Towards Current-Characteristic Simulation of p-i-n Photodiodes based on Spectral Method

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1 Introduction

Associated with the continuous shrinking of device dimension is the interconnection bottleneck. Interconnection propagation delay overwhelms transistor gate delay and thus, impedes fast switching operation [1]. In metal interconnection, high speed operation can be achieved by adopting a large cross-section of metal interconnects. However, this hinders high integration. Under such a situation, optical interconnection becomes an attractive option which involves light emitting devices and photodetectors. In order to integrate optical interconnects in circuits, models describing the electronic characteristics of the photodetectors for circuit simulation become a necessity.

In this paper, we present a formulation of the current characteristics of p-i-n photodiodes using the spectral method. Analytic solution in Fourier space, which is used for the calculation of photocurrent, has been developed. Additionally, we take into account the diffusion effect, which has been conventionally neglected in non-stationary states [2]. In spite of the significant reduction in calculation time, our calculation results are comparable to those of a 2D device simulator.

2 Procedure of simulation based on spectral method

We aim to develop an analytical description of the full non-stationary response of the photodiodes. For this purpose, we adopt the spectral method, which is composed of the following procedure:

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.

In the next section, we give analytical expressions of the output current for the solution in Fourier space, relating to the 2nd step.

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3 Formulation of device equations using the Fourier expansion

The carrier transport inside the devices is governed by the system of equations composed of the continuity equation

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

$$\frac{\partial p(\boldsymbol{x},t)}{\partial t} + \frac{1}{q}\nabla\cdot\boldsymbol{J}_p(\boldsymbol{x},t) = G_p(\boldsymbol{x},t) - R_p(\boldsymbol{x},t), \quad (2)$$

the current density equation

$$\boldsymbol{J}_n(\boldsymbol{x},t) = q\mu_n\left[n(\boldsymbol{x},t)\boldsymbol{E}(\boldsymbol{x},t) + \frac{D_n}{\mu_n}\nabla n(\boldsymbol{x},t)\right], \quad (3)$$

$$\boldsymbol{J}_p(\boldsymbol{x},t) = q\mu_p\left[p(\boldsymbol{x},t)\boldsymbol{E}(\boldsymbol{x},t) - \frac{D_p}{\mu_p}\nabla p(\boldsymbol{x},t)\right], \quad (4)$$

and the equation for the electric field

$$\nabla\cdot\boldsymbol{E}(\boldsymbol{x},t) = \frac{q}{\varepsilon_s}\left[p(\boldsymbol{x},t) - n(\boldsymbol{x},t) + N_D^+(\boldsymbol{x}) - N_A^-(\boldsymbol{x})\right]. \quad (5)$$

In this investigation, we assume low illumination intensity, under which we can neglect the perturbation of the electric field [3], that is,

$$\nabla\cdot\boldsymbol{E}_0(\boldsymbol{x}) \simeq \frac{q}{\varepsilon_s}\left[N_D^+(\boldsymbol{x}) - N_A^-(\boldsymbol{x})\right]. \quad (6)$$

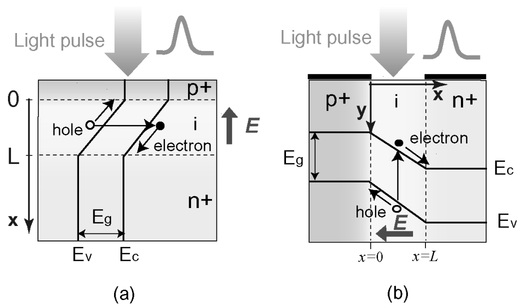

Figure 1: Structures of (a) a vertical p-i-n photodiode and (b) a lateral p-i-n photodiode.

3.1 The vertical p-i-n photodiode

The studied device structure is shown in Fig. 1(a). We now adopt the following assumptions:

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

From the first assumption, we can restrict our discussion to one dimension denoted by x. The last one is described by Eq. (6).

When we expand the current density J at $x = L$ (see Fig. 1(a)) as

$$J(L,t) = \sum_i J_{\omega_i} e^{-i\omega_i t}, \tag{7}$$

we can obtain the solution for J_{ω_i}, from Eqs. (1), (2), (3) and (4) and the above-mentioned assumptions, as

$$J_{\omega_i} = \left[\frac{q\alpha\mu_n E_0}{\alpha\mu_n E_0 - i\omega_i} \left(e^{-\alpha L} - e^{-\frac{i\omega_i}{\mu_n E_0}L} \right) - \frac{q\alpha L_p}{\sqrt{1 - i\omega_i\tau_p} + \alpha L_p} e^{-\alpha L} \right] \phi_{\omega_i}, \tag{8}$$

where α is the absorption coefficient, L is the length of i-region, $L_p = \sqrt{D_p\tau_p}$ (τ_p: lifetime of holes in the n-region), and ϕ_{ω_i} is the Fourier component of photon flux $\phi(t)$, namely, $\phi(t) = \sum_i \phi_{\omega_i} e^{-i\omega_i t}$. The first term and second term in this equation correspond to the drift and the diffusion components, respectively. The detailed derivation of this equation is given in Ref. [4].

3.2 The lateral p-i-n photodiode

Here, we consider a lateral p-i-n photodiode shown in Fig. 1(b). We adopt the following assumptions:

1. Homogeneous irradiation only for the i-region,
2. Homogeneous impurity profile in each region,
3. Constant electric field E_{x0} in the x direction of the i-region,
4. Deep n^+- and p^+-region with respect to penetration depth.

In a similar way as the case of the vertical p-i-n photodiode, under the above assumptions, we can obtain the x-component of the current density J^x at $x = L$ as [4]

$$J^x(L,y,t) = \sum_i J^x_{\omega_i}(L,y) e^{-i\omega_i t}, \tag{9}$$

where

$$J^x_{\omega_i}(L,y) = q\mu_n E_{x0} \frac{\alpha}{\omega_i} e^{-\alpha y} i \left(1 - e^{-i\frac{\omega_i}{\mu_n E_{x0}}L} \right) \phi_{\omega_i}. \tag{10}$$

Therefore, the current at $x = L$ is given by

$$\begin{aligned} I^x_n(L) &= W \int_0^\infty J^x_n(x,y,t) dy \\ &= q\mu_n E_{x0} W \\ &\times \sum_{\omega_i} \left[\frac{i}{\omega_i} \left(1 - e^{-i\frac{\omega_i}{\mu_n E_{x0}}L} \right) \right] \phi_{\omega_i} e^{-i\omega_i t}, \end{aligned} \tag{11}$$

where W is the depth in the direction perpendicular to the xy-plane.

4 Simulation results

Fig. 2 shows the photocurrent result using our model in the case of the vertical p-i-n photodiode as compared with those obtained by a conventional 2D device simulator MEDICI and by a stationary approximation [5]. The full non-stationary feature is well depicted as a tail.

5 Summary

We have derived the analytical device equations for p-i-n photodiodes in Fourier space. By spectral method, the current characteristics calculated by the model are comparable to 2D device simulation results without significant increase in computation time. This realizes the necessity of having photodiode models for circuit-simulation purposes.

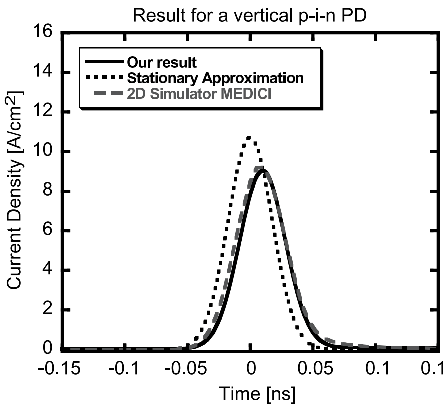

Figure 2: Photocurrent of the vertical p-i-n photodiode.

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