Abstract—A time-of-flight range finding sensor using a monolithic integrated pnp phototransistor is presented. The phototransistor was specially adapted for the requirements of the time-of-flight application. The sensor has a fill factor of 75% and achieves standard deviations down to 7.3 mm at 6250 fps and an incident optical power of -40 dBm.

Keywords—TOF; Time of Flight; phototransistor; CMOS; responsivity; bandwidth; PIN; distance measurement; noise

I. INTRODUCTION

In recent publications different Time-Of-Flight (TOF) sensors were published using various photodetectors including photodiodes [1], SPADs [2], phototransistors [3], etc. One way to determine the object distance $d_{obj}$ is with the indirect TOF measurement method. Thereby the phase difference $\phi_{TOF}$ between the received light signal and a reference clock is measured by means of a correlation method:

$$d_{obj} = c_0 \frac{\phi_{TOF}}{2} = c_0 \frac{\phi_{TOF}}{2f_{MOD}}.$$ (1)

In our presented system a continuous-wave modulated light with a modulation frequency $f_{MOD} = 12.5$ MHz was used. A correlation between both mentioned signals is performed while changing the phase in 16 steps.

II. CIRCUIT DESCRIPTION

A. Pixel description

The TOF sensor is fabricated in 0.35 µm CMOS. The pixel achieves a fill factor of 75% and consumes a power of around 5 µW. A simplified circuit of the pixel is shown in Fig. 1. In the first step the background light (BGL) is sensed and captured by the sample and hold part of the circuit. This part provides a constant current $I_{DC}$ which will extinguish the dc current portion due to background radiation from the total photocurrent $I_{PH}$ during the following measurements. The remaining current $I_{MOD}$ is integrated in both capacitors $C_1$ and $C_2$ depending on the state of $\Phi$ and $\Phi$, respectively. The differential voltage $\Delta V_{OUT}$ between both capacitors is proportional to the phase difference $\phi_{TOF}$. A negative feedback was implemented by the transistors T5/T6 in order to minimize the influence of the phototransistor’s space-charge region capacitances. Otherwise both capacitances would take a portion of the photocurrent, which will in turn decrease the output voltage $\Delta V_{OUT}$.

B. Phototransistor

The pnp pin phototransistor (Fig. 2) used in this sensor is a further improvement of the phototransistors presented in [4] especially for TOF applications. This device has a size of 50×100 µm² and consists of 18 base-emitter regions implanted in the p-epi collector. Each base-emitter region is built from a 0.7×0.7 µm² small p + emitter and a 3.1×3.1 µm² n-well base. The idea is to increase the base-collector space-charge region by reducing the base region of the whole device. Furthermore, the responsivity is increased due to more emitter area. Responsivities and -3 dB bandwidth of the device are shown in Table 1. The collector-emitter voltage $V_{CE}$ was set to -5 V. This phototransistor has a low total output noise of only $7.99 \times 10^{-24}$ A²/Hz at a collector current of 100 nA.

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III. MEASUREMENT AND RESULTS

The measurement setup (Fig. 3) consists of a control unit (PC and FPGA) for controlling the TOF pixel sensor and the 635 nm laser source. To emulate BGL a second 635 nm laser was used together with a 50/50 combiner to add a dc optical signal. The resulting light signal was directed directly to the phototransistor using a single mode optical fiber. An adjustable attenuator between both sources was used to vary the incident optical power at the phototransistor. This setup has the advantage of independence on any optical components.

Pixel characterizations were done by obtaining the standard deviation of the measured distance while sweeping the optical incident power (Fig. 4) and the BGL power (Fig. 5), respectively. The integration time was set to 10 µs per phase step, which corresponds to a frame rate of 6250 fps, if neglecting the reset and read-out time. The best standard deviation of 7.3 mm was achieved at an optical incident light power of -40 dBm together with a BGL power of -45 dBm. When reducing the optical power, the measured standard deviation shows 10dB increase per decade. However, increasing the optical power could cause the sensor saturation. The saturation can be reduced by reducing the integration time. The BGL sets the phototransistor in its optimal bias point as can be seen from the results shown in Fig. 4. Saturation of the sensor arises for BGL powers higher than -37 dBm (Fig. 5). The phototransistor based TOF circuit in [3] achieves standard deviations down to 1.6 mm, however at only 100 fps and at -32 dBm modulated signal. A frame rate reduction of the presented results by averaging over several frames would even improve the achieved standard deviations with the square root of the averaging factor.

IV. CONCLUSION

A time-of-flight sensor using an optimally adopted pnp pin phototransistor for this application is presented. The phototransistor is characterized with responsivities up to 1.99 A/W, bandwidths up to 150.8 MHz and a low total output noise of only 7.99 \times 10^{-24} \text{A}^2/\text{Hz} at a collector current of 100 nA. Standard deviations down to 7.3 mm were achieved. This value seems to be high when comparing it with the achieved 1.6 mm of a similar sensor presented in [3]. However, the presented measurements in this paper have been performed at around 60 times higher frame rates than in [3]. Furthermore the presented values were obtained at 8 dB less received optical power. Additionally, the sensor is characterized with immunity against background light up to -37 dBm.

REFERENCES