# VERSATILE ON-CHIP READ-OUT FOR COMPOUND-EYE IMAGE SENSOR ARRAY

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## ABSTRACT

Compound-eye image sensors offer the possibility to fabricate ultra-thin (<0.5mm) image sensors, that integrate micro-optics, photo-sensing elements and processing-circuitry on a single chip. Modeled after the compound eye found in insects and in many other arthropods, the compound-eye sensor has the possibility to generate a high resolution image from the simultaneous acquisition of a mosaic of low resolution images. In this paper, we propose a versatile read-out strategy enabling to view the scene from only a subset of microlenses. We demonstrate that this feature is very attractive in terms of power consumption and read-out speed, especially when the intended application does not require high resolution imaging. Simulation results are presented to validate the functionality of the circuit, using AMI 0.35µm CMOS technology.

## 1 INTRODUCTION

The recent rapid advances in CMOS imaging technology have enabled the development of high performance single chip cameras, i.e., CMOS imagers, integrating image capture and on-chip processing [1]. The fully integrated approach leading to a camera-on-chip, offers significant advantages in terms of manufacturing cost, system volume and weight, power dissipation and system integration into imaging products [1]. CMOS imagers are particularly well suited to the mobile phone market due to its high integration capability and low power consumption. CMOS camera manufacturers have been continuously improving the performance of their products in terms of resolution, power consumption, and read-out speed. The continuous aggressive scaling of the minimum feature size in CMOS technology offers the possibility to further reduce the size of the CMOS camera. However, diffraction effects do not allow for a further miniaturization of the optics [2]. To achieve an ultra-thin camera-on-a chip, Tanida *et al* have recently proposed a compound-eye imaging system emulating the visual system of arthropods [3] [4][5]. In contrast to traditional camera systems, their compound-eye sensor called TOMBO (an acronym for thin observation module by bound optics) is not based on a single lens system. Instead a microlens array is used to capture simultaneously multiple images of the scene [3]. A high resolution image is then retrieved by processing the available set of images [4]. If the intended application does not require high resolution imaging (e.g. tracking, surveillance, etc…), then having the possibility to view the scene from only a subset of the microlenses, becomes very attractive in terms of power consumption and read-out speed. In the case of the TOMBO compound-eye sensor, the entire pixel array is used for image capture. As a result, the output is always an array of low resolution images, which is subsequently subdivided off-chip using a PC. In this paper, we propose an on-chip versatile read-out to control externally which subset of microlenses is to be used to view the scene. A number of configurations are possible for the selected pixel sub-arrays with different sizes and positions, making it ideal for a number of applications such as surveillance or target tracking. In the next section, we describe briefly the structure of the TOMBO compound eye sensor. The proposed versatile on-chip read-out strategy is presented in Section 3. The adopted spiking pixel architecture is detailed in Section 4 and the imager architecture in Section 5. Finally, a conclusion is given in Section 6.

## 2 TOMBO COMPOUND-EYE SENSOR

The structure of the thin observation module by bound optics (TOMBO), recently proposed by Tanida *el al* is shown in Fig 1 [3]. This compound-eye sensor comprises a collection of imaging units, each of which consists of a microlens unit associated to a subset of the photo-detector array. Adjacent imaging units are separated by an opaque wall to prevent crosstalk. Each individual imaging unit is thus optically isolated and images part of the scene. As a result, the TOMBO compound-eye sensor captures multiple low resolution images at the same time and the output is a compound image formed by the mosaic of low resolution unit images.

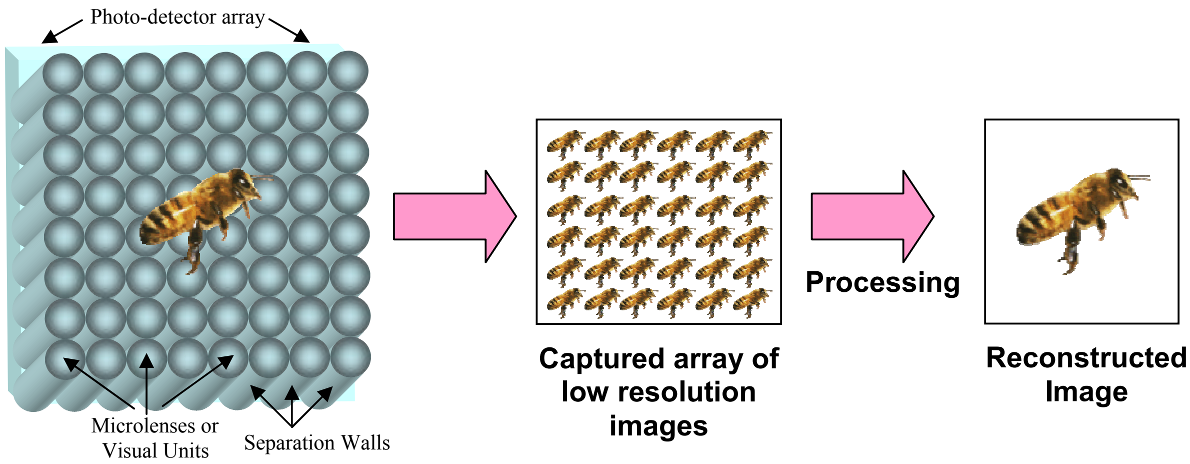


**Figure 1.** TOMBO compound-eye sensor: structure and operation [3].

Digital signal processing can then used to reconstruct a high resolution image from the available set of low resolution images [4]. As in conventional digital CMOS cameras, images are formed by scanning sequentially the entire photosensitive pixel array. This leads to a systematic and continuous sequential scan of all imaging units, resulting in excessive power dissipation since the scanner is always active. Furthermore, this serial scanning of all imaging units will significantly reduce the achievable frame rate. To overcome these limitations, we propose a versatile on-chip read-out strategy that enables a second mode of operation for the compound-eye sensor array. In this mode, only a subset of microlenses can be selected for image capture, the other units remaining dormant. As a result, increased functionality is provided as resolution, frame rate and power consumption can be controlled by selecting which imaging units will be active within the microlens array.

## VERSATILE READ-OUT

The read-out or transmission of information from a pixel array to the outer array circuitry involves typically the serial and systematic read-out of all pixels. Here, we have adopted a different scheme, namely address event representation (AER) [6]. Modelled after the transmission of neural information in biological systems, AER uses asynchronous short pulses (spikes) for communication. In our scheme, each pixel is itself a spike generator, encoding illumination information in the delay or time in obtaining the first spike (TFS). Here, instead of integrating the photo-generated electron-hole pairs for a fixed period of time, we integrate to a fixed threshold voltage. A single spike is generated each time the threshold voltage is crossed, and a request for read-out is sent by the pixel itself to the AER outer array circuitry. Because several requests may be sent at the same time, arbitration is required from the AER outer circuitry to determine which pixels should be first read-out that is should be granted access to the output digital bus. This biologically-inspired AER read-out combined with TFS, is more efficient than scanning systematically the entire compound-eye pixel array. First, it minimizes power consumption since the scanner is only active when data (i.e. spikes) is available. In addition, with TFS, power consumption is limited to only a single spike per pixel per frame, after which the pixel enters into a stand-by mode. Secondly, read-out is carried-out on pixel demand, resulting in an efficient usage of the available output bandwidth since darker pixels will request access to the bus much later than brighter pixels. In order to enable compound-eye image sensor operation with any subset of microlenses, we block the requests of non-selected imaging units at the pixel level.

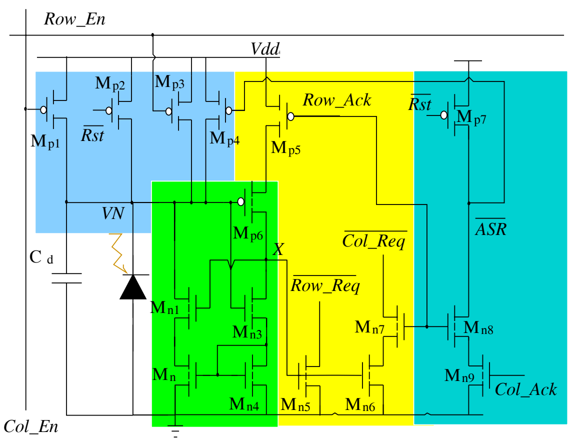


**Figure 2.** Spiking pixel architecture

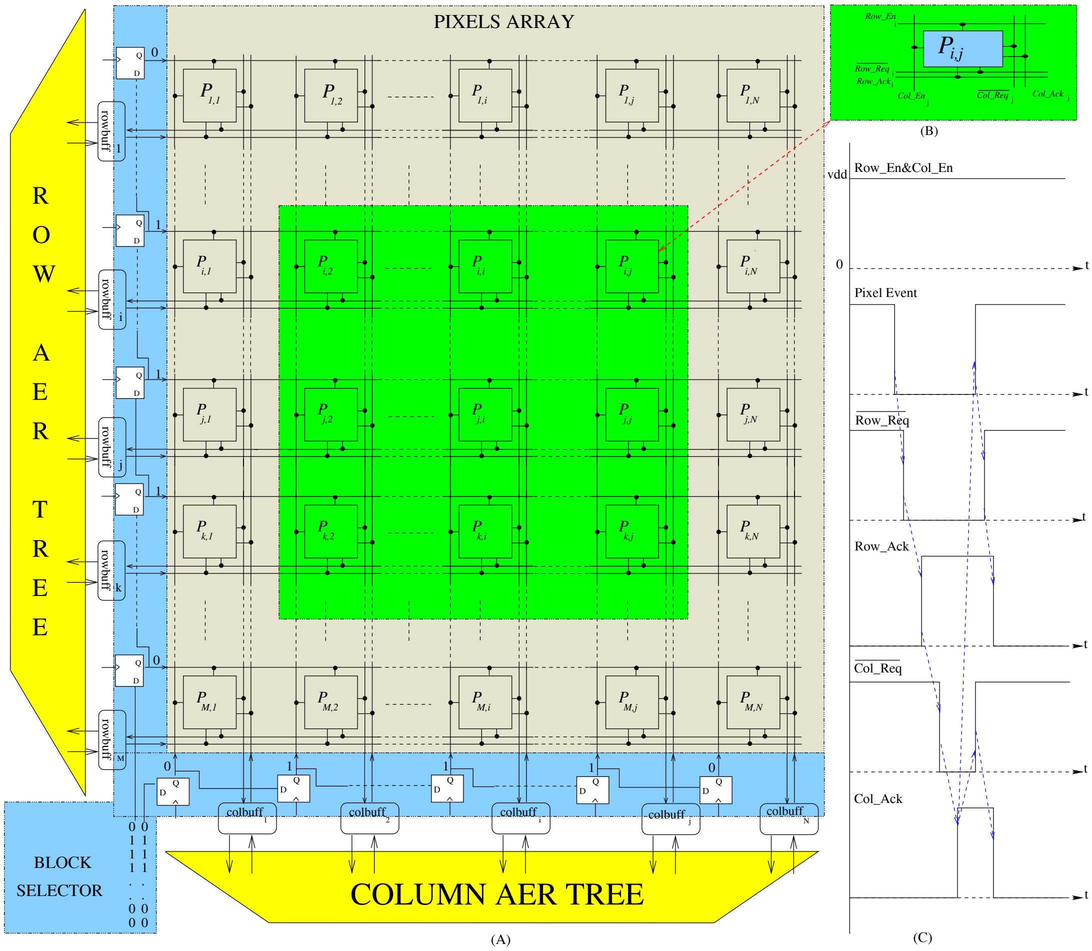


**Figure 3.** (a) imager architecture, (b) pixel and (c) control signals for block selection.

## 3 SPIKING PIXEL ARCHITECTURE

The proposed spiking pixel architecture is given in Fig 2. It comprises a photodiode represented with its internal capacitance, a reset circuitry ($M_{p2}$, $M_{p4}$) together with a low power current-feedback spike generator ($M_n$, $M_{n1}$-$M_{n3}$, $M_{n6}$) [7]. The in-pixel circuitry ($M_{p5}$, $M_{p7}$, $M_{n5}$, $M_{n6}$-$M_{n9}$) is used here to communicate with the AER outer array circuitry while transistors ($M_{p1}$, $M_{p3}$) determine whether a pixel will be used for image capture or will be made dormant. The pixel in Fig. 2 operates as follows. A global reset *Rst* signal is first used to reset each pixel ($V_N = V_{dd}$). This drives the input of the inverter ($M_{n3}$, $M_{p6}$) high while $V_x$ goes low. If both *Row_En* and *Col_En* signals are active, then the pixel is part of an active imaging unit and the collection of photo-generated electron-holes pairs (integration phase) will start after the reset operation. As the capacitor is discharged by the photo-current $I_{ph}$, the voltage $V_N$ at the sensing node decreases. When $V_N$ crosses the threshold voltage $V_{TH}$ of the inverter ($M_{n3}$, $M_{p6}$), $V_x$ is driven high and a request for read-out (Row_Req) is sent to the Row AER circuitry. Once a pixel has been granted bus access, its ASR signal goes active resetting the voltage $V_N$ at the sensing node and in turn $V_x$. The time to the first spike encodes pixel brightness and is given by $T_{fs}=\alpha/I_D$ with $\alpha=C_d(V_{dd} - V_{TH})$, where $I_{ph}$, $C_d$ and $V_{TH}$ represent the photocurrent, the photodiode internal capacitance and the threshold voltage of the ($M_{n3}$, $M_{p6}$) inverter, respectively. After resetting itself, a pixel remains dormant until the start of a new integration phase. As a result, there is only a single transition per pixel and per frame.

## 4 IMAGER ARCHITECTURE

Fig. 3 describes how the proposed versatile read-out can be implemented in a compound-eye image sensor array. Besides the photosensitive pixel array, the imager architecture comprises row and column AER circuits with associated buffers. The AER circuits are used to arbitrate between pixels and determine the read-out sequence of active pixels (i.e. pixels that have generated a spike or a request). The imager operates asynchronously. When one or more pixels within a row produce a request, the corresponding Row_Req signal goes active and is sent to the row arbitration tree. The Row AER arbitrates and selects (through Row_Ack) a single row from which at least one request has been generated. Active pixels within the selected row then send a request Col_Req to the column AER. Next, column arbitration is carried-out within the column buffer to avoid waiting for the column AER to acknowledge all column requests one by one. The column buffer will hold the requests and acknowledge back concurrently through Col_Ack. This causes the pixel to self-reset and remain dormant until the next integration phase. Performing column arbitration within the buffers, and not within the array, improves read-out speed by avoiding charging and discharging repeatedly the large capacitances of the column buses. Once column arbitration on the buffered row is completed, a new round of column arbitration can start. Pipeline processing between row and column AER is thus achieved, further speeding-up the arbitration process. The read-out process of any given pixel can be described as follows: Row Request → Row Acknowlegement → Column Request → Column Acknowledgment → Self-Reset. Here, row and column acknowledgement signals are used to identify the location of the firing pixel as well as to retrieve the pixel brightness.

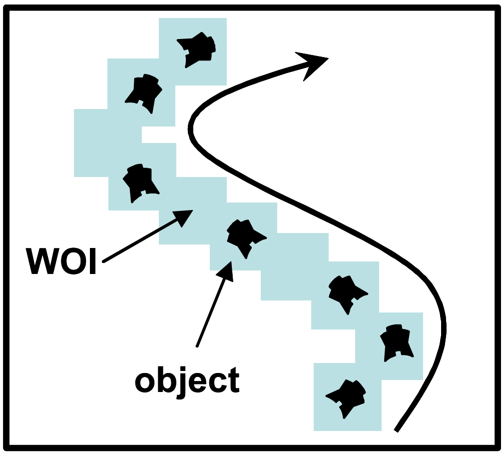


**Figure 4.** The random selection of the individual visual units that form the compound-eye vision sensor enables low power operation and fast read-out. This feature is attractive for application such as target tracking.

Fig. 2 shows the control signals for a pixel that is part of an active microlens unit or block. This corresponds to the case where both Row_En and Col_En signals are active. The pixel is allowed to integrate the photocurrent and to request read-out when a predefined threshold voltage is reached. When Row_En and Col_En signals for a pixel are inactive, the pixel is not part of an active microlens unit and the voltage at the sensing node is maintained at $V_{dd}$. To enable operation with only a subset of microlenses, the pixel array is divided into sub-arrays of identical size, each being associated to a given microlens. This configuration is realized by using a bit stream which is fed to row and column registers, as illustrated in Fig. 2. This bit stream can be generated externally or internally to define whether a given microlens unit should be active or dormant. If the pixel selection signals Row_En and Col_En are inactive then $V_X=0$ and no spike or request can be generated. The pixel remains dormant until its microlens unit becomes selected for image capture. A number of configurations are possible for the selected pixel sub-arrays with different sizes and positions, making it ideal for a number of applications such as surveillance or target tracking (Fig. 4).

## 5 CONCLUSION

This paper presents a versatile read-out strategy for compound-eye sensor array. With the proposed approach, any subset of the microlens array can be individually selected for image capture, instead of the entire array in the case of a conventional read-out. A number of configurations are possible for the selected pixel sub-arrays with different sizes and positions, making it ideal for a number of applications such as surveillance or target tracking. Increased functionality is thus provided together with improved performance in terms of power consumption and read-out speed since resolution, frame rate and power consumption can be controlled by selecting which imaging units will be active within the microlens array.

## 6 REFERENCES


[1] E. R. Fossum, "CMOS image sensors: Electronic camera-on-a-chip", IEEE Trans. on Electron Devices, vol. 44, no.10, pp. 1689–1698, 1997.

[2] R. Volkel *et al*, "Miniaturized imaging systems," Micr. Eng. vol. 67–68, pp. 461–472, 2003.

[3] J. Tanida *et al*, "Thin Observation Module by Bound Optics (TOMBO): Concept and experimental verification," Applied Optics, vol. 40, no. 11, pp. 1806-1813, 2001.

[4] Y. Kitamura *et al*, "Reconstruction of a high-resolution image on a compound-eye image-capturing system," Applied Optics, vol. 43, no. 8, pp. 1719-1727, 2004.

[5] M. Land and D-E Nilsson, Animal Eyes. Oxford University Press, 2002.

[6] M. Sivilotti, "Wiring considerations in analog VLSI systems with applications to field programmable networks," Ph.D. dissertation, California Institute of Technology, Pasadena, 1991.

[7] E. Culurciello, R. Etienne-Cummings, and K. A. Boahen, "A biomorphic digital image sensor," IEEE Journal of Solid-State Circuits, vol. 38, pp. 281–294, 2003.