# Ge-rich SiGe photonic integrated circuits for mid-IR spectroscopy

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**ABSTRACT**

Recent works towards the development of Ge-rich SiGe photonic integrated circuits will be presented, such as the demonstration of low-loss waveguides and ultra-wideband Mach Zehnder interferometer from 5.5 to 8.6 µm wavelength, as well as the first steps towards the realization of efficient wideband optical sources.

**Keywords:** mid-IR photonic integrated circuits, silicon, germanium

## 1. INTRODUCTION

Mid-infrared (mid-IR) spectroscopy is a nearly universal way to identify chemical and biological substances, as most of the molecules have their vibrational and rotational resonances in the mid-IR wavelength range. Commercially available mid-IR systems are based on bulky and expensive equipment, while lots of efforts are now devoted to the reduction of their size down to chip-scale dimensions. The demonstration of mid-IR photonic circuits on silicon chips will benefit from reliable and high-volume fabrication to offer high performance, low cost, compact, low weight and power consumption photonic circuits, which is 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 particularly interesting because of the wide transparency window of Ge up to 15 µm [3]. Furthermore a large increase of the non-linear refractive index of $Si_{1-x}Ge_x$ 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 wavelength range. Passive integrated structures will be presented first, with the demonstration of low loss waveguides and ultra-wideband Mach Zehnder interferometer from 5.5 to 8.6 µm wavelength [5]. In a second part we will review our work towards efficient mid IR surpercontinuum sources. The first experimental characterization of non-linear refractive index in SiGe alloys confirms the advantages of using Ge-rich SiGe materials [6]. Then the possibility to achieve flat anomalous dispersion waveguides will be shown, opening strong perspectives towards the realization of efficient wideband optical sources [7].

## 2. GE-RICH SIGE INTEGRATED STRUCTURES IN THE MID-IR

### 2.1 Design and fabrication

$Si_{0.2}Ge_{0.8}$ waveguides on graded $Si_{1-x}Ge_x$ substrate have been used to investigate the properties of this platform in the mid-IR. The design is reported in Fig 1(a). The Ge concentration increases linearly from 0 to 0.79 along the growth direction over 11 µm thickness. Then a 2 µm-thick $Si_{0.2}Ge_{0.8}$ core layer is grown on top of the graded layer. Vertical confinement is allowed by the refractive index profile which increases linearly in the graded layer in accordance with the Ge concentration. Low-energy plasma-enhanced chemical vapor deposition was used to grow the $Si_{1-x}Ge_x$ 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, as shown in Fig. 1(a), allowing a good confinement for both TE and TM fundamental modes, which are reported on Fig. 1 (b) and (c) at a representative wavelength of 7.5 µm.

## 2.2 Waveguide properties

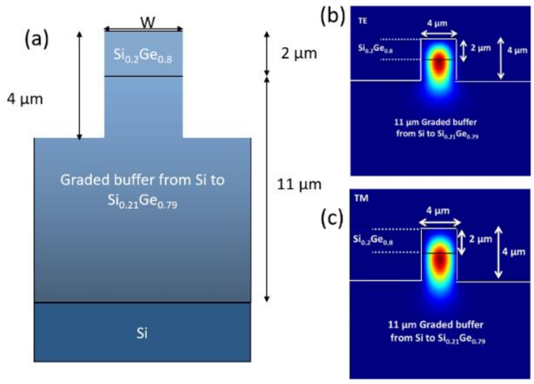


Figure 1. (a) Waveguide design for the investigation of linear waveguide properties ; (b) mode calculation in TE polarization at 7.5 µm wavelength ; (c) mode calculation in TM polarization at 7.5 µm wavelength

The propagation loss of the waveguides was inspected by fabricating a set of spiral waveguides with different lengths to perform non-destructive cut-back characterization (see Fig. 2(c)). Measurements were performed using an ad-hoc free-space mid-IR setup, placed inside an isolation box and equipped with a dry air filling system, to reduce the impact of the atmospheric absorption (Fig. 2(b)). Transmission measurements were performed using a mid-IR tunable external cavity quantum cascade laser (MIRCAT) from λ = 5.5 µm to λ = 8.6 µm. Input/output chip butt-coupling was carried out by means of aspheric ZnSe lenses. The collected signal was directed towards a polarization filter to discard any polarization rotation throughout the spiral waveguides, and finally sent to either an MCT detector or a mid-IR camera (see Fig 2. (a)).

The measurement propagation loss as a function of the wavelength is reported in Fig. 2 (d). The black line corresponds to quasi-TE polarization and the red one to quasi-TM polarization. It can be seen that the propagation loss is relatively flat in the wavelength range accessible with the experimental set-up, and losses between 1.7 and 3 dB/cm are obtained from 5.5 to 8.6 µm wavelength. This result confirms the interest of using Ge-rich SiGe waveguides for wide band operation, beyond the absorption limit of silicon at 8 µm wavelength.

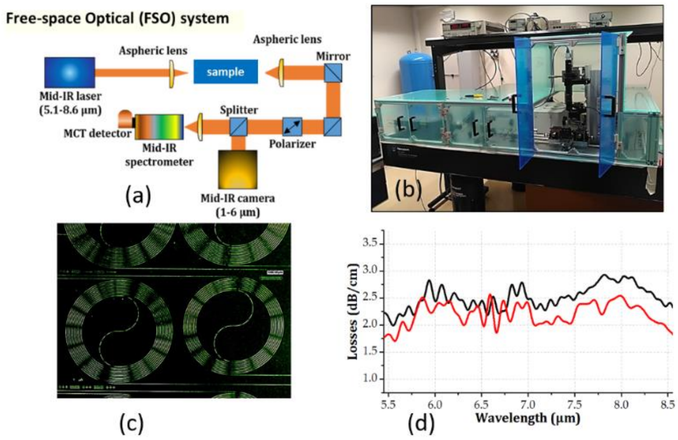


Figure 2. (a) Schematic view of the experimental set-up used for the mid-IR characterization ; (b) Picture of the experimental set-up ; (c) picture of the spiral waveguides used for the cut-back characterization ; (d) experimental result.

### 2.3 Ge-rich SiGe based Mach Zehnder interferometer

To go further Mach-Zehnder Interferometers (MZI) have been tested (Fig 3. (a)), based on multimode interference (MMI) structure as illustrated in Fig 3 (b). The test chip comprises asymmetric MZI with 3 mm long arms and arm length differences of 48 µm, 87 µm and 149 µm. The characterization of the different MZIs in both polarizations are reported in Fig 3 (c). Interestingly large extinction ratio of at least 10 dB between 5.5 µm and 8.6 µm wavelength is obtained both in TE and in 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 $Si_{1-x}Ge_x$ substrate.

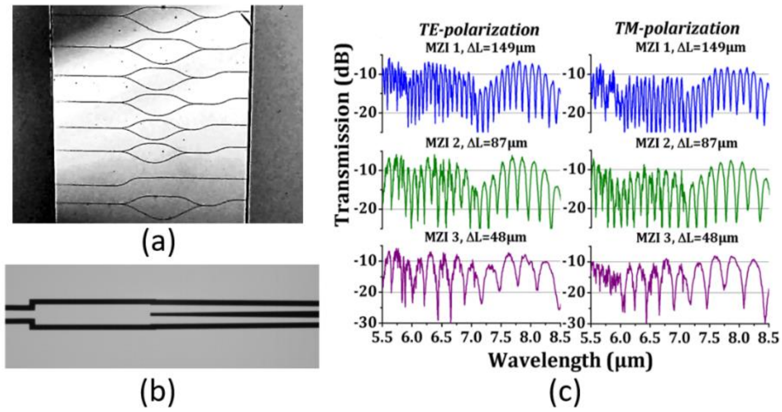


Figure 3. (a) Picture of the test sample with asymetric Mach Zehnder Interferometers (MZI); (b) optical microscope view of the MMI used in the MZI ; (c) Experimental results : the MZI show ultra-wideband properties from 5.5 to 8.6 µm wavelength, and are working both in TE and TM polarization.

## 3. ACTIVE DEVICES BASED ON NON-LINEAR EFFECTS

As a next step, the realization of integrated ultra-wideband source would complete the platform to address mid-IR spectroscopic sensing systems.

### 3.1 Non-linear refractive index as a function of Ge concentration in SiGe alloys

The modeling of the nonlinear optical (NLO) coefficients of the $Si_{1-x}Ge_x$ alloy as a function of the Ge fraction $x$ was performed previously [4], however different models were used as a function of Ge concentration, with do not converge around 80 % of Ge in the alloy. We thus investigated the NLO response Ge-rich $Si_{1-x}Ge_x$ waveguides with germanium concentrations of 70, 80 and 90 %, on top of graded buffer (Fig 4. (a)). A bi-directional top hat D-Scan method [6] was used to determine the Kerr nonlinear refractive index ($n_2$) and the two-photon absorption coefficient ($\beta_{TPA}$) at the wavelength of 1.58 µm. By measuring the spectral broadening of transmitted light as a function of the dispersion induced in the initial pulse (see Fig 4. (b)), it is possible to deduce experimentally the value of $n_2$ at 1.58 µm. These measurement can be used to model the non-linear refractive index at larger wavelength up to 10 µm (Fig 4. (c). Following Ref. [4], an indirect bandgap model is applied for x= 0.7 and 0.8, and for x=0.9, the direct bandgap model is used. Although complementary experimental data would be required to refine the presented trends specifically in the mid-IR wavelength range, the results confirm the benefit of using Ge-rich SiGe alloys to take benefit from large non-linear refractive index.

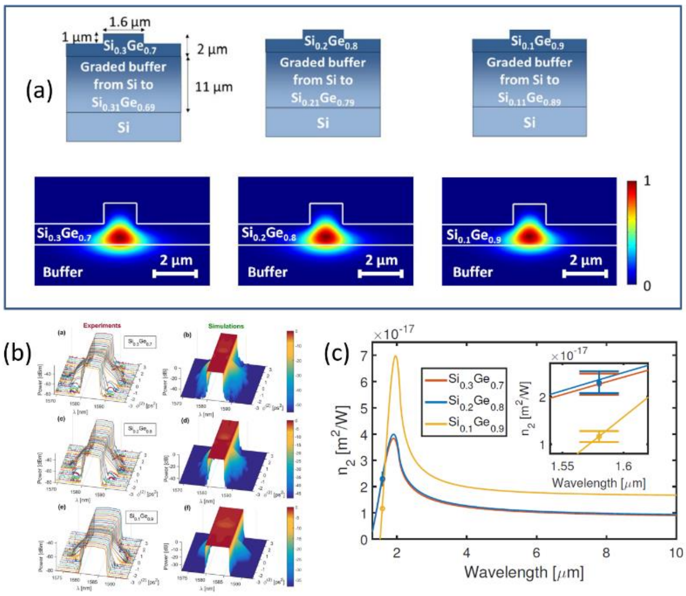


Figure 4. (a) Schematic view of the three waveguides under test for non-linear refractive index evaluation, and optical mode calculations at 1.58 µm wavelength ; (b) example of experimental result from the top hat D scan method, showing the spectral evolution of propagating beam as a function of the dispersion of the initial pulse ; (c) non-linear refractive index as a function of the wavelength. The points at 1.58 µm wavelength are the experimental points, while the curves are based on theoretical modeling.

### 3.2 Design of supercontinuum source

Based on the previously reported investigation of non-linear refractive index, we evaluated the properties of a supercontinuum source based on Ge-rich SiGe waveguide. The waveguide design has been optimized to meet three different requirements: (i) small effective mode area, (ii) good confinement of the optical mode with the Ge-rich material ; (iii) flat anomalous dispersion in a wide spectral range [7]. The final waveguide design is reported in Fig 5. (a). It is based on a 6 µm thick graded SiGe from pure Si to pure Ge. The mode calculation as a function of the wavelength reported in Fig 5. (b) illustrates 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. Such wavelength-dependent modal resizing is a unique feature of waveguides with graded guiding cores in the vertical direction, which are able to provide tight mode confinement over a broad wavelength range. The calculated spectral dispersion characteristics of quasi-TE and quasi-TM polarizations are reported in Fig 5. (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 effective nonlinear parameter ($\gamma_{eff}$) of graded $Si_{1-x}Ge_x$ waveguides has been calculated and are reported in Fig. 5 (d). A maximum value of $\gamma_{eff} \approx 10\ W^{-1}m^{-1}$ is obtained at $\lambda = 3$ µm, and decreases down to $\gamma \sim 0.6\ W^{-1}m^{-1}$ for $\lambda = 8$ µm. The comparison of these values with previously reported experimental demonstrations [8] on different platforms provide an optimistic foreseeable future for the development of supercontinuum sources using such waveguide design.

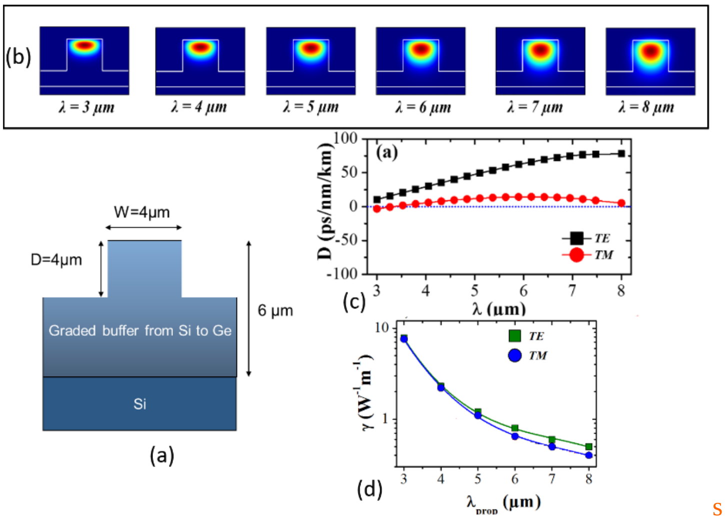


Figure 5. (a). Waveguide design for a supercontinuum source, the graded waveguide is 6 µm-thick from pure Si to pure Ge. The waveguide width and etching depth are 4 µm; (b) optical mode calculation as a function of the wavelength showing the resizing effect due to the graded waveguide; (c) dispersion properties showing flat anomalous dispersion ; (d) effective non linear parameter of the graded SiGe waveguide.

## 4. CONCLUSION

In this paper we reported our recent works towards the development of Ge-rich SiGe photonic integrated circuits for mid-IR wavelength range. First, linear properties of the platform have been investigated : low loss waveguides and Mach Zehnder interferometers have thus been demonstrated in a wide spectral range. In a second step, non-linear characteristics of SiGe alloys have been investigated, showing that a larger non-linear refractive index is expected in the mid-IR for SiGe waveguide with 90 % of Ge, in comparison with 70 and 80 % samples. Finally the possibility to achieve flat anomalous dispersion waveguides with good mode confinement opens strong perspectives towards the realization of efficient wideband optical sources. In the different reported results, confinement of light in Ge-rich SiGe alloys as well as the presence of the Ge concentration gradient bring key advantages to the proposed platform. These results pave the way towards the demonstration of a complete mid IR photonic platform for spectroscopic applications.

## ACKNOWLEDGMENTS

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