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A self-powered asynchronous image sensor with independent in-pixel harvesting and sensing operations

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Abstract

A self-powered asynchronous sensor with a novel pixel architecture is presented. Pixels are autonomous and can harvest or sense energy independently. During the image acquisition, pixels toggle to a harvesting operation mode once they have sensed their local illumination level. With the proposed pixel architecture, most illuminated pixels provide an early contribution to power the sensor, while low-illuminated ones spend more time sensing their local illumination. Thus, the equivalent frame rate is higher than the one offered by conventional self-powered sensors that harvest and sense illumination in independent phases. The proposed sensor uses a Time-to-First-Spike readout that allows trading between image quality and data and bandwidth consumption. The device has HDR operation with a dynamic range of 80 dB. Pixel power consumption is only 70 pW. The article describes the sensor's and pixel's architectures in detail. Experimental results are provided and discussed. Sensor specifications are benchmarked against the art.

Introduction

There is a notable demand for sensors with very low power consumption to deploy Wireless Sensor Networks (WSN) with multiple and distributed sensors [1]. Such a demand has been boosted by the spread of dedicated devices that can coexist and interact with other ones according to the Internet of Things (IoT) paradigm [2]. The power consumption requirements for the WSN nodes are demanding [3]. In that sense, energy harvesting capabilities can be incorporated into the devices to reduce power consumption or achieve a sustainable operation. There are several possibilities to harvest energy from the environment, i.e., piezoelectric transducers, electrodynamic microgenerators, thermoelectric generators, solar cells, and radio and microwave frequency antennas, [4]. Focusing on image sensors [5]-[8], they inherently can harvest solar energy because they are exposed to light and because their photodiodes can be biased to operate as solar cells. The majority of self-powered image sensors reported are based on APS pixels with frame-based operation [5]-[8]. This pixel architecture has some limitations to harvest energy from the environment. Firstly, all pixels operate synchronously. This implies that different pixels cannot be configured to harvest energy and sense the scene illumination independently. That is a drawback because highly illuminated pixels can sense illumination levels quickly and contribute to harvesting energy afterward. On the contrary, low-illuminated pixels require a longer readout time and the amount of energy harvested by them is low. Another limitation of the APS pixel architecture is the need for Analog-to-Digital (AD) converters to read out the pixel information. In many cases, the power consumption of the AD converters is comparable to or higher than the pixel array consumption. There is also a frame-rate limitation if the sensing and the harvesting operation are performed separately. We propose an event-based pixel architecture with a fully asynchronous operation. Pixels can harvest and sense light independently. More illuminated pixels toggle to a harvesting mode once their local illumination is read out, contributing to harvesting energy to feed the sensor. Pixel illumination levels are encoded using Time-to-First-Spike (TFS) operation [9] without requiring ADs. In this paper, we describe the sensor architecture of a sensor prototype fabricated in the UMC 180nm technology node. Experimental results are provided and discussed. Finally, the sensor performance is benchmarked against the art, showing the advantages of the proposed architecture.

Sensor architecture

Fig. 1 shows the architecture of the proposed vision sensor implementing energy harvesting capabilities. When the pixels are not actively sensing the lighting conditions of the scene, the photodiodes are configured in the photovoltaic mode and connected to the global voltage energy harvesting node, V_{EH}, allowing for the photocurrent to flow out of the chip and charge an external supercapacitor This supercapacitor serves as a charge reservoir for the entire system. Since the voltage generated at a silicon P-N junction ranges from 100 mV to 500 mV [10], [11], a DC-DC converter is incorporated in the same die to increase the voltage generated at the pixel array to 700 mV. Note that the photodiodes are not required to continuously provide energy to the DC-DC converter's output. Instead, an alternative approach consists in using the DC-DC converter to pre-charge the supply voltage, V_{DD}, before the system's operation begins.

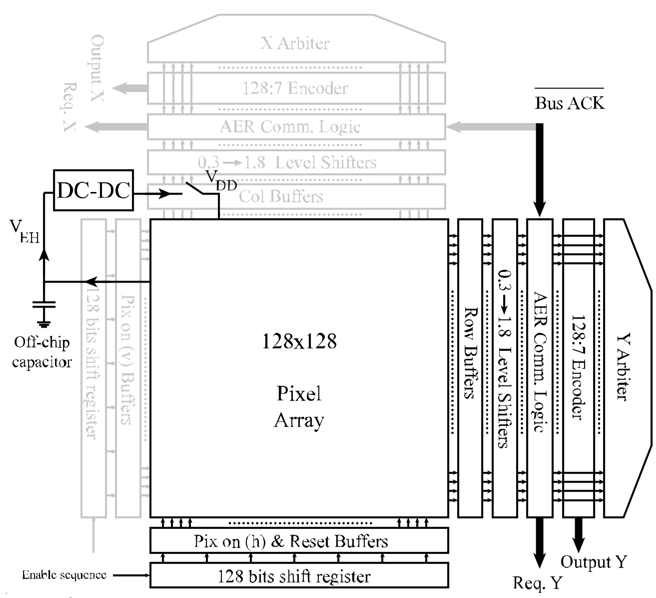

Fig. 1. Sensor architecture implementing energy harvesting capabilities and asynchronous readout.

The proposed vision sensor utilizes the Address Event Representation (AER) protocol [12] to enable asynchronous readout. As depicted in Fig. 1, the sensor comprises a pixel array, column and row buffers, level shifters (in case the peripheral circuitry is biased at a higher voltage), AER communication logic blocks, encoders, and row and column arbiter trees. When a pixel detects an event, the *X* and *Y*-arbiter trees decide which pixel accesses the address bus, and the AER communication logic generates two global signals, req_y and req_xThe AND operation of these signals indicates to the external receiver that an event has been generated by a specific pixel. The address of this pixel is a combination of the output of the encoders, $addr\_x$ and $addr\_y$. Once the external peripheral has been read out and stored the pixel address, it activates $\overline{bs\_ack}$, and the AER communication logic resets the pixel.

Additionally, two 128-bit shift registers store the enable sequence such that the pix_on and $reset$ signals are only enabled in specific rows and columns. This enables the sensor to define a specific region of interest while the rest of the pixels continue to harvest energy.

Pixel architecture

Fig. 2 shows the schematics of the proposed pixel. We can identify inside the pixel four main constitutive blocks: a photodiode with biasing control circuitry, a memory element, a comparator, and asynchronous communication logic. The first one is composed of a photodiode and digital circuitry to bias it on the photovoltaic regime (harvesting mode) or in the reverse bias region (sensing mode). The memory element (SR latch in Fig. 2) stores the state of the pixel, i.e., the operation mode.

Fig. 3 depicts how the photodiode can be configured depending on the local $\overline{lock}$ signal. In harvesting mode, the anode of the diode is connected to a global storage capacitance shared by all the pixels that are harvesting energy. This storage capacitance is connected to the on-chip DC-DC converter. Once they sense their local illumination, pixels enter harvesting mode and remain in this mode until a new frame has to be acquired. On the other hand, when the pixel operates in the sensing mode, diodes are reverse-biased and generate a photocurrent that discharges an integration capacitance, implementing a TFS operation [9].

Fig. 4 depicts the signals involved in the pixel operation. At the beginning, all photodiodes are in harvesting before until the pix_on signal is enabled. This signal is the NAND operation of two signals, pix_on_h and pix_on_v, which are shared per row and per column, respectively. Then, after an initial reset, the photodiode discharges node V_n until reaching a defined threshold voltage, at which point an event is generated, triggering the $spike$ signal. Thus, the pixel data can be encoded as [9]:

$$I_{ph} = C_{int}\frac{(V_{DD}-V_{th})}{T_{int}} \quad (1)$$

where T_{int} is the time it takes the photodiode to discharge V_n, i.e., the pixel's integration time. The event is transmitted outside the pixel array by means of the pull-down transistors, $M_{n4} - M_{n7}$. First, the pixel requests access at the row level by pulling down the $\overline{req\_row}$ signal, which is common for all pixels in the same row. Then, the *Y*-arbiter from Fig. 1 manages all requests and grants access to a specific row, activating ack_row. At this point, the pixel repeats the process at the column level by pulling down $\overline{req\_col}$ Finally, when the *X*-arbiter grants access to the pixel, an external peripheral receives and decodes the pixel data. In this implementation, the time was measured using a digital counter in the receiver part, but note that only a single counter operating at a moderate frequency is required and low-power architectures can be implemented on-chip in a future design.

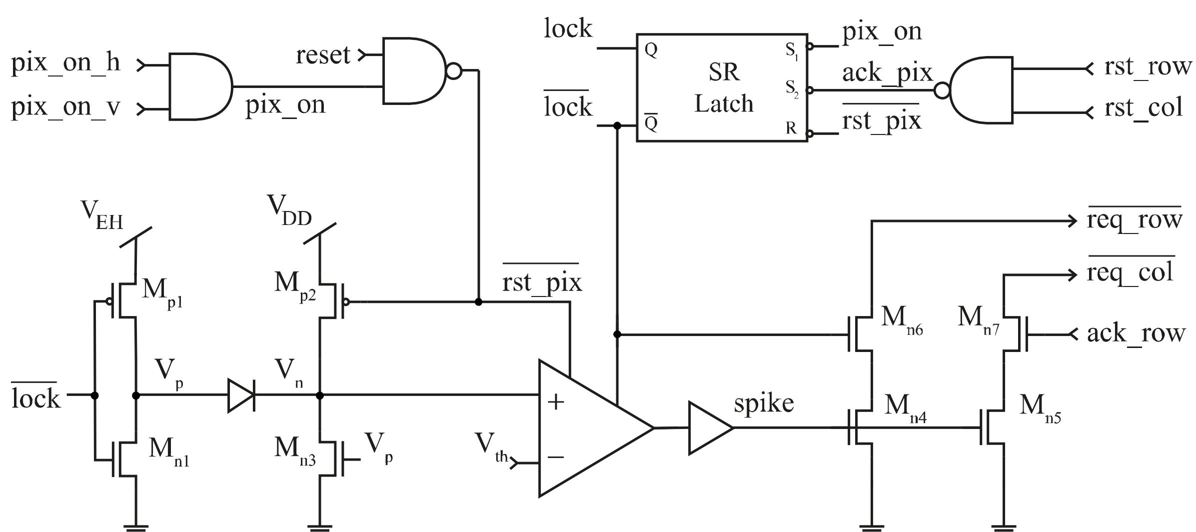

Fig. 2. Schematics of the pixel composed of a photodiode, switching circuitry, a comparator, a memory element, reset and enable logic and pull-down transistors.

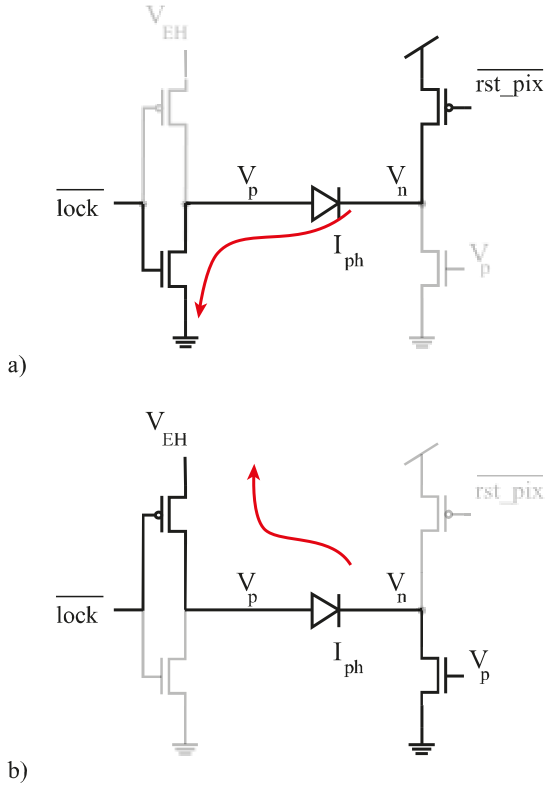

Fig. 3. Configuration of the photodiode when working in a) sensing mode, and b) harvesting mode.

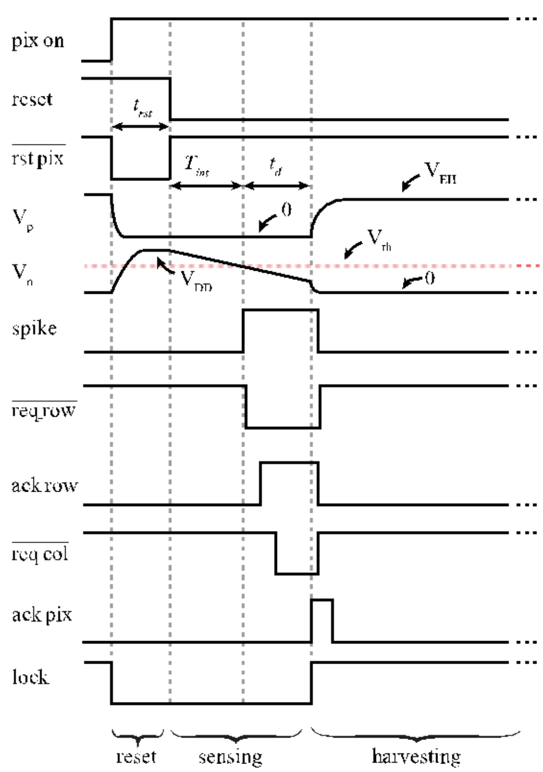

Fig. 4. Timeline of signals involved in the pixel operation.

It is important to note that the measurement depends on the value of V_{DD}. Therefore, if the application requires comparing among frames, this voltage must be properly regulated. IR drops in the VDD line inside the pixel array during reset can create systematic error in the signal (patterns), but power consumption is minimal and IR drops are negligible. Conversely, IR drops during integration phase cause comparator jitter, resulting in random signal noise. Also, from eq. (1) it can be deduced that the input-referred offset and noise of the comparator is directly added to the signal, which can be represented as $(V_{DD} - V_{th})$ in the voltage domain. Thus, increasing $(V_{DD} - V_{th})$ reduces the contribution of these effects. However, a disadvantage of TFS pixels is that dark pixels exhibit a longer T_{int}, leading to non-uniform integration times, causing substantial intensity-dependent motion blur and lag. This drawback can be mitigated by employing a time-dependent value of V_{th}, although this approach increases power consumption and requires further investigation.

Experimental results

Fig. 5 shows a snapshot taken with the sensor in 14 ms. It corresponds to an image with a large intra-scene-dynamic range. The output of the DC-DC converter was pre-charged to 700 mV prior to acquiring the image.

Fig. 6 presents the experimental data on the power consumed and harvested by the sensor during the image acquisition in Fig. 5. The top panel illustrates the percentage of pixels operating in sensing mode. At first, all pixels start in sensing mode and consume energy, leading to the sensor's maximum power consumption of 1.14 µW. Subsequently, the most illuminated pixels switch to harvesting mode, reducing the overall power consumption of the sensor over time.

Fig. 5. Image acquired with the proposed sensor. The acquisition time was 14 ms.

The bottom panel in Fig. 6 displays the balance between the sensor's power consumption and the power harvested by the pixels operating in harvesting mode. Two scenarios were considered to estimate the harvested energy: an ideal Dickson DC-DC converter and an implemented converter of 60% efficiency. Comparing the plots, we can see that the maximum energy consumed by the sensor when all pixels operate in sensing mode exceeds the maximum energy collected when all pixels harvest energy at the same time. Thus, the sensor cannot operate continuously and requires harvesting energy between acquisitions. In this example, the sensor requires 17 ms to harvest enough energy to recover from the energy expended for the acquisition, achieving an effective frame rate of 58 fps with a self-powered operation. It is important to note that the energy balance is dependent on the scene and the acquisition of a low-light scene implies higher energy consumption due to the extended operation of pixels in sensing mode. As a result, the extra time required to recover from the energy expended during the acquisition is longer under low-light conditions.

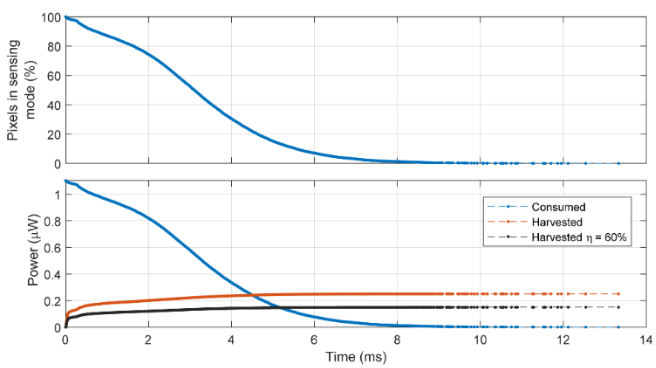

Fig. 6. Top panel: number of pixels operating in sensing mode over time. Bottom panel: balance between the sensor's power consumption and power harvested by the pixels in harvesting mode.

To evaluate the proposed sensor's performance in comparison to existing solutions, the Image Figure of Merit (iFoM) was calculated and compared. The energy required for capturing a single frame was determined by analyzing the blue trace in Fig. 6 . However, for an accurate comparison, the iFoM was calculated assuming a dark frame, where the power consumption is close to the peak power consumption (1.14 μW) for most of the time, and a frame rate of 19.9 fps under 100 lux ambient light conditions. The resulting iFoM was found to be 3.41 fJ/pixel·code.

Table I compares the specifications of the implemented sensor with other recent self-powered sensors- The selected sensors from the literature were chosen for their competitive balance between power consumption and frame rate or unique functionalities. The PWM sensor from [7] operates at 0.32 V, being compatible with voltages generated at silicon photodiodes. Also, [6] presents an APS solution with two stacked diodes (one for harvesting and the other for sensing) operating at 0.6V. Finally, [8] describes an APS architecture where the same photodiode functions as a harvester or sensing unit. The proposed sensor has the best iFoM, followed by PWM sensors, then APS sensors

Table 1. State-of-the-art comparison

Features/Work	This work	[7]	[6]	[8]
Pixel Architecture	TFS	PWM	APS	APS
Technology	UMC 0.18 μm	0.18 μm	0.18 μm	0.5 μm
Pixel complexity	54 ttos.	5 ttors.	3 ttors.	3 ttors.
Chip dimensions	2856 μm x 2824 μm	ND	660 μm x 860 μm	2000 μm x 2000 μm
Pixel count	128x 128	256x 192	100x 90	54x 50
Fill factor	30.65	30.8	46/94(*)	32
Pixel pitch	19.5 μm	7.5 μm	5 μm	21 μm
Supply voltage	0.7 V	0.32 V	0.6 V	1.2 V
Pixel power consumption	70 pW	ND	ND	26.4 pW
Sensor power consumption	1.14 μW	10.6 μW	3.9-57.8 μW	14-25 μW
Frame rate (fps)	51.5@500lux 19.9@100lux	6.5	7.5-10	7.4
Dynamic range	100 dB	141	ND	58.7
FPN (%)	5.34	0.159	9.2	0.75
iFoM (fJ/pixel·code)	3.41	8.6	225.8	606
Independent energy harvesting and light sensing operations	Yes (at the pixel level)	No	No	No

(*) The pixel includes two photodiodes: one for sensing and the other for harvesting, respectively.

Conclusions

A novel self-powered asynchronous image sensor has been proposed, which addresses the limitations of traditional synchronous pixel architectures in terms of energy harvesting. The devised architecture allows for autonomous pixels that can independently harvest energy and sense illumination, eliminating the need to divide sensor operation into separate phases for energy harvesting and sensing. Additionally, the asynchronous readout scheme is highly efficient in terms of energy harvesting, as it does not require an A/D conversion or the reading out of all pixels for image rendering. The sensor architecture allows for a balance between image quality, frame rate, and power consumption, offering opportunities for further research in optimizing sensor operation and energy harvesting under variable illumination conditions and subject to image rendering requirements.

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References

[1] "Systems and architectures," International roadmap for devices and systems 2021 edition, https://irds.ieee.org/images/files/pdf/2021/2021IRDS SA.pdf.

[2] M. M. Sandhu, S. Khalifa, R. Jurdak, and M. Portmann, "Task scheduling for energy-harvesting-based IoT: A survey and critical analysis," IEEE Internet of Things Journal, vol. 8, no. 18, pp. 13 825–13 848, 2021.

[3] H. Jayakumar, K. Lee, W. S. Lee, A. Raha, Y. Kim, and V. Raghunathan, "Powering the Internet of Things," in 2014 IEEE/ACM International Symposium on Low Power Electronics and Design (ISLPED), 2014, pp. 375–380.

[4] S. Sudevalayam and P. Kulkarni, "Energy harvesting sensor nodes: Survey and implications," IEEE Communications Surveys Tutorials, vol. 13, no. 3, pp. 443–461, 2011.

[5] A. Y.-C. Chiou and C.-C. Hsieh, "An ULV PWM CMOS imager with adaptive-multiple-sampling linear response, HDR imaging, and energy harvesting," IEEE Journal of Solid-State Circuits, vol. 54, no. 1, pp. 298–306, 2019.

[6] S. Park, K. Lee, H. Song, and E. Yoon, "Simultaneous Imaging and Energy Harvesting in CMOS Image Sensor Pixels," IEEE Electron Device Letters, vol. 39, no. 4, pp. 532–535, 2018.

[7] A. Y. Chiou and C. Hsieh, "A 137 dB Dynamic Range and 0.32 V SelfPowered CMOS Imager with Energy Harvesting Pixels," IEEE Journal of Solid-State Circuits, vol. 51, no. 11, pp. 2769–2776, 2016.

[8] S. U. Ay, "A CMOS Energy Harvesting and Imaging (EHI) Active Pixel Sensor (APS) Imager for Retinal Prosthesis," IEEE Transactions on Biomedical Circuits and Systems, vol. 5, no. 6, pp. 535–545, 2011.

[9] C. Shoushun and A. Bermak, "A low power CMOS imager based on Time-to-First-Spike encoding and fair AER," in 2005 IEEE International Symposium on Circuits and Systems, 2005, pp. 5306–5309 Vol. 5.

[10] R. Gómez-Merchán, D. Palomeque-Mangut, J. A. Leñero-Bardallo, M. Delgado-Restituto', and Á. Rodríguez-Vázquez, "A comparative study of stacked-diode configurations operating in the photovoltaic region," IEEE Sensors Journal, vol. 20, no. 16, pp. 9105–9113, 2020.

[11] R. Gomez-Merchan, R. De La Rosa-Vidal, J. A. Leñero-Bardallo, and Rodríguez-Vázquez, "On the implementation of in-pixel controlled diodes with sensing and energy harvesting capabilities," in 2022 17th Conference on Ph.D Research in Microelectronics and Electronics (PRIME), 2022, pp. 105–108.

[12] K. A. Boahen, "Point-to-point connectivity between neuromorphic chips using address events," IEEE Transactions on Circuits and Systems II, vol. 47, no. 5, pp. 416–434, 2000.

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