Towards low-loss waveguides in SOI and Ge-on-SOI for mid-IR sensing

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PAPER

Towards low-loss waveguides in SOI and Ge-on-SOI for mid-IR sensing

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Abstract

Silicon-on-insulator is an attractive choice for developing mid-infrared photonic integrated circuits. It benefits from mature fabrication technologies and integration with on-chip electronics. We report the development of SOI channel and rib waveguides for mid-infrared wavelengths centered at 3.7 μm. Propagation loss of ~1.44 dB/cm and ~1.2 dB/cm has been measured for TE and TM polarizations in channel waveguides, respectively. Similarly, propagation loss of ~1.39 dB/cm and ~2.82 dB/cm has been measured for TE and TM polarized light in rib waveguides. The propagation loss is consistent with the measurements obtained using a different characterization setup and for the same waveguide structures on a different chip. Given the tightly confined single-mode in our 400 nm thick Si core, this propagation loss is among the lowest losses reported in literature. We also report the development of Ge-on-SOI strip waveguides for mid-infrared wavelengths centered at 3.7 μm. Minimum propagation loss of ~8 dB/cm has been measured which commensurate with that required for high power mid-infrared sensing. Ge-on-SOI waveguides provide an opportunity to realize monolithically integrated circuit with on-chip light source and photodetector.

1. Introduction

Mid-infrared sensing has been an attractive area of research since most of the molecules find their vibrational resonances in 2–20 μm part of the electromagnetic spectrum. Starting with lead-salt lasers, nonlinear optical frequency conversion sources, and quantum cascade lasers (QCLs), many major breakthroughs have been reported over the decades for mid-IR sensing applications [1]. In recent times we are now seeing its revival in silicon-on-insulator (SOI) based photonic integrated circuits (PICs). There has always been an industrial need to develop mid-IR sensing PICs to trace gases which are hazardous for the working environment. Secondly, mid-IR sensing can be employed to trace pollutants in the closed environment such as hospitals and large communal spaces. Other applications which can be realized using mid-IR sensing PICs are security, forensics, clinical analysis, and food monitoring.

SOI is undoubtedly the most popular material for the development of near-infrared optical devices [2–5], and in particular, for the realization of low-loss conventional optical elements including filters, splitters/combiners, tapers, directional couplers, resonators, multiplexers, and grating couplers [6]. These elements are now readily available as constituent components for the development of PICs in all the leading foundries [7]. Although, most of the developments in SOI photonics have concentrated largely on telecommunications, however, there is a recent surge in making use of SOI for mid-IR applications. It was noted previously that the low-loss transmission for SOI waveguides is limited up to 3.6 μm [8], however, the optical elements

demonstrated for the wavelengths up to 3.8 μm have proven that SOI is still a major contender for optical interconnects in mid-IR PICs [9]. In addition to this, the suspended SOI waveguides can extend the transmission well into long-wave IR [8].

SOI waveguides have been reported with various Si layer thicknesses in literature for 3.7–3.8 μm wavelengths. A 2 μm thick Si core rib waveguide achieving minimum loss of 1.5 dB/cm has been reported in [10]. Silicon core with thickness of 400 nm has been employed in SOI strip waveguide to achieve propagation loss of 3.1 dB/cm in [11], and rib waveguide to achieve propagation loss of 1.46 dB/cm in [12]. Finally, SOI strip waveguide formed in 500 nm thick Si core has been reported to achieve propagation loss of 1.28 dB/cm in [9], which is the lowest value reported for mid-IR waveguides. It should be noted that these propagation losses have been reported only for TE polarization.

A significant challenge however is the integration of on-chip pump source in SOI based mid-IR PICs. Although hybrid integration of near-IR sources in SOI platform is now a mature technology, there have been few demonstrations to extend this integration into mid-IR [13]. More recently, we have seen integration of QCL on Si-on-N-on-insulator (SONOI) [14]. This opens up the option of developing mid-IR sensors for wavelengths beyond 3 μm and up to the available wavelength range of QCLs. It means that the detection of trace gases such as methane (CH_4) which finds its absorption peak near 3.5 μm can be realized. We can develop SOI based PICs to detect pollutants such as formaldehyde (H_2CO). Integration of tunable on-chip sources would help us achieve gas imaging systems and mid-IR spectroscopy, however, it is a challenge realizing this using QCLs whose emission is defined at the wafer growth stage. Hybrid integration of III-V nonlinear optical frequency converters with Si can be one of the ways forward to achieve tunable on-chip mid-IR pump sources, where monolithic integration of nonlinear optical frequency conversion has been previously reported for near-IR wavelengths [15]. In these sources, the signal and idler wavelengths are controlled by the phase matching period of nonlinear waveguide and can be extended to produce mid-IR wavelengths. Finally, it is encouraging to note that the foundry scale efforts have started to develop low-loss mid-IR optical elements in SOI for sensing applications [16].

Germanium is another contender to realize low-loss PIC for mid-IR sensing applications due to its transparency up to 15 μm. It has been employed to demonstrate various low-loss mid-IR optical elements on Si substrate [17]. Additionally, germanium-tin (GeSn), an alloy of Ge, has gained significant popularity as on-chip mid-IR source in Ge-on-Si [18]. GeSn has also been widely reported for photodetection, and a relatively higher concentration of 9%–10% Sn has been used to demonstrate photodetector and photoconductor for 2.2–2.4 μm wavelengths in [19] and [20], respectively. A waveguide GeSn photodetector has been reported in [21]. Therefore it is feasible to realize a monolithically integrated GeSn sensor for wavelengths near 2.2 μm in order to detect greenhouse gases such a CO_2. Finally, it has been reported that Ge-on-SOI provides better thermal stability and electrical isolation than Ge-on-Si [22–24]. Therefore it is preferred to achieve monolithic integration of GeSn mid-IR sensors in Ge-on-SOI platform.

Low-loss Ge-on-Si mid-IR waveguides have been consistently reported previously, such as in [17, 25–27]. Secondly, Ge-rich $Si_{1-x}Ge_x$ waveguides grown using low energy plasma enhanced chemical vapor deposition (LEPECVD) have demonstrated low-loss for wavelengths up to 8.5 μm [28, 29]. Mid-IR waveguides have also been demonstrated in Ge-on-insulator (GeOI) [30], and Ge-on-SOI [22]. However, the achieved propagation loss in GeOI and Ge-on-SOI is still higher than the reported values of 3–4 dB/cm or less in Ge-on-Si and Ge-rich $Si_{1-x}Ge_x$ waveguides.

In this paper we present our work on the development of low-loss mid-IR waveguides in SOI and Ge-on-SOI. The work reported here complements the development of mid-IR PICs for sensing applications. For SOI waveguides, two structures including channel and rib waveguides have been fabricated for wavelengths near 3.7 μm. Secondly, Ge-on-SOI waveguides have been developed for mid-IR wavelengths centered at 3.7 μm. Strip waveguides in Ge core of thicknesses 0.85 μm and 2 μm have been developed.

2. SOI mid-IR waveguides

In this work, Si channel waveguide is designed with a dimension of 400 nm in height and 1.2 μm in width to ensure single mode operation at the wavelength of 3.7 μm. For rib waveguide, the height and width is kept consistent to the channel waveguide, whereas, the etch depth is 240 nm. Figures 1(a) and (b) show the simulated TE_{00} mode profile for channel and rib waveguides, respectively. It is observed that the designed waveguides are indeed single-mode for 3.7 μm excitation.

The waveguide fabrication starts with commercially available 8-inch SOI wafer with 220 nm thick Si overlayer and 3 μm thick buried oxide layer. Firstly, blanket Si is epitaxially grown to achieve Si overlayer of thickness 400 nm. SiO_2 is then deposited as a hardmask for waveguide definition. The device patterning has been done using deep ultra-violet photolithography followed by single-step reactive ion etching for waveguide

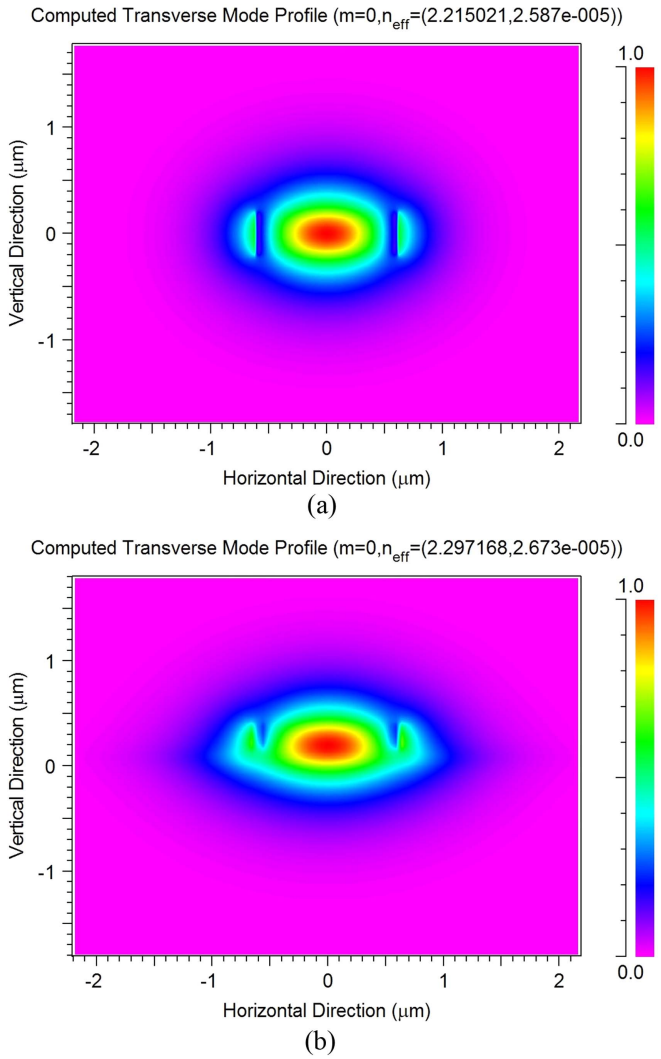

Figure 1. The simulated TE_{00} mode profile for (a) channel waveguide, and (b) rib waveguide. A commercial software has been used to perform mode-solving.

definition. Plasma enhanced chemical vapour deposition SiO_2 of thickness 3 μm is deposited as top cladding. Finally, deep trench is formed for end-fire coupling. In order to achieve efficient coupling into the waveguides, 200 μm long inverted nanotapers have been employed at each end of the waveguides. The scanning-electron micrographs (SEMs) of the fabricated rib waveguide and nanotaper are given in figures 2(a) and (b), respectively.

Cut-back method has been employed to measure the propagation loss in our SOI waveguides. The light source is a continuous wave tunable mid-IR quantum cascade laser from Pranalytica, Inc. The light set at 3.682 μm has been launched into the waveguides using ZnSe mid-IR objective. A mid-IR wave plate and polarization beam cube has been used to manipulate the polarization at the input. The output light is collimated using ZnSe mid-IR objective and detected at PbSe photodetector. An iris is used to retain the excited waveguide mode at the photodetector. In addition to this, we have used a mid-IR InSb camera from Xenics to precisely align the waveguides. Finally, the measurements have been recorded using lock-in amplifier coupled with mechanical chopper. The schematic of characterization setup is given in figure 3.

The normalized transmission of waveguides of various lengths has been plotted in figures 4(a) and (b) for channel and rib waveguides, respectively. All the transmission measurements have been performed by setting the sample temperature at 300 K. The propagation loss calculated for channel waveguides is 1.44 $\pm$ 0.03 and 1.2 $\pm$ 0.04 dB/cm for TE and TM polarized light, respectively. This value is consistent with the propagation loss of 1.28 $\pm$ 0.65 dB/cm at 3.8 μm reported for 500 nm thick Si core strip waveguide in [9]. However, it should be noted that Si core in our case is 400 nm thick which results in higher confinement of the waveguide mode. We would also like to highlight that the measured loss of 1.44 $\pm$ 0.03 dB/cm for TE polarization in this work is moderately consistent with the loss of 2.65 $\pm$ 0.08 dB/cm measured using the setup in which ZrF_4 fiber has been used to excite the same waveguide structures on a different chip [16, 31]. This demonstrates the process and performance repeatability using different measurement setups.

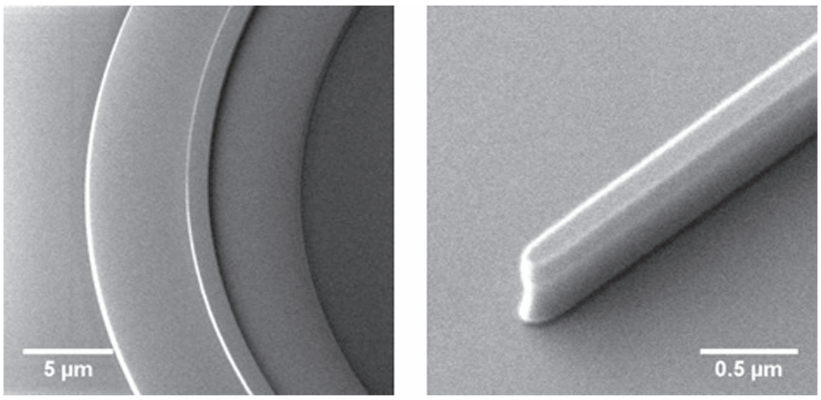

Figure 2. SEM micrographs of (a) rib waveguide, and (b) inverted nanotaper employed at each end of the waveguide.

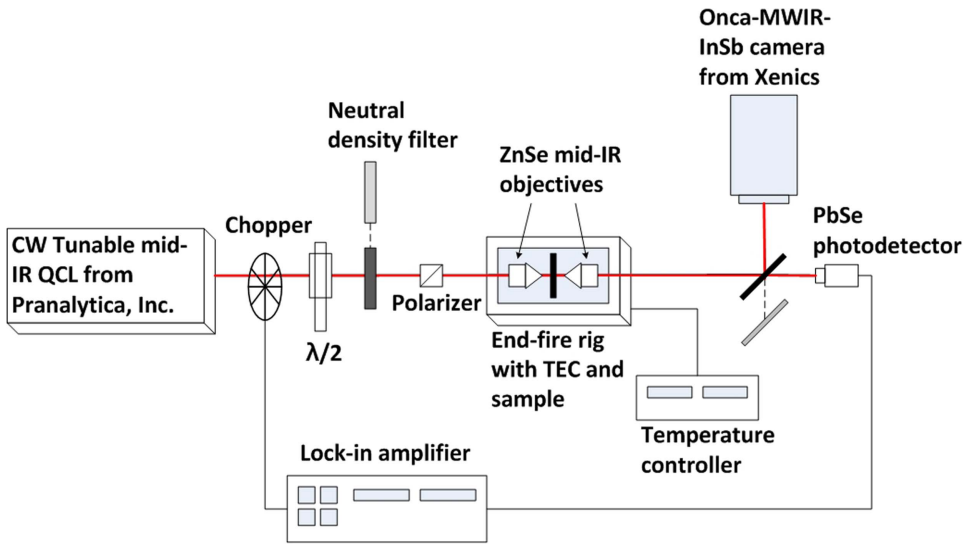

Figure 3. Schematic of the optical characterization setup.

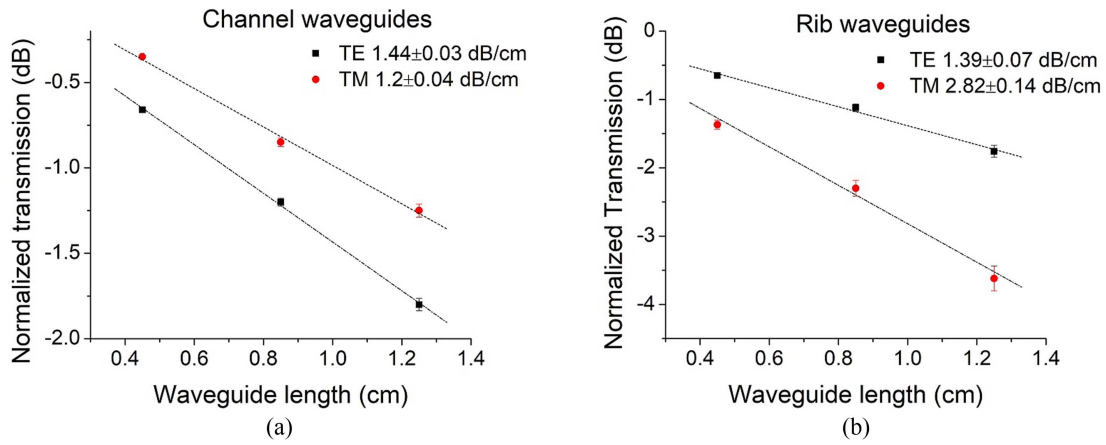

Figure 4. The normalized transmission of (a) channel waveguides, and (b) rib waveguides measured at room temperature. The dotted lines are a linear fit to the data in order to calculate the propagation loss.

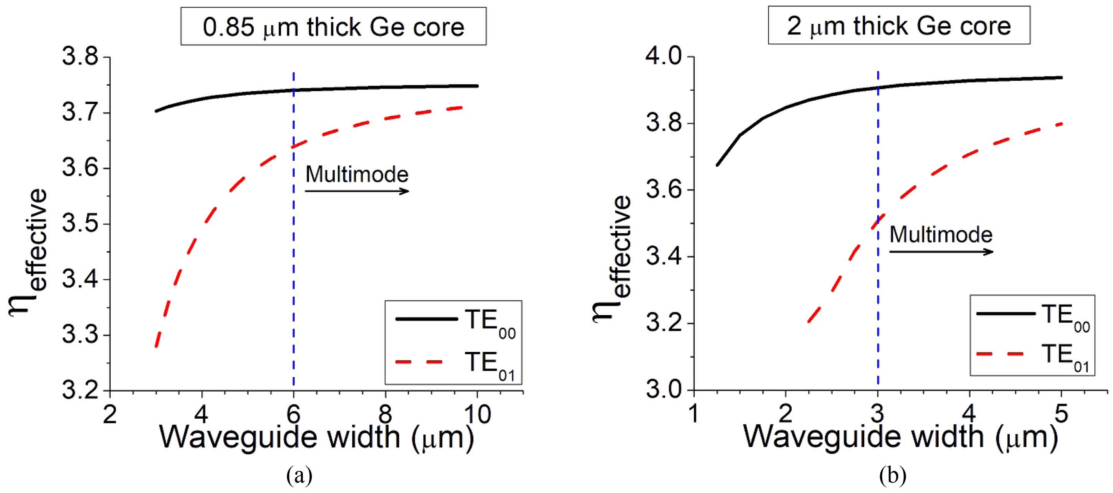

Figure 5. The calculated effective refractive index η_{eff} for the first two guided modes TE_{00} and TE_{01} for Ge core thicknesses (a) 0.85 μm, and (b) 2 μm. The small index difference indicates that the onset of multi-mode excitation is near 6 μm width for 0.85 μm thick Ge core, and 3 μm width for 2 μm thick Ge core.

The propagation loss calculated for rib waveguides using measured data is 1.39 $\pm$ 0.07 and 2.82 $\pm$ 0.14 dB/cm for TE and TM polarized light, respectively. The propagation loss in our rib waveguides is consistent with the value of 1.46 $\pm$ 0.2 dB/cm at 3.77 μm reported for 400 nm thick Si core and 220 nm deep etched rib waveguide in [12]. Again the measured propagation loss of 1.39 $\pm$ 0.07 dB/cm for TE polarization is consistent with the loss of 1.75 $\pm$ 0.22 dB/cm reported for the same waveguide structures on a different chip [16, 31].

The low propagation loss for TE and TM polarizations in our case is complemented by the buried nature of SOI waveguides where SiO_2 cladding, deposited using plasma enhanced chemical vapor deposition (PECVD), has enabled to circumvent effective surface and sidewall roughness. These results place our measured propagation losses among the lowest reported for SOI waveguides for 3.7–3.8 μm wavelengths.

3. Ge-on-SOI mid-IR waveguides

As stated in section 1, Ge-on-SOI is an attractive choice to realize a monolithically integrated mid-IR sensor. It benefits from an on-chip source and photodetector in the form of epitaxially grown direct band-gap GeSn. Secondly, it achieves better thermal and electrical isolation than Ge-on-Si material system. Therefore, we report our work on the development of low-loss Ge-on-SOI passive waveguides which provide optical routing in such PICs.

Mode-solving using a commercial software has been performed to determine the single mode condition for Ge-on-SOI strip waveguides. The calculated η_{eff} for the first two guided modes is shown in figures 5(a) and (b), for 0.85 μm and 2 μm thick Ge cores, respectively. The small index difference between the first two guided modes TE_{00} and TE_{01} indicates multi-mode excitation beyond 6 μm and 3 μm widths for 0.85 μm and 2 μm thick Ge cores, respectively. However, it has been observed in measurements that the onset of multi-mode excitation is pushed to an increased width in fabricated Ge-on-SOI waveguides due to their relatively large propagation loss, which will discussed later.

Strip waveguides have been developed in Ge-on-SOI, for which the starting SOI substrate has an overlaying Si layer of thickness 220 nm and a buried oxide of thickness 2 μm. The Ge growth process has been reported in [32]. We have prepared two samples of Ge core with thicknesses 0.85 μm and 2 μm in order to assess the loss variation. The waveguide definition process includes patterning using direct laser writing and etching in SF_6/C_4F_8 chemistry using SiO_2 hard mask. The samples are finally laser diced to the length of ~5 mm for optical measurements. The inset in figure 6 shows the SEM image of a fabricated waveguide in 2 μm thick Ge core.

Fabry–Perot method has been employed to measure the propagation loss in which the cavity oscillations have been recorded by varying sample temperature. The characterization setup is the same as described previously in section 2, and given in figure 3. The calculated propagation loss using these measurements is plotted in figure 6. The measurements show a decreasing trend in the propagation loss with an increase in waveguide width. This can be explained due to the reduction in mode overlap with waveguide sidewalls [32]. However, an abrupt increase in the propagation loss in wider waveguides, i.e., width beyond 7 μm in 0.85 μm thick Ge core and width beyond 3.5 μm in 2 μm thick Ge core, is attributed to the multi-mode excitation. This

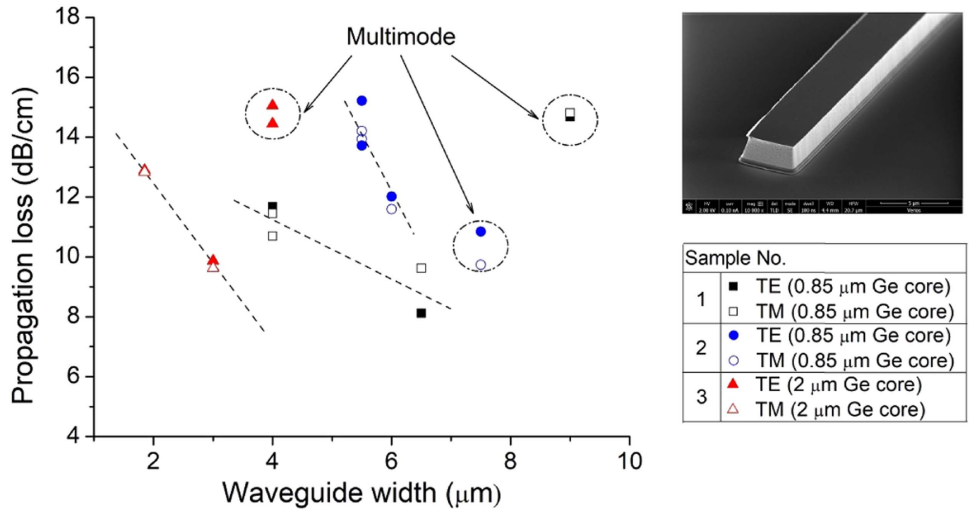

Figure 6. Propagation loss of Ge-on-SOI waveguides. (dotted lines are a linear fit to the data).

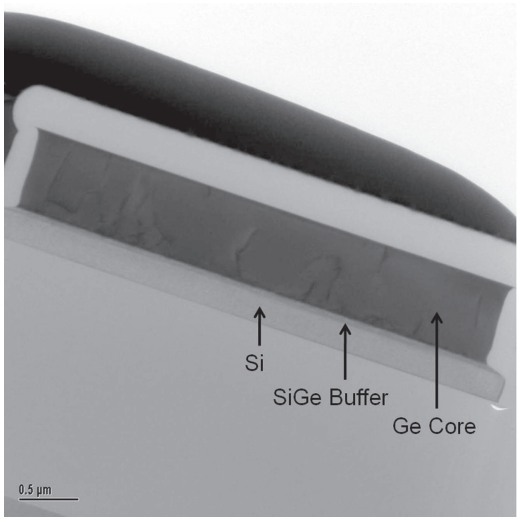

Figure 7. The cross-sectional view of transmission electron micrograph of Ge-on-SOI waveguide. Dislocation defects, which occur during material growth, have been identified as the main cause of propagation loss.

width is slightly larger than the calculated onset of the multi-mode excitation as shown in figures 5(a) and (b) and is attributed to a relatively large propagation loss.

The lowest propagation loss achieved is ~8 dB/cm in our Ge-on-SOI waveguides which is an improvement over 14 dB/cm propagation loss achieved in GeOI waveguides [30]. Secondly, the propagation loss achieved in our case is comparable to ~7 dB/cm reported earlier in [22] for Ge-on-SOI waveguides. Dislocation defects which developed during Ge growth on SOI have been identified as the main reason for a relatively large propagation loss in our case, and it has been confirmed by performing transmission electron microscopy (TEM), as shown in figure 7.

Mid-IR waveguides and devices developed in Ge-on-Si have been reported to achieve superior performance due to the techniques employed to significantly suppress the growth defects which occur at Ge/Si interface. One such method is to anneal the substrate at 850 °C [25]. Although we have reported that post-growth rapid thermal annealing in Ge-on-SOI has been able to improve the propagation loss up to 3.5 dB/cm [33], however achieving the loss performance comparable with that of Ge-on-Si is still a challenge.

Having said that, the propagation loss of ~8 dB/cm makes our Ge-on-SOI waveguides useful for high power mid-IR sensing applications due to their large footprint. Ge-on-SOI has been used previously to demonstrate high responsivity monolithically integrated near-IR photodetector in which Ge acts as an absorption layer and Si provides waveguide core [34]. Similarly, a proposed monolithically integrated Ge-on-SOI mid-IR sensor benefits from low-loss propagation provided by Ge core and the optical absorption in epitaxially grown GeSn

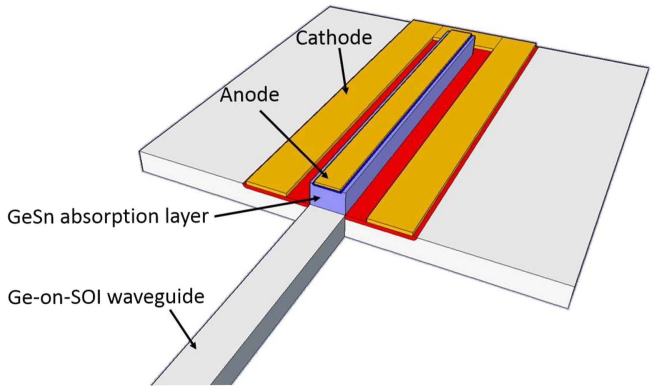

Figure 8. Schematic of a monolithically integrated GeSn mid-IR photodetector. Ge-on-SOI waveguide provides high power propagation. The light is vertically coupled into GeSn due its higher refractive index.

layer at the top, as shown in figure 8. GeSn with 9%–10% Sn concentration is able to achieve photodetection in 2.2–2.4 μm wavelengths [19, 20]. The large refractive index of GeSn provides vertical coupling of light from waveguide core into the active layer. A possibility also exists to realize on-chip light source in the form of GeSn injection laser.

4. Conclusions

To conclude, we have developed single mode waveguides in SOI and Ge-on-SOI for mid-IR wavelengths. The propagation loss of 1.44 dB/cm and 1.2 dB/cm has been measured near 3.7 μm using cut-back method for TE and TM polarizations in channel waveguides, respectively. Similarly, propagation loss of 1.39 dB/cm and 2.82 dB/cm has been measured for TE and TM polarizations in rib waveguides. These values are comparable with the lowest propagation loss reported for SOI waveguides in 3.7–3.8 μm wavelengths [9, 12]. However, we have employed a thinner Si core to achieve tightly confined single mode in channel and rib waveguides, therefore our loss performance could be considered as a relative improvement. Secondly, we have achieved a minimum loss of ~8 dB/cm in our Ge-on-SOI waveguides. This performance is comparable with the propagation loss of ~7 dB/cm reported for Ge-on-SOI waveguides [22], and a definite improvement over the propagation loss of 14 dB/cm reported for GeOI waveguides [30]. This demonstrates a feasibility to employ Ge-on-SOI in order to achieve monolithically integrated mid-IR sensors in which active regions can be realized in GeSn grown epitaxially on Ge core.

Acknowledgments

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