Automotive 3 µm HDR Image Sensor with LFM and Distance Functionality

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***Abstract*—We described a 3 µm super-exposure pixel 1.3 MP CMOS image sensor for automotive application that provided for up to 140 dB high dynamic range (HDR) coverage with multi-exposure operation, as well as effective HDR with LED flicker mitigation (LFM) operation. At junctions temperatures in excess of +100°C total signal-to-noise transitions were kept at or above 30 dB due to further development of the pixel pulsed gate operation and process optimization. Pulsed LFM operation provided for capturing flickering lights of any brightness. Two-photodiode pixel architecture in combination with single µlens covering the pixel also enabled distance extraction along with a color image using in-pixel phase detect.**

Keywords—image sensor; high dynamic range; LED flicker mitigation; CMOS; distance;

I. Introduction

Latest automotive image sensors are addressing challenging street scenarios with flickering LEDs and high dynamic range (HDR) [1] in excess of 140 dB [2] with junction temperatures up to +125°C. Image sensors providing high performance HDR with light and LED flicker mitigation (LFM) are powering the latest advancements in autonomous and assisted driving as well as better viewing application such as surround and rear view, e-mirror, digital video recording, and augmented reality displaying. Some applications also require distance data using the same camera solutions.

II. Pixel Design

We designed and tested a 3 µm pixel 1.3 MP CMOS imager that provides cinematographic HDR image quality even for high temperatures with all signal-to-noise (SNR) transitions at or above 30 dB. Two photodiodes (PDs) dual conversion gain (DCG) pixel schematic is presented in Fig. 1.

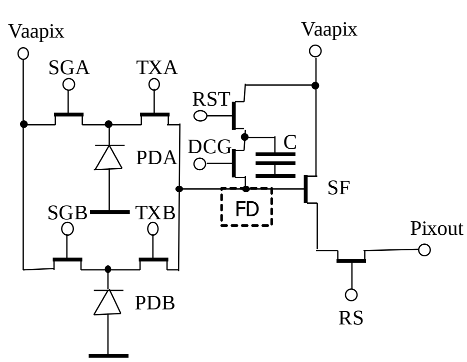
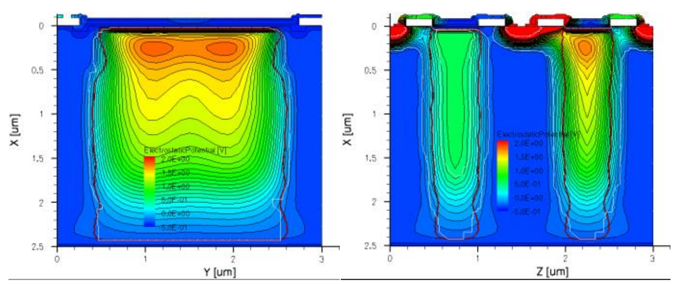


Fig. 1. Super-exposure two PDs DCG pixel schematic.

The sensor implemented a set of operations for effective:

- 4-exposure 140 dB image captures [2],
- Pulsed LED flicker mitigation (pLFM) [3] using shutter gates SGA and SGB, transfer gates TXA and TXB, and an in-pixel memory node comprised from floating diffusion (FD), DCG gate, and capacitor C,
- Super-exposure lateral overflow integrating capacitor (LOFIC) HDR LFM [4-5] using TXA and TXB in conjunction with the memory node.

In the pixel, reset gate (RST) and SGA/SGB are used for resetting photodiodes PDA and PDB, as well as the memory node FD and C. Source follower (SF) and row select (RS) gates are used to connect the pixel to the column circuitry for readout sequences.



(a) (b)

Fig. 2. TCAD potential profile simulation for pixel's two PDs and gates, (a) side view and (b) cross-sectional view.

TCAD potential profile simulation of the pixel's two PDs and gates is presented in Fig. 2 confirming excellent charge transfer and PD-to-PD extremely low crosstalk characteristics. In the simulation one PD is being readout while another PD is still holding acquired photon generated charge. Fig. 2 (a) shows cross-section of the PD being readout and some of the RST, SF, DCG, and RS gates in the periphery. Fig. 2 (b) shows TXA/TXB gates in the center, SGA/SGB gates on the periphery, left PD is holding charge, and right PD is being readout.

III. Multi-exposure High Dynamic Range

Multi-exposure implementation followed classical HDR schema [1] with delay buffers (Fig. 3). T1 stack and T2 stack memory buffers are used to hold digital representations of the pixel signal acquired during first longer T1 and second shorter T2 exposures respectively. At the end of the third shortest exposure T3 all three pixel values were combined into a HDR multi-bit value, usually 20-bit for 3-exposures or 24-bit for 4-exposures (with additional T3 stack memory). Thus 3-exposures allowed up to 120 dB and 4-exposures up to 140 dB HDR in frame image captures.

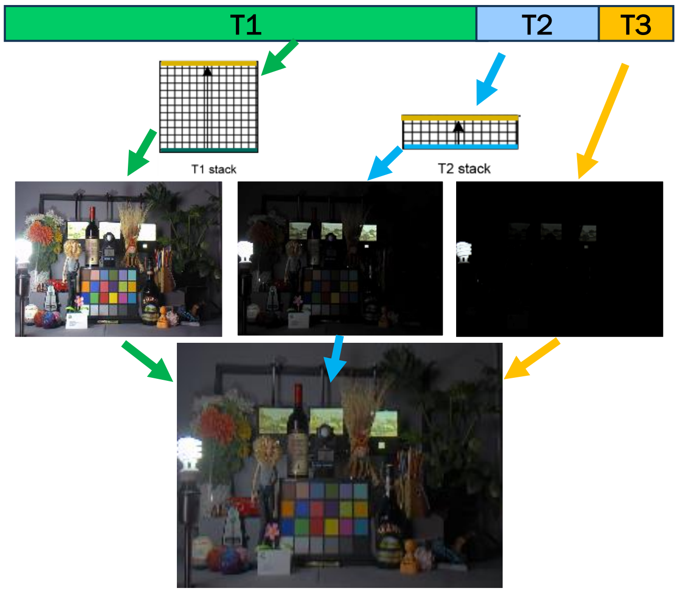


Fig. 3. Multi-exposure HDR schema with delay buffers.

Characterization of 4-exposure HDR mode at room temperature showed a 140 dB dynamic range and all total SNR transitions at or above 30 dB with first T1 exposure readout using high conversion gain (HCG) (Fig. 4).

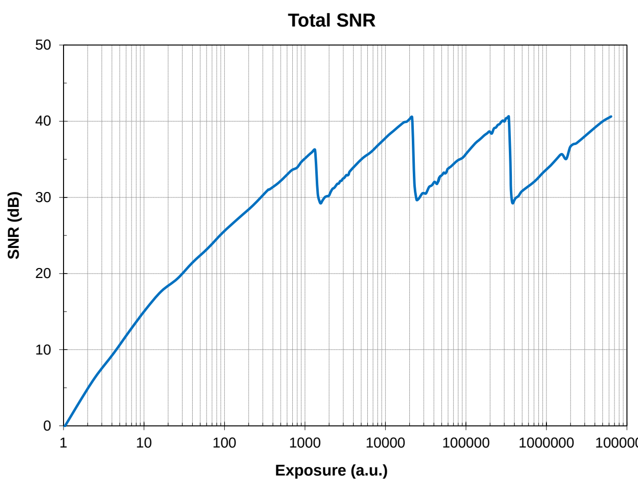


Fig. 4. 4-exposure room temperature 140 dB dynamic range total SNR (HCG T1, LCG T2, LCG T3, LCG T4 exposure readout).

Combination of HCG T1 with low readout noise and LCG T2, T3, and T4 readout with extended dynamic range provided for both excellent low and mid-to-high light performance while covering almost 7 decades of light and exposure HDR.

IV. High Dynamic Range with LED Flicker Mitigation

While classical multi-exposure HDR provides for excellent performance with static sceneries, it does suffer from motion and LED flicker artifacts. We continued our previous work on the pixel super-exposure LOFIC operation [4-5] with further improvement for high ambient temperatures. New timing and potential diagrams of the pixel LOFIC HDR operation are shown in Fig. 5. Mid-level pulsed operation of the TX and DCG gates during charge acquisition and further process optimization reduced the memory node dark noise contribution in comparison to earlier work [4, 5] and thus improved SNR transitions for high temperatures.

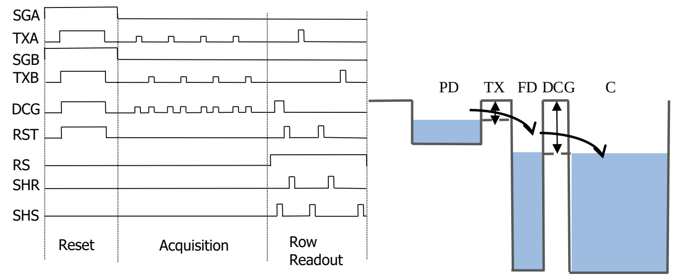
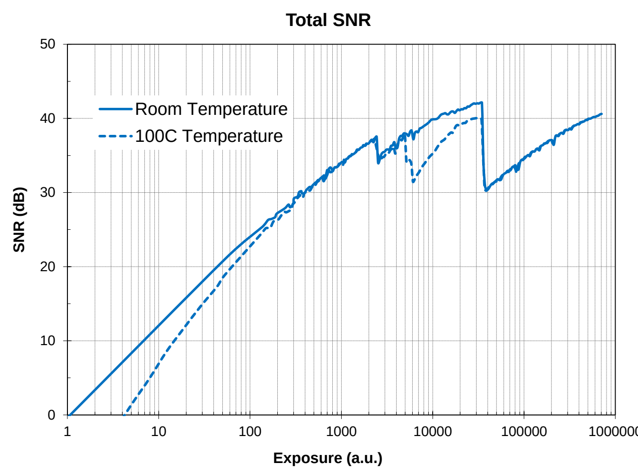
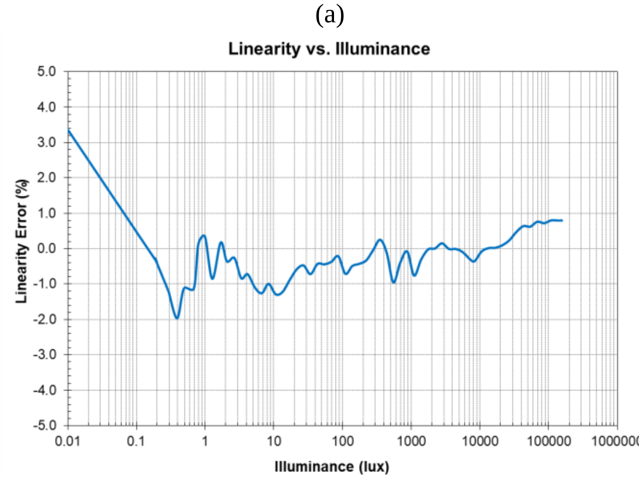


Fig. 5. Super-exposure LFM timing and potential diagrams.

Total SNR comparison of +27°C vs. +100°C junction temperature in Fig. 6 (a) reflected sensor's 120 dB HDR LFM performance.



(a)



(b)

Fig. 6. (a) Super-exposure 120 dB dynamic range total SNR vs. temperature for 16 ms integration time and (b) pixel HDR LFM signal linearity vs. lux illuminance.

This mode of operation also provided for excellent image quality with all total SNR transitions at or above 30 dB for +100°C and 16 ms integration time (Fig. 6 (a)) and even for +125°C and shorter 8 ms integration time.

Linearity measurements from 0.01 lux to almost 200K lux showed excellent color reproducibility by staying within +1% to -1.5% of signal, from less than 0.5 lux to max level in Fig. 6 (b). Pixel’s super-exposure HDR LFM operation captured bright flickering LEDs and eliminated motion artifacts in comparison to classical multi-exposure HDR (Fig. 7 (a) vs. (b)).

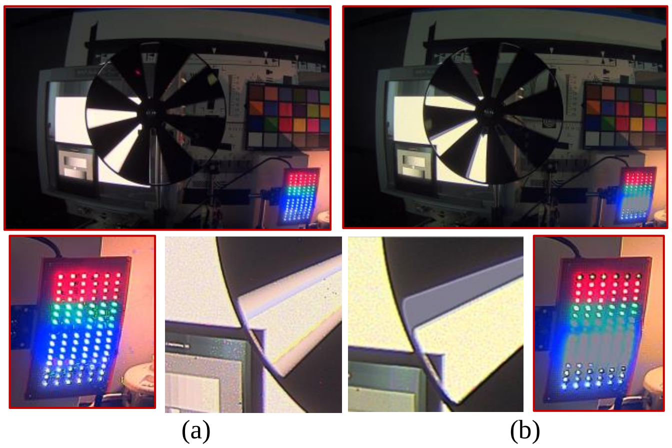


Fig. 7. Flickering LED and motion artifacts image comparison (a) super-exposure HDR LFM vs. (b) 3-exposure HDR,

pLFM method that we developed earlier [3] and implemented in the sensor allowed capturing flickering light sources of any brightness up to millions of lux. pLFM operation timing diagram is shown in Fig. 8.

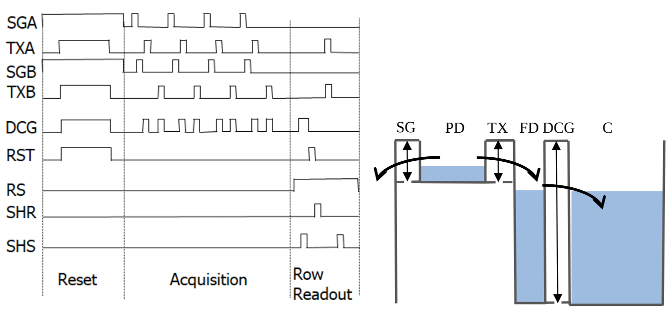


Fig. 8. Pulsed LFM timing and potential diagrams.

In Fig. 8 TXA/TXB and SGA/SGB gates are fully pulsed during charge acquisition in push-pull manner [3]. Their duty cycles regulate electronic PD responsivity in a wide range and charge summing in the memory node. DCG gate may be pulsed as shown to allow capacitor C to connect to the overflow path via the FD and thus extend dynamic range of the captured pLFM image. DCG gate may be also high for the entire length of the charge acquisition.

During readout phase acquired charge in the memory node was readout in double sampling mode followed by correlated double sampling readout of the remaining charge in both PDs.

Fig. 9. Flickering LED turn lights, headlights, and brake lights image captures 3-exposure HDR (top) vs. Pulsed LFM HDR (bottom).

Image comparison of capturing flickering LED turn lights, headlights, and brake lights using 3-exposure HDR and pLFM are shown correspondingly in top and bottom images of Fig. 9.

V. Distance and Image Simultaneous Acquisition

Two-PD pixels in the sensor covered by single μlens additionally enabled distance extraction along with a color image using in-pixel phase detect. Fig. 10 depicts a FDTD optical simulation of the pixel with two PDs in relation to angles of light.

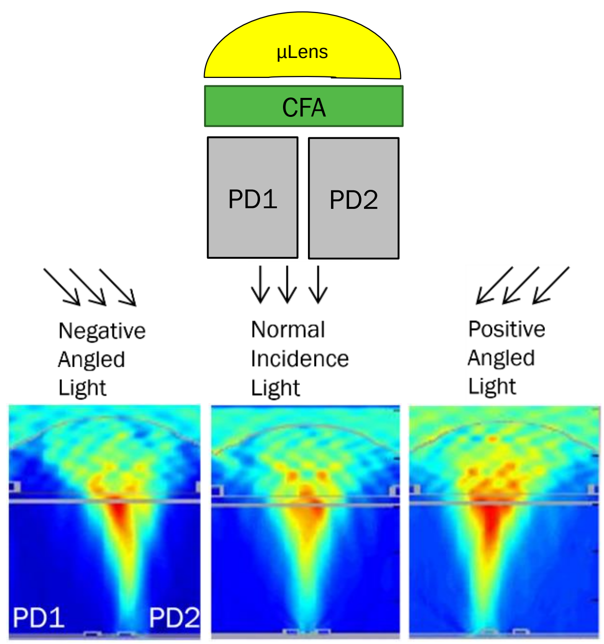


Fig. 10. Phase detect pixel with two photodiodes and its FDTD optical simulation vs. light angles.

Objects at different distances from the imaging lens generate differences in the signal acquired by each of two PDs within the pixel. Both color HDR image and distance information of up to a few meters could be acquired with reasonable accuracy as depicted in Fig. 11, where right image distance data red color showed objects closer and blue color showed objects farther from the camera.

Fig. 11. Captured color image and corresponding signal phase/distance (close objects are reddish, distant objects are bluish).

This additional feature is valuable for some automotive in-cabin and close proximity applications that require fusion of distance and image data.

VI. Conclusion

We discussed performance and features of the 1.3 MP automotive HDR image sensor based on enhanced 3 µm pixel with two PDs and eight gates. The pixel architecture allowed implementation of multiple operation modes including multi-exposure HDR, super-exposure LOFIC HDR LFM, and pLFM. These modes covered entire range of typical automotive sceneries and allowed effective mitigation of flickering LEDs and lights. Dynamic range achieved up to 140 dB with all total SNR transitions at or above 30 dB even for greater than +100°C junction temperatures. In combination with HCG low light signal readout that provided for a cinematographic image quality with sharp high color fidelity captures due to linearity between +1% and -1.5% of signal from very low to very bright light levels.

Additional mode of operation in conjunction with two PDs covered by a single µlens enabled distance extraction along with a color image using in-pixel phase detect.

Our future work is focused on smaller and better performing HDR LFM pixels that are based on the same architectural principals.

VII. Acknowledgement

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