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Germanium-on-silicon mid-infrared waveguides and Mach-Zehnder interferometers

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***Abstract*—In this paper we describe Ge-on-Si waveguides and Mach-Zehnder interferometers operating in the 5.2 - 5.4 μm wavelength range. 3dB/cm waveguide losses and Mach-Zehnder interferometers with 20dB extinction ratio are presented.**

***Index Terms*—mid-infrared, photonic integrated circuits, germanium on silicon**

I. INTRODUCTION

The mid-infrared wavelength range is a region of interest for spectroscopic sensing applications, due to strong and specific absorption features of many molecules in that wavelength range [1]. This allows for a non-contact method to detect the presence and concentration of these molecules. Quantum cascade lasers and inter-band cascade lasers are used as coherent laser sources in this wavelength range. These are typically single-wavelength lasers with limited tuning range. Other options are the use of broadband incoherent thermal sources or coherent supercontinuum sources in combination with a spectrometer. Current instrumentation is bulky, expensive and power hungry, necessitating the need for a mid-infrared photonic integration platform to mitigate these disadvantages. Several functions can be implemented on such a platform, such as wavelength multiplexers for arrays of single wavelength QCL lasers allowing to cover a broad wavelength range and the integration of spectrometers for spectral analysis of broadband sources after they passed through a gas or liquid under study.

For telecom wavelengths, Silicon-on-Insulator (SOI) is now a standard waveguide platform. One of the main reasons for this is the compatibility with CMOS fabrication technology and the associated potential for large volume manufacturing at low cost. However, beyond 3.8 μm, the underlying buried oxide layer starts absorbing heavily [2]. There are several candidates for viable waveguide platforms for the mid-IR wavelength range beyond 3.8 μm as discussed primarily in [2]. There have been reports in recent literature on Ge-on-Si waveguides [3], free-standing Si waveguides [4] and silicon-on-sapphire waveguides [5]. In this paper we describe the fabrication of Ge-on-Si photonic integrated circuits, an attractive option for mid-IR photonics and present waveguide losses and a key photonic component in wavelength multiplexers and spectrometers: the Mach-Zehnder Interferometer (MZI).

II. GERMANIUM-ON-SILICON PLATFORM

Epitaxial Ge, 1 and 2 μm thick was grown on an n-type Si(001) substrate at imec on 200mm wafers by an atmospheric chemical vapor deposition system as described in [6]. Since there is a lattice mismatch of 4.2% between Si and Ge, the threading dislocation density(TDD) is quite high at the Si-Ge interface. To reduce this threading dislocation density in the film, the Ge is annealed at 850°C for 3 minutes. In 1 μm thick Ge, the threading dislocation density is 10^8cm^{-2}, while for 2 μm thick Ge, it is about an order of magnitude less.

To define Ge-on-Si photonic integrated circuits, a Ti/Cr metal mask is used, which is defined using lift-off. i-line contact lithography is used for this purpose. Dry etching of Ge is then carried out in CF_4/O_2 plasma, followed by an HF dip to remove the metal mask. The waveguides are etched completely through the germanium device layer. A scanning electron microscope picture of such a waveguide structure is shown in Figure 1.

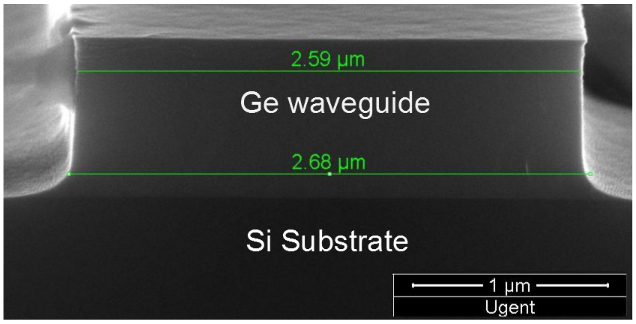

Fig. 1. Ge-on-Si waveguide

III. MEASUREMENT SET UP

Light was coupled from a commercially available Daylight Solutions Quantum Cascade Laser in an Indium Fluoride fiber from IRPhotonics using a black diamond aspheric lens. Wire grid polarizers were used to choose the desired polarization in fiber. The cleaved end of the fiber was mounted on a piezo-driven xyz stage to align accurately with the input taper waveguide. Light from the output taper was collected again using a cleaved fiber and then coupled to a InSb detector. To improve the signal to noise ratio, the output of the detector was coupled to a lock-in amplifier. For these measurements the laser was operating at 100 kHz frequency with a duty cycle of 5% and the trigger from the laser was used as reference for the lock-in amplifier. The laser and lock-in amplifier are addressed by software to scan the wavelength and record the

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corresponding output simultaneously. A schematic diagram of the measurement setup is shown in Figure 2.

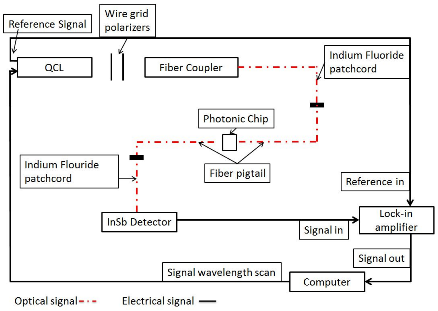

Fig. 2. Measurement Setup

IV. DESIGN AND CHARACTERIZATION OF COMPONENTS

A. Waveguide Losses

Waveguides structures of different lengths on 1 μm and 2 μm thick germanium-on-silicon wafers were realized. Since the optical mode overlaps less with the Si-Ge interface in 2 μm thick Ge and since also the TDD in the bulk of the film is lower, 2 μm thick Ge waveguides show lower losses compared to 1 μm thick Ge waveguides. The waveguides were connected to a taper for better in and out coupling. Waveguide losses were characterized using a cut back method. The results are shown in Figure 3(a) and 3(b). A waveguide loss for TE polarized light around 3-4 dB/cm in the 5.2 - 5.4 μm wavelength range for 2 μm thick Ge,which is comparable to the values cited in[3], and 7-8 dB/cm in the 3.7-3.8 μm wavelength range for 1 μm thick Ge, is obtained. The waveguide width was 2.25 μm and 2 μm respectively to obtain single mode operation.

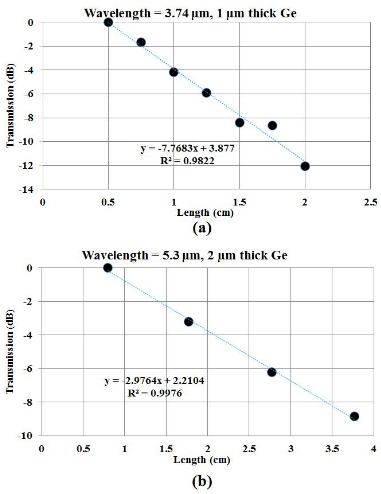

Fig. 3. Loss measurements for (a) 1 μm thick Ge waveguides at 3.74 μm wavelength and (b) 2 μm thick Ge waveguides at 5.3 μm wavelength

B. Mach-Zehnder interferometers

Since Mach-Zehnder interferometers are key components for wavelength multiplexers and spectrometers, we focus on this component in this paper. The 3dB splitters and combiners required for these devices can be implemented in various ways. In this work multimode interferometers (MMIs) are used, given the fact that they are wide-band and do not require sub-micron critical device dimensions. 1×2 and 2×2 MMIs were designed for TE polarization using the full-vectorial eigenmode expansion tool FIMMWAVE. For a 25 μm wide multimode waveguide region with 10 μm wide input and output waveguides a 50:50 splitting was obtained for a device length of 235 μm and 930 μm for a 1×2 and 2×2 MMI respectively.

C. MZI Measurements

A 1×1 MMI was combined with 2×2 MMI to form a 1×2 MZI with a path length difference of 130μm between both arms. The response of this device is shown in Figure 4. 20dB extinction is obtained around 5321nm, while the insertion loss of the device is within the measurement accuracy of the setup. This illustrates the potential of these devices to be used in wavelength multiplexers for QCL light engines and mid-infrared broadband spectrometers.

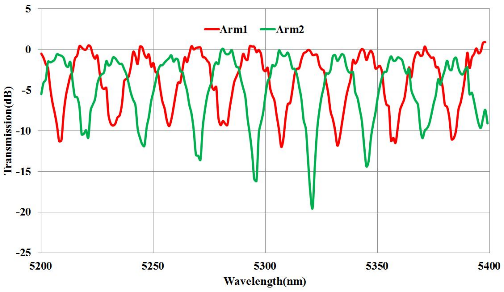

Fig. 4. Response of the realized 1×2 MZI

V. CONCLUSION

Ge-on-Si waveguides, MMIs and MZIs with low loss and promising performance in the 5 μm wavelength range have been demonstrated for the first time. This provides basic building blocks for more complicated photonic integrated circuits to realize complete on-chip spectroscopic systems.

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REFERENCES

[1] R.F.Curl et.al., "Quantum cascade lasers in chemical physics", *Chemical Physics Letters* 487 (2010) 1-18.

[2] R.A.Soref, S.J.Emelett and W.R.Buchwald,"Silicon waveguide components for the long-wave infrared region"' , *Journal of Optics A: Pure and Applied Optics*, 8(2006), pp. 840-848.

[3] Y.C. Chang et.al., "Low-loss germanium strip waveguides on silicon for the mid-infrared",*Optics Letters July 15, 2012, Vol. 37, No. 14, pp. 2883-2885.*

[4] Y.Xia et.al., "Suspended Si ring resonator for mid-IR application",*Optics Letters,Vol.38,No.7,April 1,2013, pp. 1122-1124.*

[5] T.B.Jones et.al.,"Silicon-on-sapphire integrated waveguides for the mid-infrared",*Optics Express,24 May 2010,Vol.18,No. 12,pp.12127-12135*

[6] R.Loo et.al., "High Quality Ge Virtual Substrates on Si Wafers with Standard STI Patterning",*Journal of The Electrochemical Society, 157 (1) H13-H21 (2010).*