Spatial Positioning of CMOS Structures Using Optical Position-Sensitive Detectors

Arthur R. Araújo, Carlos Felipe G. Souza, Maria Tereza C. Souza, Victor F. Muniz, Davies W. de Lima Monteiro, Luciana P. Salles
Department of Electrical Engineering – Federal University of Minas Gerais - UFMG
Av. Antônio Carlos 6627, 31270-010. Belo Horizonte, MG, Brazil
+55 31 3409-3497/4810
araujoarthur0@hotmail.com, davies@cpdee.ufmg.br, luciana@cpdee.ufmg.br

ABSTRACT

This work proposes a methodology to measure and map the spatial position of a *CMOS* structure in an integrated circuit (*IC*), and also to align it in comparison to a specific reference, using an optical position-sensitive detector (*PSD*). For optical tests with photosensitive structures, such as a *PSD* in a wavefront sensor, the optical alignment is a crucial step, necessary to verify that their behavior is exactly as expected in certain conditions and in a certain position. Experimental results show that a *PSD* of the type quad-cell (*QC*), built through *CMOS* 0.35μm technology, can be used to align an arbitrary structure in reference to a laser beam, giving a response over certain stimulus that confirmed it. Only one *QC* is needed for this process, leading to a simple and cheap alternative to design and align *CMOS* structures for optics.

Categories and Subject Descriptors

B.8.1 [**Performance and Reliability**]: Reliability, Testing, and Fault-Tolerance; C.4 [**Computer Systems Organization**]: Performance of Systems—*measurement of techniques*

General Terms

Algorithms, Measurement, Documentation, Performance, Reliability, Experimentation, Verification.

Keywords

mapping, IC, CMOS, microelectronic structures, photodetectors, quad-cell, PSD, optics

1. INTRODUCTION

Finding the position in space of any type of structure is a necessary goal for multiple applications today. For example, in photonics, the tracking of the spatial position and the timing of photons is important in order to reconstruct light signals and waveforms or to track a light source [1]. Also, augmented reality is a concept based on accurate, robust and inexpensive tracking systems, which can give useful information according to the position measured by it [2]. Another example is the measurement of the three-dimensional position of a viscosity distribution, important to obtain results over the gradient of viscosity of different fluids, for applications in biology and chemistry [3].

Finally, another case is the determination of the displacement of light centroids in the context of wavefront reconstruction, which enables the observation of how distorted a wave of light could be [4]. The aberrometer is a device used to reconstruct a wavefront of light which has a certain optical aberration inserted into it, and thus find information about the aberration. These aberrations can be inserted by our eye's surface into the light received for our vision, constituting eye diseases such as astigmatism and myopia. The positioning of the structure that receives the light and generates data from intensity and shape is a fundamental process in the construction of the aberrometer. Given that, the methodology proposed in this work is of primary importance in the development of a *PSD* array for an aberrometer [5].

All of the examples given above can be handled by the use of one type of structure, which is the position-sensitive detector. A position-sensitive detector (*PSD*) is a structure able to generate electrical signals due to the incidence of light. As the response it gives depends on how the light is projected over its surface, its response can indicate the position of a light beam. The opposite is also true, then: a fixed light beam can be used to identify the position of a *PSD*. This premise is used in a new methodology to position any kind of structure which has a *PSD* in its surface. The detector used in this article is of the type quad-cell (*QC*), a type that combines four photodetectors in a symmetric organization, enabling then also the alignment of the structure according to their placement, therefore allowing the definition of a rotation of the structure by design in a project.

The main objective of this article is the proposition of a new methodology for the alignment and positioning of any *CMOS* structure by the use of only four photosensitive detectors and an optical setup. This group of detectors is small enough so as to be easily implemented in most projects, providing an easy method to position them, and one that does not use much of their space.

2. CONCEPTS

The *QC*'s response is dependent on an underlying structure, the pixel. The pixel is the smallest entity capable of detecting light. The type used is the 4-Transistor Active Pixel Sensor (*4T APS*), consisting basically of a photodetector, a photodiode, and an amplifying circuit, with four transistors. One of the possible circuits, represented by the diagram in Figure 1a, is comprised of four transistors: a *Reset* transistor, a Selection transistor (*Ts*), a *Buffer* transistor and a transfer transistor (*Tx*).

Basically, the *Reset* transistor controls the flow of input voltage *VDD* to the photodiode. When *Reset* and *Tx* are on, *VDD* is stored in the capacitor of the photodiode. Turning only *Reset* off, the photocurrent generated due to the received light will flow reversely through the photodiode junction, and so its capacitor will start discharging. The discharged voltage will control the *Buffer* transistor, allowing, if *Ts* is turned on, a certain voltage to reach the V_{out} node, where an output value will be read [6]. In this application, *Tx* and *Ts* are always on, as *Tx* is used to sample and hold the voltage for a reading output and *Ts* is a controller in pixel matrices, and these functions are not needed.

Considering that an oscillatory square signal is sent to control the *Reset,* responses will be found according to each period of the signal (Figure 1b). The response curve is obtained from the output voltage as it is read in relation to time. When *Reset* is on, a fixed value Vi_{out} is read, correspondent to *VDD*. Then, when *Reset* is off, the response is marked by an exponential decay curve, characteristic of the decay of the charge from the photodiode's capacitor. The decay will be faster as the pixel is covered by light with more intensity, and slower as the light has less intensity. At the end of the square signal's period, the curve starts again. This method of obtaining signals can be fast, enabling a quick local response to be read as the light changes, especially if a high frequency signal is sent.

The analysis of the decay is fundamental in discovering the position of the light spot over the pixel. In this work, the type of *PSD* used, the *QC*, organizes four pixels, with square photodiodes, symmetrically, as shown in Figure 1c, representing pixels A, B, C and D in a square *QC*. Because of that, four output voltages will be read in relation to time. There is then the need to arbitrarily choose a time to read the values of each pixel to enable a valid comparison over how the light's intensity was affecting each pixel. This time is called sampling time τ_{smp}. To compare the voltage outputs (Figure 1b), a relative voltage ΔV_{out} is then measured, between the value from the start of the decay Vi_{out} and the value Vf_{out} that corresponds to τ_{smp}. A bigger ΔV_{out} will indicate that the pixel has more light over its photosensitive area than others, and the opposite is also true.

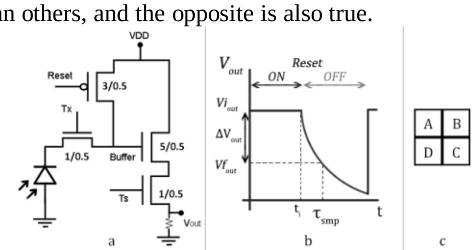


Figure 1. 1a Basic diagram of the *4T APS*. 1b Sample decay curve of a photodiode, showing a comparison between V_{out} reading time and Reset timing. 1c Quad-cell representation.

3. EXPERIMENTAL SETUP

The optical test setup consists of a laser beam of wavelength λ = 633 nm, collimated by a micro objective lens and a pinhole, passing through a polarizing variable filter and a normal filter to be then turned into a beam of circular profile and known diameter by an aperture. From the orifice, a combination of two convergent lenses is done to control the size of the spot, until it reaches a convergent lens and is focused into the *QC,* which will be on its focal plane, leading to a spot of sinc² profile of intensity. A matte ground glass can be placed instead of the convergent lens, to send a homogeneous light stimulus. The optical power from the spot can be measured by the placement of a power meter (Thorlabs S130C) near the *QC*, and the optical intensity calculated by knowing the active area of the power meter sensor (73.9 mm²).

The light coming from the laser is fixed and aimed at a structure that is in a plane orthogonal to the laser. The structure is what will be moved according to the answer given by the photodetectors from the received light. In it, a printed circuit board (*PCB*), as represented in Figure 2a, was mounted. A graphical interface was developed in LabVIEW to remotely control the pixel transistors (*Tx, Ts* and *Reset)*, and to read the pixel outputs (V_{out}) (Figure 1a). This interface is associated with a data acquisition device (NI6023E), which is in turn connected to the *PCB*. The *PCB* receives inputs to the pixels from the interface (Figure 2a - 1) and sends outputs from the pixels to the interface (Figure 2a - 2). A chip over the *PCB* (Figure 2a - 3 and Figure 2b) contains the *QC* used for testing (Figure 2b - 4). The chip used in our experiment was a testing chip which has multiple photosensitive structures and devices. The technology used to build the *PSD* is the *complementary metal–oxide-semiconductor* (*CMOS*). The *CMOS* tech offers a low rate of energy consumption, needs a low voltage to operate, allows access to every photodetector unit through digital addressing and integrates electronic (analogical and digital) functionalities.

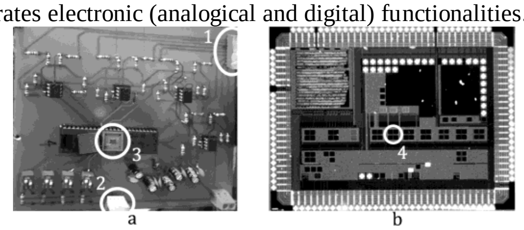


Figure 2. 2a Printed circuit board, with (1) voltage output, (2) pixel signal inputs and (3) experimental chip.
2b *QC*'s chip die, with testing *QC* (4).

We chose to hold the structure in a device mounted over four motors controlled remotely, three of translation and one of rotation. The translation motors are three step motors of 200 steps, with each step equaling 1.25 μm. They were positioned as the X, Y and Z axes, corresponding to the axes in reference to the optical table and to the laser. The other motor is a rotation step motor, which rotates the device along the YZ plane, and step resolution of 0.6 arcmin.

4. QUAD-CELL AND POSITIONING OF STRUCTURES

There are some steps involved in the process of spatial positioning, and these will be described in the following sections. The flow chart in Figure 3 starts with a brief overview.

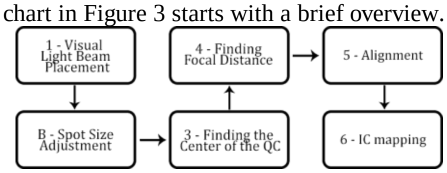


Figure 3. Chart representing the steps of the methodology.

4.1 Visual Light Beam Placement

The first step of the process involves checking the status of the *PSD*. The convergent lens is removed, the light beam is positioned circumscribing the chip's die, by moving the structure, and the matte ground glass is placed. The response from the four photodiodes of a quad-cell are then measured, leading to four waveforms, one for each photodiode, linking time and output voltage as in Figure 1b. As the light beam is uniform and covering all photodiodes equally, the curves are expected to be the same, considering the intervals of light intensity in which the quad-cell works the best and considering the standard deviation between the responses of each cell. A way to determine such parameters and compare photodiodes is left to another study [7]. The response curves will be indicative during the whole process that there is a light signal being received by the photodetectors.

4.2 Spot Size Adjustment

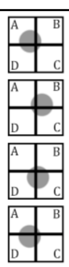
After seeing that the *PSD* responds normally to the presence of light, the laser spot has to be reduced to at least 30% of size of the *QC*, to increase resolution in the responses. For an easier alignment, the light spot diameter should be the smallest possible but big enough so it can lead to responses in the four photodiodes. If a convergent lens is used with this objective, and a sinc^2 light spot profile is guaranteed, the Airy disk diameter is a useful approximation.

After placing the lens, the translation motors are used to place the spot visually over the part of the die where the quad-cell is and the polarizing filters placed to reduce the surrounding diffraction tracks until only a small dot can be visualized over the structure. It is important to note here that the whole procedure is best done in a dark room, without the interference of light sources different than the laser.

4.3 Finding the Center of the *QC*

The objective in this part of the procedure is aligning the center of the quad-cell with the center of the light spot, where the four photodiodes will have the same area covered by light if the spot is radially symmetrical. As the response from a photodiode is proportional to the area of the spot over it, each photodiode will generate a response with the same relative voltage, within an acceptable margin of error, when such a position is found for it.

The *QC*'s response will need to be actively observed. If no response is seen, the structure will need to be scanned with the light by the motors until a response is found. When the light spot is covering over any part of the *QC*, its output can be measured and the relative voltage taken. According to the value, the structure will have to be moved in a certain direction, even though the *QC* is not yet aligned with the optical system. Visual cues (Figure 4) are to be taken into consideration, where each ΔV_{out} corresponds to the relative voltage of one pixel.



$\Delta V_{outA} > \Delta V_{outD} > \Delta V_{outB} > \Delta V_{outC}$
Action: Move structure to the left and up.

$\Delta V_{outB} > \Delta V_{outC} > \Delta V_{outA} > \Delta V_{outD}$
Action: Move structure to the right and up.

$\Delta V_{outC} > \Delta V_{outD} > \Delta V_{outB} > \Delta V_{outA}$
Action: Move structure to the right and down.

$\Delta V_{outD} > \Delta V_{outA} > \Delta V_{outC} > \Delta V_{outB}$
Action: Move structure to the left and down.

Figure 4. Visual cues of actions in the alignment process.

When the spot seems to be in the center, after following the movements above, it is important to ensure such measurements with different light intensities, in which the photodiode has already been found to work well. For example, a lower intensity would lead to a slower decay curve, enabling a better comparison between the voltages in a certain time slot. The decay curve must be neither too abrupt nor too slow. If the relative voltages differ as the light intensity is changed, it will mean the spot was not actually on the center. If not, and the voltages still are essentially equal, it will mean that the spot's central area is centered correctly. At the end of this procedure, the laser spot will be centered on the quad-cell and, considering arbitrary margins of errors, $\Delta V_{outA} = \Delta V_{outB} = \Delta V_{outC} = \Delta V_{outD}$.

4.4 Finding Focal Distance

Now, the light spot is at the center of the *QC*. However, the axes from the optical system are not yet aligned with the *QC*'s axes and the *QC* may not be at the real focal distance.

First, from the center of the quad-cell, the translation motors will be used so the laser goes down, for a distance similar to the quad-cell's radius. The spot, if small enough, will stop over either the photodiode C or the D, depending on how misaligned it is, and this photodiode will have the biggest ΔV_{out}, followed by the other one. Then, the structure is rotated in the direction of the other photodiode, until their responses are approximately similar. Roughly then, when the center is found again, the structure will be aligned. Figure 5 shows the process in more visual detail.

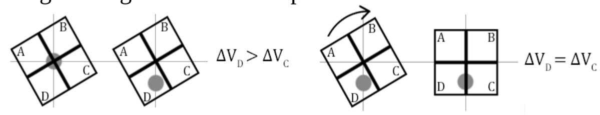


Figure 5. Representation of rough alignment of the structure.

Afterwards, to find out if the *QC* is at the approximate focal distance from the convergent lens, it has to be spatially scanned in the *XQC* or the *YQC* axis. Knowing the diameter of the spot at the focal plane and of the *QC*, one can find that the optimal point in this scan will be when the shortest curve of response vs. position of spot is seen, as it will mean that the spot has shrunk enough to not influence the photodiodes more than from its focal diameter. Repeating this step at different distances from the lens is a good way to verify the completion of the objective.

4.5 Alignment

The final step to be done is a spatial scan of the quad-cell in one specific axis. The structure is to be moved over this axis by small steps, and the relative voltages taken every time, considering the same sampling time, leading to the graphs shown in Figure 6. If the structure is aligned, the photodiodes near the axis in which the light spot is being moved would have to give similar responses, as the area of each covered by light would have to be similar. If the data suggests otherwise, the differences between the responses from such photodiodes will indicate the step to be taken. It is important to do this only at focal distance, guaranteeing the smallest spot.

Figure 6 gives a theoretical visual focus over this part. Its first row shows a *QC* rotated by a small angle to its axes, in counter-clockwise direction, and how the scan gives responses that indicate so ($\Delta V_{outA} > \Delta V_{outD}$ and $\Delta V_{outC} > \Delta V_{outB}$). A small rotation is then done in the opposite direction until another scan leads to superposed responses as in the second row, which indicates an optimal alignment.

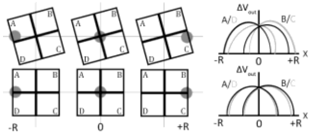


Figure 6. Representation of fine alignment of the structure, done through a spatial scan in one of the *QC*'s axes.

4.6 *IC* Mapping

The structure is now aligned according to the laser and its spatial position is known. From the center of the *QC*, the laser can now reach any other structure by moving it in the right axis by the right distance. The possibility to map an *IC* built through *CMOS* technology is then open, as the distances from each structure in the *IC* are known as specifications of the project. This way, by placing one *QC* in a project, one can, for example, align it for usage with other photosensitive structures that do not give responses according to position, but had to be organized in a particular manner. Also, if any structure in an *IC* needs to be in a specific position, placing a *QC* by a known distance to it and then aligning everything with a laser beam is an easy way to guarantee that the structure is in the place it had to be.

5. RESULTS

After having built our optical setup, procedure 1 (Figure 3) was done to verify the conditions of the devices. Procedures 2 and 3 (Figure 3) were then followed in order. The laser's intensity was changed to guarantee the center had truly been found afterwards. Figure 7 has a diagram covering the previous feats, showing the appearance of the four wave forms, for each photodiode (color label), and the relative voltages taken at arbitrary sampling times (in % of the total wave period, as in Figure 1b), for different sizes and positions of light spots and light intensity (I). These still have the sinc² configuration, but bigger light intensity leads to more diffraction tracks (represented by circles of different sizes) and so to bigger areas of the *QC* covered by light.

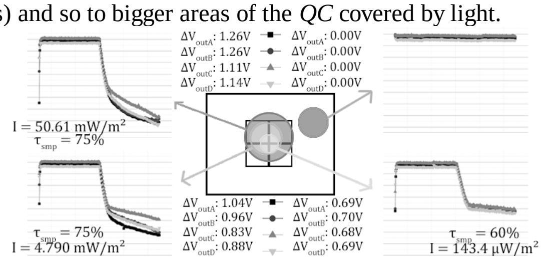


Figure 7. Results of the search for the center. Each circle represents a light spot of different intensity (I), pointed to the correspondent response waveform. The output values for each graph at sampling time are shown beside them.

Then, having experimental proof that we were over the center, we started the next step (Procedure 4 - Figure 3) using the smallest intensity. Moving the laser down, we found out that the Y axis was over the photodiode D, so we had to rotate the structure in clockwise direction, until the responses from C and D were alike. Next, the center was found again and the fine alignment (Procedure 5 - Figure 3) done until the spatial scan gave a satisfactory response. Figure 8 illustrates this procedure and our final results. The scan was completed after assuring a main diameter for the spot of approximately 8% of the *QC*'s diameter, by moving the structure in the X axis of the motors, to guarantee its position in the focal plane of the lens, which was a plane-convex convergent lens with 50 mm of focal distance.

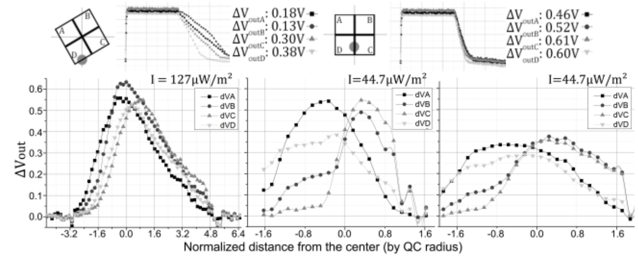


Figure 8. Results of the search for alignment. On the second row, the process was: scan with I=127 μW/m², too big a spot. Scan with I=44.7 μW/m² and focal distance found, it was a little rotated. Scan with I=44.7 μW/m², rotating the *QC* a small amount in counter-clockwise direction, best results. τ_{smp}=60% and same Y axis scale at all times.

6. CONCLUSION

The quad-cell is a powerful structure for discovering the spatial position of any *CMOS* device. Its structure is ideal for an alignment methodology for different applications, because of the axes in its structure and how its response can indicate whether a light spot is aligned with one of its axes or not.

To further demonstrate the quad-cell's usability, experimental results show how the procedure of alignment was done in an arbitrary structure, through only one *QC*, and yielded a reliable outcome. It was observed that, at the end of the process, the whole structure was aligned with the laser, as its movements over one axis led to the expected responses to be obtained in different instants of time.

7. ACKNOWLEDGMENTS

We thank the people from OptMA[lab] in UFMG, Dr. Frank Sill Torres and Matheus de Oliveira Mendonça. For financial support we thank FAPEMIG, CNPq, Programa Institucional de Auxílio à Pesquisa de Doutores Recém-contratados from PRPq/UFMG, Escola de Engenharia/UFMG and CAPES Jovens Talentos.

8. REFERENCES

[1] Tisa, S., Zappa, F., and Cova, S. 2007. *Monolithic quad-cells for single-photon timing and tracking. Proc. SPIE* 6583. Photon Counting Applications, Quantum Optics, and Quantum Cryptography. (May. 2007)

[2] Kim, D., Richards, S.W., and Caudell, T. P. 1997. *An optical tracker for augmented reality and wearable computers*. Virtual Reality Annual International Symposium, IEEE 1997, 146-150.

[3] Ługowski, R., Kołodziejczyk, B., and Kawata, Y. 2002. *Application of laser-trapping technique for measuring the three-dimensional distribution of viscosity.* Optics communications 202, no. 1: 1-8.

[4] Van Dam, M. A. 2005. *Measuring the centroid gain of a Shack-Hartmann quad-cell wavefront sensor by using slope discrepancy*. J. Opt. Soc. Am. A 22**,** 1509-1514.

[5] Vasconcelos, U. A. *et al.* 2014. *Computational test bench and flow chart for wavefront sensors*. Proceedings of the SPIE Photonics Europe 2014, SPIE Press.

[6] Retes, P. F. L. *et al*. 2011. *Evaluation of the full operational cycle of a CMOS transfer-gated photodiode active pixel*. Microelectronics Journal 42, 1269–1275.

[7] Souza, M. T. C. *et al.* in press. *Optical equalization analysis for position-sensitive-detector of the type quad-cell.*