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A Novel Wide Dynamic Range CMOS Imager with Adaptive Logarithmic Response employing an In-pixel One-transistor Comparator

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1. Introduction

A wide dynamic range CMOS image sensor that can capture a scene containing both bright and dark areas is highly desirable for applications including automobile driver aids, security cameras and consumer products. Although there have been numerous approaches proposed to expand the dynamic range [1-5], they all suffer from different problems. The main disadvantage of multiple sampling techniques is the cost of the processing needed to synthesize the final image [1-2]. Time-to-saturation approach increases the pixel size which makes it infeasible for high resolution applications [3]. On the contrary, conventional logarithmic compression methods can be implemented in a small pixel area and no frame memory is required for image reconstruction [4-5]. However, the small maximum output swing (typically 0.3V) and responsivity (50mV/decade) make them vulnerable to both fixed pattern and temporal noise.

In this work, a wide dynamic range CMOS imager pixel with a one-transistor comparator is presented for the first time. The logarithmic response is achieved by integrating the photocurrent for a time that depends upon the photocurrent. Moreover, the photo-response of the proposed pixel can be easily varied by the user to optimize the imager for a particular application.

2. Pixel Operation Principle

The proposed pixel schematic is shown in Fig. 1. In order to obtain a higher output voltage swing, a PMOS device is essential as the reset transistor rather than an NMOS. As in the conventional 3T active pixel, the process of forming an image starts when the node V_{diode} is reset to a high voltage, 2.5V, by applying a reset pulse to the gate of M_{p1}. When the reset voltage goes high, M_{p1} stops conducting and the photocurrent (I_{ph}) starts to discharge the diode capacitor. The wide dynamic range operation is achieved by integrating a PMOS comparator M_{p2} into the standard 3T active pixel. M_{p2} is connected so that when the voltage V_{diode} drops to the level a threshold voltage higher than the reference voltage applied to its gate, $V_{ref}(t)$, it will be turned off. The gate voltage (V_{stop}) of the source follower transistor M_{n1} will then be isolated from the photodiode and stops decreasing. Consequently, the comparator will be turned off earlier and the V_{stop} won't saturate to 0V when the light is stronger ($I_{ph,high}$) as illustrated in Fig.2.

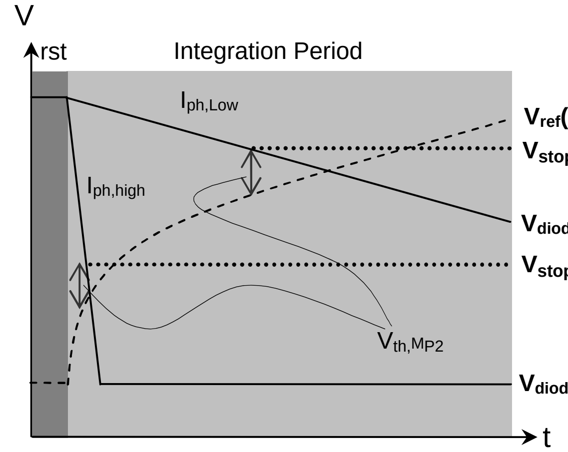

Fig. 2 V_{diode} and V_{stop} of the proposed pixel when a constantly rising $V_{ref}(t)$ is applied.

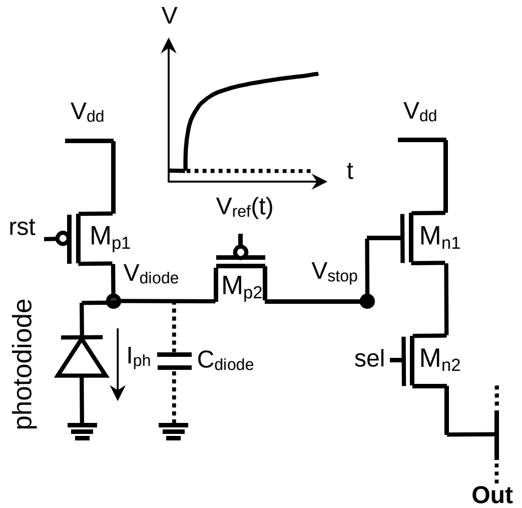

Fig. 1 Schematic diagram of the propsed pixel

Different relationships between the pixel output voltage and I_{ph} can be obtained using different functions of $V_{ref}(t)$. In the context of wide dynamic range image in logarithmic form, the aim will be to turn off the comparator at a time t_s so that the change in output voltage is proportional to the logarithm of I_{ph}. The diode voltage at a time t_s seconds after the reset has gone low:

$$V_{diode} = V_{dd} - I_{ph} \cdot t_s / C_{diode}$$

and the voltage sensed at the output node at the end of an integration period will depend on the value of V_{diode} when

$$V_{diode} = V_{ref}(t_s) + V_{th,Mp2}$$

The reference voltage required to get a logarithmic response with slope S:

$$V_{ref}(t_s) = V_{dd} - V_{th,}M_{p2} - S{\cdot}Ln(\ I_{ph} / I_{ref}\ )$$

The expression can be evaluated to determine the time at which a particular reference voltage will occur. Fig. 3 shows the reference voltages for two sets of logarithmic function calculated using MATLAB.

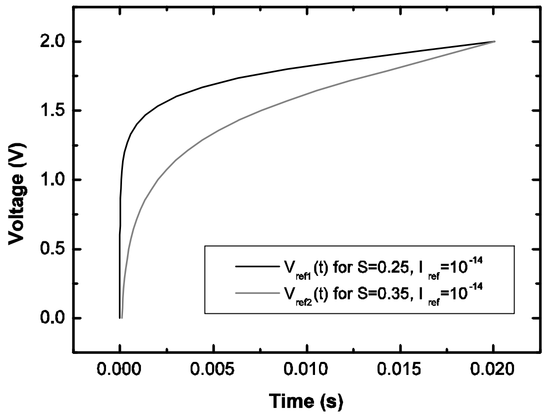

Fig. 3 The $V_{ref}(t)$s needed to realize a logarithmic response over a wide dynamic range with different slopes.

3. Experimental Results

The proposed pixel has been fabricated using the UMC 0.25μm, 1P4M, 2.5V CMOS process. The resulting layout of the pixel with pixel size 5μm×5μm and 17% fill factor is shown in Fig. 4.

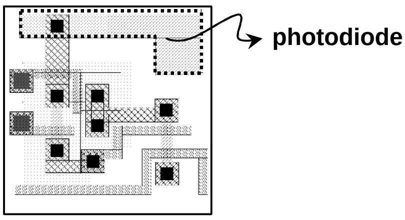

Fig. 4 Layout of the proposed pixel with pixel size of 5μm×5μm and 17% fill factor.

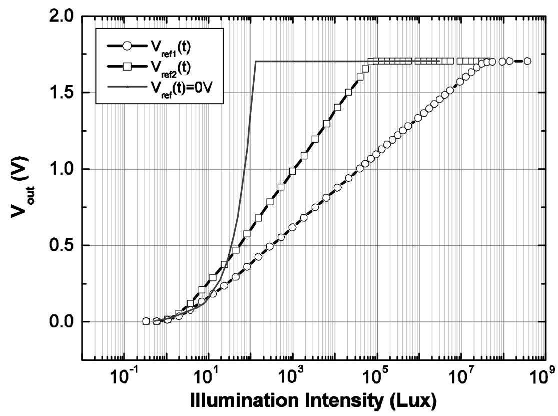

Fig. 5 Measured photoresponse of the proposed pixel using different $V_{ref}(t)$s.

The pixel response was measured using a dedicated electro-optical bench. For all the experiments the time between starting the integration of the photocurrent and sampling the output voltage was set to 20ms and the voltage is monitored by HP 4155B. The optical response of the pixel (see Fig. 5) was tested using a 150W quartz tungsten source with neutral density filter. The measured results show that the pixel has a logarithmic response over a wide dynamic range. In particular these results show that by using two different reference voltages, $V_{ref1}(t)$ and $V_{ref2}(t)$, it is possible to vary the response, in this case from 137dB to 96dB. This also means that the dynamic range of the imager can be further extended. Compared to the response of a conventional logarithmic pixel with a load transistor operating in weak inversion, the responsivity of the pixel is also significantly enlarged to 240mV/decade and 340mV/decade. This will make the pixel less vulnerable to noise. Finally, the results in Fig 5 show that if the reference voltage is held low, the pixel acts as an conventional linear integrating pixel. Other test chip characteristics are listed in Table 1.

Table I. Test Chip Characteristics

Features	Proposed Pixel
Technology	CMOS 0.25μm, 1P4M, 2.5V
Pixel size	5μm × 5μm, 4 Tr./ Pixel
Resolution	30 × 30
Power Consumption	120mW
Responsivity	240 mV / decade
Dynamic Range	137dB (adaptive)
Dark Signal	13.6 mV/sec

4. Conclusion

Several methods have been proposed previously that increase the dynamic range of CMOS pixels. Each of these methods has different disadvantages, but they suggest that the best high dynamic range pixels will match the speed of response of integrating pixels with the dynamic range compression of logarithmic pixels. An integrating pixel has been described which can achieve a dynamic range of up to 137dB by employing a PMOS comparator. Furthermore, the response of the pixel is controlled by a user generated reference voltage. The user can easily change this voltage to vary the response of the pixel to match a particular application and/or scene. The result is a imager that seems particularly well suited to applications, such as driver aids and security cameras, that demand a high dynamic range.

Acknowledgements

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References

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