# On the determination threshold of illumination-adaptive signal selection technology for multi-stage LOFIC CMOS image sensors

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## Abstract

*This paper presents illumination-adaptive signal selection technology for multi-stage LOFIC CMOS image Sensor. The developed CMOS image sensor contains a comparator for determining the amount of overflow electrons. The concept of light intensity determination function is experimentally confirmed. The distribution of dark current at LOFIC and its temperature tendency is shown for the consideration of determination threshold. Furthermore, the activation energy of all pixels was extracted, showing that most pixels are dominated by generation-recombination current. Finally, the result of determination function when the determination threshold is optimized based on the amount of dark current is shown, demonstrating its usefulness.*

## Introduction

Lateral overflow integrated capacitor (LOFIC) technology [1] which accumulates overflow electrons during exposure period into the capacitor in pixels, enables both high SNR and WDR imaging even under low and high illumination conditions with a single exposure and single PD [2]. The two-stage LOFIC CIS achieved more than 120dB WDR performance and high SNR [3] by using two capacitors in pixel.

However, concern arises for increases of output signals and power consumption. Particularly, two-stage LOFIC pixel reads out 3 different types of signals (FD converted, FD+LOFIC1 converted, FD+LOFIC1+LOFIC2 converted signal) and consequently results in output all signals from each pixel (Fig.1-(b)). For example, high conversion gain signal is inappropriate in high illumination pixel due to saturation of PD and overflow photoelectrons. Thus, an innovative method that realizes both data ratio reduction and WDR performance is desired. Toward solving the trade-off, illuminance-adaptive signal selection technologies [4-6] have been developed in recent years. However, studies of illuminance adaptive CIS using multi-stage LOFIC technology for extending DR have not been reported yet. In the case of the N-stage LOFIC pixel, it is considered possible to reduce the number of output signals to 1/(N+1) at the maximum by developing illuminance-adaptive signal selection technologies.

This paper presents a study on the determination threshold of illumination-adaptive signal selection technology for multi-stage LOFIC CIS toward signal output reduction while achieving WDR. The developed CMOS image sensor contains a new structure for determining the amount of overflow photoelectrons, and the concept of it and measurement results are presented below.

## Concept of signal selection technology and importance of determination threshold

Fig.2 and Fig.3 show an illumination-adaptive signal selection technology by judging the amount of overflow photoelectrons. In Fig.2, if the light level is low, few or no overflow electrons are accumulated, and the converted signal voltage is low. Then, HCG signal selected by the determination result of light intensity is output. On the contrary, if the light level is high, only LCG signal is selected due to the large amount of overflow electrons. In order to apply this technology to two-stage LOFIC CIS, two reference voltages ($V_{Ref1}$ and $V_{Ref2}$) are needed to determine three light intensity states (Low, Mid, High) and output only one designated signal, according to Fig.3. This concept will lead to the reduction of output signals by 1/3, which is to be useful toward low data ratio and low power consumption.

On the contrast, it may cause misjudgment at determining Low or Mid state of light intensity because of the small amount of overflow electrons and dark current at diffusion region may affect the judgment as explained in Fig.4 [7,8]. Thus, reference voltage needs to have some margin to avoid misjudgment toward the dark current. However, if the margin is too large, it leads to selecting HCG signal in its non-linear regions (Fig.5). This operation can induce a misjudgment of determination and read out inappropriate signal and is concerned about the reliability of sensing applications.

Therefore, quantified distribution of dark current at LOFIC diffusions over the entire pixels is needed to set determination threshold (hereafter, $V_{Ref}$) for the stable illumination-adaptive signal selection technology using multi-stage LOFIC pixel.

## Measurement results of the developed chip

A prototype chip that contains light intensity determination function described above was designed and fabricated, and its functions and performances were measured.

Fig.6 shows a micrograph of the developed chip, which was fabricated with a 0.18μm CMOS Image Sensor process. The pixel size is $5.6\mu m^H \times 5.6\mu m^V$ using single LOFIC, the number of effective pixels is $640^H \times 480^V$, and a comparator and a selector per column for determination function as shown in Fig.7. The only selected signal that is determined by the comparator is readout according to the figure captions.

In Fig.8, the comparator consists of an operational amplifier, register, and signal selector. The change of voltage in VLINE caused by overflow photoelectrons and

$V_{Ref}$ are input into comparator, and it determines which is larger. The results of comparison output as Bit signal (0 or 1 values) in each determination result (Low light or Mid light, Mid light or High light) and the selector is driven when the appropriate signal is read out from pixel. As a result, only signals corresponding to the determination are to be sampled to S/H capacitors. In addition, S1 signals (noise voltage and signal voltage) can be read with CDS (correlation double sampling) operation using this determination mechanism, which makes it possible to enhance SNR characteristic of S1.

Fig.9 shows the imaging results as a proof-of-concept of the proposed technology. Fig.9-(a) indicates that S2 signal, read out by the LCG is able to take an image with high saturation at the stuffed doll with high illuminance. However, the background of the picture is blacked out because of low illumination and low CG readout. Fig.9-(b) shows that Bit signal is 1 value at the region determined as high illumination such as stuffed doll. In contrast, the Bit signal outputs 0 value for low illumination pixels. As a result, only one signal is autonomously selected according to the light intensity determination and outputs from each pixel. As for Fig.9-(c), the image was generated by synthesizing both S1 signal and S2 signal. Furthermore, it was gamma-corrected ($1/\gamma = 0.56$), and digital gain ($G_{S2}$) according to the result of Bit signal (Fig.9-(b)) was applied for S2 signal (FD+LOFIC1 gain) below the equations.

$$Image_{S1} = (2^{13}-1)\cdot\left\{\frac{(DN_{raw(S1)} - DN_{dark(S1)})}{(2^{13}-1)\cdot G_{S2}}\right\}^{\frac{1}{\gamma}} \qquad (Eq.1)$$

$$Image_{S2} = (2^{13}-1)\cdot\left\{\frac{(DN_{raw(S2)} - DN_{dark(S2)})}{2^{13}-1}\right\}^{\frac{1}{\gamma}} \qquad (Eq.2)$$

As an addendum, the upper quarter of the image is dark because of the less sensibility PD pixel structure on the prototype chip.

It is shown that the proof-of-concept of light intensity determination function was successfully confirmed. For the consideration of the influence of dark current, the distribution of dark current at diffusion region of LOFIC1 has been studied next.

Fig.10 shows the distribution of dark current of diffusion region at LOFIC1 and their temperature dependency. Each of them is measured with ± 0.25K accuracy and calculated by 6 dark images with different values of exposure time (0.10s, 0.20s, 0.40s, 0.63s, 0.83s, 1.0s), respectively 100 frames averaging. Dark current has been calculated in each pixel using the least squares method. It indicates that dark current at diffusion regions cannot ignore when using light intensity determination because the mean value of it gets higher as the temperature increases. At 317K, the distribution of dark current spreads much more compared with the result of 274K.

In addition to this, Arrhenius equation makes it possible to confirm the dark current generation origins [9]. Fig.11 shows the distribution of activation energy of the dark current. The mean value of activation energy was approximately 0.51 eV. It was calculated in each pixel, and the result indicates that most pixels are dominated by generation-recombination current as their mode range of activation energy is near the half (0.57~0.58eV) of the Si bandgap (1.12eV).

Fig.12 shows that there is a negative correlation between dark current and activation energy in particular column of pixel array. The correlation suggests that pixels with large dark current measured at 317K are due to pixel defects because of the tendency of low Ea. Thus, possible origins such as metal contamination of diffusion layer must be controlled carefully when diffusion regions are formed because large dark current can affect the determination function.

Fig.13 shows the correct determination ratio. It indicates the ratio of pixels whose value of dark current is the value of the horizontal axis (necessary margin when considering dark current) or below, toward all pixels of specific region, considering distribution of dark current as for Fig.11. It shows that $V_{Ref1}$ (determination threshold) can be set according to a target value of correct determination ratio. For example, when the target values of misjudgment pixels are set within 0.1% (converted into the number of pixels: nearly 115) of the total pixels at a temperature of 317K, approximately 0.56 [arb.unit] is needed for the margin. This method is used for calculating determination threshold as explained below.

In Fig.14, the result map of determination function in dark situations at room temperature is shown. In this figure, $V_{Ref1}$ set to keep the misjudged pixels within 10 according to the correct determination ratio. The equation used for this derivation is the following:

$$V_{Ref1} \cong V_{RST} - G_{SF}\cdot V_{darkcurrent} \qquad (Eq.3)$$

where $G_{SF}$ represents SF amplifier Gain [V/V], $V_{RST}$ represents offset reject voltage of comparator [V], and $V_{darkcurrent}\,[V]$ shows the amplitude of input referred voltage of dark current as explained in Eq.4.

$$V_{darkcurrent} = \frac{Q_{darkcurrent}[q]}{C_{FD+LOFIC1}[F]} = \frac{1}{Gain\,[DN/V]}\cdot\frac{d}{dt}DN_{dark} \qquad (Eq.4)$$

As a result, misjudgment occurs in 14 pixels and 9 pixels are thought to be pixel defects because their signal output value (Digital Number) was continuing at a high level in each exposure time. After taking this factor and the values of dark current into account, 5 pixels seem to be suffering from dark current at LOFIC1. Therefore, the criteria of $V_{Ref1}$ can be determined with sufficient judgment accuracy by considering distribution of dark current for determination threshold.

## Conclusion

In this work, the concept of light-adaptive signal selection technology for multi-stage LOFIC CIS and the results of readout are shown. Also, analysis of dark current at diffusion region is demonstrated to properly set reference voltage to a level that is difficult to be affected by the dark current. The results can be useful for readout signal reduction with WDR performance.

**References**

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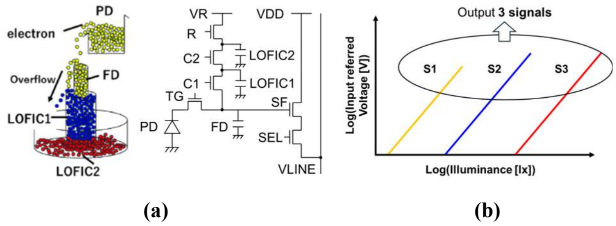



Fig.1 Illustrations of two-stage LOFIC pixel for WDR imaging and signals outputs.

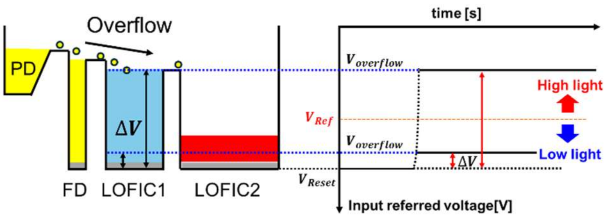



Fig.2 Concept of light intensity determination function for multi-stage LOFIC.

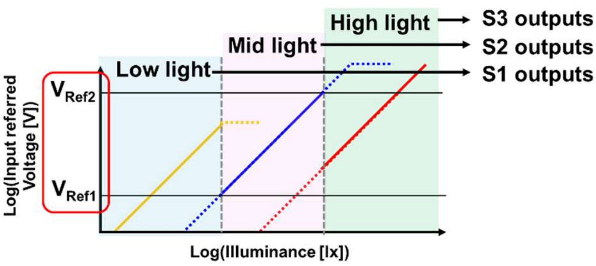



Fig.3 Summary of output signal selection.

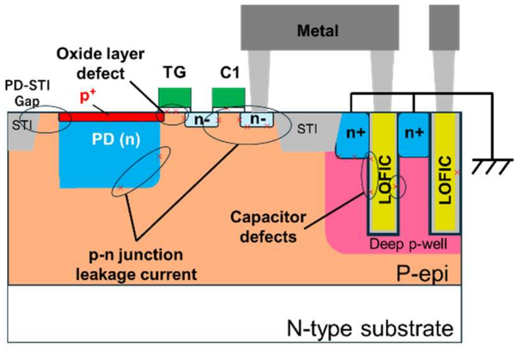



Fig.4 Dark current sources of pixel in CIS.

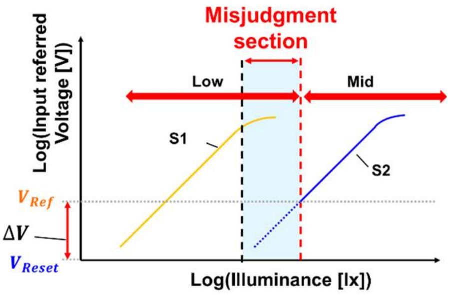



Fig.5 The effect of dark current on the result of signal determination.

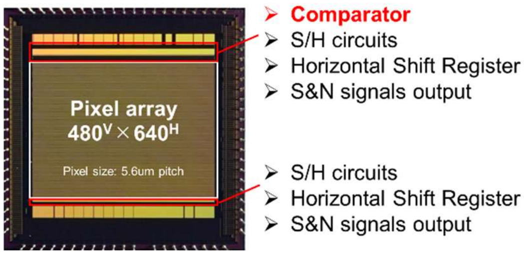



Fig.6. A micrograph of new chip, including comparator for light intensity determination function.

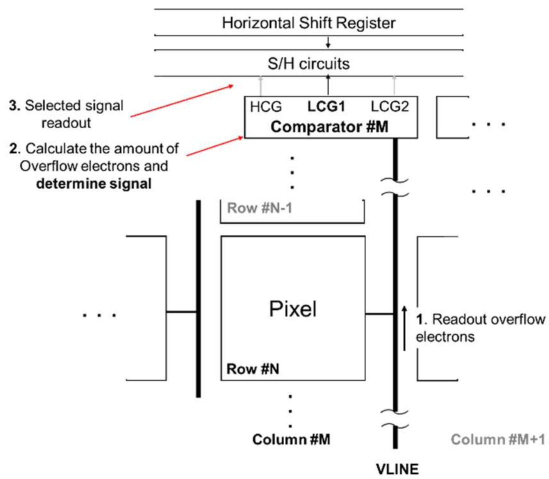



Fig.7 Block diagram of the developed chip.

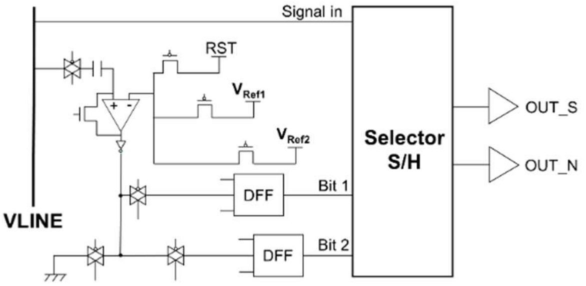
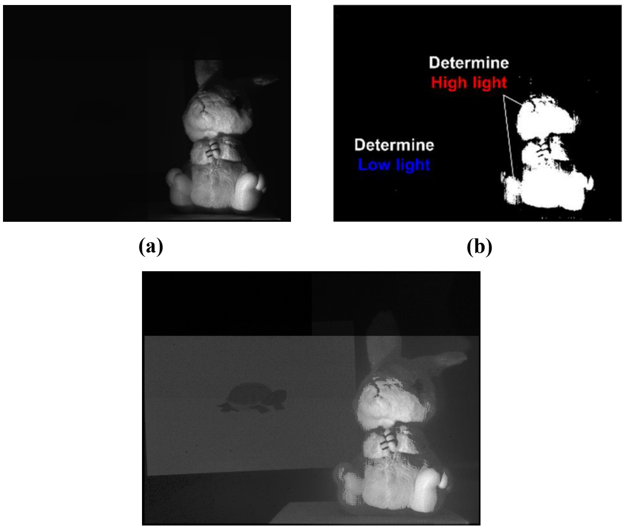



Fig.8 Schematic of comparator block.




(a) (b)

(c)

Fig.9-(a), (b) A picture of S2 signal and Bit signal by irradiating a strong illuminance on specific object. Fig.9-(c) WDR image using light intensity determination function after synthesizing S1 and S2 images by using Bit signal (Fig.9-(b)) ( $\gamma = 1.8$).

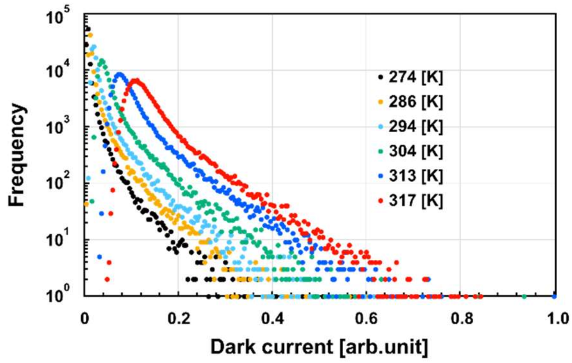



Fig.10 Distribution of dark current measured by six different temperature ranges.

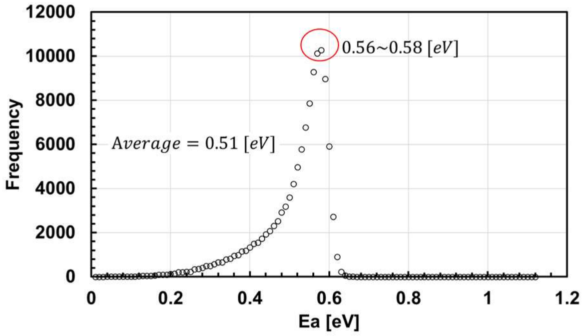



Fig.11 Distribution of activation energy.

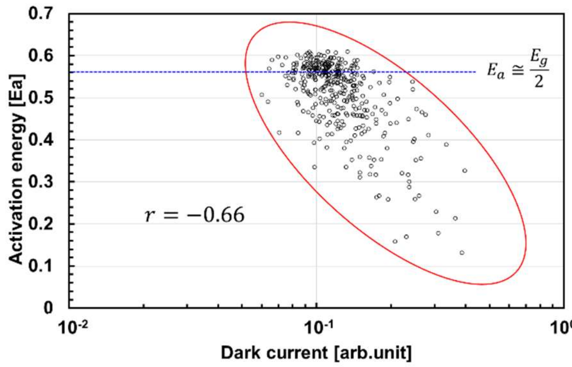



Fig.12 Scatter diagram of Ea vs dark current in a particular column of pixels at 317K.

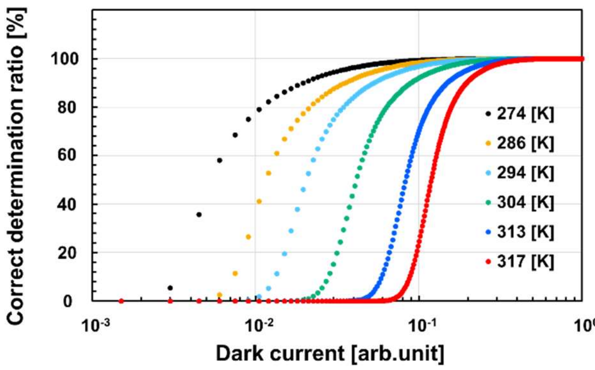



Fig.13 Correct judgment ratio as functions of dark current.

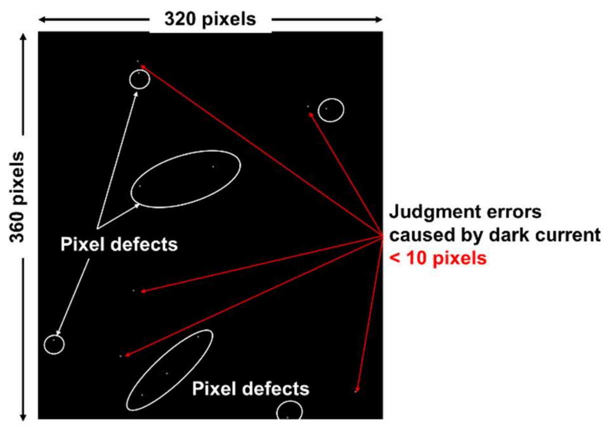



Fig.14 The result of determination function when the $V_{Ref1}$ is optimized based on correct judgment ratio in dark situations. It is measured around 300K and $V_{Ref1}$ is set to keep the error pixels within 10.