Inverted Logarithmic Active Pixel Sensor with Current Readout

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Abstract

This article describes a CMOS active pixel sensor structure for a logarithmic pixel with continuous current readout. Here, the arrangement of the photodiode and load found in a conventional logarithmic is reversed. The inverted logarithmic pixel sensor reduces pattern noise and eliminates the dependence of output voltage swing on column load, simplifying both its operation and structural design. This paper includes a detailed design of inverted logarithmic pixel sensor and its analysis, along with operational performance and experimental results**.**

I. Introduction

Current readout active pixel sensors are inherently advantageous in terms of readout speed because the fixed output line voltage at input of transresistance amplifier prevents charge-discharge phenomena [1]. Another benefit of current readout is current mode processing which is relatively compact in size and simple in its operations [2]. One drawback of the active pixel sensors is a large pattern noise caused by the electrical and lithographic characteristic deviations of the active device at the pixel. A design of current readout with pattern noise suppression is desired.

II. Inverted Logarithmic Pixel Sensors

We report a continuous current readout logarithmic active pixel in which the conventional arrangement of the photodiode and load are reversed. As shown in Fig.1(a), a conventional logarithmic pixel employs a photodiode to generate a photocurrent and one or more MOSFETs operating in subthreshold to act as a load. The voltage dropped across the load is dependent on $\ln(i_{photo})$ due to this subthreshold operation. Such a configuration has advantages of continuous operation, thereby enabling temporal as well as spatial random access, and wide dynamic range (~6 orders of magnitude of illumination). Disadvantages include high pattern noise, low contrast due to a small voltage swing (typically 200mV), and relatively poor response at low illumination [3] [4]. The complement of current readout technique of this pixel structure is also possible, where the load and photodiode positions are the same as the conventional logarithmic pixel, but a PMOS buffer transistor is used (see Fig.1(b)). The voltage generated across the load by the photocurrent appears as V_{gs} of PMOS buffer transistor (M1 in Fig. 1(b)). As the light intensity increases, the V_{gs} of the PMOS transistor increases, generating output current which is equal to $K(V_{gs} - V_T)^2$. However, PMOS transistors are known to have higher lithographical mismatch than NMOS, so this structure is expected to display higher pattern noise.

Another contribution to the low voltage swing for the conventional logarithmic pixel is a trade off in the choice of column bias; to maximise V_{out}, a low V_{bias} is required, but a high V_{out} reduces V_{gs} for M1. In our design, (see Fig. 1(c)) the positions of the photodiode and load are reversed, so the voltage generated across the load appears directly as V_{gs}. Now the impedance of the column load has relatively little influence on the pixel operation, thus eliminating another possible source of pattern noise. Moreover, the response of the pixel is now dependent on local, as opposed to global, matching of MOSFET characteristics. A larger than average local *W/L* (caused by lithographic deviation) means that, while the photocurrent generates less voltage across the load, I_{ds} for M1 will be increased in partial compensation. In contrast, a higher than average *W/L* in the conventional pixel logarithmic (see Fig.1(a)) leads to a increase of the M1 V_g, which is compounded by the increased *W/L* of M1 itself. Simulations of the effects of the lithographic deviation, shown in Fig.2 and 3, illustrate pattern noise suppression of the inverted logarithmic pixel sensors. Variations of *W/L* of transistors in the conventional logarithmic pixel sensor produce a large variation of output current, about 142% variation of output swing (from Iph = 0 and 30 pA), while generating only 18% in the inverted logarithmic pixel sensor. Similar effects are expected for V_T deviation. Hence, this inverted logarithmic pixel is expected to display reduced pattern noise and larger output swing than conventional logarithmic pixels, while maintaining continuous readout and wide optical dynamic range.

III. Testing and Measurements

Here, this pixel structure has been implemented with a current-mode readout (Fig.4), where the column load is replaced by an off-chip transresistance amplifier. Current readout has well-known advantages of reduced column charging/discharging, low noise, and ease of analog signal processing. However, it is not normally implemented in integrating pixels owing to the difficulty of on-chip pattern noise correction; this is of lesser concern here because continuous pixels typically require off-chip pattern noise correction. In our case, reading out i_{out} also serves to decompress the logarithmic dependence of V_{out} on i_{photo}, since now $\mathrm{i}_{\mathrm{out}} \propto (\mathrm{V}_{\mathrm{gs}})^2 \propto [\ln(i_{photo})]^2$. In normal operation V_{ref} = 0V.

Photoresponse characteristics for single pixels with various numbers of load transistors are shown in Fig. 5. A consequence of the structure shown in Fig. 1(c) is that M1 operates in sub-threshold at low light intensities. Now $i_{out} \propto e^{V_{gs}}$ and $V_{gs} \propto \ln(i_{photo})$, giving a region where $i_{out} \propto i_{photo}$. At higher illumination, the $[\ln(i_{photo})]^2$ variation is observed. Fig. 6(a) shows a sample unprocessed image captured on a 64 x 64 array of 30µm pixels with 3 load transistors, implemented in a standard 0.35µm CMOS process (see also Fig. 7). While the image can clearly be seen (in contrast to many conventional logarithmic pixel sensors), pattern noise is significant. Some of this is due to the fabrication process, which gives a high fixed pattern noise even for integrating mode sensors (~1.3% of saturation). An image corrected by subtraction of a background reference is shown in Fig 6(b). To obtain best results, this reference image is a white image captured at the same average illumination as the original, indicating the presence of photo-response non-uniformity (PRNU). The PRNU for the sensor is plotted in Fig. 8; this is to be compared with conventional logarithmic pixels where PRNU is typically ~50% of the mean.

To illustrate the advantages of current-mode readout for low voltage operation, the supply voltage has been reduced from its standard value of 3.3V (Fig.9); the sensor works well down to V_{DD} = 2.5V, but degrades rapidly thereafter. Variation of images with V_{ref} is shown in Fig. 10, illustrating the relative independence of the pixel operation to column voltage, and hence insensitivity to the input resistance of any subsequent image processing stages.

IV. Conclusions

The reversed arrangement of the photodiode and load causes the voltage generated across the load by the photocurrent to appear directly as the gate-source voltage of the in-pixel buffer transistor. This configuration eliminates the dependence of the voltage swing on the column load. Pattern noise is also reduced over conventional logarithmic pixels because global variations of threshold voltage are less significant. In addition, a readout technique of the pixel sensor demonstrates reduced signal compression, improved output swing and increased frame rate. However, the independence of the load is not as effective as expected: images are degraded when V_{ref} is higher than 0.7 V. Although pattern noise is expectedly enhanced, there are still noticeable degradations by the pattern noise and thus further processing on the images is expected.

Acknowledgements:

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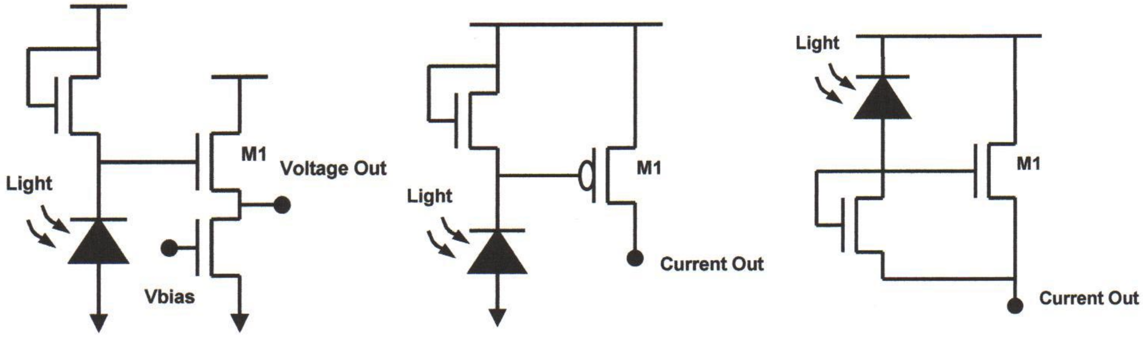

Figure 1. Structures of logarithmic pixel sensors: (a) conventional log pixel, (b) current readout with PMOS buffer, (c) inverted log pixel

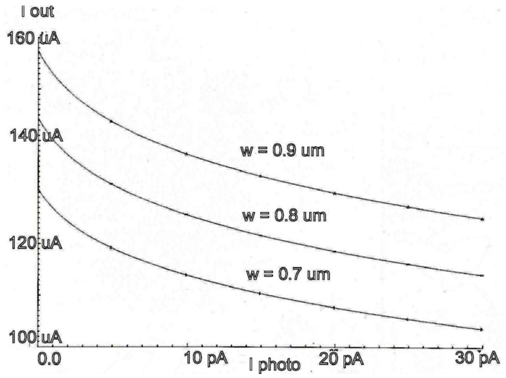

Figure 2. Simulated effect of lithographic deviation on a regular logarithmic pixel sensor. As varying w with a fixed l = 0.35 μm, the output current of the driving transistor, M1, changes significantly. At Iph = 10 pA, variation of w leads to approximately 30 μA (~ 130 % of output swing) of output current, while the output swing between Iph = 0 to 30 pA, is only 23 uA.

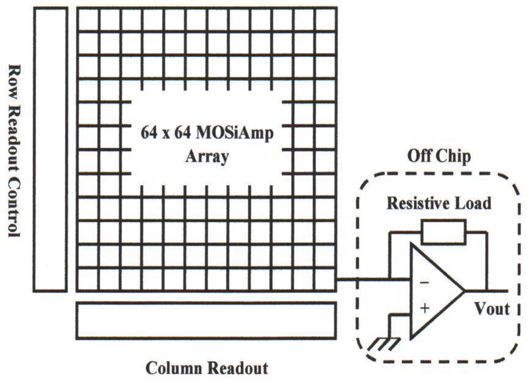

Figure 4. Schematic view of the sensor strcuutre. The output current is converted to a voltage by an external transresistance amplifier. The use of a single conversion circuit improves uniformity, and can be integrated on-chip

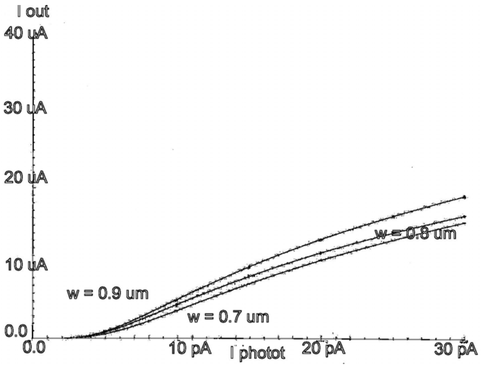

Figure 3. Simulated effect of lithographic deviation on an inverted logarithmic pixel sensor. A partially little variation of output current is caused by the lithographical deviation of W/L: about 20 % of output swing

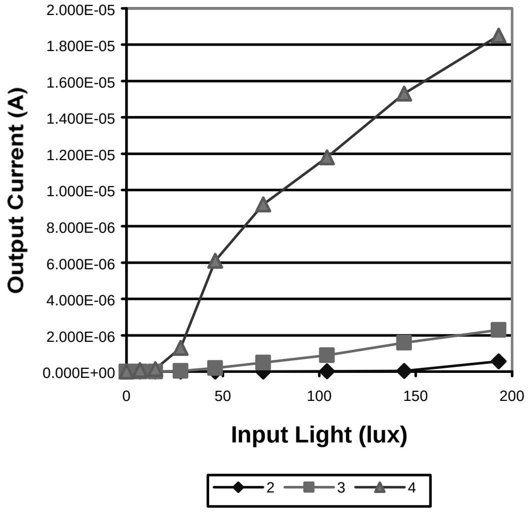

Figure 5. Variation of the photoresponse of the inverted logarithmic pixel with number of load transistors.

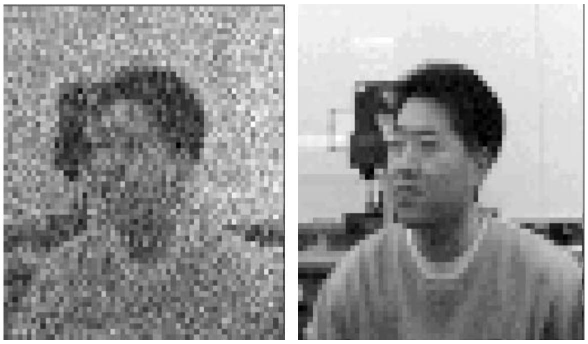

Figure 6. (a) Raw image captured under room light of approximately 200 lux. (b) Image corrected by subtraction of a white image

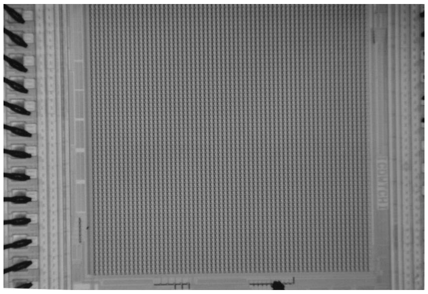

Figure 7. Photograph of the image sensor die. Total die area is 16 mm^2.

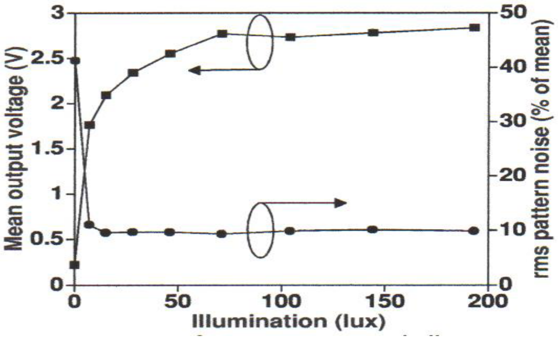

Figure 8. Variation of rms pattern noise with illumination. In the absence of a well-defined saturation signal, pattern noise is expressed as a percentage of the mean output voltage at each point.

$V_{DD} = 3.3$ V $V_{DD} = 2.5$ V $V_{DD} = 2.3$ V

Figure 9. Effect of image sensor V_{DD} on image quality. V_{DD} is nominally 3.3 V for this technology.

$V_{ref} = 0.3$ V $V_{ref} = 0.5$ V $V_{ref} = 0.7$ V

Figure 10. Effect of transresistance amplifier reference voltage on image quality.