

# A CMOS Photodiode Array with Linearized Spectral Response and Spatially Distributed Light Intensity Detection for the Use in Optical Storage Systems

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## Abstract

*This paper presents a special photodiode array layout to be used in optical pickup units in combination with optical storage systems. Apart from the features that a standard array offers, this design enables higher resolution of the data recovery diodes. Furthermore, additional diodes for the determination of the spatial light intensity are included. The special layout of the array ensures crosstalk isolation and linearizes the spectral response of the data recovery diodes enabling less circuitry needed for the readout of the photocurrent. The structure was fabricated in standard  $0.6\mu\text{m}$  twin well CMOS technology.*

## 1. Introduction

A fundamental component of every optical storage system is the optical pickup unit that reads and retrieves data from the storage media. Apart from a laser diode, optical elements, and an actuator for tracking and focussing, the optical pickup unit contains a photodetector array with readout circuitry.

The classical detector arrangement is a  $2 \times 2$  photodiode matrix as sketched in Figure 1(a). Summing the signals of quadrant A to D in different manners delivers the electrical signals for data recovery and servo signals for focus and tracking control [1].

Standard detectors have different spectral responsivities at different wavelengths so that a readout circuit with variable gain is necessary [2]. Furthermore, all approaches to generate the servo signals suffer from sensitivity to a nonideal positioning of the detector caused by misalignment or thermal drift of the laser beam position. In addition to this, optical offsets caused by substrate thickness variations and tilt of the storage media as well as radial objective lens movement are leading to a degradation of the readout signals resulting in a bit-error rate increase.

The proposed new arrangement has a higher resolution of photodiodes for data recovery (PDDR) which allows a more detailed analysis of the laser beam reflected from the storage media. Furthermore, it offers the possibility not only of sensing the position of the light spot's center of gravity but also of measuring its intensity distribution with 25 spatially distributed photodiodes (PDID). This information can be processed to generate an electrical compensation of signals affected by alignment errors and optical offsets.

The newly introduced 25 photodiodes have been used to linearize the spectral responsivity of the PDDRs employing a special layout. Their shape is used to trap diffusing charges which improves the transient behaviour and works as crosstalk isolation between the PDDRs.

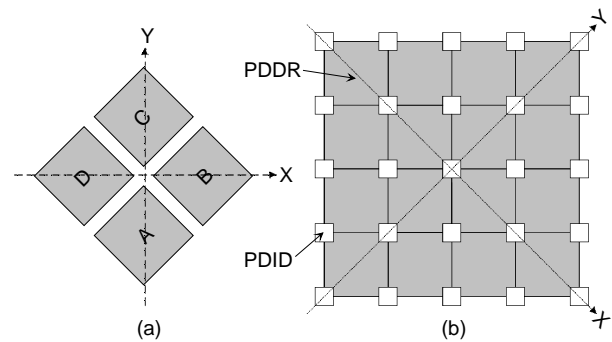


Figure 1. (a) Standard array, (b) structure of the proposed array.

## 2. Structure and Layout

Figure 1(b) shows a schematic representation of the proposed arrangement. The standard  $2 \times 2$  detector of Figure 1(a) was splitted into a  $4 \times 4$  array of PDDRs. The more detailed information achieved by the spatial refinement is usable in future generation of storage systems [3,4] to improve the storage capacity. Illumination of two tracks on the storage media due to

the finite resolution of the laser beam results in stimulation of diodes A and B (or C and D, respectively). With a standard detector this erroneous stimulation cannot be distinguished from that caused by the correct track. As a result, the new arrangement allows more narrow track pitch.

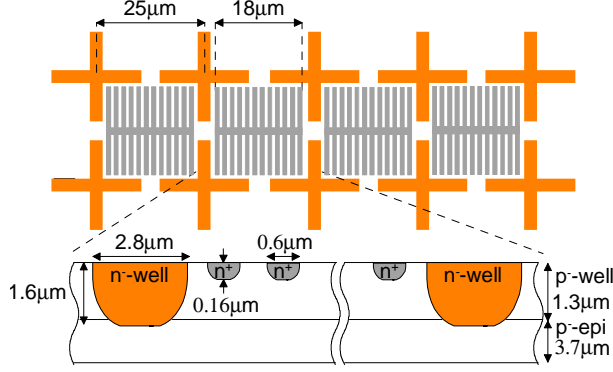


Figure 2. Layout and cross section of one row of the diode array

Figure 2 represents the layout of one row of the array and the corresponding cross section. Since the design aims at the use in future generations of storage systems, it is optimized for wavelengths in the near ultraviolet region, i.e. 405nm. The penetration depth of the photons in silicon at this wavelength is about 200nm so that the electron hole pairs are mainly generated at the surface. These charge pairs are separated more efficiently by lateral pn-junctions which leads to an improved response of stripe shaped diodes in this wavelength region [5]. For this, PDDR is realized as stripes in “double-comb” structure of  $n^+$ -diffusion.

Another advantage of arrangement used can be seen from Figure 4. In general, PDDRs are read out using transimpedance amplifiers at high bandwidth (up to 250MHz) and high transimpedance (up to 200kΩ)[7]. The bandwidth for such a configuration is

$$f_{-3dB} \propto \frac{A}{2\pi R_f} * \frac{1}{C_{diode}} \quad (1)$$

where  $R_f$  represents the transimpedance,  $A$  the DC gain of the amplifier, and  $C_{diode}$  is the photodiode capacitance. For high bandwidth it is necessary to keep the junction capacitance of the diode as low as possible to minimize the requirements imposed on the amplifier. In Figure 5(a) scaled values of the measured capacitance are plotted:  $C_{edge}$  stands for the sidewall capacitance (per unit length), while  $C_{area}$  is the area capacitance (per unit area). It shows that a stripe shaped diode shows a smaller junction capacitance than a full area diode due to high perimeter/area ratio so that the achievable bandwidth of the readout system is correspondingly higher.

For the PDIDs  $n^-$ -well diodes are clearly preferable. The main reason for this is the larger vertical extension of the well when compared to that of the  $n^+$ -diffusion (cf.

Figure 2). By layouting these diodes in a cross shape, it is possible to surround the PDDRs almost completely by an  $n^-$ -well, thus building a kind of guard ring for those diodes in lateral a vertical direction. If charges are generated at the edge of a diode they are collected by a PDID rather than by a neighboring PDDR-diode consequently yielding crosstalk isolation in lateral direction. Diffusing carriers in the epitaxial layer that have not been collected by the PDDR are trapped by the PDID so that they cannot diffuse to another PDDR. In this way a vertical crosstalk isolation is ensured.

Furthermore, collecting diffusing charges mainly by the PDDR has a positive effect on the pulse response. Since the readout of the PDID takes place in the kilohertz region the diffusion current has a negligible effect.

Another advantage of using a well diode is the small capacitance when compared to a diffusion diode of the same shape (Figure 5(a)). The readout of the PDID is usually done by the integrating photodiode approach. Here the photocurrent is integrated at the intrinsic junction capacitance of the photodiode. For such a readout system

$$SNR = 20 \log \left( \sqrt{\frac{I_{ph}^2 T_{int}^2}{e^{-} (C_{diode} U_{Th} + I_{ph} T_{int})}} \right) \quad (2)$$

yields ( $T_{int}$  is the integration time and  $U_{Th}$  is the threshold voltage of the transistor to set the diode at defined potential) [8]. Consequently, the signal-to-noise ratio increases with decreasing diode capacitance.

### 3. Simulation Results

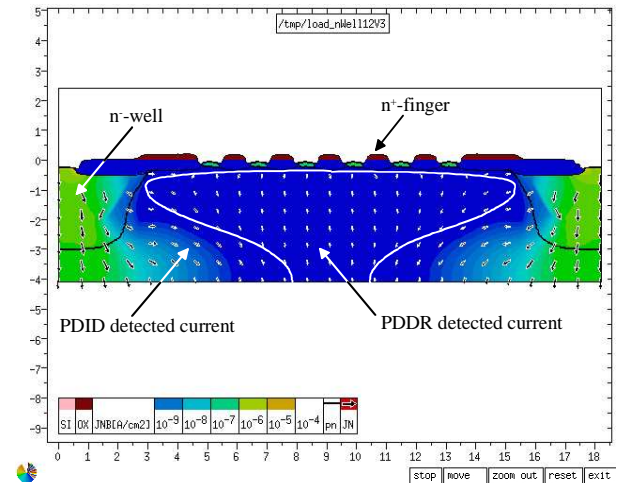


Figure 3. Device simulation of the cross section shown in Figure 2 at 3V diode PDID and 1V PDDR voltage (epitaxial layer only).

Process-/Device simulation has been performed, using DIOS/TOSCA simulation environment. Figure 3

represents the current density of thermal generated minority carriers as indicator for optical induced carriers.

It can be observed that the PDID drains most of the minority charge carriers underneath  $2\text{ }\mu\text{m}$  below the Si/SiO<sub>2</sub> surface. Only the middle part of the PDDR traps carriers generated in deeper regions. Consequently, the photo current of the PDDR exhibits only a minor part of diffusion current, promising an improved transient behaviour. Furthermore, it is prohibited that carriers can diffuse to neighbouring PDDRs, so that a good crosstalk isolation can be expected.

Wavelength	penetration depth
405 nm, blue (future systems)	0.196 $\mu\text{m}$
650 nm, red (DVD)	2.89 $\mu\text{m}$
780 nm, NIR (CD-ROM)	8.0 $\mu\text{m}$

Table 1. Penetration depth of wavelengths used in standard optical storage systems in silicon (@300K) [6].

Considering the above given penetration depths one can see that most of the carriers which are generated by irradiance of wavelengths of 650nm and 780nm do not contribute to the photo current of the PDDR. Thus, for a fixed light power the amount of photo current of the PDDR is less sensitive to the wavelength of the light. As a result the presence of the PDIDs has a linearizing effect on the spectral response of the PDDRs.

#### 4. Measurement Results

The structure described above was fabricated in a standard  $0.6\mu\text{m}$  twin well CMOS process in two different ways. For the system test a chip with the above mentioned readout circuitry was designed. Figure 4 shows a micrograph of the diode array. The surrounding circuitry is covered by the third metal layer for protection against stray light and is therefore not visible.

For the characterization of the diodes a test structure with  $20 \times 28$  PDDRs or  $22 \times 30$  PDIDs, respectively, was used. The junction capacitance was determined on-wafer by means of a Keithley 590 CV Analyzer. In a second step, the capacitance of the metal structure used for the wiring was measured separately and subtracted from the first measurement.

Figures 5(b, c) show the results of a single PDDR and a single PDID respectively. The absolute capacitance of the PDDR ranges from 98fF (@3.3V) to 165fF (@0.1V). This is a value that can easily be read out using a transimpedance amplifier at the mentioned gain and bandwidth in the used technology. The variation of the capacitance is no problem because the voltage across the diode is clamped by the readout circuit.

The absolute value of the PDIDs ranges from 19.7fF to 22.4fF in a voltage range from 3.3V to 1V, respectively, namely the range where integration of the

photocurrent takes place. In combination with the photocurrent for a typical minimum irradiance of  $14\mu\text{W}$  this leads to a sufficient SNR of 59dB for a typical integrating readout circuit, according to Equation (2). The non-linear characteristic of the readout system [8] so that, depending on the required accuracy, a correction has to be done.

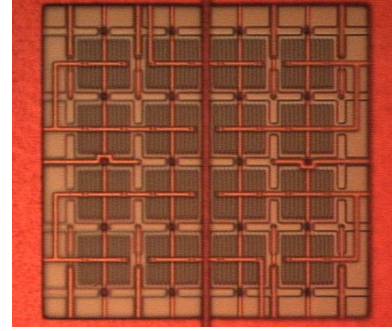


Figure 4. Micrograph of the diode array

The photocurrent was measured by a monochromator and a HP4145B Semiconductor Parameter Analyzer. For calculation of the spectral response of the two diode types the light power on the whole structure (not that corresponding diode type!) was used.

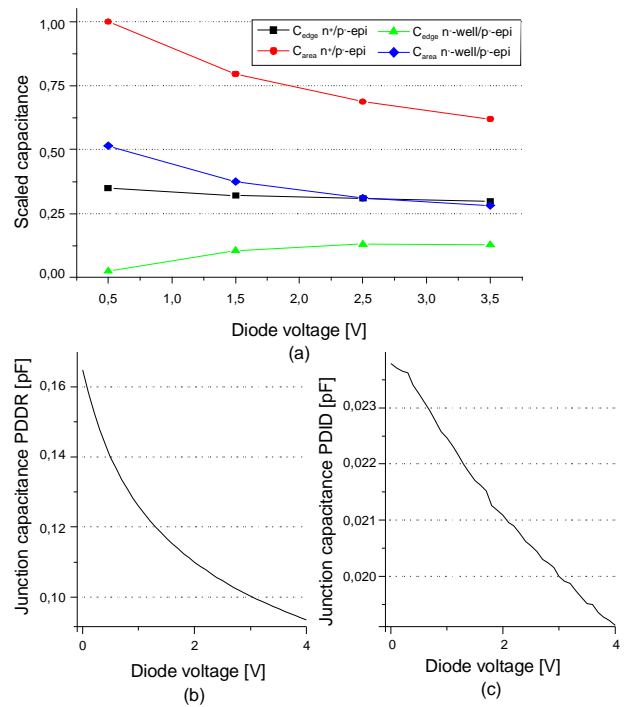


Figure 5. (a) Scaled area and sidewall capacitances of the used process, (b) capacitance of the PDDR, (c) capacitance of the PDID.

In Figure 6. four spectral responsivity curves are plotted to show the effect of the layout. The upper two

curves result from a measurement when one diode type was left floating. The typical photodiode behaviour can be observed for both types. The absolute values for 405nm are comparable to those achieved in [2]. For 650nm and 780nm, the values are higher, namely 24% (@650nm) and 139.2% (@780nm) for the PDID and 10.6% (@650nm), 88.6% (@780nm) respectively, for the PDDR.

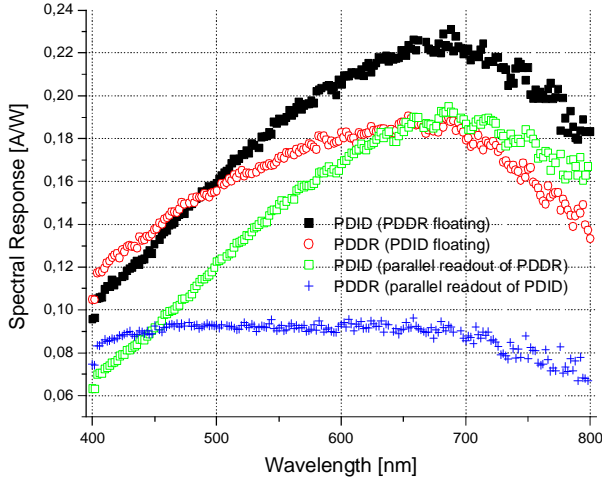


Figure 6. Spectral response of the PDDR and the PDID at parallel readout and readout with other diode type floating.

When both diodes are read out parallel, the spectral response of the PDID shows the same behaviour as before at a 0.035A/W lower level. The characteristic of the PDID is completely different in that case. It shows a slight rise of 0.008A/W in the region from 400nm to 460nm. From 460nm to 700nm it stays constant and falls off in the interval from 700nm to 800nm by 0.021A/W. Taking into account that the gain of a transimpedance amplifier with active feedback usually undergoes variations of  $\pm 5\%$  due to non-linearities of transistors use in the triode region, the spectral response can be considered as linear. This enables a readout system with constant gain for all wavelength which calculates as

$$R_f = \frac{S_{detector}}{S_{diode}} \quad (3)$$

( $S_{detector}$  is the sensitivity of the readout system). For a typical value of 20mV/ $\mu$ W this yields a transimpedance of 253k $\Omega$ . Simulation results have shown that this value is achievable with the used technology.

Only the PDID responsivity exhibits a slight interference phenomenon in the wavelength region from 650 nm to 800nm. Due to the rough surface of the finger diode structure resulting in an varying oxide thickness this is prevented in the PDDR curve. Furthermore, the PDDR shows a better responsivity for near ultraviolet wavelengths so that the finger structure proves as good choice.

The crosstalk isolation was tested using of the diode array with the readout circuitry. A laser with 675nm

wavelength and 0.7mW output power was focused on one PDID channel. No measurable crosstalk was found when reading out a neighbouring channel by a transimpedance amplifier with calculated 9.34nA<sub>rms</sub> equivalent input noise.

The fact that there is only a slight variation over the whole wavelength interval shows that the photocurrent generated by the PDDRs consists mainly of drift current. This promises a good transient behaviour that has to be measured in a next step.

## 5. Summary

In this paper a new photodiode array with linearized spectral response for the use in optical storage systems has been presented. Apart from the diodes for data readout it features diodes for intensity distribution measurements which enable the compensation of optical offsets in future generations of such systems. Simulation results corroborated by measurements of different test structures show the desired characteristics of the proposed structure. The achieved results promise a good transient that has to be determined in a next step.

## 14. References

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