Frequency-Domain-Based Carrier Transport Model for a Lateral p-i-n photodiode

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1. Introduction

Recently, optical interconnection has been studied with intense vigor to achieve fast switching operation in ULSI [1]. In order to design optoelectronic integrated circuits (OEICs), models describing the electronic and optical characteristics of optoelectronic devices for circuit simulation are necessary. We focus on a p-i-n photodiode as an optoelectronic device. Although the vertical photodiode has been studied by many authors [2], work on the lateral type as shown in Fig. 1(a) is still missing. In this paper, we present a formulation of carrier transport in a lateral p-i-n photodiode and develop a model applicable for circuit simulation of OEICs. Computational accuracy of the model is comparable with the 2-dimensional device simulator MEDICI [3]. Since the model equations are solved in the frequency domain, it is applicable for harmonic balance simulation [4].

2. Lateral p-i-n Photodiode Structure and Formulation for Carrier Transport

We consider a simplified structure of a lateral p-i-n photodiode shown in Fig. 1(b). In the case of the lateral p-i-n photodiode, the direction of electric field, which is along the x axis, is orthogonal to the traveling direction of the incident light, which is along the y axis. We adopt the following assumptions in formulating the device equations:

(i) homogeneous irradiation only on the i-region,
(ii) deep n^+- and p^+-region compared to the incident light penetration depth,
(iii) constant electric field $\boldsymbol{E} = (E_x, E_y) = (E_0, 0)$ in the i-region,
(iv) negligible change of electric field $E0$ due to the incident pulse.

The first assumption allows us to focus only on the i-region. The second assumption is introduced to realize homogeneous electric field in the i-region. This is important to achieve high-speed operation of the lateral p-i-n photodiode, because the transport of carriers is governed by the electric field existing in the region. The third assumption is validated under the second assumption and under moderately high reverse applied bias. Since under normal operating condition, the light intensity is below the level where the output current shape is distorted by screening effect associated with high illumination, the last assumption is also justified.

The equations governing the transient carrier transport is given by

$$\frac{\partial n(x,y,t)}{\partial t} - \frac{1}{q}\frac{\partial J_{x,n}(x,y,t)}{\partial t} = G_n(x,y,t),$$

$$\frac{\partial p(x,y,t)}{\partial t} - \frac{1}{q}\frac{\partial J_{x,p}(x,y,t)}{\partial t} = G_p(x,y,t),$$

where n and p are the carrier number density of electrons and holes, q is the elementary charge, $J_{x,n}$ and $J_{x,p}$ are the x components of current density vectors for electrons and holes, and G_n and G_p are the generation rate of carriers. Here we neglected recombination terms, because photogenerated carriers quickly evacuate to the n^+ or p^+ region by the high electric field. The current density is described dominantly by the drift component

$$J_{x,n}(x,y,t) = q\mu_n n(x,y,t)E_0,$$
$$J_{x,p}(x,y,t) = q\mu_p p(x,y,t)E_0,$$

where μ_n and μ_p are the mobility of electrons and holes, respectively. Furthermore, the generation rate of carriers is written as

$$G_{n,p}(x,y,t) = \alpha e^{-\alpha y}\phi(t),$$

where α is the absorption coefficient, and ϕ is the effective photon flux. The shape of the input incident light determines the functional form of $\phi(t)$.

We focus on the non-stationary description of carrier transport in the p-i-n photodiode. For this purpose, we expand time dependent variables via Fourier expansion as

$$f(x,y,t) = \sum_i f_{\omega_i}(x,y)e^{-i\omega_i t},$$

where f denotes n, p, ϕ, $J_{x,n}$ or $J_{x,p}$. Under the boundary condition

$$n_{\omega_i}(0,y) = 0, \quad p_{\omega_i}(L,y) = 0,$$

we can obtain the solution for current as

$$I = q\mu E_0 W \sum_{\omega_i}\left[\frac{i}{\omega_i}\left(1 - e^{-i\frac{\omega_i}{\mu E_0}L}\right)\right]\phi_{\omega_i}e^{-i\omega_i t},$$

where W is the device width.

3. Modeling Results and Discussion

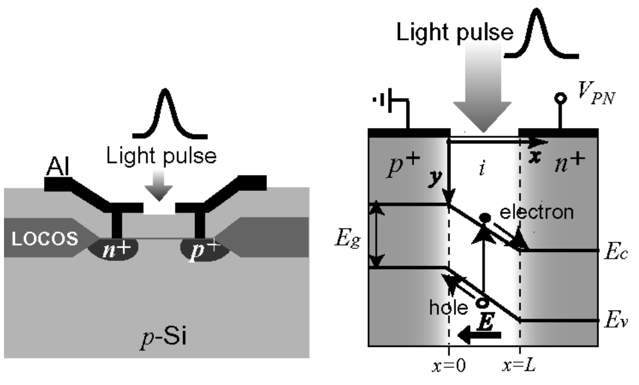
To demonstrate the photodiode transient response using the developed model, we consider a sinusoidal input with a single frequency and constant optical amplitude ϕ_0. In our calculations, $L = 2\mu$m and $V_{PN} = 5$V. The output photocurrent is given by the real part of I_ω. For an input of 1GHz, the photocurrent response exhibits no transit delay as shown in Fig.2. At 10GHz, which is in the device cut-off region, the photocurrent shows phase shift and reduced amplitude as shown in Fig.2. Both are due to the fact that carriers can no longer respond to very fast switching input.

The ω-dependence of Re[I_ω] for fixed ϕ_0 exhibits the frequency response characteristics of the photodiode. The cut-off frequency f_T is derived from the value of Re[I_ω] / Re [I_ω=0] at −3dB. Using the developed model, two methods for enhancing the frequency response are recognized. One method is by increasing the applied bias, which increases f_T as shown in Fig.3(a). The next is by reducing the i-region length L of the photodiode. Figure 3(b) shows increasing f_T as L is reduced for two different applied biases. Steep increase in f_T is observed for L below 1μm, in the ideal case. Similar results can be obtained for any light intensity lower than the critical value from which screening effect occurs.

Next, we validate the accuracy of our model with measured transient photocurrent of a fabricated Si lateral p-i-n photodiode. The device structure is shown in Fig.1(a) with i-region length L=2μm. For our calculation, we adopt the spectral method using the Fast Fourier Transform in obtaining the time-domain model response. The model correctly reproduces measured photocurrent response for a Gaussian light pulse (λ ~ 532nm) with ~ 100ps full width at half maximum and applied bias V_{PN} = 7V as shown in Fig.4(a). In this calculation, we used the same values of device dimension as those of the fabricated device. The difference in the end region can be attributed to carriers generated in the p^+ and/or n^+ region due to diffraction effects along the perimeter of the Al opening. Computational accuracy of the model as compared with MEDICI is shown in Fig.4(b).

4. Conclusion

We have developed an analytical model for carrier transport in a lateral p-i-n photodiode. The frequency response of the photodiode is enhanced by reducing the i-region length and applying higher reverse bias. The model achieves excellent reproduction of measured photocurrent down to ~ 100 ps pulse width input at high reverse bias. At low applied bias, the y-dependence of E_0 becomes significant and thus, should be included in the modeling to achieve more accurate results. The developed model is appropriate for circuit simulation of OEICs.



(a) (b)

Fig.1 (a) Fabricated lateral p-i-n photodiode. (b) Simplified Structure of a lateral p-i-n photodiode for a model.

References

[1] See e.g. L.C. Kimerling, Appl. Surf. Sci. **159-160**, 8 (2000).

[2] K. Konno, O. Matsushima, D. Navarro, and M. Miura-Mattausch, J. Appl. Phys. **96**, 3839 (2004) and references therein.

[3] MEDICI User's Manual, Synopsys (2003).

[4] K. S. Kundert and A. Sangiovanni-Vincentelli, IEEE Trans. CAD-**5**, 521 (1986).

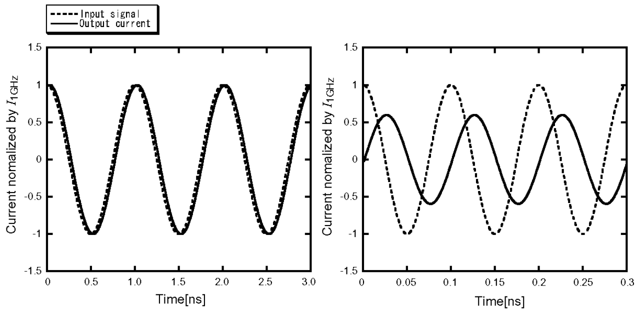
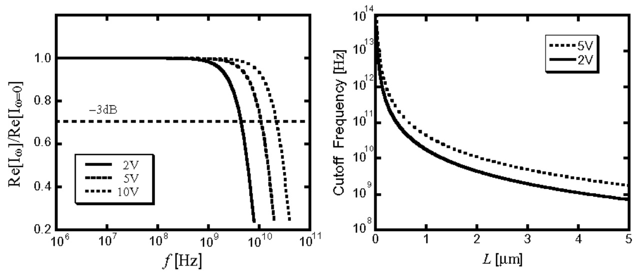


Fig.2 Photodiode response for (a) 1GHz and (b) 10GHz input.



(a) (b)

Fig.3 (a) Photoresponse as a function of ω. (b) Cutoff frequency as a function of L.

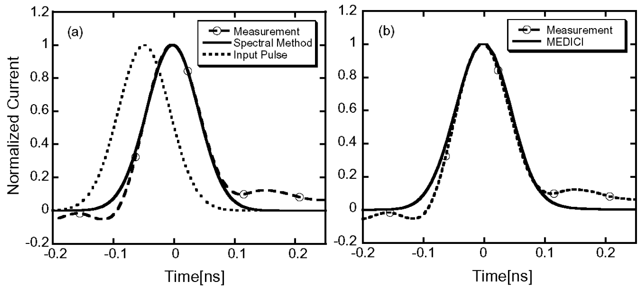


Fig.4 Normalized photocurrent calculated using the spectral method. (a) Calculated transit delay agrees with experimental result. (b) Computational accuracy is comparable with the two-dimensional device simulator MEDICI.

Frequency-Domain-Based Carrier Transport Model for P-I-N Photodiodes

—— Towards Circuit Simulation for Optoelectronic Integrated Circuits ——

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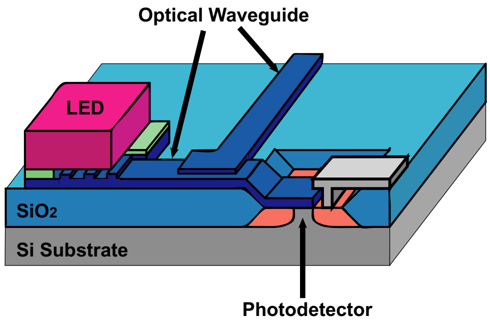
Background

"Interconnection Bottleneck"

Continuous shrinking of device dimensions brings about higher device cut-off frequency.

Signal propagation delay due to conventional interconnects overwhelms transistor gate delay and hinders fast switching operation.

Necessity of Optical Interconnection



Optoelectronic Integrated Circuit (OEIC)

Purpose

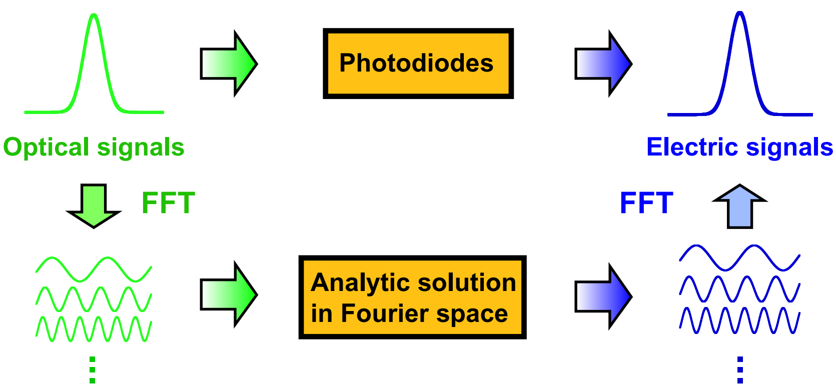
In order to fully utilize optical interconnects in circuits, models describing the optical and electronic characteristics of optoelectronic devices are necessary.

We present a frequency-domain-based formulation of carrier transport in p-i-n photodiodes, which are used as photodetectors in optical interconnects.

We aim at developing a photodiode model suitable for circuit simulation of OEICs.

Procedure for Time-Domain Simulation

1. **Expanding input optical signals into Fourier modes with single frequency ω_i by using Fast Fourier Transform (FFT).**
2. **Deriving the solution of output current for each mode labeled by ω_i .**
3. **Summing the Fourier modes of current to construct the final output current in real space.**



BASIC EQUATIONS FOR DESCRIBING CARRIER TRANSPORT

Continuity equation:

$$\frac{\partial n(t,x)}{\partial t} - \frac{1}{q}\nabla \cdot J_n(t,x) = G_n(t,x) - R_n(t,x)$$

$$\frac{\partial p(t,x)}{\partial t} + \frac{1}{q}\nabla \cdot J_p(t,x) = G_p(t,x) - R_p(t,x)$$

Current density equation:

$$J_n(t,x) = q\mu_n\left[n(t,x)\,E(t,x) + \frac{D_n}{\mu_n}\nabla n(t,x)\right]$$

$$J_p(t,x) = q\mu_p\left[p(t,x)\,E(t,x) + \frac{D_p}{\mu_p}\nabla p(t,x)\right]$$

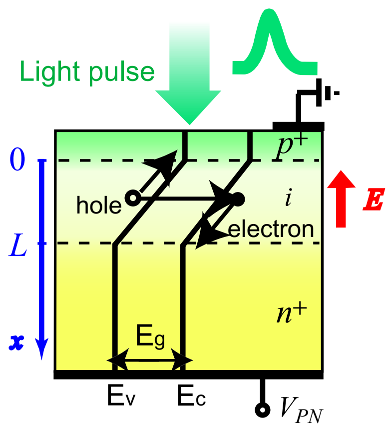
Equation for the electric field:

$$\nabla \cdot E(t,x) \cong \frac{q}{\varepsilon}\left[N_D^{+}(x) - N_A^{-}(x)\right]$$

VERTICAL P-I-N PHOTODIODE

Assumptions:

1. Homogeneity in all device parameters and in radiation intensity perpendicular to the light radiation
2. Constant electric field E_0 in the i-region
3. Negligible potential drop in the p^+ and n^+ region
4. Shallow p^+ region with respect to penetration depth
5. No change of the electric field due to the incident light pulse



Fourier Expansion Method

Generation rate:
$$G_{n,p}(x,t) = \alpha\,\phi(t)\,e^{-\alpha x} = \alpha\left(\sum_{\omega_i}\phi_{\omega_i}\,e^{-i\omega_i t}\right)e^{-\alpha x}$$

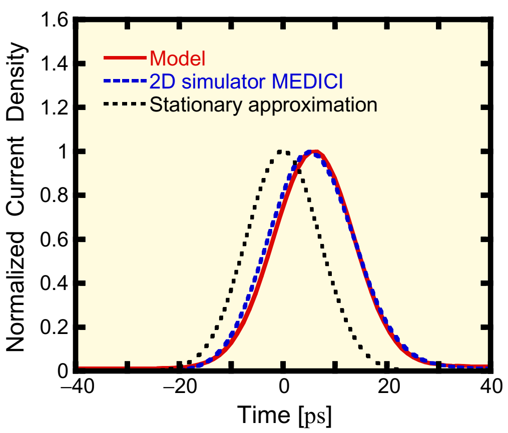
Recombination rate:
$$G_p(x,t) = \frac{p(x,t) - p_0}{\tau_p}$$

$$\left(n(x,t),\ p(x,t),\ J_n(x,t),\ J_p(x,t)\right) = \sum_{\omega_i}\left(n_{\omega_i}(x),\ p_{\omega_i}(x),\ J_{n,\omega_i}(x),\ J_{n,\omega_i}(x)\right)e^{-i\omega_i t}$$

Solution:

$$J_{\text{total}}(L,t) = \sum_{\omega_i}\left[\frac{q\alpha\mu_n E_0}{\alpha\mu_n E_0 - i\omega_i}\left(e^{-\alpha L} - e^{-i\omega_i L/\mu_n E_0}\right) - \frac{q\alpha L_p}{(1 - i\omega_i\tau_p)^{1/2} + \alpha L_p}\,e^{-\alpha L}\right]\phi_{\omega_i}\,e^{-i\omega_i t}$$

Current Simulation



This figure shows the photocurrent using our model as compared with those obtained by a conventional 2D device simulator MEDICI and by a stationary approximation:

$$J_{\text{total}}(L,t) = -q\left(1 - \frac{e^{-\alpha L}}{1 + \alpha L_p}\right)\phi_0(t).$$

[See S. M. Sze (1981)]

Si vertical p-i-n photodiode

depth of p^+ and i-region: $0.1\ \mu\text{m},\ 1.0\ \mu\text{m}$

impurity concentration in p^+,n^+ and i-region: $\sim 10^{20}\text{cm}^{-3},\ \sim 10^{20}\text{cm}^{-3},\ \sim 10^{15}\text{cm}^{-3}$

Gaussian light pulse

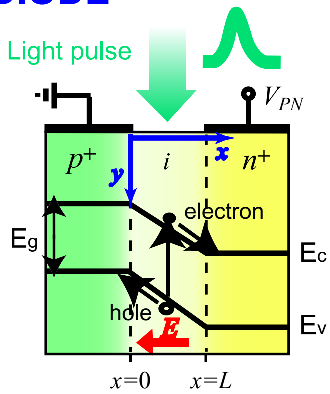
width: $\sigma \sim 10\text{ps}$

wavelength: $\lambda \sim 532\text{nm}$

Lateral P-I-N Photodiode

Assumptions:

1. Homogeneous irradiation only for i-region
2. Deep p^+ and n^+ region with respect to penetration depth
3. Constant electric field E_{x0} in the x-direction of the i-region
4. No change of the electric field due to the incident light pulse

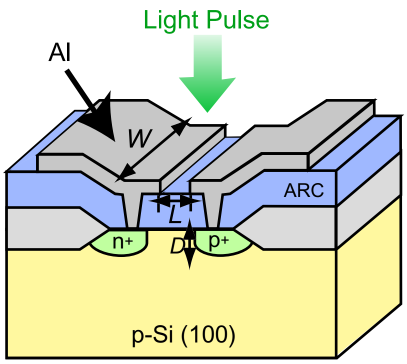


Fourier Expansion Method

Solution:

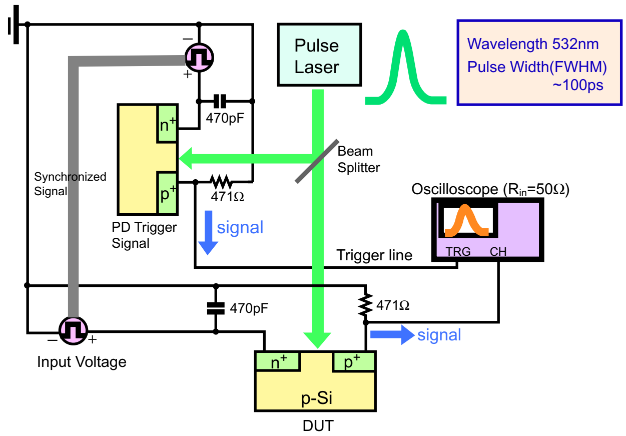
$$I_n(L) = \int_0^W dz \int_0^\infty Jn(x,y,t)dy = \sum_\omega \left[\frac{i}{\omega}\left(1 - e^{-i\omega L/\mu_n E_{x0}}\right)\right] q\,\mu_n E_{x0} W\,\phi_\omega\, e^{-i\omega t}$$

Fabricated Device and Measurement

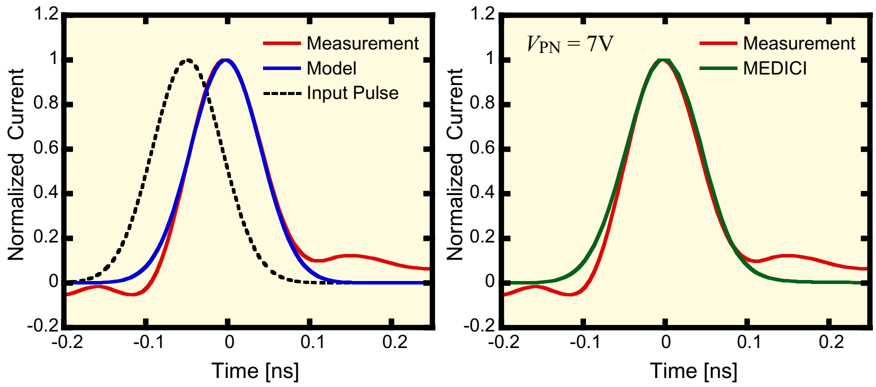


$L = 2\mu m$, $D = 0.5\mu m$

$p^+ \sim 10^{20}cm^{-3}$, $n^+ \sim 10^{20}cm^{-3}$, substrate $\sim 10^{15}cm^{-3}$



Current Simulation



This figure shows the photocurrent using our model as compared with those obtained by a conventional 2D device simulator MEDICI and by a stationary approximation:

$$J_{total}(L,t) = q\,L\,W\,\phi_0(t).$$

Summary

Analytic solution of p-i-n photodiode current in Fourier space has been derived.

Simulation using spectral method has been successfully performed to construct photocurrent in spite of a significant reduction in calculation time.

Our model is applicable to circuit simulation of OEICs.