60Gb/s waveguide-coupled O-band GeSi quantum-confined Stark effect electro-absorption modulator

S. A. Srinivasan[1*], C. Porret[1], S. Balakrishnan[1], Y. Ban[1,2], R. Loo[1], P. Verheyen[1], J. Van Campenhout[1], M. Pantouvaki[1]

[1]imec, Kapeldreef 75, 3001 Leuven, Belgium, [2]IDLab, Department of Information Technology, Ghent University-imec, 9052 Ghent, Belgium

[*]Author e-mail address: ashwyn.srinivasan@imec.be

Abstract: We report O-band GeSi quantum-confined Stark effect waveguide-coupled electro-absorption modulator with 50GHz bandwidth. Static extinction ratio of 5.2dB, insertion loss of 7.6dB and 60Gb/s NRZ-OOK operation are shown for a 2V swing.

OCIS codes: (230.4205) Multiple quantum well (MQW) modulators, (130.3120) Integrated optics devices

1. Introduction

Next-generation optical transceivers in application fields such as cloud datacenter networking, AI and HPC will require multi-Tb/s capacity and power consumption well below 5pJ/bit [1]. Such multi-Tb/s transceivers require electro-optical modulators supporting data rates between 50-200Gb/s, with a compact footprint, low capacitance, low insertion loss and high extinction ratio from a low drive voltage. Silicon microring modulators are considered as a promising approach, but they require power-hungry heaters and control circuits to mitigate the modulator's narrow optical bandwidth [2] and have an intrinsic trade-off between modulation bandwidth and optical loss. On the other hand, Ge-based Franz-Keldysh effect modulators are compact and optically broadband while having bandwidths well beyond 50GHz, but they operate only in the C- and L-band [3]. As most datacom standards require O-band operation, here we present an O-band GeSi based quantum-confined Stark effect (QCSE) electro-absorption modulator (EAM) integrated in and coupled to a 220nm Silicon photonics platform. With a 3dB bandwidth of 50GHz, these electro-absorption modulators are shown to operate at a data-rate of 60Gb/s NRZ-OOK at 1321 nm wavelength. Compared to earlier results [4], the GeSi QCSE EAMs in this work have two times lower insertion loss and operate at highest data-rates reported so far.

2. Fabrication and Design of the Modulator

The working principle of multi-quantum well based electro-absorption modulator is based on quantum-confined Stark effect, according to which the absorption coefficient of the material is modulated by an applied electric field. For the O-band modulation presented in this work, a vertical p-i-n diode is implemented, comprising a GeSi-based strain-compensated multi-quantum well (MQW) stack located in the intrinsic region of the diode [4-7]. A ~170nm thick *in-situ* n-type doped GeSi strain-relaxed buffer (SRB) layer and *in-situ* p-type doped toped contact layer serves as the n and p sections of the diode respectively. A description of the composition and thickness of the O-band MQW stacks considered in this work is shown in Table 1. The stacks were selectively grown using reduced pressure chemical vapor deposition on 300mm SOI wafers. The SRB layer was first grown at 500˚C and annealed to reduce the threading dislocation density, while the spacer, MQW and top contact layers were grown at 470˚C. The GeSi devices were planarized with chemical mechanical polishing to a final thickness of 450nm [4-5]. Conventional NiSi/W/Cu BEOL contacts and interconnects were later implemented, resulting in a final device cross-section as shown in Fig. 1. The modulators were coupled to a Si waveguide using poly-Si tapers. Grating couplers for transverse electric (TE) polarization with peak-coupling wavelength at 1310nm were used for fiber coupling to and from the chip. The QCSE EAMs presented in this work have a length of 40µm and an active area of $2\times40\mu m^2$.

(a) (b)

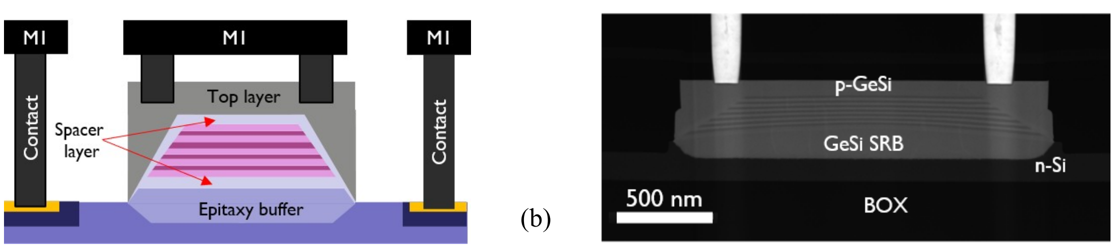


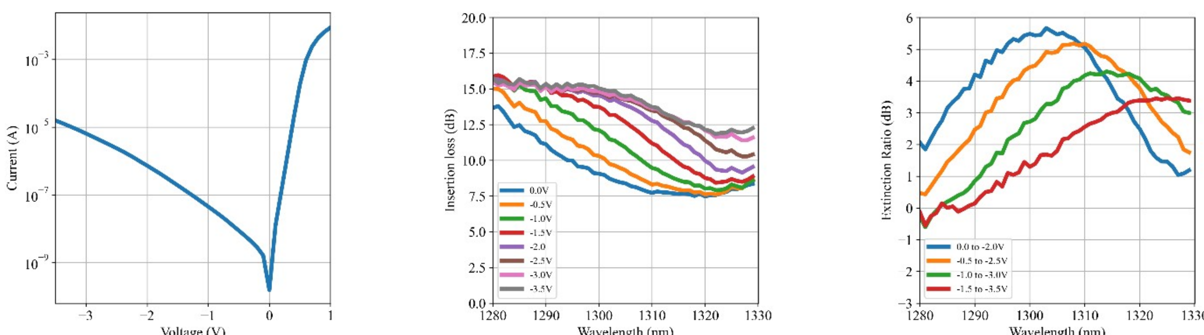
Fig. 1. (a) Cross-sectional schematic of the GeSi quantum-confined Stark effect electro-absorption modulator. (b) Transmission electron micrograph of a fabricated device.

Table 1. Stack description

Top contact layer	90nm of p-$Si_{0.15}Ge_{0.85}$
Spacer layer	20 nm of i-$Si_{0.15}Ge_{0.85}$
Multi-quantum well region	(6×) 13nm of $Si_{0.02}Ge_{0.98}$ quantum wells (7×) 11nm of $Si_{0.29}Ge_{0.71}$ barriers
Spacer layer	20nm of $Si_{0.15}Ge_{0.85}$
Epitaxy buffer	170nm of n-$Si_{0.15}Ge_{0.85}$

3. Modulator Performance:

(a) Static Characteristics: Fig. 2(a) shows a typical measured IV characteristics of the fabricated device. A dark current of 0.2µA was measured at a bias of -1.5V. The insertion loss (IL) and extinction ratio (ER) at varying bias voltages is shown in Fig. 2(b) and Fig.2(c). The ER peaks around 1310nm at -1.5V bias for a 2V swing, where the insertion loss is 7.6dB and the extinction ratio is 5.2dB. The insertion loss includes the coupling loss between the Si waveguide and the GeSi modulator, the metal loss due to contacts landing on the GeSi waveguide, the indirect band gap absorption, and QCSE absorption tail, but does not include the losses due to the input and output grating couplers. The modulator transmitter penalty defined as $TP=10\times\log_{10}(2P_{in}/(P_1-P_0))$ [8], is shown in Fig. 3(b). For an operating bias of -1.0V, the minimum TP is 12.3dB at 1310nm with the 1dB optical bandwidth of 16nm, whereas for an operating bias of -1.5V, the minimum TP is 12.8dB at 1315nm with the 1dB optical bandwidth of 20nm. When measured across 73 dies in a 300mm SOI wafer, the peak ER averaged at 5.7dB and a standard deviation of 2.6dB with the corresponding wavelength averaging at 1302nm and a standard deviation of 10nm as shown in Fig. 3(a). The insertion loss in these modulators can be reduced by exploring advanced butt-coupling schemes and aggressive contact geometries landing on the GeSi waveguide.



(a) (b) (c)

Fig. 2. (a) Dark I-V of a 2×40µm^2 GeSi QCSE electro-absorption modulator, (b) measured insertion loss of a representative device and (c) the extracted extinction ratio for a 2V swing. All measurements were performed at room temperature.

(a) (b)

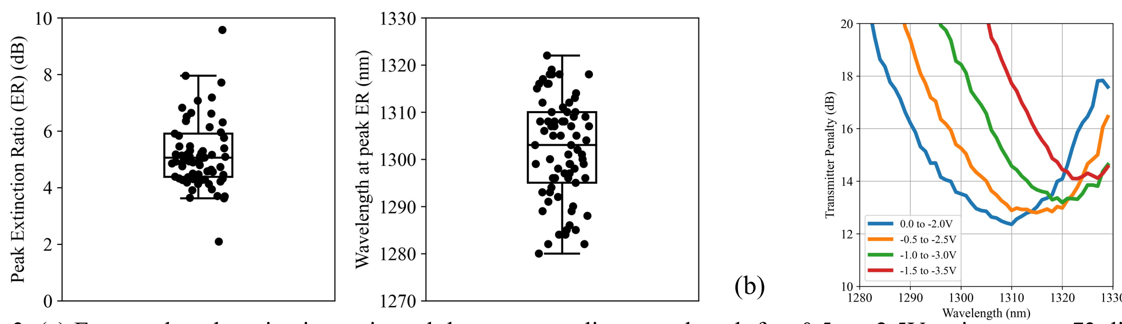


Fig. 3. (a) Extracted peak extinction ratio and the corresponding wavelength for -0.5 to -2.5V swing across 73 dies in the 300mm wafer. (b) Estimated transmitter penalty for a 2V swing.

(b) High-Speed Performance: The 3dB modulation bandwidth of the modulator was extracted from electro-optic S21 measurements using a 50GHz lightwave component analyzer (LCA), using an input optical power of 0dBm in the Si waveguide. The modulators have a bandwidth of 50GHz as shown in Fig. 4(a). The large signal modulation of the device was studied with up to 60Gb/s NRZ-OOK data stream (PRBS31) generated using a bit pattern generator

(SHF 12105 A) and delivered to the device using a 50Ω terminated 67GHz RF probe. The modulated light was amplified with a semiconductor optical amplifier and fed directly to an oscilloscope. Clear and open eye diagrams are measured at 40, 50 and 60Gb/s with a dynamic extinction ratio of 2.66dB, 2.58dB and 2.5dB for 2Vpp respectively (Fig. 4(b)). They were obtained for an operating wavelength of 1321nm with an input optical power of 3dBm and a bias voltage of -1.5V. Table 2 benchmarks the presented work by comparing the key figure of merits with other Si, Ge and GeSi based electro-optical modulators.

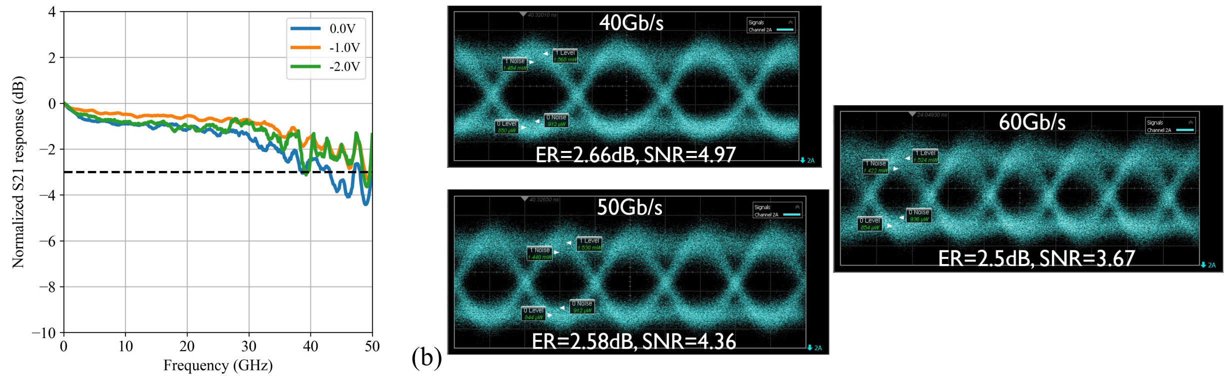


Fig. 4. (a) The RF S21 response of the device at 0V, -1.0V and -2.0V. (b) Measured eye diagrams at room temperature at 1321nm with 2Vpp and -1.5V bias voltage at 40, 50 and 60Gb/s NRZ-OOK data rates with an input optical power of 3dBm in the Si waveguide.

Table 2. Benchmarking table comparing the presented GeSi QCSE EAM with other start-of-the-art Si, Ge and GeSi electro-optical modulators.

Modulator Type	Ref	Footprint	Operating wavelength	Voltage swing	Optical Range	ER	IL	3-dB Bandwidth	Data Rate	Modulation Type
		μm^2	nm	V	nm	dB	dB	GHz	Gb/s	
Si MRM	[9]	~20×20	1280	1.0-1.6	<0.3	4.4	3.8	<42	60	NRZ-OOK
Ge FKE	[8]	~40×10	1615	2.0	>22.5	4.6	4.9	>50	56	NRZ-OOK
GeSi FK	[3]	~40×10	1560	2.0	30	4.2	4.4	>50	50	NRZ-OOK
GeSi QCSE	[4]	~40×10	1350	1.0	15	8	16	-	-	-
GeSi QCSE	This work	~40×10	1310	2.0	20	5.2	7.6	50	60	NRZ-OOK

4. Conclusion

We have demonstrated a 60Gb/s O-band GeSi quantum-confined Stark effect electro-absorption modulator waveguide-coupled in a 220nm Silicon photonics platform. The operation wavelength ranges from 1300-1330nm at room temperature. The modulator has a DC extinction ratio of 5.2dB with an insertion loss of 7.6dB and transmitter penalty of 12.8dB for 2V swing at an operating bias of -1.5V. The device has a 3-dB modulation bandwidth of 50GHz and can operate up to 60Gb/s with a dynamic extinction ratio of 2.5dB for 2Vpp at 1321nm. To the best of our knowledge, this is the fastest O-band GeSi based electro-absorption modulator demonstrated so far.

5. Acknowledgements

This work is carried out under imec's industry-affiliation R&D program on Optical I/O. This work has also received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017194. The authors acknowledge the imec pilot line for their support.

6. References

[1] https://www.oiforum.com/meetings-events/oif-webinar-co-packaged-optics-why-what-and-how/
[2] S. Fathololoumi, et al. Optical Fiber Communication Conference, ppT3H-1 2020.
[3] M. Pantouvaki, et al. Journal of Lightwave Technology, 35.4: 631-638, 2017.
[4] C. Porret, et al. IEEE Symposium on VLSI Technology, 2020.
[5] S. A. Srinivasan, et al. IEEE Journal of Quantum Electronics, 56.1: 1-7, 2019.
[6] P. Chaisakul, et al. Journal of Applied Physics, 116.19: 193103, 2014.
[7] M-S, Rouifed, et al. IEEE Journal of Selected Topics in Quantum Electronics, 20.4: 33-39, 2013.
[8] S. A. Srinivasan, et al. Journal of Lightwave Technology, 34.2: 419-424, 2016.
[9] Y. Ban, et al. IEEE Optical Interconnects Conference (OI), 2019.