Hybrid Graphene-Silicon Photonics Devices

Dries Van Thourhout(1,2), Yingtao Hu(1,2), Marianna Pantouvaki(3), K. Alexander(1,2), Bart Kuyken(1,2), Steven Brems(3), Inge Asselberghs(3), Cédric Huyghebaert(3), Chiara Alessandri(1,2,3), Philippe Absil(3), Joris Van Campenhout(3)

(1) Ghent University – IMEC, Photonics Research Group, Gent, Belgium, dries.vanthourhout@ugent.be
(2) Center for Nano- and Biophotonics, Ghent University
(3) IMEC, Kapeldreef 75, 3001 Leuven, Belgium

Abstract We will review state-of-the-art of hybrid graphene silicon photonics devices, discussing electro-absorption modulators, detectors and controllable saturable absorption.

Introduction

When a light beam is normally incident on a single sheet of graphene, about 2.3% of its power is absorbed. Interestingly, this remains the case over a very broad wavelength range, from the UV up to the MIR. People have exploited this feature to demonstrate optical detectors [1] but for practical applications in the datacom or telecom domain the efficiency of such a single pass configuration is too low. A possible solution to enhance the absorption is to embed the graphene layer in a Fabry-Perot cavity. However, this introduces a strong wavelength dependence in the response of the device, negating the intrinsic broad band response of graphene. An alternative is to integrate the graphene layer on top of a waveguide. In that way the interaction length can be increased at will. As an example, when integrated on a 220 nm x 600 nm silicon waveguide, about 0.1 dB of the light (@ 1550nm) is absorbed per micrometer for light propagating in the fundamental quasi TM-mode. In addition, when applying a voltage between the graphene layer and the silicon waveguide (Fig. 1a) the Fermi level and hence the absorption in the graphene layer can be controlled. This was demonstrated first in [2], where a graphene based intensity modulator with a bandwidth of 1 GHz and extinction ratio of ~0.08 dB/μm, operating over the wavelength range 1.35-1.60 μm was shown. In a follow up paper [3], the authors showed a variant of this device whereby also the bottom electrode is formed by a graphene layer (Fig. 1b). This roughly doubles the extinction ratio, without increasing the capacitance of the device. An additional advantage of this approach is that the waveguide no longer serves as the bottom electrode and in principle can be realised from any dielectric material, e.g. Silicon Nitride.

Since these first demonstrations several other groups have demonstrated graphene based waveguide modulators [4-9] and detectors [12-15]. Also several theoretical studies were made [10-11]. The biggest trade-off to make lies in the selection of the gate-oxide thickness. Decreasing the drive voltage, as required for combining the modulators with advanced CMOS drivers, requires reducing the gate oxide thickness. However, this increases the capacitance of the device and hence decreases its bandwidth. One approach to overcome this trade-off is to enhance the optical confinement in the graphene layer(s). This can be achieved by embedding a short modulator section in a planar resonator, e.g. a ring resonator [6][7]. However, this again introduces strong wavelength dependence in the response. Alternatives that do not introduce this wavelength dependence are to embed the graphene layer in the centre of a waveguide (Fig. 1c, [10]) or to combine it with a metal contact, which supports a plasmon-like mode (Fig. 1d, [11]). Such configurations have not yet been shown experimentally however.

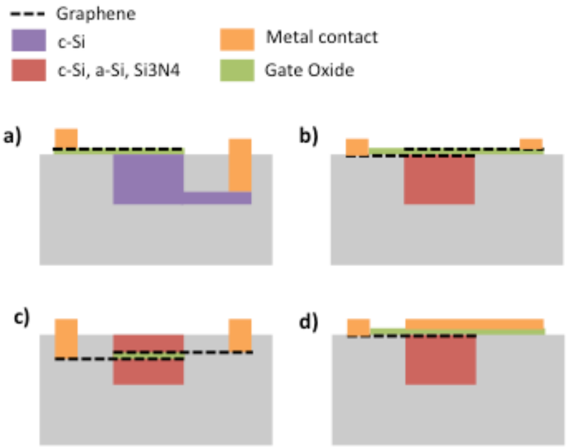

Fig. 1 The crossection of a number of possible implementations for hybrid silicon-graphene devices

EA-modulator

Earlier demonstrations of hybrid graphene-silicon modulators were relying on non-intentionally doped or lightly doped silicon waveguides (Fig. 1a), increasing the resistance of the bottom electrode and hence limiting the RC-bandwidth of the device. We recently demonstrated an improved version of the device, relying on imec's standard iSIPP25G platform, whereby the waveguide and the silicon contact area were intentionally doped (Fig. 2). This considerably improved the performance of the device, allowing us to demonstrate open eye diagrams for data-rates up tot 10 GBit/s.

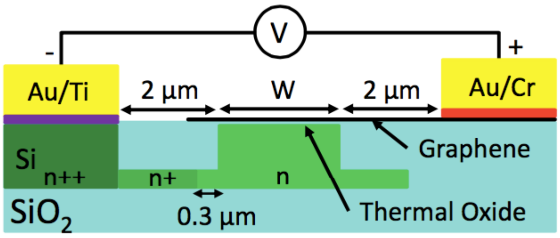

Fig. 2 Fabricated EA-modulator (from [9])

Fig. 3 shows the fabrication scheme. The silicon waveguide is planarized using SiO_2 before transferring the graphene layer.

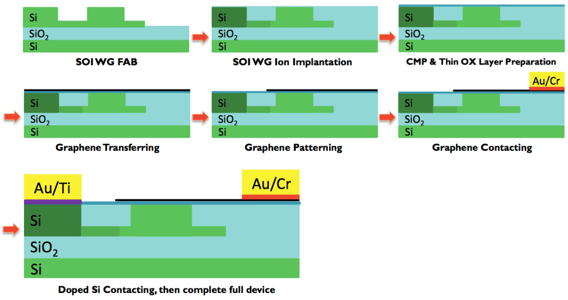

Fig. 3 Fabrication scheme for hybrid graphene-silicon modulators

Fig. 4 shows the eye diagrams for a 50 µm long device, operated at speeds up to 10 GB/s, demonstrating that this device can indeed operate at data rates relevant for optical communication purposes. Further improvement (lower drive voltage, higher extinction ratio) is expected through improving the quality of the graphene layer.

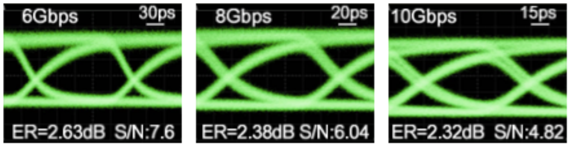

Fig. 4 Optical eye diagrams measured at 1560nm for a 50µm modulator at 6Gb/s, 8Gb/s and 10Gb/s modulation speed, using a drive voltage of 2.5Vpp swing and 1.75V forward bias delivered with a 50 terminated probe (from [9]).

Saturable Absorption

Graphene has been used extensively as the saturable absorber in modelocked lasers, allowing to generate ultrashort pulses [16]. In [17] an all fiber based modulator was demonstrated for that purpose. Recently, we demonstrated that also the planar integrated device shown in Fig. 2 can be used to control the saturable absorption in graphene [18]. Preliminary results are shown in Fig. 5. This opens routes towards fully integrated graphene mode locked devices with controllable pulse shape.

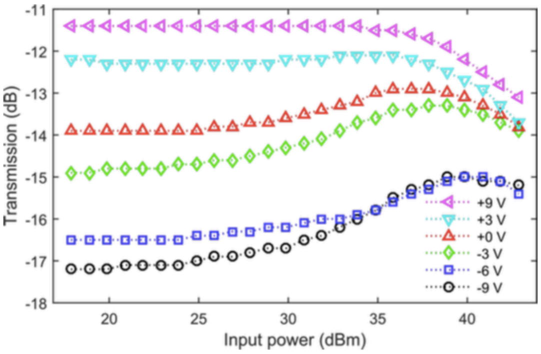

Fig. 5 Control of saturable absorption in hybrid silicon graphene modulator (see [18] for details). At high input powers the transmission is reduced through two photon absorption in the silicon waveguide.

Conclusions

Hybrid silicon-graphene devices are rapidly gaining maturity. Their ultra wide band operation and potentially low cost processing are very promising for applications in optical telecom and datacom.

Acknowledgements

This work was supported by the European Commission through the ERC-project ULPPIC and the Graphene Flagship. K. A. thanks the FWO for a PhD grant. Part of this work was supported by imec's core partner program.

References

[1] F. H. L. Koppens, T. Mueller, P. Avouris, a C. Ferrari, M. S. Vitiello, and M. Polini, "Photodetectors based on graphene, other two-dimensional materials and hybrid systems.," Nat. Nanotechnol., vol. 9, no. 10, pp. 780–93, Oct. 2014.

[2] M. Liu, X. Yin, E. Ulin-Avila, B. Geng, T. Zentgraf, L. Ju, F. Wang, and X. Zhang, "A graphene-based broadband optical modulator." Nature, vol. 474, no. 7349, pp. 64–7, Jun. 2011.

[3] M. Liu, X. Yin, and X. Zhang, "Double-layer graphene optical modulator.," Nano Lett., pp. 10–13, Feb. 2012.

[4] N. Youngblood, Y. Anugrah, R. Ma, S. J. Koester, and M. Li, "Multifunctional graphene optical modulator and photodetector integrated on silicon waveguides," Nano Lett., vol. 14, no. 5, pp. 2741–2746, 2014.

[5] N. Gruhler, C. Benz, H. Jang, J.-H. Ahn, R. Danneau, and W. H. P. Pernice, "High-quality Si_3N_4 circuits as

a platform for graphene-based nanophotonic devices," Opt. Express, vol. 21, no. 25, p. 31678, 2013.

[6] C. Qiu, W. Gao, R. Vajtai, P. M. Ajayan, J. Kono, and Q. Xu, "Efficient Modulation of 1.55 μm Radiation with Gated Graphene on a Silicon Microring Resonator," Nano Letters, pp. 6811-6815, 2014.

[7] Phare, C. T., Lee, Y-H. D., Cardenas, J., and Lipson, M., "30 GHz zeno-based Graphene electro-optic modulator", arXiv:1411.2053, 18 Nov. 2014.

[8] H. Li, Y. Anugrah, S. J. Koester, and M. Li, "Optical absorption in graphene integrated on silicon waveguides," Optics Express, vol. 20, no. 18, p. 20330, May 2012.

[9] Y. Hu, M. Pantouvaki, S. Brems, I. Asselberghs, C. Huyghebaert, M. Geisler, C. Alessandri, R. Baets, P. Absil, D. Van Thourhout, J. Van Campenhout, "Broadband 10Gb/s Graphene Electro-Absorption Modulator on Silicon for Chip-Level Optical Interconnects", Electron Devices Meeting (IEDM), United States, (2014) S. J. Koester and M. Li, "High-speed waveguide-coupled graphene-on-graphene optical modulators," Appl. Phys. Lett., vol. 100, no. 17, p. 171107, 2012.

[10] Z. Lu and W. Zhao, "Nanoscale electro-optic modulators based on graphene-slot waveguides," JOSA B, vol. 29, no. 6, pp. 1490–1496, 2012.

[11] C. Ye, S. Khan, Z. R. Li, E. Simsek, and V. J. Sorger, "λ -Size ITO and Graphene-Based Electro-Optic," IEEE J. Sel. Top. Quantum Electron., vol. 20, no. 4, p. 3400310, 2014.

[12] X. Gan, R.-J. Shiue, Y. Gao, I. Meric, T. F. Heinz, K. Shepard, J. Hone, S. Assefa, and D. Englund, "Chip-integrated ultrafast graphene photodetector with high responsivity," Nat. Photonics, vol. 7, no. 11, pp. 883–887, Sep. 2013

[13] A. Pospischil, M. Humer, M. M. Furchi, D. Bachmann, R. Guider, T. Fromherz, and T. Mueller, "CMOS-compatible graphene photodetector covering all optical communication bands," Nat. Photonics, vol. 7, no. 11, pp. 892–896, Sep. 2013.

[14] C.-H. Liu, Y.-C. Chang, T. B. Norris, and Z. Zhong, "Graphene photodetectors with ultra-broadband and high responsivity at room temperature.," Nat. Nanotechnol., vol. 9, no. 4, pp. 273–8, Apr. 2014.

[15] D. Schall, D. Neumaier, M. Mohsin, B. Chmielak, J. Bolten, C. Porschatis, A. Prinzen, C. Matheisen, W. Kuebart, B. Junginger, W. Templ, A. L. Giesecke, and H. Kurz, "50 GBit/s Photodetectors Based on Wafer-Scale Graphene for Integrated Silicon Photonic Communication Systems," ACS Photonics, pp. 1–4, 2014.

[16] Popa, D., et al. "Sub 200 fs pulse generation from a graphene mode-locked fiber laser." Applied Physics Letters 97.20 (2010): 203106

[17] Lee, Eun Jung, et al. "Active control of all-fibre graphene devices with electrical gating." Nature Communications 6 (2015).

[18] K. Alexander, Y. Hu, M. Pantouvaki, S. Brems, S. Gorza, C. Huyghebaert, J. Van Campenhout, B. Kuyken, and D. Van Thourhout, "Electrically Controllable Saturable Absorption in Hybrid Graphene-Silicon Waveguides," vol. 2, no. c, pp. 4–5.