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Review article

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Germanium-based integrated photonics from near- to mid-infrared applications

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Abstract: Germanium (Ge) has played a key role in silicon photonics as an enabling material for datacom applications. Indeed, the unique properties of Ge have been leveraged to develop high performance integrated photodectors, which are now mature devices. Ge is also very useful for the achievement of compact modulators and monolithically integrated laser sources on silicon. Interestingly, research efforts in these domains also put forward the current revolution of mid-IR photonics. Ge and Ge-based alloys also present strong advantages for mid-infrared photonic platform such as the extension of the transparency window for these materials, which can operate at wavelengths beyond 8 µm. Different platforms have been proposed to take benefit from the broad transparency of Ge up to 15 µm, and the main passive building blocks are now being developed. In this review, we will present the most relevant Ge-based platforms reported so far that have led to the demonstration of several passive and active building blocks for mid-IR photonics. Seminal works on mid-IR optical sensing using integrated platforms will also be reviewed.

Keywords: silicon photonics; germanium; datacom; mid-infrared; absorption spectroscopy.

1 Introduction

Today, silicon photonics is a mature technology for integrated photonics, which benefits from a reliable and high-volume fabrication to offer high performance, low cost and compact photonic circuits. Among the different materials available in silicon photonics, germanium (Ge), silicon-germanium (SiGe) and germanium-tin (GeSn) play a key role at different maturity level in establishing essential functionalities required for a photonic integrated platform. First applications of silicon photonics were dedicated to Datacom in the near-InfraRed (near-IR) wavelength range. While Ge photodetectors have been considered for a long time as a key component in the receiver part, the small energy difference between the direct and the indirect band gap energy of Ge also makes it an ideal candidate to develop compact electro-absorption modulators and to envision on-chip monolithically integrated lasers. Besides the demonstration of efficient devices, an in-depth understanding of the properties of Ge, SiGe and GeSn is required to properly and finely tune several parameters such as the concentration of Ge or Sn in the alloys, doping or lattice strain.

More recently, it appeared that Ge also presents distinctive advantages for mid-infrared (mid-IR) photonics owing to its wide transparency window up to 15 µm and a strong non-linear refractive index. Main foreseen applications stand for the development of new mid-IR spectroscopic sensing systems that need to be portable and cost-effective, or free space optical communications for wavelengths beyond 8 µm. Previous works at telecom wavelength paved the way towards a new playground for photonic researchers as manifold engineering possibilities are now opened using Ge, SiGe and GeSn for both passive and active functions.

In this context, we will review the development of Ge-based photonic integrated circuits. For near-IR photonics

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applications, previous review papers have been devoted to monolithic integrated Ge-on-Si active photonics [1–4]. Thus, we will just recall hereafter the main motivations for the development of Ge-based devices and summarize major results. Interestingly, we will see how these works put forward the current revolution of mid-IR photonics [5]. Indeed Ge is a unique candidate for extending the operating wavelength of Group IV-based photonic integrated circuits beyond 8 µm. The different integrated platforms used up to now will be presented, emphasizing on the development of passive functions such as cavities or spectrometers and on preliminary sensing demonstrations. Current demonstrations have already been reported up to 8.5 µm, typically for the moment, in a rapidly growing research field with a strong potential to reach wavelengths up to 15 µm. In parallel, state-of-the-art Si-based mid-IR photonics circuits can be found in recent review papers [6–8]. Finally, the progress towards integrated active devices such as a monolithically integrated source, the modulator and the photodetector will be presented and future perspectives opened by these works will be drawn. The fine comprehension of a myriad of physical effects including the non-linear optical effect, the free-carrier plasma effect or intersubband transitions in quantum systems can thus lay the foundations for the implementation of efficient mid-IR chip-scale systems with an unprecedented number of applications such as absorption spectroscopy for chemical or biological sensing, environmental monitoring, datacom or free-space optical communications, to name a few.

2 Ge-based near-IR photonic integrated circuits

The investigation of Silicon-on-Insulator (SOI) as a platform for photonic integration dated back to 1990s with the first demonstrations of low-loss propagation in the near-IR range [9]. The large refractive index contrast between silicon (Si) and silicon dioxide (SiO_2) provides a strong light confinement, leading to ultra-compact waveguides such as nanowires with transversal dimensions of a few hundreds of nanometers with tight bend radius. Up to now, the development of silicon photonics has been mainly driven by telecom and datacom applications, requiring fiber-to-chip light coupling, on-chip routing, wavelength filtering and polarization management. All of these passive functions have been successfully demonstrated and miniaturized based on the SOI platform. However, transceivers also require the on-chip integration of active photonic functionalities such as light emitter, modulator and photodetector (Figure 1). Si is an indirect bandgap material, having a bandgap energy of 1.1 eV. It thus exhibits poor emission and detection properties in the near-IR wavelength (1.3–1.55 µm). This frequency window is used for telecom applications due to the dispersion characteristics and low-propagation losses in optical fibers at these wavelengths. Thus, different strategies have been used to develop active devices on SOI platform, mainly based on monolithic or heterogeneous integration of other materials. Rapidly, Ge appeared to be a material of choice for monolithic integration, due to its compatibility with Si CMOS technology. Furthermore, its direct bandgap energy of 0.8 eV is compatible with near-IR light absorption. Ge photodetectors have thus been developed since the late 1990s [10–13]. To deal with the lattice mismatch between Si and Ge, a two-step growth process has been proposed and largely adopted, in which a thin

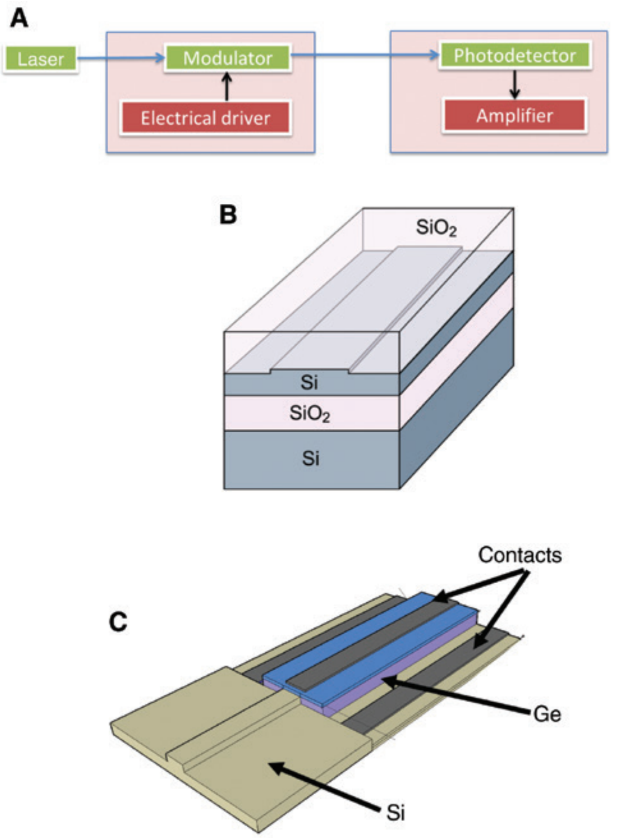

Figure 1: Silicon photonics for Datacom.
(A) Communication link requires the development of different building blocks: laser (external or on-chip), modulator and photodetector; (B) SOI waveguide is currently the platform of choice for photonic integration. Strong light confinement is indeed achievable in the top Si layer; (C) Ge photodetectors integrated at the end of a SOI waveguide for high performance photodetection.

layer is first epitaxially grown at low temperature to relax the strain between Si and Ge and confine dislocations at the two material interface. Then, in a second step, a thick Ge layer can be grown at high temperature, allowing for the achievement of an active material with a good crystalline quality. Post-grown temperature annealing can also be used. Based on this approach, Ge photodetectors rapidly achieved outstanding performances. High responsivity, high speed operation and low dark current have been demonstrated in different configurations [13–27]. Ge photodetectors are now considered to be a mature device, available in multi-project-wafer (MPW) platforms [https://mycmp.fr/IMG/pdf/overwier_cea_leti_ic_si310-phmp2m_june2017.pdf, http://www.aimphotonics.com/pdk, https://www.imec-int.com/en/silicon-photonic-ICs-prototyping, https://www.a-star.edu.sg/ime/SERVICES/R-D-Fab/silicon_photonics_multi-projects-wafer] and also in industrial foundries [[28], https://www.globalfoundries.com/technology-solutions/silicon-photonics].

In parallel with the development of Ge photodetectors, an extensive number of works has been devoted to silicon-based optical modulators. Phase modulation by free-carrier concentration variation is used to achieve high-speed modulation in silicon, and many different configurations have been proposed to optimize the typically trade-offs between efficiency, loss and speed. Electrical structures such as PN, PIN, PIPIN diodes or MOS capacitors have been integrated in SOI waveguides to achieve carrier injection, depletion or accumulation. An overview of the early evolution of Si modulator can be found in Ref. [29]. State-of-the-art silicon on-off keying (OOK) modulators are currently reaching 50-Gb/s operation [30–33] while advanced multi-level modulation formats such as n-level pulse amplitude modulation (PAM-n), quadrature phase-shift keying (QPSK), or even 16-level quadrature amplitude modulation (16-QAM) allow to increase transmission data rate up to 224 Gb/s [34–39]. Interestingly, while most of the reported works have been carried out in the conventional communication band (C-band) centered around 1550 nm, silicon photonics systems are also highly attractive for short-reach applications such as intra-datacenter communications. Those are typically located in the original communication window (O-band), around the wavelength of 1310 nm, to benefit from negligible chromatic dispersion of standard optical fibers. Despite the lower free-carrier dispersion effect at this wavelength in comparison with the C-band, high-performance devices have been demonstrated, showing 50-Gbit/s OOK modulation [32] or low-voltage operation [40]. Developing higher-order modulation formats in the O-band is also receiving significant amount of research attention [41–44].

Like Ge photodetectors, Si modulators are currently mature devices available for applications. However for some specific applications, for instance short-reach communications, the power consumption of the modulator is recognized as a key metric that has to be minimized to overpass current electrical-based interconnects. It has thus been evaluated that to effectively replace copper wire for chip-to-chip or on-chip communications, the power consumption of the optical modulator has to be below 100 fJ/bit [45]. Silicon modulator based on carrier concentration variations typically requires the use of an active region with a length of a few millimeters, altogether with voltages of a few volts. The energy consumption required to charge/discharge the corresponding capacitance is typically of a few pJ/bit. Resonant structures can take benefit from a nonlinear transfer function to reduce the active region surface, the price to pay being a reduced optical bandwidth. Electroabsorption can be used to overcome this problem and to provide compact (<100 μm) and low power consumption (<100 fJ/bit) optical modulator. Despite being an indirect bandgap material, the small difference between the direct and the indirect bandgap energy of Ge allows the achievement of strong electroabsorption at its direct bandgap energy. Ge or SiGe Franz-Keldysh modulator monolithically integrated on silicon have been reported since 2008 [46], and followed by different demonstrations [47–49]. Recent works have shown that these SiGe modulators are now reaching a strong maturity towards applications in telecommunications field [50–53]. Electroabsorption using Ge/SiGe Multiple Quantum Wells (MQW) has also been studied, with a first demonstration in 2005 [54]. As a main advantage in comparison with Franz-Keldysh effect, the absorption band-edge of the QW structure can be tuned to achieve modulation at 1.55 [55, 56] or 1.3 μm [57, 58] wavelengths, i.e. in the C- or O-band of communications. Strain compensated Ge/SiGe QW can be grown on Ge-rich SiGe virtual substrates, obtained by the growth of a thick (typically 10 μm) graded buffer from Si to Ge-rich SiGe layer, followed by a 2-μm-thick Ge-rich SiGe layer. Good quality of Ge/SiGe QW was obtained, with a reduced width of the excitonic absorption peak of about 6 meV [59]. A review of the early achievements towards photonic integrated circuits based on Ge/SiGe QW can be found in Ref. [3]. More recently, attention has been dedicated to the possibility to achieve phase modulation by QCSE [60]. A giant electro-optic effect has already been demonstrated in coupled quantum-well structures [61]. As a main challenge, the integration of Ge/SiGeQWs with SOI waveguides remains the main limiting factor to develop silicon photonics transceivers based on Ge/SiGe QW [62–65]. As an alternative path, it was proposed to use

Ge-rich SiGe virtual substrates as a passive waveguide, allowing the demonstration of an on-chip transmission link using Ge/SiGe QW modulator and photodetector grown on Si substrate [66]. This new platform was further explored, and the possibility to achieve tight bends, MMIs and Mach-Zehnder interferometers was demonstrated [67].

The possibility to use the direct gap transition of Ge and SiGe alloys has also opened an exciting research field towards the monolithic integration of light sources on photonic integrated circuits [68–73]. The realization of a Ge-based laser source requires band engineering to tailor the Ge properties accordingly, targeting an efficient direct band gap emission. An alternative approach has been proposed, using GeSn alloys to achieve a direct band gap material. GeSn laser has thus been demonstrated both optically and electrically pumped [74–76]. It can be noted that increasing Sn concentration in the alloy also creates a reduction of the bandgap energy, shifting the operation wavelength towards 2–3 µm, opening a perspective, for instance, in the use of new communications wavelengths.

3 Ge-based mid-IR photonic integrated circuits: passive circuits

During the last 15 years, Ge-based active devices have been developed to complement Si passive photonics circuits. This evolution, which was first driven by Telecom and Datacom applications in the near-IR, later became preclude of promising new perspectives using longer wavelengths in the mid-IR range. Figure 2 shows material transparency windows with optical loss below 2 dB/cm [77].

While Si is transparent up to 8 µm wavelength, the strong absorption of SiO_2 is expected to limit the operating wavelength range of conventional SOI waveguides beyond 4 µm. However, different strategies have appeared recently such as a proper design of SOI waveguide to limit the overlap of the optical mode with the lower silicon dioxide cladding [78]. Other options rely on the combination of Si membrane engineered by sub-wavelength grating nano-structuration to achieve air-cladded Si waveguides [79], the use of Si nanopillars [80], or Si on Sapphire [81]. The state-of-the-art Si-based mid-IR devices such as waveguides, sources, modulators or photodetectors can be found in recent review papers [6–8].

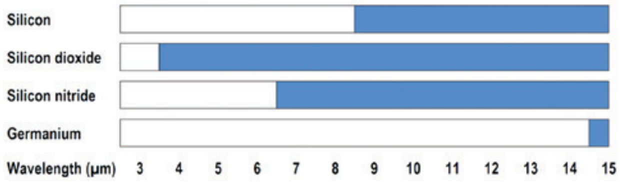

Figure 2: Materials available for monolithic integration on Si: transparency window in the mid-infrared is the white bar. The blue bar corresponds to wavelength range over which waveguide propagation loss is more than 2 dB/cm, adapted from Ref. [77].

In parallel with the development of Si-based mid-IR photonic circuits, Ge is a prime candidate to extend the operating wavelength of Group IV-based photonic integrated circuits beyond 8 µm, potentially up to 15 µm [6, 77]. Furthermore, Ge benefits from a strong third-order nonlinearity which can also be advantageously exploited for the development of active devices [82]. In the last years, the development of photonic platforms dedicated to longer mid-IR wavelengths has witnessed a burst of research activity, mainly based on Ge or SiGe alloys. We will first review the different Ge-based photonic platforms. In the different cases, the characterization of the waveguide propagation losses is the starting point to evaluate the potential usefulness of each platform. Then, passive photonic devices have been developed to create a set of building blocks that can be further combined to form future mid-IR photonic integrated circuits. Among all, on-chip resonators are one of the key building blocks to be exploited in the mid-IR spectral range, for the development of on-chip sensing, spectroscopy, as well as nonlinear optical functionalities. In the following, we will review the different proof-of-concepts towards molecular sensing, before focusing on the active devices such as optical sources or modulators.

3.1 Different waveguide platforms

Initial works used Germanium-on-Silicon (GOS) waveguides. Losses of 2.5 dB/cm have been obtained at 5.8 µm wavelength [83]. Mid-IR wavelength (de)multiplexers based on planar concave gratings (PCGs) [84] and Arrayed Waveguide Grating (AWG) Multiplexers [85] have been demonstrated, providing an operation in the 5-µm wavelength range. The GOS platform is widely used in photonics research presently and many impressive achievements have been performed even on active building blocks as will be shown later. The lowest propagation loss on that platform reported so far had a loss of only 0.6 dB/cm at 3.8 µm wavelength [86]. However, the silicon bottom cladding is expected to limit the device operation to wavelengths shorter than 8 µm. Recent work reported propagation from

7.5 to 8.5 μm wavelength. A minimum value of 2.5 dB/cm at λ ~7.5 μm was obtained; however, losses rapidly increased for longer wavelengths up to 20 dB/cm [87]. Optical and nonlinear properties of GOS waveguides have also been studied theoretically to define waveguide design guidelines for several applications [88]. GOS cavities have been developed around 3.8 μm wavelength, based on racetrack resonators [89].

In parallel with the GOS platform, Ge-on-SOI could present some advantages, especially in terms of thermal and electrical isolation due to the underlying SiO_2 buffer. However, optical absorption in the buried oxide buffer can limit the transparency range of the Ge-on-SOI platform beyond 3.6 μm wavelength. Losses of 8 dB/cm have been achieved for 0.85-μm-thick Ge core at 3.682 μm wavelength [90], while comparable values of 7 dB/cm have been reported previously in the wavelength range of 5.25–5.35 μm [91]. Thermo-optic phase shifters have also been developed [91] and used to achieve thermally tunable racetrack resonators in the 5 μm wavelength range [92].

Ge-On-Insulator (GeOI) and Ge-on Silicon Nitride (SiN) have also been proposed to benefit from larger index contrast between Ge (n = 4) and SiO_2 (n = 1.4) or SiN_x (n = 1.9). Propagation loss was found to be 1.4 dB/mm for GeOI rib waveguides at 2 μm wavelength, while negligible bend loss was obtained even with a 5-μm bend radius, owing to the strong optical confinement in the GeOI structure [93]. Ge-on-SiN should benefit from a transparent cladding up to about 7.5 μm wavelength. At the wavelength of 3.8 μm, the Ge-on-SiN waveguide has a propagation loss of 3.3 dB/cm and a bend loss of 0.14 dB/bend for a radius of 5 μm [94].

Ge membrane is an ultimate way to take benefit from the wide transparency of Ge, without any limitation from cladding absorption. Resonators have been demonstrated around 2 μm wavelength based on air-cladded Ge membranes. Photonic crystal cavity has offered a moderate Q factor of 200 [95], while more recently a loaded Q-factor of ~57,000 has been achieved around 2 μm wavelength, using an air-cladding Ge micro-ring resonator [96].

Fiber-to-chip grating couplers have been demonstrated for the different waveguide platforms, first at 3.8 μm wavelength for GOS substrate [97] and then at 5.2 μm wavelength for both GOS and Ge-on-SOI platforms [98]. In the last case, –5 dB efficiency with a 3-dB bandwidth of 100 nm was obtained for GOS grating couplers, while –4 dB efficiency with a 3-dB bandwidth of 180 nm was achieved for Ge-on-SOI case. Coupling into suspended Ge membrane was also demonstrated using focusing subwavelength grating coupler at a wavelength of 2.37 μm [99].

In parallel with pure Ge-based waveguides, the use of SiGe alloys presents the advantage to allow fine tuning of the waveguide properties such as refractive index and dispersion. Graded SiGe/Si waveguides have been investigated first. In this case, the core itself of the waveguide was graded, with a Ge concentration from 0% to 40% and losses as low as 1 dB/cm at λ = 4.5 μm and 2 dB/cm at 7.4 μm was thus demonstrated [100]. Passive functions such as AWG multiplexer have then been obtained, operating at 4.5 μm [101]. $Si_{0.6}Ge_{0.4}$ waveguide on Si substrate has also been used to define dispersion engineered strip waveguides [102]. Minimal losses of 0.5 dB/cm at 4.75 μm was obtained [103].

On another hand, we have recently proposed Ge-rich $Si_{1-x}Ge_x$ alloys on graded $Si_{1-x}Ge_x$ layers as an alternative approach for mid-IR integrated photonics. One of the relevant features of these waveguides is their expected wide transparency window, which could potentially extend up to λ = 15 μm, as the refractive index gradient allows to push the optical mode far from the Si substrate.

Propagation losses lower than 2 dB/cm were first obtained at 4.6 μm wavelength [104], while losses of 2–3 dB/cm were then demonstrated between 5.5 and 8.5 μm wavelength [105]. Broadband Mach-Zehnder interferometers have been demonstrated, working in both quasi-TE and TM polarizations [106]. Interestingly, these structures also allow to finely tune the refractive index profile, permitting an efficient tailoring of the waveguide properties such as mode confinement and dispersion. An optimal design was investigated and a graded 6-μm-thick $Si_{1-x}Ge_x$ stack was defined as an attractive platform to develop mid-IR nonlinear approaches requiring broadband dispersion engineering [107]. Additionally wideband and polarization-insensitive waveguides can also be designed by optimizing waveguide dimensions, opening new perspectives for mid-IR free-space communications [108]. First resonators on this platform, based on Fabry-Perot cavity, demonstrated a Q-factor of more than 1200 at 8.4 μm wavelength [109].

So far, first generations of Ge-based waveguides have already exhibited interesting properties up to 8.5 μm wavelength as summarized in Figure 3. Waveguide performance is continuously improving, and their operation wavelength is rapidly increasing towards 15 μm which is the theoretical maximum that can be expected. Efforts have also been devoted to build basic elements for further complex functionalities within the Ge platform.

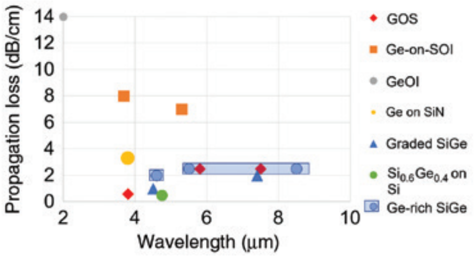

Figure 3: Development of photonic platforms dedicated to MIR wavelength based on Ge or SiGe alloys: propagation losses reported in the literature, Refs. [83, 86, 87, 90, 91, 93, 100, 103–105].

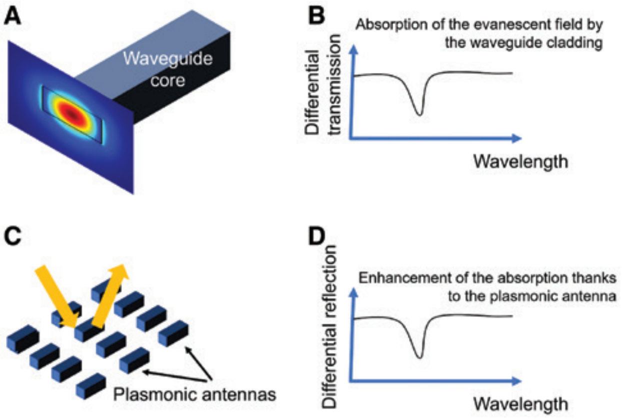

Figure 4: Different methods for optical biosensing using mid-IR absorption in the fingerprint region; (A) and (B) absorption spectroscopy experiment based on the absorption of the evanescent component of an optical mode. The measurement of the transmission of the waveguide with and without the substance to be detected as a top cladding allows to retrieve and quantify the different molecules in the substance; (C) and (D) sensing experiment using plasmonic antennas, based on the measurement of the reflexion of the nanoantenna with and without the substance to be detected as a top cladding. The sensitivity is increased by the plasmonic effect. Adapted from Ref. [113].

3.2 Sensing demonstrations

In parallel to the development of passive devices based on the Ge platform, the potential for sensing is also being evaluated by several research groups. Optical biosensors are generally based on the sensitivity of optical structures to changes in the surrounding materials to detect the presence of molecules. Refractive index variations can then be detected using Si- or Ge-based photonics devices, such as resonators [110], photonic crystals [111] or PIN photodetectors [112]. Most of these works are reported around 1.5 µm wavelength because of the availability of test equipments in this wavelength range. On another side, by using mid-IR integrated photonics, absorption spectroscopy can rely on the unique absorption characteristics in the fingerprint region to unambiguously identify different molecules, without the need for waveguide functionalization. The monitoring of the absorption of the evanescent component of mid-IR propagating guided modes to probe surrounding cladding environments is illustrated in Figure 4A and B. This method has been reported on different material platforms such as chalcogenide [114, 115] or silicon [116]. This method has also been used with Ge-based photonic integrated circuits. A Ge strip waveguide on a Si substrate, integrated with a microfluidic chip, has been used to detect cocaine in tetrachloroethylene (PCE) solutions. The demonstration was done at 5.8 µm wavelength, and small concentrations of 100 µg/ml have been successfully detected [117]. This technique has also been explored in Ge-rich graded SiGe waveguides. The measurement of the absorption of a standalone photoresist spin-coated onto spiral Ge-rich SiGe waveguides allowed us to identify a particular optical loss characteristic within the spectral window of 5.2–7 µm and to correlate it with the inherent photoresist absorption. Based on this result, the ability of this platform to sense small concentrations of methane gas has been discussed [118].

Plasmonics is generally known as a way to enhance sources, sensors and detectors for applications in chemical sensing or thermal imaging. Surface plasmons can be used to confine the optical field at the surface and to strengthen the interaction between the material to be detected and the optical beam [119, 120]. The challenge of mid-IR plasmonics is to propose cost-effective, compact and reliable platforms. In this context, the implementation of heavily doped Ge films is interesting as it possesses plasma frequencies in the mid-infrared range. Mid-IR plasmonics sensing using antenna made of heavily doped Ge has thus been proposed to take advantage of the CMOS platform to revolutionize plasmonic sensors usually based on gold. Detailed study of the dielectric function and the losses of heavily doped Ge in the mid-IR has been reported [121]. Among the key challenges, increasing the doping concentration up to a value approaching 1020 cm^{-3} over uniform doping profile of the order of 300–500 nm would be desirable to cover the whole fingerprint region. A combination of *in situ* doping and excimer laser annealing has been used to improve the activation of phosphorous in germanium. An activated n-doping concentration of 8.8×10^{19} cm^{-3} was used [122]. In terms of sensing demonstration, up to 2 orders of magnitude signal enhancement for molecules located in the heavily doped Ge antenna hot spots compared to those located on a bare silicon substrate has been obtained using an experiment schematically illustrated in Figure 4C and D [113]. The detection and amplification of molecular absorption lines from a mustard gas simulant was also demonstrated at 14 μm wavelength [123].

GeSn alloys present also some interest for plasmonics sensing. Compared to Ge, GeSn alloys offer an additional benefit of lower conductivity effective mass and, thus, higher plasma frequency. Highly doped $Ge_{0.95}Sn_{0.05}$ films have been characterized by ellipsometric tools to evaluate their suitability as plasmonic materials in the IR wavelength range. It was demonstrated that n-type doped $Ge_{0.95}Sn_{0.05}$ exhibits metallic behavior at wavelengths larger than 6.4 μm, thus making the material potentially suitable for plasmonic applications even at wavelengths below 10 μm [124].

All these demonstrations, using absorption of the evanescent field of propagating guided modes or surface plasmon enhancement, pave the way towards the demonstration of compact, portable, label-free and highly sensitive photonic integrated sensors based on Ge mid-IR photonics circuits.

4 Ge-based mid-IR photonic integrated circuits: active building blocs

Besides the development of waveguide, resonators or sensors, the successful development of active devices to manipulate light and convert signals from electrical to optical domain can put the Ge-based platforms at the first level for future mid-IR photonics systems.

4.1 Non-linear optics in Ge and SiGe

Lots of works as well as previous review papers have been dedicated to non-linear photonics based on Si and Ge [6] and to mid-IR integrated photonics on Si [8]. We have thus chosen to recall the main motivations and to focus on recent works using non-linear optics (NLO) in Ge and SiGe platform in the mid-IR.

Both Si and Ge exhibit strong third-order NLO coefficients while two-photon absorption (TPA), which is known to limit the efficiency of nonlinearities, vanishes in the mid-IR [125, 126]. In terms of SiGe alloys, the properties of both Si-rich and Ge-rich waveguides have been investigated. The NLO response of $Si_{0.6}Ge_{0.4}$ waveguides has been investigated from 3.25 to 4.75 μm using picosecond optical pulses, allowing the measurement of three- and four-photon absorption coefficients as well as the Kerr nonlinear refractive index [103]. Third-order nonlinear experimental characterizations of $Si_{1-x}Ge_x$ waveguides have also been reported at a wavelength of 1580 nm for $x = 0.7$, 0.8 and 0.9, and extrapolated in the mid-IR [127].

Furthermore, numerical simulations have shown that octave spanning nonlinear applications, including on-chip supercontinuum generation, ultrashort pulse compression and mode-locked wideband frequency comb generation based on micro-resonators require dispersion-flattened waveguides [6]. Nonlinear characterizations and numerical simulations are particularly interesting as they provide insights for the design of nonlinear integrated optical based devices [128].

As a fundamental NLO-based device, supercontinuum generation is a way to achieve on-chip wideband source. This relies on self-phase modulation due to Kerr effect. Ge-on-Si waveguides have been designed with flat and low dispersion profile, ranging from 3 up to 11 μm. Numerical simulations have shown that such waveguide enables the generation of coherent supercontinuum in a spectral range from 2 to 12 μm [129]. Similarly, graded-index SiGe waveguides have been engineered, allowing for broadband tight modal confinement and flat anomalous dispersion for the perspective of supercontinuum generation [130].

In terms of experimental demonstrations, supercontinuum has been obtained from 1.45 to 2.79 μm in a graded SiGe waveguide [131] and from 3 to 8.5 μm in a $Si_{0.6}Ge_{0.4}/Si$ waveguide [132]. Interestingly, an average power of more than 10 mW on-chip was obtained in the latter, attributed to the low loss of the waveguide.

Recently, third harmonic generation has also been demonstrated in plasmonic antennas made of highly doped germanium, allowing the demonstration of a coherent light source tunable between 3 and 5 μm wavelength on Si substrate [133].

NLO can also been used for wavelength conversion based on four wave mixing. Signal conversion from 2.65 to 1.77 μm was demonstrated using a pump at 2.12 μm in phase matched graded SiGe waveguide [134].

4.2 Mid-IR monolithically integrated optical modulators and photodetectors

While spectroscopic application would require on-chip modulator for synchronous detection to increase detection sensitivity, most of the works towards Si- and Ge-based optical modulator and photodetectors are developed up to now in the framework of data communication, in the short-wave infrared, i.e. below 4 µm wavelength. Extending the wavelength of data communications towards 2 µm wavelength is envisioned typically for chip-to-chip or board-to-board communications [135]. In this context, the monolithic integration of electro-optic components such as modulator or photodetector is highly required to increase the functionality of the chip.

The field of mid-IR group IV-based optical modulators is still at its infancy. As reported before, Ge-based materials can be used for electro-absorption using Franz-Keldysh in Ge, SiGe or Quantum Confined Stark effect Ge/SiGe QW. These demonstrations have been performed at 1.3–1.5 µm wavelength, the wavelength being determined by the absorption band-edge of the material. Doping Ge with Sn results in a transition from indirect to direct bandgap, but also in a decrease of the bandgap energy. This is the reason why GeSn lasers operate at 2 µm wavelength. Thus the use of GeSn materials has been proposed to achieve light modulation by electro-absorption at this wavelength range. Franz-Keldysh GeSn modulator was designed, with 6 dB extinction ratio for a 2 V_{pp} drive signal and a 35-GHz bandwidth [136]. It was also proposed to use Quantum Confined Stark Effect in GeSn/SiGeSn QW. Modeling indicates that more than 6 dB extinction ratio should be obtained with a 215-µm long device [137]. To achieve wavelengths beyond 2 µm, alternative effects have to be used. Silicon modulators in the near-IR use free-carrier plasma dispersion effect. The extension of this effect in the MIR has been theoretically evaluated first in Si [138] and then in Ge [139]. Interestingly, it was predicted that the plasma dispersion effect becomes more effective when the wavelength increases. Experimental demonstrations have then been reported using carrier injection in a silicon PIN diode. Modulation at 2.165 µm has been reported using phase modulation in a Mach-Zehnder interferometer [140], followed by the demonstration of variable Optical Attenuator at 2–2.5 µm wavelength [141]. Intensity modulation was also demonstrated in the 2-µm band by injecting current through a lateral p-i-n junction in a Ge on Insulator waveguide [93]. Finally, modulators have also been demonstrated working at 3.8 µm wavelength using free-carrier absorption by carrier injection both in a SOI and a Ge-on-Si waveguide [142].

In parallel with these studies of electro-optic modulation, all-optical modulation has also been demonstrated using free-carrier absorption across wavelength range of 2–3.2 µm [143].

So far several approaches have been considered for mid-IR on-chip photodetection, most of them relying on heterogeneous integration of III–V material on Si [144] or other material such as graphene [142] or nanoparticles [145]. Monolithically integrated Ge-based photodetectors could offer considerable potential for low-cost and high-performance systems. As mentioned earlier, GeSn provides a lower bandgap energy than Ge or SiGe. Photodetection beyond 2 µm was obtained in surface illuminated photodiodes using GeSn/Ge multiple quantum wells [146, 147], GeSn-on-Silicon [148] or Ge/$Ge_{1-x}Sn_x$/Ge heterostructures grown on Silicon [149].

These different approaches related to band-to-band transition are intrinsically limited to SWIR, while there is a need for practical monolithically integrated sensors at longer wavelength. As a good candidate, quantum well infrared photodetectors (QWIPs) rely on intersubband transitions within the QW, thus shorter photon energy is achievable. QWIPs based on SiGe alloys have been demonstrated in different configurations. In initial works, Si-rich structures were considered thanks to the easier procedure for obtaining Si-rich relaxed SiGe virtual substrates [150]. More recently, with the achievement of good quality Ge-rich SiGe virtual substrates [151], it has been possible to conceive Ge-rich SiGe QW showing intersubband absorption from 6 to 9 µm wavelength at room temperature that can be tuned by adjusting the quantum well thickness [152].

5 Conclusion and perspectives

Silicon photonics is now a well-established technology. While the use of SOI wafers allows for strong field confinement and tight bends, the combination with Ge permits to obtain high performance active devices required for telecom and datacom applications, at near-IR wavelength. The evolution of Ge-based active devices within Si photonics paved the way towards new wavelength range capabilities, as it allows extending the operation of photonic integrated circuits deep inside the mid-IR range.

Today, wavelengths up to 8.5 µm have been achieved, with propagation loss of only a few dB/cm. A whole set of passive building blocks have also been developed, such as wavelength mulitplexers, fiber couplers or resonators. Main applications are related to absorption spectroscopy, as in this fingerprint wavelength range, most of the molecules have a unique absorption signature, which enables to retrieve and quantify their presence without any waveguide functionalization. First proof of concepts of molecular optical sensing has been demonstrated, based on the absorption of the evanescent tail of the optical mode, or on surface plasmon-enhanced absorption. These works have shown a huge potential for mid-IR absorption spectroscopy.

Active devices such as mid-IR wideband source, modulator and the photodetector are thus required to complete the Ge-based mid-IR platforms. Differents works have already been reported towards this objective, based on a myriad of different physical effects such NLO, plasma dispersion effect, intersubband transitions, Franz-Keldysh or Quantum Confined Stark Effect, to name of few.

Ge-based mid-IR photonics is an exciting and rapidly expanding field. The performance of passive and active devices is continuously improving, and the maximum attainable wavelength range is rapidly expanding. Efforts have been devoted to build basic elements for further complex functionalities within the Ge platform. Interestingly, this evolution relies on the fine comprehension of physical mechanisms of Ge, GeSn and SiGe materials. Based on the current evolution, the use of Ge-based photonics in commercial devices can be expected in a short term.

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