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Prospects and Challenges for Microphotonic Waveguide Components Based on Si and SiGe

D.-X. Xu, J.-M. Baribeau, P. Cheben, S. Janz, W. N. Ye

Institute for Microstructural Sciences, National Research Council Canada, 1200 Montreal Rd., Ottawa, Canada

Research into Si and SiGe as photonic materials has made steady progress since it began two decades ago.[1] Being semiconductors, amplitude and phase modulations can be achieved using carrier injections, as well as thermal effects. Si/ $Si_{1-x}Ge_x$ /Si waveguides were the original focus of this field. The refractive index of $Si_{1-x}Ge_x$ increases with the Ge content. The increments are small though, comparable to the typical refractive index contrast in glass–based waveguide systems. There is also a large intrinsic birefringence in SiGe (Fig. 1a), due to the biaxial stress in the pseudomorphic layers.[2] On the other hand, the material quality of silicon-on-insulator (SOI) has improved significantly over the last 10 years, and SOI has evolved into a platform of choice for integrated photonic circuits. Modulators,[3] variable optical attenuators (VOA),[4] optical switches and passive components such as arrayed waveguide grating (AWG) demultiplexers[5] have been realized on the SOI platform. Devices with integrated VOAs and AWGs were made commercially available.

To extend the spectral response of photodetectors beyond the Si band-edge, the addition of Ge is a natural choice. With Ge grown on Si, photodetectors with high responsivity beyond 1600 nm and operating at high speeds have been demonstrated.[6] Embedding SiGe layers in the center of an SOI structure yields well confined waveguides, with the maximum optical power aligned with the SiGe layers to maximize the absorption. Using Stranski-Krastanow growth conditions to form undulating layers, high Ge content can be incorporated without exceeding the kinetic stability limit (Fig. 2a). In waveguide photodetectors using these structures, responsivities of 0.1 A/W were demonstrated for λ=1520 nm. With silicides serving both as the electrodes and lateral claddings (Fig. 2b), high speed operation was achieved. Using selective area deposition, photodetectors and transparent waveguides can be integrated on the same chip. With Si capping layer, metastable SiGe layers maintain their strain and optical properties even under rather severe thermal treatments, making these structures compatible with CMOS fabrication technologies.

One distinct advantage offered by SOI is the capability for device size reduction, owing to the high index contrast. Using sub-micron waveguide cores, components with micron-scale sizes have been demonstrated. However, as the waveguide dimensions shrink, a number of challenges arise, such as interface scattering loss, waveguide to fiber coupling, and polarization sensitivity. Fig. 1b shows that the geometrical modal birefringence in SOI waveguides increases drastically with reduced core dimensions. We have demonstrated that cladding layers can be used to induce stress anisotropy in SOI waveguides (as shown in Fig. 3 (a) and (b)), significantly modifying the modal birefringence via the photoelastic effect.[7] By adjusting the cladding thickness or the stress level, waveguides with large geometrical birefringence can be rendered birefringence-free (Fig. 3c). It was also reported that the tensile strain residing in Ge as a result of thermal mismatch reduced the bandgap of Ge. The Ge bandgap was further decreased through tensile strain enhancement from forming $TiSi_2$ at the back of the wafer.[8] We will discuss various design possibilities opened by stress engineering in optical components based on Si, SiGe or Ge.

Our recent design of a 100 channel SOI microspectrometer with spectral resolution of ~ 0.1 nm and the free spectral range (FSR) of 20 nm occupies less than 5×5 mm^2 of wafer estate. Microspectrometers with FSR of ~1μm and several thousand channels can be fitted within 2x2 cm^2. Compared with the current state of the art devices based on free-space diffraction gratings, waveguide microspectrometers present a significant improvement in performance, particularly in resolution and spectral range, along with unprecedented compactness. Given pass achievements and new advances,[9] silicon-based optical platforms promise to fulfil the requirements for a variety of applications in telecommunications, optical interconnects, environmental and bio-sensing.

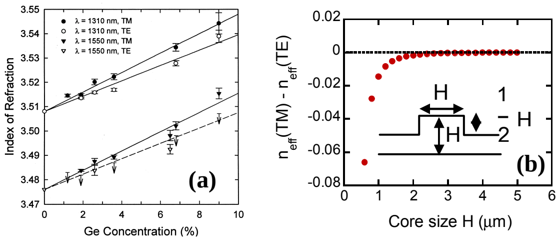

Fig. 1 (a) Variation of $Si_{1-x}Ge_x$ refractive index with Ge content x, for TE and TM polarized light; (b) Modal birefringence due to the waveguide geometry in SOI guides.

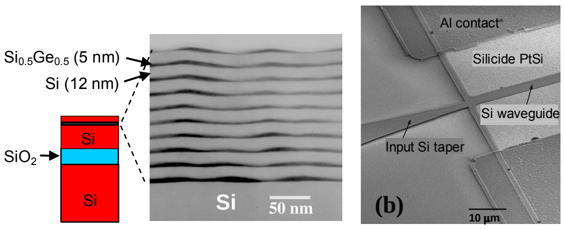

Fig. 2 (a) Undulating SiGe layers embedded in an SOI structure; (b) Waveguide detectors with silicide lateral claddings.

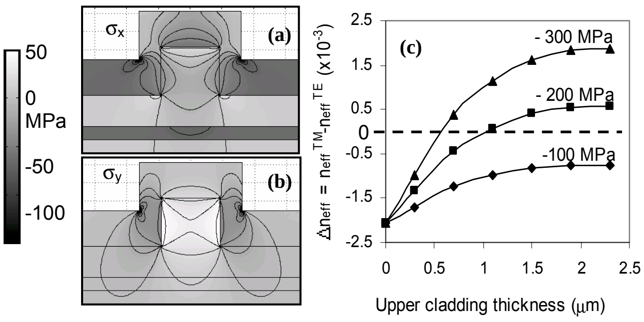

Fig. 3. Stress distributions in a SOI ridge waveguide (a) in-plane and (b) out-of-plane, for cladding stress of -220 MPa (compressive). (c) Modal birefringence as a function of upper cladding thickness, for different cladding stress levels.

References

1. R. A. Soref, Proc. IEEE **81**, 1687 (1993).
2. S. Janz, J.-M. Baribeau, A. Delâge, H. Lafontaine, S. Mailhot, R. L. Willams, D.-X. Xu, D. M. Bruce, P. E. Jessop and M. Robillard, IEEE J. Sel. Top. Quant. Elec. **4**, 990 (1999).
3. C. A. Barrios, V. R. de Almeida and M. Lipson, J. Lightwave Technol. **21**, 1089 (2003).
4. R. R. Whiteman, A. P. Knights, D. George, I. E. Day, A. Vonsovici, A. A. House, G. F. Hopper and M. Asghari, Proc. SPIE **4997**, 146 (2003).
5. P. Cheben, D.-X. Xu, S. Janz and A. Delâge, Proc. SPIE **5117**, 147 (2003).
6. S. Fama, L. Colace, G. Masini, G. Assanto and H.C. Luan, Appl. Phys. Lett. **81**, 586 (2002).
7. D.-X. Xu, P. Cheben, S. Janz, and D. Dalacu, Proc. 5th CLEO-Pacific Rim, TU3I-(8)-5. Taipei (2003).
8. J. Liu, D. Cannon, K. Wada, Y. Ishikawa, S. Jongthammanurak, D. Danielson, J. Michel and L. Kimerling, Appl. Phys. Lett. **84**, 660 (2004).
9. A. Liu, R. Jones, L. Liao, D. Samara-Rubio, D. Rubin, O. Cohen R. Nicolaescu and M. Paniccia, Nature **427**, 615 (2004).