3.0µm Backside illuminated, lateral overflow, high dynamic range, LED flicker mitigation image sensor

Minseok Oh[1], Steve Nicholes[2], Maheedhar Suryadevara[3], Lin Lin[1], Hung-Chih Chang[1], Daniel Tekleab[1], Michael Guidash[1], Shaheen Amanullah[1], Sergey Velichko[2], Manuel Innocent[4], Scott Johnson[2]
[1]ON Semiconductor, Santa Clara, CA, USA, [2]ON Semiconductor, Meridian, ID, USA,
[3]ON Semiconductor, Bangalore, India, [4]ON Semiconductor, Mechelen ,Belgium
ON Semiconductor, 2975 Stender Way, Santa Clara, CA, 95054, Minseok.Oh@onsemi.com

1) Introduction

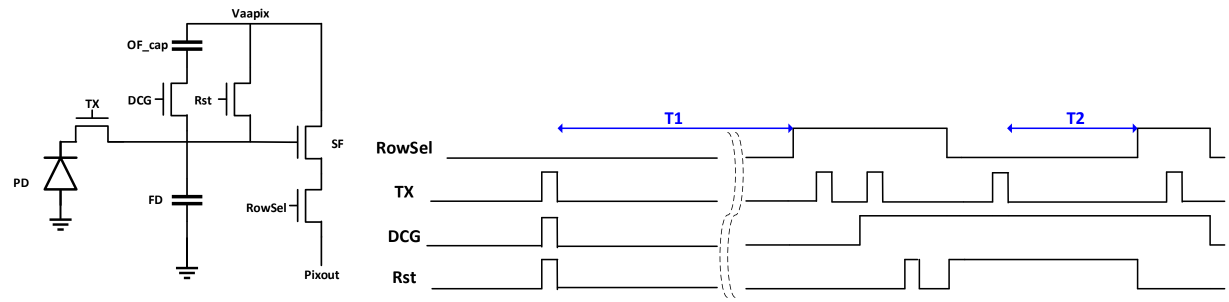
High dynamic range (HDR) operation along with acceptable signal-to-noise ratio (SNR) at wide temperature range is required for automotive, security, medical, IoT, factory automation, and many other applications. In addition, due to the need to match limitations in human visual response, LED flicker mitigation (LFM) is needed to capture low duty cycle LED pulses at all light levels. Linear response and high spatial resolution are preferred for accuracy of color processing and recognition rate, especially for machine vision applications in automotive space. In order to meet these LFM requirements, attenuating the number of integrated photoelectrons by temporal operation has been proposed [1]. It is efficient for high speed operation with the extension of the effective full-well capacity (FWC) by programming the duty cycle of photoelectron integration, but has poor noise floor due to the uncorrelated double sampling (UDS) readout. Another idea using lateral overflow along with split photodiode (PD) has been presented in [2]. Using high conversion gain (HCG) with large PD and lateral overflow with small PD, low noise floor and high effective FWC are achieved. However, due to the high gain ratio between large and small PDs caused by optical gain and conversion gain ratio, dark signal non-uniformity of small PD utilizing UDS is amplified and could be visible at high temperature. This paper presents a Backside illumination (BSI) lateral overflow 3.0um 2.6Mpixels HDR LFM CMOS image sensor with single exposure 96dB dynamic range. In addition, the proposed sensor employs second exposure with short integration time subsequent to lateral overflow capture in order to extend to 120dB dynamic range.

2) Proposed pixel and measured performances

Figure 1 shows the schematic of the proposed pixel and its timing diagram. The pixel circuit consists of a PD, a transfer gate (TX), a floating diffusion (FD) to convert charge to voltage, a reset gate (Rst), a source follower amplifier (SF), a row select switch (RS), an overflow capacitor (OF_cap), and a dual conversion gate (DCG). Once PD is fully filled with photoelectrons under a given illumination after electronic shutter, photoelectrons overflow to FD and OF_cap, in turn. During readout after integration time of T1, overflowed photoelectrons in FD and OF_cap (E2) are sampled via UDS in low conversion gain (LCG) and photoelectrons in PD (E1) are sampled via correlated double sampling (CDS) in HCG. Combination of E1 and E2 provides 96dB based on single exposure. Then, normal CDS with T2 shorter than T1 in LCG is followed in order to achieve 120dB dynamic range. As for image quality at high temperature of combined images of T1, fixed pattern noise (FPN) needs to be considered along with temporal noise (TN) because of UDS readout in lateral overflow pixel operation. To the best our knowledge, fixed pattern noise at high temperature hasn't been considered for lateral overflow pixel performance so far. Figure 2-(a) shows response curve measured at 100°C. Figure 2-(b) shows the corresponding total SNR curve where

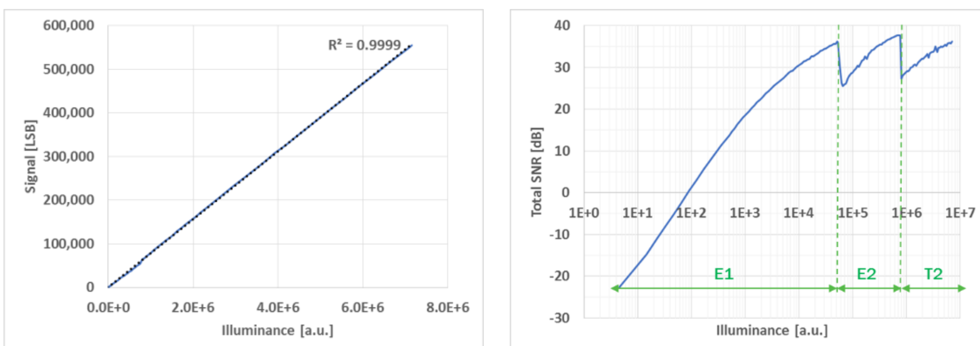
$$total\ SNR = 20log_{10}\frac{Signal}{\sqrt{TN^2+FPN^2}}$$

Minimum total SNRs at both transition regions are higher than 25dB at 100C° in the case of T1=16.6ms and T2=0.13ms. Figure 3 shows image comparison between total SNR 32dB and 20dB at E1 and E2 transition. It is obvious that low total SNR at transition cause poor image quality. Figure 4 shows images of an indoor scene to mimic road conditions at night where the tail light and speed limit traffic sign flickerss at 100Hz with 10% duty cycle. Comparing images taken in overflow mode (a) and in triple exposure mode (b), it is shown that the proposed sensor offers LFM with high image quality and resolution.



(a) (b)

Figure 1. (a) Pixel schematic, (b) Timing diagram



(a) (b)

Figure 2. (a) Signal vs. illuminance plot and (b) Total SNR vs. illuminance plot at 100C° (T1 : 16.6ms & T2 : 0.13ms)

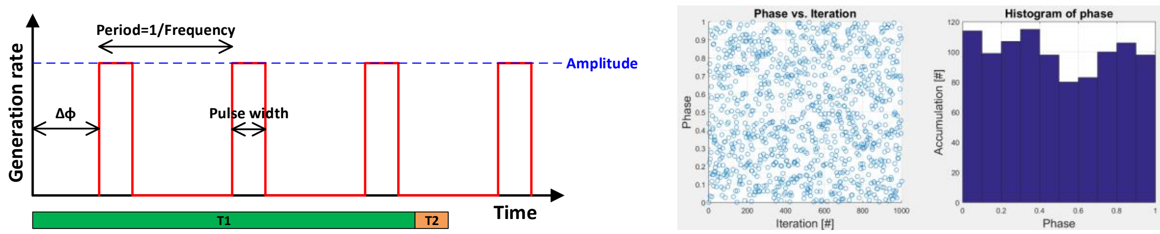
(a) (b)

Figure 3. Images in cases total SNR at E1 and E2 of (a) 32dB (b) 20dB

Figure 4. Images

3) Monte Carlo Simulation for Detection probability and signal modulation

Monte Carlo simulation was carried out to determine LED pulse detection probability (LDP) and LED signal fluctuation (LSF) depending on LED frequency and photoelectron generation rate (PGR) for the given pixel. Figure 5-(a) shows waveform and parameters used for the simulation. Assuming square wave with 10% duty cycle, Δϕ is a random variable with uniform probability distribution and each case is simulated with 1,000 random samplings as shown in figure 5-(b). Amplitude is 'PGR/duty cycle' where duty cycle is 'Pulse width/Period'. In this simulation, T1=16.6ms and T2=0.13ms for 120dB dynamic range.



(a) (b)

Figure 5. (a)Waveform and parameters used for Monte Carlo simulation & (b) An example of Δφ distribution

a) LED pulse detection probability

LDP is defined as '1 - probability to detect nothing in combined signal (T1+T2) during integration time'. As shown in Figure 6, the result of the simulation shows 100% detection probability when T1 integration time is longer than Period of LED pulses.

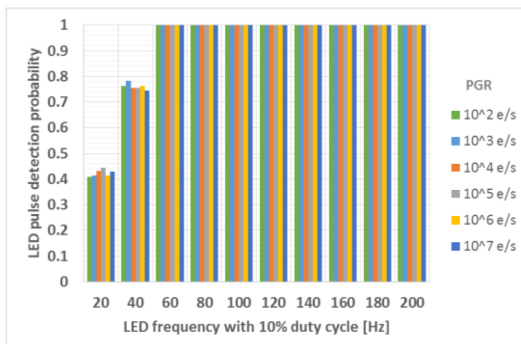


Figure 6. Results of LED pulse detection probability vs. LED frequency vs. Photoelectron generation rate

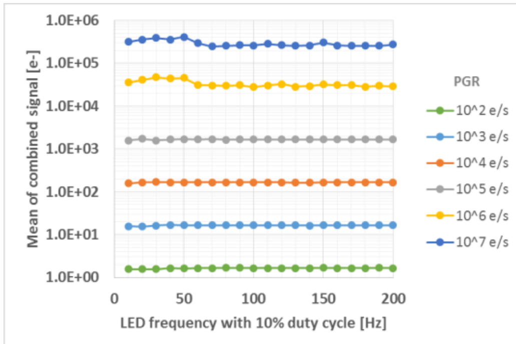
b) LED signal fluctuation

Figure 7-(a) shows the mean of combined signal depending on LED frequency and PGR. The mean of combined signal is proportional to PGR until T2 signal participates into the combined signal (PGR<10^6e/s). As a LFM metric in this paper, LSF in percentage is introduced and defined as 'the standard deviation of the combined signal'/'the mean of combined signal'×100%. As shown in Figure 7-(b), LSF trend before LED frequency reaches at PGR of 10^6e/s is consistent since all the LED signal belongs to T1. In general, as LED pulse period is longer than T1 integration time, LSE is degraded due to the stochastic number of LED pulses captured during integration time as shown in figure7-(c). As PGR > 10^6e/s, LSF becomes greater than 100% because T2 signal that captures a LED pulse stochastically starts to participate in combined signal as shown in figure 7-(d).

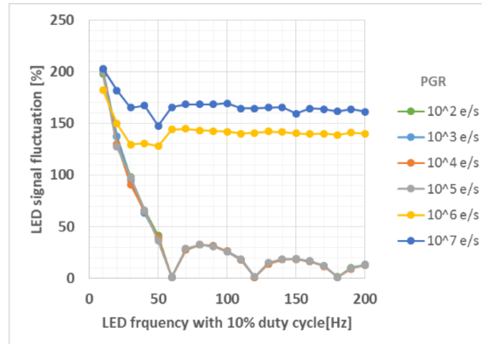
4) Conclusion

The proposed pixel is verified to provide total SNR > 25dB at transitions up to 100°C for automotive application. Table 1 shows the sensor performance developed in this study. As T1 integration time is longer than the period of LED pulse, the proposed pixel achieves 100% detection probability. When integrated LED signal belongs to the range of T1, LSF reaches at the theoretical limit. When integrated LED signal belongs to the range of T2, LSF degrades, but the pixel still detects LED pulse. ON

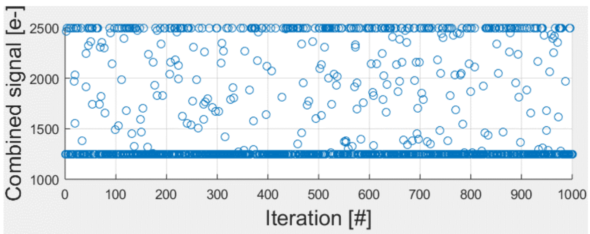
Semiconductor will continue to improve the LSF along with efforts to shrink pixel size since the proposed concept allows.



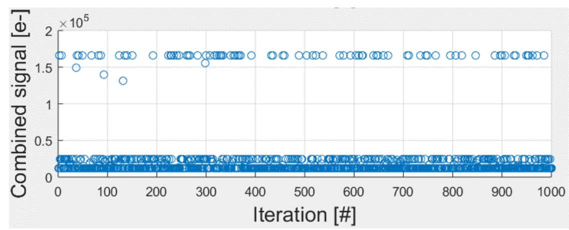
(a)



(b)



(c)



(d)

Figure 7. (a) The mean of combined signal, (b) LED signal fluctuation,
(c) LED frequency=80Hz, PGR=10^5e/s, & (d) LED frequency=80Hz, PGR=10^6e/s

Parameter	Value
Power Supply	2.8V/1.8V/1.2V
Process technology	65nm 2P5M CMOS BSI
Optical format	1/2.5 inch
Chip size	8.8^H x 8.0^V mm^2
Pixel size	3.0^H x 3.0^V μm^2
Number of active pixels	2048 x 1280 = 2.6M
Responsivity (Green, D65, 670nm IRCF, 0.9 lens transmission)	30.4Ke-/lux·sec
Dark TN (Input referred noise)	270 μV_{rms}
Total linear full-well	175Ke-
Dark signal non-uniformity(T_j=80°C, 33ms)	<3e-*
Min. total SNR at E1/E2 transition (T1=16.6ms)	32dB@25C°, 31dB@60C°, 29dB@80C°, 25dB@100C°
Dynamic range	T1 : 96dB, T1+T2 : 120dB(T1/T2=126)

**defect pixels removed (0.01%)*

Table 1. Sensor performance

Reference

[1] C. Silsby et al., ‘A 1.2MP 1/3” CMOS image sensor with light flicker mitigation,’ in Proc. IISW 2015

[2] S. Iida et al., ‘A 0.68e-rms random-noise 121dB dynamic-range sub-pixel architecture CMOS image sensor with LED flicker mitigation’, in Proc. IEDM 2018, pp. 221-224