Phototransistor Based Time-of-Flight Range Finding Sensor in an 180 nm CMOS Process

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Abstract—Time-of-Flight (TOF) sensors using different kinds of integrated phototransistors as photodetectors are presented in this work. The sensors as well as the phototransistors are implemented in a standard 180 nm CMOS process. A fill factor of 67 % is reached. At optimal working points of the phototransistors standard deviations better than 2.6 mm are achieved.

Keywords—Time of flight, TOF sensor, Phototransistor, distance measurement, depth sensor, PIN

I. INTRODUCTION

Applications in military industry, robot vision systems, automotive, gaming electronics, etc. are placing increasing emphasis on the introduction of contactless depth-sensors. Such sensors can be realized based on different physical principles. The indirect time-of-flight (TOF) method was used in the present work and will be introduced in the following. Being part of the TOF device, a light source emits a continuous-wave modulated light signal with the modulation frequency $f_{\text{MOD}}$. The backscattered component is consequently detected in the sensor, whereby the phase difference $\phi_{\text{TOF}}$ between the emitted and received light is obtained. Thereby the optical signal passes twice the distance between the sensor and the object. $\phi_{\text{TOF}}$ is measured by means of a correlation technique. Finally the object distance $d$ can be calculated with:

$$d = \frac{c \phi_{\text{TOF}}}{4 \pi f_{\text{MOD}}}.$$  \hspace{1cm} (1)

A laser can be used as illumination source. Considering the transmitted light $P_{\text{out}}$ a received optical power $P_{\text{in}}$ can be calculated as

$$P_{\text{in}} = P_{\text{out}} \frac{D^2}{4d^2} \rho \tau \cos \theta.$$  \hspace{1cm} (2)

In (2) $d$ is the distance to the object, $D$ is the lens diameter, $\rho$ is the reflectivity of the target, $\tau$ is the total optical transmission coefficient and $\theta$ is the object inclination from the optical axis. Having a low $P_{\text{in}}$, the correlation principle has to be used. A deeper introduction into the correlation principle could be found in [1].

A TOF sensor based on a PN photodiode with a minimum standard deviation (STD) of 2 cm is presented in [1]. An approach with a pinned photodiode and a STD of ~5 cm at 1 m and more than 20 cm at 2 m is presented in [2]. In [3] a CMOS TOF sensor with a special photodetector is presented. This device achieves STDs down to 48 mm. A RGB TOF sensor achieving STDs <6 cm up to 3 m is presented in [4].

II. SENSOR DESIGN

A. Phototransistors

The TOF sensor was realized with three different 40×40 µm² sized pnp phototransistors (PTs) in a 180 nm CMOS process, achieving a fill factor of 67 %. The used PTs (50BCenterE, 100BEdgeE and 100 BQuadE) are presented in [5]. The cross section of one PT (50BCenterE) is depicted in Fig. 1. A 15 µm thick, low doped $p$- epitaxial layer starting material was used, which forms the collector. This thick epi layer provides sufficient bandwidth for a proper TOF operation. The base of each PT was left floating. To reduce the effective base doping the 50BCenterE PT was implemented as a striped n-well base. These stripes diffuse due to the total thermal budget into one layer. The emitter was formed by small $p$+ source/drain contacts. Depending on the device these contacts were placed in different locations on the photosensitive area.

Characteristics of the PTs at 850 nm are shown in Table 1. Maximum responsivities of 2.18 A/W as well as -3 dB bandwidths of 50.7 MHz with $V_{CE} = -10$ V were achieved. For the following measurement results $V_{CE}$ was set to -3.0 V.

B. Pixel circuit

A simplified read out circuitry of the TOF single-pixel sensor for performing the correlation is presented in Fig. 2. The photocurrent $I_{\text{phot}}$ generated in the PT consists on one hand on the background light part ($I_{\text{bg}}$) and on the other hand on the backscattered modulated light part ($I_{\text{mod}}$). $I_{\text{phot}}$ is integrated via
Thereby both capacitors C1 and C2 are connected via T3 and T4 the integration time of the sensor. Furthermore, by averaging sensor starts to saturate. This can be counteracted by reducing optical power is decreased. For a higher optical power the around 10 dB per decade of the measured distance when the power can be calculated. The results show a STD increase by mated object distance corresponding to the applied optical
power. In the optimal working point of each PT, STDs
results, where the STD is shown as a function of the applied
optical power. In the optimal working point of each PT, STDs
formed at a frame rate of 100 fps. Fig. 4 presents the measured
setup allows a precise measurement of the sensor’s perform-
ance independent of any optics. All measurements were per-
TABLE I

<table>
<thead>
<tr>
<th>VCE = -2V</th>
<th>VCE = -10V</th>
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</thead>
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<tr>
<td>BW [MHz]</td>
<td>R [A/W]</td>
</tr>
<tr>
<td>BW [MHz]</td>
<td>R [A/W]</td>
</tr>
<tr>
<td>50%Center_E</td>
<td>12.8</td>
</tr>
<tr>
<td>100%Edge_E</td>
<td>14.2</td>
</tr>
<tr>
<td>100%Quad</td>
<td>18.6</td>
</tr>
</tbody>
</table>

III. MEASUREMENT RESULTS

The TOF sensor was characterized by determining the standard deviation (STD) while changing the optical power at the PT. Fig. 3 depicts the setup used for the measurements. The setup allows a precise measurement of the sensor’s performance independent of any optics. All measurements were performed at a frame rate of 100 fps. Fig. 4 presents the measured results, where the STD is shown as a function of the applied optical power. In the optimal working point of each PT, STDs between 1.6 and 2.6 mm were achieved. Based on (2) an estimated object distance corresponding to the applied optical power can be calculated. The results show a STD increase by around 10 dB per decade of the measured distance when the optical power is decreased. For a higher optical power the sensor starts to saturate. This can be counteracted by reducing the integration time of the sensor. Furthermore, by averaging over several frames a reduction of the STD can be achieved.

IV. CONCLUSION

We present an integrated time-of-flight sensors using pnp phototransistors as photodetectors. Each sensor has a fill factor of 67 % whereby the phototransistor occupies 40×40 µm². The sensor was characterized by measuring the standard deviation as a function of the incident optical power. Standard deviations down to 1.6 mm were achieved. An improvement of the sensor performance will be possible by trimming the phototransistor into its optimal operating point. This could be done by an active gain control which regulates the base potential depending on the incoming light power.

REFERENCES