the test images. For the 2 layer pixel sensor test images, interpolation results in Nx4, Nx6 and Nx8 arrays depending on the number of different DBRs in the kernel. For these test images, 4x3, 6x3 and 8x3 color correction matrices are used. Alternatively, the 6-channel and 8-channel outputs can be selectively combined such that 3x3 and 4x3 color correction matrices can be used.

IV. LOW LIGHT PERFORMANCE TESTING

To compare the low light performance of the new two layer pixels with interlayer dielectric reflectors to the conventional Bayer and the 2L-GrMg pixel sensor, the fully interpolated test images are color corrected and the color error and visual SNR are determined. Color correction matrices (CCMs) are usually obtained by determining the transformation that minimizes the error between measured pixel values and a reference image. The color correction approach used in [6] which minimizes the sum of the color error and a weighted value of the noise variance is used here. The function minimized in the color correction process is given by

$$J = \varepsilon_C + w \cdot \varepsilon_N \quad (5),$$

where ε_C and ε_N are the color error and noise variance respectively and w is the weight of the noise variance. The weight w determines how much color accuracy is traded off for a higher SNR in the process of calculating the CCMs.

As mentioned earlier, color accuracy may readily be traded for higher SNR in low light conditions. We therefore compare the SNR-Color error trade-off curves for the different test images. To obtain these trade-off curves, color correction matrices are determined for different weights, w of the noise variance in equation 5. The CCMs obtained are applied to the simulated test images to obtain color corrected images from which the color error and SNR are calculated.

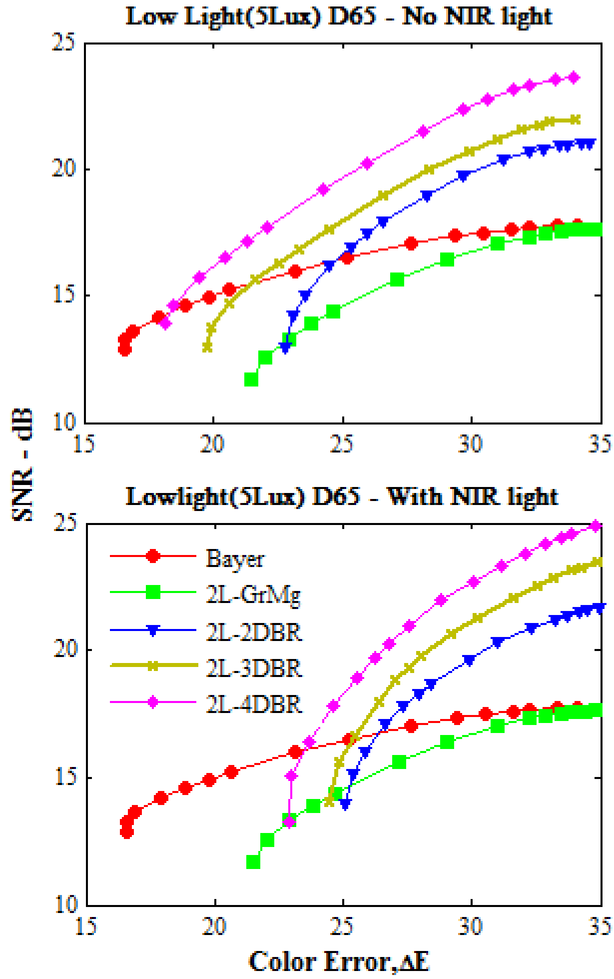

Fig.4. SNR-Color Error Curves for simulations in low light.

The CIELAB ΔE_{ab} metric is used for determining the color error since a wide range of color errors is investigated. This is given by the Euclidean norm of the difference in the reference and test images in Lab color space.

$$\Delta E_{ab} = \left[(L_{ref} - L_{test})^2 + (a_{ref} - a_{test})^2 + (b_{ref} - b_{test})^2\right]^{\frac{1}{2}} \quad (6)$$

The visual SNR metric described in ISO 12232 [7] was used in these simulations. The SNR is defined as the ratio of the luminance to the visual noise in the image. The luminance is determined from the linearized RGB values as follows:

$$Y = 0.2125R + 0.7154G + 0.0721B. \quad (7)$$

The visual noise in the image is dependent on the luminance value as well as the two chrominance values (R-Y) and (B-Y).

$$\sigma = \left[\sigma^2(Y) + C_1\sigma^2(R - Y) + C_2\sigma^2(B - Y)\right]^{\frac{1}{2}} \quad (8)$$

Where C_1=0.279 and C_2=0.088 are weighting factors.

V. RESULTS

As discussed earlier, color correction matrices which decrease noise at the expense of color accuracy can be determined by increasing the noise variance weight w, in equation (5). The color error and SNR in the final image obtained after color correction with these matrices is reported. Figure 4 shows simulations of the proposed pixel concept as well as the Bayer pattern and a 2-Layer pixel with green and magenta color filters, 2L-GrMg. For our 2-Layer pixels which use DBRs, simulations were performed with and without a NIR cut-off filter to study the impact of NIR light collection on the SNR.

We observe from figure 4 that for all simulations, a higher SNR can be attained as we allow increased color error. The Bayer pattern has the best color reproduction as expected. However, when we allow higher color error levels, the new pixel array patterns have significant SNR advantage over both the Bayer pattern and the 2-Layer pixel with Green-Magenta filters. For instance at $\Delta E=30$, the 2L-4DBR simulation has SNR about 4-5dB higher than the Bayer pattern. Figure 4 shows reproductions of the Macbeth color chart in 2 Lux illuminations. Color correction matrices were selected for ΔE close to 30. It can be observed that the image produced using the Bayer pattern shows significantly more visible noise compared to the proposed 2-Layer pixel.

Simulation results also showed that combining 8-channel and 6-channel outputs into 4 and 3 color channels respectively before color correction didn't significantly affect SNR or color accuracy. It was noticed that including NIR light had an adverse effect on the color reproduction accuracy as expected. A slight increase in SNR can be observed at higher color error, ~1dB. It is hypothesized here that a higher gain in SNR isn't achieved because the conventional color correction method doesn't effectively utilize the NIR light.

VI. CONCLUSION

From this study, it is evident that the two layer pixel concept proposed is capable of color reproduction. If color correction matrices are optimized for high SNR, this pixel concept has a significant advantage when compared to sensors which use the Bayer pattern or two layer pixels with green and magenta filters. Simulations using NIR light did not significantly increase the SNR in the color error range considered. Conventional color correction doesn't effectively utilize the NIR light. For instance, as pointed out earlier, the bottom (L_2) layers have a much higher NIR sensitivity and so have much larger signal than the L_1 layers. If conventional white balancing is done, the L_1 color channels will have very large white balance weights. Noise in these channels will therefore be amplified greatly by the white balance process. Therefore, alternative color correction algorithms are needed to successful leverage NIR light for enhancing SNR for low light. It should also be mentioned that the parameters used in these simulations have not been optimized. The color error and SNR depend on the dielectric reflector reflectance as well as the depths of the two detector layers. Optimization of these parameters should result in an even higher advantage in SNR performance.

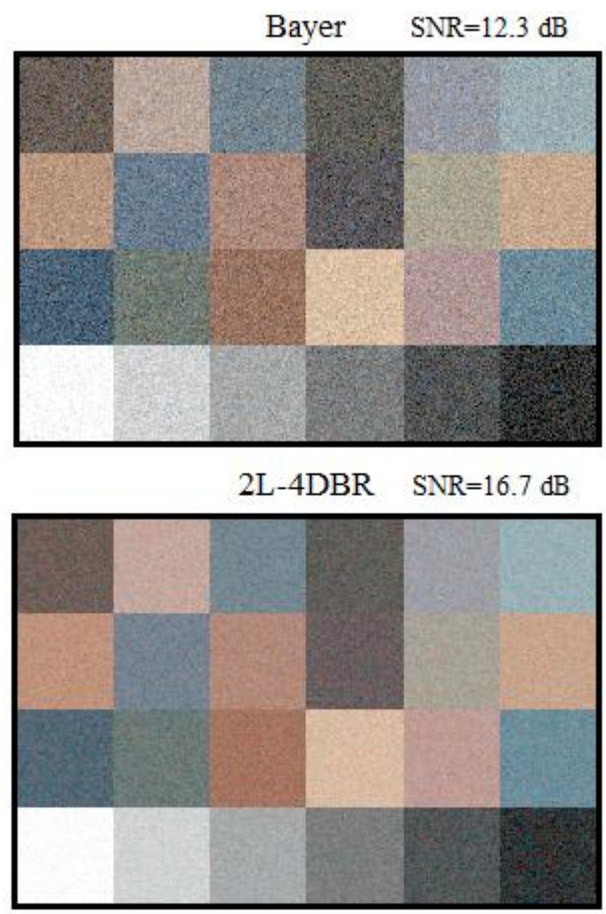

Fig.5. Images simulated using Bayer pattern and 2-Layer pixel kernel with 4DBRs in low light (2Lux). Their color errors are 29.9 and 29.1.

VII. ACKNOWLEDGMENT

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VIII. REFERENCES

[1] R. B. Merrill, "Color Separation in an active pixel cell imaging array using a triple-well-structure". US Patent 5965875, 1999.

[2] K. M. Findlater, "Buried double junction pixel using green and magenta filters," in *IEEE Workshop on CCDs and Advanced Image Sensors*, Japan, 1999.

[3] D. J. Tweet, J. J. Lee, J. M. Speigle and D. Tamburino, "2PFC image sensors: better image quality at lower cost," in *IS&T/SPIE Electronic Imaging: Digital Photography V, 7250*, 2009.

[4] E. R. Fossum, "Investigation of Two-Layer Photodetectors for YSNR10 Improvement in Submicron Pixels," in *International Image Sensor Workshop*, Hokkaido, Japan, 2011.

[5] B. Mansoorian and D. Van Blerkom, "Stacked Photodiodes for Extended Dynamic Range and Low Light Color Discrimination". US20150090863

[6] Yap-Peng Tan and Tinku Acharya, A Method for Color Correction with Noise Consideration, Proc. SPIE 3963, 329-337 (2000)

[7] ISO 12232:2006, "Photography - Digital still cameras - Determination of exposure index, ISO speed ratings, standard output sensitivity, and recommended exposure index"