

A Two-Dimensional Array Imager Demonstrating Active Reset Suppression of kTC-Noise

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ABSTRACT

The design and performance of a two-dimensional photodiode visible imager with a means of reducing the reset noise below the kTC limit is discussed. This active reset scheme uses feedback with an opamp per column in order to increase the gain and therefore the noise reduction over that seen for ordinary "soft" or "flushed" reset. The scheme is compatible with a practically-sized visible imager pixel, 10 μm in this case.

I. INTRODUCTION

The so-called kTC noise greatly limits the low light level performance of photodiode CMOS imagers, being the dominant noise source. Whereas a typical CCD or photogate imager running at video rates may have an input-referred noise floor of 3 to 5 electrons, a typical photodiode imager may have a noise floor of 50 electrons or more because of kTC noise.

The kTC noise is caused by the integration of Johnson noise onto the photodiode capacitance and (in terms of charge) is given by:

$$q_{\text{noise}} = \sqrt{kTC} \quad (1)$$

where k is Boltzman's constant, T is the absolute temperature, and C is the photodiode capacitance. It has been expressed by some that the kTC noise is "fundamental" (that is, unavoidable) but in no sense is this true. It has long been known that kTC noise can effectively be eliminated by correlated double sampling (CDS), but for photodiode imagers this requires a full frame memory so is normally not practical.

Another more recent technique of mitigating kTC noise is to use feedback to reduce the noise below the kTC limit. It had been noticed by Konsonocky[1], Fossum[2], and probably others that the reset noise is reduced by $\sqrt{2}$ in pixels where the n-channel reset transistor goes into the

subthreshold region during reset, as the photodiode voltage approaches a threshold voltage below V_{DD} . The noise reduction in this so-called "soft reset" mode was ultimately understood as a result of a feedback effect [3]. The noise reduction associated with soft reset is modest because the effective gain of the feedback is small, but it became apparent that that if the gain of the feedback could be artificially increased then it might be possible to reduce the reset noise substantially.

Fowler *et. al.* demonstrated a feedback technique using an op-amp within the pixel, and achieved a reset noise reduction of approximately a factor of 4 using bandlimiting and capacitive feedback [4]. As discussed in the opening paragraph, a reduction of this magnitude makes the noise floor of photodiode imagers comparable to scientific CCDs or photogate or pinned photodiode CMOS imagers, without requiring CDS or the use of an external frame memory. Unfortunately, it is not possible to incorporate a complete op-amp in the pixel size available to typical visible CMOS imagers, though this could certainly be done for many types of infrared imagers.

Another feedback method that has been reported [5] uses a capacitive divider to reduce kTC noise in a two-step reset process. This method demonstrated noise reduction of approximately a factor of 10, but again it also wasn't very suitable for resetting photodiodes in a two-dimensional array.

Loose, Koslowski, *et. al.*[6] of Rockwell Science Center presented a method that uses column-based circuitry to convert the pixel source-follower into an inverter in order to get the necessary feedback. This allowed the technique to be used with conventional-sized visible imager pixels. This operation is done in conjunction with a so-called "tapered reset", where the turning off of the reset transistor is carefully controlled. According to their patent, this technique provides a 4 \times reduction in read noise.

II. OUR COLUMN-BASE OPAMP APPROACH

We have developed an active reset method using a single op-amp per column to effect the feed back. This allows us to use the method with practical-sized visible imager pixels as in the Rockwell technique, while still getting the high-gain and fully differential advantages of using a full op-amp, as in Fowler's technique.

We have previously presented the results for a one-dimensional prototype demonstrating this method [7]. The reset noise in this prototype was reduced to about 8 electrons per pixel for a pixel with a conversion gain of $15 \mu\text{V}/e^-$.

III. DESIGN, FABRICATION, AND OPERATION

For the results presented in this paper, we have fabricated a complete two-dimensional imager. It contains a 256×256 array of $10 \mu\text{m} \times 10 \mu\text{m}$ pixels. The array is surrounded by the readout circuitry as well as the column-based reset circuitry that creates the active reset. The chip was fabricated in a two-poly, three-metal $0.5 \mu\text{m}$ process, and entire chip is $8.678 \text{ mm} \times 5.178 \text{ mm}$.

Our method requires only one extra transistor in each pixel added to the conventional 3T structure. This extra transistor controls whether the column feedback line is connected to the gate of the reset transistor. The layout of the pixel is shown in Figure 1.

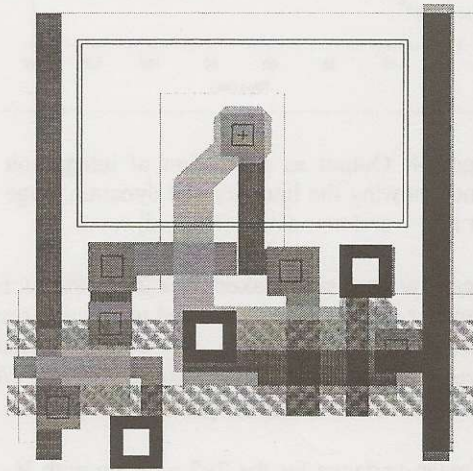


Figure 1: The pixel for active reset contains only one extra transistor. The $10 \mu\text{m}$ pixel is laid out in a $0.5 \mu\text{m}$ process.

A schematic of the pixel and column circuitry is shown in Figure 2. The circuit operates as follows:

First, a hard reset is done. Φ_{Sel} and Φ_{Reset} are brought high, turning on M_{Sel} and M_{Act} . M_{Flush} is turned off, dropping $\text{Pixel-}V_{\text{DD}}$ to a threshold voltage below HTS_VN . The column line V_{Fbk} is forced high through $M_{\text{Init-High}}$, turning on M_{Rst} and resetting the photodiode. V_{Fbk} is then forced low through $M_{\text{Init-Low}}$ ending the hard reset.

In preparation for active reset, M_{Flush} is turned back on, returning $\text{Pixel-}V_{\text{DD}}$ to AV_{DD} (Analog V_{DD}). V_{Ref} is held at ground, making the output of the opamp low. $M_{\text{Init-Low}}$ is turned off and the transmission gate is turned on, disconnecting V_{Fbk} from the external voltage driving it low and connecting it instead to the output of the opamp. Since the output of the opamp is initially low, this has no immediate effect on the photodiode.

To effect the active reset, V_{Ref} is released and the RC network is allowed to bring V_{Ref} towards a bias called V_{Slew} . As soon as V_{Ref} crosses V_{Col} , the output of the opamp begins to rise, making V_{Col} follow V_{Ref} .

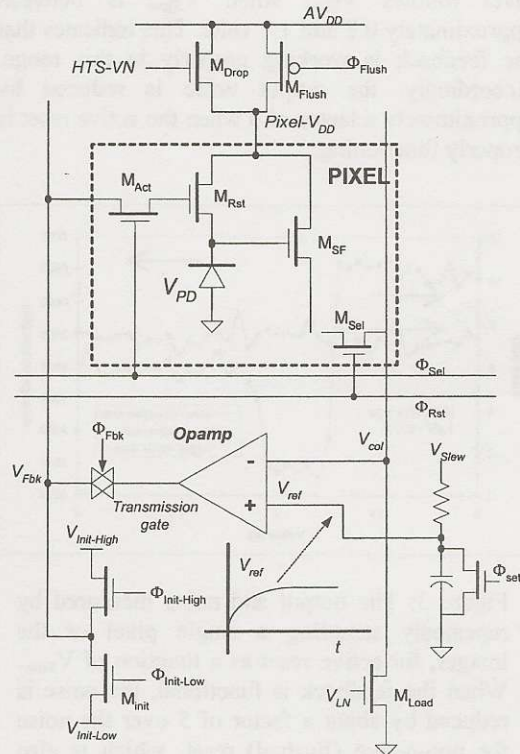


Figure 2: The schematic of the pixel and column feedback electronics for the active reset scheme.

As V_{Ref} reaches V_{Slew} , subthreshold current through M_{Rst} continues to increase V_{PD} and therefore V_{Col} , although very slowly. As V_{Col} rises, the opamp reduces V_{Fbk} , turning M_{Rst} off more strongly and reducing the subthreshold current. The overall effect is a soft reset with increased gain, as desired. This results in a noise reduction roughly proportional to the gain (but ultimately limited by other factors).

The two-dimension imager has decoders and ac-coupled analog signal handling circuitry on chip. However, the pixel address and control timing must be generated off-chip.

IV. RESULTS

We have tested the two-dimensional imager under a variety of conditions, including repeatedly sampling only a single pixel as well as operating the chip as a full imager.

The noise and dc output level for a single pixel as a function of V_{Slew} is shown in Figure 3. The output level follows V_{Slew} when V_{Slew} is between approximately 0.8 and 1.1 volts. This indicates that the feedback is working properly in this range. Accordingly, the output noise is reduced by approximately a factor of 5 when the active reset is properly functioning.

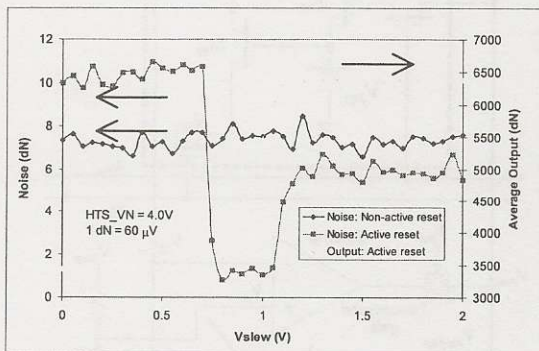


Figure 3: The output and noise measured by repeatedly sampling a single pixel of the imager, for active reset as a function of V_{Slew} . When the feedback is functional, the noise is reduced by about a factor of 5 over the noise for non-active (flushed) reset, which is also shown for comparison.

When it is not, the noise is comparable to the case for non-active reset (that is, ordinary flushed reset). The slight difference between the noise values non-functioning active reset and non-active reset is

probably due to the slight difference in conversion gain (due to the variation in photodiode capacitance with voltage).

We have also operated the chip in the imaging mode, but unfortunately the chip has proved considerably less robust than desired. First, because of the extra transistor and its associated threshold drop, the dynamic range is quite limited. In fact, as mentioned in the previous discussion, the active reset is only functional at all over a quite limited range. Furthermore, the active reset degraded or failed to function altogether unless sufficient time was allowed for the operation. This greatly limited the functionality of the chip.

The output as a function of integration time for non-active (flushed) reset and active reset is shown in Figure 4. As one can see, the response for active reset shows a smaller dynamic range and increased non-linearity.

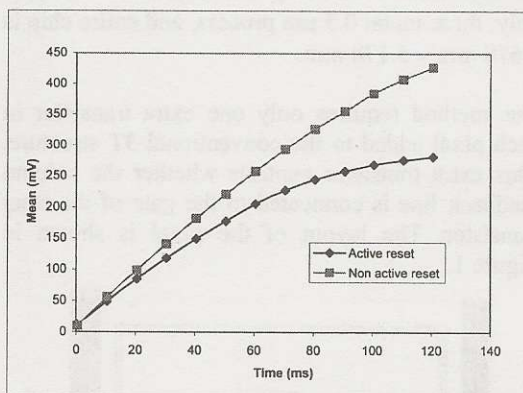


Figure 4: Output as a function of integration time, showing the linearity and dynamic range for active and non-active (flushed) reset.

A mean variance curve taken for a 2×2 window for the imager operating in active and non-active reset modes is shown in Figure 5. The conversion gain derived from the curves is approximately $9.6 \mu V/e^-$ for the non-active versus $6.9 \mu V/e^-$ for the active.

The mean-variance for the 2×2 window with $V_{Slew} = 0.9 V$ shows the effect of the noise reduction, but again it is not very robust.

An image taken with the chip operating in the active reset mode is shown below in Figure 6. The column fixed pattern noise is somewhat high, but otherwise the imager is fully operational.

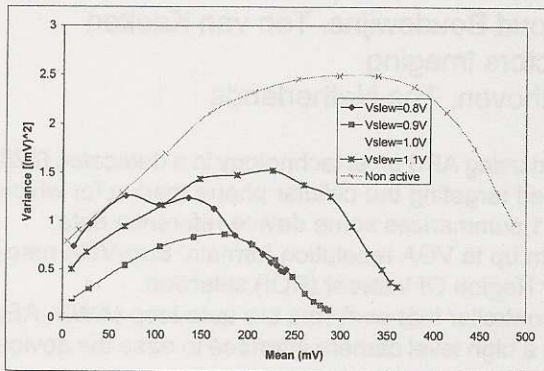


Figure 5: The mean-variance curve taken for the imager in active and non-active reset modes.



Figure 6: An image taken using the imager in active reset mode.

IV. SUMMARY

We have demonstrated a two-dimensional imager with a column-based active reset. This scheme uses one op-amp per column, so it is compatible with practically-sized pixels for visible imagers while still making use of the high gain provided by a full opamp. The imager demonstrated a noise reduction on approximately a factor of 5 when a single pixel was repeatedly measured.

However, the active reset for this imager is much less robust than desired. The dynamic range is limited and the circuit tends to fail to properly produce active reset if perturbed.

Further research and improvements are necessary. Nevertheless, this column-based technique for active reset has demonstrated its potential. With further refinement, the technique may allow photodiode imagers to operate at video rates with a noise floor equal or better than comparable scientific CCDs.

V. ACKNOWLEDGEMENT

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

VI. REFERENCES

- [1] W. Kosonocky, private communication.
- [2] E.R. Fossum, private communication.
- [3] B. Pain, G. Yang, B. Hancock, T. Cunningham, M. Ortiz, and C. Wrigley, "Analysis and enhancement of low-light-level performance of photodiode-type CMOS active pixel imagers operated with sub-threshold reset", *Proc. 1999 IEEE Workshop on CCDs and Advanced Image Sensors*, Nagano, Japan (1999), pp. 140-143
- [4] B. Fowler, M. Godfrey, J. Balicki, and J. Canfield, "Low noise readout using active reset for CMOS APS", *Proc. SPIE 3965*, pp. 126-135, 2000.
- [5] I. Takayanagi, Y. Fukunaga, T. Yoshida, and J. Nakamura, "A Four-Transistor Capacitive Feedback Reset Active Pixel and its Reset Noise Reduction Capability", *2001 IEEE Workshop on Charge Coupled Devices and Advanced Image Sensors*, pp. 118-121, 2001.
- [6] L. Kozlowski, et al, "Low-noise active pixel sensor for imaging arrays with global reset" *United States Patent, US 6493030 B1*, 2002.
- [7] B. Pain, T.J. Cunningham, B. Hancock, G. Yang, S. Seshadri, and M. Ortiz, "Reset noise suppression in two-dimensional CMOS photodiode pixels through column-based feedback-reset", *Tech. Dig. IEEE International Electron Devices Meeting*, pp. 809- 812, 2002.