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

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Background

"Interconnection Bottleneck"

Due to the continuous shrinking of device dimension, interconnection propagation delay overwhelms transistor gate delay and thus, impedes fast switching operation.

Necessity of Optical Interconnection

Purpose

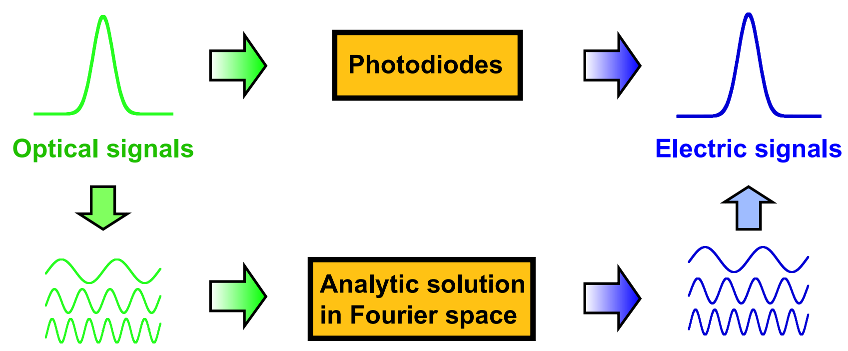
In order to investigate optical interconnection in circuits, models describing the electronic characteristics of photodiodes, which is essential for the optical interconnection, become a necessity for circuit simulation.

We present a formulation of the current characteristics of *p-i-n* photodiodes using Fourier expansion.

We develop a simulation tool based on spectral method.

Procedure of simulation based on spectral method

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

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:

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

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

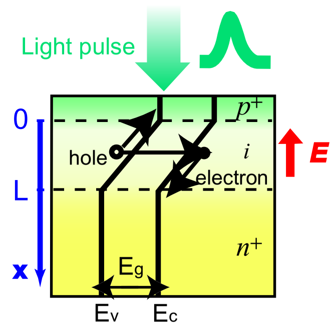
Equation for the electric field:

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

Vertical *p-i-n* photodiode

Assumptions:

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



Fourier expansion

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

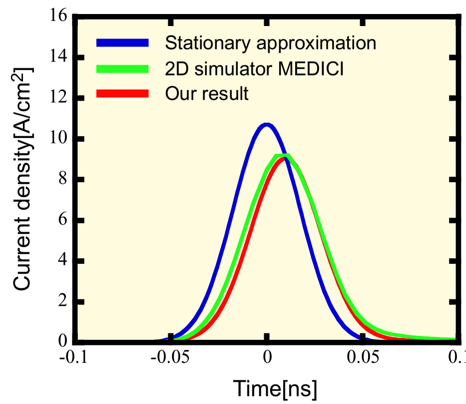
Recombination rate: $G_p(x,t) = \dfrac{p(x,t) - p_0}{\tau_p}$

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

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: $\sigma \sim 25\text{ps}$

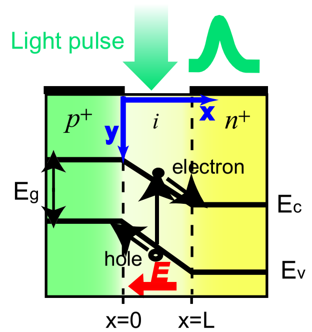
peak intensity: $I_{\text{peak}} \sim 25\text{W/cm}^2$

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

Lateral *p-i-n* photodiode

Assumptions:

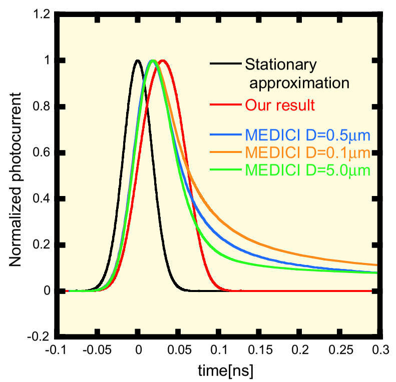
1. Homogeneous irradiation only for *i*-region
2. Homogeneous impurity profile in each region
3. Constant electric field E_{x0} in the x-direction of the *i*-region
4. Deep p^+ and n^+ region with respect to penetration depth



Fourier expansion

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

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:

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

Si lateral *p-i-n* photodiode

length of *i*-region: 4.0μm

depth of p^+ and n^+-region: D (only for MEDICI)

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

Gaussian light pulse

width: $\sigma \sim 25\mathrm{ps}$

peak intensity: $I_{peak} \sim 25\mathrm{W/cm}^2$

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

The delay of the pulse is reproduced, but the tail part cannot be described by our model.

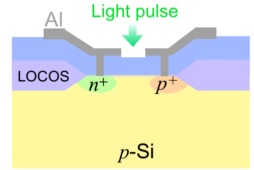
Summary

Taking into account the diffusion effect, which has been conventionally neglected in non-stationary state formulation, analytic solution of *p-i-n* photodiode current in Fourier space has been developed.

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

Future works

1. Extension to higher illumination cases.
2. Comparison with experimental data.
3. Modeling more realistic carrier transport feature in the deep substrate for the lateral *p-i-n* photodiode.



fabricated lateral *p-i-n* PD