Twinkling Behavior in Ultra-High-Resolution CMOS Global Shutter Pixels

Tsung-Hsun Tsai, David Marchesan, Naser Faramarzpour, Matthias Sonder, and Eric Fox
Teledyne DALSA Inc.
605 McMurray Rd., Waterloo, ON, Canada N2V 2E9
Phone: 1-519-886-6000 E-mail: elliott.tsai@teledynedalsa.com

Abstract**—We present a twinkling behavior observed in ultra-high-resolution CMOS global shutter (GS) pixels. According to our measurements, the magnitude of twinkling pixels increases proportionally with increased idle time between charge transfer and readout. This suggests that the dark signal causing twinkling is originated from sense node (SN). Further study on activation energy for twinkling pixels shows that the non-stationary dark signal is due to meta-stable oxide Shockley-Read-Hall (SRH) Recombination/Generation (R-G) centers, likely located at the shallow trench isolation (STI) interface. Since twinkling is directly influenced by readout idle time, this artifact becomes prominent in particular with ultra-high-resolution CMOS image sensors operated in GS mode.**

I. INTRODUCTION

Pixel artifacts caused by various random telegraph signal (RTS) sources in CMOS image sensors have been extensively studied and reported in the last decade [1-7]. These previous studies typically focused on a 3-transistor (3-T) or 4-transistor (4-T) pixel where rolling shutter (RS) applies. In this study we have investigated twinkling behavior in a 5-transistor (5-T) pixel with pinned photodiode (PPD) operated in global shutter (GS) mode. What makes GS pixels unique is that collected charges are stored on the sense node (SN) for much longer durations than in RS pixels. As a result, any slight increase of the dark current at SN would manifest itself given enough time before readout. A large resolution of CMOS image sensor usually comes with a relatively slower frame rate, so dark current generated in SN has more time to build up and contribute to normal, hot, and twinkling pixels. While both normal and hot pixels have temporally constant dark current, twinkling pixels have a non-stationary dark current over time. The phenomenon has been measured and analyzed to provide information toward improving area-scan GS pixel design.

II. PIXEL OF INTEREST

The 5-T pixel (Fig. 1) used in this study consists of a PPD, a reset transistor (RST), a source follower (SF), a row select switch (RSEL), a transfer gate (TG) and a pixel reset transistor (PR). It has a pixel pitch of 6 µm and is suitable for GS operation, and the applied timing for such mode is shown in Fig. 2. The test sensor is fabricated in a 0.18-µm CMOS image sensor (CIS) process, and the analog-to-digital converter (ADC) is implemented in a column-parallel fashion with a 12-bit resolution. The measurement is done at dark and under room temperature unless otherwise specified. Different pixel timings are applied in a later section to help the analysis. V_{RST} on-state is set high to enforce a hard reset.

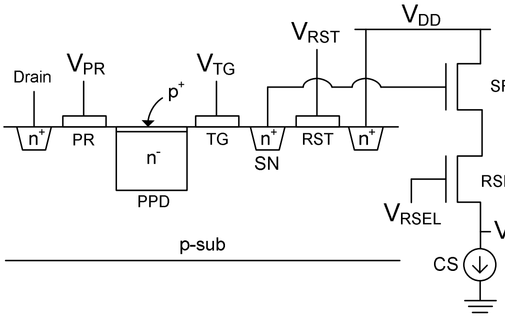

Fig. 1. Conventional 5-T pixel.

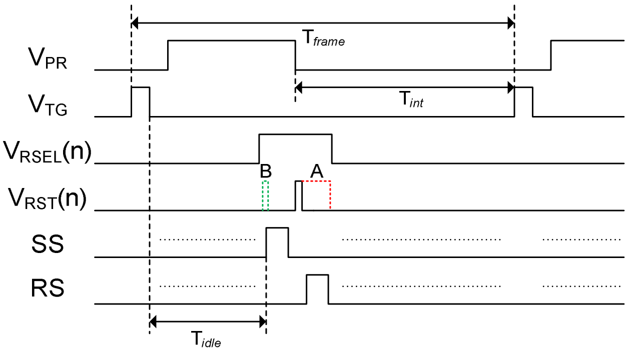

Fig. 2. Timing diagram. Signal sampling (SS) and reference sampling (RS) are required to complete one ADC conversion, and n indicates the number of row being processed.

III. CHARACTERIZATION BACKGROUND AND SETUP

The temporal behavior of each twinkling pixel is collected over a long period of time. Since the twinkling is found to happen primarily at low frequencies, the frame rate of the sensor is reduced to around 1 Hz and over 1,000 consecutive samples are used to capture its behavior. At room temperature, the sensor is around 44 degrees Celsius (°C) during operation. Fig. 3 shows the temporal output of six pixels with twinkling behavior, and a few conclusions can be made from this. First, the twinkling frequency can be very low (from 1 to 0.001 Hz or lower); secondly, the jumping amplitude can vary significantly; thirdly, each pixel can sit at various distinct levels. These indicate an RTS source exists in the pixel.

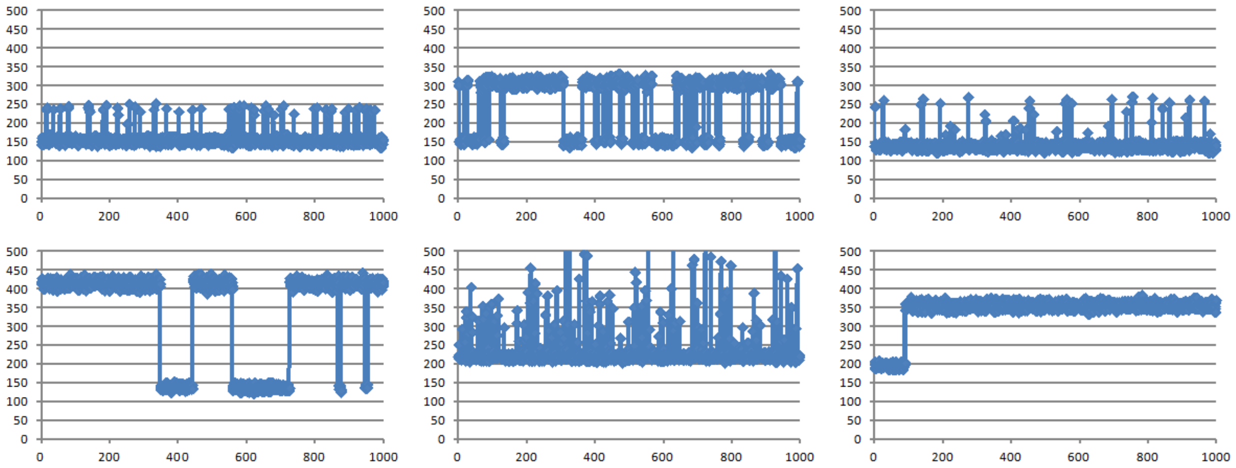

Fig. 3. Temporal behavior of the twinkling pixel (unit of x-axis is second, y-axis is DN).

IV. TWINKLING PIXEL CHARACTERIZATION

Fig. 4 illustrates the measured maximum signal variation at different idle time (T_{idle}) (the top curve), which changes between 0 (the first read-out row) and 178 ms (the last read-out row) when the frame rate is 5 Hz. In another separate test, we have found that changing integration time (T_{int}) does not affect the twinkling behavior; therefore T_{int} is set to the minimum to minimize dark current contribution from PPD. The red horizontal dashed line indicates a threshold defined by 6 times of the sigma (σ) which equals the sensor random noise (RN). In the left side of the figure is a green circle, where the enclosed area shows that the maximum variation is well under the 6σ range when T_{idle} is short; however as T_{idle} increases, the maximum variation gradually moves above the threshold (contributed by the nominal SN dark current) and a growing number of huge jumps occur randomly. These huge jumps are what one sees as twinkling pixels where sometimes their dark currents are higher than the nominal. Another curve in this figure shows how many pixels are twinkling above the red line threshold under the given 100 frames, which increases almost linearly from 0 to nearly 1,000 ppm when T_{idle} changes from 0 to 178 ms. According to this figure, the twinkling pixels increase in magnitude and amount with increased T_{idle}.

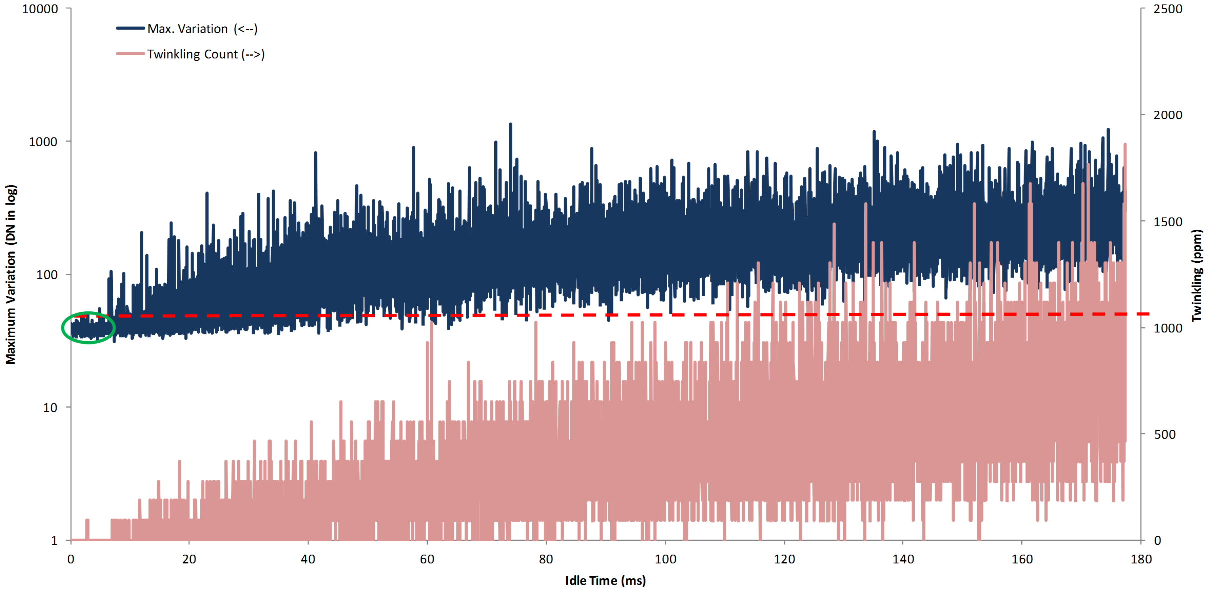

Fig. 4. Measured maximum pixel variation over 100 frames with different idle time.

In order to prove that the dark current which contributes to twinkling behavior accumulates over T_{idle}, we modify the pixel timing in Fig. 2 to two different schemes. In timing A, the reset pulse extends to enclose the whole RS period, and in timing B the reset pulse moves to the beginning of each row, prior to SS. The measured histograms of maximum signal variation of the two modified timings along with the regular operation are plotted in Fig. 5, where the y-axis is normalized. According to this figure, the dark signal is not affected by extending the reset pulse (timing A, the peak of histogram shifting toward left is due to the absence of reset kTC noise), but cleared out completely if the reset happens prior to SS (timing B, reset kTC noise is cancelled and no SN dark current present). Although this twinkling is somehow similar to the SF RTS noise, we have learned from [3] that the commonly known SF RTS noise is introduced by the interface trap in the SF, and highly dependent on the period between two samplings. In order to rule out this theory, we have changed the double sampling period of our timing and find the twinkling does not change in magnitude or amount. In addition, the SF RTS noise shows up as a three-state mechanism, whereas the twinkling pixel could have multiple levels in some cases. These results support the claim that this twinkling is dependent to T_{idle} and not due to the SF RTS noise.

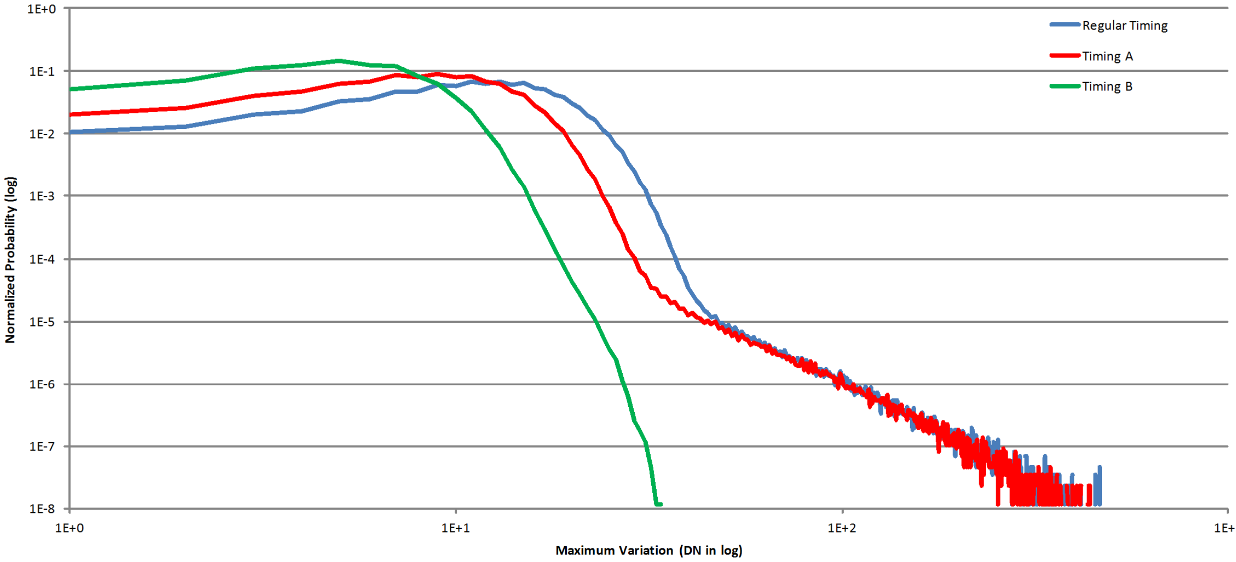

Fig. 5. Normalized histogram with different timing schemes.

Origin of the discrete and high dark signal has been proved to be originated from SN; however the underlying cause has two possibilities [7]. One approach to further distinguish them is to find their activation energy, which was shown to be lower than the mid band gap for the trap-assisted tunneling (TAT) mechanism [5-6] and around mid band gap (0.6 eV) for meta-stable Shockley-Read-Hall (SRH) generation mechanism at shallow trench isolation (STI) depleted oxide interface [7]. As a result, we measured the temperature dependency of dark signal to extract the activation energy of twinkling pixels. In Fig. 6, the histograms show the dark signal histogram of twinkling pixels calculated individually with respect to corresponding T_{idle} at different temperatures. According to the plot, the dark signal increases as temperature rises, where a long tail manifests and the peak gradually flattens.

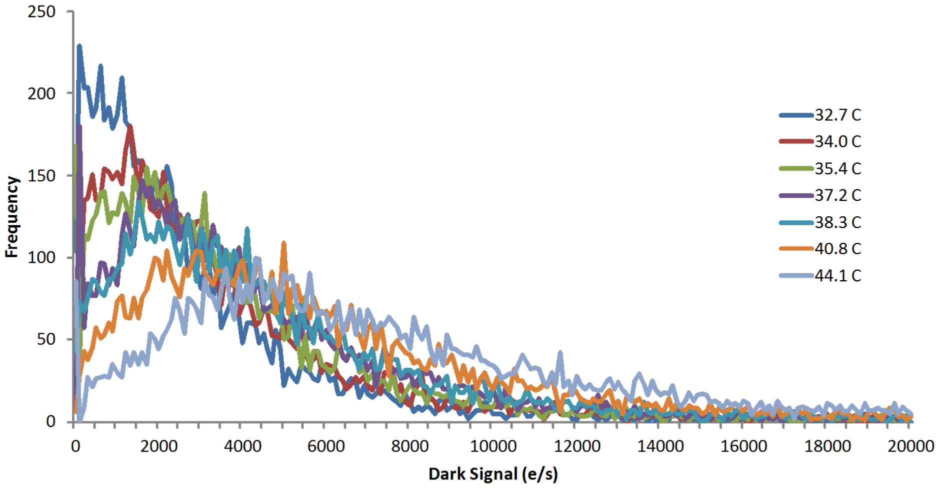

Fig. 6. Dark signal histogram at different temperatures.

We then choose one single pixel out of the twinkling ones and compare its temperature dependency with one normal and one hot pixel in an Arrhenius plot shown in Fig. 7. It is clearly seen that hot pixels have a higher doubling temperature (15 °C), while twinkling and normal pixels are similar in this regard (around 9.5 °C). The extracted activation energy for normal, hot, and twinkling pixels are 0.62, 0.38, and 0.63 eV, respectively, where both the normal and twinkling pixels have activation energy close to the mid band gap (typical for SRH generation mechanism [7]). For the twinkling pixel, we have also observed a proportional linear relationship between its dark signal and the supply voltage (V_{DD}). These findings indicate that twinkling is unlikely a TAT mechanism at the lightly doped drain (LDD) region under RST gate, which would have much lower activation energy and a dark signal that grows exponentially with V_{DD} [5-6].

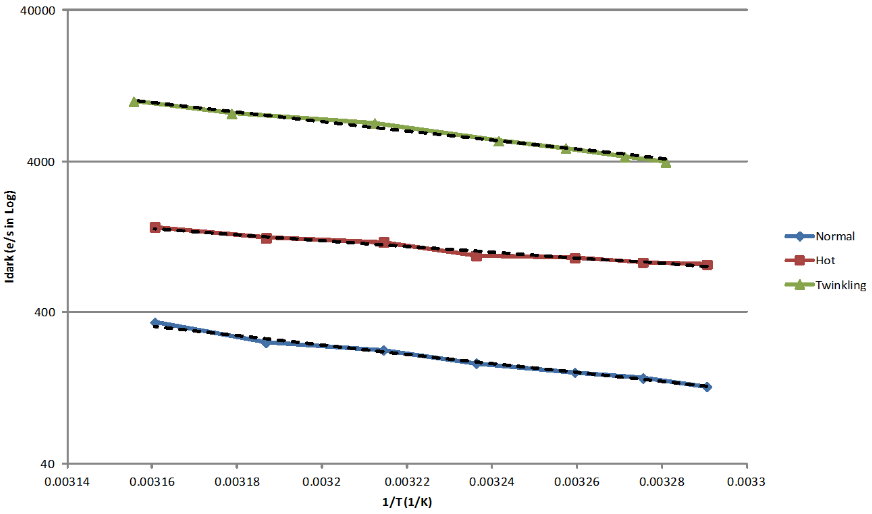

Fig. 7. Arrhenius plot of dark currents from normal, hot, and twinkling pixels. Black dashed lines are fitting lines.

V. CONCLUSION

An over 50-million-pixel CMOS image sensor, which provides GS mode for various applications, is manufactured, and a pixel twinkling behavior is studied based on it. In GS operation mode, the signal charges are kept on SN, which is sensitive to any kinds of dark signal due to its relatively small capacity, for a long time before readout. A twinkling of some pixels is observed and believed to be caused by a large, non-stationary dark signal. Based on the experimental results and available references, we believe that the twinkling is induced from meta-stable oxide SRH Recombination/Generation (R-G) centers [7]. In this previous work the STI depleted interfaces near photodiode depletion region is the primary location where the mechanism takes place, whereas with a 5-T GS pixel we believe the same mechanism applies to STI-enclosed SN region. Measurement results have shown that the dark signal causing twinkling originates from SN and is dependent on T_{idle}. Temperature dependency of the twinkling pixels is also studied, and its activation energy is consistent with the typical for SRH generation mechanism at depleted oxide interface. The analysis in this paper suggests that further experiments on SN optimization can help reduce or minimize the discrete and high dark signal that causes twinkling. An overview of the pixel specification and measurement results is summarized in Table I.

TABLE I. PIXEL SPECIFICATION

Pixel Architecture		5-T with PPD
Pixel Pitch (μm)		6
Resolution (M)		> 50
Shutter Type		GS
Average Twinkling Dark Signal at 45 °C (e^-/s)		~ 7,000
Dark Signal Activation Energy (eV)	Normal Pixel	~ 0.62
	Hot Pixel	~ 0.38
	Twinkling Pixel	~ 0.63

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