# Silicon-Based Photonic Integration Beyond the Telecommunication Wavelength Range

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*(Invited Paper)*

***Abstract*—In this paper we discuss silicon-based photonic integrated circuit technology for applications beyond the telecommunication wavelength range. Silicon-on-insulator and germanium-on-silicon passive waveguide circuits are described, as well as the integration of III–V semiconductors, IV–VI colloidal nanoparticles and GeSn alloys on these circuits for increasing the functionality. The strong nonlinearity of silicon combined with the low nonlinear absorption in the mid-infrared is exploited to generate picosecond pulse based supercontinuum sources, optical parametric oscillators and wavelength translators connecting the telecommunication wavelength range and the mid-infrared.**

***Index Terms*—Heterogeneous integration, mid-infrared, nonlinear optics, silicon photonics.**

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## I. Introduction

SILICON photonics is attracting a lot of attention for optical interconnect applications in the datacenter [1]. This is mainly driven by the compactness of the integrated optical components and the fact that these devices can be fabricated using the mature CMOS fabrication infrastructure, resulting in high yield and high volume fabrication. In recent years, the scope of applications for silicon photonics has broadened to e.g. the area of bio-sensing [2] and bio-medical instrumentation [3], which are potentially also high volume markets. In these devices one typically holds on to the telecommunication wavelength range for their implementation. A particular class of sensing applications would however benefi from the availability of photonic integrated circuit technology in other wavelength ranges, while still being able to fabricate these devices in a CMOS environment. This has happened recently for visible wavelength applications, using SiN as the waveguide material [4]. This enables applications such as Raman and fluorescenc spectroscopy. On the long-wavelength side of the telecommunication window photonic integrated circuit technology could be of particular interest for mid-infrared spectroscopic sensing systems that need to be portable and low-cost [5]. These systems, which probe the very specifi and strong mid-infrared absorption spectrum of molecules in a gas, liquid or solid, are currently implemented using bulky and expensive equipment, preventing their widespread deployment. This is in stark contrast with the wide range of applications that could benefi from such a technology, ranging from the fiel of environmental sensing (e.g., air and water quality monitoring), life sciences (e.g., exhaled breath analysis and high throughput histopathology) to industrial process control and security. Besides spectroscopy, these waveguide circuits can fin applications in emerging field such as astrophotonics [6] or provide the toolset for next-generation optical communication systems operating in the 2-$\mu$m wavelength range [7]. This work discusses the firs steps in the direction of silicon-based photonic integrated circuits for the short-wave infrared (up to a wavelength of 2.5 $\mu$m) and the mid-infrared, in order to fil this gap. In this paper we will discuss the realization of integrated millimeter-scale spectrometers operating in the 2–5.5 $\mu$m wavelength range, as well as the integration of other materials on the silicon waveguide platform (III–V semiconductors, IV–VI colloidal quantum dots and GeSn alloys) to extend the functionality with integrated lasers and photodetectors. Finally, we will discuss the potential of nonlinear optics on this waveguide platform, either to generate coherent mid-infrared radiation over a broad wavelength range or to translate mid-infrared radiation to the telecommunication wavelength window, where very well developed optical components are available.

## II. Silicon-Based Passive Waveguide Circuits for the Mid-Infrared

Silicon-on-insulator has become a standard material platform for the integration of photonic devices in the telecommunication wavelength window. Well-developed processes are available including high quality waveguide definition germanium epitaxy etc. Therefore we have explored the use of this material platform for operation at longer wavelengths, using the standard silicon photonics technology that is used today in multi-project wafer approaches. These waveguide structures consist of a 220 or 400-nm thick silicon waveguide layer on a 2-$\mu$m thick buried oxide layer on a silicon substrate. Using this technology very low waveguide losses ($\sim$0.5 dB/cm) in the 2–2.5-$\mu$m wavelength range have been obtained [8]. Similarly, on the 400 nm silicon waveguide platform 3-dB/cm waveguide losses at a wavelength of 3.8 $\mu$m were obtained [9]. Besides low-loss waveguides, functional components for spectroscopic sensing systems were also demonstrated [10], including planar concave grating spectrometers and arrayed waveguide gratings in the 2–2.5 $\mu$m [11] and 3.8-$\mu$m wavelength range [9]. The transmission spectrum of a silicon-on-insulator wavemeter (a wavelength demultiplexer circuit where the output channels intentionally overlap in order to accurately measure the wavelength of a laser line injected into the spectrometer through centroid detection) based on an arrayed waveguide grating is shown in Fig. 1(a). This device is implemented on the 220-nm silicon waveguide platform and measures 525 $\mu$m by 775 $\mu$m. Fig. 1(b) shows the transmission spectrum of a planar concave grating spectrometer operating at 3.8 $\mu$m implemented on the 400-nm silicon waveguide platform [12].

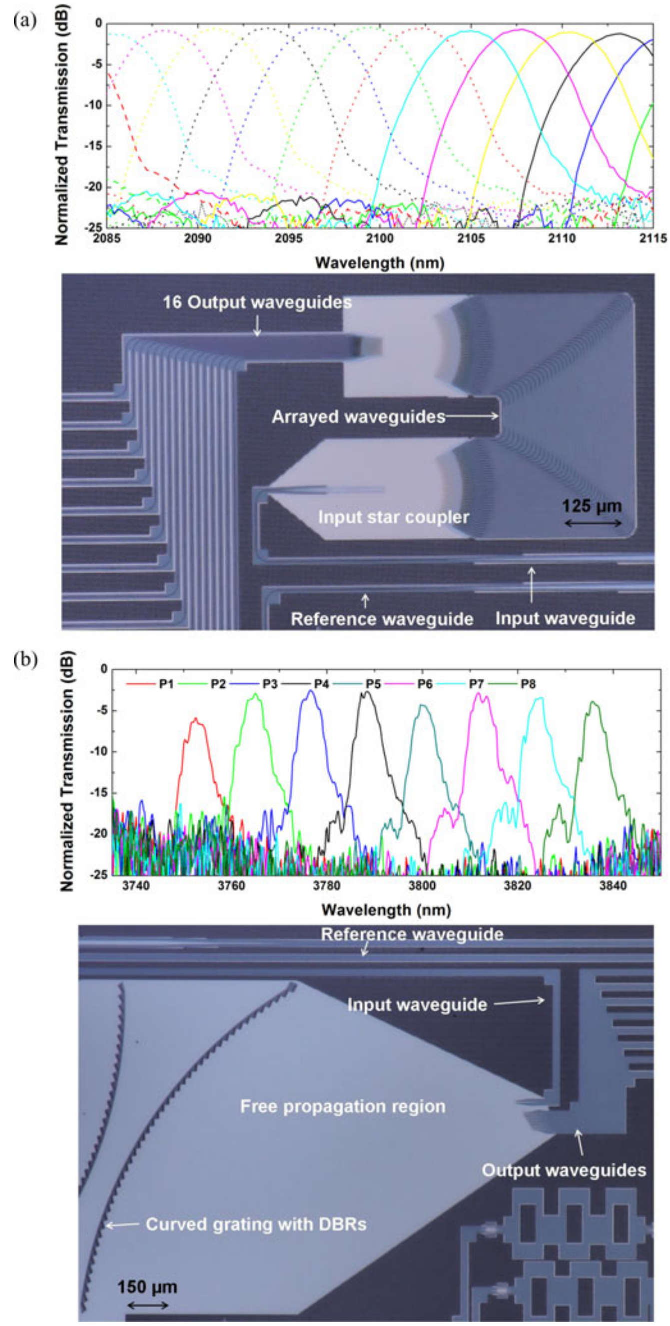


Fig 1. (a) Normalized transmission spectrum and microscope picture of an integrated wavemeter operating in the 2–2.5 $\mu$m wavelength range; (b) normalized transmission spectrum and microscope picture of a planar concave grating operating at 3.8 $\mu$m.

While silicon-on-insulator waveguide circuits are ideal for long-wavelength photonic integrated circuits operating in the 2 to 4-$\mu$m wavelength range, the $SiO_2$ buried oxide layer starts absorbing heavily beyond that wavelength. Also the leakage to the silicon substrate through the standard 2-$\mu$m thick $SiO_2$ layer becomes an issue. Therefore alternative silicon-based waveguide platforms need to be considered for operation beyond 4-$\mu$m wavelength. Several options are being explored, including free-standing silicon [13], [14] and air-clad silicon pedestal structures [15], [16] (which however limits the type of components that can be implemented since it is for example very difficul to make the free propagation region of a planar concave grating free-standing/on a pedestal), silicon-on-sapphire [17]–[21], silicon-on-siliconnitride (which involves wafer bonding) [22] and SiN waveguide circuits [23]. The waveguide platform that we have adopted is germanium-on-silicon [24], since the epitaxial growth of germanium on a silicon wafer is well mastered and the processing of the germanium waveguide layer can be done in a CMOS fab. Germanium-on-silicon waveguides with waveguide losses of 3 dB/cm in the 5 to 5.5-$\mu$m wavelength range have been demonstrated (using a 2.2-$\mu$m wide and 2-$\mu$m thick germanium waveguide core on a silicon substrate) [25].

Given the wide transparency range of germanium from 2 to 14 $\mu$m, this platform should be able to handle most mid-infrared spectroscopic sensing applications. The lower index contrast between germanium and silicon compared to the silicon-on-insulator waveguide platform makes devices less compact however. Nevertheless, high performance arrayed waveguide grating spectrometers and planar concave grating spectrometers were recently realized as illustrated in Fig. 2 [25], [26].

## III. Extending the Functionality of Long-Wavelength Photonic Integration Platforms

In order to really make photonic integration a promising technology for spectroscopic sensing applications, the functionality of the passive waveguide platform needs to be extended with integrated photodetectors and laser sources. Different material systems can be used for this purpose. In this section we elaborate on the integration of GaSb-based photodetectors and lasers, and on the integration of PbS and HgTe colloidal nanoparticles and monolithically integrated GeSn for photodetection on the silicon-on-insulator waveguide platform. All these devices operate in the short-wave infrared (2–2.5-$\mu$m wavelength range) since photodetection at longer wavelengths typically requires thermo-electrically or cryogenically cooled devices for high performance operation. Integrating these on a silicon photonic IC would require cooling the whole IC which prevents the interaction between the liquid, gas or solid with the light to take place on the chip (due to condensation, freezing). In cases where photodetection at longer wavelengths is required, either off-chip cooled sources are envisioned or the use of nonlinear optics based wavelength translators can be considered, as will be discussed in Section IV.

A firs  approach to realize integrated photodetectors and lasers on a silicon chip is based on the epitaxial layer transfer of a GaSb-based compound semiconductor layer stack to the silicon waveguide circuit by means of die-to-wafer bonding. This process is well developed for InP-based epitaxy for operation in the telecommunication window [27] and has been ported to transfer GaSb-based epitaxy as well. In our work we use an adhesive bonding approach based on DVS–BCB, which is forgiving in terms of silicon and III–V wafer quality (surface roughness and contamination). The absorption spectrum of DVS–BCB is shown in Fig. 3(a), showing reasonably low absorption losses in the 1.5–3-$\mu$m wavelength range. The photodetector/laser process fl  w is shown in Fig. 3(b). For the photodetector integration, the epitaxial layer stack consists of a 500-nm thick InGaAsSb absorption layer (cut-off wavelength 2.5 $\mu$m) surrounded by p- and n-doped GaSb cladding layers. Both evanescently coupled and grating-assisted photodetectors have been demonstrated with responsivities up to 1.4 A/W at 2.3-$\mu$m wavelength [28]. The scalability of the heterogeneous integration of such photodetectors is illustrated in Fig. 4, showing the realization of a spectroscopic sensing system with 46 channels, covering the 1.5 to 2.3-$\mu$m wavelength range [11].

While GaSb-based detector integration provides the highest quality photodetectors for the 2 to 4-$\mu$m wavelength range, the cost of such devices can be quite high, due to the complex

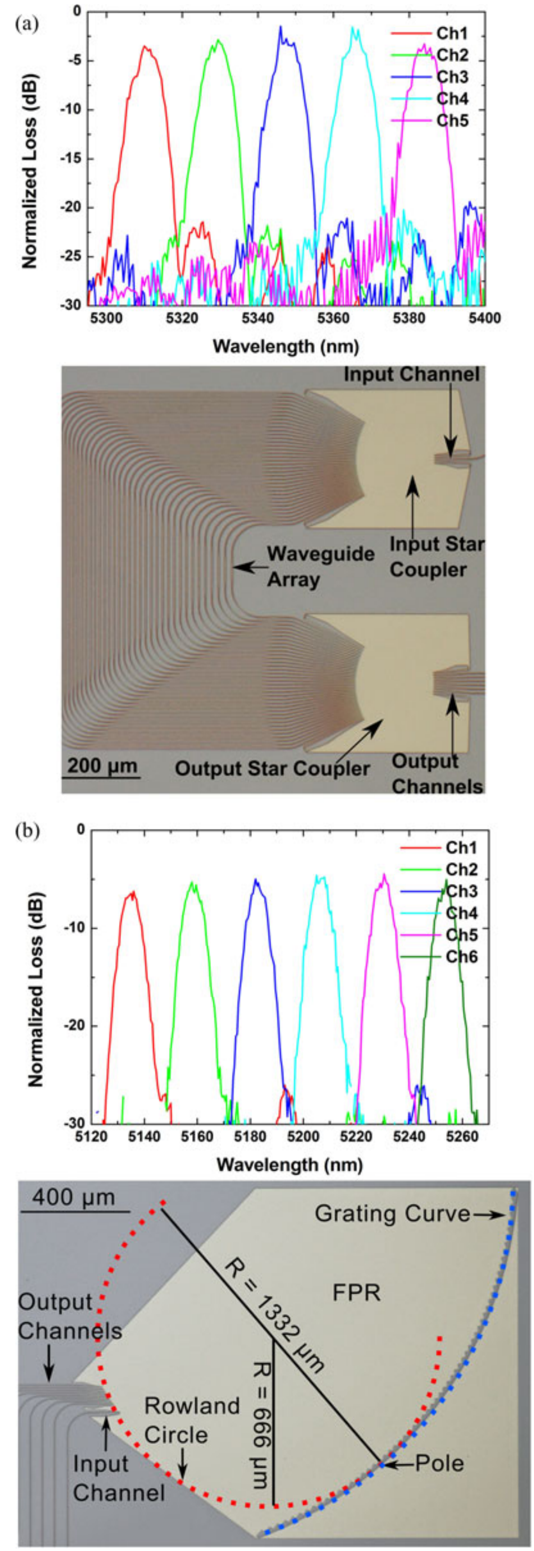


Fig. 2. (a) Normalized transmission spectrum of a germanium-on-silicon arrayed waveguide grating spectrometer operating in the 5–5.5 $\mu$m wavelength range and a microscope picture of the fabricated device; (b) normalized transmission spectrum of a germanium-on-silicon planar concave grating and a microscope picture of the fabricated device.

epitaxial growth required. Therefore, alternative solutions have been explored, namely the monolithic integration of GeSn layers on silicon as well as the integration of PbS/HgTe colloidal

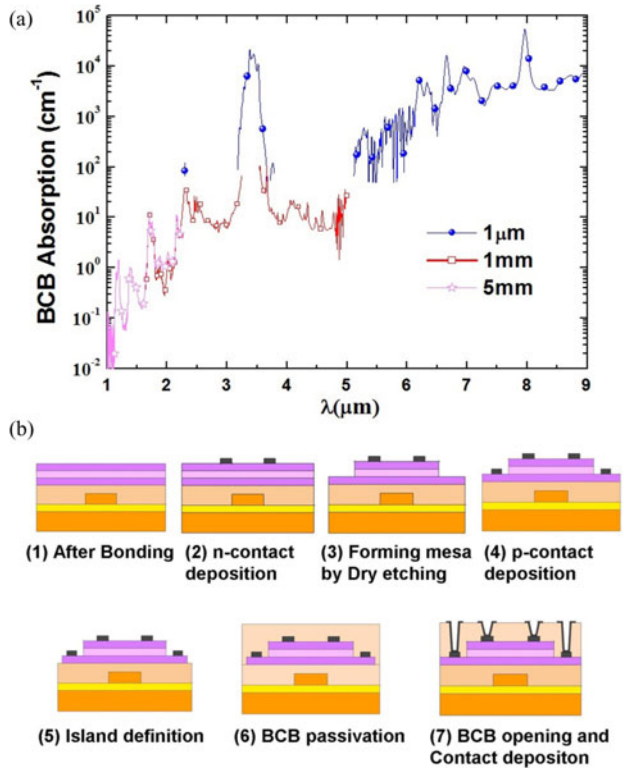


Fig. 3. (a) DVS-BCB absorption spectrum in the mid-infrared wavelength range; (b) InGaAsSb/GaSb photodetector/laser integration on silicon process fl w.

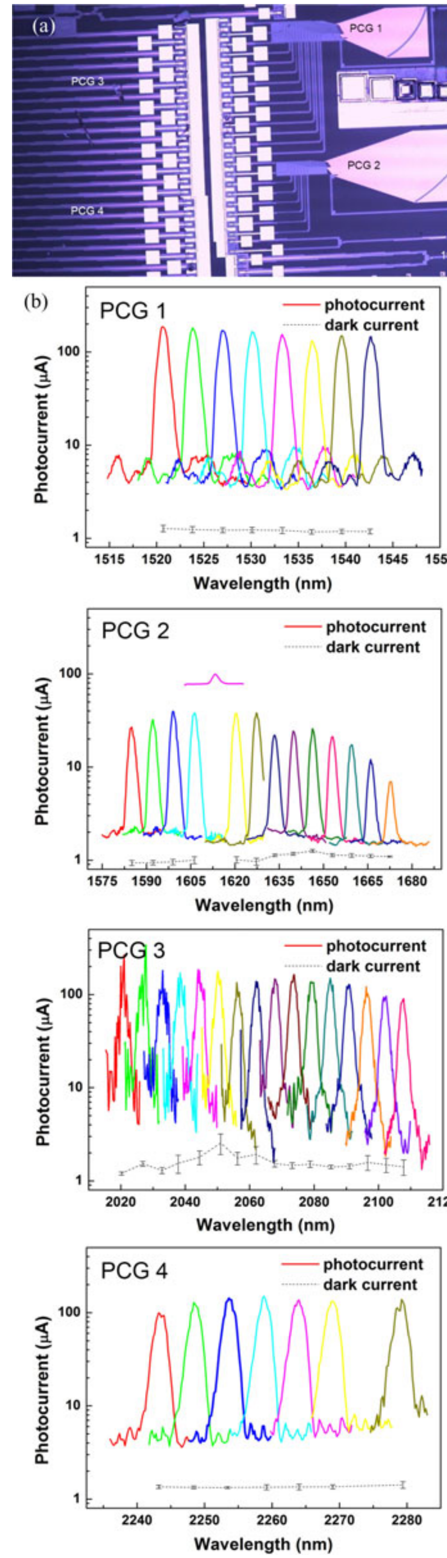


Fig. 4. (a) Microscope picture of the 46 channel integrated spectrometer covering the 1.5–2.3-$\mu$m wavelength range; (b) photocurrent versus wavelength for the various channels. The dark current at room temperature of the detectors is also indicated.

nanoparticles for cost-sensitive (but perhaps less demanding) spectroscopy applications.

The use of GeSn epitaxy is inspired by the fact that the indirect (and direct) bandgap of germanium reduces when adding tin to the matrix [29]. This allows extending the cut-off wavelength of germanium detectors to the short-wave infrared ($\sim$2.5 $\mu$m). Fig. 5(a) shows the photoresponse of a $Ge_{0.91}Sn_{0.09}$ multi-quantum well photoconductor structure as a function of the number of GeSn quantum wells [30]. Clearly, an extension of the cut-off wavelength compared to pure germanium detectors can be observed. These structures were grown on a germanium on silicon virtual substrate immediately providing a path to co-integrate these GeSn photodetectors with germanium-on-silicon waveguide structures, which have a propagation loss of 5 to 2 dB/cm in the 2.0 to 2.6-$\mu$m wavelength range as shown in Fig. 5(b).

An alternative approach relies on the integration of IV–VI semiconductors such as PbS, PbSe or Hg(Cd)Te on silicon waveguide circuits. Given the narrow bandgap of these materials, mid-infrared photodetectors can be realized. Current commercially available devices are based on epitaxial growth of these materials making it again an expensive technology. Therefore we developed a wet chemical synthesis method to grow PbS and HgTe nanoparticles in solution. These nanoparticles (ranging from 2–10 nm in size) can be deposited on silicon waveguide circuits in various ways, including spin-coating, drop-casting or inkjet-printing. Especially this last method is of great interest since it allows the efficien use of the nanomaterials. While nanoparticle layers can easily be deposited to form integrated photoconductors or photodiodes, the organic ligands at the surface of the dots (which are required to prevent clustering of the

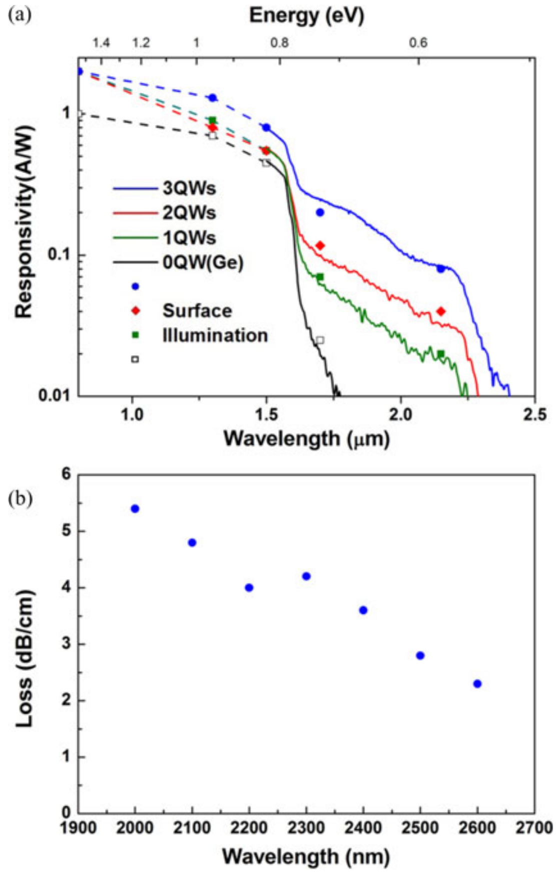


Fig. 5. (a) GeSn/Ge photoconductor integrated on a 200-mm silicon wafer demonstrating the potential of GeSn heterostructures for the realization of short-wave infrared optoelectronic devices on silicon photonic integrated circuits: responsivity as a function of wavelength and as a function of the number of GeSn quantum wells; (b) waveguide loss of germanium-on-silicon waveguides in the 2.0 to 2.6-$\mu$m wavelength range.

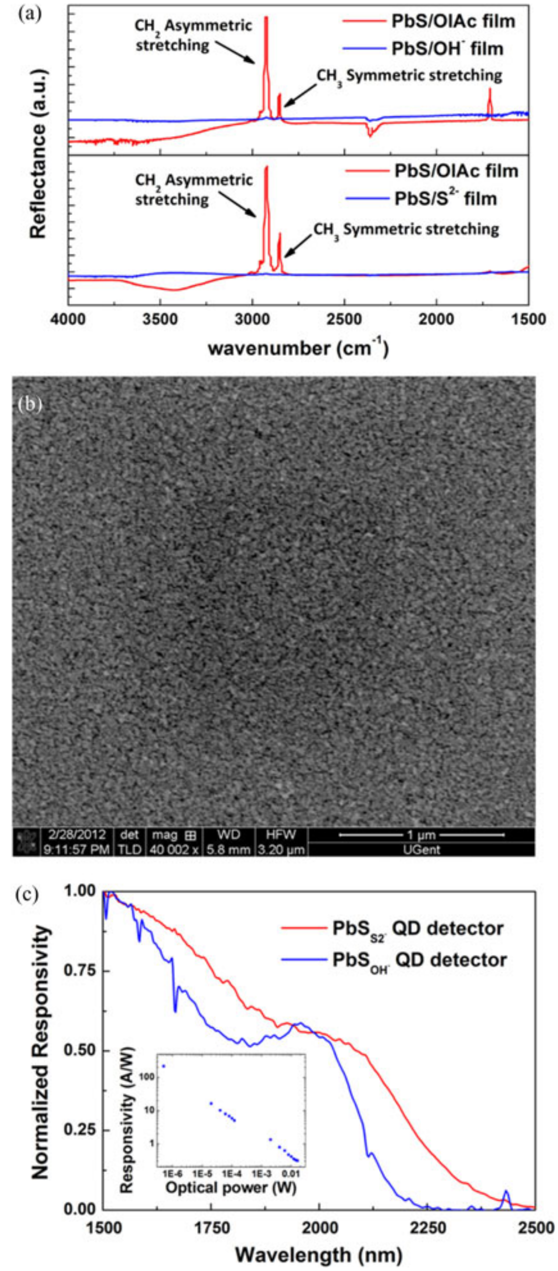


Fig. 6. (a) FTIR absorption spectrum of a colloidal nanoparticle fil before ligand exchange and after ligand exchange–the peaks observed in the spectrum indicate absorption from C-H bonds coming from the oleic acid (OlAc) ligands, which are absent after ligand exchange; (b) SEM picture illustrating the good surface morphology based on the developed layer deposition technique; (c) responsivity and spectral response characteristics of a PbS colloidal quantum dot based photoconductor.

dots in a solution) prevents efficien carrier transport through such a layer [31]. In order to mitigate this problem, a wet chemical ligand exchange procedure was developed in which the long ($\sim$2 nm) organic ligands are replaced by very short inorganic ones ($OH^-$ and $S^{2-}$). This ligand replacement is done in a layer by layer fashion in order to prevent the formation of cracks in the nanoparticle fil due to the compaction of the fil after ligand exchange. Organic ligand free film with good surface morphology have been realized as can be seen in Fig. 6, showing the Fourier Transform InfraRed (FTIR) spectrum of a nanoparticle fil before and after ligand exchange and a scanning electron microscope image (SEM) of the realized fil [32]. Based on this fil deposition technology, surface illuminated photoconductors were realized as shown in Fig. 6(c), showing operation up to 2.4 $\mu$m and a high responsivity due to an internal gain mechanism typical of photoconductors which is related to the long carrier lifetime in the quantum dot film This is attributed to trapping of photogenerated holes in nanoparticle surface states. Using HgTe nanoparticle film photodetection up to 2.8 $\mu$m has been demonstrated in our work, while others have shown the potential of this material system to go to the 5-$\mu$m wavelength range [33]. The integration of these nanoparticle film on silicon-on-insulator waveguide circuits is currently being developed.

While integrated photodetectors are of paramount importance for advanced integrated spectroscopic sensing systems, the availability of integrated laser sources operating in the short-wave or mid-infrared enable many more applications. While interband-cascade laser and quantum cascade lasers dominate the wavelength range beyond 3 $\mu$m, in the 2–3-$\mu$m wavelength range GaSb-based band-to-band semiconductor diode lasers

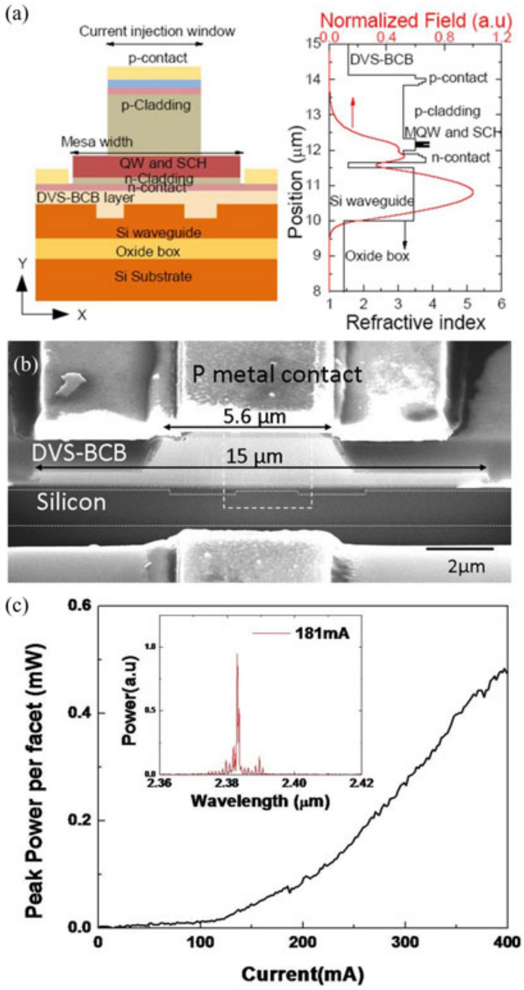


Fig. 7. (a) Schematic of the hybrid GaSb on silicon laser and the device mode profile (b) SEM cross-section of the fabricated device; (c) light-versus-current and spectral characteristic of the fabricated Fabry–Perot laser cavity.

provide excellent performance. As an integration process for GaSb-epitaxy on silicon waveguide circuits is available and since several III–V on silicon laser designs were developed for the telecommunication wavelength range (using InP-based epitaxy) these device concepts can be ported to the GaSb on silicon platform. Fig. 7 illustrates a firs generation Fabry–Perot GaSb-on-silicon hybrid laser using adhesive wafer bonding operating at 2.38-$\mu$m wavelength. The device is designed for high optical confinemen in the silicon waveguide layer as illustrated in Fig. 7(a). The silicon waveguide layer thickness was therefore increased to 1.5 $\mu$m. A device cross-section is shown in Fig. 7(b), while the light–current characteristic of the device (pulsed operation at 10 °C) is shown in Fig. 7(c). While these are still preliminary results it shows the potential of the GaSb on silicon waveguide platform. Another encouraging evolution is that recently GaSb on Si lasers have been realized based on hetero-epitaxial growth [34].

While in-plane emitting lasers allow for a straightforward interfacing to the silicon waveguide circuit, lower power consumption surface emitting devices operating in the 2–2.5-$\mu$m wavelength range are also of great interest. GaSb-based vertical cavity surface emitting lasers (VCSELs) provide a solution here [35], [36]. However, the epitaxial growth of such structures is far from trivial given the very thick distributed Bragg reflector mirrors that are required. The high refractive index contrast available on the silicon waveguide platform can alleviate this issue. High contrast grating structures can be designed that provide very high reflect vity (>99.9%) over a broad wavelength range [37]. Using such high contrast gratings, hybrid VCSEL structures can be designed in which one DBR mirror is replaced by a high contrast grating, which – when made free standing- can be actuated in order to change the resonance wavelength of the cavity. The design of the grating can be adapted in such a way as to promote surface emitting operation or to promote coupling to the silicon waveguide layer. The device cross-section is illustrated in Fig. 8(a). In order to achieve operation around 2.3-$\mu$m wavelength, the grating structure was designed to have a period of 1.52 $\mu$m, a duty cycle of 50% and a silicon waveguide layer thickness of 220 nm. The fiel profil of the cavity mode (electrical fiel orientation along the grating lines) with a quality factor of 1600 is shown in Fig. 8(b). An analysis of the tuning behavior for this type of VCSEL (by electrostatic actuation of the high contrast grating) results in a wavelength tuning of 0.2 nm per 1 nm of grating displacement [38], allowing the realization of a widely tunable laser source.

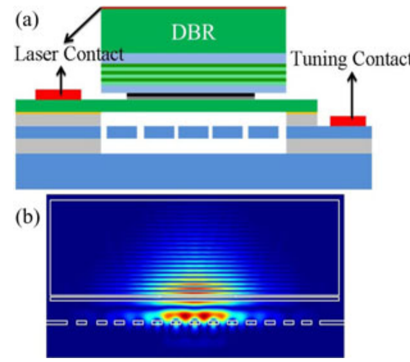


Fig. 8. (a) Schematic of the widely tunable GaSb/silicon hybrid VCSEL structure based on a high contrast grating as a bottom mirror. (b) Field profil of the resonant mode of the structure.

## IV. Silicon Nonlinear Optics in the Mid-IR

While the integration of III–V semiconductors on silicon waveguide circuits allows the generation and detection of mid-infrared light, the wavelength range of operation of a single III–V epitaxy is quite limited. Also, inherently detector performance decreases when moving to longer wavelengths. Nonlinear optics on a silicon waveguide platform can provide a solution to this problem. Silicon-on-insulator is a very attractive material platform for nonlinear optics, given the high refractive index contrast available and the high intrinsic Kerr nonlinearity of silicon. Especially in the short-wave infrared wavelength range silicon becomes an excellent material for nonlinear optics due to the absence of parasitic two-photon absorption [39]. Based on these properties several new device functionalities were demonstrated on the 220-nm silicon waveguide platform

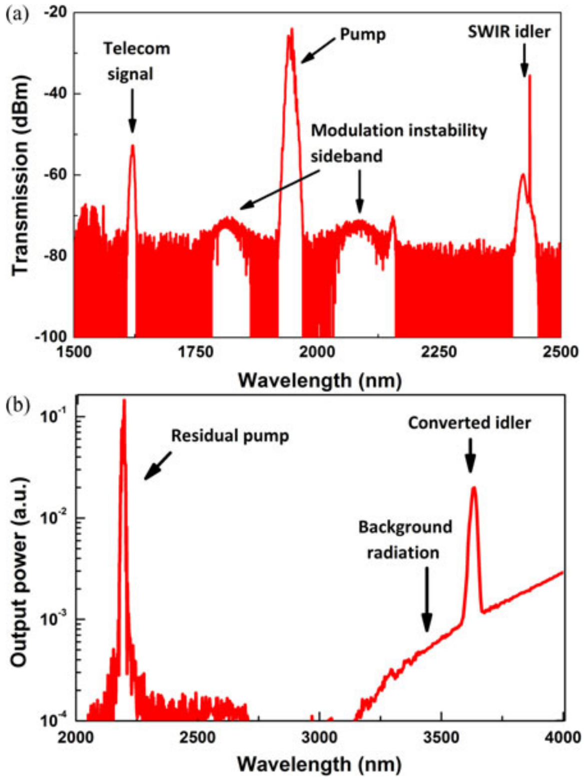


Fig. 9. (a) Wavelength translation over 800 nm using four-wave mixing in a 220 nm by 900-nm wide waveguide (pump: ps-pulse source operating at 1946 nm); (b) wavelength translation to the mid-infrared using a telecom-band tunable laser and a ps-pulse source operating at 2190 nm.

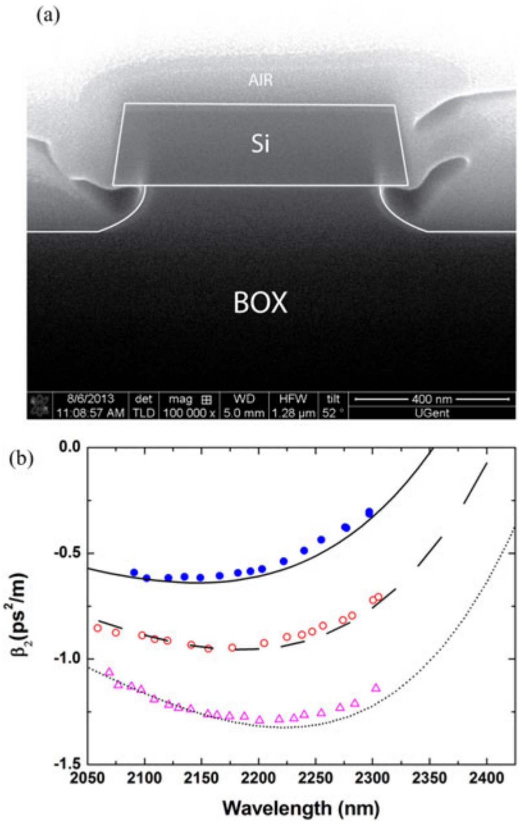


Fig. 10. (a) SEM cross-section of the undercut silicon waveguide for pushing the zero dispersion wavelength further into the infrared; (b) simulated and measured group velocity dispersion characteristic as a function of waveguide underetch (0-nm underetch, 55-nm underetch, 113-nm underetch).

such as 1.5 to 2.5-$\mu$m supercontinuum generation using a 2120-nm wavelength picosecond pulsed laser source in crystalline silicon waveguides [40] or a similar bandwidth supercontinuum source using a 1950-nm picosecond thulium-doped fibe  laser in hydrogenated amorphous silicon waveguides [41]. Also, given the very high parametric gain (>60 dB) that can be realized in a 2-cm long silicon waveguide, a fibe  loop-based synchronously pumped optical parametric oscillator was demonstrated that was tunable from 2045 to 2125 nm [42]. As silicon high index contrast waveguides provide ample opportunity for dispersion engineering, the wavelength bands for which efficien  four wave-mixing is achievable can be widely tuned. Of special interest is the phase matching of wavelength bands far away from the pump since this allows connecting the mid-infrared wavelength range to the telecommunication wavelength range. This might have different applications such as the generation of mid-infrared light based on the mixing of a telecom-band tunable laser and a short-wave infrared pump or the upconversion of mid-infrared light to the telecommunication band, which allows the detection of the mid-infrared signal using high performance uncooled detectors. This wavelength translation between the telecommunication band and the mid-infrared is illustrated in Fig. 9. Fig. 9(a) shows the up and down conversion over 800 nm using four-wave mixing in a 220-nm thick and 900-nm wide silicon waveguide [43], while Fig. 9(b) illustrates the same downconversion process to the 3.6-$\mu$m wavelength range using a 400-nm thick and 1650-nm wide silicon waveguide [44].

Using standard 220-nm thick silicon waveguides, the only degree of freedom to engineer the waveguide dispersion of a silicon photonic wire in a standard CMOS fabrication fl w is the width of the silicon waveguide. This limits the range over which the waveguide dispersion can be tuned. This issue can be tackled by, e.g., depositing dielectric layers on top of the waveguides (through chemical vapour deposition or atomic layer deposition [45]). However, such an approach does not allow tuning the anomalous dispersion regime to longer wavelengths, which is essential, since many nonlinear processes (broadband parametric amplification  solitonic propagation,...) rely on anomalous group velocity dispersion waveguides and longer wavelength operation is beneficia  due to the reduced nonlinear losses. In order to accommodate this, underetching of the silicon waveguide structures was used to push the anomalous dispersion region (and the associated zero dispersion wavelength) further in the infrared. Using buffered HF the underetching can be very well controlled and as such, also the dispersion. This is illustrated in Fig. 10, showing the SEM cross-section of an undercut waveguide and the simulated and measured (according to the method described in [46]) second order dispersion characteristic of such a waveguide as a function of waveguide undercut. The waveguide loss increases from 0.6 to 0.9 dB/cm after underetching, which is acceptable for the envisioned applications.

## V. Conclusion and Prospects

Silicon photonics is an enabling technology for the realization of photonic integrated circuits since it leverages the mature CMOS technology for the realization of such components. While mainly developed for telecommunication wavelength range applications, it provides an excellent platform for applications both in the visible/near-infrared as in the mid-infrared. The silicon-on-insulator and germanium-on-silicon platform are ideally suited for the mid-infrared wavelength range, providing ample opportunity for novel and compact devices and systems operating in the mid-infrared. A tantalizing prospect is the realization of complete lab-on-a-chip spectroscopic sensing systems that can be based on various techniques such as absorption spectroscopy, photothermal [47] and photoacoustic [48] spectroscopy. Also, the co-integration of 'novel' materials such as graphene [49] and mid-infrared plasmonics [50] can spark the further development of next-generation integrated sensing systems.

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