Variable Dynamic Range Linear-Logarithmic Pixel

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Abstract - This paper presents a charge compensated photosensor, designed for variable dynamic range, based on environmental conditions. The pixel is based on a three-transistor active pixel sensor, able to switch between linear and logarithmic outpus, based on a self-actuating threshold voltage. The system is meant to reduce the amout of data provided in logarithmic domain, in order to achieve greater accuracy for low light conditions.

I. Introduction

Image capture based on active-pixel sensor (APS) supports a significantly lower dynamic range (DR), between $55dB$ and $80dB$, compared to human perception, at around $90dB$, with real-world scenes able to surpass $180dB$. For this reason, several methods for increasing DR have been researched in the past decades, including sampling multiple frames at different exposures [1], modifying the integration time on the fly [2], and switching between linear and logarithmic response to the charge build-up [3]–[5].

This paper presents an architecture based on the linear-logarithmic pixel based on charge compensation [5], as it induces the least amount of overhead. It also makes use of the independently self-actuated design choices of the variable integration time [2], in order to generate a specific dynamic range for each individual pixel.

II. Implementation

A. Linear-logarithmic pixel

The primary design idea is the linear-logarithmic APS, using a threshold voltage to switch between the two operation modes automatically [3], [5]. It is based on a $3T$ pixel, with an additional photodiode used to compensate the current of the primary detector. In this particular case, the threshold will be variable based on the output, instead of being set to a fixed value for the entire operation.

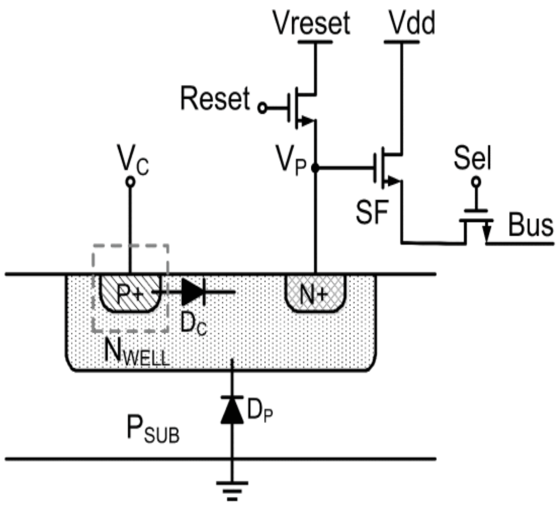

Figure 1: Pixel schematic. [5]

In (1), photodiode D_C is connected to the voltage source, V_C, as well as the other photodiode, D_P. It acts as a switch, based on V_C and the current illumination. In low light conditions, the D_C is reverse biased and the potential in point V_P is higher than V_C. In this case, the output voltage increases linearly with the illumination and integration time:

$$V_{out-lin} = V_{DD} - t_{int} I_P \tag{1}$$

with t_{int} the integration time and I_P the current provided by D_P.

For higher illumination or integration time, D_C becomes forward biased and compensates the voltage of D_P, with the potential in V_P falling under V_C. In this case, the output is no longer linear, but logarithmic:

$$V_{out-log} = V_C - V_T \ln \frac{I_P}{I_S} \tag{2}$$

with I_S denoting the saturation current provided by D_c, and V_T denoting the thermal voltage.

In logarithmic mode, there is potential for significantly higher amounts of fixed pattern noise (FPN). This issue is mitigated by [3] by introducing a two-step charge transfer. This process however introduces and additional gate for signaling when each readout is triggered. The current Implementation aims to resolve the noise issue by allowing each pixel to reduce the threshold voltage based on previous outputs.

B. Individual threholding

Similar to the feedback loop in time variant APS systems [2], this implementation uses a feedback loop in order to change the cutoff point between linear and logarithmic outputs. Based on the results of [3], [5], the optimal threshold value, obtaining a dynamic range of $168dB$, is $1.5V$. This approach however, leads to significant amounts of the output being computed in the logarithmic domain.

In order to circumvent the aforementioned issue, the current approach makes use of the relation between the threshold voltage and the cutoff intensity, being that the switch-off happens at lower illumination values as V_C increases.

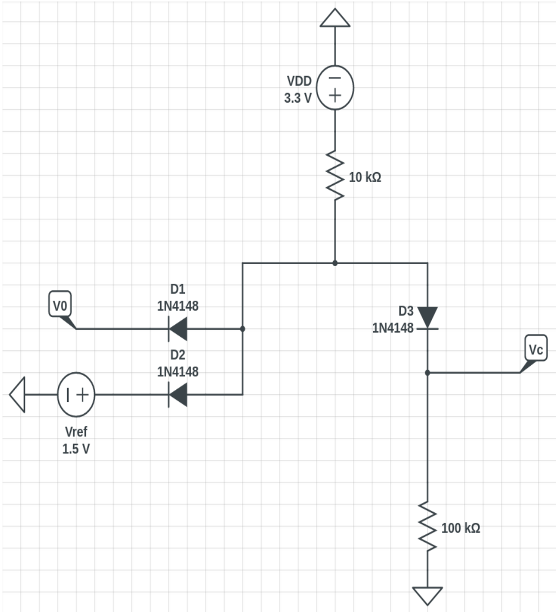

Figure 2: Feedback loop.

Showcased in (2) is the feedback loop, a minimizing circuit meant to set

$$V_C = \min(V_{out}, V_{ref}) \tag{3}$$

with the reference voltage V_{ref} set to the aforementioned $1.5V$. This ensures that, if the output surpasses $1.5V$, the threshold voltage will remain at the level that allows for best performance. In all other cases, if lower illumination levels are detected for an individual pixel, the specific DR is reduces, allowing more information to be passed as a linear response.

III. RESULTS

Individual frame results are best showcased by [5], with the threshold voltage being set to a constant value, and the logarithmic response presented on an exponential scale:

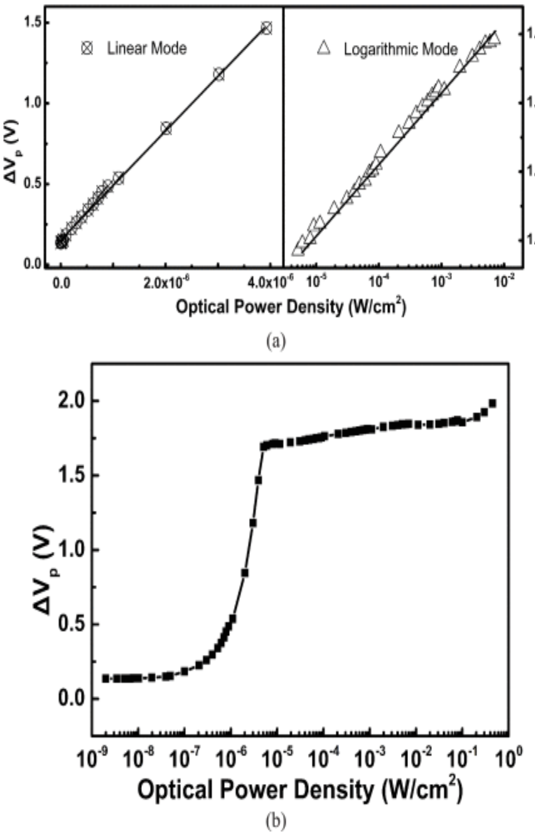

Figure 3: Linear-Logarithmic response scaled. [5]

As showcased in (3), the output in logarithmic domain is generally greater than the reference voltage, ensuring similar performances to previous systems. In lower light conditions however, the circuit will remain in linear response mode, ensuring a denser value range and more accuracy when outputting low intensity results.

Because even in linear mode the circuit can pick up spikes that reach above the $1.5V$ reference, it is ensured that no pixel can be permanently locked in a feedback loop forcing a linear response after each iteration. At the same time, the sensitivity to significant in illumination can lead to temporary situations in which the pixel is over-saturated for one frame. This will be, however, mitigated on the frame immediately following, and the system will resume a stable state.

IV. Conclusion

This paper proposes an HDR system based on a feedback loop on top of a preexisting linear-logarithmic pixel implementation, in order to increase the amount of time the pixel outputs in linear mode. The variable cutoff point ensures that the optimal dynamic range for the current lighting conditions. At the same time, it is ensured that the system will resume a stable state, regardless of the spike in environmental values.

References

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