All-optical modulation and nonlinear absorption in germanium-on-silicon waveguides near the $2\,\mu$m wavelength regime

L. Shen, N. Healy, C. J. Mitchell, J. S. Penades, M. Nedeljkovic, G. Z. Mashanovich, and A. C. Peacock*

Optoelectronics Research Centre, University of Southampton, Southampton SO17 1BJ, United Kingdom

*acp@orc.soton.ac.uk

Abstract: Low loss germanium-on-silicon waveguides are characterized over $2-3\,\mu$m and demonstrated for all-optical modulation based on free-carrier absorption. The results indicate the suitability of this platform for optical processing in the mid-infrared.

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1. Introduction

Group IV mid-infrared photonics is currently generating increased interest with potential applications ranging from broadband telecommunications to sensing and spectroscopy. Although much of this work has leveraged off the well-developed silicon-on-insulator (SOI) platform, more recently several demonstrations of low loss germanium-on-silicon (Ge-on-Si) waveguides have emerged [1,2]. Importantly, relative to silicon, germanium has a number of advantageous properties such as extended mid-infrared transmission from $2-14\,\mu$m, higher nonlinear coefficients, and superior electronic properties, making it of use for a wide range of active and passive waveguides. Here we report the fabrication and characterization of Ge waveguides for operation over $2-3\,\mu$m, a promising region for next generation telecommunications [3, 4] and where we have recently shown the potential for integration of Ge waveguides with GeSn-based photodetectors [2]. In particular, to demonstrate the value of this platform for optical signal processing, we present the first results of all-optical modulation in a Ge waveguide based on a free-carrier absorption scheme. The free-carrier lifetime (τ) was estimated from the material recovery to be of the order of nanoseconds, comparable to the recombination rate measured in silicon waveguides with similar dimensions. Additional measurements were also performed to characterize the two-photon absorption (TPA) coefficient in this region, where we expect the large measured β_{TPA} parameter to facilitate efficient, high-speed TPA-based modulation and wavelength conversion schemes.

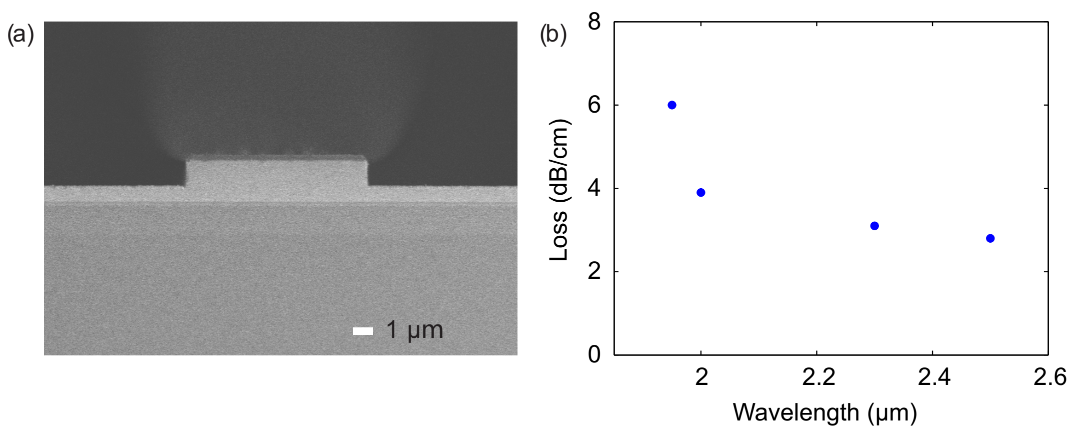

Fig. 1. (a) A SEM micrograph for a typical Ge ridge waveguide cross section. (b) Linear losses over the $1.9-2.5\,\mu$m wavelength range.

2. Germanium-on-silicon (Ge-on-Si) waveguides

The Ge-on-Si wafer on which our waveguides are based are fabricated by epitaxially depositing the Ge layer onto a Si substrate using chemical vapour deposition. Ridge waveguide structures are then defined using a standard photolithography and chemical etch method, as shown in Fig. 1(a). The waveguides used in this work were fabricated from a $2\,\mu$m thick Ge layer on Si substrate with an etch depth of $1.2\,\mu$m and a core width of $2.25\,\mu$m. To facilitate coupling, input and output tapers are fabricated at each end with a maximum width of $10\,\mu$m. The propagation loss for the TE mode was measured using a cut-back method over the wavelength range $1.9-2.5\,\mu$m, with the results shown in Fig. 1(b). These losses are similar to those previously reported in Ge waveguides over this wavelength region, which were of the order of a few dB/cm [2]. It is hoped that with further optimization of the etching conditions the losses in these waveguides could approach those of the lowest values measured for SOI waveguides in the mid-infrared [5].

3. All-optical modulation and nonlinear absorption in Ge-on-Si waveguides

The setup for the free-carrier-based all-optical modulation experiment is illustrated in Fig. 2. The probe source is a continuous-wave ZnSe laser tuned to 2006 nm, with a coupled input power of only ~ 1 mW, and the high power pump is a pulsed mode locked fiber laser operating at 1540 nm, with a coupled pump energy of only 43 pJ, pulse duration of 720 fs, and 40 MHz repetition rate. The two beams are combined with a beam-splitter before coupling into the waveguide using a $64\times$ microscope objective. The modulated output signal is collected using a tapered lens fiber and amplified by a custom built $2\,\mu$m thulium-doped fiber amplifier before detection via a InGaAs photodetector (10 GHz bandwidth). The temporal response is recorded with a 12 GHz real-time oscilloscope (RTOS).

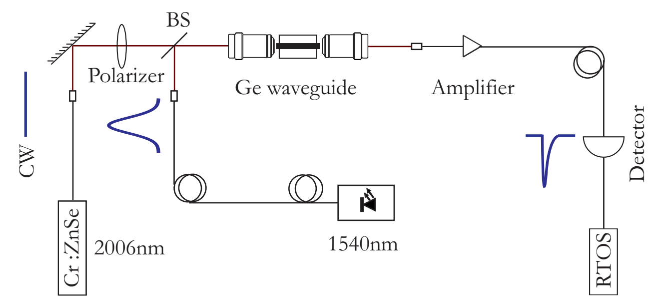

Fig. 2. Experimental set-up to demonstrate all-optical modulation in a Ge waveguide.

As the pump wavelength is positioned below the bandgap of Ge, the absorption and free-carrier generation occurs near the waveguide input in tapered region. Nevertheless, Fig. 3(a) shows that the probe amplitude is strongly modulated by the free-carrier absorption (FCA). Owing to the limited bandwidth of the $2\,\mu$m detector, it was not possible to fully resolve the fast build-up of the free-carriers that are generated on the timescale of femtosecond pump pulse in this experiment; however, it is apparent that the ultimate speed of this system will be limited by the slower free-carrier recombination process. By fitting the recovery with an exponential decay, the free-carrier lifetime can be estimated to be $\tau \sim 18$ ns, which is similar to what would be expected for a Si waveguide of these large micron-sized dimensions. Thus in order to increase the speed of this process it will be necessary to either employ a carrier sweep out scheme or decrease the size of the waveguide region where the free-carriers are generated. It is worth noting that a possible solution to increasing the speed would be to pump the core waveguide from the top, though the practicality of this geometrical setup would be more limited.

An alternative means to increase the modulation speed is to employ a cross-absorption modulation (XAM) process based on TPA. Thus, in order to investigate the potential for XAM at $\sim 2\,\mu$m we measure the TPA parameter in the Ge waveguides using a mode locked $1.94\,\mu$m fiber laser that generates 1 ps pulses at a 25 MHz repetition rate. Fig. 3(b) plots the measured output power as a function of coupled input power showing the characteristic optical limiting behaviour associated with strong TPA induced absorption. The value of β_{TPA} is found by the reciprocal transmission technique to be 1240 cm/GW [6], in good agreement with a simple band model prediction of Ref. [7]. As the values of the TPA coefficient of Ge are much larger than those of Si ($1000\times$) [8], we anticipate that these waveguides should be efficient for ultrafast modulation and wavelength conversion schemes in the increasingly important $2-3\,\mu$m regime.

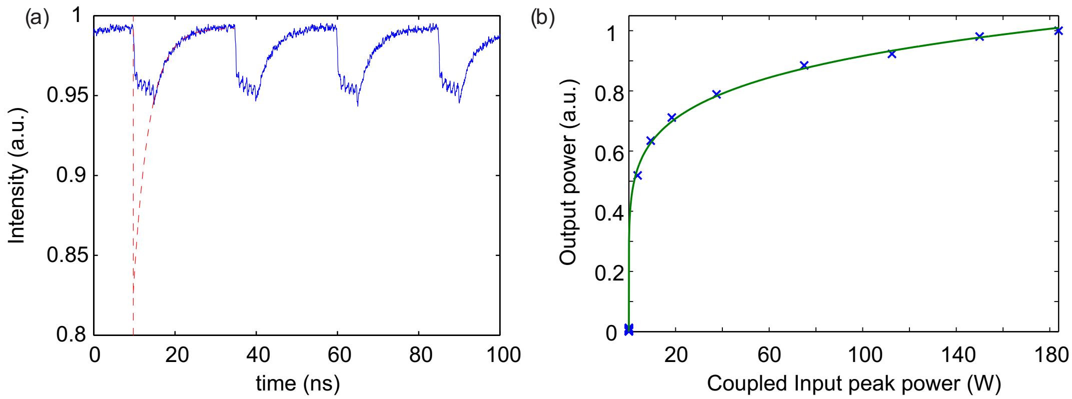

Fig. 3. (a) Free-carrier-based all-optical modulation of 2 μm light in a Ge waveguide. The red dashed line is an exponential fit to determine the free-carrier lifetime. (b) Normalized output power as a function of coupled input peak power showing the onset of nonlinear absorption.

4. Conclusion

We have characterized low loss Ge waveguides in the $2-3\,\mu$m regime and demonstrated their use for all-optical modulation using a free-carrier absorption mechanism. Although the speed of the modulation is limited by the free-carrier lifetime, the large TPA coefficient measured at 2 μm indicates a route towards ultrafast TPA-based modulation schemes. These results highlight the suitability for these waveguides to find use in all-optical processing applications at mid-infrared wavelengths.

References

1. Y. C. Chang, V. Paeder, L. Hvozdara, J. M. Hartmann, and H. P. Herzig, "Low-loss germanium strip waveguides on silicon for the mid-infrared," Opt. Lett. **37**, 2883 (2012).
2. G. Roelkens, U. Dave, A. Gassenq, N. Hattasan, C. Hu, B. Kuyken, F. Leo, A. Malik, M. Muneeb, E. Ryckeboer, S. Uvin, Z. Hens, R. Baets, Y. Shimura, F. Gencarelli, B. Vincent, R. Loo, J. Van Campenhout, L. Cerutti, J. Rodriguez, E. Tourni, X. Chen, M. Nedeljkovic, G. Z. Mashanovich, L. Shen, N. Healy, A. Peacock, X. Liu, R. Osgood, and W. Green, "Silicon-based heterogeneous photonic integrated circuits for the mid-infrared," Opt. Mater. Express **3**, 1523 (2013).
3. Y. Jung, P. Shardlow, M. Belal, Z. Li, A. Heidt, J. Daniel, D. Jain, J. Sahu, W. Clarkson, B. Corbett, J. O'Callaghan, S. Alam, and D. Richardson, "First demonstration of a 2 μm few-mode TDFA for mode division multiplexing," Opt. Express **22**, 10544 (2014).
4. D. J. Thomson, L. Shen, J. J. Ackert, E. Huante-Ceron, A. P. Knights, M. Nedeljkovic, A. C. Peacock, and G. Z. Mashanovich, "Optical detection and modulation at 2m-2.5m in silicon," Opt. Express **22**, 10825 (2014).
5. G. Z. Mashanovich, M. M. Milǒsević, M. Nedeljkovic, N. Owens, B. Xiong, E. Teo, and Y. Hu, "Low loss silicon waveguides for the mid-infrared," Opt. Express **19**, 7112(2011).
6. B. Kuyken, H. Ji, S. Clemmen, S. Selvaraja, H. Hu, M. Pu, M. Galili, P. Jeppesen, G. Morthier, S. Massar, L. Oxenlwe, G. Roelkens, and R. Baets, "Nonlinear properties of and nonlinear processing in hydrogenated amorphous silicon waveguides," Opt. Express **19**, B146 (2011).
7. G. W. Bryant, "Two-photon absorption in Ge: Band effects," Phys. Rev. B **22**, 1992 (1980).
8. N. Hon, R. Soref, and B. Jalali, "The third-order nonlinear optical coefficients of Si, Ge, and $Si_{1-x}Ge_x$ in the midwave and longwave infrared," J. Appl. Phys. **110**, 011301 (2011).