PS-5-03

Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp1001-1002

Composition Engineering of GeSi Franz–Keldysh Optical Modulator

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Abstract

We present experimental measurements of an electro absorption modulator developed on a 800 nm thick SOI platform with data rate characteristics up to 56Gb/s. We also introduce compositional engineering of a silicon-germanium waveguide for bandgap tuneability. Our results reveal a significant change in the material composition, which provide the ability to tune the operating wavelength of individual optical modulators.

1. Introduction

The strong need for high performance data center has led to the fast development of low cost CMOS compatible devices and circuits. A wide variety of research studies have been carried out in order to enhance the now standard Silicon-On-Insulator (SOI) platform with novel functionalities. Among them the development of fast, efficient, and compact integrated optical modulators is critical for the realization of next generation data transceivers [1-3].

The last decade has seen a growing interest dedicated to the growth of Silicon Germanium (SiGe) alloys [4, 5, 6] within the SOI platform. In particular, GeSi alloys with small compositional fraction of Si (e.g. <2%) have been demonstrated more than 10 years ago [4] to be an excellent solution to obtain fast and efficient Electro-Absorption Modulators (EAM) [4,7] around 1550nm. Based on the Franz-Keldysh effect, such EAMs operate close to the GeSi alloy direct band gap energy, hindering the operation over the whole C-Band. For this reason, a method to tune the material composition within each device is most awaited. For example, engineering of the diffusion rates during a Rapid Melt Growth of Ge on Si [6] has been presented as a route to obtaining structures with different adjusted GeSi alloys, in a controlled way and on the same chip. However, this process is done at a high temperature (above 930 °C) hindering back end integration on a standard CMOS line. In parallel, Laser Annealing with short exposure duration has been used [7] to prevent Ge/Si interface intermixing and decrease the number of Thread Dislocations (TD).

In this work, we firstly present an innovative Si/GeSi hetero-structure waveguide modulator developed on an 800 nm SOI platform, that achieves a dynamic ER of 5.2 dB at a data rate of 56.2 Gb/s with a modulator power of 44 fJ/bit and electro optic bandwidth of 56 GHz [13]. We then report the compositional modification of GeSi planar microstructures using rapid thermal annealing and continuous wave (c.w.) laser radiation. The analysis of the transmission spectra of integrated SiGe waveguides that have been annealed using RTA or laser annealed with different thermal energy shows a noticeable change in the absorption band-edge, revealing the change in material composition.

2. Modulator design

We propose a wrap-around PIN hetero-structure device realized in a rib waveguide, with dimensions of 1.5 µm x 40 µm, etched within a selectively grown GeSi-on-Silicon layer in a 800 nm thick SOI wafer. The advantage of this heterostructure design, shown in Fig. 1 relies on the electric field distribution independency from the waveguide width which can also be tailored to improve, if required, the optical mode confinement and propagation of both polarizations [11].

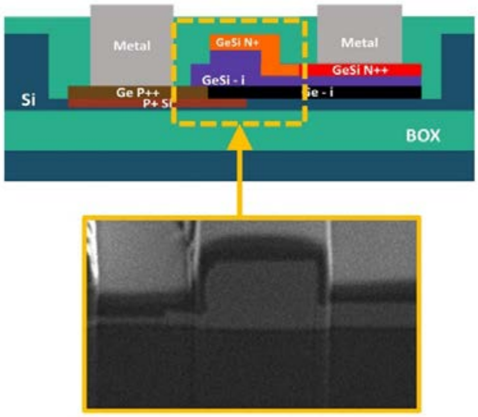

Fig. 1 A schematic Cross-section design of heterostructure (Top) and SEM images cross-section from FIB cut (Bottom). [11]

As all the EAMs are fabricated at the same time on awafer scale, the GeSi alloy composition is the same for all devices, which therefore operate around the same electronic band-gap. In order to extend the spectral range of operation, the fabricated SiGe waveguides can go through two different type of anneals such as wafer scale RTA or localized laser annealing. The measurement results are summarized in TABLE I for RTA anneals. Annealing the samples causes a blueshift of the band edge up to 32 nm suggesting an increase of Silicon in the alloy and/or a reduction of strain.

TABLE I. RTA data: Bandgap energy measured for SiGe waveguides against annealing time.

Anneal Time [min]	Bandgap Energy (800nm) [nm]
0	1579
5	1569
10	1547

In order to extend the work to localized waveguide, the fabricated modulators are then exposed to a laser radiation of several watts at 940nm using the setup depicted in Fig.2. A CCD camera is used to image the sample surface and control the relative position between the laser beam spot and our device using a set of linear micro-precision stages. Finally, the laser beam is focused on the GeSi EAM using a 10x microscope objective, producing a spot with a diameter of ~50 µm on the sample surface. The devices are exposed to the pump laser for several duration to assess the effective band-gap shift. Transmission measurements on each annealed devices allowed for the retrieval of the band-gap energy by means of the well-known Tauc band-edge absorption model. Fig. 3 plots the band-edge wavelength of the annealed devices as a function of the dose energy of the laser. A reference device is kept unexposed and presents and band-edge at 1585nm. Devices pumped with higher energy and exposure time present a red-shift up to 18nm depending on the dose which appears to saturates for doses as low as 50J. Such red-shifts are coherent with the gradual separation of Ge and Si atoms as the silicon segregate towards hotter area of the material in line with the phase diagram of the compound.

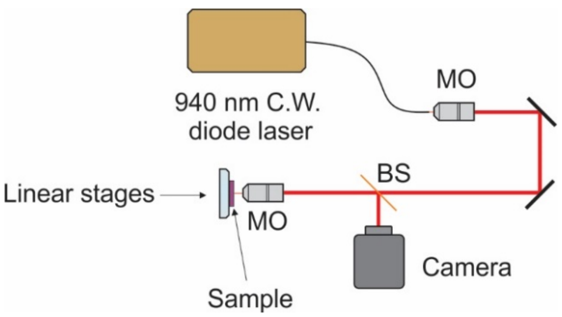

Fig. 2. Experimental setup. BS, beam splitter; MO, microscope objective.

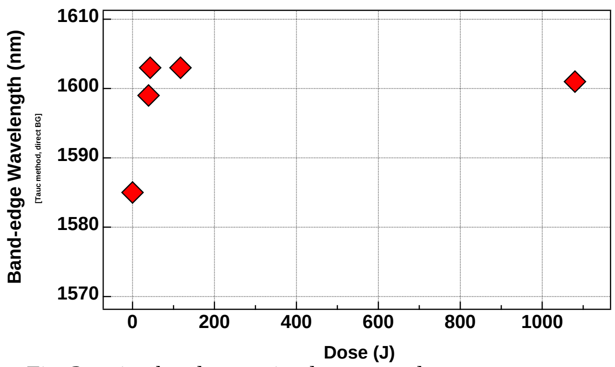

Fig. 3 tuning band-gap using laser anneal.

3. Conclusions

We have developed a high-speed GeSi waveguide EAM on an 800 nm SOI platform, operating at 1566 nm, with a data rate, limited by the measurement setup, of 56.2 Gb/s, and dynamic ER of 5.2 dB. Having a compact footprint (60 µm^2), a power consumption of 44 fJ/bit and EO modulation bandwidth of 56 GHz, this wrap-around junction design permits, a simple, customizable and tolerant fabrication of compact-high-speed electro absorption modulators. RTA enables a blue shift of the bandgap of the waveguides whereas the technique to engineer the composition of GeSi via laser-induced localized heating of the material results in a clear red-shift trend of the absorption band-edge of the devices. Our technique allows for wafer scale and highly localized tuning of the material composition to control the optoelectronic properties, such as the optical transmission, which could be used for the production of multiple modulator in same area with different operation wavelength.

References

[1] B. Jalali, and S. Fathpour, “Silicon photonics,” J. Lightwave Technol. vol. 24, 4600-4615 (2006).

[2] G. T. Reed, G. Mashanovich, F. Y. Gardes, and D. J. Thomson, “Silicon optical modulators,” Nat. Photon. Vol. 4, 518-526 (2010).

[3] Saito, Shinichi, Frederic Yannick Gardes, Abdelrahman Zaher Al-Attili, Kazuki Tani, Katsuya Oda, Yuji Suwa, Tatemi Ido et al. "Group IV light sources to enable the convergence of photonics and electronics." *Frontiers in Materials* 1 (2014): 15.

[4] J. Liu et al., *Design of monolithically integrated GeSi electro-absorption modulators and photodetectors on an SOI platform*, Opt. Express, **15**(2), 2007.

[5] V. Sorianello, et al., “High responsivity SiGe heterojunction phototransistor on silicon photonics platform,” Opt. Express Vol. 23, 28163-28169 (2015).

[6] C. G. Littlejohns, et al., “Towards a fully functional integrated photonic-electronic platform via a single SiGe growth step,” Sci. Rep. vol. 6, DOI: 10.1038/srep19425 (2016).

[7] S. Nagamoto et al, *Near-infrared laser annealing of Ge layers epitaxially grown on Si for high-performance photonic devices*, Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena, **35**, 051206 (2017); doi: 10.1116/1.4995321.

[8] D. Feng, w. Qian, H. Liang, C. C. Kung, Z. Zhou, Z. Li, J. S. Levy, R. Shafiiha, J. Fong, B. J. Lu, and M. Asghari, IEEE Journal of Selected Topics in QuantumElectronics, 19, 64-73 (2013).

[9] L. Mastronardi et al., “SiGe bandgap tuning for high speed eam,” *in transactions of 231st ECS Meeting*, **77**(6), 59-63 (2017).

[10] D. A. Coucheron, et al., “Laser recrystallization and inscription of compositional microstructures in crystalline SiGe-core fibres,” Nat. Commun. vol. 7, DOI: 10.1038/ncomms13265 (2016).

[11] Mastronardi, Lorenzo, Mehdi Banakar, A. Z. Khokhar, Nannicha Hattasan, Teerapat Rutirawut, T. Domínguez Bucio, K. M. Grabska et al. "High-speed Si/GeSi hetero-structure Electro Absorption Modulator." *Optics express* 26, no. 6 (2018): 6663-6673.

Acknowledgements

This work had support from the Optoelectronic research Centre (ORC), the Southampton Nanofabrication Centre, EPSRC First Grant (EP/K02423X/1), EPSRC Platform Grant (EP/K02423X/1) and H2020 project COSMICC (688516).

Appendix

All data supporting this study are openly available from the University of Southampton repository at https://doi.org/10.5258/SOTON/D0354