Physics-Based Photodiode Model Enabling Consistent Opto-Electronic Circuit Simulation

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Abstract

We have developed a photodiode (PD) model for circuit simulation considering, contrary to existing models, the transient carrier generation explicitly in the solution of the continuity equation. The developed model is compatible with conventional compact electrical device models and is demonstrated to enable accurate simulation of opto-electronic integrated circuits. The electric field distribution along the depth direction of the PD is found to cause a tail in the photo current, which has an adverse effects on optical response of PD and the performance of opto-electronic circuits. The developed opto-electronic circuit model is also applicable to predict how circuit performance is improved with respect to the improvement of photo diode characteristics.

Introduction

Requirement for opto-electronic integrated circuit (OEIC) simulations is intensively increasing due to emerging applications such as camera-on-chip or optical interconnects [1,2]. Consequently, accurate circuit simulation models for opto-electronic (OE) devices are in urgent demand. In this paper, we present a newly-developed accurate physics based model of the p-i-n photodiode (PD), which is used as a photodetector and transforms optical signals into electrical ones. The model called HiSIM-PD includes the optically excited photo current and the PD device feature solved in time domain, and provides accurate and flexible OEIC simulation.

Photo Current Model of the Photodiode

Figure 1 (a) schematically shows the device structure of a lateral p-i-n PD and the energy band diagram along the p-i-n direction under reverse bias condition. The main subjects of the PD-model development are the carrier generation process due to photo excitation and the carrier flows across the p-i-n structure. Modeling of the photocurrent response begins with the current continuity equations for electrons and holes expressed as

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

$$\frac{\partial p(x,y,t)}{\partial t} - \frac{1}{q}\frac{\partial J_{x,\mathrm{p}}(x,y,t)}{\partial x} = G_\mathrm{p}(y,t) \qquad (2)$$

$$J_{x,\mathrm{n}} = q\mu_\mathrm{n}(E_x)E_x(y)n(x,y,t) \qquad (3)$$

$$J_{x,\mathrm{p}} = q\mu_\mathrm{p}(E_x)E_x(y)p(x,y,t) \qquad (4)$$

where n and p are the electron and hole concentrations, respectively. J_x is the current density along the p-i-n direction (the x direction), and G is the carrier generation rate. The subscripts n and p represent electron and hole, respectively. Since carrier generation in PDs is mainly caused by the photo excitation, generation rates of electrons and holes are assumed to be identical. The carrier generation rate at the distance y from the PD surface is represented as

$$G_\mathrm{n}(y,t) = G_\mathrm{p}(y,t) = \alpha \exp(-\alpha y)\phi(t) \qquad (5)$$

where α is the LASER attenuation coefficient, and ϕ is the photon flux. Note that a homogeneous electric field along the x direction is assumed, and only the depth (i.e. y) dependence of the electric field is considered. The assumption is not serious because of the sufficiently low carrier concentration in the intrinsic region compared to the doping densities in the p and n regions as shown in Fig. 1 (b). In order to solve Eqs. (1)-(5) analytically, we employed a coordinate transformation

$$\xi_\mathrm{n,p} = \frac{1}{2}\left(t + \frac{x}{v_\mathrm{n,p}}\right); \quad v_\mathrm{n} = -\mu_\mathrm{n}E_x \qquad (6)$$

$$\eta_\mathrm{n,p} = \frac{1}{2}\left(t - \frac{x}{v_\mathrm{n,p}}\right); \quad v_\mathrm{p} = \mu_\mathrm{p}E_x \qquad (7)$$

where μ_n and μ_p are the mobility of electron and hole, respectively. The final expression of the transient photo current I_PD is

$$I_\mathrm{PD}(t) = \alpha qW \int_0^\infty dy \int_{t-L/|v_{\mathrm{p}_y}|}^t dt' \, \mu_\mathrm{p}(E_x)\,|E_x(y)|$$
$$\times \exp(-\alpha y)\phi(t') \qquad (8)$$

where L is the length of the intrinsic region, and W is the device width. For the resulting PD model, α is the only model parameter describing the LASER attenuation coefficient (Eq. (5)), which is a material constant [3]. Therefore, the developed model is valid for any shape of the LASER input pulse.

For accurate circuit simulations, modeling of charges associated with each terminal is necessary, because SPICE-like circuit simulators require these charges for transient mode simulations. In the charge model, photo excited carriers are assumed to be negligible, because of the dominantly large depletion charge in the high doping p and n regions (Fig. 1 (b)). The 1-D Poisson equation is solved to
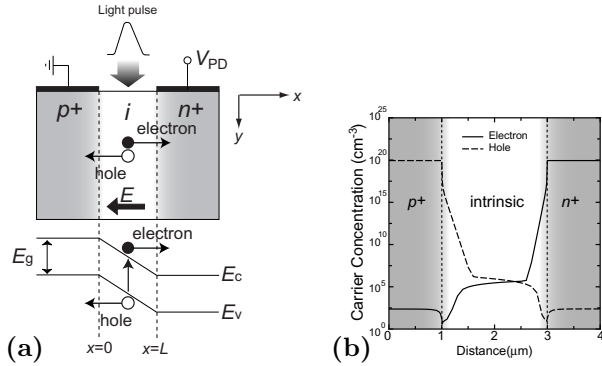
Figure 1: (a) Schematic illustration of a lateral *p-i-n* photodiode and the energy band diagram across the *p-i-n* structure under reverse bias condition. The electron-hole pair generation due to a light pulse and the carrier flows are also shown. (b) Carrier concentration across the *p-i-n* structure calculated by the 2-D device simulator during carrier generation.
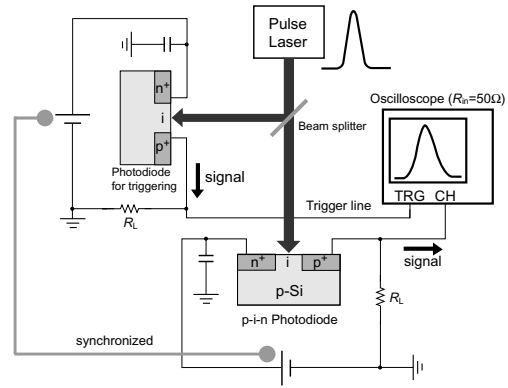

Figure 2: Measurement system for observing the photo current signal from a photodiode. The laser wavelength is 532nm and the full width of half maximum is about 10ps for the studied case. R_L is used for transforming current to voltage signals. The voltage signals are observed by an oscilloscope.

obtain the depletion charge in the p and n regions, which are assigned to the p and n terminals, respectively.

The measurement shown schematically in Fig. 2 was performed to verify the developed model. Measurement results of the photo current I_{PD} for a Gaussian LASER pulse with 532nm wavelength are successfully reproduced as shown in Fig. 3. Here the lateral field, E_x, distribution in depth is modeled by the Gaussian function as

$$E_x(y) = E_0 \exp\left(-\frac{y^2}{D^2}\right) \qquad (9)$$

where D is the attenuation length. A homogeneous electric field in depth direction, on the other hand, fails to capture the signal tail of the I_{PD} as also verified in Fig. 3. Figure 4 shows the simulated induced I_{PD} with a box shaped incident LASER pulse, to extract the essence of the field-distribution related effects and to separate them from effects related to the shape of the LASER pulse. The simulation result with the homogeneous field distribution in depth direction is also depicted for comparison and shows no current tail at all. Consequently, neglecting the field distribution in depth direction results in the serious problem of a neglection of the current tail, which is unavoidable in the LASER excitation of the PD.

Application to Circuit Simulation

The transient photo current determines the transient response of an OEIC. There are two ways how to implement the PD model into SPICE for enabling OEIC simulation. Figure 5 (a) depicts the complete PD model, which solves the transient PD response in conjunction with the complete PD device model involving the junction capacitance model. This complete simulation model is called HiSIM-PD. Fig. 5 (b) shows a simpler case, treating the photo current model of the PD as a current source, which is fitted to the measured current waveform [4].
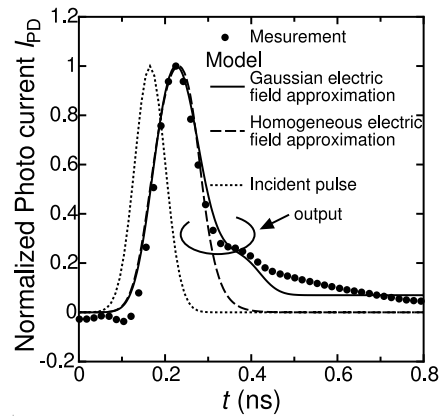
Simulation with HiSIM-PD is performed first to ver-

Figure 3: Comparison of photo currents obtained by measurement (solid circles) and simulation (solid and broken lines) for the LASER incident pulse (dotted line) with a Gaussian intensity distribution.

ify the simulated I_{PD} of the basic test circuit shown in Fig. 6, where V_{PD} is the applied DC bias inducing the field E (see Fig. 1 (a)) for collecting the generated carriers. Figure 7 compares simulation results, where the resistance R_L, used for transforming the I_{PD} into a voltage, is 500Ω and 250Ω. The difference between the two different R_L cases is obvious. HiSIM-PD considers the I_{PD} modification due to the induced current flow in the PD. On the other hand, the simple implementation treats the I_{PD} as a phenomenological current source, which is independent of the internal current flow in the PD. Thus the simpler current-source model shows no R_L dependence of I_{PD} (see Fig. 7 (b)) and an enhanced magnitude of V_{out} results, which even exceeds the applied bias V_{PD} of 2V (see Fig. 7 (e)). 2D-device simulation results are depicted for comparison (see Fig. 7 (c,f)) and verify that
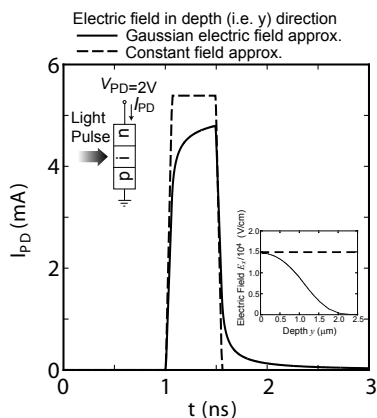
Figure 4: Photo currents I_{PD} calculated with the Gaussian (solid line) and homogeneous (dashed line) electric field approximations in depth (i.e. y) direction for a box-shaped intensity distribution of the LASER pulse. The solid line in the inset shows an electric field obtained by 2-D device simulator.
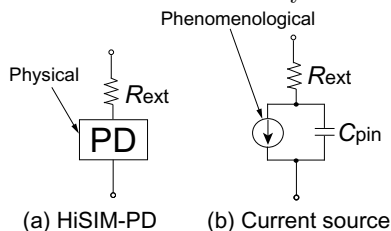

Figure 5: Two photodiode models for opto-electronic circuit simulation. R_{ext} is an external resistance. (a) Physical photodiode model HiSIM-PD according to Eqs. (1) to (8). (b) Phenomenological photodiode model, where measured photo currents are modeled by a current source [4]. The capacitive component of the p-i-n photo diode is approximated by the constant capacitance C_{pin}.

HiSIM-PD results are close to the 2D-device simulation (see Fig. 7 (a,d)). Since the simple current-source model fails to predict the R_L dependence of the I_{PD} accurately, the measurement shown in Fig. 2 would have to be performed for all individual R_L values to secure accurate simulation results. This is of course a very impractical requirement. Consequently, a complete implementation such as HiSIM-PD is prerequisite for accurate OEIC simulation and design.

The developed PD model enables us to analyze performance improvement of a photodiode itself, and to estimate performance improvement of OEICs as a result of optimization of opto-electronic characteristics of PDs, because HiSIM-PD is completely based on physics solving the continuity equation explicitly. Figure 8 shows that the delay of the photo current with respect to the incident light signal increases by increasing the intrinsic re-
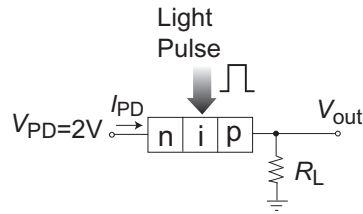

Figure 6: Basic circuit for studying opto-electronic circuit simulation with HiSIM-PD.

gion length, because of the carrier transit delay in the intrinsic region. Figure 9 (a) shows HiSIM results of the photo current response for various attenuation length D of the electric field distribution in Eq. (9). The tails of the photo currents become shorter with increase of the attenuation length, because the carriers in the intrinsic layer are quickly swept out by the larger lateral electric field even deep in the substrate. This behavior is also demonstrated by the 2-D device simulation shown in Fig. 9 (b), which assures model accuracy as well as applicability of HiSIM-PD to device optimization. Note that D can be controlled by the junction depth (Fig. 10). Thus the proposed optimization strategy is well applicable to the practical devices.

Figure 11 shows a simple OEIC with a PD and a single MOSFET in order to verify capability of HiSIM-PD for circuit performance optimization. Figures 12 (a)-(c) show the calculated MOSFET drain currents of the OEIC for different D values. For these calculations, continuous Gaussian light pulse series were injected into the PDs. With increasing the attenuation length D, the amplitudes of output current become large, and also time to achieve steady state become short. This is because the quicker photo current response with the larger D value as shown in Figs. 9 (a) and (b). For example, the current amplitude for $D = 2\mu m$ is more than twice as large as that of $D = 0.5\mu m$ case. Therefore HiSIM-PD successfully predicts not only photo diode performance improvement but also overall circuit performance gain.

Conclusion

The developed physics based photodiode model, called HiSIM-PD, solves the transient carrier generation together with the continuity equation, and captures important features of the photodiode by considering the electric-field distribution in the substrate. The model is applicable to estimate the OEICs performance gain with respect to the performance improvement of photo diodes. HiSIM-PD is a powerful tool for optimizing performance of both OEICs and photo diodes.

References

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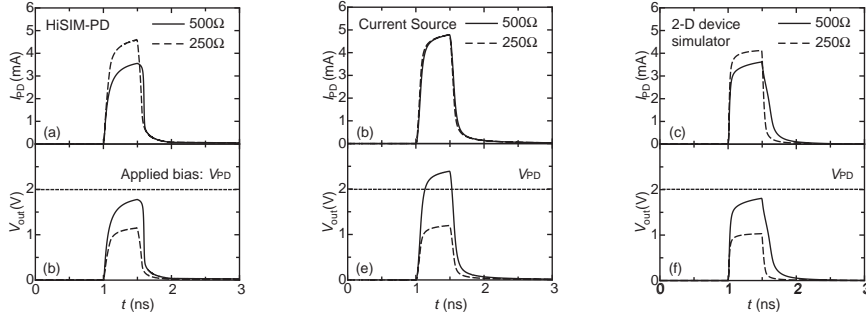[4] G. Suzuki *et al.*, Proc. SISPAD, pp. 107, 2005.

Figure 7: Simulation results of the photodiode currents (from (a) to (c)) and the output voltages (from (d) to (f)) for the test circuit of Fig. 6 as obtained for (a) & (d) HiSIM-PD, (b) & (e) current-source model, and (c) & (f) 2-D device simulator. The horizontal dotted lines indicate the bias voltages applied to the photodiode.
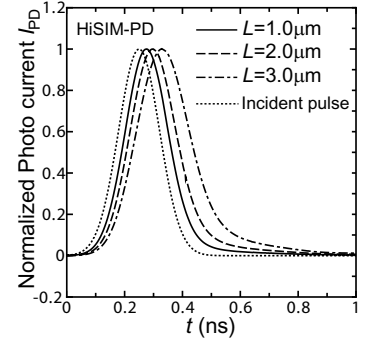
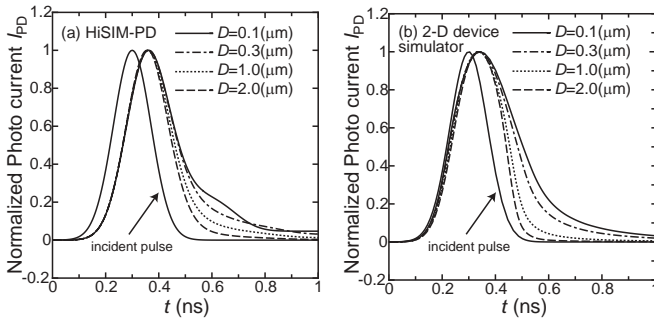Figure 8: Photo currents calculated by HiSIM-PD for different intrinsic layer lengths L.

Figure 9: Photo currents I_{PD} calculated by (a) HiSIM-PD and (b) the 2-D device simulator for various characteristic length values, D, of Gaussian electric field distribution.
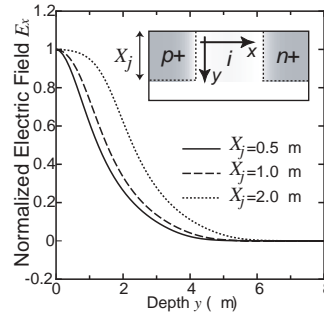
Figure 10: Lateral electric field distribution calculated by the 2-D device simulator as a function of depth y for various junction depths.
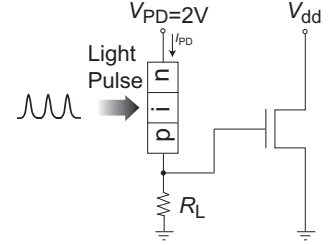
Figure 11: Typical circuit example for photo current amplification. The photo current pulse is converted by the resistance R_L to a voltage signal applied to the MOSFET gate.
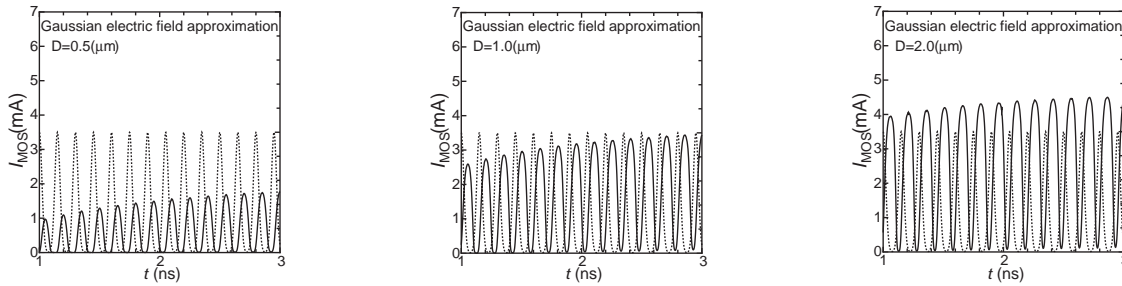

Figure 12: Drain currents (solid lines) of the MOSFET for a continuous sequence of input light pulses (dotted lines) simulated by HiSIM-PD for (a) $D = 0.5\mu$m, (b) $D = 1\mu$m and (c) $D = 2\mu$m.