High-Speed Low-Noise PNP PIN Phototransistor
Integrated in a 0.35 µm CMOS Process

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Abstract—A low noise 50×100 µm² pnp pin phototransistor is presented in this paper. The phototransistor is fabricated in a 0.35 µm CMOS process. An optimized layout leads to responsivities up to 1.99 A/W and bandwidths up to 151.4 MHz. Noise measurements show a low total output current noise spectral density of only 6.67×10⁻²⁴ A²/Hz for a collector current of 2 µA.

Keywords—phototransistor; PNP; PIN; light detection; noise; responsivity; bandwidth; CMOS;

I. INTRODUCTION

Next to p(i)n photodiodes and avalanche photodiodes, phototransistors (PTs) offer an additional possibility for light detection. Their integration in silicon paves the way for light detection in the visible and near-infrared range up to wavelengths of 1.1 µm. The properties of silicon lead to a wavelength dependent penetration depth of the photons (e.g. the penetration depth at 850 nm is ~16 µm, while at 410 nm it is only ~0.2 µm) [1]. The wavelength dependent penetration depth causes a different ratio of drift and diffusion parts of the photogenerated current. Thus, common CMOS integrated PTs, like the one in [2], achieve small bandwidths for photons with longer wavelengths. E.g. the pnp PT presented in [2] achieves a bandwidth of only 33.9 kHz and a responsivity of 0.83 A/W which results in a responsivity-bandwidth product (RBP) of 28.1×10⁻³ A/W·MHz for red light. A bandwidth reduction for longer wavelengths can be avoided by placing a thick low doped p-epi layer between the base and the collector of the PT, changing the layout of the base and the emitter. Such a PT with a RBP of 171.1 A/W·MHz at 675 nm is presented in [3]. The increased RBP, especially the higher bandwidth, opens the possibility to use these PTs as photodetectors in additional application fields, e.g. fast opto-coupler, shear sensors, time-of-flight sensors, etc.

In the presented pnp PT the BC-SCR works as a photodiode. The generated photocurrent equals a base current and is amplified by the inherent transistor. Each photogenerated electron-hole pair is split in the BC-SCR. The generated photocurrent equals a base current and is amplified by the inherent transistor. Each photogenerated electron-hole pair is split in the BC-SCR. The electron drifts in the base making its potential more negative. When the base potential approaches the forward voltage of the BE-diode the emitter starts injecting holes through the base towards the collector. The relationship between the injected holes and the electrons in the base is expressed by the current gain β, which is mainly dependent on the doping concentrations of the base and emitter (N_B and N_E) and on the effective base width W_B [4]:

\[
\beta = \frac{I_C}{I_{PH}} \propto \frac{N_B}{W_B N_B}
\]

The small BE pairs lead to an inhomogeneous electrical field in the BC-SCR between the pairs and thus to a higher probability for electron recombination in the field free region of the p-epi layer. This causes a reduction of the responsivity. However, a larger BE area would cause an increase of the BE capacitance, thus reducing the bandwidth of the PT. Furthermore, the -3 dB bandwidth of the PT depends on the BC-SCR capacitance C_{BC}, the transconductance g_m, the base transit time τ_b and the current gain β [4]:

\[
f_{-3dB} \propto \frac{1}{\beta \left( \frac{C_{BC} + \frac{g_m}{\beta} + \frac{g_m}{\beta C_{BC}}}{g_m} \right)}
\]

A third important equation is necessary for describing the output noise current density of the PT [5]:

\[
\frac{\sqrt{I_{out}^2}}{dt} = \left( \frac{\beta}{\sqrt{\frac{1}{\tau_b^2}} + \frac{\tau_b}{\sqrt{\frac{1}{\tau_b^2}}} + \frac{I_{PH}^2}{\sqrt{\frac{1}{\tau_b^2}}}} \right) = \beta \left( \frac{\tau_b}{\sqrt{\frac{1}{\tau_b^2}}} + \frac{I_{PH}^2}{\sqrt{\frac{1}{\tau_b^2}}} \right) + 2\sigma \left( \frac{\beta}{\sqrt{\frac{1}{\tau_b^2}} + \frac{\tau_b}{\sqrt{\frac{1}{\tau_b^2}}} + \frac{I_{PH}^2}{\sqrt{\frac{1}{\tau_b^2}}} \right)
\]

II. PHOTOTRANSISTOR LAYOUT AND THEORY

Fig. 1 shows a 3D depiction of the presented pnp PT. The PT was built in a standard 0.35 µm CMOS technology. A low doped epi-layer with a thickness of ~15 µm was placed on top of the high doped p+ substrate, leading in a thicker BC-SCR and thus in a reduced BC capacitance C_{BC}. The PT has a size of 50×100 µm² and consists of 18 base-emitter (BE) pairs. Each emitter is 0.7×0.7 µm² large. A 3.1×3.1 µm² n-well under each emitter forms the base. Between the BE-pairs a gap of 17.6 µm and 16.1 µm, respectively, is present in both directions.

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The small BE pairs lead to an inhomogeneous electrical field in the BC-SCR between the pairs and thus to a higher probability for electron recombination in the field free region of the p-epi layer. This causes a reduction of the responsivity. However, a larger BE area would cause an increase of the corresponding capacity C_{BE}. This will lead to a reduced -3 dB bandwidth of the PT. Furthermore, the -3 dB bandwidth of the PT depends on the BC-SCR capacity C_{BC}, the transconductance g_m, the base transit time τ_b and the current gain β [4]:

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\]

Figure 1. 3D depiction of the presented phototransistor.
As can be seen from (3) the total output current noise density consists of three terms; the base noise current multiplied with the squared current gain, the noise current caused by the collector current and the correlation between both noise sources. The correlation factor $C$ describes the correlation strength. It equals 1 for an open-base configured PT [6].

III. MEASUREMENTS & RESULTS

The PT’s responsivity and bandwidth were characterized at 410 nm, 675 nm, and 850 nm with optical powers of -13.0 dBm, -19.2 dBm, and -15.8 dBm, respectively. These light power values have been chosen to get the same collector current for each wavelength. The collector-emitter voltage $V_{CE}$ was set to three different values: -2 V, -5 V, and -10 V. Fig. 2 depicts the frequency response of the PT at $V_{CE} = -10$ V. Bandwidths $>100$ MHz for the three wavelengths were achieved. Bandwidths and responsivities at different $V_{CE}$ are shown in Fig. 3. A maximum responsivity of 1.99 A/W was measured. Furthermore at 675 nm and $V_{CE} = -10$ V the highest RBP with 245.5 A/W·MHz is achieved. Table I summarizes the measured responsivity and bandwidth values together with the corresponding RBPs at $V_{CE} = -10$ V.

In addition to responsivity and bandwidth measurements the output noise current density $\overline{i_n^2}$ of the PT was measured. The measurements were performed by means of a light bulb as light source. For the characterization the intensity of the light was adjusted to meet four different collector currents: 100 nA, 500 nA, 1 µA, and 2 µA. $\overline{i_n^2}$ was measured with a low noise transimpedance amplifier (TIA) with 300 kΩ feedback resistor together with a spectrum analyzer (SA) [6]. The noise spectral density is depicted in Fig. 4. A low mean output noise current level of $6.67 \times 10^{-24}$ A²/Hz was measured for $I_{C} = 2$ µA.

IV. CONCLUSION

In this paper a low-noise, high-speed pnp pin phototransistor is presented. The device is built in a 0.35 µm CMOS process and consists of a low doped p-epi layer together with 18 small base-emitter pairs. Bandwidths up to 151.4 MHz and responsivities up to 1.99 A/W are achieved. Compared to common pnp phototransistors built in the same technology [2] the introduced phototransistor exceeds the presented values: For red light the achieved responsivity-bandwidth product of 152.8 A/W·MHz for $V_{CE} = -5$ V exceeds that of [2] under the same conditions by more than 5400 times. The highest responsivity-bandwidth product of 245.5 A/W·MHz was achieved for $V_{CE} = -10$ V. Compared to the results presented in [3], the introduced phototransistor has a 1.43 times better responsivity-bandwidth product under the same conditions. Furthermore, very low output noise current densities down to $0.78 \times 10^{-24}$ A²/Hz at $I_{C} = 100$ nA were measured.

TABLE I. RESPONSIVITIES, BANDWIDTHS AND RESPONSIVITY-BANDWIDTH PRODUCT AT THREE DIFFERENT WAVELENGTHS FOR $V_{CE} = -10$ V

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Bandwidth (MHz)</th>
<th>Responsivity (A/W)</th>
<th>RBP (A/W·MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>410</td>
<td>151.4</td>
<td>0.69</td>
<td>104.5</td>
</tr>
<tr>
<td>675</td>
<td>125.9</td>
<td>1.95</td>
<td>245.5</td>
</tr>
<tr>
<td>850</td>
<td>109.6</td>
<td>1.41</td>
<td>154.5</td>
</tr>
</tbody>
</table>

REFERENCES