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A Smart Range Image Sensor

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Abstract

In the present paper we discuss a smart image sensor, specifically designed for sheet of light range imaging. The image sensor is capable of measuring the projection of a light stripe on an object. The sensor consists of an array of Position Sensitive Detectors (PSD's), as well as some on-chip electronics. The sensors are made in a standard 3GHz bipolar process. Each PSD measures a light center of gravity, and this way the line of light is sampled in the plane of the image sensor. 3D information is computed by means of triangulation. On chip circuitry takes care of preamplification of the sensorsignals, and multiplexing of the different sensor signals to a single output channel.

1. Introduction

The last couple of years, a lot of effort has been devoted to the development of camera's that are capable of measuring the 3D shape of an object, rather than an ordinary intensity image. These, so called, range finding camera's can be useful in a wide number of automation applications. To name a few, one could think of bin picking, robotic assembly of industrial parts, robot navigation, quality inspection and product classification. An extensive overview of various methods for acquiring range information has been given by P.J. Besl [1].

One of the approaches described in [1] is sheet of light range imaging. This technique was first introduced by Y. Shirai [2]. The idea is depicted Figure 1. A sheet of light is projected onto the object that has to be measured. In the situation of Figure 1 this is a semisphere on an flat background. The cross sectional line of the sheet of light with the object is projected onto an image sensor. 3D coordinates are derived from the sensor signals using triangulation. In order to do this, the only extra information needed is the angle between the lightsheet and the optical axis of the camera lens. If a complete surface has to be measured, the object has to be moved perpendicularly with respect to the lightsheet. This can be accomplished, e.g., by placing the object on a conveyor belt.

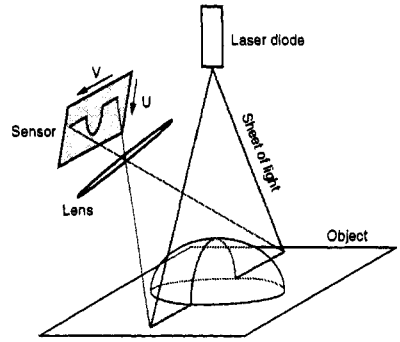

Figure 1: Sheet of light range imaging

The sensor of Figure 1 that is being developed consists of an array of Position Sensitive Detectors (PSD's) [3] [4]. For each discrete V-value in the image plane of the camera, a PSD measures the position of the incident illumination. In the next section is explained how a PSD works. Each separate PSD has a length of 2 cm (in the U-direction), and the pitch in the array (in the V-direction) is 28μm. On-chip electronics take care of preamplification of the sensor-signals and multiplexing of the sensorsignals to a single output channel. This is the topic of Section 3. AD-conversion and computation of the range values proceeds off-chip. The goal is to be able to record 2 million range values per second at a 12 bits resolution.

In this paper we will start with the basic theory on Position Sensitive Detecors. Next, some details are given on the signal processing that takes place on the image sensor, and we will explain how we produced PSD's that exceed the standard die size for the chosen process (i.e. 1 cm^2). The paper ends with some measurements on a prototype device containing 6 PSD's and on-chip electronics.

2. Position Sensitive Detectors

In the present section we will tentatively describe how a PSD works. We regard a planar pn-junction (like the one depicted in Figure 2, and we will start by describing

the effects that occur if this pn-junction is illuminated at a specific position. Due to the photo electric effect electron hole pairs are generated, and if they are generated close enough to the depletion layer, they can be separated by the electric field. Once the holes have arrived at the p-type layer a (hole-)current will flow to the end-contacts of the layer (if they are placed at a proper potential).

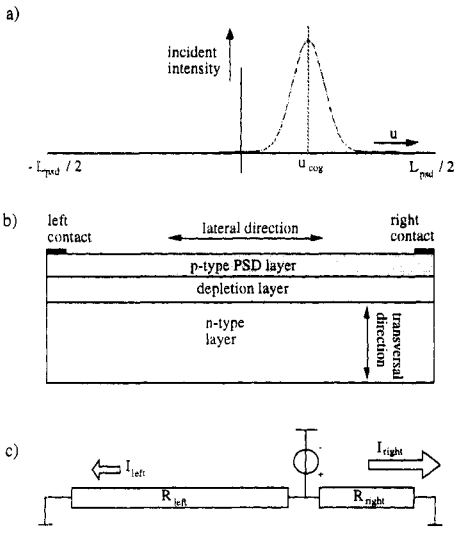

Figure 2: Model of a pn-junction under non-uniform illumination.

Figure 2 gives an idea of what happens: Figure 2a shows the incident illumination that has its center of gravity at U_{cog}. At this point optically generated electron hole pairs will be separated by the depletion layer. The holes will flow to the end-contacts, as indicated in Figure 2c: because there is a large resistance to the left contact only a small current will flow to the left side, and a large current will flow to the right side (according to Ohm's law).

Now suppose the implanted p-type layer has a perfectly homogeneous resistivity. In the one dimensional situation this means that the resistance to the left and right sides are perfectly proportional to the distance to the left and right contact, respectively. This implies that the ratio of the left and right lateral current gives us the exact position of incidence as follows [see Figure 2 for the parameters]:

$$\frac{I_{left}}{I_{right}} = \frac{R_{right}}{R_{left}} = \frac{.5L_{PSD} - U_{cog}}{.5L_{PSD} + U_{cog}} \qquad (1)$$

If we solve Eq. 1 for U_{cog}, we get:

$$U_{cog} = .5L_{PSD}\frac{I_{right} - I_{left}}{I_{right} + I_{left}} \qquad (2)$$

Eq. 2 is the well-known PSD-equation [5]: the center of gravity of a Position Sensitive Detector can be determined from the photocurrents to the left and right side.

The PSD's have been fabricated in a standard bipolar process, DIMES-01 [6], at our university IC-facility DIMES (the Delft Institute for Micro Electronics and Submicrontechnology). With regard to reaction speed and noise considerations it is possible to compute what the ideal implantation level for the PSD's should be [4]. In order to be able to use the standard process, a p-type implantation from DIMES-01 was used that was closest to the ideal implantation level.

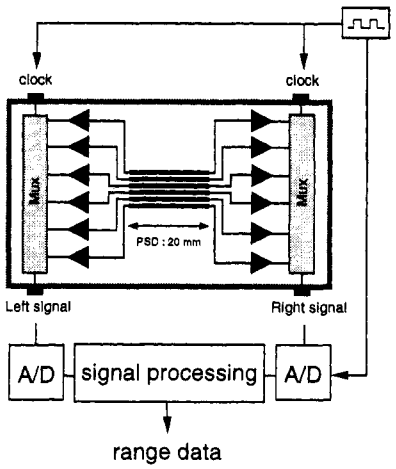

Figure 3: Prototype of the smart PSD sensor containing 6 PSD's and on-chip circuitry. A/D-conversion and further signal processing proceeds off-chip.

3. On chip circuitry

The on-chip electronics consists of two preamplifiers for each PSD-strip (one for the left, and one for the right current) and two multiplexers. The preamplifiers perform low-pass filtering on the sensorsignals at 16kHz (video linespeed).

The main reason for the on-chip electronics is that we wish to perform multiplexing on-chip. This way we avoid having to make a chip with a large amount of bonding pads (i.e. twice the number of PSD's since each PSD produces two photocurrents). The on-chip multiplexer is implemented in ECL technology. The ECL-signals drive the switches of the preamplifiers. Each PSD is connected to the output node once, every 64μs. The values that are presented at the output node can be regarded as the average of the photocurrent over the last 64μs.

In Table 1 we have enclosed a number of characteristics of the PSD-chip. Figure 3 gives the idea of the on-chip signal processing for a prototype device that consists of 6 PSD's, 12 preamplifiers and 2 multiplexers.

4. Exceeding the standard die-size

In order to be able to make PSD's with a length that exceed the standard die-size in the IC-process used (i.e. 1 by 1 cm), and also be able to integrate electronics on the same die a special trick in the photolithographic process had to be performed. Two separate masksets were

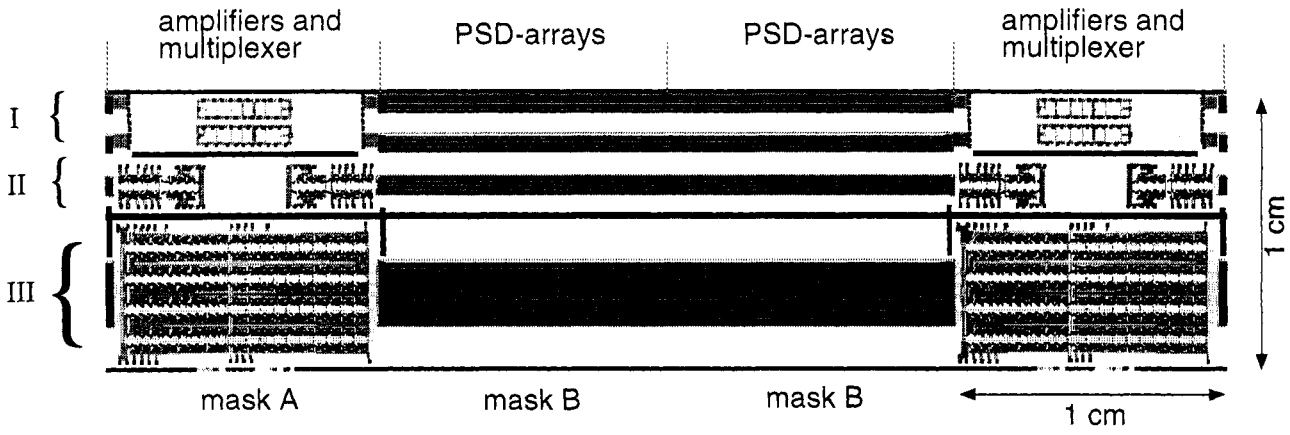

Figure 4: Masksets of the PSD-chip: area I separated PSD arrays and electronics, area II array of 6 PSD's connected to the on-chip electronics, area III array of 80 PSD's connected to the on-chip electronics

Table 1: Specifications of the prototype PSD-chip

Die size for 80 PSD's	1.5cm^2
Nr. of PSD's	6 or 80
Size of PSD's	2cm by 20μm
Supply voltages	+/- 5V
Total power dissipation	0.5mW per PSD
Linearity	1:2000
Nr. of bits	12
Clock readout frequency	500kHz
Light source (type/power)	LASER-diode 5mW
Sensitivity of PSD's	0.6A/W for λ=780nm
Input current noise	55pA (BW=16kHz)
(analog) Outputsignal	4-5 V

designed: one containting the electronics, and one containing the PSD-arrays. By accurate alignment during illumination, the PSD's and the electronics were "stitched" together. This can be seen in Figure 4. Using this technique, a wafer has been produced that contains PSD's with a length of 2 cm.

5. The prototype device

In the present section we will discuss the prototype PSD-chip. In this section we will start with the measurement results on the linearity of the PSD's. Finally, we will show some examples of the sensor signals for different circumstances of illumination.

5.1. Linearity

The most important feature of a PSD is its high linearity. As explained in Section 2 for a highly linear PSD, a very homogeneous PSD layer is needed. Otherwise the relations of Eqs. 1 and 2 lose validity. What we would like to know is if linearity is maintained if we produce 2cm PSD's by stitching two adjacent dice, as explained in Sec. 4. In order to determine this, a laserdiode was placed on

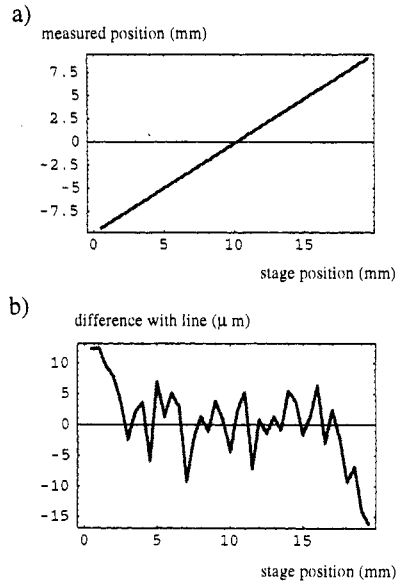

Figure 5: Linearity measurements: a) Measured position vs. translation stage position b) difference of Figure 5a with a linear fit.

a translation stage. The laserbeam was focused on one of the separated PSD's [see Figure 4]. In this experiment, the PSD-signals were measured with an off-the-shelf opamp.

In Figure 5a the horizontal axis represents the position of the translation stage. The vertical axis contains the measured data, i.e. the position as determined from the PSD signals. The PSD position measurement has its origin at the center of the PSD (this is due to the factor .5 L_{PSD} in Eq. 2). Figure 5b gives the difference of Figure 5a with a linear fit through the data as a function of the stage position. From Figure 5b can be seen that the PSD stays linear within 10 μm for the inner cm of the PSD. It is possible to calibrate for the deviation from linearity at the outer regions of the PSD.

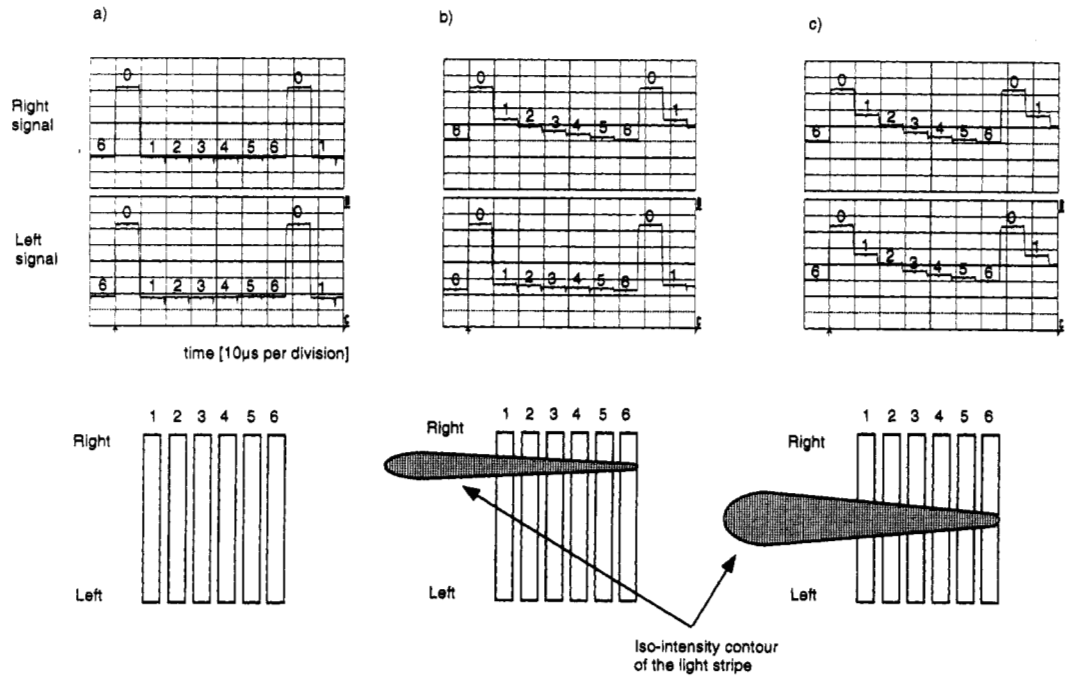

Figure 6: The sensor signals: a) no light signal: the preamplifier offset values, b) projected light stripe at right side of the PSD's, c) projected light stripe at the center of the PSD's.

5.2. The sensor signals

In the present section we will shortly describe the sensor signals that are produced by the smart PSD-chip. Figure 6 shows the signals for the prototype chip containing 6 PSD's. Three situations are taken into consideration. Figure 6a shows the situation where no light falls onto the sensor. The upper oscilloscope signals correspond to the photocurrents to the right side of the PSD's, and the lower signals to the left photocurrents. The numbers in the scope plots correspond to the PSD that is placed to the output channel by the multiplexer. The difference in signal-level in the "dark-image" of Figure 6a, is due to offset differences between the on-chip preamplifiers. This will be corrected for by off-chip signal processing. In this particular example the readout frequency was 100kHz.

In Figure 6b the center of gravity of the incident illumination is at the right side of the PSD's. In Figure 6c the PSD's are illuminated near the center. In Figures 6b and Figure 6c PSD nr.1 captures the highest light intensity, and the amount of light decreases for PSD 2-6. This is indicated by the iso-intensity contours, depicted below the scope signals.

6. Conclusions

In the present paper we discussed a smart image sensor, specifically designed for sheet of light range imaging. We have succeeded in making a prototype sensor with 6 PSD's and on-chip circuitry consisting of 12 preamplifiers and two multiplexers implemented in ECL technology. Present work concentrates on a redesign of the electronics in order to improve linearity and readout frequency. It was shown that long PSD's can be made by aligning two masks in the lithographic process. For these stitched PSD's a linearity has been measured of 1:2000.

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