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Bandwidth of integrated photodiodes in standard CMOS for CD/DVD applications

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Abstract

This paper analyzes the bandwidth of high-speed photodiodes in a fully standard 0.18 μm CMOS technology for the CD/DVD optical pick-up units. Three diode structures are investigated: nwell/p-substrate, p+/nwell/p-substrate and p+/nwell. The photodiode performances are compared for $\lambda = 780$ nm and $\lambda = 650$ nm wavelength, corresponding to the lasers for CD and DVD, respectively. Slow substrate photocurrent component limits the bandwidth of nwell/p-substrate and p+/nwell/p-substrate photodiodes to 6 MHz and 7 MHz for a CD application as well as 70 MHz and 100 MHz for a DVD application. The third analyzed photodiode has bandwidth in the low GHz range for both applications, with the cost of at least 12 dB lower responsivity.

1. Introduction

The motivation to produce high-speed optical detectors in fully standard CMOS technology has increased markedly as the electronic speed of today's CMOS circuits is well in GHz range. In order to keep the cost of the short-haul data system low, monolithically integrated CMOS optical detectors are preferred in both data communication [1] and optical storage systems (inside pick-up units) [2]. The integrated photo diodes avoid the relatively high capacitance of discrete photo diodes (device and interconnect) and its influence on the bandwidth.

In the literature, several methods have been implemented to obtain high-frequency photodetectors in standard CMOS. In [3], the spatially modulated light detector, which cancels the effect of the slow substrate carriers, is introduced. As a tradeoff, the responsivity of the photodiode is sacrificed. A high-speed finger n+/p-substrate CMOS photodiode for optical storage system is presented in [4]; here, the photodiode performance for four different geometries and one diode structure is discussed based on only time-response measurements.

This paper analyzes the influence of various structures and geometries (layouts) of CMOS photodiodes on their bandwidth. The analyzed diodes have the same area which provides easier comparison of their responsivity. The band-widths are compared for $\lambda = 780$ nm and $\lambda = 650$ nm wavelength lights which are used in today's CD and DVD optical pick-up units. The photodiodes are first analyzed as stand-alone detectors i.e. without subsequent electronic circuitry. This allows an

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analysis of the *intrinsic* photodiode behavior. The intrinsic behavior is related to the movement (drift and diffusion) of the generated carriers inside the diode. Based on the frequency analysis, the intrinsic diode bandwidth is determined. In the second part of this chapter, the diode is investigated as an"in-circuit" element, integrated together with the subsequent electronics. The *extrinsic* bandwidth of the diode is determined by the diode capacitance and the input impedance of the subsequent amplifier. These two bandwidths determines the total diode bandwidth which is by approximation the lower of the two.

2. Intrinsic photodiode bandwidth

2.1. nwell/p-substrate photodiode

General intrinsic frequency behavior of standard CMOS photodiodes is investigated first on a nwell/p-substrate diode, shown in Fig. 1. Photodiode responses for both input wavelengths $\lambda = 780\,\text{nm}$ and $\lambda = 650\,\text{nm}$ are calculated with the following procedure:

The overall photodiode response is the sum of the drift current response inside depletion region and the diffusion currents responses inside the nwell and *p*-substrate. The diffusion currents under impulse light radiation $G(t) = \alpha\Phi_0(t)e^{-\alpha x}|_{x\in[0,L_x]}$, are solved analytically from the excess carriers profiles following a procedure similar to that in [3]. In the previous equation α is the absorption coefficient of light, L_x and L_y are the depth and the width of the nwell region respectively and Φ_0 is the input flux of light.

For the nwell current calculation, the surface is assumed to be reflective (the normal component of the gradient of the carrier density is zero) and the hole densities on the other three nwell sides are assumed to be zero. The carrier profile p_n in the frequency domain is calculated by taking the Laplace transform of the diffusion equation in time domain [3]. The carrier distribution function $p_n(t)$ and the carrier generation function $G(t)$ [3] are rewritten as a product of two Fourier series, one of a square wave in the *x*-direction (with index n) and the other of a square wave in the *y*-direction (with index m). Each of these decomposed terms of $G(t)$ drives one of the terms of decomposed of p_n. Once the carrier profile is calculated, the hole-current frequency response can be determined for each set of indexes *n* and *m*. The total contributed current is the integral of the current through the two side-walls and the bottom layers. The final expression for the nwell diffusion current is:

$$\frac{J_{\text{nwell}}}{\Phi_0} = 32\frac{eL_p^2\alpha}{l\pi^2}\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\frac{(2n-1)\pi e^{-\alpha L_x} + (-1)^{\frac{(2n-1)-1}{2}}\alpha L_x}{4\alpha^2L_x^2 + (2n-1)^2\pi^2} \times \frac{\frac{2L_x}{L_y}\frac{1}{2n-1} + \frac{L_y}{2L_x}\frac{2n-1}{(2m-1)^2}}{\frac{(2n-1)^2\pi^2L_p^2}{4L_x^2} + \frac{(2m-1)^2\pi^2L_p^2}{L_y^2} + 1 + s\tau_p} \tag{1}$$

where L_p is the diffusion length of the holes in the p-doped layer, τ_p is the minority-carrier lifetime.

Secondly, we solved the substrate current response using an one-dimensional (vertical) diffusion equation. The two "p" layers are placed at the top of each other (Fig. 1). There is a boundary condition between the two layers related to both the current density and the minority carrier concentration. Due to the continuity of currents, the current densities are equal in a plane between the two layers:

$$-qD_{n1}\frac{\partial n_1(x,s)}{\partial x}|_{x=L_{\text{epi}}} = -qD_{n2}\frac{\partial n_2(x,s)}{\partial x}|_{x=L_{\text{epi}}}. \tag{2}$$

where D_{n1}, D_{n2} represent the diffusion coefficients and n_1 and n_2 are the density of the minority carriers in the epitaxial layer and the substrate, respectively. The second boundary condition is related to the continuity of the concentration of the minority carriers:

$$n_1(L_{\text{epi}}, s) = n_2(L_{\text{epi}}, s) \tag{3}$$

where L_{epi} is the depth between the bottom of the depletion region and the bottom of the p-epi substrate. The other two boundary conditions for both electron densities at the bottom of the depletion region and at the infinite substrate depth are taken to be zero. The infinitely large substrate is taken in order to avoid long and complex calculations. Finite substrate depth would certainly result in a faster diode response [3]. The third addend, the drift current responses are taken independent of frequency for simplicity reasons since their bandwidth is

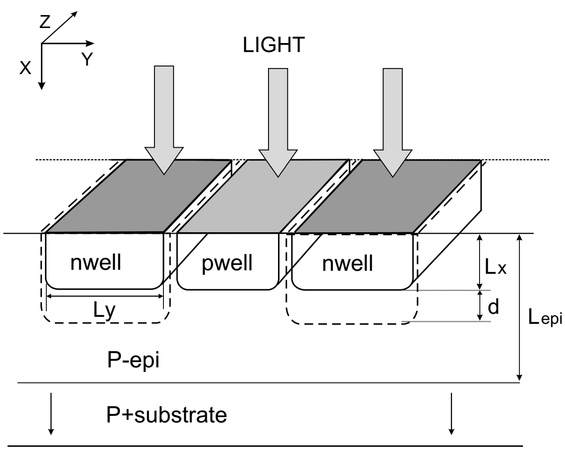

Fig. 1. Nwell/p-substrate photodiode structure in standard CMOS technology.

much larger than the bandwidth of diffusion currents. The amount of the drift current is directly related to the depletion volume in which carriers are generated:

$$J_{\text{dep}} = \Phi e\left[e^{-\alpha L_x} - e^{\alpha(L_x+d)}\right]\frac{A_{\text{total}}}{A_{\text{eff}}} \tag{4}$$

where A_{eff} is the effective depletion region area in comparison with the total photodiode area A_{total}.

In the calculations discussed above, all parameters are taken as follows Table 1:

2.1.1. CD application

In general, for $\lambda = 780$ nm, the substrate current dominates the overall photocurrent frequency behavior up to a few hounders of MHz, also illustrated in Fig. 2. Since the cut-off frequency of the substrate current is in the low MHz range, it significantly limits the overall photodiode bandwidth. Both the fast diffusion response in nwells and the fast drift current response are overshadowed with this large substrate current (Fig. 2). A diode geometry has no influence on a total diode bandwidth. Maximal data-rate (for CD application) with non-return-to-zero data is about 18 Mb/s which is 13× CD speed. In order to increase the photodiode bandwidth, the designers has to minimize the effect of the slow substrate current.

2.1.2. DVD application

Fig. 3 shows the calculated intrinsic frequency responses of two finger nwell/p-substrate diodes with minimum nwell width (which is typically twice its depth) 2 μm and the nwell width much larger than minimum 10 μm, for $\lambda = 650$ nm. The values for the parameters in the analytical expressions were directly obtained from the process technology parameters given in Table 1.

Generated holes need 10ts ns time to diffuse towards the junctions above and limit the substrate current bandwidth to 28 MHz. The larger bandwidth of the nwell diffusion current is mainly determined by the length of the shortest side of the nwell, which further determines the excess carrier concentration gradient responsible for the diffusion process. For $L_y = 2\,\mu$m, the shortest sides are both lateral and vertical dimensions. The carrier concentration gradient is high and $f_{3\,\text{dBnwell}} = 2$ GHz. For $L_y = 10\,\mu$m, the shortest side is the nwell depth and the charge gradient is lower than in the previous case, $f_{3\,\text{dBnwell}} = 1$ GHz. Thus, the larger the nwell width L_y, in comparison with its depth $L_x(L_y > 2L_x)$, the lower its influence on the hole diffusion current bandwidth (see Fig. 3). The overall maximal intrinsic photodiode bandwidth is 160 MHz and the photodiode geometry has again almost no influence on it. The slow response decay after a −3 dB point is due to the combination of three current components in the diode. Maximal data-rate (for DVD application) with non-return-to-zero data is about 360 Mb/s which is about 10× DVD speed.

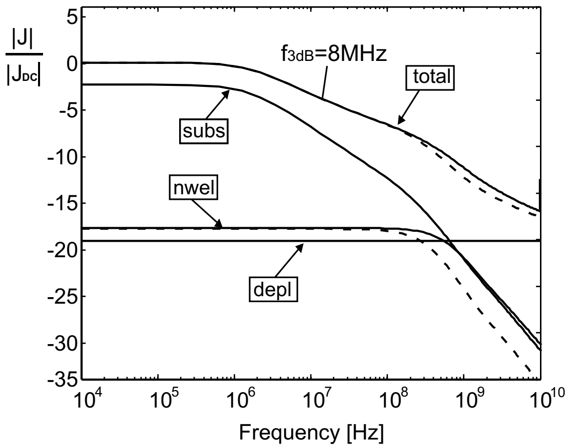

Fig. 2. The calculated amplitude response of nwell/p-substrate photodiodes with: 2 μm (solid lines) and 10 μm nwell size (dashed lines) for $\lambda = 780$ nm.

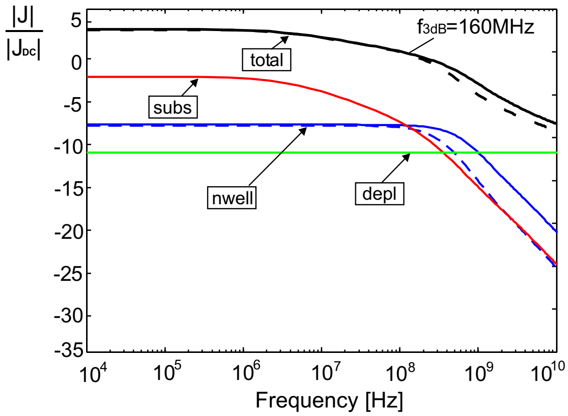

Fig. 3. The calculated amplitude response of nwell/p-substrate photodiodes with: 2 μm (solid lines) and 10 μm nwell size (dashed lines) for $\lambda = 650$ nm.

Table 1
The calculation parameters

α(CD)	α(DVD)	D_n	τ_n	D_p	τ_p	L_x	d
$1\times10^3\,\text{cm}^{-1}$	$3\times10^3\,\text{cm}^{-1}$	$32.2\,\text{cm}^2/\text{s}$	$2\times10^{-6}\,\text{s}$	$8\,\text{cm}^2/\text{s}$	$1\times10^{-8}\,\text{s}$	1 μm	1 μm

2.2. p+/nwell/p-substrate photodiode

The second diode structure analytically analyzed in this paper is p+/nwell/p-substrate shown in Fig. 4. The diffusion current responses are again calculated using two-dimensional diffusion equation given in [3]. Main difference in comparison with the nwell/p-substrate photodiode analyzed in previous section is diffusion response inside nwell region. The boundary conditions for the holes density on every nwell side are zero since it is enclosed by junctions:

$$p_n|_{x,y@\text{boundary}} = 0 \tag{5}$$

The current response of the nwell is calculated and final result is given in Eq. (1) in [5]. For the p+ region, the hole current response is calculated using the nwell response in previously analyzed diode and changing diffusion coefficient and diffusion length as well the depth of the junction ($D_{p1} \to D_{n1}, L_{p1} \to L_{n1}, L_x \to L_{x1}$). The substrate current response for both diodes is the same due to the same nwell depths.

2.2.1. CD application

The frequency responses of two finger p+/nwell/p-substrate diodes with 2 μm and 10 μm nwell sizes, for $\lambda = 780$ nm wavelength are shown in Fig. 5. This picture illustrates that the bandwidths of p+ and nwell diffusion currents are mainly determined by low physical depth of the junctions ($2L_{x1} < L_y$); changing the nwell and p+ widths does not influence the cutoff frequency. The bandwidth of the junction-framed nwell current is $f_{3\,\text{dBnwell}} = 5$ GHz for $L_y = 2$ μm, and $f_{3\,\text{dBnwell}} = 4.2$ GHz for $L_y = 10$ μm. That is more than twice the nwell bandwidth of the nwell/p-substrate diode. The distances towards the junctions are lower providing higher charge gradient and faster diffusion process. The current bandwidth of the p+ region is lower than the bandwidth of the nwell current; the calculated value is about 3 GHz for all diode geometries. The p+ surface is reflective for the carriers that are repelled back to the other three p+ sides with the junctions. Thus, the carriers need extra time to start contributing to the overall photocurrent. The intrinsic photodiode bandwidth is 8 MHz, and the photodiode geometry has no influence on it (see Fig. 5). Maximal data-rate (for CD application) with non-return-to-zero data is again about 13× CD speed.

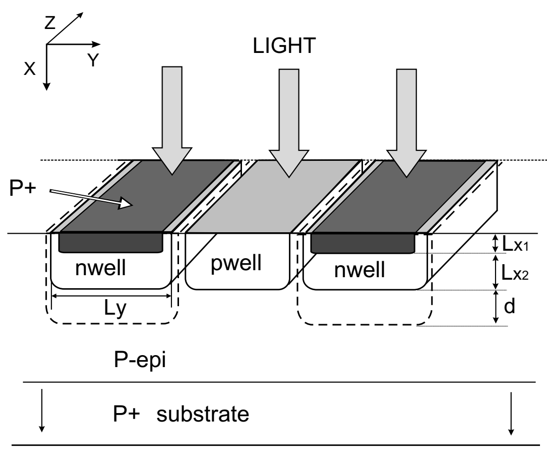

Fig. 4. P+/nwell/p-substrate photodiode structure in standard CMOS technology with p+/p-epi substrate in a twin-well.

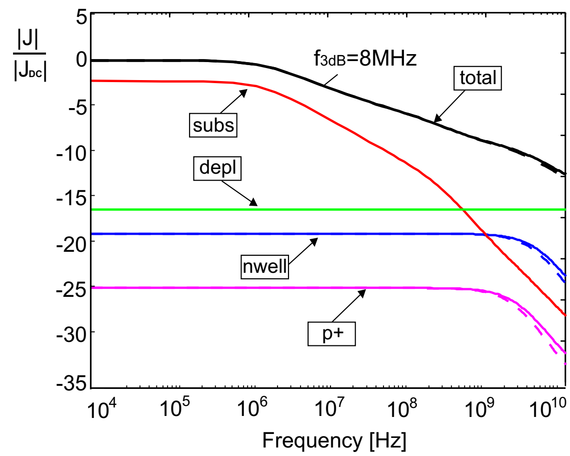

Fig. 5. The calculated amplitude response of p+/nwell/p-substrate photodiode with p+/p-epi substrate in a twin-well technology: 2 μm (solid lines) and 10 μm nwell size (dashed lines) for $\lambda = 780$ nm.

2.2.2. DVD application

The frequency responses of two finger p+/nwell/p-substrate diodes with 2 μm and 10 μm nwell sizes, for $\lambda = 650$ nm wavelength are shown in Fig. 6. The bandwidth of the junction-framed nwell current is $f_{3\,\text{dBnwell}} = 5$ GHz for $L_y = 2$ μm, and $f_{3\,\text{dBnwell}} = 4$ GHz for $L_y = 10$ μm. That is more than twice the nwell bandwidth of the nwell/psubs diode because of the lower distances towards junctions and thus, higher charge gradient leading to a faster diffusion process. The current bandwidth of the p+ region is lower than the nwell current and is about 3 GHz for all diode geometries. This is expected, since part of the carriers are repelled back from the surface towards other three p+ sides with junctions; and these carriers need extra time to start contributing to the overall photocurrent.

The overall intrinsic photodiode bandwidth is 190 MHz, and the photodiode geometry has no influence on it (see Fig. 6). Maximal data-rate (for DVD application) with non-return-to-zero data is 400 Mb/s which is about 16× DVD speed.

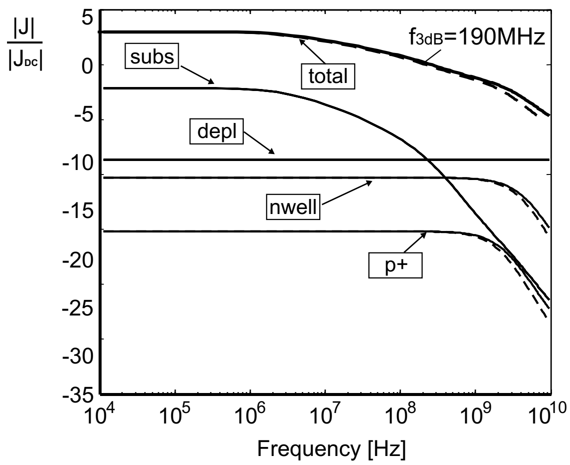

Fig. 6. The calculated amplitude response of p+/nwell/p-substrate photodiode with p+/p-epi substrate in a twin-well technology: 2 μm (solid lines) and 10 μm nwell size (dashed lines) for $\lambda = 650$ nm.

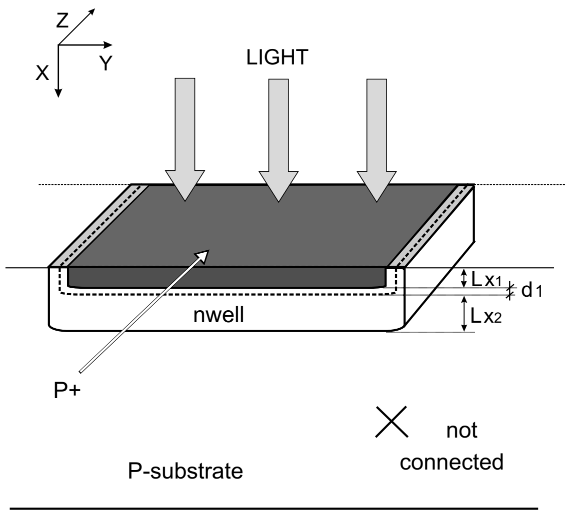

Fig. 8. The calculated amplitude response of p+/nwell photodiodes with: 2 μm (solid lines) and 10 μm nwell size (dashed lines) for $\lambda = 650$ nm.

2.3. p+/nwell photodiode

By exploiting only p+/nwell structure of the photodiode i.e. by disconnecting the p-substrate, it is possible to achieve high intrinsic bandwidth of the photodiode. The responsivity is however lower than in the other two diode structures because the carriers generated inside p-substrate do not contribute the overall photocurrent. For $\lambda = 650$ nm, the calculated responsivity of this photodiode is 10 dB lower (see Fig. 7). The p+/nwell photodiode is presented in Fig. 8.

Charge movement inside nwell will be constant in lateral direction since there is no lateral current towards the substrate. Thus, the geometry of the photodiode has no influence on nwell diffusion current bandwidth. The nwell diffusion response is calculated using one-dimensional diffusion equation. The hole density at the top of the nwell (below the depletion region towards p+) is taken to be zero while the gradient of the holes density at the nwell-bottom is zero since there is no current flowing. The current response of the nwell is given in Eq. (2).

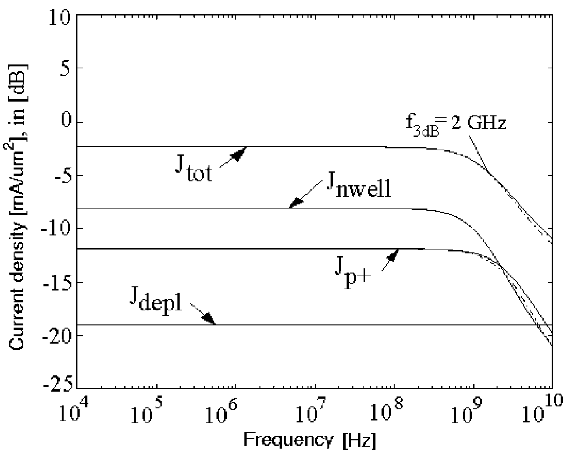

Fig. 7. The calculated amplitude response of p+/nwell photodiodes with: 2 μm (solid lines) and 10 μm nwell size (dashed lines) for $\lambda = 650$ nm.

The amount of the nwell current contributing the overall photocurrent is the same as in p+/nwell/psubs photodiode, but its bandwidth is five times lower: $f_{3\,\mathrm{dBnwel}} = 1$ GHz. The decrease in bandwidth is because the carriers moving towards p-substrate are repelled back to the top of the nwell so they need extra time to sink into the junction. The diffusion current response inside the p+ is the same as in the previously discussed photodiode.

The frequency responses of two finger p+/nwell diodes with 2 μm and 10 μm nwell sizes, for $\lambda = 650$ nm are shown in Fig. 8. The overall intrinsic photocurrent bandwidth is about 2 GHz, meaning that this photodiode structure is the fastest among the three, and can be used for high-speed optical data transport. However, the sensitivity of the subsequent transimpedance amplifier has to be larger than in the case for the other two diode structures, due to the lower diode responsivity.

Bandwidth of p+/nwell photodiode for DVD application is similar to the one with CD application. However, photocurrent amplitude is even lower than photocurrent for CD application (4 times less). Low photocurrent value (low responsivity) makes this diode non-implementable in real-life applications [6].

Table 2
Parasitic capacitance for different photodiode structures in 0.18 μm CMOS

Diode structure	nwell (μm) size	Capacitance
nwell/p-substrate	2	2.42pF
nwell/p-substrate	10	0.63pF
p+/nwell/p-substrate	2	4.63pF
p+/nwell/p-substrate	10	2.83pF
p+/nwell	2	2.61pF
p+/nwell	10 m	2.12pF

Maximal data-rate for CD and DVD application with non-return-to-zero data is 4 Gb/s which is about 1000× CD and 160× DVD speed. However, the photocurrent is very low (10 times lower them with previously discussed photo-diodes) and there is no practical application of this photocurrent structure.

3. Extrinsic (electrical) photodiode bandwidth

Apart from the intrinsic bandwidth, the in-circuit photodiode bandwidth is also determined by the extrinsic (electrical) bandwidth, which is proportional to the diode parasitic capacitance. Table 2 shows calculated values of the parasitic capacitances for two different geometries of nwell/p-substrate and p+/nwell/p-substrate photodiodes. The depletion region depths that strongly determine diode capacitance are calculated from the process technology parameters. For all discussed finger photodiodes, by decreasing the diode nwell size (for a constant diode area), the parasitic capacitance increases. In order to keep the total bandwidth high (for pF diode capacitance), the subsequent tran-simpedance amplifier (TIA) should be designed to have low input impedance ($\leqslant 50\Omega$). Two possible solutions using common source and common gate amplifiers presented in [6].

4. Conclusion

This paper presented integrated photodiodes in standard 0.18 μm CMOS technology that can be used for the CD/DVD optical pick-up units. The maximal speed for CD/DVD unit was achieved using p+/nwell photodiode and it was more than 160× CD/DVD speed. However, the calculated responsivity of this diode is 10 dB lower than specified for CD application and 18 dB lower than in DVD application [6]. Therefore, this diode structure is non-realistic for these applications.

The maximal speed for CD unit for nwell/p-substrate and p+/nwell/p-substrate photodiode is about 13× CD speed. In order to increase this speed the effect of slow substrate carriers has to be minimized. For DVD application on the other hand, the speed of analyzed photodiodes is 13× DVD (nwell/p-substrate) and 16× DVD (p+/nwell/p-substrate) and that corresponds to state-of-the-art achievable data-rates while the cost of the total pick-up unit can be minimized.

The diode geometries have almost no influence on their overall intrinsic bandwidth. The electrical photodiode bandwidth determined by the parasitic diode capacitances and the input impedance of the typical TIA's, is in the GHz range and do not limit the total diode bandwidth.

For deeper nwells (related to the technology), and for lower wavelengths ($\lambda < 650$ nm), photodiode geometry will certainly become important due to the smaller contribution of slow substrate current.

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