Enhancing Low Light Color Imaging with pixel concept utilizing two vertically stacked detector layers

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CMOS image sensor performance in ideal light conditions has been vastly improved over the years. However, for low light operation, there is much room for improvement. Monochrome sensors tend to dominate the field of low light imaging because their lack of color filters enhances their light collection. However, color is essential for proper object identification and target discrimination. Two junction pixels have been widely investigated for the purposes of enhancing sensitivity however, they produce only two color samples and so the use of color filters is necessary to produce at least 3 color samples. This makes them non-ideal for lowlight imaging. In this work, we investigate a two layer pixel concept which avoids the use of absorption color filters and enhances SNR performance. A conceptual illustration of this pixel is shown in fig. 1.

In order to produce 3 or more color samples in a two layer pixel array, a wavelength dependent dielectric reflector is implemented between the top and bottom pixel layers. A dielectric reflector such as the distributed Bragg reflector (DBR) can be implemented easily by deposition of alternating quarter wavelength films of SiO_2 and Si_3N_4. The reflected light makes two passes through the top pixel layer thus enhancing its absorption in that layer. By varying the reflection properties of the DBR from pixel to pixel in a kernel, different color samples can be produced. For instance, if 4-pixel kernel consists of pixels with two different DBRs, then 4 color samples can be obtained. Similarly using 3 and 4 different DBRs in a kernel produces 6 and 8 color outputs respectively as depicted in figure 3. This concept may be implemented monolithically or by means of wafer bonding. It is understood that wafer stacking technology is still in its nascent stages especially as pertains to image sensors.

The pixel concept is tested by modeling performance in MATLAB. We model a two layer pixel with a DBR made of SiO_2 and Si_3N_4 between the top and bottom layer. As shown in figure 2, near total reflection for the wavelength of interest can be realized with 10 dielectric layer pairs. Shot noise is factored into simulations and a read noise of 2e- is assumed for the low light performance testing. A Macbeth color chart is used as an imaging target and test images are simulated for different kernels shown in figure 2. For comparison, we included simulations with a Bayer pattern and a 2-Layer pixel with green and Magenta color filters (2L-Mg,Gr). For the proposed pixel concept we also investigate the benefits of enhancing low light sensitivity with near infrared light by eliminating the NIR filter. For the kernels with 3 and 4 DBRs which produce 6 and 8 color outputs after interpolation, we investigate the possibility of combining the color channels to 3 and 4 respectively in order to cut the computational costs of color correction. The SNR as defined in ISO 12232 [2] and the CIELAB color difference metric, ΔE_{ab} are used to evaluate the different pixel structures. Simulations were performed using D65 illumination.

From simulations, the kernels using the proposed pixel structure have better low light color and SNR performance than the two junction pixel with green and magenta filters. From the trade-off curves, it can be observed that the Bayer pattern attains the best color performance even in low light. However, when color performance is traded for SNR, the new pixel concept shows much higher SNR than the Bayer pattern as shown in figs. 5. Such a trade may be acceptable for certain applications such as security and surveillance. Figure 4 shows a comparison of Macbeth color charts reproduced by a Bayer pattern and the proposed pixel concept under 5 Lux of D65 illumination. At a ΔE of 25, the new pixel concept has SNR 4.3 dB higher than the Bayer pattern. Finally, selectively combining/binning the 6 and 8 channel outputs to reduce computational cost doesn't deteriorate color or SNR performance. NIR light addition however doesn't significantly improve low light performance. Future work will explore alternative color correction schemes to better utilize NIR light.

References

1. R. B. Merrill, "Color separation in an active pixel cell imaging array using a triple-well-structure". US Patent 5965875, 1999.
2. ISO 12232:2006, "Photography - Digital still cameras - determination of exposure index, ISO speed ratings, standard output sensitivity, and recommended exposure index"

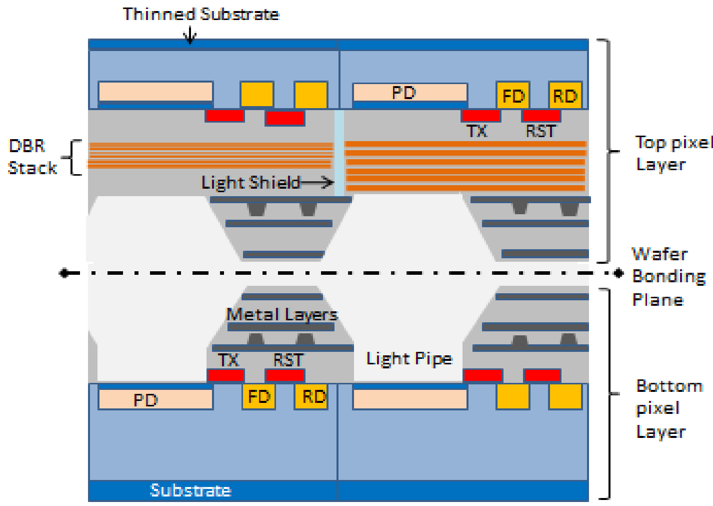


Fig.1. Conceptual Illustration of proposed two junction pixel

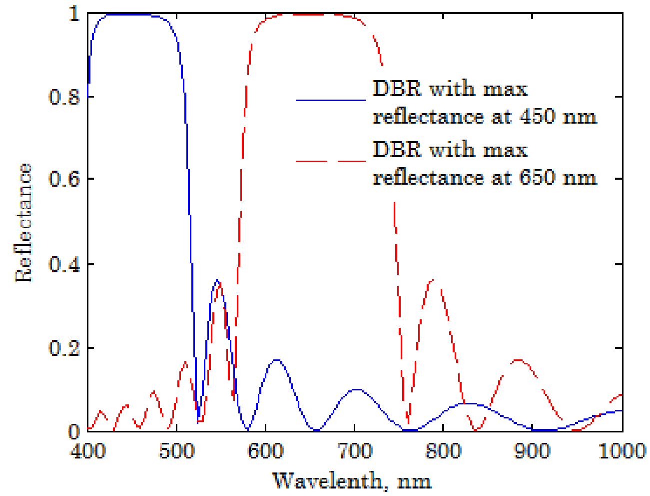
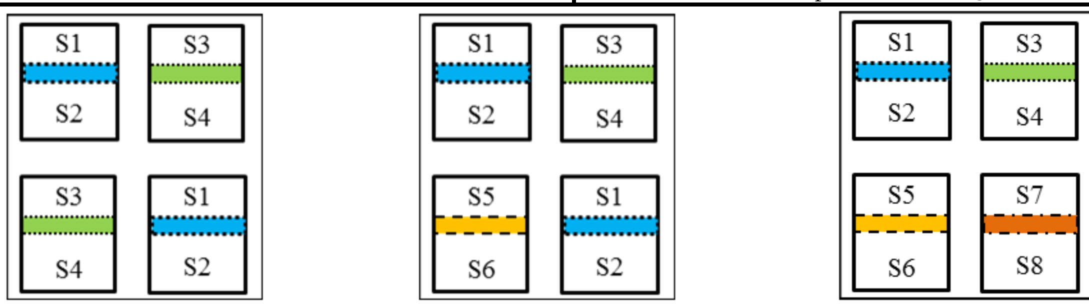


Fig.3. Simulated Reflectance for DBRs consisting of 10 pairs of $Si0_2/Si_3N_4$



a. Kernel with 2DBRs (**2L-2DBR**) b. Kernel with 3DBRs (**2L-3DBR**) c. Kernel with 4DBRs (**2L-4DBR**)

Fig.3. Different 4 pixel kernels – a, b and c produce 4, 6 and 8 color samples respectively

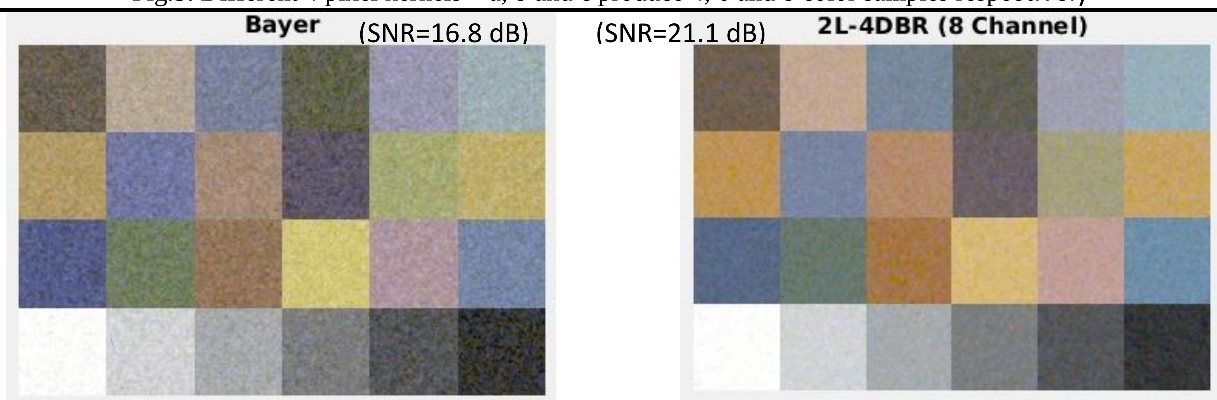


Fig.4. Comparison of Macbeth Chart reproduced using Bayer pattern and the 8 Channel, 2-Layer pixel (2L-4DBR) under 5Lux D65 Illumination. Color Correction matrices chosen to produce nearly the same ΔE=25.

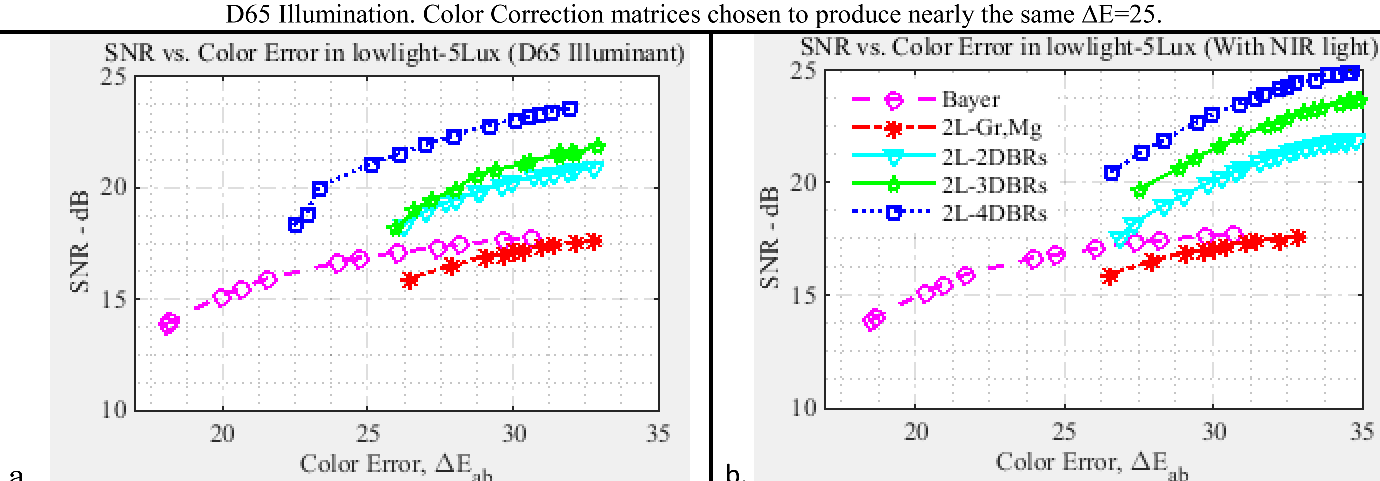


Fig.5. SNR vs. Color Error curves simulated for D65 illuminant both without NIR light (a) and with NIR light included (b)