Available online at www.sciencedirect.com

SciVerse ScienceDirect

PHOTONICS AND NANOSTRUCTURES
Fundamentals and Applications

Photonics and Nanostructures – Fundamentals and Applications 12 (2014) 54–68

www.elsevier.com/locate/photonics

Effects of germanium incorporation on optical performances of silicon germanium passive devices for group-IV photonic integrated circuits☆

Seongjae Cho [a], Joonsuk Park [b], Hyungjin Kim [c], Robert Sinclair [b], Byung-Gook Park [c,*], James S. Harris Jr. [a]

[a] *Department of Electrical Engineering, Stanford University, Stanford, CA 94305, USA*
[b] *Department of Materials Science and Engineering, Stanford University, Stanford, CA 94305, USA*
[c] *Inter-university Semiconductor Research Center (ISRC) with Department of Electrical Engineering and Computer Science, Seoul National University, Seoul 151-742, Republic of Korea*

Received 7 January 2013; received in revised form 17 July 2013; accepted 26 July 2013
Available online 8 August 2013

Abstract

Optical interconnect in integrated optoelectronic circuits is one of the promising next-generation technologies for replacing metalized interconnect. Efforts have been made to use silicon (Si)-compatible materials such as germanium (Ge) and Ge-buffered III–V compound semiconductors, along with Si, as optical sources for Si and group-IV integrated optoelectronic systems. This opens the possibility that higher fraction of Ge with its high refractive index (n) can be incorporated in Si waveguide for optical interconnect and the graftability between Si and group-IV or III–V materials would be improved in silicon photonics. In this work, advantageous features of nano-structured silicon germanium ($Si_{1-x}Ge_x$) optical waveguide with different Ge fraction (x) were evaluated by both optical simulations and theoretical calculations, which are mainly found in the enhanced optical confinement and better interfacing capability. Along with the SiGe waveguide, performance of $Si_{1-x}Ge_x$ microring resonator under material loss in the effect of extinction coefficient (k) has been investigated to suggest the necessity of optimizing the Ge content in $Si_{1-x}Ge_x$ passive devices. While carrying out the establish design criteria, n and k have been modelled in closed-form functions of Ge fraction at 1550 nm. Furthermore, by examining high-resolution transmission electron microscopy (HR-TEM) images, process compatibility of Ge with either group-IV alloys or III–V compound semiconductors is confirmed for the monolithically integrated photonic circuits.

Keywords: Optical interconnect; Integrated optoelectronic system; Silicon germanium; Optical simulation; Material loss; Transmission electron microscopy

* Corresponding author at: Department of Electrical Engineering and Computer Science, Seoul National University, Building 301, Room 1003, Seoul 151-742, Republic of Korea. Tel.: +82 2 880 7270; fax: +82 2 880 4658.
E-mail address: bgpark@snu.ac.kr (B.-G. Park).

1569-4410/$ – see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.photonics.2013.07.012

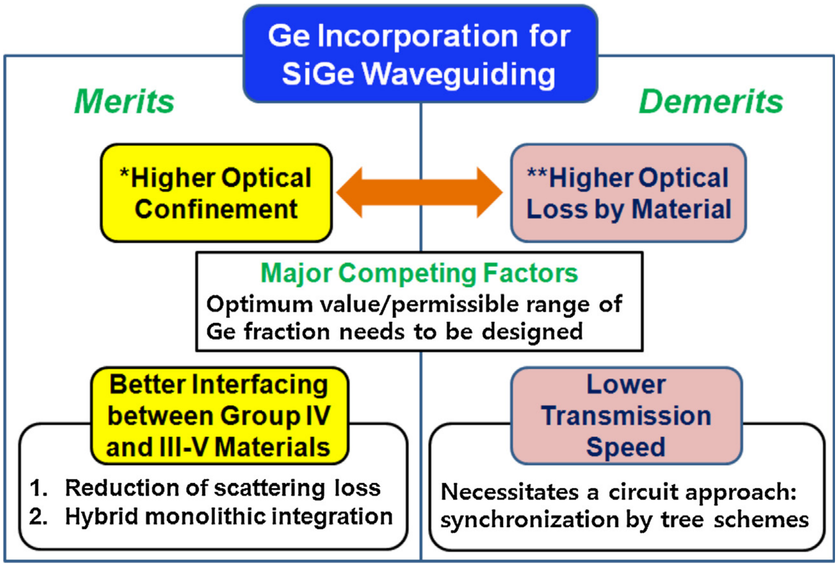

Fig. 1. Effects of Ge incorporation on the performances of SiGe passive optical components.

1. Introduction

Optical interconnect is considered one of the emerging technologies for replacing copper (Cu), particularly, in its application to chip-level (on-chip and chip-to-chip) interconnect, owing to its genuine virtues of high bandwidth, low power, low latency, and noise immunity [1]. The most attractive aspects of fabricating waveguides from Si are the low initial cost of the material; the mature and well-characterised processing techniques that are underpinned by decades of research, development, and manufacturing in the microelectronics industry; and the potential for straightforward integration with electronic devices on the same substrate [2]. The majority of silicon (Si) waveguides for Si photonics have been fabricated on the silicon-on-insulator (SOI) platform. However, Si has internal quantum efficiency as low as the order of 10^{-5} which restricts its potential as an efficient optical source in Si photonics. Although there have been attempts to achieve lasing from Si in many ways, the processing is quite complicated, and the optical efficiency still has much room to improve [3–5]. To address this concern, opportunities have been found by developing optical sources using Si-compatible materials such as germanium (Ge) or even III–V compound semiconductors on Si with a Ge buffer [6–10]. Under these circumstances, Ge can be incorporated for constructing SiGe waveguide and other passive devices owing to its intermediate lattice constant and higher optical confinement for Si and group-IV integrated photonic circuits. Although several merits are definitely expected by incorporating Ge, there are competing demerits in device performances, as summarized in Fig. 1. Optical confinement is one of the most crucial requirements for waveguiding material, for example, increased material loss by higher refractive index (n) should be considered simultaneously in designing the passive devices.

In this work, we evaluated the optical confinement of $Si_{1-x}Ge_x$ waveguides with different Ge fractions (x), time delays caused by introducing higher-n material, and permissible range of x in consideration of extinction coefficient (k) in order to confirm the validity of $Si_{1-x}Ge_x$ as a waveguiding material for on-chip interconnect by a series of optical simulations and theoretical calculations. Optical cavity performances including full wave width at half maximum (FWHM) and quality factor (Q-factor) of $Si_{1-x}Ge_x$ microring resonator are also investigated along with the effect n and k, by which $x = 0.4–0.6$ comes as a permissible range of Ge content. While carrying out the evaluations, n and k have been mathematically modelled in a closed-form function of x at 1550-nm wavelength light signal, which is another genuine task performed in this work. Furthermore, analysis images from Ge interfaces were provided by high-resolution transmission electron microscopy (HR-TEM) to ensure its process viability in various material systems and confirm surface roughness within the permissible range to obtain interface scattering loss below a magnitude of 10^{-2} dB/mm order at sub-micron dimension.