Integration of Mid-Infrared Light Sources on Silicon Based Waveguide Platforms

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***Abstract*—We present our improvements on the standard waveguide platforms for photonic integrated circuits for extending the operating range in the mid-infrared band. Results are shown on low loss mid-infrared passive waveguides and devices. Integration of mid-infrared light engines on silicon based waveguide platforms using heterogeneous integration is presented to realize Fabry-Perot and distributed feedback lasers.**

***Keywords*—Mid-infrared; Quantum Cascade Laser; Integrated Optics Devices**

I. Introduction

The advent of quantum cascade lasers (QCLs) and interband cascade lasers (ICLs) has allowed for efficient, compact semiconductor based light sources emitting light in the mid-infrared wavelength range (2 - 12 μm) instead of bulky solid state based laser sources. Mid-infrared light sources are attractive for infrared countermeasures, spectroscopic sensing and thermal imaging. The current state of the art commercially available mid-infrared lasers relies on external feedback elements, thus making the entire package bulky and not scalable. Therefore, further development is needed to enhance power scaling, wavelength tuning range and compactness of these lasers.

Heterogeneous integration of light sources emitting at telecom wavelength range with silicon-on-insulator (SOI) based waveguide circuits has allowed realizing extensive variety of photonic integrated circuits (PICs) [1]. This method allows optimizing both the material stacks independent of each other and then integrating them by wafer bonding using Van der Walls forces.

SOI based waveguide circuits are preferred over other waveguide platforms because the high index contrast between the silicon waveguide core and the buried silicon dioxide (BOX) cladding allows for tight bends resulting in compact waveguide circuits. Additionally, these waveguide circuits can be manufactured in CMOS pilot lines on 300 mm wafers lowering the cost of individual devices [2], [3]. Integration of mid-infrared light sources with silicon based waveguides will allow them to reach similar scaling as to their telecom counterparts.

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II. Passive Waveguide Platform

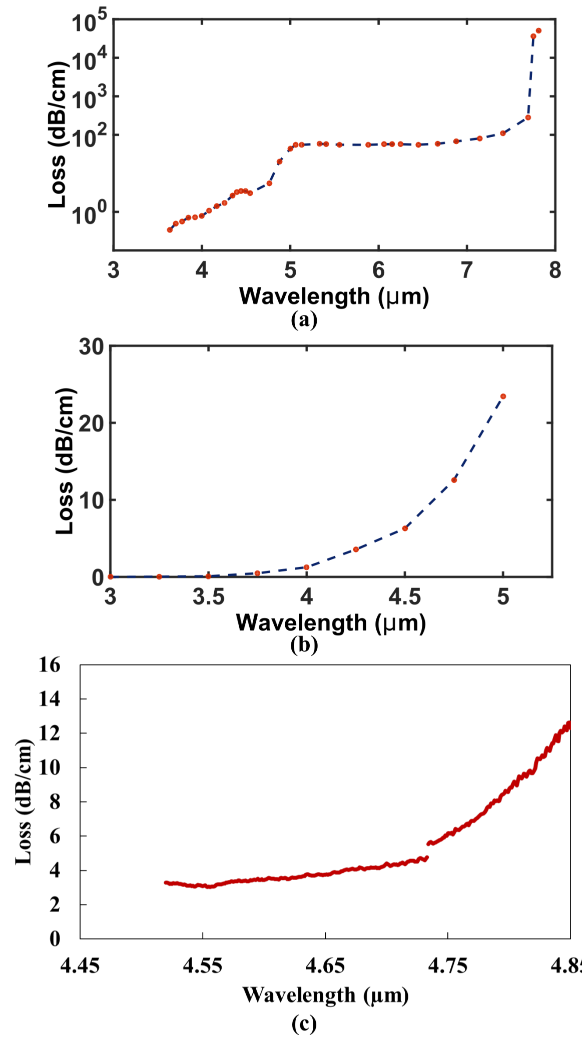

Fig. 1. (a) Absorption loss of SiO_2 as a function of wavelength, (b) absorption loss of the fundamental TM mode due to the BOX absorption in a fully etched 400 nm thick SOI waveguide and (c) measured propagation loss of a fully etched 1500 nm thick SOI waveguide.

The traditional silicon based waveguides consists of silicon device thickness in range of 220 - 500 nm. For operation beyond 4 µm wavelength, there are two major issues with this particular configuration of SOI waveguide platform. Firstly, as shown in Fig. 1 (a), the BOX layer starts absorbing heavily. Secondly the fundamental mode starts to loose confinement in the waveguide core at longer wavelengths and hence has a higher loss arising from the BOX layer absorption. The loss of the fundamental TM mode for a fully etched 400 nm SOI waveguide is shown in Fig. 1 (b).

Therefore, to allow for low loss operation beyond 4 µm, the silicon waveguide core thickness is increased to 1550 nm. This reduces the overlap of the fundamental TM mode with the absorptive BOX layer. The measured propagation loss of such a waveguide is shown in Fig. 1 (c) and it can be seen that low loss operation can be achieved below 4.75 µm wavelength.

A second waveguide platform which allows operation in the entire mid-infrared wavelength range while being CMOS compatible is Germanium-on-Silicon. Both these materials are compatible with CMOS foundries and thus pose no contamination issues. The main origin for loss in Ge-on-Si waveguides is the threading dislocations arising from the lattice mismatch of silicon and germanium. To obtain low loss waveguides it is important to keep the mode away from this defective boundary. A 2 µm thick Ge film is used to realize photonic devices and both shallow etched and fully etched geometries are tried. For fully etched waveguides, the propagation loss is found to be around 3 dB/cm in 4.5 - 5 µm wavelength range while it gets lowered to 1.5 dB/cm for a shallow etched waveguide. Beam combiners in the form of Mach-Zehnder interferometers (MZIs) and arrayed waveguide gratings (AWGs) have also been demonstrated on this waveguide platform [4], [5]. 2×2 MZI with a free spectral range (FSR) of 25 nm were designed using multi-mode interferometers (MMIs) and showed high extinction ratio (35 dB) and low insertion loss (0.4 dB). AWGs were designed in different configurations and etch depths. For fully etched AWGs, the insertion loss was found to be 3.24 dB and the cumulative cross talk was found to be 29.63 dB while for a shallow etched AWG these numbers were 1.54 dB and 28.24 dB respectively.The performance of the Ge-on-Si waveguides and passive devices is shown in Fig. 2.

III. Integrated Lasers

A. *Integration on SOI Waveguides*

Several types of mid-infrared lasers have been integrated on silicon based waveguide platforms [6]. These lasers include Fabry-Perot (FP) [7] and Distributed Feedback (DFB) QCLs [8] and FP ICLs [9]. Light is generated in the active laser mesa and is then transfered to the passive silicon waveguide using adiabatic tapers. The optical feedback is provided by the gratings defined in the passive silicon waveguide and take advantage of DUV lithography thus enabling higher throughout. An attractive function which can be obtained using the silicon photonic circuits is beam combining of individual DFB QCLs using a SOI AWG [10]. This allows emission of multiple wavelengths from a single source and can be used

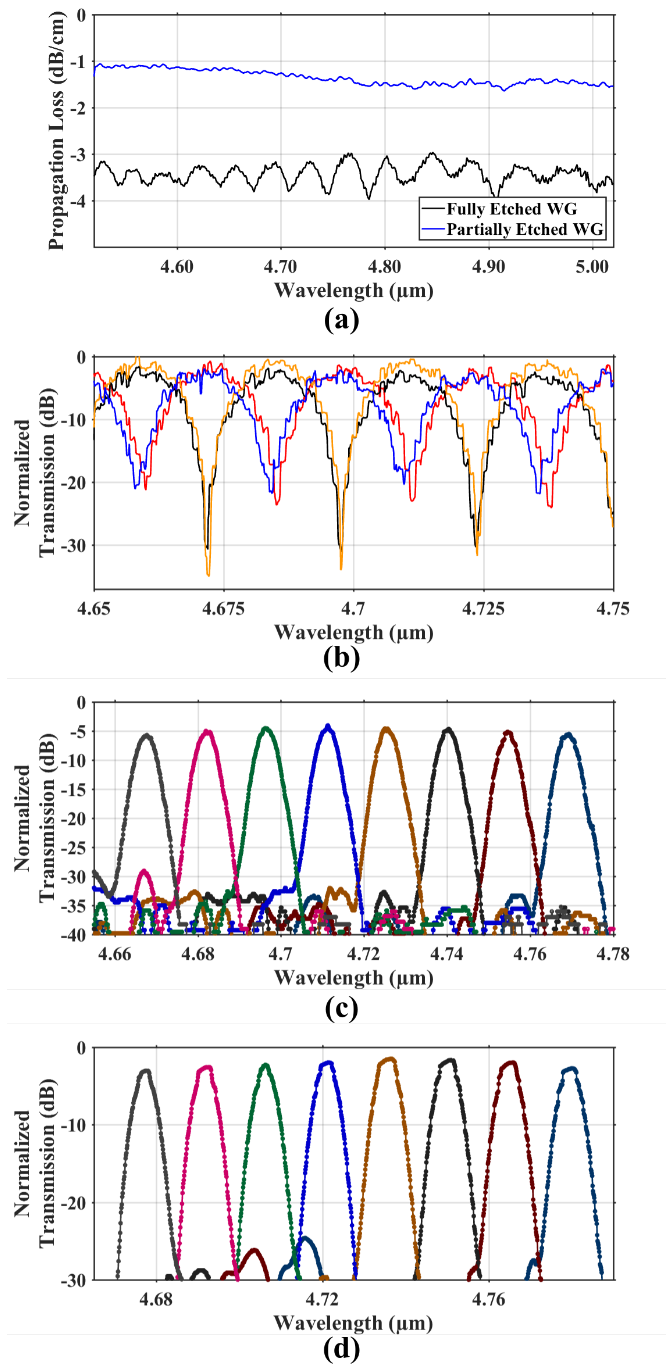

Fig. 2. Passive characteristics of passive Ge-on-Si devices (a) Propagation loss of fully etched and partially etched waveguides, (b) Transmission characteristics of 2×2 MZI, (c) Transmission characteristics of a fully etched 8 channel AWG and (d) Transmission characteristics of a shallow etched 8 channel AWG.

for IRCM or sensing applications.

The LIV characteristics of DFB lasers operating at temperatures as high as 100°C is shown in Fig. 3(a). Fig. 3(b) shows the output spectrum of the integrated QCL at several different temperatures.

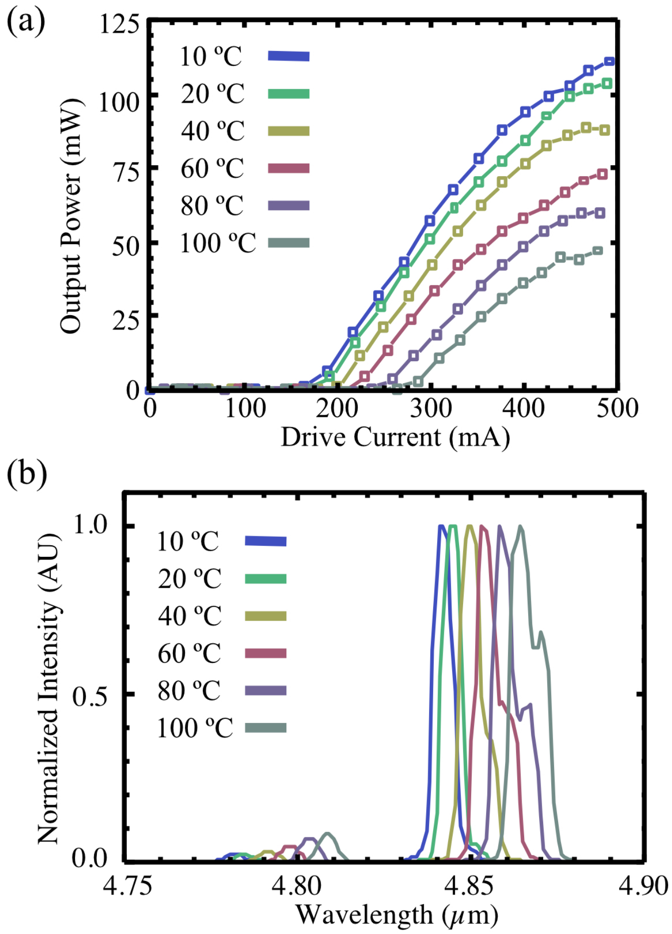

Fig. 3. (a) LIV characteristics of a DFB QCL integrated on SOI waveguide and (b) Output spectra of the integrated QCL.

B. Integration on Ge-on-Si Waveguides

Ge-on-Si waveguides paves a way for CW operation of integrated QCLs. This comes from the fact that there is no thermally insulating layer in between the passive waveguide and active laser mesa. The first integrated QCLs on this waveguide platform were demonstrated recently and the LIV characteristics at various temperatures together with the emission spectra is shown in Fig. 4.

IV. Conclusions

In conclusion, we have demonstrated low loss waveguide platform for the mid-infrared wavelength range and have shown that both SOI and Ge-on-Si can be used. Ge-on-Si is much more promising than SOI since it allows the possibility of covering the entire mid-infrared range. Further, we have demonstrated integrated lasers on both these waveguide platforms. Further experiments will include realizing low loss passive waveguides in the long wave infrared, improving the performance of the integrated lasers and realizing a widely tunable mid-infrared laser on silicon based waveguide.

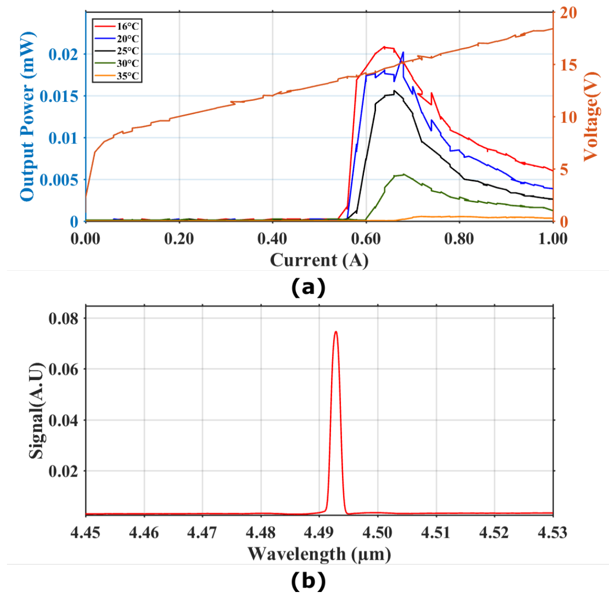

Fig. 4. (a) LIV characteristics of a QCL integrated on Ge-on-Si waveguide and (b) Output spectra of the integrated QCL.

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