IMPROVED ON/OFF TEMPORALY DIFFERENTIATING ADDRESS-EVENT IMAGER

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ABSTRACT

We fabricated an improved version of an imager reported earlier [1], primarily by using better pixel circuit and layout principles. The new imager functions over 5 decades of background illumination and has much more symmetrical ON and OFF responses. This imager achieves massive redundancy reduction by temporally differentiating the image contrast. The ideal functions of the pixels are to compute the rectified derivatives

$$\frac{d}{dt}(\log I) = \frac{dI/dt}{I},$$

where I is the photocurrent in the pixel. The values of these derivatives are rectified and output as rate-coded events on the AER bus. This 2.2mm by 2.2mm chip was built in a 0.35um 4M 2P process. The pixels are 40um by 40um and the array has 32 by 32 pixels, each with ON and OFF output. System power consumption is about 30mA at 3.3V.

1. INTRODUCTION

Visual scenes contain a high degree of redundant information. Image data compression is a major issue for image transmission and processing. Although available electronic processing power is always increasing, real-time image processing is still a big challenge. Focal plane image processing is a biologically inspired solution for real-time applications because it makes use of massive parallel processing at the front end and compresses image information before any transmission takes place. Human retinas perform spatial and temporal filtering directly in the retina and transmit data via digital pulses to the subsequent visual processing stages.

Various approaches to focal-plane image processing are underway in the neuromorphic engineering community. The late Jörg Kramer opted for pure temporal filtering, suitable for high compression rates and dense implementations.

We present an improved implementation of Kramer's integrated optical transient sensor. The individual pixels respond to positive (ON) and negative (OFF) illumination changes at separate terminals. Derivatives that exceed the threshold generate ON/OFF events. The events initiate a fully arbitrated four-phase communication cycle that leads to the asynchronous read-out of the pixel-address on a binary bus. The improved implementation has a more symmetrical and more uniform response than its predecessor. It is currently in use as front end for orientation tuning and feature extraction experiments in our lab and also by other partners in the EU project CAVIAR, which seeks to build a vision system based on communication using the address-event representation (AER) [2].

2. CIRCUITRY

The circuits are discussed in detail in [1, 3]. We briefly describe the architecture of the imager, the functionality of the pixel and the AER structure to illustrate the motivation for our changes.

The present imager consists of an array of 32x32 pixels, a y-arbiter, an x-arbiter and a common address bus with two encoders [4]. Each pixel computes the rectified derivatives of the log of the irradiance magnitude it senses by a photodiode. The outputs of the pixels are digital pulses, called ON/OFF events, which rate code the illumination transients. The arbiters are tree structures that handle the communication between the array and the chip to the outside interface. Events are dealt with in order of their time arriving and in case of colliding events the later is queued. The imager interface to a receiver consist of a request, an acknowledge and 11 data bit lines. An event occurring in the pixel undergoes the arbitration in the arbiters and is subsequently communicated to the outside of the chip as an 11-bit address that encodes the pixel location. The imager is a real-time device, which means that an event is communicated after 50ns up to 1ms (dependent on the speed of the receiver) after its occurrence. The AER communication system is particularly beneficial for this application because it dedicates the full communication bandwidth to the active pixels of the imager and conserves the timing information.

2.1 Pixel

The pixel, shown in Figure 1 transduces illumination into a photocurrent with a photodiode. The photodiode is in series with M_{fb} that is in source-follower configuration with a negative feedback loop from its source to its gate. Embedded in this negative feedback loop is the rectifying and thresholding temporal differentiator stage [3]. The feedback configuration clamps the voltage across the photodiode, thus speeding up the photoreceptor circuit. This speedup is especially beneficial for sensing illumination changes. Changes in illumination lead to changes in the gate voltage of M_{fb}, that are proportional to $\frac{d}{dt}(\log I)$, where I is the light intensity. The current flowing onto the capacitor C represents the temporal derivative of the log illumination. It is proportional to $C\frac{d}{dt}(\log I)$. For increasing illumination, the gate voltage of M_{fb}, rises and an ON current flows from the source of the NMOS transistor onto C. For decreasing illumination, an OFF current flows from the capacitor into the source of the PMOS transistor. The ON and OFF currents are multiplied by tilted mirrors and integrated on the nodes V_{ON} and V_{OFF}. Tunable leakage currents I_{TOn} and I_{TOff} provide signal thresholds for ON and OFF events.

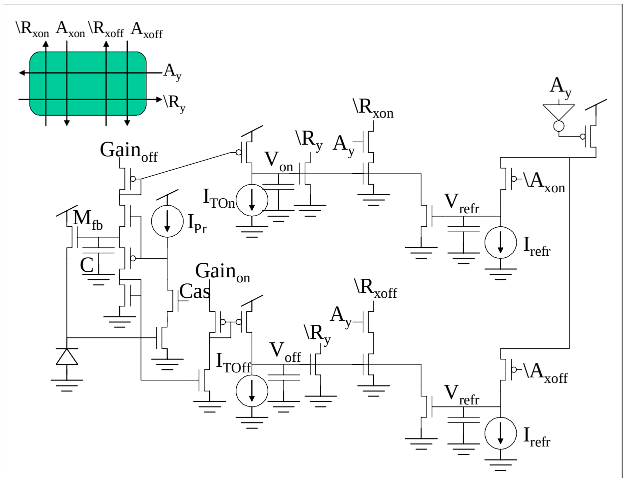

Figure 1: Schematic of a pixel with icon to show array organization.

An event corresponds to a request of a pixel to the y-arbiter and subsequently to the x-arbiter. In contrast to other AER imagers, events are not digitally restored within the pixel; this imager uses distributed row-column AD conversion, meaning that analog events in the pixel are converted into fully-restored digital events at the interface of the pixels to the arbiters. A request to the arbiter is triggered if the pull-downs $M_{\backslash RY}$, $M_{\backslash RON}$ and $M_{\backslash ROFF}$ in the pixel overcome the shared row and column pull-ups (not shown). The pixel is reset by the acknowledge signals coming back from the arbiters. V_{ON} and V_{OFF} are clamped to ground during a tunable refractory period. The refractory period limits the maximum spiking rate of the pixel.

To increase the signal to noise ratio in the pixel we increased the capacitance C. We also separated the ON/OFF thresholds for better tuning of the symmetry of the ON/OFF responses.

2.2 Layout

To reduce the mismatch in Kramer's imager we did several changes to the layout.

1. We implemented the photodiode with an N-well instead of an N-source. This speeds the photoreceptor response to illumination changes because the parasitic capacitance is reduced by a factor of about 10.
2. We rounded the corners of the diode to reduce dark leakage current.
3. We clearly separated analogue and digital circuits spatially and split the power supplies to reduce cross talk.
4. The critical analogue transistors are drawn in large geometry to reduce mismatch. This is especially important for the transistors in the mirrors and for the threshold transistors.
5. To increase the signal we increased the capacitance in the photoreceptor circuit by using a MOS capacitor instead of poly capacitor.

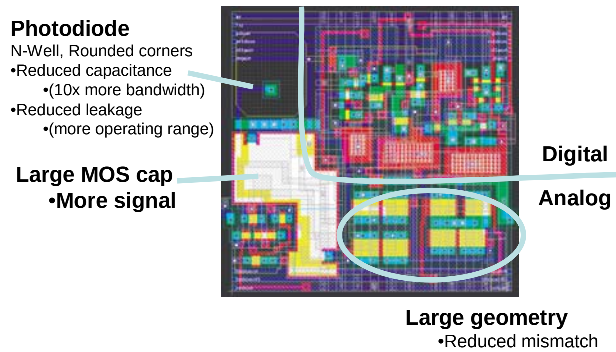

Figure 2: Layout of the pixel. Significant differences to the earlier version are pointed out.

Figure 2 shows the pixel layout with the photodiode in the upper left corner. The fill factor is about 10%. The MOS capacitor on the left side and the large analog transistors on the lower right side occupy a large part of the pixel area. The digital circuits are separated from the analog circuitry and the space between is used for the small capacitors.

3. RESULTS

The chip was fabricated in a 0.35µm, 4 metal, 2 poly process. A custom PCB provides the tunable biases and connectors to interface the retina to receivers. A 9-volt battery supplies the power. The whole device is mobile, small and therefore well suited for experimental use.

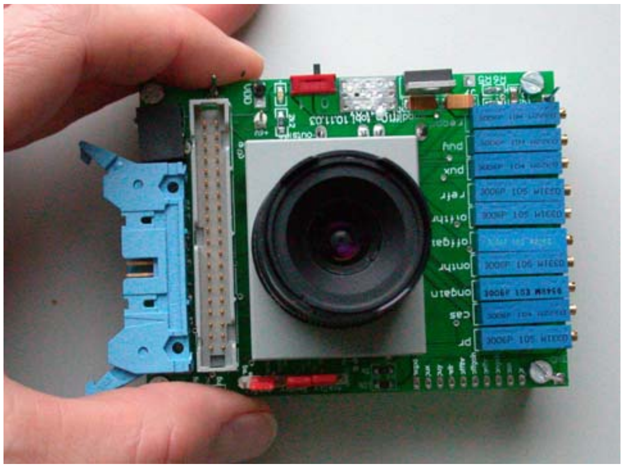

Figure 3: Imager on special PCB. A forty pin header complying with the CAVIAR standards and a twenty pin header complying with multisender standards are visible on the left side. The battery is mounted on the back side.

3.1 Pulsed LED measurements

Figure 4 shows raster plots of the ON and OFF channels. Each dot signifies an event generated by a pixel, numbered on the y-axis. The stimulus we used for this experiment was an LED modulated with an 8HZ square wave with a contrast of 2:1 shining directly on the entire array. The stimulus was chosen so that it nominally evoked one event per pixel per illumination change.

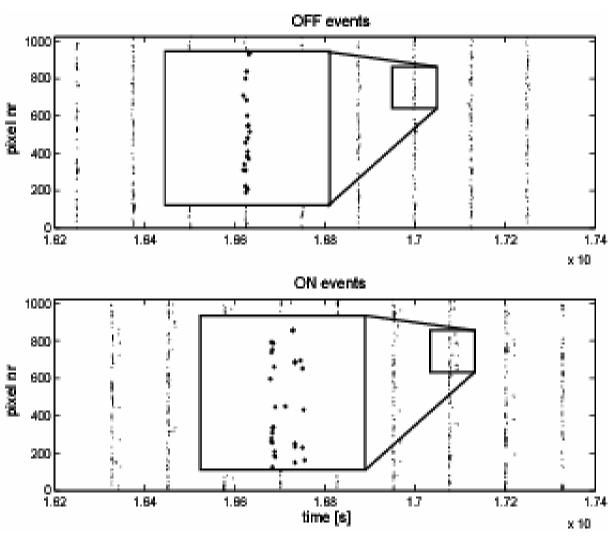

Figure 4: Raster plots of the response of the whole array exposed to an LED modulated with a square wave.

The plots show the clear separation of events to ON and OFF changes. With these bias settings the ON response was less clean than the OFF response. Although the majority of the pixels respond with one event per illumination change, some did not respond and others responded with several events.

Figure 5 displays collected events to the stimulus described above over 15 seconds. We used the identical biases. These settings would lead to 8x15=120 events per pixel for ON and the OFF channel.

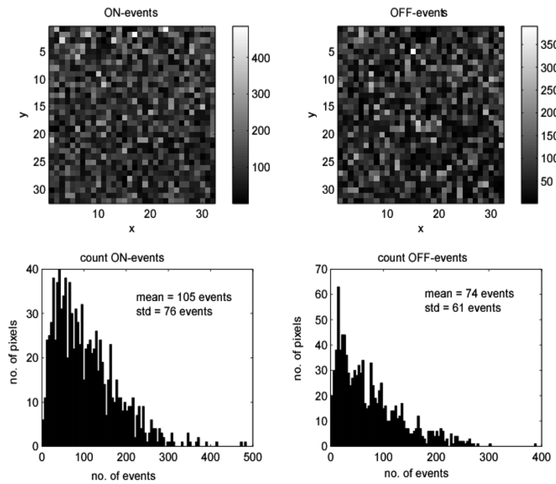

Figure 5: Uniformity measurements with pulsed LED.

The grayscale images over the histograms show no systematic pattern but the few very active outliers tend to be towards the top, which is close to the x-arbiter. There are hints of periodicity in the histograms that suggests integration over multiple cycles could be occurring.

3.2 Moving edges and dynamic range

The classic stimulus for temporal filtering imagers and in biological vision experiments is a moving edge. We mounted a black bar, wide enough to cover the whole visual field of our imager, on a rotating drum and presented it to the retina using an 8mm *f*/1.2 lens.

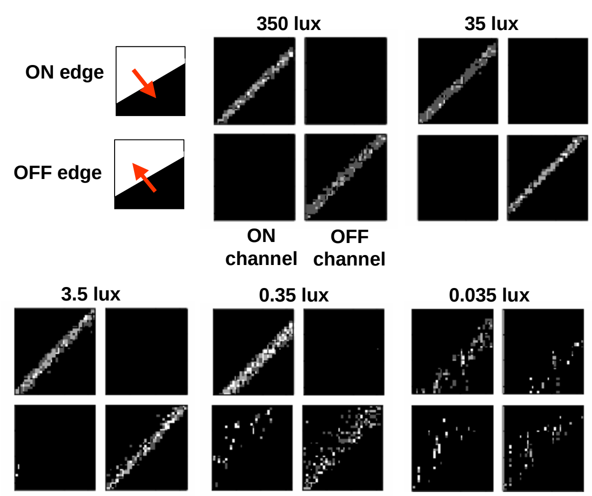

Figure 6: ON/OFF responses to moving edge for different scene illuminations.

The edge had a contrast of 10:1 (white to black paper). Neutral density filters were used to attenuate the light falling onto the imager. Figure 6 shows the responses of the imager to the moving edge under equivalent scene illumination levels ranging over 5 decades, from 350 lux to 0.035 lux. The grayscale images show snapshots of spikes integrated over 50ms. The responses only begin to be affected by the scene illumination below 0.35 lux, mainly in the OFF channel, but are still reliably detected at 0.035 lux. Because it is difficult to believe that this imager functions at nearly moonlight scene illumination levels (0.1 lux), we are not certain that the incandescent light source was actually attenuated by the nominal decade ratio specified for the Kodak Wratten filters that we used. It could be that near infrared light that the imager is sensitive to was not attenuated as much as visible light. On the other hand, given our setup, we were not able to explore the upper limit on illumination, which is probably substantially higher than 350 lux. Given these measurements, we believe that the imager has over 100dB operating range.

4. DISCUSSION

This AER imager is one of an evolving population. At one extreme there are the Johns Hopkins Octopus Retina[5] and the University of Florida Time-to-First-Spike Imager[6] that output events that directly represent pixel illumination. These devices do no redundancy reduction but efficiently use the AER bus to transmit brightness information. They have relatively small pixels and low fixed pattern noise. At the other extreme are devices like the University of Pennsylvania silicon retina[7] and the CSEM steerable filtering chips[8, 9], which have large and complex pixels, sometimes with substantial fixed-pattern noise, but which do substantial redundancy reduction by a combination of spatial and temporal filtering. The present device falls somewhere between these extremes; it has no spatial filtering capability, but it does substantial redundancy reduction by using logarithmic compression and temporal filtering. The usefulness of particular capabilities will be determined by applications, of which there are few so far.

The application of the present device is specific: it serves as the front end for the CAVIAR project (http://www.imse.cnm.es/~bernabe/CAVIAR/), which seeks to build an AER-based system that can learn to classify a moving object into classes of trajectories (e.g. left/right, getting larger/smaller, changing direction, etc.). The imager will send its events to subsequent AER components that implement the higher-level processing. Two other partners in the CAVIAR project presently are using the imager in their developments.

5. ACKNOWLEDGMENTS

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6. References

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