R47 Pixel continues to shrink….Small Pixels for Novel CMOS Image Sensors

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Abstract

This paper presents recent results of small pixel development for different applications and discusses optical and electrical characteristics of small pixels along with their respective images. Presented are basic optical and electrical characteristics of pixels with sizes in the range from 2.2µm to 1.1µm,. The paper provides a comparison of front side illumination (FSI) with back side illumination (BSI) technology and considers tradeoffs and applicability of each technology for different pixel sizes. Additional functionalities that can be added to pixel arrays with small pixel, in particular high dynamic range capabilities are also discussed.

1. FSI and BSI technology development

Pixel shrinking is the common trend in image sensors for all areas of consumer electronics, including mobile imaging, digital still and video cameras, PC cameras, automotive, surveillance, and other applications. In mobile and digital still camera (DSC) applications, 1.75µm and 1.4µm pixels are widely used in production. Designers of image sensors are actively working on super-small 1.1µm and 0.9um pixels. In high-end DSC cameras with interchangeable lenses, pixel size reduces from the range of 5 – 6 µm to 3 – 4 µm, and even smaller. With very high requirements for angular pixel performance, this results in similar or even bigger challenges as for sub 1.4µm pixels. Altogether, pixel size reduction in all imaging areas has been the most powerful driving force for new technologies and innovations in pixel development.

Aptina continues to develop FSI Aptina™ A-Pix™ technology for pixel sizes of 1.4µm and bigger. Figures 1a and 1b illustrate a comparison of a regular pixel for a CMOS imager with Aptina's A-Pix technology. Adding a light guide (LG) and extending the depth of the photodiode (PD) allow significant reduction of both optical and electrical crosstalk, thus significantly boosting pixel performance [1]. A-Pix technology has become a mature manufacturing process that provides high pixel performance with lower wafer cost compared to BSI technology. The latest efforts in developing A-Pix technology were focused on improving symmetry of the pixel, which resulted in extremely low optical cross-talk, reduced green imbalance and color shading. Improvements stem from improvements in the design and manufacturing of LG, along with the structure of Si PD. LG allows one to compensate for pixel asymmetry (at least its optical part) thus providing both optimal utilization of Si area, and minimal green imbalance / color shading. Figure 2 shows an example of green imbalance for 5Mpix sensors with 1.4µm pixels size designed for 27degree max CRA of the lens. Improvement of the LG design reduces green imbalance by more than 7x.

BSI technology allows further reduction of pixel size to extremely small 1.1µm and 0.9µm, and more symmetrical pixel design for larger pixel nodes. Similar to A-Pix, the use of back side illumination in pixel design allows significant reduction of optical and electrical crosstalk, as illustrated in Figure 1c. Both BSI and Aptina Apix technology use the 90nm gate and 65nm pixel manufacturing process.

Aptina's BSI technology uses cost-effective P-EPI on P+ bulk silicon as starting wafers. The wafers receive normal FSI CMOS process with skipping some FSI p modules. Front side alignment marks are added for later backside alignments. The device wafers are bonded to BSI carrier wafers, and are thinned down to a few microns thick through wafer back side grinding, selective wet etch, and chemical-mechanical planarization process. The wafer thickness is matched to front side PD depth to reduce cross-talk. Finally, anti-reflective coatings are applied to backside silicon surface and micro-lens to increase pixel QE.

Figure 3 shows normalized quantum efficiency spectral characteristics of 1.1µm BSI pixels. Pixels exhibit high QE for all 3 colors and small crosstalk that benefit overall image quality. Figure 4 presents luminance SNR plots for 1.4µm FSI and BSI pixels and 1.1µm BSI pixel. Due to advances of A-Pix technology, characteristics of FSI and BSI 1.4µm pixel are close, with the BSI pixel slightly outperforming FSI pixel, especially at very high CRA. However, the difference in performance is much smaller compared to conventional FSI pixel. For 1.1µm pixels, BSI technology definitely plays a key role in achieving high pixel performance. Major pixel photoelectrical characteristics are presented in Table 1.

2. Image quality of sensors with equal optical format

Figure 5 presents SNR10 metrics for different pixel size inversely normalized per pixel area - scene illumination at which luminance SNR is equal to 10x for specified lens conditions, integration time, and color correction matrix. As can be seen from the plot, the latest generation of pixels provides SNR10 performance that is scaled to the area, and as a result, provides the same image quality at the same optical format for the mid level of exposures.

The latest generation of pixels with the size of (1.1µm – 2.2µm) in Figure 5 uses advances of A-pix technology to boost pixel performance. Many products for mobile and DSC applications use 1.4µm pixel; the latest generations of 1.75µm, 1.9µm, and 2.2µm are in mass production both for still shot and video-centric 2D and 3D applications. Bringing the latest technology to the large 5.6µm pixel has allowed us to significantly boost performance of that pixel (shown as a second bar of Figure 5 for 5.6µm pixel) for automotive applications.

As was mentioned earlier, BSI technology furthers the extension of array size for the optical formats. The latest addition to the mainstream mobile cameras with ¼" optical format is 8Mpix image sensor with 1.1µm pixels size. Figure 6 compares images from the previous 5Mpix sensor with ¼" optical format with 1.4µm pixel size with images from the new 8Mpix sensor with 1.1µm pixel that fits into the same 1/4" optical format. Images were taken from the scene with ~100 lux illumination at 67ms integration time and typical f/2.8 lens for mobile applications. Zoomed fragments of the images with

100% zoom for 5Mpix sensor show very comparable quality of the images and confirm that similar image quality for a given optical format results when pixel performance that is scaled to the area continues to be the same.

Figure 4 shows also the lowest achievable SNR10 for 1.4μm pixel at similar conditions for the ideal case of QE equal to 100% for all colors and no optical or electrical crosstalk – color overlaps are defined only by color filters. The shape of color filters is taken from large pixel sensor for high-end DSC application and assumes very good color reproduction. It is interesting to see that current 1.4μm pixel has only 40% lower SNR at conditions close to first acceptable image, SNR10 [2].

3. Additional functionality for arrays with small pixels

With the diffraction limits of imaging lenses, the minimum resolvable feature size (green light, Rayleigh limit) for an f-number 2.8 lens is around 1.8 microns [3]. As pixel sizes continue to shrink below 1.8 microns, the image field produced from the optics is oversampled and system MTF does not continue to show scaled improvement based on increased frequency pixel sampling. How can we take advantage of increased frequency pixel sampling then?

High Dynamic Range. Humans have the ability to gaze upon a fixed scene and clearly see very bright and dark objects simultaneously. The typical maximum brightness range visible by humans within a fixed scene is about 10,000 to 1 or 80dB [4]. Mobile and digital still cameras often struggle to match the intra-scene dynamic range of the human visual system and can't capture high range scenes (50-80dB) primarily because the pixels in the camera's sensors have a linear response and limited well capacities. HDR image capture technology can address the problem of limited dynamic range in today's camera. However, a low cost technique that provides adequate performance for still and video applications is needed.

Frame Multi-exposure HDR. The frame multi-exposure technique, otherwise known as exposure bracketing, is widely used in the industry to capture several photos of a scene and combine them into an HDR photo. Although this technique is simple, effective, and available to anyone with a camera with exposure control, the drawbacks relegate this technique to still scene photography and frame buffer-based post processing. If an HDR camera system is desired that doesn't require frame memory and can reduce motion artifacts to a level where video capture is possible, the common image sensor architecture used in most cameras today must be changed. Can we use smaller pixels to provide multi-exposure HDR that doesn't require frame memory for photos and reduces motion artifacts and allows video capture?

Interleaved HDR Capture. With pixel size reduction there is an opportunity to take advantage of the diffraction limits of camera optical systems by spatially interleaving pixels with differing exposure time controls to achieve multi-exposure capture. Figure 7 shows an example of a dual exposure capture system using interleaved exposures within a standard Bayer pattern.

This form of intra-frame multi-exposure HDR capture can be easily incorporated into standard CMOS sensors and doesn't require the additional readout speed or large memories. The tradeoff of interleaving the exposures is that fewer pixels are available for each exposure image and can affect the overall captured image resolution. This is where the advantage of small pixels comes into play: as pixels shrink below the diffraction limit, the system approaches being oversampled such that the MTF doesn't improve proportionally to pixel size. We propose that greater gain in overall image quality may be achieved by spatially sampling different exposures to capture higher scene quality rather than oversampling the image.

In Figure 7, pairs of rows are used for each exposure to ensure there are R, G, and B signals recorded for both T1 (long) and T2 (short) exposures. Since the T1 and T2 exposures are interleaved, the readout of the pixels can be performed the same as a standard sensor without requiring large memory buffers for readout alignment. The exposures are also overlapped in time such that there is less than one half of a frame time difference on average between the longest and shortest exposures providing less motion artifacts. This technique may be extended to non-standard CFA patterns to improve compactness of the interleaved pattern and/or increase the number of exposures to 3 or 4 to further increase dynamic range.

HDR with 1.1μm and smaller pixels. 1.1μm and 0.9μm pixels provide typical maximum SNR = 34dB and 32.5dB based on projected full wells of 3000 and 2000 electrons, respectively. SNR generally limits the maximum exposure ratios that may be used between adjacent exposures in an HDR system. An SNR discontinuity occurs as the image transitions from a long T1 to a short T2 exposure and the magnitude of the discontinuity must be controlled by limiting the maximum ratio between exposures.

For a typical 1.1μm pixel, a ratio of 8x between exposures provides an SNR at the exposure transition of around 25dB and may be boosted at least an additional 6dB through noise processing and provides sufficient image quality. The plot in Figure 8 shows the SNR vs. relative light level for a 1.1μm pixel with no noise reduction processing. An 8x exposure ratio increases the overall dynamic range by 8x, leading to 78dB DR for a 1.1μm pixel sensor. The image in Figure 9 shows an interleaved HDR capture vs. a standard single exposure image using an 8M 1.1μm pixel sensor.

Reducing pixel size below 1.1μm to 0.9um, 0.7um, will allow more interleaving functions to be implemented without scaled loss of resolution and open up new opportunities for extended functionality.

4. Conclusion

By introducing BSI technology, Aptina has extended its portfolio of small pixels and products based on them to 1.1μm and 1.4μm BSI pixels. Performance of 1.4μm BSI pixel is slightly better than that of FSI pixel. However the difference is not that big due to advances of A-Pix technology. New pixels exhibit scale to the area performance and provide similar image quality for the sensors with the same optical format. Adding HDR capabilities to the arrays with small pixels allows improving image quality and extending dynamic range without noticeable reduction of spatial resolution.

5. Acknowledgements

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[4] Erik Reinhard, et al."High Dynamic Range Imaging: Acquisition, Display and Image-based Lighting", ISBN-10: 0-12-585263-0, Morgan Koffman Publishers, 2006.

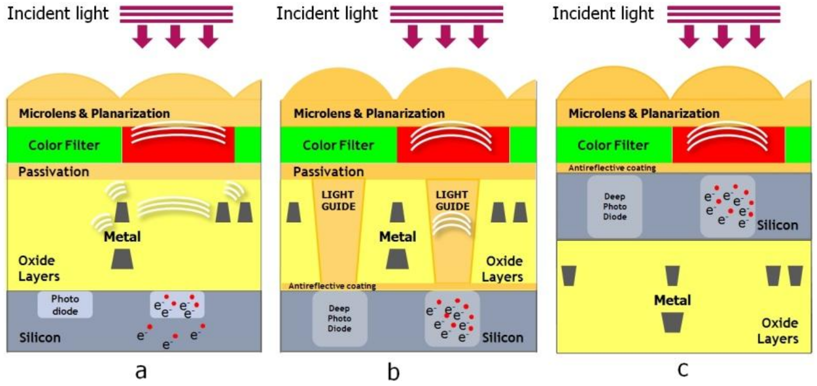

Figure 1. Illustration of pixel technology improvement:
a – conventional pixel, b – FSI A-pix technology, c – BSI technology

Pixel size, µm	1.1	1.4	1.4
Technology	BSI	FSI	BSI
QE max, %	60	60	65 / 70
Crosstalk aver, %	12	10.5	13 / 17
Linear Full Well, ke-	2.7	4.2 - 4.5	4.2 - 4.5
Dark Current @ 60C, e-/s	20	15	15
PRNU, %	< 1.2	0.8	< 1.0

Table 1. Major pixel characteristics

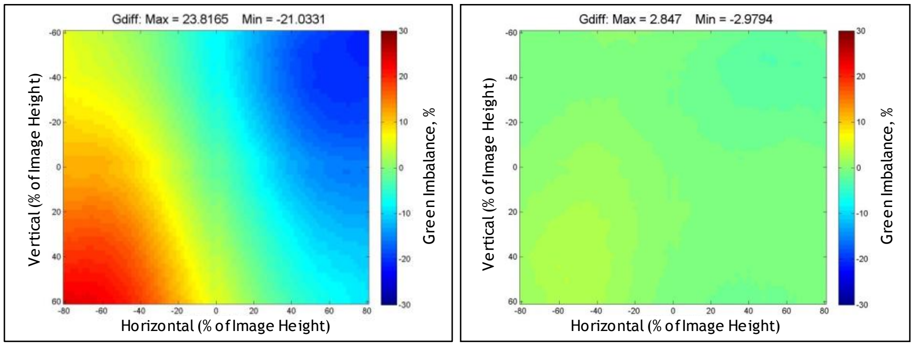

Figure 2. Improving green imbalance and color shading in 1.4µm FSI pixel
Left –5Mpix sensor previous design, Right – 5Mpix sensor new design

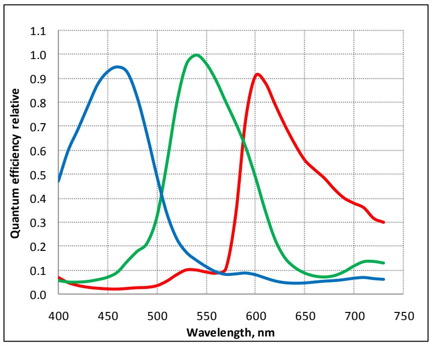

Figure 3. Normalized Quantum Efficiency Spectral characteristic of 1.1µm BSI pixel

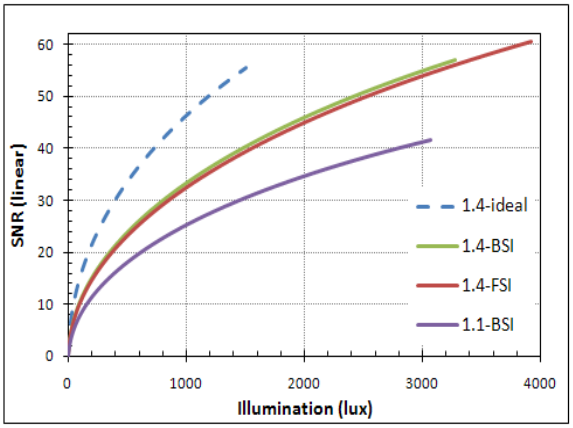

Figure 4. Luminance SNR plot for 1.4um FSI and BSI pixels and 1.1um pixel

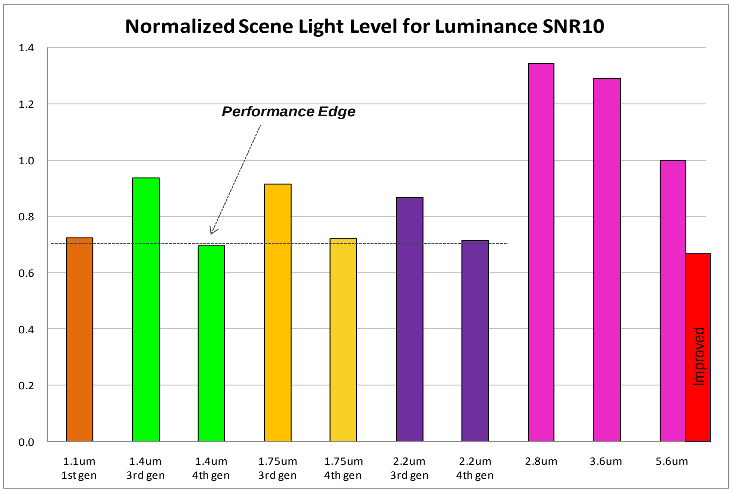

Figure 5. Luminance SNR10 inversely normalized to the pixel area

Figure 6. Image comparison between 5Mpix-1.4µm pixel (left) and 8Mpix-1.1um (right) pixel at 100 lux scene illumination and 67ms integration time. Similar noise with sharper Image from 8Mpix-1.1µm sensor.

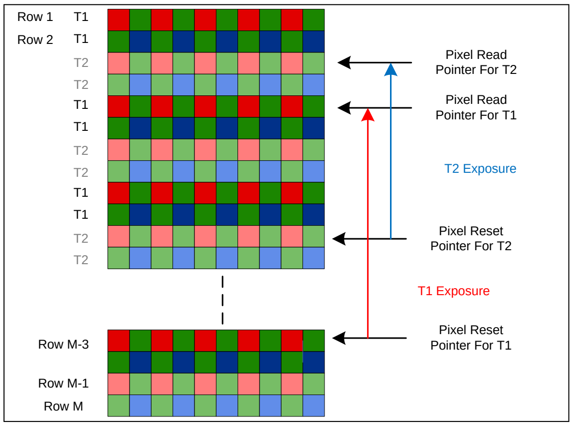

Figure 7. Spatially interleaved dual exposure HDR readout

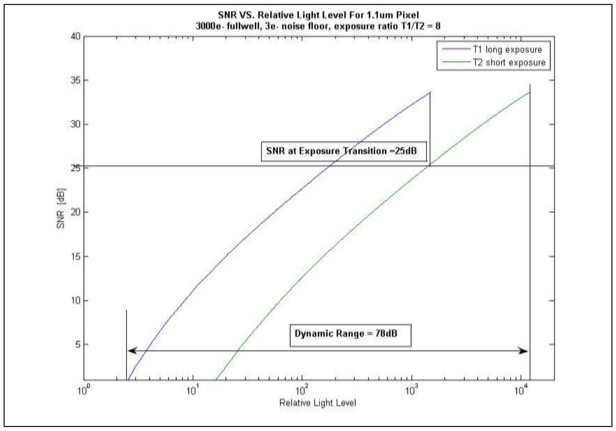

Figure 8. SNR vs. relative light input for 1.1um pixel with dual exposure

Figure 9. Image Comparison of Single (left) VS Interleaved Dual Exposure With 1.1µm Pixel (right)