Microelectronics Journal 46 (2015) 997–1001

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

A comparative experimental investigation on responsivity and response speed of photo-diode and photo-BJT structures integrated in a low-cost standard CMOS process

Nikola Katic *, Alexandre Schmid, Yusuf Leblebici

Swiss Federal Institute of Technology (EPFL) Batiment ELD, Station 11, 1015 Lausanne, Switzerland

ARTICLE INFO

Article history:
Received 20 May 2014
Received in revised form
5 July 2015
Accepted 14 August 2015
Available online 25 September 2015

Keywords:
Photo-diode
Photo-transistor
Responsivity
Standard CMOS

ABSTRACT

A variety of smart imaging and neuromorphic applications perform time-domain image acquisition in order to imitate biological systems and reduce the growing transmission bandwidth of the modern imaging devices. Because they operate in time-domain, they require the highest possible pixel responsivity and response speed. This work provides a comparative experimental study of different unconventional photodetecting structures with respect to these parameters. Several on-chip photo-detecting device structures are designed using a low-cost standard 0.18 µm CMOS process. The comparison in terms of measured quantum efficiency, light responsivity and the response speed is presented between conventional and comb-shaped N-well/P-substrate photodiodes, conventional and comb-shaped, vertical and lateral photo-bipolar-junction-transistors (photo-BJTs) and a Darlington pair of bipolar-junction phototransistors. The photodetectors are embedded in a conventional three transistor active pixel topology and measured using a customized low-cost measurement setup. The pixel quantum efficiency, responsivity and response speed are measured for each structure and the results are presented in detail. The obtained results demonstrate the benefits of using standard-CMOS-compatible BJT structures in time-domain applications. The BJT-based photodetectors show increased responsivity to green–yellow light region (500–600 nm wavelength) compared to conventional N-well/P-substrate diode. The highest responsivity is achieved by a combination of lateral and vertical BJT. The fastest response is achieved by the rarely used Darlington pair configuration of BJTs, which demonstrates the potential benefit of using this structure for time-domain imaging applications. A low-cost measurement setup and the measurement methodology are described in detail to make the experiment reproducible for any other standard CMOS process.

1. Introduction

In recent years, modern CMOS image sensors and systems have become increasingly complex following the growing demand for high-quality and high-resolution imaging [1,2]. Commercially available sensors having 30–40 mega-pixel resolutions are common nowadays, while professional and scientific imaging systems (e.g. telescope and satellite sensors) often have hundreds of mega-pixels or even giga-pixel resolution. Such sensors or multi-sensor systems generate extreme amounts of data and require an excessive amount of power in order to process and stream-out the acquired data at required speed. Consequently, three difficult and closely related bottlenecks appear in such systems: power consumption, data bandwidth and memory storage. Nevertheless, the vast majority of applications (such as machine vision, bio-medical, surveillance, and space imaging) do not process all the data acquired from the conventional image acquisition. In fact, most of the image (video) data is extremely redundant, and in many of these applications, the excessive data is simply discarded despite the additional resources that were used to acquire it.

In order to circumvent the waste of resources, many different approaches target more optimal ("smart") ways of image acquisition, compression and processing. The highest efficiency is achieved by sensors that utilize data redundancy within the sensor array (focal-plane compression), which means they perform compression during the image acquisition process. An exhaustive research in exploiting spatial-redundancy of images developed a variety of CMOS image sensors that perform different focal-plane algorithms such as predictive coding [3,4], discrete-cosine transform [5,6], wavelet-based processing [7,8], SPIHT algorithm [9], FBAR and QTD processing [10], and compressive acquisition or compressive sensing [11,12]. The most

* Corresponding author.
E-mail address: nikola.katic@epfl.ch (N. Katic).

http://dx.doi.org/10.1016/j.mejo.2015.08.004

promising concepts for exploiting temporal redundancy are mainly biologically inspired (e.g. artificial retina, or address-event representation (AER), [13–17]).

The smart imagers operating in temporal domain [13–20], require the highest possible pixel responsivity and response speed. A very promising high sensitivity current-mode pixel with pinned photo-diode for smart imaging applications is presented in [21]. In [21], triple-well photo-detector and the pixel topology are customized and the results are analyzed in detail based on the simulation results. Photo-detector comparative studies can be very helpful when it comes to selecting the appropriate photo-detector during the sensor design stage. The study presented in [22] compares three most common (vertical) photo-detector structures and two different standard pixel circuits for the use in conventional applications. This work focuses on several different types of customized photo-detecting structures convenient for time-domain imaging applications and presents the measurement results. The results of the presented comparative experimental study are very useful for the development stage of the time-domain image sensors. Moreover, CMOS processes that are optimized and characterized for photo-detection are typically very expensive. To reduce the development costs, the structures presented in this work can easily be implemented even in twin-well standard CMOS process. Because light responsivity and response speed information are not available for low-cost standard CMOS processes, this type of investigation reduces the costs of additional test chip fabrication and photo-detector characterization. Finally, a low-cost measurement method is presented in detail in order to make the presented experiment reproducible for any other standard CMOS process.

The paper is organized as follows. The fabricated photo-detecting structures are presented and analyzed in Section 2. The low-cost measurement setup is presented in Section 3. The obtained measurement results are presented in Section 4, followed by a conclusion in Section 5.

2. Photo-detecting structures

When a CMOS image sensor gets exposed to light, a portion of the light is reflected thanks to the imperfect interfaces between the top (inter-metal dielectric – mainly silicon-dioxide) layers. Unless the process is optimized and characterized for light sensing (which is not the case in standard processes), a portion of the light that will be reflected can be significant and is unknown. In this case, in order to determine the actual pixel response, the sensor's responsivity measurements are needed. Once the light reaches the substrate, it gets absorbed and generates the photo-current. The intensity of the monochromatic light depending on how deep it penetrates into a material (x) is given by

$$I = I_0 e^{-\alpha x}, \tag{1}$$

where I_0 is the intensity of monochromatic light absorbed at the surface, and α is the absorption coefficient. Absorption coefficient depends on the material exposed to light and the light wavelength. For silicon (substrate), absorption coefficient varies two orders of magnitude within the visible light spectrum (approximately between $10^5\ \text{cm}^{-1}$ at a 400 nm and $10^3\ \text{cm}^{-1}$ at 700 nm wavelength – Ref. [23], p. 14). A photon is absorbed if it provides an electron with enough energy to move it to the conduction band and generate an electron-hole pair. Therefore, photons with lower wavelengths (i.e. higher energy) can interact with more electrons increasing the probability of their absorption. Consequently, blue and violet light ($\alpha \approx 10^5\ \text{cm}^{-1}$) are absorbed closer to the substrate surface, while the red light ($\alpha \approx 10^3\ \text{cm}^{-1}$) penetrates deeper in the substrate. Alternatively, if the absorption length is defined by $L_{abs} = \alpha^{-1}$, it will vary between approximately 100 nm for the blue side of the spectrum, and 10 μm for the red side of the spectrum [23]. Preferably, the carriers are generated near the electric field of the photo-detector (mainly P–N junction depletion-region electric field), because the carriers need to be accelerated by the electric field to form the photo-current (signal). Longer the distance between the carrier generation and the electric field, larger the portion of carriers that will get recombined before reaching the field, which results in signal attenuation. This is especially the case for carriers generated by blue and violet light which are close to the substrate surface (Si/SiO_2 interface). Thanks to the dangling bonds at Si/SiO_2 interface, a significant number of recombination centers exist at the surface, preventing the light-generated carriers to diffuse to the electric field. Therefore,

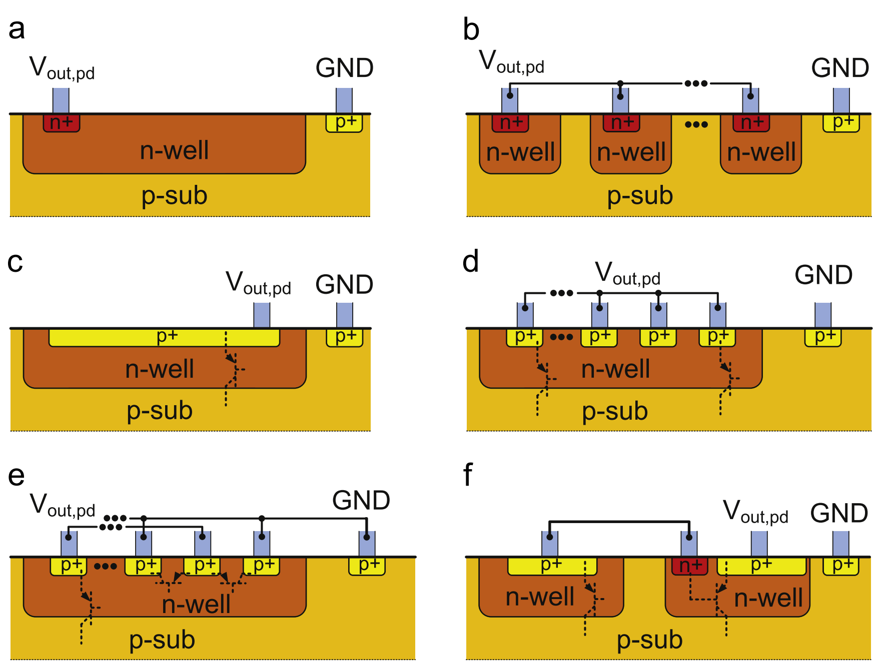

Fig. 1. Standard CMOS compatible photo-detecting structures (cross-section): (a) Conventional diode: N-well/P-substrate photo-diode (b) Comb-shaped diode: N-well/P-substrate photo-diode (c) Vertical BJT: Conventional PNP photo-transistor (d) Comb-shaped BJT: comb-shaped emitter PNP photo-transistor (e) Lateral and vertical BJT: P+/N-well/P-substrate PNP and P+/N-well/P+ PNP photo-transistor (f) Darlington pair.