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On response time of semiconductor photodiodes

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Abstract. The effect of displacement currents due to dielectric relaxation of majority carriers in the charge-neutral region of a semiconductor photodiode is discussed. The dielectric relaxation is often neglected when treating the response time of photodiodes. We show that this component may dominate the slow response of not fully depleted photodiodes and has to be taken into account for correct analysis of silicon photodiode response to a brief laser pulse. A phenomenological expression for the photodiode response time that accounts for the displacement current effects is proposed and used to compare with the experimental results. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.56.9.097101](https://doi.org/10.1117/1.OE.56.9.097101)]

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1 Introduction

The response time to a brief external injection of excess (nonequilibrium) carriers through light absorption is one of the most important figures of merit of optical detectors, including semiconductor photodiodes and photoconductors. Correct description of the photocurrent transients in semiconductor photodetectors is not trivial and requires accurate analysis of the continuity equations, time-dependent drift/diffusion equations, and Poisson's equation for the mobile carriers as it was done in a recent work by the UCLA researchers.¹ Such analysis involves extended efforts, and for practical reasons, a simpler approach is usually used to describe the response time of photodetectors.

In case of a pulsed source of light, the detector response time is considered as either the rise time or fall time required for the output signal to change from 10% to 90% of its final value or vice versa. Both the rise and fall time depend on the RC time constant ($\tau_{RC} = RC$) of the detector and time required to collect nonequilibrium carriers by the external electrodes. For semiconductor photodetectors, the collection of nonequilibrium carriers created via light absorption is treated conventionally through drift and diffusion processes.^{2,3} The drift component of the photocurrent is determined by a relatively fast movement of nonequilibrium carriers in the electric field of a space-charge (depletion) region toward its edges. Correspondingly, the drift component τ_{drift} of the photodiode response time is conventionally defined as the time required for the nonequilibrium minority and majority carriers to reach the edges of the space-charge region. The diffusion component of the photocurrent is determined by a relatively slow movement of nonequilibrium minority carriers driven by carriers' concentration gradient in the charge-neutral (nondepleted) region of a photodiode toward its edges. The diffusion component τ_{diff} of the photodiode response time is defined conventionally as the time required for both minority and majority carriers to reach the edges of the charge-neutral region of the semiconductor.

Using the approximation described briefly above, the 10% to 90% response time of semiconductor photodiodes is defined in the literature through a sum of three independent components: the RC time constant of the detector (τ_{RC}), the drift of nonequilibrium carriers in the space-charge region, and the diffusion of nonequilibrium carriers in the charge-neutral region^{2,4-7}

$$\tau_r = \sqrt{(2.2\tau_{RC})^2 + \tau_{drift}^2 + \tau_{diff}^2}, \quad (1)$$

where the multiplier 2.2 accounts for the fact that the parameter τ_{RC} is the time constant of an exponential relaxation process and to get the 10% to 90% rise/fall time this parameter value has to be multiplied by 2.2. When the whole volume of a semiconductor is depleted at relatively high reverse bias operation conditions, all carriers are generated within the space-charge region and are collected by the drift process alone. Then, the term due to the diffusion of nonequilibrium carriers in the undepleted region can be neglected. However, if the semiconductor volume is not fully depleted, then Eq. (1) may not be valid. Missing from the equation is displacement currents (i.e., dielectric relaxation currents), which is a dominant charge current component for the majority carriers in the charge-neutral region of a semiconductor.^{3,8} They may be a major contribution to the charge collection time (and consequently the response time). The goal of this paper is to analyze effects of displacement currents on the total response time of semiconductor photodiodes. We do not intend to simulate the kinetics of a photodiode response to a brief pulse of light; therefore, we will consider an ideal case of photodiode without losses of nonequilibrium carriers and will use the classical phenomenological approach to evaluate the significance of the displacement currents in description of the photodiode's response time.

2 Model

The model considers the most common applicable case of *pin* Si photodiode (Fig. 1), schematically shown as a heavily doped *p*-type anode region on top of a lightly doped (intrinsic) *n*-type region with doping concentration N_0 . The heavily doped *n*-type cathode region on the bottom completes the photodiode structure. The *p/n* junction in this structure is

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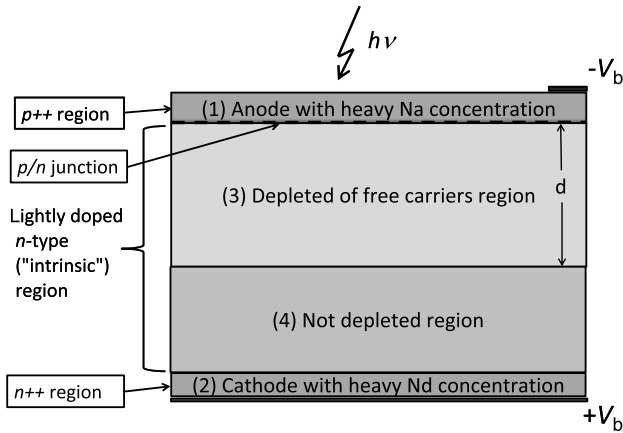


Fig. 1 Simplified schematic structure of a planar *pin* photodiode studied in the work. The depletion region width d depends on the resistivity of the Si substrate and applied reverse bias voltage V_b .

created along the surface separating the anode from the lightly doped n -type region. Under the applied reverse bias V_b , the portion 3 of the intrinsic region between the anode (region 1) and cathode (region 2) becomes depleted of free carriers, leaving the remaining portion 4 of the intrinsic region not depleted (charge-neutral region). Note that we consider here a simplified case neglecting the creation of space-charge regions within heavily doped anode and cathode areas. Let us further assume that the thickness of the anode and cathode regions is very small and the total number of nonequilibrium carriers created through light absorption inside these two regions is comparatively small to the total number of the carriers created via light absorption in the semiconductor's bulk. With these assumptions, nonequilibrium carriers are collected only from the space-charge region 3 and nondepleted region 4. In the following sections, we treat the collection of carriers from these two regions separately.

2.1 Minority Carriers Created by Light Within the Depletion Region

Nonequilibrium carriers inside the space-charge region 3 of Fig. 1 will be swept out of that region toward its edges by the electric field $E = \frac{V_{bi} + V_b}{d}$, where V_{bi} is a built-in potential of the semiconductor p/n junction and d is the depletion region width. This process is conventionally considered as drift of carriers. It is important to consider the drift of minority and majority carriers separately to correctly evaluate the individual contributions to the total response time. The minority carriers (holes in the case of the structure of Fig. 1) drift toward the p/n junction where they recombine with the majority carriers creating the input to the overall photocurrent transient signal. The drift time for the minority carriers in the depletion region is described by

$$\tau_{\text{drift}}^p = \frac{L_p^{\text{drift}}(\alpha_{\text{Si}})}{v_p(E)}, \quad (2)$$

where $v_p(E)$ is the electric field-dependent hole drift velocity in the depletion region and $L_p^{\text{drift}}(\alpha_{\text{Si}})$ is the drift distance inside the depletion region, which depends on the wavelength-dependent absorption coefficient α_{Si} of Si.

2.2 Majority Carriers Created by Light Within the Depletion Region

Nonequilibrium majority carriers (electrons in the case of Fig. 1) drift through the region 3 of the structure of Fig. 1 toward the cathode and enter the nondepleted region 4. The majority carriers drift time through region 3 is

$$\tau_{\text{drift}}^n = \frac{d - L_p^{\text{drift}}(\alpha_{\text{Si}})}{v_n(E)}, \quad (3)$$

where $v_n(E)$ is the electric field-dependent electron drift velocity and d is the depletion region width. To contribute to the overall photocurrent transient signal, the majority carriers that entered the nondepleted region of the semiconductor need to reach the cathode. This process is missing in Eq. (1). In accord with classical electrodynamics and using Poisson's equation, the dissipation of the majority carrier charge in the nondepleted region of a semiconductor occurs through dielectric relaxation processes and can be described in a one-dimensional case with the following equation (see, e.g., Refs. 3, 8, and 9):

$$\frac{\partial n}{\partial t} + \frac{n - n_0}{\epsilon \epsilon_0 / q \mu_n n_0} - D_n \frac{\partial^2 n}{\partial x^2} = 0, \quad (4)$$

where n is the majority carrier concentration, n_0 is the equilibrium carrier concentration in the "intrinsic" region, q is the elementary charge, μ_n is the majority carrier mobility, D_n is the majority carrier diffusion constant, and ϵ and ϵ_0 are the dielectric constant of Si and vacuum permittivity, respectively. Equation (4) can be solved by separation of variables assuming that the spatial variation of the carrier concentration n occurs independently of the time variation of n . With this assumption and for the case of a small excess carrier density ($n - n_0 \ll n_0$), Eq. (4) is transformed to a first-order differential equation $\frac{\partial n(t)}{\partial t} + \frac{n(t)}{\epsilon \epsilon_0 / q \mu_n n_0} = 0$, allowing to estimate the evolution of the majority carrier concentration with time in response to a disturbance in the charge density^{3,8,9}

$$n - n_0 = (n - n_0)_{t=0} \exp(-t/\tau_{\text{diel}}^n), \quad (5)$$

in which the characteristic time constant is given by

$$\tau_{\text{diel}}^n = \frac{\epsilon \epsilon_0}{\mu_n q n_0}. \quad (6)$$

Equation (6) is valid for a small signal case when nonequilibrium carrier concentration is of the order of n_0 or smaller, which we assume valid in our further analysis. For high doping densities N_0 (large value of n_0), the dielectric relaxation time becomes rather small and can be neglected. However, we show below that for relatively low doping concentrations (high resistivity of the semiconductor material), this term becomes significantly large and has to be taken into account when discussing and quantifying the photodiode's response time.

Note that the two processes examined above with Eqs. (3) and (6) occur in a consecutive manner—the majority carriers first drift toward the edge of the depletion region and then dissipate due to dielectric relaxation in the charge-neutral region, creating displacement current transient at the

electrodes. As a result, the input of the majority carriers created inside the depletion region to the total photocurrent transient is described with an arithmetic sum of two components: $\tau_{\text{drift}}^n + 2.2\tau_{\text{diel}}^n$. Similarly to the discussion of Eq. (1), the multiplier 2.2 in this expression is to account for the fact that the parameter τ_{diel}^n is the time constant of an exponential relaxation process of Eq. (5) and to get the 10% to 90% rise/fall time this parameter value has to be multiplied by 2.2.

2.3 Minority Carriers Created by Light Within the Charge Neutral Region

Minority carriers created via light absorption events inside the nondepleted region 4 of a Si photodiode in Fig. 1 dissipate due to slow diffusion toward the anode. The time required for a hole to diffuse through distance $L_p^{\text{diff}}(\alpha_{\text{Si}})$ inside the nondepleted region, from the location where it has been created by light to the edge of the depletion region is described using Einstein relation as

$$\tau_{\text{diff}}^p = \frac{[L_p^{\text{diff}}(\alpha_{\text{Si}})]^2}{\mu_p k_B T / q}, \quad (7)$$

where μ_p is the minority carriers' mobility, k_B is the Boltzmann's constant, and T is the temperature. After reaching the edge of the depletion region, the minority carriers are swept promptly by the electric field through the depletion

region toward the anode, adding therefore to the photocurrent transients.

2.4 Majority Carriers Created by Light Within the Charge Neutral Region

Majority carriers created via light absorption events inside the nondepleted region of Si photodiode dissipate through dielectric relaxation processes. These processes are also missing in Eq. (1). The time required for the majority carriers to dissipate adding a displacement current transient to the photocurrent is described by Eq. (6). Note that this component of the photocurrent transients usually can be neglected because the majority carriers created by light absorption in the charge-neutral region dissipate through dielectric relaxation much faster than the minority carriers that created by the same quanta of light dissipate through thermal diffusion.

2.5 Carriers Created by Light Within the Anode Region

As assumed above, the portion of light absorbed within the heavily p -type-doped anode region of Fig. 1 is very small, but it may still be noticeable especially at short wavelengths, for which the absorption length is very small. The majority carriers are holes within this region, and dissipation through dielectric relaxation of nonequilibrium holes created within the anode region is very fast ($\ll 1$ ns) because the

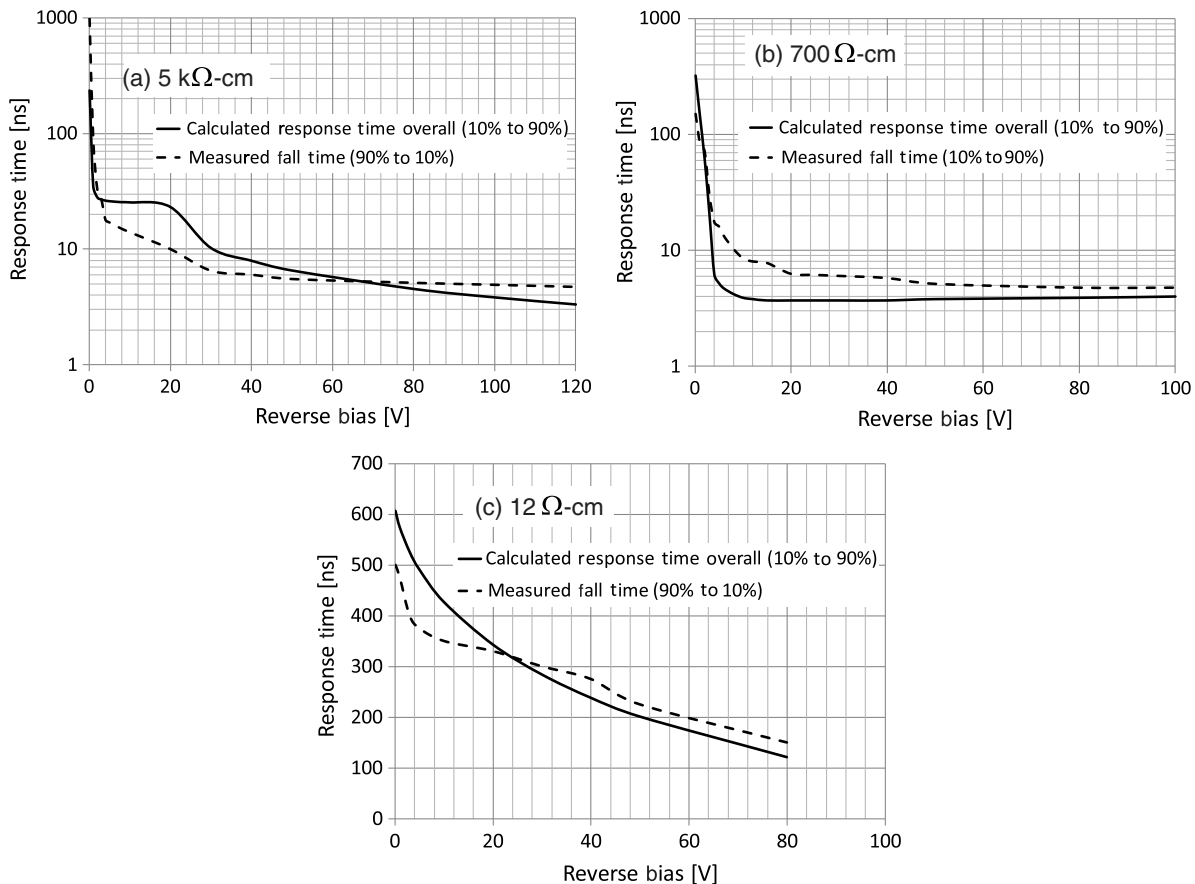


Fig. 2 Dependence of the fall time on the reverse bias measured for three photodiodes (dashed lines): (a) 5 kΩ-cm, 200-μm-thick substrate, (b) 700 Ω-cm, 400-μm-thick substrate, and (c) 12 Ω-cm, 400-μm-thick substrate. The calculation results are also shown for each device as described in the text in details.

equilibrium doping density N_0 within the anode region is very high—see Eq. (6). The minority carriers are electrons within this region, and they are collected via drift and diffusion processes. Whereas the drift part is very fast, the diffusion part is slow, which may significantly delay the overall time response of the photodiode if the portion of light absorbed within the anode region is not negligible. We will not consider this case in our work since optimization of responsivity and time response for Si photodiodes in the short-wavelength spectral range is well-developed technology and is not among the goals of this study. We will discuss, in more details below, the impact of processes occurring within the space-charge and charge-neutral regions of the photodiode only.

In accord with the features of charge collection and relaxation described above, we can conclude that the final expression to describe the photodiode response time in terms of 10% to 90% change in the signal amplitude following excitation with a brief laser pulse will not be straightforward. Obviously, the expression for the 10% to 90% response time depends on the depth of light absorption within the photodiode bulk. If light is fully absorbed within the depletion region 3 (Fig. 1) of the photodiode, then the only process within the charge-neutral region 4 of Fig. 1 that influences

the response time will be the dielectric relaxation of the majority carriers that entered the charge-neutral region after drifting through the depleted region of the photodiode. Alternatively, if the absorption depth is large enough and the reverse bias is not very high, then light absorption may occur in both the space-charge and charge-neutral regions of the photodiode and the diffusion of minority carriers in the charge-neutral region needs also be taken into account. In fact, the 10% to 90% response time τ_r could be best described as

$$\tau_r = \sqrt{(2.2\tau_{RC})^2 + [\text{drift} + (\text{dielectric relaxation})]^2 + (\tau_{diff}^p)^2}, \quad (8)$$

in which the term [drift + (dielectric relaxation)] is given by the larger of the two values, $(\tau_{drift}^n + 2.2\tau_{diel}^n)$ or (τ_{drift}^p) . The choice between the two assumes that the response time is dominated by the slowest of the two partially independent processes: one is holes drift through the space-charge region and their collection at the p/n junction (τ_{drift}^p), and the other is electrons drift through the space-charge region followed by the dielectric relaxation of the electron charge in the non-depleted region $(\tau_{drift}^n + 2.2\tau_{diel}^n)$.

Table 1 Response time and its components calculated for the photodiode built on $\sim 5 \text{ k}\Omega\text{-cm}$, $200\text{-}\mu\text{m}$ -thick substrate.

Bias (V)	Depletion width ($200 \mu\text{m}$ maximum) (μm)	Processes within depletion (space-charge) region		Processes within not depleted (charge-neutral) region		$2.2\tau_{RC}$	τ_r	Measured fall time (90% to 10%) (ns)
		τ_{drift}^p	τ_{drift}^n	τ_{diff}^p	$2.2\tau_{diel}^n$			
		Minority carrier (holes) drift time (10% to 90%) (ns)	Majority carrier (electrons) drift time (10% to 90%) [ns]	Minority carriers (holes) diffusion time (10% to 90%) [ns]	Majority carrier (electrons) dielectric relaxation time (10% to 90%) (ns)	RC component for $50\text{-}\Omega$ load resistor (10% to 90%) (ns)	Calculated response time overall (10% to 90%) [ns]	
0.1	36	236	90	0	12.5	1.8	236	1000
1	53	35	19.5	0	12.5	1.21	35	90
2	67	22	15.5	0	12.5	0.96	28	33
3	78	17	14.5	0	12.5	0.82	26.8	27
4	88	14.5	13.5	0	12.5	0.73	26.2	18
5	97	12.9	13.4	0	12.5	0.66	25.9	17
8	120	10	12.9	0	12.5	0.53	25.4	15
10	133	8.9	12.8	0	12.5	0.48	25.3	14
20	184	6.2	12.7	0	12.5	0.35	23.1	10
30	200	4.6	10.2	0	0	0.32	10.2	6.5
40	200	3.5	7.9	0	0	0.32	7.9	6
50	200	2.8	6.5	0	0	0.32	6.5	5.5
80	200	1.8	4.4	0	0	0.32	4.5	5.1
100	200	1.5	3.8	0	0	0.32	3.8	4.9
120	200	1.3	3.3	0	0	0.32	3.3	4.7

3 Experimental Results and Discussion

We compared the measured response time for a few engineering samples of Si *pin* photodiodes with calculations based on a model of Eq. (8) discussed above. The photodiodes for this study were manufactured at Luna Optoelectronics using three different *n*-type Si resistivity substrates ($\sim 5 \text{ k}\Omega\text{-cm}$, $\sim 700 \text{ }\Omega\text{-cm}$, and $\sim 12 \text{ }\Omega\text{-cm}$) with (111) crystal orientation. The substrate thickness for each engineering sample is given in the caption of Fig. 2. The active area of all samples was 5 square millimeters. The choice of three different substrates allowed us to cover different modes of *pin* photodiode operation—from a fully depleted mode at moderate and high voltage bias to partially depleted case at moderate voltage bias to only slightly depleted case at low bias condition. The response time at various reverse bias values was measured using 825-nm diode laser with subnanosecond leading and falling edges of a pulse. The accuracy of rise/fall time measurements was $\pm 10\%$ but was never

better than $\pm 1 \text{ ns}$. In each experimental run, the 10% to 90% rise time and 90% to 10% fall time were recorded. Figure 2 shows dependencies of the measured response time on the reverse bias for each photodiode. The calculated response time in accord with the model described above [Eq. (8)] was also plotted on the same graphs.

The photodiode response to a brief laser pulse is obviously a multimodal process. Note that for our goal of pinpointing the role of dielectric relaxation effects in the total response of the *pin* photodiode, the kinetic analysis of the actual rise and fall time traces may not be useful at all. From the dependencies of Fig. 2, it is clear that the modality of the response time changes with the applied reverse bias. To analyze the impact of dielectric relaxation effects, it is most useful to examine each component of the response time simulation in accord with Eq. (8). Tables 1–3 show the actual calculation results for the three photodiodes studied in this work.

Table 2 Response time and its components calculated for the photodiode built on $700 \text{ }\Omega\text{-cm}$, $400\text{-}\mu\text{m}$ -thick substrate.

Bias (V)	Depletion width ($400 \text{ }\mu\text{m}$ maximum) (μm)	Processes within depletion		Processes within not depleted		$2.2\tau_{\text{RC}}$	τ_r	Measured fall time (10% to 90%) (ns)
		τ_{drift}^p	τ_{drift}^n	τ_{diff}^p	$2.2\tau_{\text{diel}}^n$			
		Minority carrier (holes) drift time (10% to 90%) [ns]	Majority carrier (electrons) drift time (10% to 90%) (ns)	Minority carriers (holes) diffusion time (10% to 90%) (ns)	Majority carrier (electrons) dielectric relaxation time (10% to 90%) (ns)			
0.1	14	37	13	288	1.7	4.7	324	150
1	20	7.7	2.7	138	1.7	3.3	146	85
2	25	6.1	2.2	55	1.7	2.6	61	71
3	29	5.6	2	14.4	1.7	2.2	20.2	29.5
4	32	5.4	2	0.42	1.7	2	6.2	17.5
5	35	4.8	1.9	0	1.7	2.3	5.2	16
6	38	4.4	1.9	0	1.7	1.7	4.7	13.25
8	44	3.8	1.9	0	1.7	1.5	4.2	10.25
10	48	3.4	1.9	0	1.7	1.3	3.9	8.5
12	53	3.1	1.9	0	1.7	1.2	3.8	8
15	59	2.8	1.9	0	1.7	1.1	3.7	7.75
20	67	2.4	1.9	0	1.7	0.95	3.7	6.25
25	75	2.2	1.9	0	1.7	0.85	3.7	6.125
30	82	2	2	0	1.7	0.77	3.7	6
40	94	1.8	2	0	1.7	0.67	3.7	5.75
50	105	1.6	2.1	0	1.7	0.6	3.8	5.125
80	133	1.3	2.2	0	1.7	0.48	3.9	4.75
100	149	1.2	2.3	0	1.7	0.43	4	4.75

Table 3 Response time and its components calculated for the photodiode built on 12 Ω -cm, 400- μ m-thick substrate.

Bias (V)	Depletion width (400 μ m maximum) (μ m)	Processes within depletion (space-charge) region		Processes within not depleted (charge-neutral) region		$2.2\tau_{RC}$	τ_r	Measured fall time (90% to 10%) (ns)
		τ_{drift}^p	τ_{drift}^n	τ_{diff}^p	$2.2\tau_{diel}^n$			
		Minority carrier (holes) drift time (10% to 90%) (ns)	Majority carrier (electrons) drift time (10% to 90%) (ns)	Minority carriers (holes) diffusion time (10% to 90%) (ns)	Majority carrier (electrons) dielectric relaxation time (10% to 90%) (ns)			
0.1	2	0.72	0.26	606	0.029	33	607	500
1	3	0.15	0.06	573	0.029	24	574	475
3	4	0.12	0.05	526	0.029	17	526	400
5	5	0.12	0.05	491	0.029	14	491	375
10	6	0.12	0.06	427	0.029	10	427	350
20	9	0.13	0.09	343	0.029	7.2	343	330
30	11	0.14	0.11	283	0.029	5.9	284	300
40	12	0.16	0.12	238	0.029	5.1	238	275
50	14	0.17	0.14	200	0.029	4.6	201	225
80	17	0.22	0.17	121	0.029	3.7	121	150

The calculations were made using the following rules:

- The time τ_{drift}^p of minority carriers drift through the space-charge region was estimated for the value of $L_p^{drift}(\alpha_{Si})$ in Eq. (2) at which 90% of light was absorbed;
- The time τ_{drift}^n of majority carriers drift through the space-charge region 3 was estimated as the time required to drift through the whole width d of the space-charge region;
- The time τ_{diff}^p of minority carriers diffusion through the charge-neutral region was estimated for the value of $L_p^{diff}(\alpha_{Si})$ in Eq. (7) as
 - equal to $[L(90\%) - d]$, where $L(90\%)$ is the depth in Si at which of 90% of incident light is absorbed for the case $L(90\%) > d$;
 - equal to 0 for the case $L(90\%) \leq d$.

Since the dielectric relaxation time τ_{diel}^n (as well as the related parameter, Debye length) is defined only through the semiconductor material parameters and does not depend on the depletion width, light absorption depth, etc., the time constant of the dielectric relaxation remains unchanged for all bias values at which the semiconductor's volume is not fully depleted. Zero value of the dielectric relaxation time for the cases of fully depleted structure means simply that no majority carrier charge dissipation occurs through dielectric relaxation at these values of the reverse bias. Similarly, zeros in the τ_{diff}^p column mean that all minority carriers are collected through the drift mechanism, which occurs when

the applied reverse bias pushes the depletion edge beyond the absorption depth of the laser light.

For the photodiode built using ~ 5 -k Ω cm Si substrate, the value of τ_{diel}^n becomes comparable to the other relaxation times for the reverse bias higher than ~ 3 V and up to the reverse bias of a full depletion (see Table 1). Note that dielectric relaxation (and consequently, the value of the displacement current) may become the longest component in the response time transients for photodiodes built using even higher resistivity semiconductor material.

For the photodiode built using ~ 700 - Ω cm Si substrate, the value of τ_{diel}^n becomes comparable to the other relaxation components for the reverse bias higher than ~ 6 V and remains among dominant components up to the reverse bias of a full depletion (over 120 V, see Table 2).

Unlike the first two photodiodes for the device built using 12 Ω -cm Si substrate, the value of τ_{diel}^n was never high enough to impact the response time. This last observation is very well understood since it is known that dielectric relaxation in the moderately and heavily doped semiconductors occurs on very fast time scales.

The last column in Tables 1–3 contains data of the experimentally measured fall time, the same data as plotted with solid lines in Figs. 2(a)–2(c), respectively. Obviously, there is some discrepancy in the calculated and measured values of 10% to 90% response time. We attribute this to limitations of the model, which did not take into account, e.g., possible ambipolar character of carriers' transport processes, features of light absorption in the semiconductor crystal, peculiarities of dielectric relaxation effects at high excitation levels, as well as uncertainty in Si resistivity values. However, we

consider that the results presented are convincing enough to evidence importance of displacement currents through dielectric relaxation of major carriers in evaluation of the total response time of the semiconductor photodiodes.

4 Conclusion

Although in many cases the numbers for the photodiode response time obtained using Eq. (1) are close to the measured 10% to 90% rise/fall time values, the description of processes involved as given by Eq. (1) may not always be correct. In fact, it is not correct to claim that the photodiode response time depends only on “three independent parameters, namely the RC time constant of the photodiode circuitry, the carriers diffusion time in the nondepleted region, and the carriers drift time in the depletion region” as it is often done in the literature. Furthermore, showing the diffusion component in the response time expression of Eq. (1) assumes that the semiconductor bulk is not fully depleted, which also entails the necessity to include the dielectric relaxation component for the majority carriers in the charge-neutral region. Our results showed that the majority carriers’ dissipation in the charge-neutral region of the semiconductor photodiode that occurs through dielectric relaxation process creating displacement currents at the electrodes, may provide a major addition to the overall response time especially for the photodiode built using high resistivity material and operating at a not full depletion mode. This component of photocurrent transients may be significantly large for the light wavelengths at which most of optical quanta are absorbed within the depleted region of a not fully depleted semiconductor bulk. For the longer wavelengths, when absorption occurs partially in nondepleted region, the diffusion of minority carriers prevails and

photocurrent transients due to a displacement current of majority carriers can be neglected.

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