OSI Optoelectronics
An OSI Systems Company

PHOTODETECTORS

PSD Time Response: Dependence on Illumination Location and IER

POSITION SENSING DETECTORS

Multiple studies showed that the time response of the lateral photovoltaic effect detectors depends not that much on the resistance between the illumination spot and charge collection electrode but rather on the type of the junction, mode of operation (fully depleted or not), specific properties of semiconductor material, and illumination conditions.

In particular, it was shown that the response time of the two-dimensional lateral photovoltaic effect PSD is determined by a characteristic junction time constant of the detector, τ_c:

$$\tau_c = \frac{R_s C_A d^2}{\pi^2}$$

where R_s is a sheet resistance of the “resistive” layer, C_A the junction unit area capacitance (in F/mm2), d (mm) the separation between a pair of electrodes within the resistive layer.

It was shown that for relatively small-size PSDs with high position resolution, the response time did not depend on the illumination location if the incident pulse had rise/fall time characteristics that were not shorter than the characteristic time constant. τ_c. For 2mm diameter InGaAs PSD developed by Advanced Photonix, the T_c value is approximately 10ns.

For large-size PSDs with a rather long characteristic time constant τ_c, the response to a short laser pulse with rise/fall time characteristics shorter than τ_c exhibited non-trivial dependence on the laser spot location. In many cases, the pulse response was shown to delay when the spot location shifted away from the signal electrode, and the shape of the response pulse changed in a nonlinear fashion.

Analysis showed that lateral photovoltaic effect PSDs can be described using the formalism of heat-transfer or transmission line equations. No straightforward relation between the response time and the resistance between the illumination location and signal electrode was found. Also, no reliable SPICE model was reported to adequately describe the lateral photovoltaic effect of PSD performance.

INTRODUCTION

The response time performance of lateral effect position-sensitive detectors (PSD) and its correlation with the illumination spot location within the active area is not trivial. To a certain extent, difficulties in understanding this problem came from attempts to interpret the lateral photovoltaic effect in terms of “resistances”—inter-element resistance (IER) and series resistance of the photodiode.

In lateral-effect PSD, the collection of non-equilibrium carriers created via light absorption can be considered a two-phase process:

1) transverse motion of minority carries towards the (p/n) junction and majority carriers in the opposite direction – this is due to a well-known transverse photovoltaic effect across the junction that leads to charge separation and creation of the potential barrier and

2) lateral transfer of charges towards equilibration to compensate local disturbance of a (p/n) junction potential barrier created due to transverse photovoltaic effect.

The slowest process determines the overall response time of lateral photovoltaic effect photodiodes. The transverse motion of carriers and its effect on the response time of semiconductor photodiodes was well studied and described in the literature (see e.g. [1]). It does not depend on the illumination location within the active area of a photodiode. Below, we will concentrate on the time response features related to the lateral photovoltaic effect in photodiodes.

LATERAL PHOTOVOLTAIC EFFECT AND RELATED TIME RESPONSE IN PHOTODIODES

EARLY WORKS ON LATERAL PHOTOVOLTAIC EFFECT

J.T. Wallmark (RCA Labs) first described the lateral photovoltaic effect in semiconductor photodiodes in 1957 [2]. He considered specifically the p+/n junction, but he admitted that the same effects, with some modifications, also apply to all other types of junctions (n+/p, n+/n, p+/p, Schottky, etc.).

Wallmark concluded that the lateral effect of the charge redistribution and reemission and subsequent space charge neutralization – is majority carrier conduction and may be assumed to have a negligible time delay.

Note that such consideration agrees with the general approach accepted in semiconductor physics (see, e.g. [3,4,5]), showing that the dissipation of non-equilibrium majority carriers occurs through fast effects of the dielectric relaxation. Per classical electrodynamics and using Poisson’s equation, the dissipation of the majority carrier charge in the non-depleted region of a semiconductor occurs through dielectric relaxation processes. It can be described in a one-dimensional case with the following equation:

$$\frac{\partial n}{\partial t} + \frac{n-n_0}{\varepsilon\varepsilon_0 / q\mu_n n_0} - D_n \frac{\partial^2 n}{\partial x^2} = 0 \qquad (1)$$

where n is the majority carrier concentration, n_0 the equilibrium carrier concentration, q the elementary charge, μ_n the majority carrier mobility, D_n the majority carrier diffusion constant, and $\varepsilon, \varepsilon_0$ are the dielectric constant of Si and vacuum permittivity, respectively. Assuming $(n-n_0 \ll n_0)$ and independence of a spatial variation of n from its time variation, the characteristic time constant for majority carriers dissipation is given by:

$$T^{n}_{diel} = \frac{\varepsilon\varepsilon_0}{\mu_n q n_0} \qquad (2)$$

For the doped semiconductor, n_0 has to be replaced with the doping concentration N_D or N_P. Equation (2) applied to PSDs means that the lateral photovoltaic effect response time is independent of the illumination spot location.

For 2mm InGaAs PSD developed at APX, the dielectric relaxation time within the resistive Anode layer (p-type doped), as estimated using Equation (2), is $\tau_{diel}^{p}<10$fs. It means that τ_{diel}^{p} does not impact the response time of such PSDs because it is determined by much slower processes of the transverse motion of charges and by the capacitance of the junction.

One of the early works on the lateral photovoltaic effect by Lucovsky ([6], Philco, then Ford, then Philips) concluded that if, in the p+/n junction photodiode, an ohmic contact is made to the entire surface of the n region, making this region an equipotential, it then follows that the lateral flow of current is consistent with current continuity requirements and conditions imposed by the presence of the p/n junction barrier. In this case, the characteristic time required for the lateral redistribution of the separated charge is generally determined by the junction impedance and the junction capacity only. Since the junction impedance and capacitance do not depend on location, it follows then that the response time of a lateral-effect PSD does not depend on the light spot location.

ADVANCED ANALYSIS OF RESPONSE TIME OF PSDS

The practical situation is not that simple. Equation (2) was obtained under certain assumptions, which may not always be valid for PSDs. A more comprehensive analysis of time evolution of the lateral photo-voltage involved the formalism of a heat-transfer equation (see [7], Univ. of Nijmegen, Netherlands) or transmission line equation ([8], Raytheon Company, Mass), which allowed to conclude that the time response of the lateral effect photovoltaic detectors depends on the type of the detector, mode of operation (fully depleted or not), and the characteristic junction time constant per unit area [7,8].

In particular, it was shown that the frequency response of the two-dimensional lateral photovoltaic effect PSD can be characterized using a fundamental bandwidth. f_c of the detector:

$$f_c = \frac{\pi/_2}{R_S C_A d^2} \tag{3}$$

where R_s is a sheet resistance of the “resistive” layer, C_A the (p/n) junction unit area capacitance (in F/mm^2), d (mm), the separation between a pair of electrodes. The frequency response of PSD will not depend on the illumination location for $f<f_c$. The lateral fall-off parameter

$$\alpha = \sqrt{\frac{R_s q J_s}{d k_B T}} \tag{4}$$

first introduced in ref. [6] depends on R_s in an opposite way compared to f_c (J_s is the reverse saturation current density, q the elementary charge, T the absolute temperature, k_B the Boltzmann constant). The lateral photovoltaic effect becomes more pronounced as α increases. In the limit as α goes to zero, the lateral photovoltage disappears. That is, to get PSD with high spatial resolution (high value of α), the design with high R_s value is advantageous. However, this will adversely impact the PSD bandwidth, f_c. Using Equation 3, the characteristic response time of PSD is

$$\tau_c = 1/2\pi f_c = \frac{R_s C_A d^2}{\pi^2} \tag{5}$$

The measured response time depends on τ_c given by Equation (5). For the detectors are characterized by small τ_c value (large f_c), the response time does not depend on the illumination location within the active area if the incident pulse has a rise/fall time longer than the characteristic response time τ_c of PSD. For large separation between electrodes, the τ_c value becomes large, and PSD response to short laser pulses becomes nontrivial. Many publications have shown that in such a case, the pulse response exhibited delay, which increased with the illumination spot moving away from the signal electrode, but the shape of the pulse did not change significantly or even remained unchanged [8,9].

REPRESENTATIVE EXPERIMENTAL RESULTS ON RESPONSE TIME OF PSDS

1.1. KLEIN ET AL. [8], RAYTHEON COMPANY

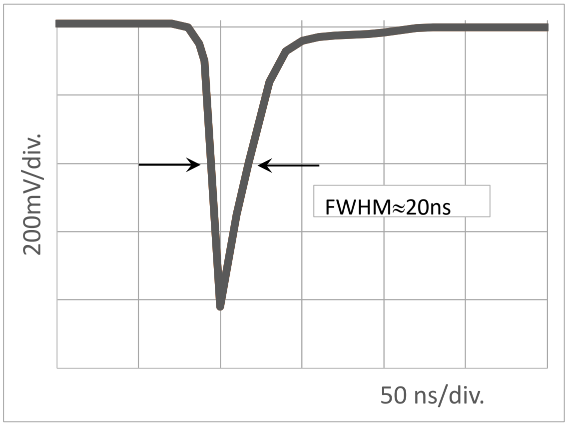
The authors studied two different tetra-lateral silicon PSD (p+/n/n+ structure) with n+ resistive layers:

a) Small-size device with d=5mm, C_A=0.42 pF/mm^2, and R_s=5 kOhm/sq. The characteristic fundamental bandwidth f_c of this device calculated using Equation (3) was 30 MHz ($\tau_c \approx 10$ns). The response to a ~8ns duration Q-switched Nd:YAG laser pulse at 1064nm showed no degradation when the laser spot location shifted between two electrodes (see Figure 1).

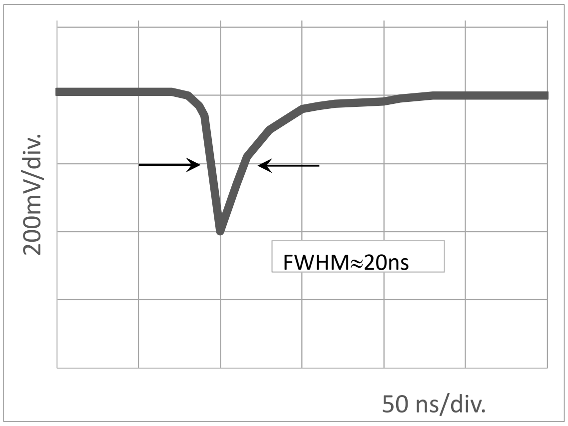
Figure 1. Nd:YAG laser response of a small-size PSD device a) as studied in reference [8]. The pulse response followed the shape of the Q-switched laser pulse almost precisely independently on the illumination location relative to the signal electrode. See text for details. The Figure is the schematic representation of the results from ref. [8].

LASER PULSE INCIDENT ON:

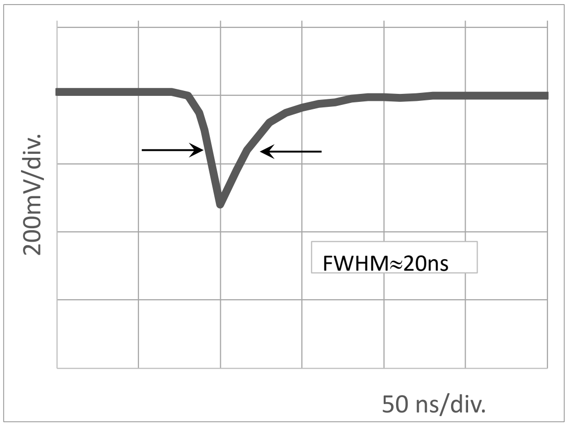
1. SIGNAL ELECTRODE



2. CENTER LOCATION



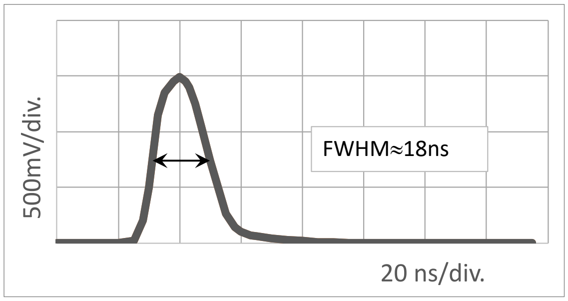
3. OPPOSITE ELECTRODE



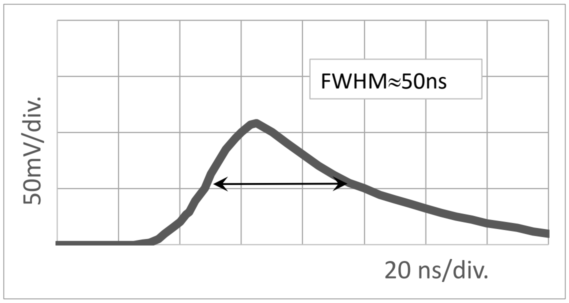
b) large-size device with d=20mm, C_A=0.42 pF/mm^2, and R_s=2 kOhm/sq. The characteristic fundamental bandwidth f_c of this device calculated using Equation (3) was below 5 MHz (τ_c=70ns), thus inducing considerable distortion of 18-ns GaAs laser pulse (at 850nm) when the spot location shifted from a signal electrode to the center location, see Figure 2. Note that no further distorsion of the pulse was observed for a continuing shift of the laser spot from the center location to the opposite electrode.

LASER PULSE INCIDENT ON:

1. SIGNAL ELECTRODE



2. CENTER LOCATION



3. OPPOSITE ELECTRODE

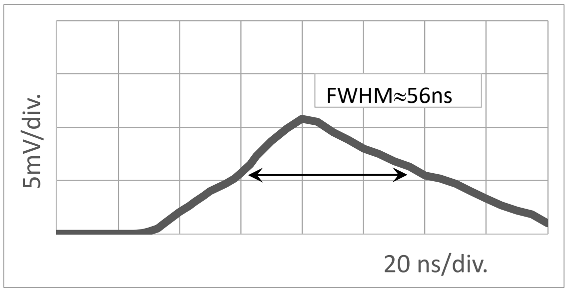


Figure 2. GaAs laser response of a large-size PSD device b) as studied in reference [8]. The pulse response followed the shape of the laser pulse precisely for the laser spot location next to the signal electrode. The rise and fall time of the pulse response became ~3 times longer when the laser spot shifted to the center of the 20-mm active area device. See text for details. The Figure is the schematic representation of the results from ref. [8].

1.2. WOLTRING, UNIV. OF NIJMEGEN, NETHERLANDS [7].

The impulsive responses of the duo-lateral and tetra-lateral p+/n/n+ detectors with the n+ resistive sheet were analyzed and compared. The responses consisted of a single and slightly delayed impulse with a fast-rising and slow decaying character, at least for moderate values of $\alpha d \leq 3$ (α is a lateral fall-off parameter, d is the separation between contacts) and not too small distances to the output contact under consideration. The response approximated a true and delayless Dirac delta function for decreasing distance. The tetra-lateral detector appeared to be somewhat faster than the duo-lateral version. Although the current amplitude of the tetra-lateral detector varied when the light spot was displaced in parallel with the contact under consideration, the shape of the impulse remained virtually unaltered.

1.3. HIROHIKO NIU ET AL., OSAKA UNIVERSITY [9].

It was shown that the phase and amplitude of the n+/p junction lateral effect photodiode depended on the illumination position. Still, the shape of the pulse was not dependent on the light spot location, i.e., the response time was not dependent on the light spot location. The maximum of the pulse response was delayed upon the spot location shift from the electrode to the center of the active area. Samples studied: Si PSD, ~100 Ohm-cm p-type (resistive) bulk, and heavily doped n+ region; contacts are on the p-type substrate.

RESPONSE TIME OF PSD AND INTER-ELEMENT RESISTANCE

Assuming a tetra-lateral PSD or 1D duo-lateral PSD with a single rectangular-shaped resistive layer having the length d (which is equal to the separation between electrodes) and width w, Equation (5) can be transformed in the following way:

$$\tau_c = \frac{R_s C_A d^2}{\pi^2} = \frac{1}{\pi^2}\frac{R_s d}{w}[C_A(wd)] = \frac{1}{\pi^2} R_{ie}[Cj] \qquad (6)$$

In which:

$R_{ie} = \frac{R_s d}{w}$ is the inter-element resistance, and

$C_j = C_A(wd)$ is the total junction capacitance of PSD.

Equation (6) shows a straightforward relationship between the characteristic time constant. τ_c and inter-element resistance R_{ie}. Note, however, that the time constant τ_c is just a parameter that characterizes the features of the PSD response to optical pulses of different durations. PSD with high-frequency bandwidth $f \geq f_c = 1/2\pi\tau_c$ has to be built using low R_{ie} value. For such PSD, the frequency response will not depend on the illumination location. The drawback of designs with a low R_{ie} value is poor position resolution, as can be characterized by the lateral fall-off parameter α from Equation (4).

CONCLUSION NOTES

Because the behavior of lateral-effect PSD photodiodes is not trivial, no general SPICE model was found to simulate either the PSD photodiode itself or PSD in a TIA circuit. The most successful attempts to simulate PSDs' behavior employed distributed network modeling and TCAD simulation software, but those attempts were very limited.

LITERATURE

1. A.O Goushcha and B. Tabbert, "On response time of semiconductor photodiodes," Opt. Eng. 56(9), 097101 (2017), doi: 10.1117/1.OE.56.9.097101
2. J.T. Wallmark, "A new Semiconductor Photocell Using Lateral Photoeffect", Proceedings of the I.R.E., 45, 474 (1957).
3. S. M. Sze, Physics of Semiconductor Devices, 2nd ed., John Wiley and Sons Inc., New York (1981).
4. E.L. Dereniak and G.D. Boreman, Infrared Detectors and Systems, John Willey & Sons, Inc., New Chichester, Brisbane, Toronto, Singapore (1996).
5. G. Rieke, Detection of Light. From the Ultraviolet to the Submillimeter, 2nd edition, Cambridge University Press, Cambridge (2003).
6. G. Lucovsky, "Photoefiects in Nonuniformly Irradiated p-n Junctions", Journal of Applied Physics 31, 1088 (1960); https://doi.org/10.1063/1.1735750.
7. H.J. Woltring, "Single- and Dual-Axis Lateral Photodetectors of Rectangular Shape", IEEE Transactions On Electron Devices, 22, no.8, 581, (1975); doi:10.1109/T-ED.1975.18181.
8. C. A. Klein and R. W. Bierig, "Pulse-response characteristics of position-sensitive photodetectors," IEEE Transactions on Electron Devices, 21, no. 8, pp. 532-537, (1974); doi: 10.1109/T-ED.1974.17960.
9. Hirohiko Niu et al. "Dynamic Characteristics of the Lateral Photovoltaic Effect and Their Application to the Measurement of Junction Capacitance", Jpn. J. Appl. Phys. 16 1589 (1977); doi: 10.1143/JJAP.16.1589.