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Comparison of SFR and Edge Artifacts between Single Photodiode and Split Photodiode Pixels in HDR Image Sensors

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Abstract

High dynamic range (HDR) image sensors have become increasingly important for automobile applications, particularly for advanced driver-assistance systems (ADAS) in recent years. The traditional single photodiode and split photodiode pixels are the two most commonly used technologies to build HDR image sensors in the industry. This study used a monochrome CMOS image sensor to model single and split photodiode pixel images to examine image quality. Slanted edge images were used to calculate the spatial frequency response (SFR), and the results showed a significant difference in modulation transfer function (MTF) from the split photodiode. MTF of the large photodiode in the split photodiode pixel at half Nyquist was lower than MTF of the small photodiode, as expected. However, the sampling area and the spatial separation of the small photodiode in the split pixel caused edge artifacts in the image. The traditional single photodiode pixel does not experience a change in MTF with light level and edge artifacts were not observed.

Split pixel and lateral overflow integration capacitor technology

HDR mode in image sensors is designed as a feature to capture scenes under a significant difference in brightness (dynamic range). It plays a significant role in automotive use by improving visibility of objects in diverse environments. At present, common HDR approaches can be spatially categorized as: pixels with a single photodiode(PD) and pixels with dual PDs, as represented schematically in Figure 1, the single PD is denoted as PD1 and the dual photodiode pixel has two PDs: a large photodiode denoted PD2_L and a small photodiode denoted PD2_S. In the split pixel architecture [1, 2], the two photodiodes are used under certain signal levels: PD2_L for low-intensity light and PD2_S for high-intensity light. On the other hand, the single PD with lateral overflow integration capacitors (LOFIC) utilizes the overflow capacitor to store photoelectrons under high intensity light. When the PD becomes fully saturated with photoelectrons, the excess electrons subsequently overflow into the floating diffusion (FD) and then the overflow capacitor in a sequential manner [3]. Both technologies can produce HDR images within one exposure. The dual PD pixel architecture combines the signals from PD2_L and PD2_S, while the single PD pixel with LOFIC outputs the signals from PD1 and overflow capacitor over the entire dynamic range.

The single PD pixel maintains a consistent sampling area across its entire HDR response range which keeps the SFR and signal sampling consistent under different light conditions. However, image sensors based on split PD pixels include an algorithmic approach to adapt to different light levels by combining PD2_L and PD2_S signals. SFR changes under different light conditions because of utilization of distinct photodiode sizes. Also, the array of small photodiode has wider separation between the photodiodes, and this results in edge artifacts. SFR measurement and signal sampling simulations described in this paper explain the performance differences between single and split photodiode pixels.

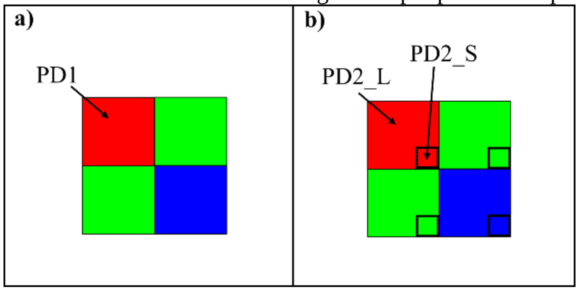

Figure 1. *Schematic Representation of Pixel Geometries for a) single photodiode, and b) dual photodiode pixels*

Spatial frequency response calculation methodology

SFR measurement followed the slanted-edge method specified in the ISO12233 standard [4]. Figure 2 shows the setup which is used to measure SFR. The light panel used diffuser to keep the uniformity of light across the lighting area and the slanted edge was put in front of the light panel with a black box between them to keep out any stray light. The lens used in the measurement is near diffraction limited grade and its MTF has been measured. During the test, by moving the sensor with 2um increment, the best focused image has been identified. To get sensor MTF, the lens MTF is factored out from system MTF using equation (1), where λ is the light wavelength and f is the spatial frequency. MTF calculation was performed using a commercial software package provided by Imatest, LLC.

$$\text{MTF\_Sensor}(\lambda,f) = \text{MTF\_System}(\lambda,f) / \text{MTF\_Lens}(\lambda,f) \qquad (1)$$

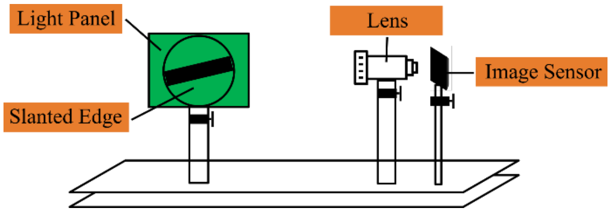

Figure 2. *MTF measurement setup*

Modeling Methodology

The sensor used in this study is a 3µm monochrome CMOS image sensor. The slanted edge and Siemens star pattern targets were captured by this sensor with lens. Modeling PD1 used 3x3 kernel binning which average 3x3 pixels into one pixel in Figure 3a. Each PD1 pixel is averaged from nine 3um monochrome pixels. Small split photodiode pixel PD2_S is represented by one corner pixel which is marked with "x" in 3x3 pixels in Figure3b. Large split photodiode pixel PD2_L is represented by the other 8 pixels of the 3x3 kernel binning which average the other 8 pixels into one large pixel in Figure3b. Both slanted edge images and Siemens star images were using the same modeling methodology. This image modeling methodology will help to avoid the noise created by the electric circuit design and factor out any image correction from the Image Signal Processor (ISP).

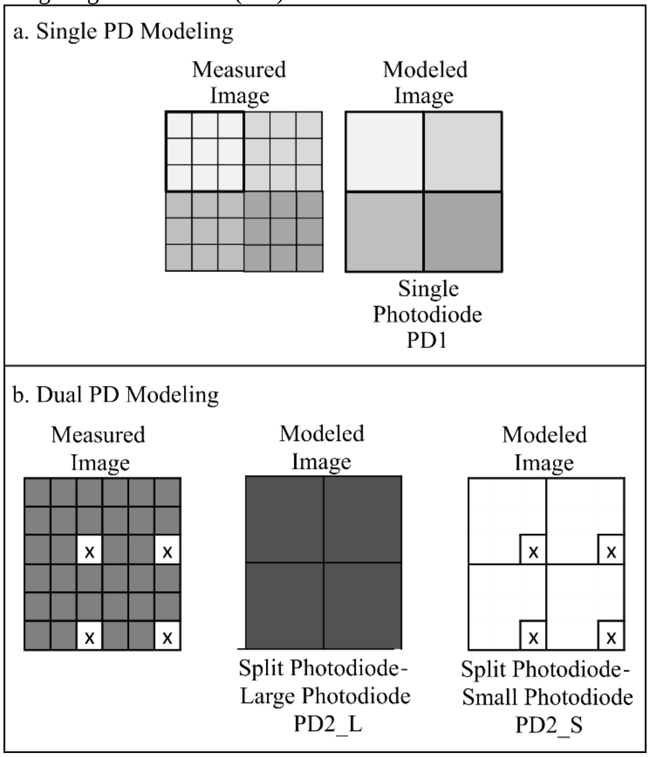

Figure 3. *Image Modeling Methodology*

Results and Discussion

Figure 4 shows a comparison of the SFR of single PD and split PD pixels under the same illumination conditions. PD2_S (red dashed line) and PD2_L (red solid line) have different MTF due to the difference in the size of their respective sampling areas. MTF of PD2_S at half Nyquist is 0.68 and PD2_L is 0.48 and the difference increases towards the Nyquist frequency. PD2_S is expected to have a higher MTF compared to PD2_L, which is because smaller sampling area achieves higher SFR [5]. However, PD1 with the largest sampling area has the lowest MTF, 0.45 at half Nyquist.

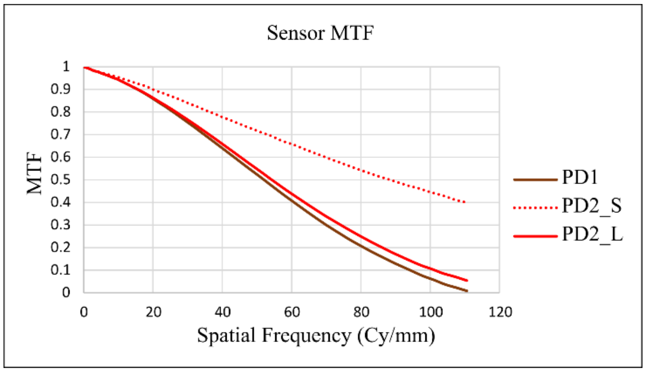

Figure 4. *Comparison of SFR between Single and Split PD Pixels*

The slanted edge images that are used for MTF calculation of single and split PD pixel are presented in Figure 5. The edge in the PD2_S image has jagged artifacts which are caused by the spatial separation between the small photodiodes. PD1 and PD2_L show similar smooth edges without any jagged artifacts. When sampling the PD2_S pixel, there are pixels information missing which is shown in Figure6. The green area is the slanted edge which is the sampling target. On the top flat edge, the PD2_S pixel with "x" mark has 2 pixels information missing between each PD2_S pixel. It does not affect the edge because the edge has no tilt angle. However, the bottom edge shows a different pattern. From "x1" to "x2", there are 2 pixels information missing. There are 14 pixels missing from "x2" to "x3" and 17 pixels missing from "x3" to "x4". This uneven missed pixel information will cause jagged artifacts. Although the PD2_S has higher MTF among all 3 pixels, the edge artifacts may cause edge detection failure [6].

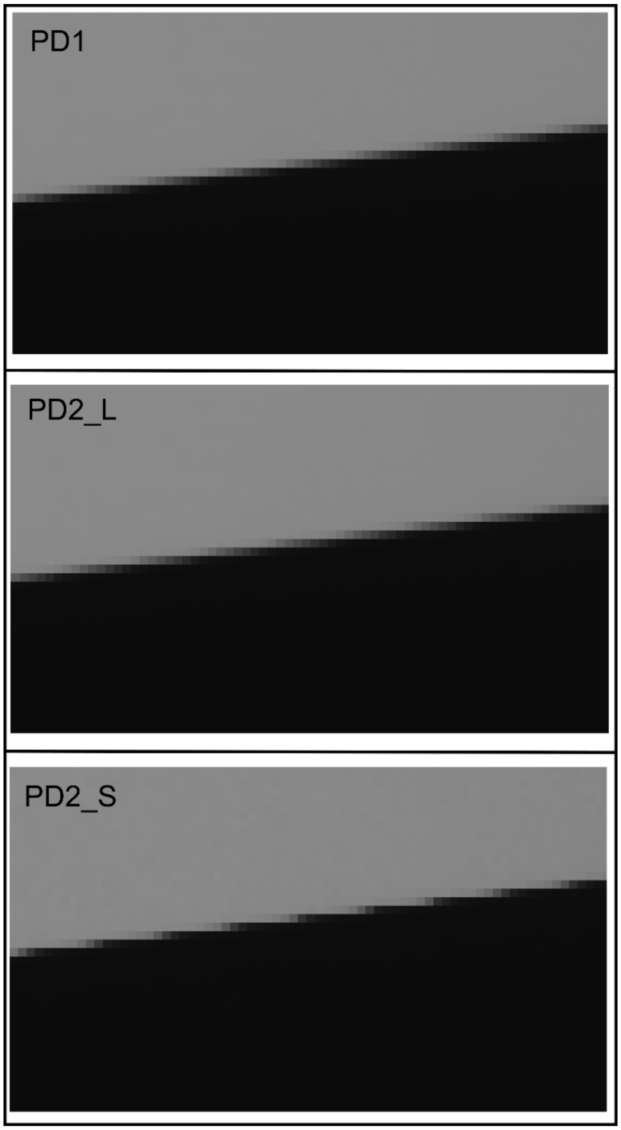

Figure 5. *Edge Artifacts in Split Pixel PD2_S*

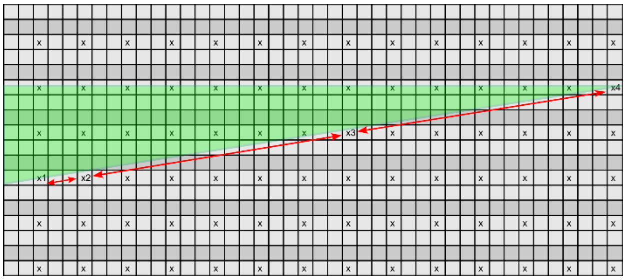

Figure 6. *Split Small Pixel PD2_S Missing Pixel Information*

Figure 7 presents simulated Siemens star images. The images of PD1 and PD2_L have similar aliasing effects due to the same sampling area. However, PD2_S demonstrates more serious aliasing due to the smaller sampling area. Although the PD2_S yields better MTF results, as shown in Figure 4, the small sampling area of small photodiode leads to the serious aliasing [7].

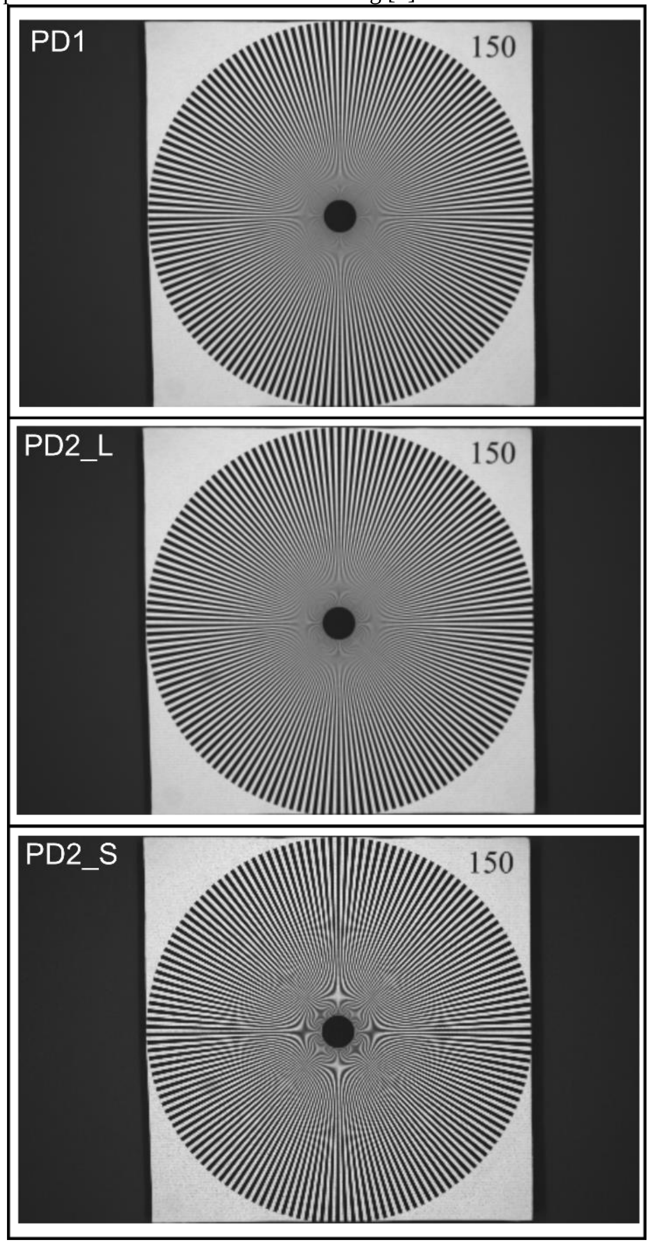

Figure 7. *Siemens Star*

When the HDR mode is activated in both pixels, the MTF will change based on the different light intensities in the split PD pixel. The PD2_L pixel helps to capture low light conditions and PD2_S pixel captures high light conditions. There will be a specific point at which the MTF increases. This occurs when the pixel switches from the PD2_L to the PD2_S. Conversely, in single PD pixel, the MTF remains constant as the light level increases because the sampling area keeps the same. Besides, the jagged artifacts and aliasing will show up when PD2_S pixel is active. The MTF difference in the split PD pixel requires extra ISP to turn the image sensor under HDR mode.

Conclusion

This study used a monochrome CMOS image sensor to model single and split PD pixels images to examine image quality. The SFR results showed a significant difference in MTF from the split PD pixel. The MTF at half Nyquist is about 29% lower for the PD2_L compared to the PD2_S in the split PD pixel. And the drop increased dramatically after half Nyquist and ended at 87% lower at Nyquist. The spatial separation of the PD2_S pixel in the split PD pixel caused edge artifacts in the image. On the other hand, the single PD pixel did not experience a change in MTF, and no edge artifacts were observed. The small photodiode in split photodiode pixel shows more serious aliasing in Siemens star image due to smaller sampling area.

References

[1] Y. Motohashi, "The challenges of human and computer vision from a single automotive camera", AutoSens Brussels, 13 September 2022.

[2] Y. Oh et al., "A 140 dB Single-Exposure Dynamic-Range CMOS Image Sensor with In-Pixel DRAM Capacitor," 2022 International Electron Devices Meeting (IEDM), San Francisco, CA, USA, 2022, pp. 37.7.1-37.7.4

[3] M. Innocent, S. Velichko, et al., "Automotive CMOS Image Sensor family with 2.1 µm LFM pixel, 150 dB Dynamic Range and High Temperature Stability", 2023 International Image Sensors Workshop, May 2023.

[4] International Organization for Standardization. (2023). Photography — Electronic still picture imaging — Resolution and spatial frequency responses (ISO/DIS Standard No. 12233). Retrieved from https://www.iso.org/obp/ui/en/#iso:std:iso:12233:ed-4:v1:en

[5] Liu, C., Lin, J., & Tseng, M. "Design of CMOS sensor fill factor for optimal MTF and SNR." In Sensors, Systems, and Next-Generation Satellites XIV (Vol. 7826, pp. 439-448). SPIE, Oct. 2020.

[6] Fua, P., Leclerc, Y.G. "Model driven edge detection." Machine Vis. Apps. 3, 45–56 (1990).

[7] Deegan, Brian M. "The effect of split pixel HDR image sensor technology on MTF measurements." Digital Photography X. Vol. 9023. SPIE, 2014.

Author Biography

Xunzhi Li received his PhD in Chemical Engineering from the University of Rochester (2019). Since then, he has worked in the Intelligent Sensing Group at Onsemi Company in Boise, ID. His work has focused on the development of image sensor pixel and packaging.

Bob Gravelle received a BSEE from the University of Colorado at Colorado Springs in 1991. Soon after, he joined Micron Technology working on Process Parametrics. In 2005, moved to Micron's Imaging Group, Aptina and Onsemi focusing on Optical Pixel R&D.

Rujul Desai received his MSc in Imaging Science from Rochester Institute of Technology in 2021. He joined the Intelligent Sensing Group at onsemi in 2021 and working on pixel characterization and image quality of image sensors for various applications.

Radu Ispasoiu is Director of R&D Engineering at onsemi Image Sensor Group. He has held management and technology leadership roles in the semiconductor industry for 25+ years. He holds a PhD in Physics (1996).