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Nonlinear properties of Ge-rich SiGe waveguides

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Abstract— **We report the first third order nonlinear characterization of Ge-rich $Si_{1-x}Ge_x$ waveguides, with Germanium concentrations ranging from 0.7 to 0.9. A bi-directional top hat D-Scan method was used to determine the waveguide nonlinear parameters and to deduce the Kerr nonlinear refractive index and the two-photon absorption coefficient at the wavelength of 1.58 µm.**

Keywords-Integrated photonics; nonlinear optics; bandgap engineering; optical characterization

Silicon photonics technology is at the core of on-chip applications targeting mass production. While silicon is the material of choice for passive functions and for optical modulators based on carrier concentration variations, germanium (Ge) is largely used for photodetectors, electro-absorption modulators and light sources. Moreover both semiconductors exhibit large third order nonlinear susceptibilities, a feature that makes them interesting for all-optical functionalities exploiting small confinement areas in integrated waveguiding configurations. Another advantage of Ge in photonics is its transparency in the mid-IR wavelength range (1.55 to 14 µm), so this material shows strong potential for spectroscopic and nonlinear purposes in this spectral region. The exploitation of such properties would require the development of active devices based on nonlinear phenomena such as supercontinuum sources. Interestingly, $Si_{1-x}Ge_x$ alloys have been studied recently 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 $Si_{1-x}Ge_x$ alloys are expected to be very sensitive to any modification of the energy bands [1], despite this, a systematic study performed at different Ge content x is still lacking.

Due to the small difference between the energy of direct and indirect bandgaps of Ge, the energy band distribution of SiGe alloys is strongly affected by the Ge percentage. It has been proposed theoretically that for Ge-rich $Si_{1-x}Ge_x$ (resp. Si-rich $Si_{1-x}Ge_x$), 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. Meanwhile, it is not clear to which concentration x, each model is applicable. Some numerical explorations have been performed recently showing a limit around $x = 0.80$, where the disagreement for the expected TPA from one model to the other varies by two orders of magnitude [1].

In this context, we report here the experimental evaluation of modal nonlinear parameters (nonlinear Kerr index and TPA coefficient) for three different Ge concentrations of $Si_{1-x}Ge_x$ waveguides. The measurements have been performed at 1.58 µm wavelength, where accurate and reliable experimental set-ups are available. From these measurements, it is possible to evaluate the dominant bandgap effects and extrapolate the nonlinear indices of these materials at larger wavelengths, namely in the mid-IR spectral range, where TPA vanishes, and where SiGe alloys are expected to give rise to stronger nonlinear effect that silicon.

We have explored three Ge concentrations around the x=0.8, which is considered the inflexion point according to Ref. [1]. The different samples consisting in 2µm-thick Ge-rich $Si_{1-x}Ge_x$ waveguides with x=0.7, 0.8 and 0.9. In order to obtain a good quality Ge-rich SiGe material grown on silicon, an 11 µm-thick graded layer was used to smoothly accommodate the lattice parameter from Si to the 2µm-thick Ge-rich SiGe waveguide [2]. The chosen geometry to operate in a single-mode (TE) regime was a rib waveguide with 1.6 µm width and an etching depth of 1 µm, as shown in the inset of Fig. 1 (a). Then a single beam nonlinear characterization technique called top hat D-Scan was applied to the waveguides in a bi-directional configuration [3]. It consists in measuring the output pulse spectral broadening induced by self-phase modulation for various dispersion coefficients $\phi^{(2)}$ applied to incident picosecond pulses (Fig. 1).

The results for the three chosen concentrations [0.7/0.8/0.9] are $FOM_{TPA} = \frac{\gamma}{4\pi\gamma_{TPA}}$ =[0.26/0.18/0.04] ± 6% and $\gamma = \frac{k_0 n_2}{A_{NL}} = [14.0/15.5/8.3]/\mathrm{m/W} \pm 10\%$. The measurements for x=0.8 are shown in Fig. 1.

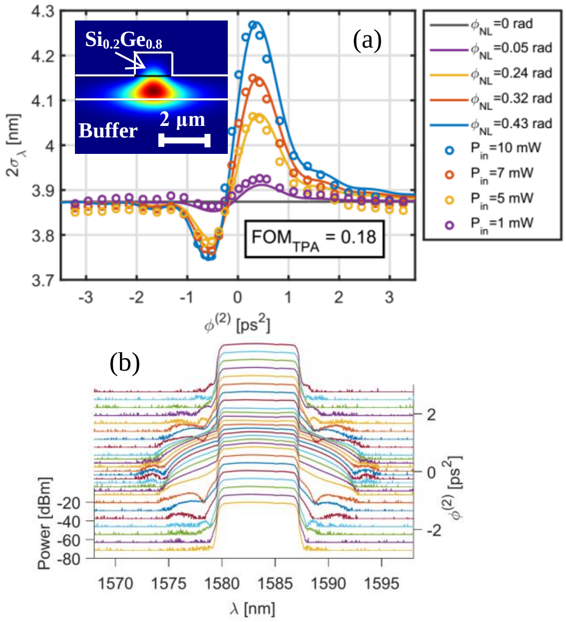

Fig. 1. (a) At different input powers, measured r.m.s. spectral linewidth with the dispersion coefficients $\phi^{(2)}$ applied to ps pulses injected in a 80% Ge-rich SiGe waveguide. Inset: Optical mode at 1580 nm. (b) Output spectra measured at P_{in}=10 mW for various $\phi^{(2)}$ coefficients.

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement N°639107-INsPIRE).

The detailed procedure will be presented, as well as the comparison between the experimental results and the theoretical modeling. This comparison will give important tools to nonlinear optical and material designers to understand the bandgap engineering of Ge rich SiGe devices and to show the potential of this material for nonlinear applications in the mid-IR spectral region.

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