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 $\omega_i$ by using Fast Fourier Transform (FFT).
2. Deriving the solution of output current for each mode labeled by $\omega_i$.
3. Summing the Fourier modes of current to construct the final output current in real space.
### Basic equations

**Continuity equation:**
\[
\frac{\partial n(t,x)}{\partial t} + \frac{1}{q} \nabla \cdot J_n(t,x) = G_n(t,x) - R_n(t,x)
\]

**Current density equation:**
\[
J_n(t,x) = q \mu_n [n(t,x) E(t,x) + \frac{P_n}{\mu_n} \nabla n(t,x)]
\]

**Equation for the electric field:**
\[
\nabla \cdot E(t,x) \equiv \frac{q}{\varepsilon} [N_n^0(x) - N_i^0(x)]
\]

### 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:**
\[
G_{n,p}(t,x) = \alpha \phi(t) e^{-\alpha t} = \alpha \left( \sum_{\omega} \phi_{\omega} e^{-i \omega t} \right) e^{-\alpha t}
\]

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

**Solution:**
\[
J_{\text{total}}(L,t) = \sum_{\omega} \left[ \frac{q \alpha \mu_p E_0}{\omega q \mu_p E_0 - i \omega} \left( e^{-\alpha L} - e^{-i \omega L} \right) \phi_{\omega} \right] e^{-i \omega t}
\]

### 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:
\[
J_{\text{total}}(L,t) = \frac{q}{1 + e^{-\alpha L}} \phi_0(t).
\]

Si vertical $p-i-n$ photodiode
- Depth of $p^+$ and $i$-region: 0.1 µm, 1.0 µm
- Impurity concentration in $p^+$ and $i$-region: $10^{20} \text{cm}^{-3}$, $10^{19} \text{cm}^{-3}$, $10^{19} \text{cm}^{-3}$
- Gaussian light pulse
  - Width: $\sigma \sim 25 \text{ps}$
  - Peak intensity: $I_{\text{peak}} \sim 25 \text{W/cm}^2$
  - Wavelength: $\lambda \sim 532 \text{nm}$

[See S. M. Sze (1981)]
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:**
$$L_0(L) = \int_0^W \int_0^L J_{n}(x,y,t)dy \ dx = \sum_n \left[ \frac{1}{L} \left( 1 - e^{-n0L/m_E} \right) \right] q \mu_n E_{x0} W \Phi_0 e^{-iwL}$$

**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:
$$J_{n0}(L,t) = q L W \Phi_0(t).$$

**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: ~ $10^{20}$cm$^{-3}$, ~ $10^{20}$cm$^{-3}$, ~ $10^{15}$cm$^{-3}$

**Gaussian light pulse**
- width: $\sigma$ ~ 25μm
- peak intensity: $I_{peak}$ ~ 25W/cm$^2$
- wavelength: $\lambda$ ~ 532nm

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](image_url)