Small-Signal Compact Modeling and TCAD Validation of Ultra-Fast Lateral Ge-On-Si Waveguide Photodetectors

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Small-signal compact modeling and TCAD validation of ultra-fast lateral Ge-on-Si waveguide photodetectors

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***Abstract*—We present a compact small-signal equivalent circuit for ultra-fast lateral Ge-on-Si waveguide photodetectors, validated against full 3D drift–diffusion TCAD simulations. By evaluating the contributions of intrinsic and parasitic elements, the model enables prediction of device performance and offers direct insight into the RC limitations of the photodetector, useful in circuit level designs.**

I. Introduction

Silicon photonics [1], [2] have become increasingly important in optical interconnects, enabling chip-level integration of optical links. This is particularly useful in datacenters [3], [4] where the high modulation bandwidth is an essential feature. A key advantage is its CMOS compatibility, making it both cost-effective and integrable [5].

Ge-on-Si waveguide photodetectors are used for operation in the typical wavelengths exploited in optical communications, i.e. in the O- and C-band and beyond [6]. Among the explored configurations, the ultra-fast lateral structure studied in this work offers > 200 GHz electro-optic bandwidth, as measured in the literature [7], but at the cost of reduced responsivity.

This device features a Ge absorber between highly doped silicon contacts, resembling a FinFET structure. Figure 1 illustrates the geometry and lists the key parameters. This work extends a known small-signal equivalent model by extracting parameter values from 3D TCAD simulations.

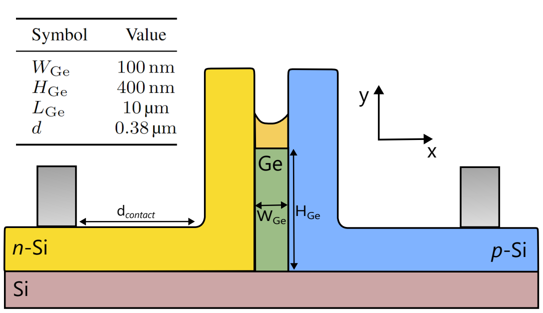


Fig. 1: Cross-section of the lateral Ge-on-Si photodetector. Key device dimensions are reported in the table.

II. Methodology

Following prior work [8]–[10], drift-diffusion TCAD simulation [11] is used to extract the overall electro-optic frequency response, showing good agreement between measurements and simulations. Here this methodology is used to evaluate the frequency-dependent electrical small-signal admittance. A compact model is developed using the topology in [12], [13], reported in Figure 2.

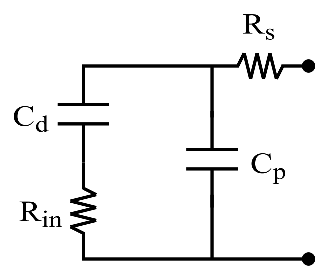


Fig. 2: Small-signal equivalent circuit of the lateral Ge-on-Si photodetector. C_d and R_{in} represent the intrinsic components; R_s and C_p represent the parasitic components.

The impedance in the Laplace domain is:

$$Z(s) = R_s + \cfrac{1}{sC_p + \cfrac{1}{R_{in} + \cfrac{1}{sC_d}}} \tag{1}$$

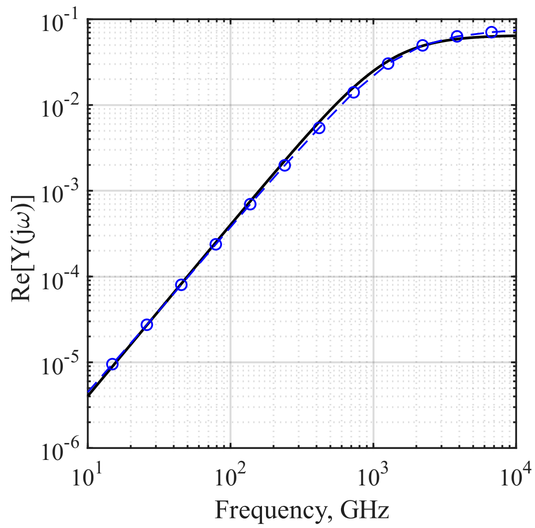
which expands to:

$$Z(s) = \frac{s^2 R_s R_{in} C_p C_d + sR_s(C_p + C_d) + sR_{in}C_d + 1}{s(sR_{in}C_pC_d + C_p + C_d)}. \tag{2}$$

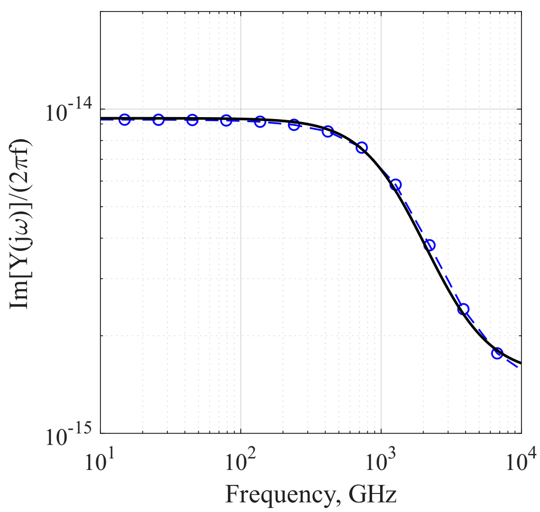
The admittance $Y = A + \mathrm{i}\omega C$ is extracted from TCAD, providing a characterization of the device's small-signal behavior for a wide range of frequency, here reported between GHz and tens of THz to facilitate the fitting procedure.

III. Results

Figure 3 shows the admittance comparison between the model and the simulation. Plateaus in the real and imaginary parts reveal the series resistance and total capacitance respectively. In the imaginary part, at low frequency, the intrinsic junction dominates; at high frequency, parasitic effects prevail.



(a)



(b)

Fig. 3: Admittance from TCAD (dots) and fitted circuit model (line): (a) real part, (b) imaginary part versus frequency.

The fitted circuit values are summarized in Table I.

TABLE I: Fitted circuit parameters at $-2\,\mathrm{V}$.

Component	Value
R_s	$17.2\,\mathrm{m}\Omega$
R_{in}	$15.3\,\Omega$
C_p	$1.51\,\mathrm{fF}$
C_d	$7.86\,\mathrm{fF}$

Displacement current analysis further confirms these results:

1) At low frequency, current is localized in the Ge absorber and close to silicon;
2) At high frequency, current spreads to parasitic paths.

Figure 4 shows the imaginary part of the displacement current at $1\,\mathrm{THz}$ in the cross-section, where the impact of the capacitance can be observed.

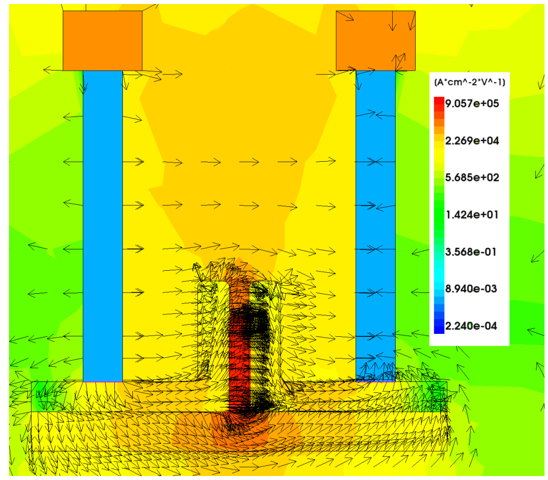


Fig. 4: Displacement current (imaginary part) at $1\,\mathrm{THz}$ in the cross-section, showing effects of both intrinsic and parasitic capacitance.

IV. Conclusion

A compact equivalent circuit for lateral Ge-on-Si photodetectors was developed and validated with TCAD simulations. The model captures parasitic and intrinsic effects, enabling performance prediction and design integration in high-speed photonic systems.

Acknowledgment

This work was supported in part by the European Union under two initiatives of the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU: the partnership on Telecommunications of the Future (PE00000001 – program "RESTART"), and the National Centre for HPC, Big Data and Quantum Computing (CN00000013 – CUP E13C22000990001).

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