Silicon Germanium Platform Enabling Mid-Infrared to Near-Infrared Conversion for Telecom and Sensing Applications

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Abstract *This paper presents the potential of silicon germanium waveguides in the nonlinear conversion of light from mid-infdrared wavelengths to the telecom band utilizing four-wave mixing. Design aspects and first characterization results of fabricated devices are presented.*

Introduction

The mid-infrared (mid-IR) spectral region has attracted a significant amount of interest in recent years. It contains the absorption "fingerprints" of most molecules of interest, thus suggesting several applications both in spectroscopy and chemical and biomolecular sensing. The recent development of mid-IR sources, most notably quantum cascade lasers (QCLs) [1], has further stimulated the interest of the research community in this area. However, the lack of small size, room temperature detectors exhibiting suitably high sensitivity at this wavelength region still remains an issue.

To overcome this difficulty, wavelength conversion of the mid-IR signals into the near-infrared (near-IR) is a promising alternative. This conversion can be done either through sum-frequency generation in a second-order nonlinear medium, such as periodically poled lithium niobate [2], or through four-wave mixing (FWM) using a third-order nonlinear medium, such as silicon [3]. Silicon is an excellent candidate for such applications, thanks to its transparency up to 8 μm, the reduced two-photon and free-carrier absorptions beyond 2 μm and its potential for monolithic integrated solutions. These features however, are not restricted to pure silicon. For instance, silicon germanium (SiGe) alloys have been identified as promising candidates for nonlinear applications in the midwave and longwave infrared thanks to their enhanced nonlinearity compared to pure Si [4]. Very recently [5], we have demonstrated that $Si_{1-x}Ge_x$

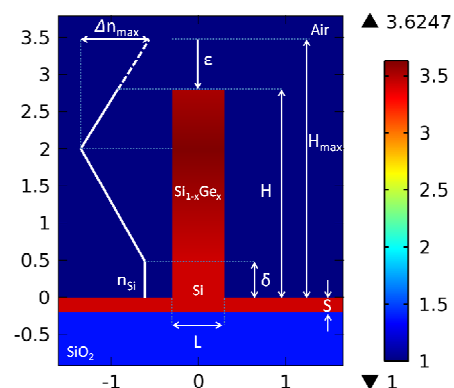waveguides also exhibit good wavelength

Fig. 1: Schematic of the waveguide structure

conversion performance for all-optical processing applications at telecommunication wavelengths. In this paper, we discuss the design aspects and fabrication of this type of devices and demonstrate the nonlinear conversion of a mid-IR signal to the near-IR.

Design aspects and modeling

The nonlinear wavelength conversion from the targeted mid-IR region (4μm – 5μm) to the near-IR region is based on the four-wave mixing process pumped by a tunable and continuous wave source covering the 2-2.5 μm wavelength region4. Therefore, the proposed waveguide must be able of carrying the mid-IR signal, the pump wave at the 2-2.5 μm region as well as the idler near-IR product at the same time while still maintain: a) Good confinement with small effective mode area for intense nonlinearities b)

low loss throughout the wavelength span and c) sufficient coupling with the dominant mid-IR sources, namely the quantum cascade la-sers (QCLs).

On top of the low index substrate a continuous Si slab layer of thickness S = 210 nm was introduced [see Fig.1] under the nonlinear waveguide. The waveguide itself was constituted of a buffer with pure Si section of thickness δ surrounded by a SiGe section. This section exhibited a specific index profile, with a standard step index in the horizontal direction and a graded index profile in the vertical direction. The step-index fiber-like behavior of the waveguide allows the centralization of the optical field in the high Ge region where the Kerr coefficient n_2 is higher, thus enhancing its nonlinear properties. The graded profile in the vertical direction (y) followed a symmetric double linear gradient, peaking in the middle of the distance ($H_{max} - \delta$). In the schematic, L denotes the waveguide width and H the total waveguide height after etching of the waveguide. H corresponds to the initial deposition height (H_{max}) reduced by the quantity ε after etching. The index would then normally vary from n_{Si} at y = δ to $n_{Si}+\Delta n_{max}$ at y = ($\delta + H_{max}$)/2 and then back down to n_{Si} at y = H_{max}. The maximum allowed Ge concentration at y = ($\delta + H_{max}$)/2 was 42%. Throughout the simulations H_{max} was kept constant at 3 μm. However, H (translating to a combination of ε and δ, since $H = \delta + H_{max} - \varepsilon$), L and S could be varied in order to properly engineer the waveguide's dispersion characteristics. The existence of a higher index core adjustable by geometrical characteristics proved to be a valuable tool in positioning the mode profile in the vertical direction. Calculations were performed using COMSOL's Finite Elements solver. The evolution of the effective index of the fundamental mode with wavelength was calculated by taking into account the material dispersion. Finally, the contribution of SiGe in each mode profile was estimated by calculating the integral:

$$n = \frac{\iint n(\mathrm{x,y})|E|^2 dxdy}{\iint |E|^2 dxdy} \qquad (1)$$

where $n(x,y)$ is the material wavelength dependent index over the Si, SiGe plane.

The main factor affecting the waveguide dispersion is the ratio H/L. For a given H value, an increase in L results in a blue shift of the ZDW (see fig. 2). However by further increasing the waveguide width, the effective mode area becomes too large to support strong non-linear phenomena. An interesting concept ascends when varying the offset, δ. As δ increases the waveguide tends to resemble a bulk Si wave-
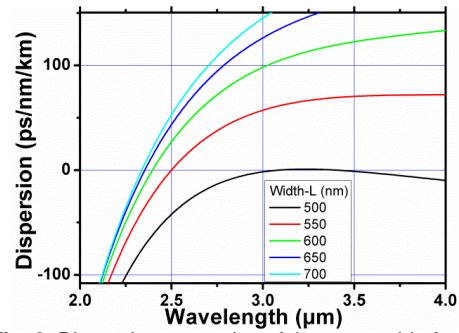

Fig. 2: Dispersion properties of the waveguide for 5 waveguide width values and height H=2.05μm (δ=1μm)
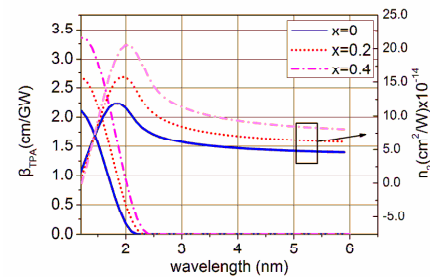

Fig. 3: Non-linear properties of Si$_{1-x}$Ge$_x$ alloys

guide. Although higher overlap between the modes at different wavelengths occurs, the Ge contribution is reduced which results in weaker Ge induced non-linearity. As δ goes to zero the conditions are reversed.

The numerical model regarding the propagation of the pump, signal and idler obeys the nonlinear coupler propagation equations [6]. The critical parameters for the model are the Kerr coefficient n_2, two photon absorption β_{TPA}, effective mode area, modal refractive index and mode overlap factors are known for all possible combinations [6]. The parameters n_2 and β_{TPA} characterize the material. According to ref. 4, the Garcia's model fitted to available experimental measurements can be utilized to predict the n_2, β_{TPA} evolution of Si$_{1-x}$Ge$_x$ alloys for all the wavelengths of interest. Effective mode area, modal refractive index and mode overlaps can be calculated with COMSOL. Fig. 3 shows the calculated n_2, β_{TPA}. As x increases, the n_2 parameter, which is crucial for efficient parametric interaction, also increases and its maximum value shifts towards longer wavelengths. An x value between 0.0 to 0.4 reassures that pump wavelengths within 2 - 2.4 μm experience enhanced nonlinearity and therefore generate idler photons with higher efficiency. The designed waveguide exhibits the ZDW around this region, hence phase matching can be almost combined with maximum nonlinearity.
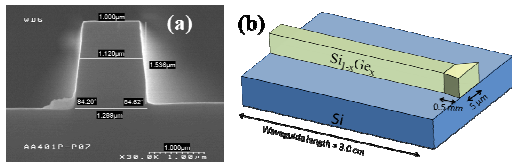
Fig. 4: a) Scanning Electron Microscopy (SEM) image of the SiGe waveguide, (b) Sketch of the SiGe waveguide

Fabrication and Experiments

The SiGe waveguide structure was grown by reduced pressure chemical vapor deposition on a SOI (silicon on insulator) wafer with 2µm buried oxide layer (Box). A buffer Si layer was first grown to adjust the SOI layer thickness to the desired value (S + δ). The linear gradient in germanium concentration on the waveguide profile was then achieved by varying the germane mass-flow during growth of the SiGe layer while keeping the dichlorosilane mass-flow constant. As a result, the concentration of Ge in the SiGe layer was linearly increased from 0 % to 42 % and then decreased back to pure Si symmetrically, as shown in Fig. 1(a). The top of the SiGe graded index layer was lowered by etching while monitoring in situ the Ge content in the etched by-products with mass spectroscopy. The process was stopped when the SiGe concentration was such that yielded the appropriate H value of 1.536 µm. Then the waveguide was realized by photolithography and etching. Etching ensured that the thickness of Si on the box layer that constituted the slab was 210 nm. Figure 4(a) shows a scanning electron microscopy (SEM) image of the fabricated waveguide cross-section.

Fig. 5 summarizes our measurements and compares them with numerical simulations which considered an input launched power of 75 mW for the pump and 10 mW for the signal, and waveguide losses of 2 dB/cm, in line with the experimental values. The comparison is in qualitative agreement. The difference between the experimental and numerical data can be attributed to several factors, such as the exact dispersion characteristics of the waveguide. As an example, we show in Fig. 5 the difference that a shift of just + 6 nm (green dashed line) or -6 nm (red dashed line) in the ZDW would make to the wavelength conversion performance. It was found that the nonlinear losses could be neglected for the pump powers considered in our experiments (< 100 mW). The experimental characterization of the waveguide revealed one of the broadest wavelength conversion performances obtained for a signal at 2650 nm to an idler at 1771 nm.
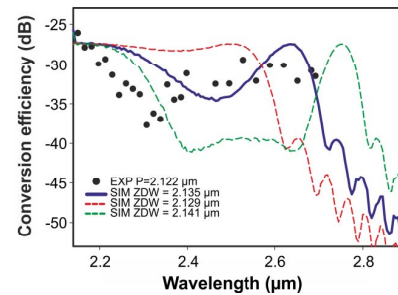

Fig. 4: a) Conversion efficiency as a function of the signal wavelength. Comparison between experiments (black dots) and numerical simulation for the dispersion shown in Fig. 2(a) (blue solid line) and for the zero dispersion shifted of + 6 nm (green dashed line) and - 6 nm (red dashed line).

Conclusions

We have reported the design, fabrication and characterization of SiGe waveguides tailored for the conversion of mid-infrared signals to the near-infrared based on four-wave mixing. The waveguide exhibited a linearly graded concentration in germanium, which allowed both for an enhanced nonlinear performance (as compared to pure Si waveguides) and a tailored ZDW. The broadest conversion we observed was from 2.65 µm to 1.77 µm using a pump at 2.12 µm. The experiment demonstrates that dispersion-engineered SiGe waveguides could lead to the realization of mid-IR spectrometers and high-sensitivity sensors. The same technique can be applied for down-conversion as well, however limited by the onset of two-photon absorption at the signal wavelengths.

Acknowledgements

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