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Chip-scale integrated photonics for the mid-infrared

(Invited paper)

Delphine Marris-Morini ¹, Qiankun Liu ¹, Joan-Manel Ramirez ¹, Vladyslav Vakarin ¹, Andrea Ballabio ², Daniel Chrastina ², Jacopo Frigerio ², Xavier Le Roux ¹, Samuel Serna ¹, Eric Cassan ¹, Daniel Benedikovic ¹, Carlos Alonso-Ramos ¹, Laurent Vivien ¹, Giovanni Isella ²

¹ Centre de Nanosciences et de Nanotechnologies, Univ. Paris-Sud, CNRS, Université Paris-Saclay, C2N – Orsay, 91405 Orsay cedex, France

e-mail: delphine.morini@u-psud.fr

² L-NESS, Dipartimento di Fisica, Politecnico di Milano, Polo di Como, Via Anzani 42, 22100 Como, Italy

ABSTRACT

Recent works towards the development of Ge-rich SiGe photonic integrated circuits for on-chip mid-IR spectroscopy will be presented. First, the demonstration of ultra-wideband passive circuits will be discussed, followed by the first proofs of concepts towards the realization of efficient wideband active devices. The combination of on-chip integrated spectrometers with on-chip mid-IR sources will provide a solid basis for the development of a competitive mid-IR integrated platform from 3 to 15 μm wavelength.

Keywords: silicon photonics, germanium, silicon-germanium, mid infrared.

1. INTRODUCTION

Mid-infrared (mid-IR) integrated photonics undergoes a growing interest, for applications in mid-IR spectroscopy or free-space telecommunications. Silicon photonics presents strong advantages for integrated photonics as it benefits from reliable and high-volume fabrication to offer high performance, low cost, compact, low-weight and low-power-consumption photonic circuits, which can be particularly interesting for mid-IR spectroscopic sensing systems that need to be portable and cost effective [1,2]. Among the different materials available in silicon photonics, Germanium (Ge) and Silicon-Germanium (SiGe) alloys with a high Ge concentration are noticeable because of the wide transparency window of Ge up to 15 μm [3]. Furthermore, a large increase of the non-linear refractive index of $\text{Si}_{1-x}\text{Ge}_x$ alloys has been predicted for Ge concentrations x larger than 0.8 [4].

In this context, we will review our recent works towards the development of Ge-rich SiGe photonic integrated circuits for mid-IR wavelengths. The Ge-rich SiGe platform will be presented first, with the demonstration of ultra-wideband passive circuits. In a second part the strategy for the development of active devices based on non-linear effects will be presented.

2. GE-RICH SIGE PLATFORM FOR MID-INFRA-RED

Ge-rich SiGe materials have been used for a long time in Si photonics, for optical modulation and photodetection [5]. Due to the differences in lattice constants and thermal expansion coefficient between Si and Ge, graded buffer layers have been proposed and used to realize fully relaxed virtual substrates with a low density of threading dislocations suitable for the growth of Ge quantum wells with high crystalline quality. While this integration scheme was initially developed for near-IR wavelength range, to demonstrate electro-absorption modulator and photodetector for telecom and data com applications [6], the extension of this approach for mid-IR wavelength range has been proposed. The use of graded based SiGe layers and Ge-rich SiGe alloys can provide definite advantages for mid-IR integrate photonics. Indeed, a gradual increase of the Ge content in the SiGe graded buffer allows a smooth increase of the refractive index, thus confining the optical mode in the Ge-rich part of the epitaxial structure. Low-loss optical waveguides are thus expected, potentially up to $\lambda = 15 \mu\text{m}$, as the refractive index gradient allows to push the optical mode far from the Si substrate where absorption begins to be prohibitive beyond $\lambda \sim 8.5 \mu\text{m}$. Furthermore, confining light in Ge-rich $\text{Si}_{1-x}\text{Ge}_x$ is also beneficial for non-linear based devices, as an increase of the non-linear refractive index n_2 has been demonstrated when x is larger than 80% [7]. Finally the use of SiGe alloys allows tailoring the light propagation properties by playing on the gradient shape and layers composition. The dispersion and the modal confinement can thus be engineered very precisely.

As a first proof-of-concept of the potential of this new platform for mid-IR photonics, the first waveguide design that was investigated uses a 2 μm -thick $\text{Si}_{0.2}\text{Ge}_{0.8}$ layer on a 11 μm -thick linearly graded $\text{Si}_{1-x}\text{Ge}_x$ substrate from Si to $\text{Si}_{0.21}\text{Ge}_{0.79}$. This structure directly comes from previous work at near-IR wavelengths [6]. The waveguide design is shown in Fig 1(a). The vertical confinement is allowed by the refractive index profile (Fig 1 (b)) which increases linearly in the graded layer according to the Ge concentration. Low-energy plasma-enhanced chemical vapor deposition was used to grow the $\text{Si}_{1-x}\text{Ge}_x$ material, with a typical growth rate of 5–10 nm/s. The

waveguides were then patterned using lithography followed by inductively coupled plasma etching. The etching depth was 4 μm , and the waveguide width was 4 μm , allowing a good confinement of the fundamental TE and TM modes. As a key building block for the development of the mid-IR photonics platform, Mach-Zehnder Interferometers (MZI) have been demonstrated [8]. The asymmetric MZI have been designed with 3 mm long arms and arm length differences of 48 μm , 87 μm and 149 μm , and Multimode Interference (MMI) coupler and splitter. The characterization of the different MZIs in both polarizations is reported in Fig 1(c). Interestingly large extinction ratios of at least 10 dB between 5.5 μm and 8.6 μm wavelength are obtained for both TE and TM polarizations. In all the characterized structures the expected decrease of the free spectral range (FSR) with the increase of arm length difference ΔL and the increase of the FSR with the increase of the wavelength are observed. The unique broadband properties of the MZI and corresponding MMI are explained to be due to the vertical refractive index gradient in the graded $\text{Si}_{1-x}\text{Ge}_x$ substrate. Finally, while the reported wavelength range is limited by the available experimental set-up, numerical simulations indicate that the MZI operation can be extended up to 11 μm wavelength, being limited only by the MMI coupler bandwidth.

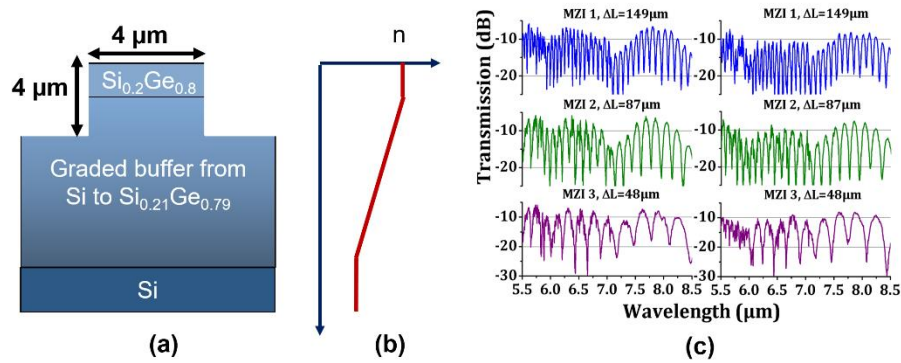


Figure 1. (a) first waveguide design; (b) refractive index profile along the vertical direction ; (c) transmission of the Mach Zehnder interferometers for different length difference between both arms, from 48 to 149 μm , in TE (left column) and TM (right column)

3. TOWARDS ACTIVE DEVICES

As a next step towards a complete integrated platform for spectroscopic applications, active devices such as wideband supercontinuum sources can be envisioned. While it has been previously demonstrated that Ge-rich SiGe alloys present a large non-linear Kerr refractive index n_2 , optimising light confinement is a key parameter to achieve efficient non-linear based devices. From the initial waveguide design, two additional epitaxial layer designs have been proposed to increase light confinement. The three platforms are then compared in Fig 3, where (a) refers to the former waveguide reported in Fig. 1, the platform (b) corresponds to a reduction of waveguide thickness by using a 6 μm graded layer from pure Si to pure Ge, and the platform (c) is based on two graded layers, first a 3 μm -thick layer from Si to $\text{Si}_{0.5}\text{Ge}_{0.5}$ followed by a 1 μm -thick graded layer from $\text{Si}_{0.5}\text{Ge}_{0.5}$ to pure Ge. All three platforms have been investigated in terms of propagation losses, and the results are reported in Fig 2. Interestingly low propagation losses between 2 and 3 dB/cm are obtained with platforms (a) and (b), while the platform (c) provides prohibitive losses in the longer wavelength range, which can be correlated to an increase of the overlap of the optical mode with Si and Si-rich SiGe layer, which could be responsible for such increase of the propagation losses at long wavelengths [9].

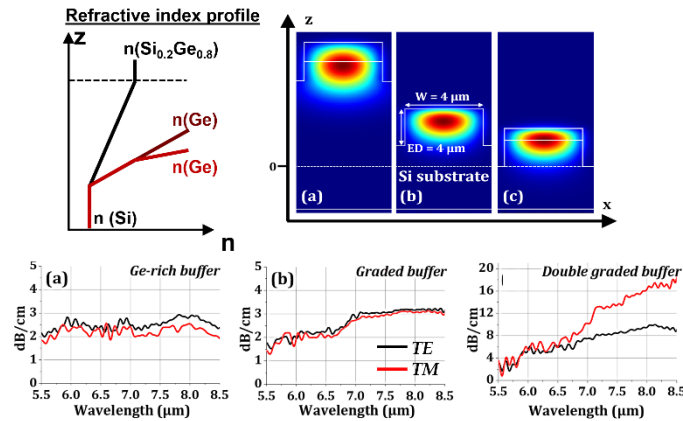


Figure 2. Different SiGe platforms investigated in this work (a) 11 μm thick graded buffer followed by 2 μm -thick $\text{Si}_{0.2}\text{Ge}_{0.8}$, as shown in Fig 1 ; (b) 6 μm thick graded layer from Si to Ge ; (c) double graded buffer layer : 3 μm thick graded layer from Si to $\text{Si}_{0.5}\text{Ge}_{0.5}$ followed by 1 μm thick graded layer from $\text{Si}_{0.5}\text{Ge}_{0.5}$ to Ge . Refractive index profile, illustration of mode confinement increases when the waveguide thickness decreases, and comparison of the propagation losses determined experimentally by a non-destructive cut-back technique.

From this work it was possible to conclude that the platform (b) based on a 6 μm -thick SiGe graded layer from pure Si to pure Ge is the most promising one for active devices. The waveguide has thus been engineered to evaluate the possibility to generate a supercontinuum [10]. In addition to the good modal confinement, a flat anomalous dispersion in a wide spectral range is required. The final design is reported in Fig 3 (a). The waveguide width and etching depth are 4 μm . The optimized confinement of the optical mode which is always located in the upper part of the waveguide, overlapping with the Ge-rich part of the SiGe graded buffer waveguide is illustrated by the calculation of the modal effective area (Fig 3.(b)). The spectral dispersion characteristics of quasi-TE and quasi-TM polarizations are reported in Fig 3.(c). Both polarizations provide broadband anomalous dispersion over a 1.4 octave spanning, having the quasi-TM mode an almost flat profile with a maximum value of ≈ 14 ps/nm/km. Finally the value of n_2 as a function of the wavelength and for different Ge fraction of $\text{Si}_{1-x}\text{Ge}_x$ alloys has been used to calculate the effective nonlinear parameter (γ_{eff}) of graded $\text{Si}_{1-x}\text{Ge}_x$ waveguides (Fig 3 (e)). A maximum value of $\gamma_{\text{eff}} \approx 10 \text{ W}^{-1}\text{m}^{-1}$ is obtained at $\lambda = 3 \mu\text{m}$, and decreases down to $\sim 0.6 \text{ W}^{-1}\text{m}^{-1}$ for $\lambda = 8 \mu\text{m}$. The comparison of these values with previously reported experimental demonstrations [11] on different platforms provide an optimistic foreseeable future for the development of supercontinuum sources using such waveguide design.

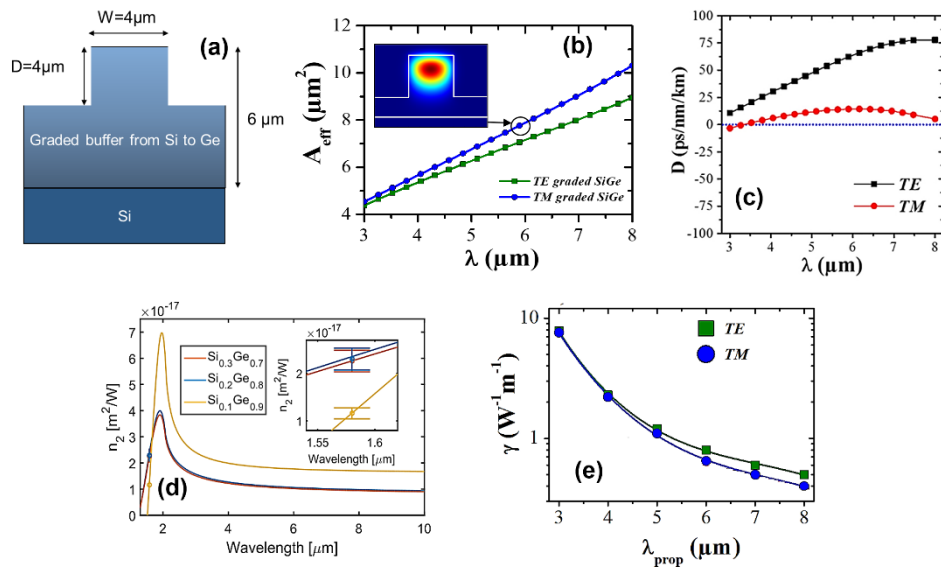


Figure 3. (a). Waveguide design for a supercontinuum source (b) optical mode effective area as a function of the wavelength; (c) dispersion properties showing flat anomalous dispersion; (d) non-linear Kerr refractive index n_2 as a function of the wavelength and for different Ge fractions; (e) effective non-linear parameter of the optical mode.

4. CONCLUSION

Recent works towards the development of Ge-rich SiGe photonic integrated circuits for mid-IR wavelength range have been reported. While passive devices have demonstrated good operation properties, current challenges are the demonstration of active devices based on non-linear effects. The design of a wideband supercontinuum source paves the way towards the demonstration of a complete mid IR photonic platform for spectroscopic applications.

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