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# PHOTONIC GE-BASED PLATFORMS FOR MID-IR INFRARED APPLICATIONS

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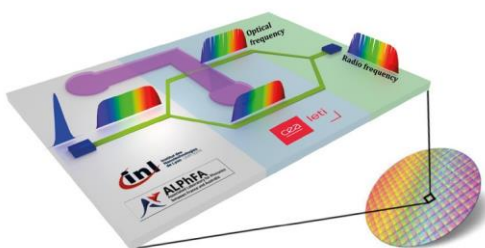
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pectroscopic systems operating in the Mid-infrared (e.g. the MIR- wavelength region between 3 and 15  $\mu\text{m}$ ) can track specific chemical and biological fingerprints for molecule identification and quantification. They are based on light absorption induced by the excitation of rotational and vibrational energy levels of target molecules. As the light is absorbed by the target molecule, and analysed spectrally (e.g via the spectral analyser), multiple absorption lines appear in the absorption spectrum, their linewidths and peaks depending on the surrounding

Silicon photonics, initially developed for data communications in the near infrared (NIR), has been extended over the last ten years to the mid-infrared (MIR) region. Efforts have been made to fully integrate MIR functions at chip level on Ge and Si planar substrates, to achieve greater reliability and higher performance at lower cost. The fields of application are vast, ranging from IR imaging of biological tissues to environmental monitoring, control of industrial processes, security and many more.

environment (gas/liquid phases, temperature, pressure etc.). The wavelengths and amplitudes of the absorption in the spectrum provide information about the detected species and their amounts. Figure 1 shows examples of molecules of interest accessible in the mid-infrared covering the field of environmental monitoring, defence and security, industrial process monitoring and medical diagnostics.

Our long-term vision is to create integrated photonic absorption sensors wherein the evanescent part of the propagating optical mode is absorbed by a medium/target molecule located outside in the vicinity of the

waveguide. One approach relies on the use of tunable light sources (or an array of light sources) with narrow linewidths, with wavelengths that are absorbed by the substances/analytes to be detected. The transmission is then measured with a detector. Another approach involves using a broadband and bright optical source called supercontinuum (SC) generated in Ge or SiGe waveguides and placing a spectrometer before the photodetector to measure transmission as a function of wavelength. We present here examples of Ge-based integrated photonic circuits used for environmental detection

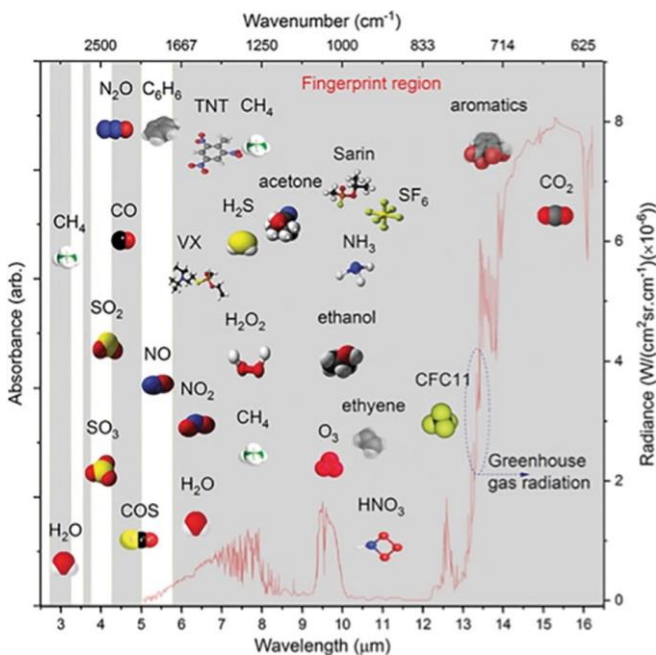
and the working principles of super-continuum light sources and integrated spectrometers.

### GE-BASED INTEGRATED PHOTONIC CIRCUITS

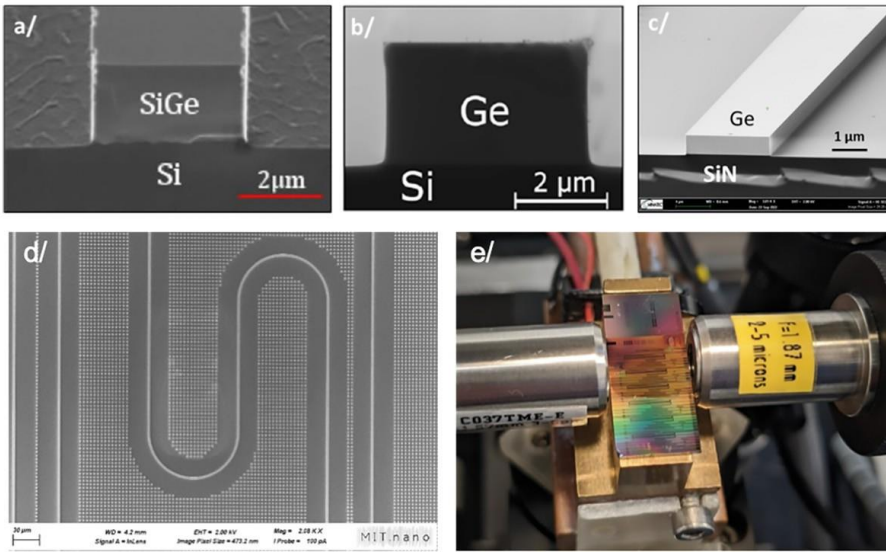
Over the past 10 years, optoelectronic components based on germanium (Ge) have been developed to expand the potential of silicon (Si) photonic circuits. Photodetectors, modulators, and Ge-on-Si lasers have been demonstrated in the mid-infrared region. Ge's main advantage lies in its large transparency window, ranging from 1.8 to 14  $\mu\text{m}$  in wavelength and its CMOS compatibility. Ge and SiGe alloys have quickly been regarded as preferred materials for the development of integrated photonic components. Thick Ge and SiGe layers (up to 40% of Ge) are conventionally grown on 200 mm and 300 mm Si(001) wafers by chemical vapor deposition in industrial epitaxy cluster tools. Further details on Ge and SiGe growth can be found in reference [1]. SiGe or Ge on insulator (like SiN) wafers can be fabricated from the previous epitaxies. In such a case, two wafers need to be bonded: the first ones with Ge or SiGe epitaxial layers capped with SiNx layers and thin SiO<sub>2</sub> layers, the second ones being oxidized Si wafers. After SiO<sub>2</sub> to SiO<sub>2</sub> bonding, the starting

substrates on which Ge or SiGe thick layers were grown, are removed by grinding followed by chemical mechanical polishing steps. Polishing improves the Ge crystalline quality by removing the heavily dislocated interface between Si and Ge. Waveguides are then patterned by conventional photolithography and deep reactive ion etching (RIE) down to the Si substrate (Figure 2a and Figure 2b) or the SiN layer (Figure 2c).

A set of passive functions, such as wavelength multiplexers, couplers, paperclips, spirals, Mach Zehnder interferometers and ring resonators can be fabricated using conventional lithographic steps on epitaxial wafers. A review on silicon-based mid-IR integrated photonics can be found in reference [1,2]. Such miniaturized integrated devices offer higher accuracy, reliability, portability, and cost effectiveness compared to existing systems, enabling their use in new application fields like oil and gas process monitoring, gas leak detection, agri-food manufacturing monitoring, and point-of-care and portable laboratory bioanalyses. On-chip absorption sensing of paraffin oil has, for example, been achieved with Ge/SiN spiral waveguides (Figure 2c and Figure 2d). The propagation losses were evaluated for several wavelengths (5.9  $\mu\text{m}$ , 6.7  $\mu\text{m}$ ) ●●●



**Figure 1.** Examples of molecules of interest accessible in the mid-infrared covering the field of environmental monitoring, defence and security, industrial process monitoring and medical diagnostic. Reproduced from Laser Photonics Rev. 11, No. 2, 1700005 (2017).



**Figure 2.** Electron microscopy image of a/ a cleaved SiGe 40% on Si waveguide, b/ a Ge on Si waveguide and c/ a Ge on SiN waveguide, d/ SEM top view of a Ge spiral waveguide on SiN, e/ Injection set-up of laser light at 5.9 μm and 6.7 μm into the spirals of a silicon photonics circuit.

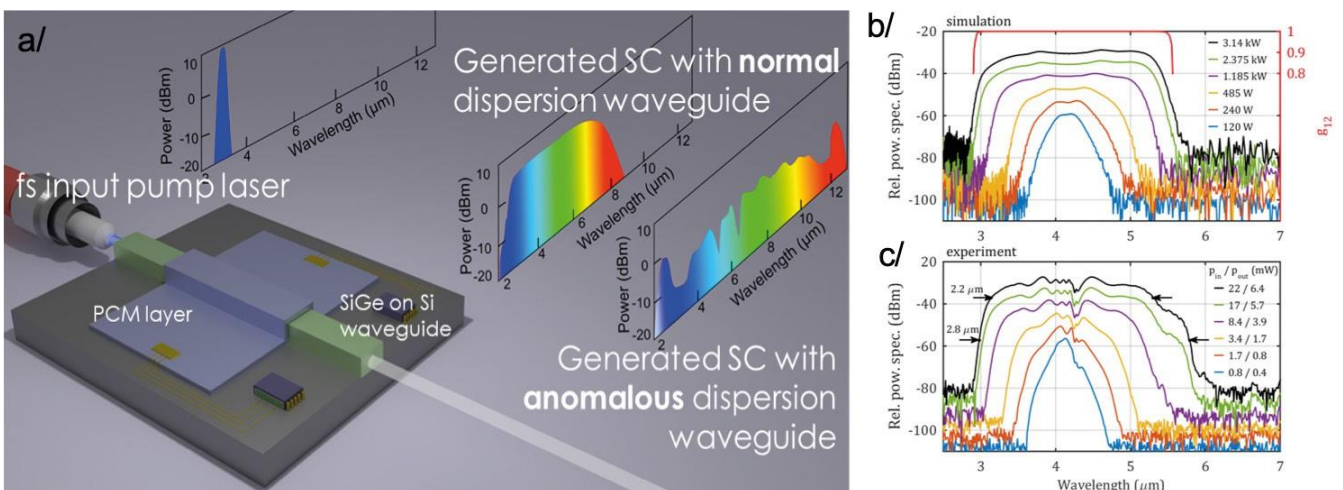
in so-called butt-coupling configurations (Figure 2e). An increase in propagation losses of 0.9 dB/cm in the presence of chemically inert paraffin oil was obtained at 6.7 μm corresponding to the maximum peak absorption of the paraffin liquid. Apart from the absorption peak at 6.7 μm, an increase less than 0.15 dB/cm in propagation losses at 5.9 μm was measured in the presence of the oil (the mode deconfinement due to the presence of the liquid explains, among other things, this increase of losses at 5.9 μm). Such approach could also be applied in the medical field to identify chemicals and quantify the concentration of liquids thanks to their characteristic infrared

absorption features. For example, more patients could benefit from absorption spectroscopy analysis to detect biomarkers of metabolic variations or inflammatory phenomena. These biomarkers provide valuable information for the early detection of cancer, avoiding false positives, improving prognosis and lowering treatment costs.

**GE-BASED LIGHT SOURCES**

A key ingredient for MIR integrated spectroscopic systems is the light source. A lot of progress has been made with important research efforts on direct band gap lasers (as III-V or group-IV lasers), interband cascade lasers (QCLs), optical parametric oscillators (OPO) or fiber-based-lasers, to name a few. QCLs, probably the current MIR sources of choice, are already commercially available but often require low temperature operation and are costly. They otherwise have a restricted tunable spectral

**Figure 3.** (a) Illustration of supercontinuum generation in a SiGe waveguide with either normal or anomalous dispersion dynamically controlled by top cladding phase change material (credit Alberto Della Torre), (b) Simulated and (c) measured (b) SC spectra for All Normal Dispersion waveguide for various coupled average powers. The top red curve in (b) shows the SC spectra's calculated coherence at the highest (3.14 kW) peak power. The black arrows in (c) indicate the 10 dB and 30 dB limits of the spectrum. The measured coupled input and on-chip output average powers are given in the inset (c) and the estimated coupled peak powers in the inset (c). Reproduced from [4].



range, so that a single QCL cannot cover the entire molecular fingerprint. Instead of multiplexing the output of a series of fixed wavelength QCLs, a single bright and broadband source that can access all the wavelengths in parallel like a supercontinuum (SC) [3], seems an attractive alternative. Supercontinuum generation is usually achieved by broadening, via cascaded nonlinear effects (Figure 3), the spectrum of a mode-locked pump laser, constituted of hundreds of thousands closely spaced frequency lines (frequency comb). This comb structure results in a supercontinuum that can cover a spectral band of more than one octave in the molecular fingerprint region. It is therefore well suited for high-resolution multi-species parallel molecular spectroscopy with high throughput.

Generally speaking, SC generation can be achieved in either anomalous dispersion (*i.e.* positive group velocity dispersion) or normal dispersion (*i.e.* negative group velocity dispersion) regime (Figure 3). The former is characterized by a broad spectrum, which is, however, not spectrally flat, and has low coherence. Our group demonstrated such SC back in 2018, with the first SiGe waveguide-based SC reaching the onset of Si absorption (8.5  $\mu\text{m}$ ) that was broadband (1.4 octave span) and bright (20 mW on-chip average power with potentially 70% conversion efficiency). The latter allows to generate flat and low noise SC spectra but generally to the detriment of the bandwidth. We demonstrated these so-called ANDi SC for the first time in the MIR in SiGe waveguides in the early 2020 [4]. Recently, we leveraged the potential of integrated optics for a precise dispersion control to go a step further. We designed a multi stage waveguide (anomalous dispersion section followed by a varying width section resulting in a varying dispersion from anomalous to normal) to simultaneously increase the bandwidth of the generated SC and improve its spectral flatness. We exploited such SC for a proof-of-principle demonstration of multi-species gas (water vapour and carbon dioxide) spectroscopy in our laboratory environment [5]. We are currently exploring heterogeneous integration schemes with phase

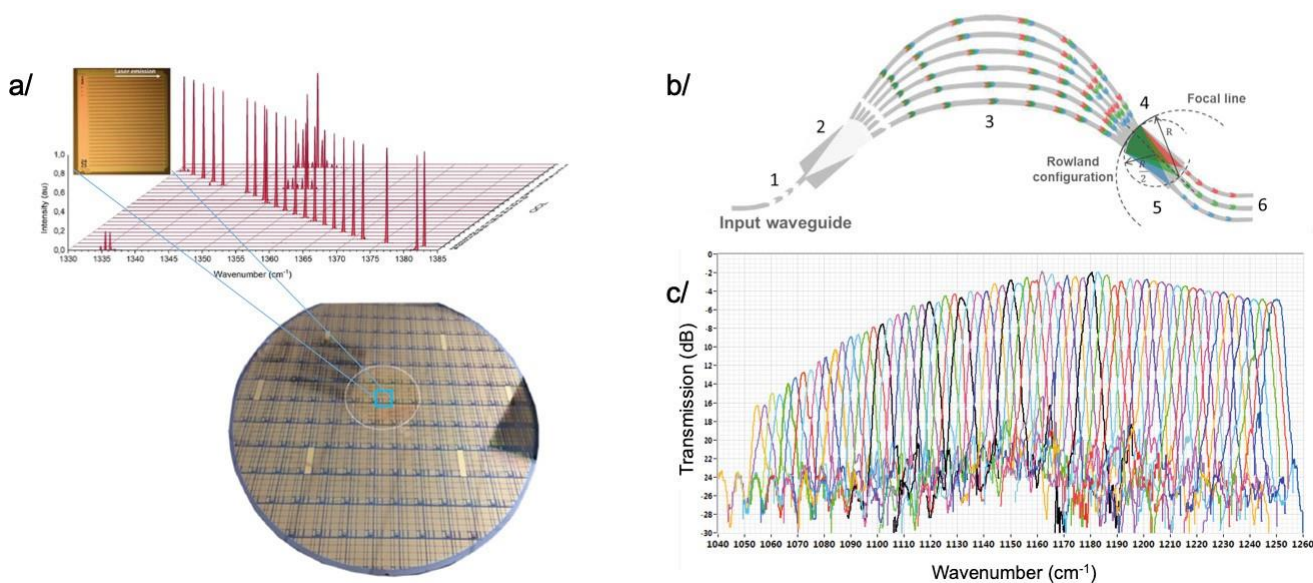
ange material to dynamically control the waveguide dispersion state and therefore the supercontinuum spectral and temporal properties (Figure 3).

As previously stated, the high manufacturing cost of quantum cascade lasers remains a significant hurdle in their widespread adoption for chemical sensing applications. However, the integration of Mid-Infrared sources onto silicon substrates utilizing CMOS technology presents a promising way for mass production at a low cost. Additionally, leveraging a silicon-based fabrication platform enables the simultaneous integration of QCL Mid-Infrared sources with SiGe-based waveguides, facilitating the development of fully integrated optical sensors on a planar substrate. Distributed-feedback QCL sources, operating at 7.4  $\mu\text{m}$  and bonded onto 200 mm Si wafers, were recently fabricated in the CEA 200 mm CMOS pilot line (Figure 4a). This advancement is a significant step toward the realization of Mid-Infrared spectrometers at the silicon chip level [6].

### GE-BASED INTEGRATED SPECTROMETERS AND DETECTION

Various integrated spectrometers based on SiGe or Ge waveguides have been evaluated to analyse the absorbed light that was beforehand emitted by a supercontinuum. SiGe 40 % arrayed waveguide gratings (AWG) on Si and Ge AWG on Si have been demonstrated in the 3 to 8  $\mu\text{m}$  and the 8 to 12  $\mu\text{m}$  ranges, respectively. They were operational for both TE and TM light polarizations. The working principle of a demultiplexing AWG is presented in Figure 4b: (1) waveguide containing several wavelengths from a supercontinuum or from an array of lasers, (2) planar waveguide, (3) an array of waveguides, (4, 5) a recombination guiding area, (6) several output waveguides containing different wavelengths. Figure 4c shows transmission losses and spectral characteristics of a multiplexing device with a Ge core embedded in thick Si<sub>80</sub>Ge<sub>20</sub> layers. A channel spacing of  $2.96 \pm 0.16 \text{ cm}^{-1}$  was reached with a crosstalk of 7.4 dB in this particular AWG [3].

Photodetection within this wavelength



range requires semiconductors having small, direct band gaps, typically less than 0.4 eV to be placed after the spectral analyser. Widely used mid-infrared (mid-IR) photodetector materials encompass mercury cadmium telluride (HgCdTe), III–V compounds like InAs and InSb and group-IV compounds such as GeSn alloys. Additionally, commercially available detectors use lead salts or lead chalcogenides such as PbSe, and PbS or PbTe [7]. Interband cascade detectors with III-V materials or quantum cascade detectors are among the device architectures currently under investigation. Finally, photoacoustic detectors are as well good candidates for MIR detection as they can be integrated onto planar substrates [2].

**CONCLUSION**

Ge-based photonics is a solution widely explored today for the development of photonic systems in the mid-infrared. Common technological platforms for integrated and cost-effective mid-IR photonic components are essential for novel applications such as chemical sensing in liquid and gas phase and could have an important impact in the field of sensors for the general public. Currently, the research primarily focuses on demonstrating various aspects with elementary components. Ultimately, the integration of these different elements

ensities of a QCL array emitting at 7.4 μm bonded on 200 mm silicon wafer, reproduced from [6], (b) Principle of operation of an AWG, (c) Spectra measured for 67 outputs of the AWG, reproduced from [3].

will be key to fabricate complex systems. The upcoming challenges will focus on the integration of MIR light sources and photodetectors on photonic platforms. ●

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Figure 4. (a) Typical spectral power

