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Third Order Nonlinear Optical Properties of Ge-Rich SiGe Waveguides

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Abstract- We report on the first third order nonlinear experimental characterization of Ge-rich $\text{Si}_{1-x}\text{Ge}_x$ waveguides, with Germanium concentrations x ranging from 0.7 to 0.9. The experimental values will be compared with theoretical models. These results will provide helpful insights to assist the design of nonlinear integrated optical based devices in both the near- and mid-IR wavelength ranges.

Keywords: Silicon; Germanium; Integrated photonics; nonlinear optics; bandgap engineering.

I. INTRODUCTION

Silicon photonics is a powerful platform for applications from long-haul optical telecommunications to intra-chip interconnects [1]. However, while silicon itself is transparent up to a wavelength of about $8\ \mu\text{m}$, the SiO_2 -buried layer limits the use of SOI at a wavelength around $4\ \mu\text{m}$.

Among the materials compatible with large volume and large scale integration, Germanium (Ge) is particularly compelling as it has a large transparency window from $1.5\ \mu\text{m}$ to $15\ \mu\text{m}$ [2]. Furthermore, Ge is predicted to have a much higher third-order nonlinear coefficient than silicon. Interestingly, $\text{Si}_{1-x}\text{Ge}_x$ alloys have been recently studied due to their ability to fine-tune the refractive index and bandgap, opening the possibility of tuning the optical properties by changing the Ge concentration (x). The nonlinearities of $\text{Si}_{1-x}\text{Ge}_x$ alloys are expected to be very sensitive to any modification of the energy bands. Indeed, the modeling and estimation of nonlinear optical (NLO) coefficients of $\text{Si}_{1-x}\text{Ge}_x$ as a function of the Ge fraction x was performed in Ref [3]. However, there is no experimental data related to the NLO coefficient of these Ge-rich $\text{Si}_{1-x}\text{Ge}_x$ alloys (x typically larger than 0.7). In this contribution, we report on the investigation of third order nonlinear properties of $\text{Si}_{1-x}\text{Ge}_x$ waveguides, with x from 0.7 to 0.9.

Due to the small difference between the energy of direct and indirect bandgaps of Ge, the bandstructure of SiGe alloys is strongly affected by the Ge percentage. It has been proposed theoretically that for Ge-rich $\text{Si}_{1-x}\text{Ge}_x$ (resp. Si-rich $\text{Si}_{1-x}\text{Ge}_x$), a direct bandgap (resp. indirect bandgap) model is the most

appropriate to estimate nonlinear properties such as optical Kerr and Two-Photon Absorption (TPA) effects. Recently, some numerical explorations have been performed showing a limit around $x = 0.80$, where the discrepancy between the two models reaches two orders of magnitude for TPA coefficient [3].

II. DESIGN AND LINEAR PROPERTIES

The fabricated waveguides consisted of $1\ \mu\text{m}$ etched in a $2\ \mu\text{m}$ thick $\text{Si}_{1-x}\text{Ge}_x$ alloy. In order to obtain a good quality Ge-rich SiGe material grown on silicon, a $11\ \mu\text{m}$ -thick graded layer was used to smoothly accommodate the lattice parameter (Fig. 1(a)) [4]. To compare similar effective areas, we have chosen a waveguide width of $1.6\ \mu\text{m}$. In this configuration we have single mode waveguides at $1580\ \text{nm}$ for the three x concentrations investigated: $x = 0.7, 0.8$ and 0.9 . In Fig. 1(b), the normalized $|\vec{e}|^2$ field for the quasi-TE fundamental mode is plotted for the waveguide with 70% Ge concentration, showing a good confinement in the $2\ \mu\text{m}$ -thick $\text{Si}_{0.3}\text{Ge}_{0.7}$ top layer.

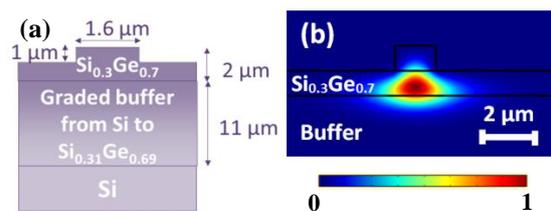


Fig.1 (a) Schematic description of the fabricated waveguides. The dimensions are identical for the three devices. (b) Normalized $|\vec{e}|^2$ at $1580\ \text{nm}$ for the Ge concentration of 70 %.

III. NONLINEAR CHARACTERIZATION

Optical pulses (150 fs duration at a repetition rate of 50 MHz) delivered by a mode-locked Erbium doped fibre laser are sent through a grating based pulse shaper, which introduces an adjustable 2nd order dispersion coefficient $\phi^{(2)}$ and a rectangular spectrum with a linewidth of $7.3\ \text{nm}$. The measured auto-correlation pulse duration at $\phi^{(2)} = 0\ \text{ps}^2$ is $2\ \text{ps}$, close to the Fourier-limit [5].

When a waveguide presents TPA, a linear relation for the output power (P_{out}) with the input power (P_{in}) can be derived, $P_{in}/P_{out} = bP_{in} + a$, with $a = 1/(\kappa_{in}\kappa_{out}\exp(-\alpha L))$, $b = 2\gamma_{TPA}\eta L_{eff}/(\kappa_{out}\exp(-\alpha L))$. L_{eff} is the effective length of the waveguide and η is a parameter that relates the average power with the peak power. κ_{in} and κ_{out} are the coupling efficiencies, depicted in Fig.2(a). The spectral output measurements are done in the propagation direction $+z$ with pulses under different dispersion $\phi^{(2)}$ varying from -3.5 to $+3.5$ ps². This dispersive scan [6] changed the waveguide nonlinear response depending on the sign and magnitude of the instantaneous third order nonlinear effects. Applying four different input powers P_{in} , the spectral r.m.s. width $2\sigma_\lambda$ from the transmitted pulses was used to determine the sign of the Kerr coefficient and the magnitude of the figure of merit $FOM_{TPA} = \frac{\gamma}{4\pi\gamma_{TPA}}$. The nonlinear phase shift $\phi_{NL} = 2\pi FOM_{TPA} \ln(1 + 2P_{in}\kappa_{in}\eta L_{eff}\gamma_{TPA})$, can be rewritten in terms of the measured coefficients a and b (Fig.2(b)) such that $\phi_{NL} = 2\pi FOM_{TPA} \ln(1 + P_{in}b/a)$. So, the FOM_{TPA} could be extracted from the experimental curves of $2\sigma_\lambda$. In Fig. 2(c), the simulation and experiments in the Si_{0.1}Ge_{0.9} are shown.

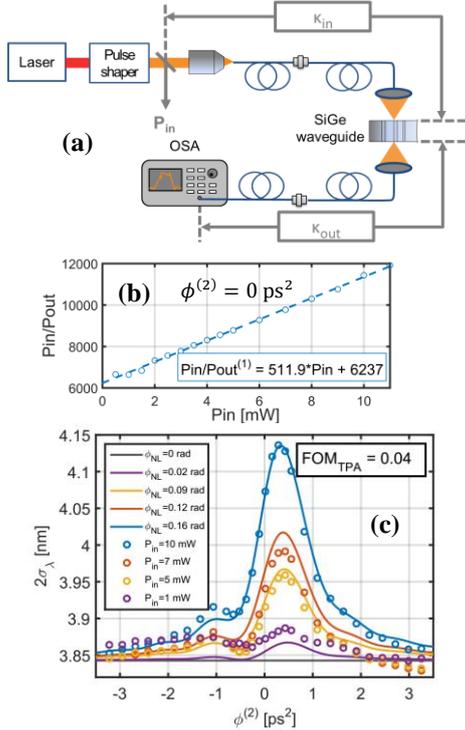


Fig.2. Simulations and measurements of the r.m.s. width as a function of the introduced dispersion for the Si_{0.1}Ge_{0.9} waveguide.

While the coupling efficiency directly impacts their nonlinear response, nonlinear characterizations currently reported in literature for waveguides rarely includes a precise determination of the coupling efficiencies. To avoid an uncertain determination, a second set of measurements was then performed in the direction $-z$ at $\phi^{(2)} = 0$ ps². By comparing the two

nonlinear transmission $P_{in}/P_{out}^{(1,2)}$ lines (Fig.3), it was then possible to extract the coupling efficiencies in each sample facet. Then, the effective TPA nonlinear parameter, $\gamma_{TPA} = b^{(1)}/(a^{(1)}\kappa_{in}^{(1)}\kappa_{FA}\eta L_{eff})$, can be calculated.

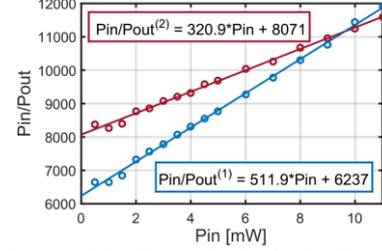


Fig.3. Bidirectional Pin/Pout vs Pin for the Si_{0.1}Ge_{0.9} waveguide.

The γ_{TPA} parameter and the FOM_{TPA} , measured via the D-Scan technique allow finally accessing the real nonlinear susceptibility $\gamma = \frac{k_0 n_2}{A_{NL}}$. The results for the three concentrations are summarized in Table 1. The FOM_{TPA} and the γ parameter uncertainties are about 6% and 10%, respectively.

Table 1. Summarized measured values.

Concentration	$FOM_{TPA} = \frac{\gamma}{4\pi\gamma_{TPA}}$	$\gamma = \frac{k_0 n_2}{A_{NL}}$
Si _{0.3} Ge _{0.7}	0.26	14.0 /m/W
Si _{0.2} Ge _{0.8}	0.18	15.5/m/W
Si _{0.1} Ge _{0.9}	0.04	8.3/m/W

The detailed metrological procedure will be presented, as well as the comparison between the experimental results and the theoretical modelling.

IV. CONCLUSION

The reported results give an insight on the interesting physical phenomena in Ge-rich SiGe integrated devices and highlight the possibility of engineering the nonlinear optical properties by changing the Ge concentration. Moreover the potential of this material for nonlinear applications in diverse spectral regions will be demonstrated.

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