Modeling the electronic transport in FinFET-like lateral Ge-on-Si *pin* waveguide photodetectors for ultra-wide bandwidth applications

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***Abstract*—We determined the velocities of photogenerated electrons and holes in FinFET-like lateral Ge-on-Si waveguide photodetectors with Monte Carlo transport simulation. The calculated carrier velocities were used in a 3D multiphysics model focused on the investigation of the electro-optic frequency response. The good match between the bandwidths predicted by the model and the corresponding experimental values available from the literature, larger than 200 GHz, indicates the importance of moving beyond conventional drift-diffusion models for a realistic description of next-generation high-speed integrated photodetectors.**

I. Introduction

The increasing demand for short-length wide-bandwidth communication systems, driven e.g. by cloud computing and AI training, makes Silicon Photonics (SiPh) a very promising technology thanks to its CMOS compatibility [1]. Germanium-on-silicon (Ge-on-Si) waveguide photodetectors (WPDs) are one of the main building blocks of any SiPh transceiver chain. We present a simulation study of a state-of-the-art FinFET-like lateral WPD [2] that features an experimental electro-optic bandwidth greater than 200 GHz thanks to the thin Ge absorption layer positioned between two highly *n*- and *p*-doped Si layers (see the device cross-section in Fig. 1(a)). Because of the critical role played by the velocities of photogenerated carriers in determining the transit time across the Ge absorption layer and therefore the electro-optic cutoff frequency of the device [3, Sec. 4.9], our modeling approach is organized in two separate steps. First, we study a simplified version of the lateral WPD (Fig. 1(b)) with the FBMC3D full-band Monte Carlo transport simulator [4] in order to get detailed carrier velocity profiles across the Ge layer. Then, from these profiles, equivalent saturation velocities are extracted and used in a 3D multiphysics model [5] allowing the determination of the WPD frequency response.

II. Methods

To simulate the Ge-on-Si device in FBMC3D, we use the full electronic structure of Ge computed with the empirical pseudopotential method (EPM) [6] along with an analytical approximation of the electronic structure of Si. Energy-dependent scattering rates in Ge are determined from the EPM electronic structure, and their values are validated by comparing the simulated carrier velocities in bulk Ge against available experimental values [7]. In the Monte Carlo study of the simplified FinFET-like structure, carriers are generated in the Ge layer to simulate photon absorption and are then accelerated by the electric field. From the FBMC3D velocities of the individual carriers traveling through the Ge layer, average velocities of photogenerated charge packets are estimated.

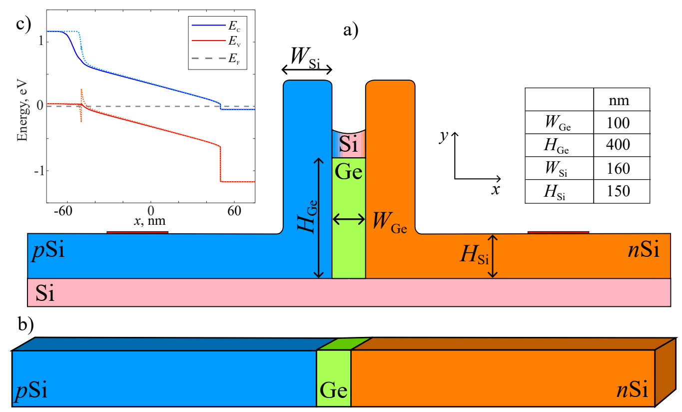

Fig. 1. (a) Cross-section of the Ge-on-Si FinFET-like lateral WPD, (b) simplified structure simulated with FBMC3D, and (c) equilibrium band diagram with (solid line) and without (dashed line) Si/Ge graded interface.

The Monte Carlo average velocities in Ge are then used by the multiphysics (electromagnetic and electric) simulation which considers the full 3D WPD structure. The electromagnetic problem, i.e., studying the light propagation and absorption along the detector, is addressed with the finite-difference time-domain method (FDTD) as implemented in Synopsys RSoft FullWAVE [8]. The absorbed photon density calculated with FDTD is converted in a distribution of the optical generation rate due to interband optical absorption,

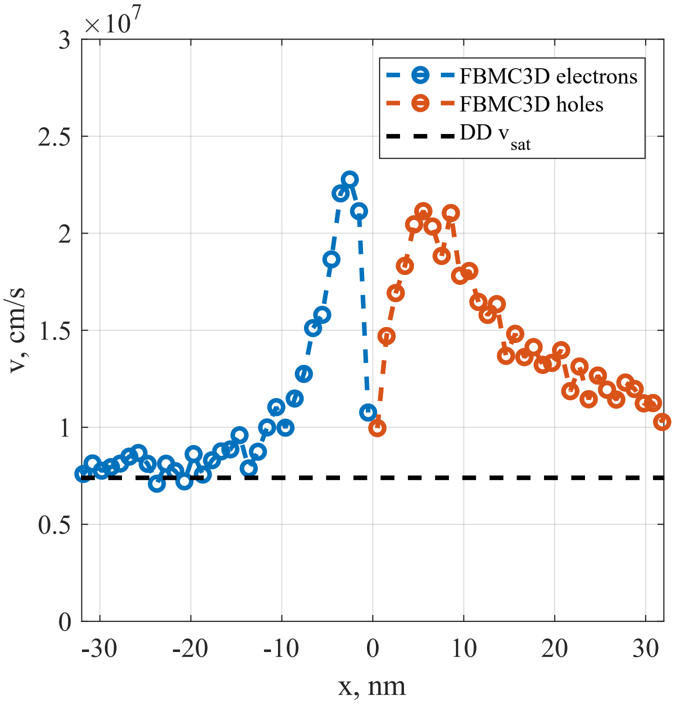

Fig. 2. Electron (blue) and hole (red) velocity across the Ge absorption layer predicted by Monte Carlo transport simulation for carriers photogenerated at the center of the absorber under a -2 V bias, compared with the saturation velocity used in conventional DD.

which is an input of the electrical problem, solved within the drift-diffusion (DD) approximation using Synopsys TCAD Sentaurus [9]. To improve the DD convergence, an erf-shaped compositional grading at the Ge/*p*-Si interface is included as discussed in [10] (see the resulting band diagram in Fig. 1(c)).

III. Results

In Fig. 2, the electron and hole velocities predicted by FBMC3D across a 100 nm-wide Ge absorption layer under a -2 V bias for carriers photogenerated at the center of the absorber are compared with the saturation velocity used in conventional DD models. It can be observed that both electrons and holes experience a significant velocity overshoot before reaching the respective saturation velocities. Under typical operating conditions, according to FBMC3D the steady-state velocity is reached after a propagation across a region with extension between 20 nm and 40 nm, which represent a considerable fraction of the whole Ge absorber.

Fig. 3 compares the experimental electro-optic frequency responses reported in [2] for the devices labeled Ge_100_10 and Ge_150_10 with the predictions of the 3D multiphysics model. The use of conventional steady-state carrier velocity models does not allow to take into account the overshoot shown in Fig. 2 and leads to an underestimation of the cutoff frequency. However, using in the DD simulations the average carrier velocities extracted from Monte Carlo simulation, one may observe a significantly better agreement with experiments.

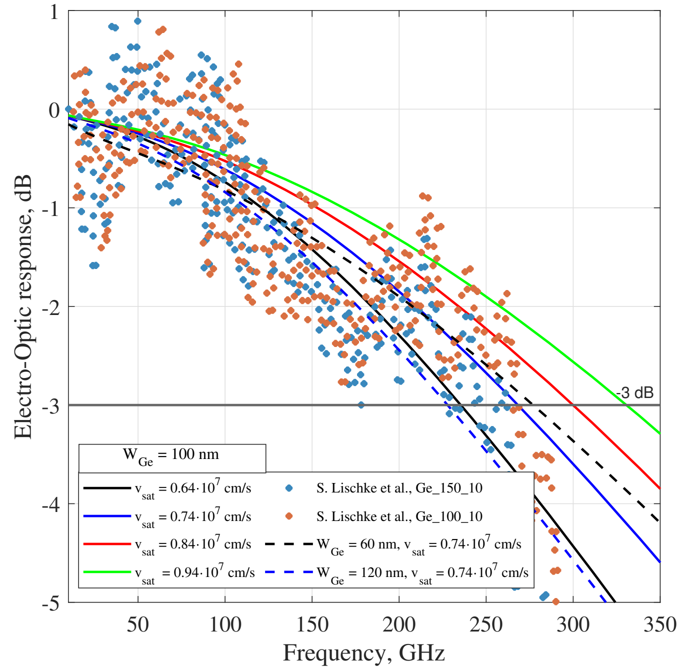

Fig. 3. Experimental frequency response of the Ge-on-Si WPD under study [2] compared with numerical simulations where average carrier velocities obtained from FBMC3D are used in the 3D DD model.

In conclusion, this study highlights the importance of full-band Monte Carlo carrier transport simulation across FinFET-like Ge-on-Si lateral WPDs to enhance the predictive capability of the frequency response through 3D multiphysics models.

Acknowledgments

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