Effects of input optical power in lateral Ge-on-Si waveguide photodetectors: a 3D multiphysics modeling study

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ABSTRACT

We present a three-dimensional (3D) multiphysics model that examines how increasing input optical power degrades the electro-optical frequency response performance of lateral Ge-on-Si waveguide photodetectors. Our approach combines finite-difference time-domain (FDTD) simulations and drift-diffusion modeling to capture both optical and electrical behaviors. Simulation results show that once the input power exceeds a few mW, the detector bandwidth is significantly reduced due to electric-field screening effects.

Keywords: Silicon Photonics, Ge-on-Si Photodetectors, 3D Multiphysics Modeling, FDTD, Drift-Diffusion Model, Electro-Optic Bandwidth

1. INTRODUCTION

Within the context of silicon photonics,[1,2] germanium-on-silicon (Ge-on-Si) waveguide photodetectors (WPDs) are particularly attractive because of their low parasitic capacitances and high-speed potential.[3] Among Ge-on-Si WPDs, one of most promising configurations[4,5] is based on a thin, intrinsic Ge absorber region surrounded by heavily doped *p*- and *n*-type silicon layers to form a lateral *p*-*i*-*n* junction (LPIN, Fig. 1a). This configuration provides electro-optic bandwidths higher than 250 GHz,[4] although the responsivity is of the order of $0.2 - 0.4\,\mathrm{A\,W^{-1}}$. Hence, higher optical power[6,7] may be required to compensate for lower responsivities. This work explores with a validated 3D multiphysics model how input optical power influences device non-idealities that affect the modulation bandwidth.

2. MODELING APPROACH

A multiphysics model[8,9] is used to describe the behavior of the device. For the optical problem, 3D finite-difference time-domain (FDTD) simulations[10] solve Maxwell's equations by propagating the light from the waveguide to the Ge absorber. An example of the optical generation rate G_{opt} determined from the FDTD solution is shown in Figure 1b. Next, G_{opt} is included as a source term into a 3D drift-diffusion solver.[11] A small-signal analysis is performed by imposing a sinusoidal modulation on the input optical power and evaluating the corresponding frequency response of the photocurrent. Figure 2a reports the WPD responsivity in reverse bias (-2 V and -1 V) as a function of the wavelength. Figure 2b shows how the experimental frequency response[4] at low input optical power and a reverse bias of -2 V can be reproduced by the multiphysics model for two different values of W_{Ge}.

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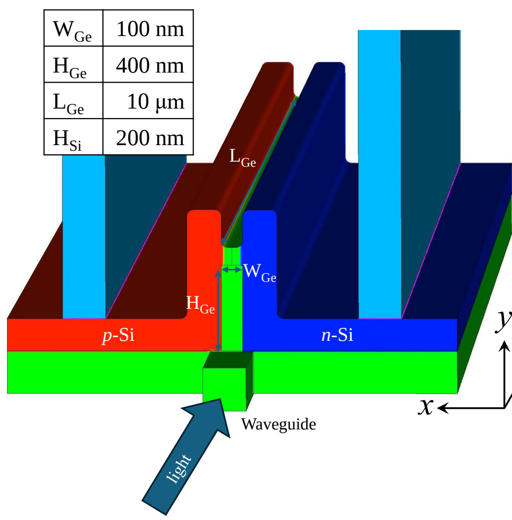
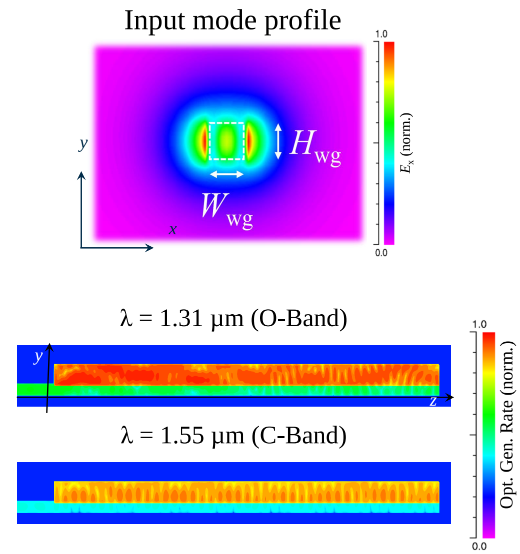
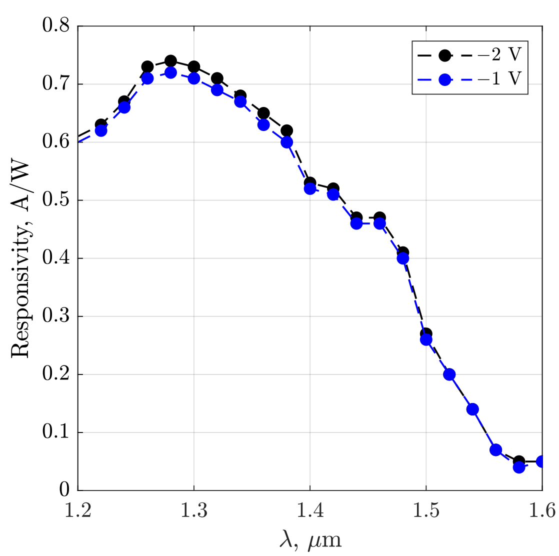


(a)

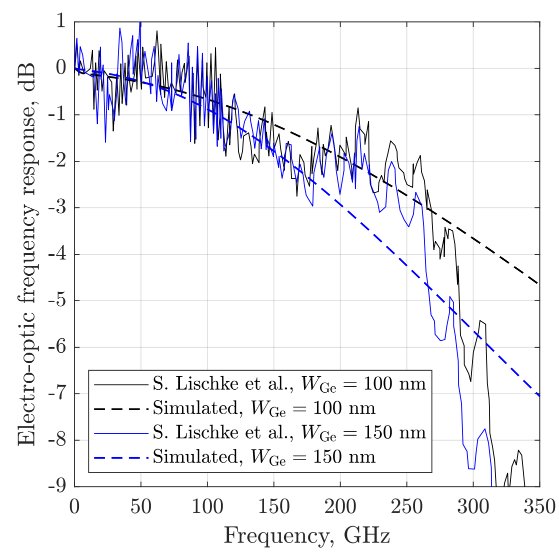


(b)

Figure 1: (a) Perspective view of the LPIN structure with the Ge absorber (green) surrounded by doped Si regions (blue and red). (b) Input optical source, evaluated as the mode of the input waveguide (above), and optical generation rate along the absorber (below).



(a)



(b)

Figure 2: (a) Responsivitity as a function of the wavelength for low input optical power. (b) Experimental vs. simulated electro-optic frequency response at low optical power.

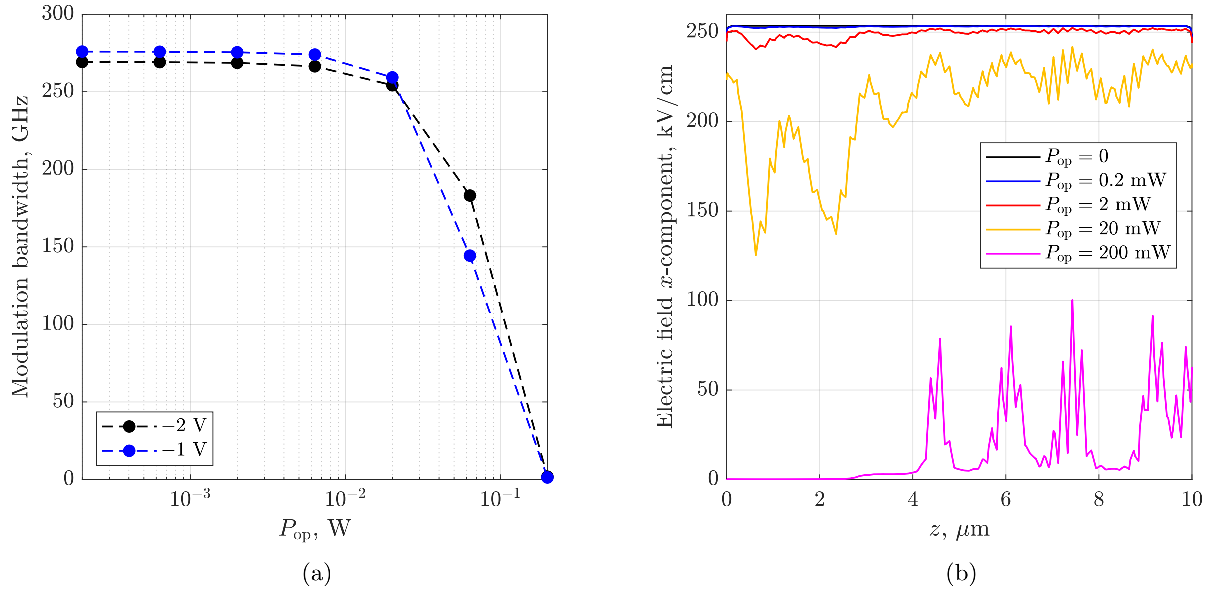


Figure 3: (a) $-3\,$dB bandwidth vs. input optical power. (b) Transverse electric field E_x at the center of the Ge absorber vs. input optical power.

3. RESULTS AND DISCUSSION

Figure 3a displays the simulated $-3\,$dB electro-optic bandwidth as a function of input optical power, ranging from 2 µW to 200 mW. The bandwidth remains nearly constant up to 2 mW, then gradually decreases, showing a pronounced drop above 20 mW.

Figure 3b illustrates the transverse electric field E_x in the Ge absorber along the light propagation direction z at different input powers. Below 2 mW, the electric field profile remains nearly unchanged. Above this value, E_x significantly drops, indicating that electric-field screening (space-charge effects) becomes severe, particularly at the beginning of the device ($z \approx 0$) where the optical generation rate is higher. This mechanism prevents carriers from reaching their saturation velocity, hence limiting the device bandwidth.[12]

Since any structural modification aimed at improving the LPIN WPD responsivity would have an impact on the density of photogenerated carriers inside the Ge absorber, potentially making the screening effects more relevant at lower input optical power, the assistance of a multiphysics model could be instrumental towards a careful performance optimization.

Acknowledgments

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