Investigation of the SiGe Waveguide Photodiodes Using FDTD Method for High Speed Optical Communication

Introduction

Silicon as a photonic medium has unique advantages in telecommunication systems. It is transparent in the range of optical telecommunications wavelength (1.3 and 1.55 um) and has a high index of refraction. In addition, mature Si integrated circuit CMOS technology enables the implementation of dense silicon-based OEICs[1]. The development of SiGe photodetectors, and especially the fist demonstration of high performance SiGe Avalanche photodiode(APD)[2], has drawn more attention to high speed SiGe APDs development for low cost optical communication.

In this paper, we present two high performance SiGe Waveguide PhotoDiodes[3], for high-speed applications. Both the waveguides and the photodiodes were simulated self-consistently using the vector helmholtz equation for mode calculation and Finite Difference Time Domain FDTD for light propagation analysis.

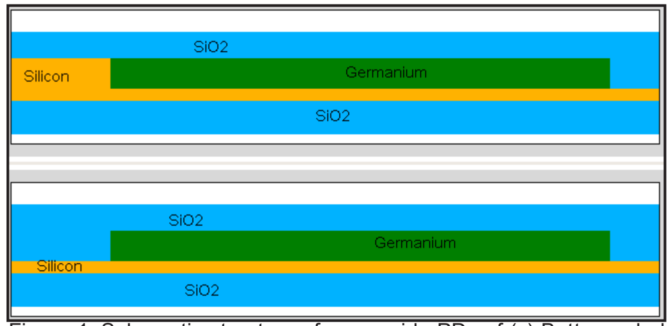

Figure 1. Schematic structure of waveguide PDs of (a) Butt-coupled type (b) Evanescent-coupled type.

Device Structure and Models

3D FDTD is available in ATLAS but simulation time is quite significant because the mesh space should be smaller than at least, 1/5 times the wavelength along x, y and z directions. In this article, we consider x-y plane and optical mode coupling using the Vector Helmholtz equation, and the y-z plane was considered using the two dimensional FDTD method.

Device Structure and Mode Analysis

Two types of waveguide photodiodes are considered for the light wave coupling. The butt-coupled and evanescent-coupled types shown in Figure 1 on SOI wafer. The evanescent-coupled device has a Ge absorber layer sitting on the top of a Si waveguide, while the butt-coupled device has the Ge absorber layer directly in contact with the Si waveguide output facet.

The Si waveguide thickness is 250nm the width is 450nm the Germanium thickness is 500nm and the length is 10, 30, 50 and 80 um to get the responsivity at 1.55um. These waveguides exhibit single-mode operation for both TE and TM-like modes and the calculated optical mode overlapped into the 2 dimensional structure, which is shown in Figure 2. [4]

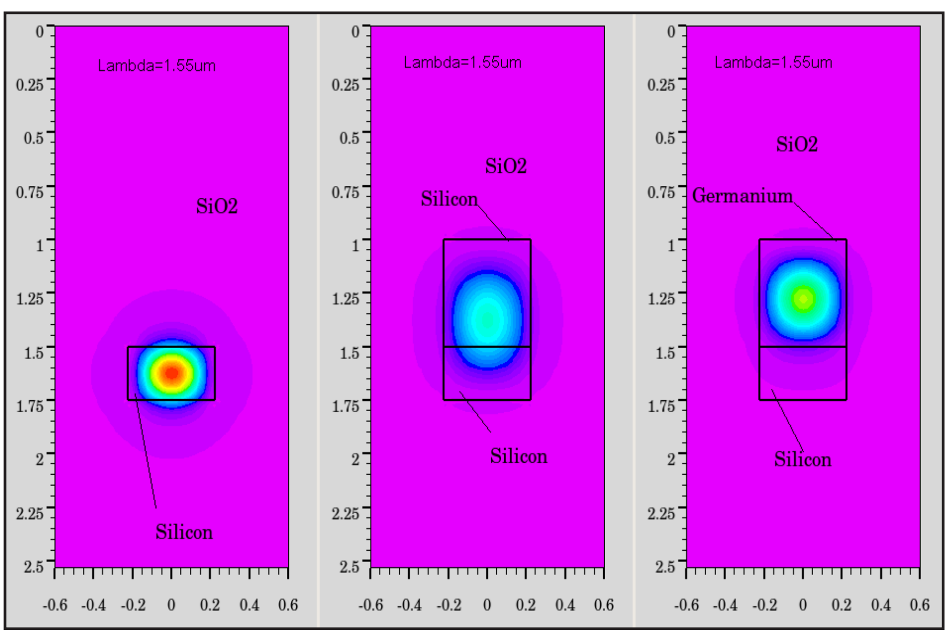

Figure 2 Fundamental optical mode-field profile of (a) a typical SOI high-index-contrast strip Si on waveguide for 1.55um wavelength and (b) Si-Si SOI (c) Ge/Si on SOI photodiode.

Figure 2 shows the optical fundamental mode on the waveguide of the x-y plane. The figure at the left (a) shows only the Si waveguide with 450nm width and 250nm thickness. The second figure (b) shows silicon on top of silicon waveguide. The last one (c) shows germanium on top of silicon waveguide. The butt-coupled modes combine with (b) and (c) and the evanescent-coupled modes combine with (a) and (c).

Figure 3 shows normalized optical field along the center of the 3 different structures shown in Figure 2. These field distributions show the mode-coupling between butt-coupled and evanescent-coupled waveguides.

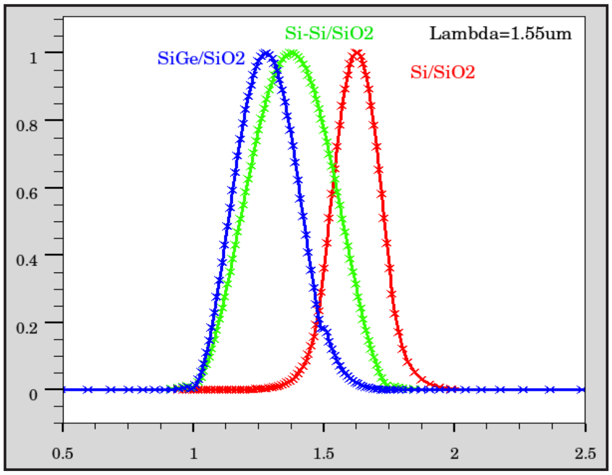

Figure 3. The normalized the mode distribution of the Vertical plane of the each center of structures.

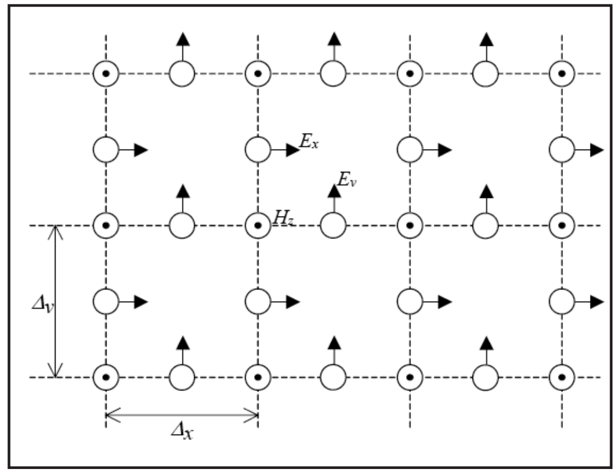

Figure 4. Two-dimensional FDTD calculation grid for TE-waves. The E- and H-evaluations are shifted half a step-size in time.

Finite-Difference Time-Domain Method

The FDTD is a direct discretization of Maxwell's differential equations, where the differentials are replaced by finite differences. A well-known, efficient implementation is based on Yee's mesh, where the electric and magnetic field components are evaluated at different grids having the same pitch, but which have been shifted over half a grid spacing, both in space and in time. This is illustrated in the 2-dimensional case for TE waves (electric field in the plane of calculation) in Figure 4. The half step sizes have been introduced for obtaining accurate approximations of the derivatives; the algorithm proceeds with full step size. A very detailed and practical overview of the FDTD method is given in the book by Taflove [5].

Boundary Conditions

In order to obtain a finite-sized calculation, the number of grid points should be finite. At the spatial boundaries of the calculation domain, the electromagnetic field should satisfy conditions such, that the space outside this domain is modeled in a desired way, e.g. a non-reflective continuation of the structure inside the calculation window, or free space.

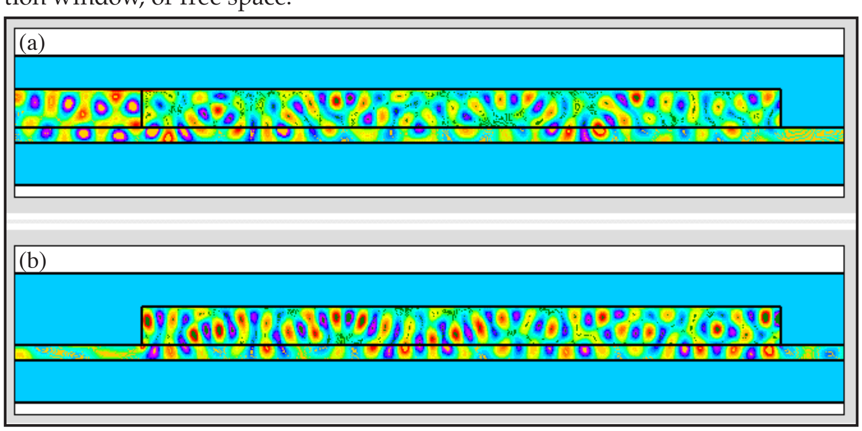

Figure 5. 2D FDTD simulated Ex profiles for TE mode of (a) Butt-coupled waveguide and (b) Evanescent-coupled waveguide.

As mentioned previously, the equations are solved in a 2D rectangular domain. You must specify boundary conditions to complete the problem description. FDTD has 3 types of boundary conditions: Perfect Electrical Conductor (PEC) boundaries, Perfectly Matched Layer (PML) boundaries, and source boundaries (plane and point)

The perfectly matched layer boundary is used to absorb outgoing light. This is useful when we want to simulate an unbounded domain. In other words, we try to absorb (rather than reflect) all outward bound waves. There are several main concepts for PMLs that you should know.

- PMLs are not really boundary conditions in the conventional sense. These boundary conditions have a thickness associated with them and are included in the mesh. We hope to select the absorption coefficient of the layer to allow absorption of the outgoing light to a specified minimum.
- A PMLs is terminated by a PEC. Thus, all light passing through the PML, after accounting for absorption, is reflected back into the simulation domain after making two trips through the PML.
- PMLs are designed to be impedance matched to the simulation domain so that there is no reflection at the interface between the PML and the simulation domain.
- PMLs absorb only in one direction x or y depending on their location. Therefore, light propagating parallel to a PML is not affected by the PML.

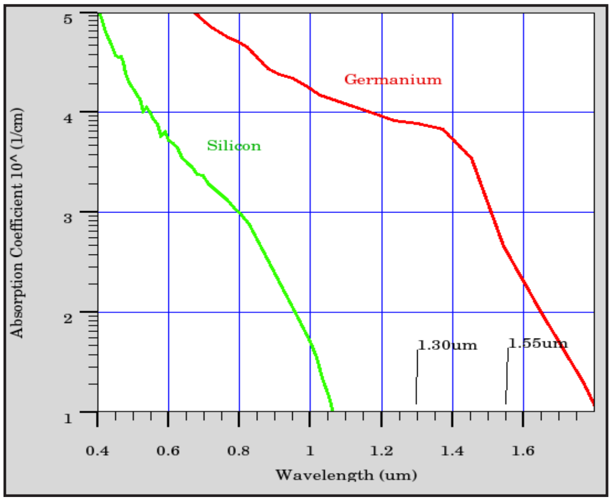

Figure 6 Absorption coefficient of the Silicon and Germanium.

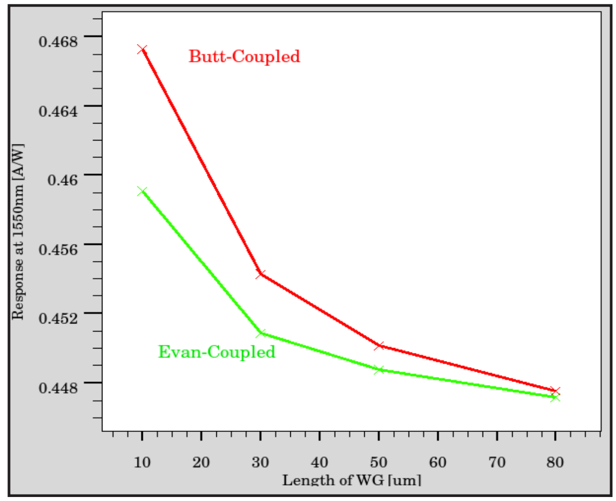

Figure 8. Inter responsivity at 1.55um as a function of Ge waveguide length for butt-coupled and evanescent-coupled photodiodes.

Simulation Results

Finite-different time-domain (FDTD) method was used to calculate the resonance modes of the coupling between the silicon waveguide and SiGe photodiode.[6]

a. Optical Characteristics

Figure 5 shows the cross -section of the mode field patterns obtained by the incidence of the guided modes at the 1.55um wavelength.

The figure (a) is the butt-coupled type waveguide and (b) is the evanescent-coupled type waveguide. In Si and Ge media, the absorption loss is dependent to the wavelength. Figure 6 show the absorption coefficiency of the Silicon and Germanium material, which depends on the wavelength.

The Silicon shows low absorption coefficient between 1.30um and 1.55um whereas germanium absorption coefficient is higher and wavelength dependent. So illuminating the structure with 1.30um wavelength will give different results as shown in Figure 7.

b. Electrical Characteristics

The responsivity at 1.55um is shown in Figure 8 for the butt-coupled and evanescent-coupled Photodiodes with SiGe waveguide lengths of 10 to 80um. Here, the optical transmission loss and the optical coupling loss between lens fiber and the Si waveguide was ignored.

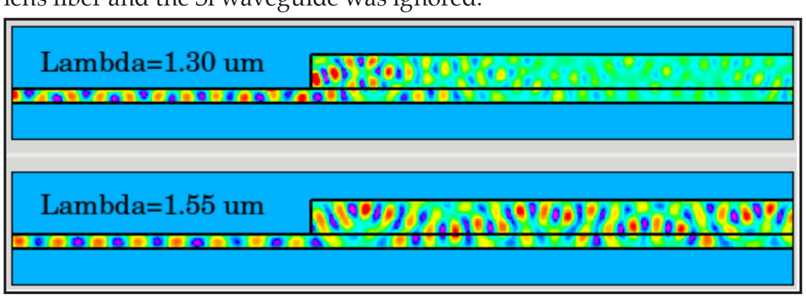

Figure 7 The Ex modes of the Evanscent-coupled waveguide at (a) 1.30um and (b) 1.55um of wavelength.

Conclusion

An electro-optic SOI high-index-constrast waveguide has been investigated using the 2D FDTD method and Vector Helmholtz equation for the mode analysis. Both optical and electrical properties of two types of germanium based waveguide photodiodes were investigated. FDTD gives more accurate results than ray-tracing because the ray-tracing method can not calculate properly the beam propagation along the coupled waveguides.

Reference

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