Modeling of high performance SiGeC/Si near-IR photonic devices

Martin F. Schubert and Farhan Rana
Department of Electrical and Computer Engineering, Cornell University, Ithaca, New York 14853

Abstract – Numerical simulations are performed for SiGeC/Si electro-optic modulators and photodetectors operating at near-IR wavelengths. The addition of carbon provides the ability to lattice match layers with high germanium composition to silicon, which is shown to give a substantial increase in the optical confinement factor. The large optical confinement factor yields higher device performance than can be achieved in SiGe/Si devices.

INTRODUCTION

The advantages of CMOS compatible manufacturing have made the silicon material system an attractive target for photonic system applications. However, both all-silicon and SiGe/Si devices suffer from fundamental limitations that hinder performance and system integration. An all-silicon platform does not allow for both light modulation and photodetection at the same wavelength. In addition, the silicon-on-insulator (SOI) designs which are typically used suffer from poor thermal characteristics which keep maximum current low and limit device performance [1-3]. Finally, it is difficult to design structures that confine both the electrons/holes and photons to the same location in space while keeping the optical mode away from highly doped contact layers [1-3]. Although SiGe/Si heterostructures have the potential to meet these challenges, the large lattice mismatch between germanium and silicon results in very small values for the critical thickness of epitaxial layers. Consequently, the results for SiGe modulators and detectors that have been reported in literature suffer from small optical confinement factors, long device lengths, and small RC limited bandwidths [4-8].

Silicon-germanium-carbon structures make it possible to tightly confine both carriers and the optical mode to the same spatial location, thereby offering design opportunities similar to those available in optoelectronic devices based on III-V materials. Typically up to 4% carbon can be incorporated in SiGeC epitaxial layers, which allows for thick defect-free layers with high germanium content that are perfectly lattice matched to silicon [9]. Fig. 1 shows the Matthews-Blakeslee critical thickness of SiGeC as a function of the composition. Thick layers with high germanium content can be used as the core for optical waveguides to achieve high modal confinement factors. In this talk, we will show that the high confinement factors achievable with SiGeC/Si heterostructures combined with superior thermal characteristics can produce integrated electro-optic modulators and photodetectors with significant performance benefits over conventional designs.

ELECTRO-OPTIC MODULATOR DESIGN

In simulations we consider the p-i-n diode modulators in the familiar Mach-Zehnder configuration. In silicon the index change due to the presence of carriers is nearly linearly related to the change in carrier concentration. With a current level I, this yields

$$\Delta\phi \approx \frac{2\pi}{\lambda}\frac{\Gamma}{h}\frac{1}{q}\frac{fIt}{w} \tag{1}$$

where Γ is the optical confinement factor, h and w are the active region height and width, t is time, and f relates the carrier concentration to the change in index. The key figure of merit for modulator designs is Γ/h – maximizing this term gives the minimum current needed to achieve the π phaseshift. Fig. 2 and 3 plot Γ and Γ/h for a modulator at 1550 nm as a function of active region height for several carbon fractions. The germanium composition is maximized while keeping within the limits of the critical thickness. While Γ monotonically increases, Γ/h has a maximum value which occurs between 0.2 μm and 0.5 μm. This is the optimum point for device operation – with the addition of carbon, Γ/h increases by more than a factor of 7. The switching speed of a p-i-n modulator is typically dominated by the turn-on time, where carriers flow by diffusion. Fig. 3 plots the turn-on time as a function of the current injection level for several active region compositions. With carrier recombination time was assumed to be 1 ns, switching speeds faster than 0.5 ns are achieved with currents around 50 mA.

PHOTODETECTOR DESIGN

Because a reduction in strain increases the bandgap, optical absorption of SiGeC is slightly below that of SiGe for the same germanium composition. Fig. 4 shows the calculated material absorption for SiGeC alloys at 1300 nm as a function of the composition using a model for phonon-assisted indirect optical transitions [10]. The addition of carbon to SiGe enables larger critical thicknesses for high germanium content layers and allows the use of SiGeC separate-confining-heterostructures (SCH) which increases the confinement factor of the optical mode in the active region. Superlattice active regions can also improve the modal overlap with germanium-rich layers. Fig. 6 shows the confinement factor and modal absorption as a function of germanium content for optimized photodetectors with 2 periods in the active region and carbon concentrations of 3% and 4%. The increase in critical thickness for the germanium-rich active region is more than enough to compensate for the reduced material absorption. As a result, large values for modal waveguide absorption are possible. The maximum waveguide absorption achieved is 67 cm^{-1}. This corresponds to a quantum efficiency of 48.8% in a 100 um device and 96.5% in a 500 um long device.

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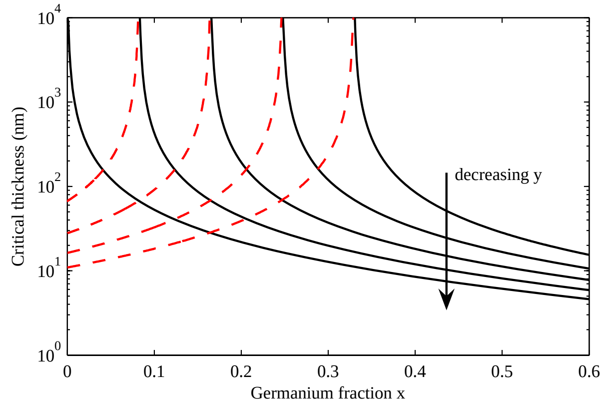


FIG. 1 – Critical thickness of $Si_{1-x-y}Ge_xC_y$ as a function of germanium content for carbon fractions of 0.04, 0.03, 0.02, 0.01, and 0

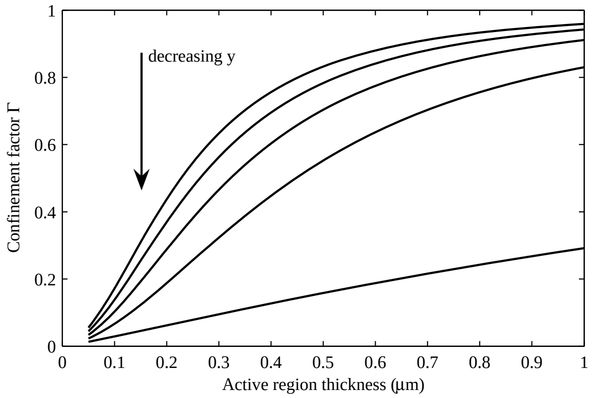
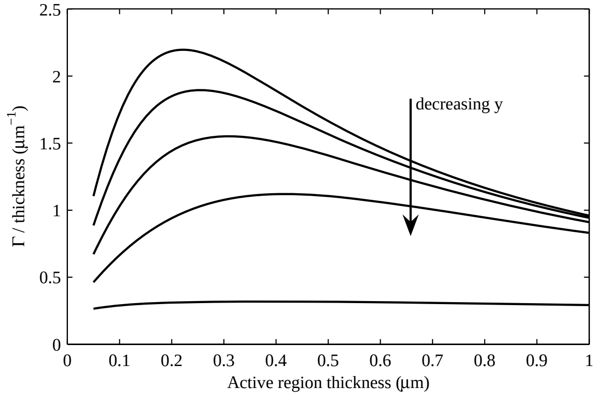


FIG 2 – Confinement factor Γ at 1550 nm with carbon composition y of 0.04, 0.03, 0.02, 0.01, and 0.



IG 3 – Γ/*h* for the modulator at 1550 nm with carbon compositions of 0.04, 0.03, 0.02, 0.01, and 0.

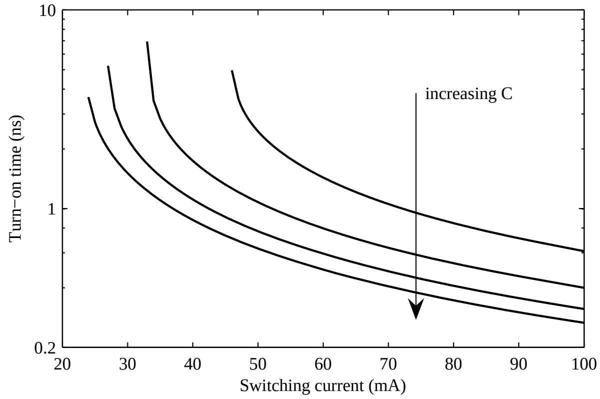


FIG 4 – Switching time for optimized modulators at 1550 nm with carbon concentrations of 0.04, 0.03, 0.02, and 0.01.

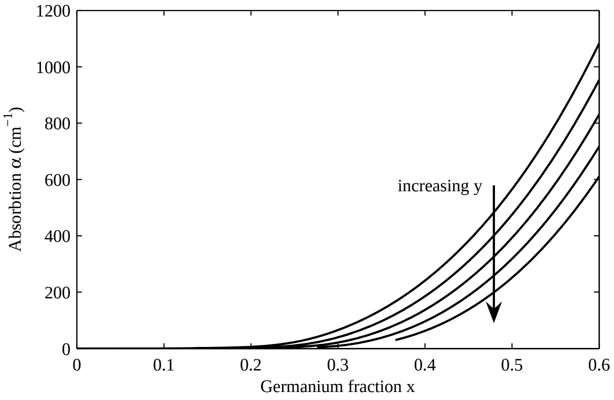


FIG. 5 – Optical absorption coefficient of $Si_{1-x-y}Ge_xC_y$ at 1300 nm as a function of germanium content for carbon fractions of 0, 0.01, 0.02, 0.03, and 0.04.

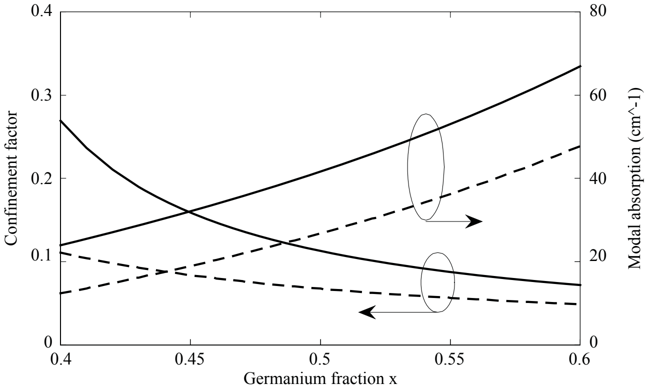


FIG. 5 – Confinement factor and modal absorption coefficient at 1300 nm for photodetectors with 3% carbon (dashed) and 4% carbon (solid) in the active region and SCH.