Nonlinear Pulse Response of P-I-N Photodiode Caused by the Change of the Bias Voltage

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Abstract

An analytical expression is derived for nonlinear response of a p-i-n photodiode, commonly used in optical communications. Nonlinearity is caused only by the change of bias voltage, in case of pulse light excitation. The response time increases slowly with increasing the incident pulse power as a result of this nonlinearity. It is assumed in calculations that the optical excitation is not so strong to cause space charge redistribution.

Keywords: photodiode, bias voltage, nonlinear response, response time.

1. Introduction

Nonlinear photodiode response is caused either by the appeareance of space charge or by the change of bias voltage due to the existence the load resistance ([1-5]). According to [4] the harmonic distortion is caused both by the effects of the space charge influence on the carriers transit time and by the finite resistance of the electric circuitry to which the photodiode is connected, i.e. by changes of the bias voltage. However, this work does not investigate the quantitative influence of this effect on the p-i-n photodiode response time.

The model used in this paper is analogons to that presented in [6], where the simulation of fast rise time light-activated diode switches was performed. Here we present an analysis of the influence of nonlinearity caused by the change of bias voltage on the photodiode pulse response, assuming that the optical excitation is not so strong to cause the appearance of free carriers space charge. The p-i-n photodiode response time vs. the optical pulse energy dependence is considered in detail. Furthermore, the photodiode voltage variation during the detection process is also given.

2. Model

The electric circuit of the photodiode used for detection is shown in Fig. 1. The detected signal is $U_R(t)$, and $U(t)$ is the voltage of the reverse biased p-i-n photodiode, $I(t)$ is its photocurrent and R the load resistance. In the equivalent circuit of the photodiode the resistance of the diode contacts is neglected, as also is the parasitic capacitance of the external circuitry, while the p-i-n photodiode capacitance is taken into account via the displacement current. During the detection of the incident radiation, the photodiode generates photocurrent which causes a voltage drop on the load resistance, and thus changes the photodiode voltage:

$$U(t) = Vcc - RI(t) \tag{1}$$

This causes a perturbation of the electric field controlling the carriers transport, inducing in turn photocurrent to change and nonlinearity effects to appear.

The analysis of this nonlinearity is performed according to the model based on the following assumptions. We consider a GaAs p-i-n photodiode fabricated by LPE process. The photodiode structure is shown in Fig. 2. The effects of the space charge are neglected. In such a case the electric field perturbation in the depletion region is caused only by the change of bias voltage. We assume the semiconductor doping level in the i-region to be low, so that the electric field in this region is homogeneous. We also assume that the length of the i-region is much larger than that of p- and n-regions, therefore the photon absorption in the latter two regions, and hence the diffusion currents, may be neglected. Finally, the reverse bias voltages are assumed not to be very high, so we can take μ_i(i=n,p)=const. In accordance with the above assumptions, we can write the following relations defining the adopted model.

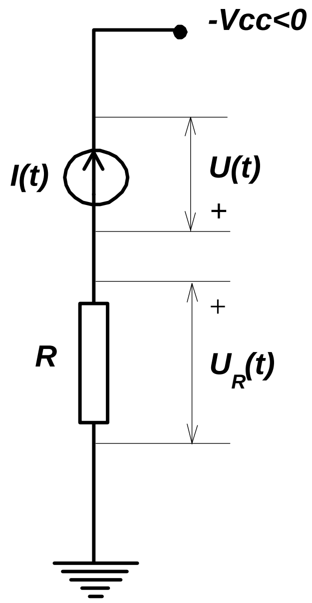

Fig. 1. Electric circuitry of p-i-n photodiode.

The electric field in the i-region is [5]:

$$E(x,t) = E_W(x,t) = E_W(t) = \frac{U(t) - V_D}{d} \tag{2}$$

where d is the width of the i-region, and $V_D = \dfrac{eNd^2}{2\varepsilon_0\varepsilon_r}$ is the punch-through voltage (N is the small residual donor concentration in the absorption layer). We take that $U(t)/V_D > 1$, thus ensuring the depletion of the whole i-region.

The electron and hole velocities are:

$$v_n(x,t) = v_n(t) = \mu_n E_W(t) \tag{3}$$

$$v_p(x,t) = v_p(t) = \mu_p E_W(t). \tag{4}$$

The continuity equations for electrons and holes read:

$$\frac{\delta n}{\delta t} + \vec{i}\frac{\delta}{\delta x}(n\vec{v_n}) = G_{op}(x,t) \tag{5}$$

$$\frac{\delta p}{\delta t} + \vec{i}\frac{\delta}{\delta x}(p\vec{v_p}) = G_{op}(x,t) \tag{6}$$

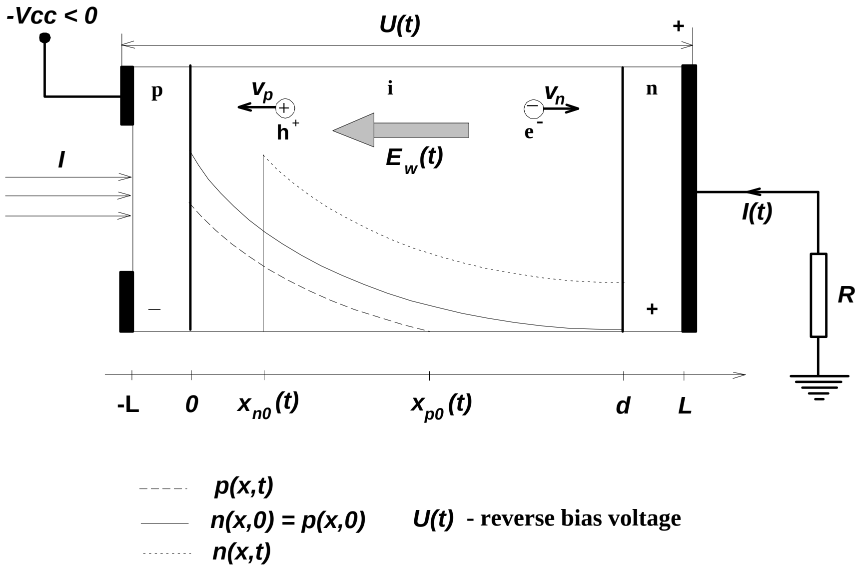

Fig. 2. p-i-n photodiode structure.

In the above equations we neglected recombination, because the processes we consider are supposed to be fast. We also neglected thermal generation, because the dark current it creates is negligible when compared to the photocurrent. The pulsed optical generation rate is:

$$G_{op}(x,t) = \alpha I e^{-\alpha x}\delta(t) \tag{7}$$

where I is the incident photon flux density, and α is the optical absorption coefficient of GaAs. The optically generated current density is now determined by:

$$\vec{j}(x,t) = qn(x,t)\vec{v_n}(x,t) + qp(x,t)\vec{v_p}(x,t) \tag{8}$$

The p-i-n photodiode response is given by the relation[5,7]:

$$I(t) = \frac{S}{d}\int_0^d j(x,t)dx + \frac{\varepsilon S}{d}\frac{dU(t)}{dt} \tag{9}$$

where S is the p-i-n photodiode active area, and ε is GaAs dielectric permittivity. The first term in the above equation is the conduction

current, and the second term is the displacement current.
Equations (1-9) together with the boundary conditions

$$\begin{aligned} n(x,0) = p(x,0) &= \alpha I e^{-\alpha x} && (10) \\ n(0,t) = p(d,t) &= 0 && (11) \end{aligned}$$

are a closed system which enables one to determine the current response, i.e. the change of the photodiode voltage during detection.

3. Calculation of Photodiode Voltage Change and Defined Time Response

By solving the closed system of equations (1-11) using algebraic and integro-differential transformations we obtain an equation giving the p-i-n photodiode voltage after the pulsed optical excitation is applied:

$$\begin{aligned} U(t) &= V_{cc} - \\ &- \frac{ReSI}{d}\Big\{(a_1 U(t) - b_1)\Big[1 - e^{-\alpha(-a_1\int_0^t U(t)dt + b_1 t + d)}\Big] + \\ &\quad + (a_2 U(t) - b_2)\Big[e^{-\alpha(a_2\int_0^t U(t)dt - b_2 t)} - e^{-\alpha d}\Big]\Big\} - \\ &- \frac{R\varepsilon S}{d}\frac{dU(t)}{dt}. \end{aligned} \qquad (12)$$

where $b_i = a_i V_D$ (i=1,2), $a_{1,2} = \dfrac{\mu_{n,p}}{d}$.

To solve equation (12) for U(t) we take into account the nature of physical processes in the photodiode. There are two characteristic time constants. The first one (shorter) represents the time in which all the electrons leave the depletion region, t_{cn}. The second one (longer) is the time in which all the holes leave this region, t_{cp}. Before the moment $t \leq t_{cn}$ equation (12) is valid. After the electron concentration reaches zero in the whole i-region, the dominant role is played by holes, and for $t > t_{cn}$ equation (12) with $a_1 = b_1 = 0$ is valid, and remain such until the hole concentration in the i-region also reaches zero in at $t = t_{cp}$. After this moment the only current component is the displacement current.

The characteristic times t_{cn} and t_{cp} are defined by the relations

$$\begin{aligned} \int\limits_{0}^{t_{cn}} V(t)dt &= \frac{d}{a_1} \\ \int\limits_{t_{cn}}^{t_{cp}} V(t)dt &= d\frac{a_1 - a_2}{a_1 a_2} \end{aligned} \tag{13}$$

To recast the integro-differential equation (12) into a differential equation, we neglect all the fast changes, i.e. the higher order derivatives of $U(t)$, because they essentially do not increase the response time, but just influence the signal shape. Having in mind the physics of the process, the p-i-n photodiode voltage is defined by the following equations:

$$U(t) = V(t) + V_D$$

$$\begin{aligned} &0^+ \leq t \leq t_{cn}, \quad \frac{dV(t)}{dt} + \frac{1}{\tau}\frac{V^2(t)(CV(t) - (V_{CC} - V_D))}{V^2(t) + \frac{(V_{CC} - V_D)Z}{\tau}} = 0 \\ &t_{cn} \leq t \leq t_{cp}, \quad \frac{dV(t)}{dt} + \frac{1}{\tau}\frac{V^2(t)(C_1 V(t) - (V_{CC} - V_D))}{V^2(t) + \frac{(V_{CC} - V_D)Q}{\tau}} = 0 \\ &t_{cp} \leq t < +\infty, \quad \frac{dV(t)}{dt} + \frac{1}{\tau}V(t) - \frac{1}{\tau}(V_{CC} - V_D) = 0 \end{aligned} \tag{14}$$

where: $C = 1 + Aa_1 - Aa_2 e^{-\alpha d}$, $A = \dfrac{Re\lambda W}{hcd}\left(I = \dfrac{W}{\frac{hc}{\lambda}S}\right)$, $\tau = \dfrac{R\varepsilon S}{d}$, $Z = \dfrac{a_1^2 + a_2^2}{\alpha a_1 a_2 (a_1 - a_2)}$, $Q = \dfrac{1}{\alpha a_2}$, $C_1 = C(a_1 = 0)$, λ is the wavelength of the incident radiation and W the energy of the incident radiation.

By solving equation (14) we obtain expressions determining the voltage $U(t)$ in the whole time interval $t \geq 0^+$:

$$U(t) = V(t) + V_D$$

$$0^+ \leq t \leq t_{cn} \ ,$$

$$Y ln \left| \frac{V(t) - \frac{X}{Z}}{V(0+) - \frac{X}{Z}} \right| - X ln \left| \frac{V(t)}{V(0+)} \right| + Z \left(\frac{1}{V(t)} - \frac{1}{V(0+)} \right) = -t$$

$$t_{cn} \leq t \leq t_{cp} \ , \tag{15}$$

$$Y_1 ln \left| \frac{V(t) - \frac{X_1}{Q}}{V(t_{cn}) - \frac{X_1}{Q}} \right| - X_1 ln \left| \frac{V(t)}{V(t_{cn})} \right| + Q \left(\frac{1}{V(t)} - \frac{1}{V(t_{cn})} \right) =$$
$$= -(t - t_{cn})$$

$$t_{cp} \leq t < +\infty \ ,$$

$$V(t) = (V_{CC} - V_D) + (-(V_{CC} - V_D) + V(t_{cp}))e^{-\frac{t - t_{cp}}{\tau}}$$

where $X = \frac{C}{V_{CC} - V_D} Z$, $X_1 = \frac{C_1}{V_{CC} - V_D} Q$, $Y = \frac{\tau}{C} + X$, $Y_1 = \frac{\tau}{C_1} + X_1$ and

$$V(0^+) = \frac{V_{CC} - V_D}{1 + A(a_1 + a_2)(1 - e^{-\alpha d})} \tag{16}$$

while $V(t_{cn})$ is defined by the second equation in (15).
The set of expressions (15) gives the time behavior of the photodiode voltage for the case of the pulsed optical stimulation. The characteristic times defined by equation (13) are obtained by numerical integration.

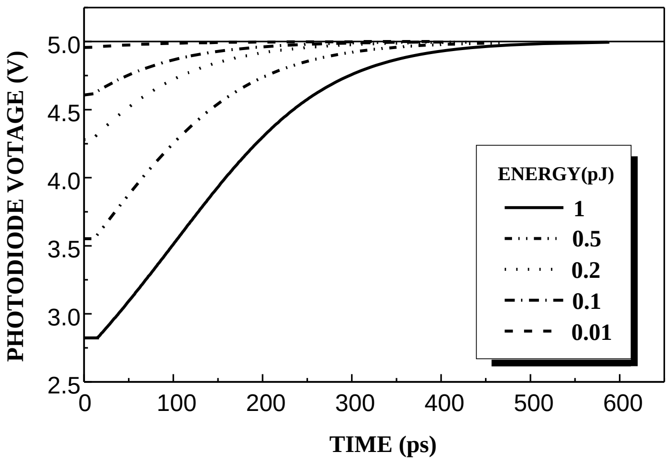

Fig. 3. Time dependence of p-i-n photodiode voltage.

Values of t_{cn} and t_{cp} found that way enable us to estimate the response time of the p-i-n photodetector. Taking that the response time is proportional to the time in which all carriers leave the depletion region [7], the response time is essentially determined by the holes characteristic time t_{cp}.

4. Results and Discussion

The shape of the p-i-n photodetector voltage for the case of the pulsed optical stimulation is shown in Fig.3 for several values of the incident radiation energy(W). The calculation was performed for the photodiode with parameters given in Table 1. Fig. 3 and 4 show the time dependence of p-i-n photodiode voltage and the dependence of the response time on incident radiation energy, respectively.

After pulsed excitation a sudden drop of the photodiode voltage occurs (Fig. 3), causing a decrease of the electric field in the depletion region, and hence a decrease of the charge carriers velocity. Therefore the carriers remain in the depletion zone for a longer time, thus increasing the photodiode response time (Fig. 4). This increase will be more prominent for larger voltage drops, caused by larger photocurrents. We note that the p-i-n photodiode voltage does not drop much only at vary low radiation energies($W \leq 0.01pJ$), and only then can

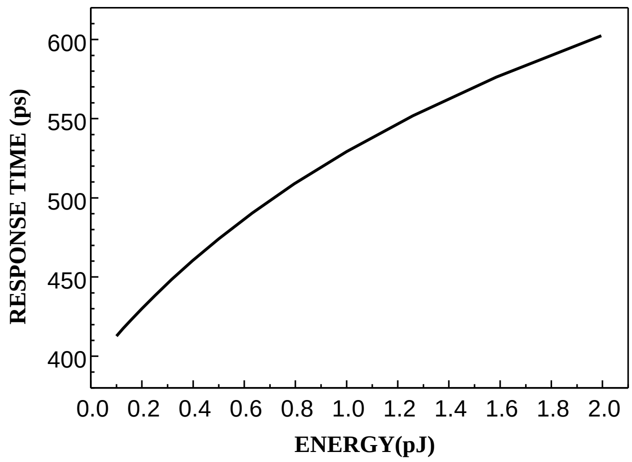

Fig. 4. The dependence of p-i-n photodiode response time on optical pulse energy.

α	=	$10^4 cm^{-1}$	λ	=	$0.8\mu m$
d	=	$5\mu m$	S	=	$700\mu m^2$
μ_n	=	$7500\frac{cm^2}{Vs}$	μ_p	=	$420\frac{cm^2}{Vs}$
R	=	50Ω	ε_r	=	12
V_D	=	$0.6V$	V_{cc}	=	$5V$

Table 1. Parameters of the p-i-n photodiode considered.

one take that the voltage is practically constant.

5. Conclusion

The nonlinearity of p-i-n photodiodes response caused by the photodiode voltage change, was analyzed and found to be more pronounced as the incident radiation energy increases. It is manifested in increasing of the response time, because the load resistance R influences it not only via the RC constant, but also via the nonlinearity itself. The presented model for calculation of the photodiode voltage time behaviour and the photodiode response time, for the case of the pulse excitation, is practically an instrument for optimization of p-i-n photodiode performance. It enables one to determine the energy range in which the photodetector response speed is high.

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