Integrated Photodiodes in Standard BiCMOS Technology

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Abstract

Photodiode structures were integrated in a low cost 0.5 µm silicon BiCMOS process using standard process flow without any technology modification. Rise times of 1.3ns and 1.4ns were measured for wavelengths λ of 660nm and 780nm with a responsivity of 0.23 A/W and 0.14 A/W, respectively. Photodiodes with a high responsivity of 0.42 A/W are reaching a risetime of 4ns for λ = 780nm. Comparable low values for the risetime at 780nm are reported in the literature for integrated photodiodes in standard silicon technologies only with a modification of the epitaxial substrate material. So this photodiodes are suitable for a wide variety of low-cost high-speed optical sensor applications, for optical fiber communication and fiber in home applications.

1. Introduction

For high-speed applications in the field of data transmission via plastic optical fiber, laser light with a wavelength λ of 660nm is commonly used. Short range optical data transmission via fibers and optical free space communication uses a wavelength of 780 nm. An implementation of optical receivers in silicon optoelectronic integrated circuits (OEIC´s) is therefore appropriate due to cost reasons. An important issue for the OEIC´s is to reach high responsivity and high speed in low cost standard technologies without process modification. The most serious speed limitation in standard IC technologies is the photo current contribution of slowly diffusing carriers from regions with no internal electric fields even for red light with a penetration depth of about 2.8 µm [1, 3]. Usually bandwidths of only about 10 MHz are reported for OEICs in standard silicon technologies [1]. The double photodiode (DPD) in [2] achieved a bandwidth of 150 MHz. Especially in the case of infrared light with λ=780nm (penetration depth appr. 8µm), carrier diffusion effects might be a problem for many different low cost integrated photodiode structures without technology modification. In this paper we introduce a DPD structure [2] in a low cost BiCMOS process without any process modification (see Figure 1), which combines a high speed performance for 660nm as well as for 780nm, with a reasonable high responsivity, even for larger photodiode areas. We present responsivity as well as transient and small signal bandwidth measurements of the two photodiodes in the proposed DPD structure for 660nm and 780nm. Finally the dependence of the transient behavior for varying photodiode illumination will be presented.

2. Photodiode characterization

For the characterization photodiode testchips were die bonded directly on a PCB. To avoid a bandwidth limitation due to the RC-time constants of the measurement setup in combination with the photodiode capacitance, we integrated a SMD resistor of 50 Ω on the PCB board near to the photodiode. The PCB strip lines were matched to 50 Ω, to minimize wave propagation losses. As light sources we used laser diodes with a wavelength of 660nm and 780nm. The light was coupled into the 50 x 50 µm² photodiodes with a single mode optical fiber. The RF-signal of a pulse generator Agilent 81130A was coupled into the laser diode through a bias-tee network with a bandwidth of 1GHz. The transient response of the photodiodes was measured with a digital sampling oscilloscope Tektronix TDS7054 on the 50 Ω input. In combination with the 50 Ω integrated SMD resistor, the measurement transimpedance is therefore only 25 Ω, and so the RC time constant of the measurement setup is not the speed limiting factor. The measurements of the photodiode small signal bandwidth were performed with a network analyzer Rohde&Schwarz FSEA30 modulating the laser light and measuring the AC output signal. For the transient measurements and small signal bandwidth measurements, the reverse voltage of the photodiodes was 3V. The photodiode responsivity measurements were performed on 200x200 µm² photodiodes for the wavelength of

660nm and 780nm to ensure, that the total laser light of the optical fiber is focused on the photodiodes. A reference measurement was performed on the Coherent LabMaster Ultima light power meter. The simulations of the electric field distribution in the photodiode and the calculations of the carrier diffusion length were performed with the device simulator MEDICI.

3. Double Photodiode (DPD)

The cross section of the proposed DPD photodiode is shown in Figure 1. We implemented the DPD with a p^+-S/D layer / n epitaxial layer / n^+ buried layer / p-substrate. Therefore two pn-junctions were formed named "upper" photodiode (UPD) and "lower" photodiode "LPD".

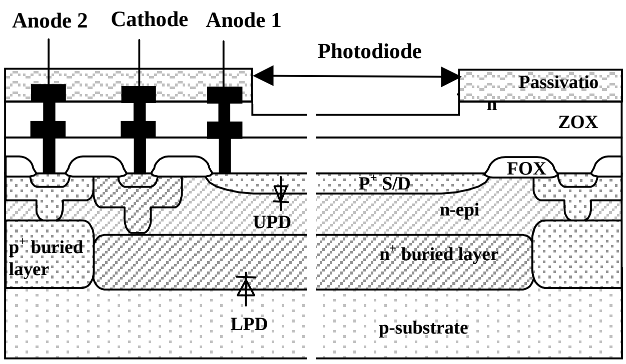

Figure 1: Cross section of the double photodiode

The "upper" photodiode (UPD) is situated between the flat and highly doped p^+-S/D layer (approx. 10^{20} cm^{-3}) as anode and the quite low doped n-epitaxial layer (approximately 10^{15} cm^{-3}) as cathode, which acts as intrinsic zone. To avoid a large RC time constant, the high ohmic n-epi layer is connected by the low ohmic n^+ buried layer (approx. 10^{20} cm^{-3}). The space charge region is taking up the whole n epi layer, causing a high electric field inside (see Figure 2), which means high carrier drift velocity. Due to its high doping concentration, the n^+ buried layer has no space charge region inside. Only a small electric field is build up at the edges of the n^+ buried layer, due to a gradient in the doping concentration. The electric field in the center is vanishing. Nevertheless, the high doping concentration in the p^+-S/D layer and the n^+ buried layer reduces the carrier diffusion length to below 0.3µm (see Figure 3). So the low electric field in the p^+-S/D and in the center of the n^+ buried layer in depths of 0-0.3 µm and 3-4µm, respectively, (see Figure 2) does not cause a strong diffusion part in the resulting photodiode current.

The second, "lower" photodiode (LPD) consists of the low ohmic n^+ buried layer as cathode and the high ohmic p-substrate (approx. 10^{15} cm^{-3}) as anode. The space charge region appears in the p substrate only, causing a high electric field in a depth of 4.7-7µm. The LPD is more sensitive for 780nm, because a higher percentage of carriers is generated in the substrate due to the large penetration depth of the 780nm light (see also Table 1). Nevertheless the carrier diffusion part in the photodiode current is not very strong, because the space-charge region of the substrate is extending to a depth of approximately 7.5 µm. The capacitance of the photodiodes is also low, due to the wide space-charge regions (C_{UPD}=0.16pF, C_{LPD}=0.12pF for 50x50µm² photodiodes with a reverse voltage of 3V).

Figure 2 shows the simulated distribution of the electric field in the double photodiode structure. We clearly see the two peaks of the electric field in the space charge region of the UPD and LPD. The small electric field near the silicon surface (p^+-S/D layer) and in a depth of approximately 3 µm (n^+ buried layer) is due to the high doping concentration. Figure 3 shows a calculation of the carrier diffusion length in an n-doped silicon semiconductor.

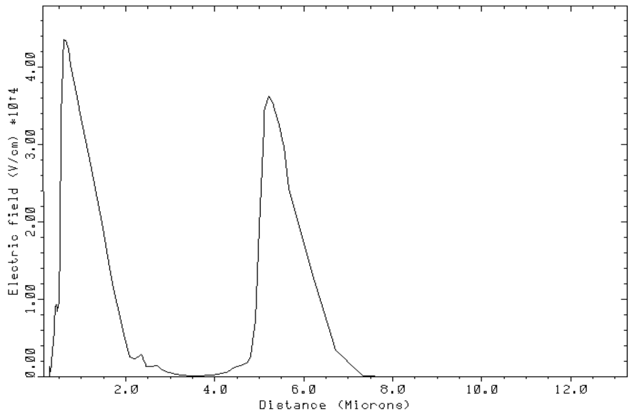

Figure 2: Distribution of the electric field (absolute values) in the DPD for a reverse bias voltage of 3 V (reference for the distance is the silicon surface)

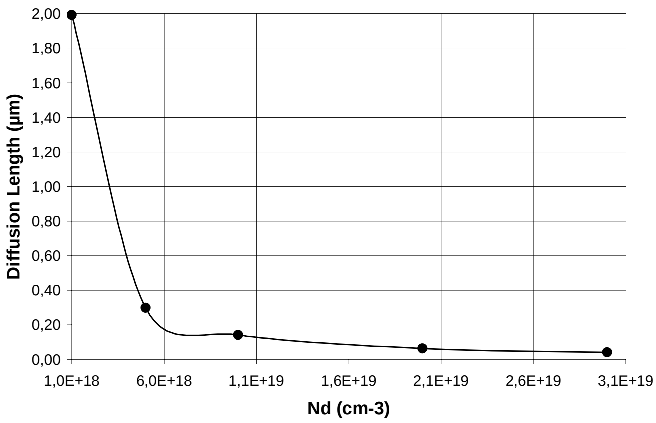

Figure 3: Minority carrier diffusion length in n doped silicon in dependence on the doping concentration

3.1. Photodiode responsivity

The measured photodiode responsivity of the two photodiodes UPD and LPD for 660nm and 780nm can be seen in Table 1. In a practical application the two photodiodes can be used in parallel, with a high responsivity of 0.4 A/W for 660 nm and 0.5 A/W for 780 nm. For high speed applications, only the UPD might be used with an acceptable high responsivity of 0.23 and 0.14 A/W for 660nm and 780nm

Table 1: Photodiode responsivity at 660nm, 780nm

Wavelength (nm)	Responsivity (A/W)	
	UPD	LPD
660	0.23	0.17
780	0.14	0.36

3.2. Transient and AC behavior for 660nm

Figure 4 shows the transient behavior of the “upper” photodiode UPD and the “lower” photodiode LPD at a wavelength of 660nm. The rise time and fall time of the UPD was found to be 1.3ns. For the LPD we measured 1.8ns for the rise time and 1.9ns for the fall time. The overshoot, especially for 660nm, is an effect of laser modulation. The transient response shows no diffusion component for the upper photodiode (UPD), as well as for the lower photodiode (LPD).

The AC small signal response of the two photodiodes UPD and LPD at a wavelength of 660nm can be seen in Figure 5. Bandwidths of f_{-3dB} = 250MHz and 150 MHz were found for UPD and LPD. The high bandwidth at 660nm wavelength makes the two photodiodes suitable for high speed applications up to data rates of approximately 300 Mbit/s. An application of the two photodiodes in parallel gives a high responsivity performance of 0.4 A/W.

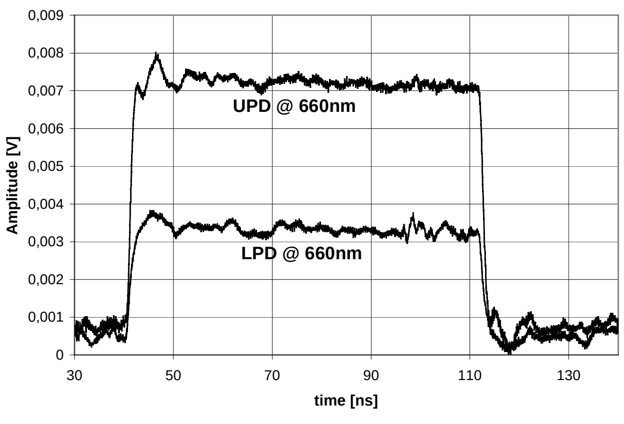

Figure 4: Transient response of the upper (UPD) and the lower photodiode (LPD) at 660 nm

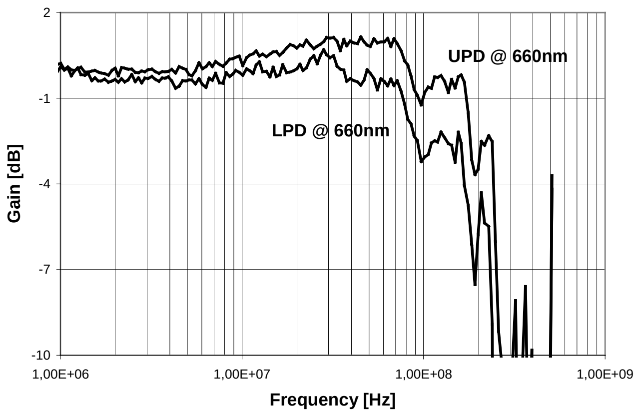

Figure 5: Small signal bandwidth of the upper (UPD) and the lower photodiode (LPD) at a wavelength of 660 nm

3.3. Transient and AC behavior for 780nm

The measured transient behavior of the photodiodes for a wavelength of 780nm can be seen in Figure 6. The risetime and falltime of the UPD was measured to be t_r=1.4ns and t_f=1.8ns, respectively. For the LPD we found t_r=7ns and t_f=10ns. The transient response for the lower photodiode (LPD) at 780nm shows a slow component of approximately 10%-15% of the total amplitude, caused by carrier diffusion in the p-substrate. Nevertheless in other approaches a comparable small risetime of about 7ns at a wavelength of 780nm was only published in a BiCMOS process with a modification of the epitaxial substrate material [4]. In contrast, this approach uses an unchanged low cost BiCMOS process with standard substrate material.

Figure 7 shows the small signal bandwidth measurements of the two photodiodes at 780nm wavelength. Values of f_{-3dB} = 250 MHz and 100 MHz were found for UPD and LPD.

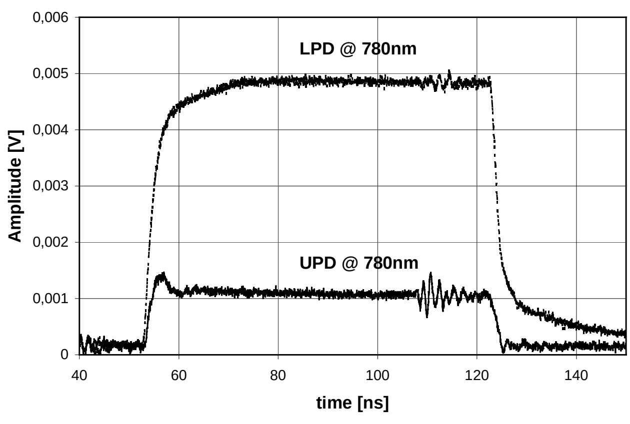

Figure 6: Transient response of the upper (UPD) and the lower photodiode (LPD) at 780 nm

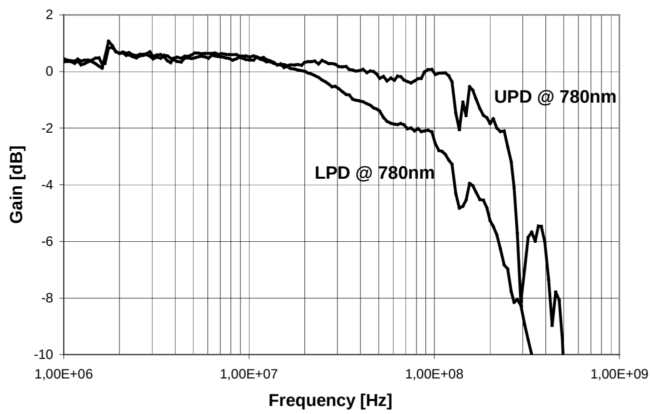

Figure 7: Small signal bandwidth of the upper (UPD) and the lower photodiode (LPD) at a wavelength of 780 nm

The response time of the “upper” photodiode is very low for 660nm and even for 780nm wavelength with a responsivity of S=0.23A/W and 0.14A/W. If a higher responsivity at 780nm is necessary, both photodiodes UPD and LPD can be used in parallel (S=0.4A/W). The resulting rise time for 780nm is still only 4-5ns and therefore very fast, for a photodiode with absolutely no process modification. The DPD gives high flexibility in terms of responsivity and speed for several applications (eg in the field of fiber communication OEICs).

3.4. Response sensitivity to beam diameter

We have observed that the transient behavior of the “lower” photodiode LPD depends on the diameter of the incident laser beam. The diffusion part of the photodiode current becomes larger with increasing laser beam diameter. This is valid for 660nm and for 780nm.

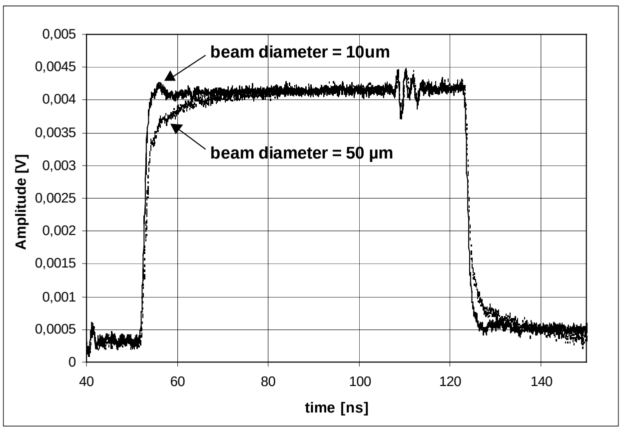

Figure 8: Transient response of the “lower” photodiode LPD for different beam diameters at 660nm

Figure 8 shows the transient response of the LPD at 660nm for two different beam diameters of 10 µm and 50 µm. To exclude edge effects, we performed the measurements with 200x200 µm² photodiodes. This behavior was also confirmed by device simulations. The effect may be due to a higher concentration of photo generated carriers in the p-substrate, leading to a higher electron gradient for higher light intensity in the case of lower beam diameter.

4. Conclusion

A high speed and high responsivity double photodiode DPD was integrated in a standard low-cost BiCMOS process without any process modification. Rise times down to 1.3ns for 660nm and 1.4ns for 780nm were measured with a responsivity of 0.23A/W and 0.14A/W respectively. When using both photodiodes of the DPD in parallel, we found a high responsivity of 0.5 A/W in combination with a low rise time of 4-5ns for 780nm, which is, as far as we know, the highest performance of an integrated standard photodiode at 780nm wavelength, without any changes in the technology process flow. To minimize disturbing diffusion effects in the lower photodiode, the laser beam diameter should be as small as possible. The low capacitance and the high speed for 660 and 780nm makes the DPD suitable for several applications in the field of optical sensors and plastic optical fiber OEICs.

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