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3D multiphysics transient modeling of vertical Ge-on-Si *pin* waveguide photodetectors

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***Abstract*—We report transient simulations of Ge-on-Si vertical *pin* waveguide photodetectors (WPDs), where the optical generation term used by the time-domain model is the FDTD solution of the electromagnetic problem treated as a spatially-distributed pulsed signal. This approach, validated against experimental measurements of the frequency response, paves the way to future studies of the dynamic response of WPDs, enabling the description of complex modulation schemes including saturation effects and current tails due to slow carriers.**

I. Introduction

Ge-on-Si waveguide photodetectors (WPDs) are mature, fundamental components in silicon photonics [1], [2]. State-of-the-art multiphysics WPD simulations provide static solutions to the transport problem [3], [4] and small-signal device analysis [5]. This work proposes a large-signal description of WPDs based on a time-domain multiphysics model. The present approach is demonstrated on the vertical *pin* WPD structure whose cross section is shown in Fig. 1, and is validated against both an electro-optic small-signal model and measurements at low input optical power performed by Cisco Systems. Table I reports the significant geometrical quantities of two devices under study, whose main difference is the lateral extension of the implanted region under the Ge contact, varying from $3\,\mu\text{m}$ of Device 1 to $3.5\,\mu\text{m}$ of Device 2.

II. Model

The workflow of the time-domain model is summarized in Fig. 2. The FDTD solution of the optical problem is used as a spatially-distributed time-dependent optical generation term in the transport problem. This approximation is valid since the

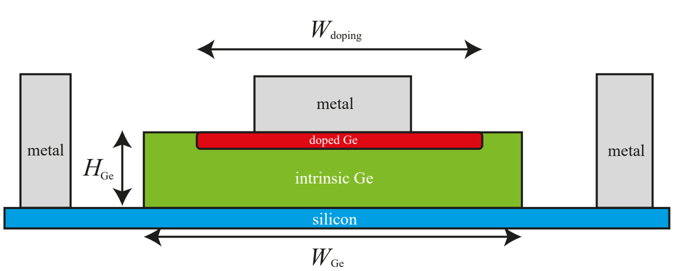

Fig. 1. 2D transverse cross section of the 3D photodetector geometry. The length of the devices is $15\,\mu\text{m}$.

TABLE I
WPD GEOMETRY.

	W_{Ge}	H_{Ge}	W_{doping}
Device 1	$4\,\mu m$	$0.8\,\mu m$	$3\,\mu m$
Device 2	$4\,\mu m$	$0.8\,\mu m$	$3.5\,\mu m$

propagation length of the light in the complete $15\,\mu\text{m}$-long WPD is in the order of $50\,\text{fs}$.

The time evolution of the solution of the transport problem is described through the continuity equations [6], [7]:

$$\nabla \cdot \vec{J}_n = q\left(R_n - G_n\right) + q\frac{\partial n}{\partial t}, \tag{1}$$

$$-\nabla \cdot \vec{J}_p = q\left(R_p - G_p\right) + q\frac{\partial p}{\partial t}, \tag{2}$$

where $\vec{J}_n$ and $\vec{J}_p$ are the electron and hole current densities, and R_n, R_p, G_n, G_p are the electron and hole recombination and generation rates, respectively.

The tool used for the simulation is Synopsys Sentaurus Device [8]. The time-integration scheme is based on the implicit discretization of the continuity equations (1)–(2) with a composite trapezoidal rule / backward differentiation formula (TR-BDF2) [9]–[11].

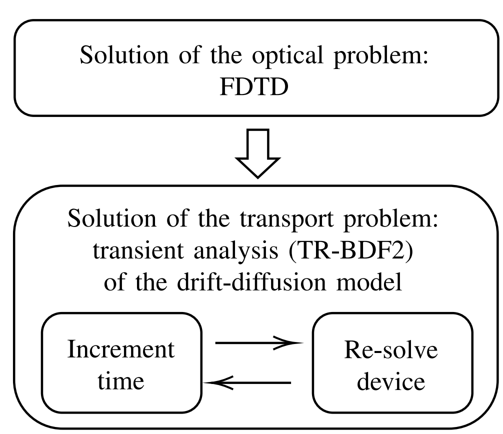

Fig. 2. Block diagram of the time simulation process. The solution of the electromagnetic problem is used as a spatially-distributed time-dependent optical generation rate in the transport problem.

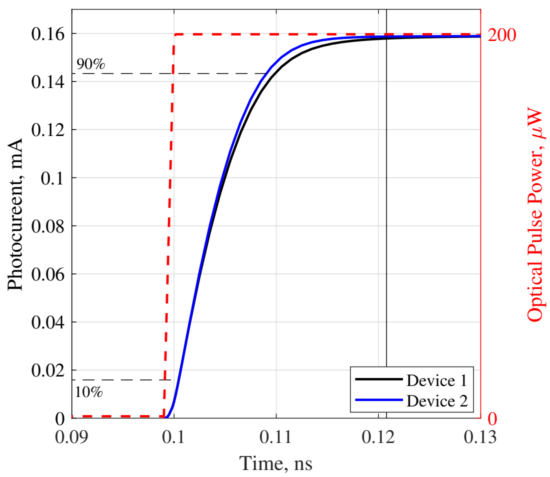

Fig. 3. Transient simulations performed with a reverse bias voltage of $-2\,\mathrm{V}$.

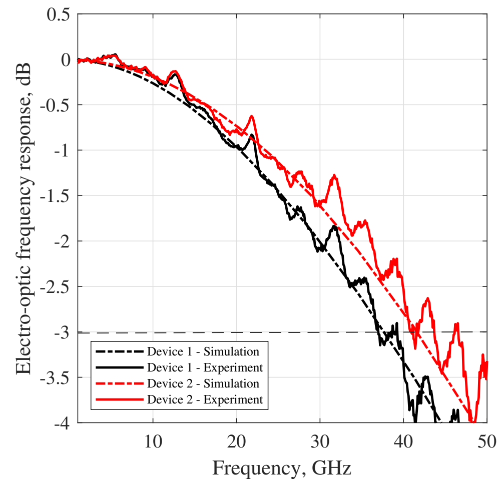

Fig. 4. Measurements and simulations of the electro-optic frequency response of the two devices considered, performed at a bias of $-2\,\mathrm{V}$ and a laser power of $0\,\mathrm{dBm}$.

III. Results and conclusions

The solutions of the transient simulation for the devices under study are reported in Fig. 3. The optical pulse has a power measured at the beginning of the detector of $200\,\mu\mathrm{W}$, starting at $0.1\,\mathrm{ns}$. This signal power is compatible with the $0\,\mathrm{dBm}$ optical power measured at the laser output, assuming $-7\,\mathrm{dBm}$ for coupling and waveguide losses. The calculated photocurrent rise time from $10\,\%$ to $90\,\%$ is $9.43\,\mathrm{ps}$ for Device 1 and $8.58\,\mathrm{ps}$ for Device 2.[1] These values correspond to electro-optic cutoff frequencies of a single-pole transfer function of $37.1\,\mathrm{GHz}$ and $40.7\,\mathrm{GHz}$, respectively. These results can be compared with the small-signal electro-optic simulations and experimental data [5] reported in Fig. 4. Measurements and simulations show a $-3\,\mathrm{dB}$ cutoff frequency between $37\,\mathrm{GHz}$ and $37.5\,\mathrm{GHz}$ for Device 1, between $41\,\mathrm{GHz}$ and $41.5\,\mathrm{GHz}$ for Device 2. The device with a wider Ge implanted region presents a faster electro-optic frequency response, as demonstrated both by simulations (transient and small-signal) and by measurements. The difference between the electro-optic response obtained with the transient and the small-signal simulations is minimal. However, since small-signal simulations are inherently limited to the cyclostationary steady state, they cannot account for effects related to slower carriers, that can be studied starting from current tails.

In conclusion, despite their much higher computational cost, transient simulations have been shown to offer a significant, and still largely unexplored, potential contribution to the field of WPD modeling and optimization.

IV. Acknowledgments

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[1]The calculated rise time in the WPDs under study is compatible with the theoretical transit time $t_{\text{transit}} = H_{\text{Ge}}/v_{\text{sat}} \approx 11\,\mathrm{ps}$, evaluated as the ratio between the thickness of the intrinsic Ge absorption layer $H_{\text{Ge}} \approx 0.8\,\mu\mathrm{m}$ and the carrier saturation velocity $v_{\text{sat}} \approx 7\times10^{6}\,\mathrm{cm\,s^{-1}}$ [12]. This may lead to an *equivalent* description of the saturation velocity of these devices.

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