Doctoral Dissertation

Doctoral Program in Electrical, Electronics and Communications Engineering (36th cycle)

Ge-on-Si photodetectors for silicon photonics: multiphysics modeling and design

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Summary

In recent years, there has been a remarkable increase in the volume of information being transmitted, continuously expanding alongside the increasing complexity and quality of services offered to global users. The driving force behind this transformation has been the concept of *centralized computation*, where the majority of data processing takes place in data centers. These data centers are strategically located to handle the majority of traffic and subsequently deliver the processed data to end users. In this context, the importance of short-range interconnects is reaching a level equal to or greater than that of telecommunications, leading to a demand for effective and energy-efficient optoelectronic devices.

A fundamental limitation of this architecture is the boundary between the optical domain, which handles data communications, and the electrical domain, which focuses primarily on data processing. Until the technological feasibility of an all-optical computer is achieved, one of the most promising methods to overcome this limitation is through the use of silicon photonics (SiPh). SiPh provides a harmonious, cost-efficient, and completely CMOS-compatible integration of optical and electronic systems. Nevertheless, exploring new device ideas or improving current designs requires extensive and expensive prototyping efforts that involve multiple iterations.

The objective of this thesis is to create a computer-aided design framework for waveguide photodetectors that surpasses the current state of the art SiPh receiver. From a simulation perspective, it is challenging to deal with both the optical and electrical domains. This requires a multiphysics approach that involves solving Maxwell's equations and a carrier transport model. First, the spatially-resolved distribution of photogenerated carriers is determined by evaluating the absorbed photon density using a full-wave electromagnetic

simulation. Then, this distribution is used as a source term in an electrical simulation, which involves solving the electron and hole continuity equations with drift-diffusion constitutive relations, coupled to the quasistatic Poisson's equation.

The thesis is organized as follows:

- Chap. 1 introduces the goals set for the doctoral research at the beginning of the program. It then describes the context of silicon photonics, presenting its various components, and concludes with an explanation about waveguide photodetectors and their coupling configurations.
- Chap. 2 describes the operation of photodetectors. The crucial role played by these devices in converting the optical signal to the electrical signal is measured by figures of merit (or metrics) that are defined in this chapter. It is shown how the various figures of merit correspond to different measurable aspects of the device, such as the relationship between the input optical power and the electro-optical bandwidth. Also in this chapter are derived some simple analytical models, showing the main relationships between the electrical properties of materials, geometry, and figures of merit.
- Chap. 3 presents the state of the art of the photodetectors for silicon photonics that will be studied in the following chapters. The drift-diffusion model, the generation and recombination rates, and the Finite Difference Time Domain (FDTD) method, that are the main building blocks of the multiphysics simulation model, are then presented.
- Chap. 4 and Chap. 5 present the research results achieved for waveguide photodetectors having lateral and vertical configuration, where the difference is in the placement of silicon versus germanium. In fact, the vertical configuration has a contact on top of the Ge layer, while the lateral configuration has a fully intrinsic germanium absorber surrounded by two highly doped silicon regions. For both configurations, a study in dark is presented first, and then the performance under illumination and the device dynamics are addressed also through validation with experimental data. Chap. 6 finally presents the conclusions.