SILICON PHOTONICS

Graphene benefits

Silicon-waveguide-integrated graphene photodetectors offer high responsivities, high speeds and broad spectral bandwidths, paving the way for graphene-based optical interconnects.

Ming Liu and Xiang Zhang

Optical communications, the core of broadband networks, has superseded copper wires in long-haul data communication systems, significantly improving their speed, bandwidth and signal quality. The integration of optical cable in short-distance communication systems (such as those within or between computer clusters, within a motherboard or within a microprocessor chip) will not only further boost Internet speeds, it will also enable the development of extremely powerful computers. Silicon photonics can provide broad bandwidths with very low optical absorption; it has been successfully implemented in low-loss optical waveguides and other passive components. However, germanium or compound semiconductors are usually required to produce high-performance active components, such as light sources, modulators and photodetectors. At present, the commercialization of active components based on these materials is hindered by technological problems and high costs.

Graphene, a single layer of carbon atoms arranged in a honeycomb lattice, exhibits exceptional electrical and optical properties, and hence may be able to overcome these obstacles. Recent intensive research on the integration of graphene into silicon-based photonic devices has led to the realization of various high-performance optoelectronic devices, including modulators, polarizers and photodetectors. These advances have deepened our fundamental understanding of the unique optoelectronic properties of graphene, and they clearly demonstrate the potential of graphene optoelectronic devices in developing cost-effective technologies for inter- and intra-chip optical communications.

Writing in *Nature Photonics*, three independent research groups — Andreas Pospischil and co-workers[1] at Vienna University of Technology and Johannes Kepler University, Linz (Austria), Xuetao Gan and co-workers[2] at Columbia University, MIT and the IBM T. J. Watson Research Center (USA), and Xiaomu Wang and co-workers[3] at Chinese University of Hong Kong (China) — report the first demonstrations of chip-integrated graphene photodetectors covering wavelengths in the near- to mid-infrared range (1.3–2.75 µm) with high responsivities and speeds. The evanescent electrical field of optical signals is confined and guided by silicon waveguides running parallel to a graphene sheet. This field excites excitons or hot carriers in graphene during propagation, so that the entire length of this two-dimensional material is utilized, maximizing the optical interaction.

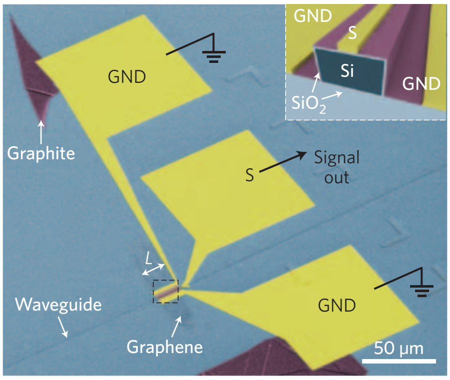

Figure 1 | False-colour scanning electron micrograph of a waveguide-integrated graphene photodetector in the work by Pospischil and co-workers[1].

A graphene photodetector was first realized by locally illuminating the edge of metal contacts of a back-gated graphene transistor with light incident normal to the graphene sheet[4]. However, its maximum responsivity (6.1 mA W^{-1}) was largely limited by the finite absorption of the atomically thin graphene layer. To increase the absorption, cavities and plasmonic resonators have been integrated with graphene, but this reduces the spectral bandwidth[5,6]. Integrating quantum dots on graphene can also dramatically increase the responsivity, but at the expense of the operation speed[7]. The best solution seems to be to use silicon waveguides, which have extremely low losses over an ultrawide bandwidth. Photons propagating in a silicon waveguide aligned parallel with a graphene sheet will interact with the graphene layer along the entire length of the waveguide, significantly enhancing light–graphene interactions without reducing the bandwidth or speed or increasing the device footprint.

The interaction between photons and electrons can give rise to electron–hole pairs in graphene. Separation of these photon-generated charge carriers (for instance, by applying an external bias voltage) can generate a measurable photocurrent. The device layout used will strongly affect harvesting of the photocarriers. Gan *et al.*[2] designed a pair of asymmetric electrodes placed parallel to the waveguide at distances of 100 nm and 3.5 µm, to produce an asymmetric electrical potential, which helps separate photocarriers generated around the silicon waveguide and reduce recombination. They report an impressive responsivity of 0.1 A W^{-1} for a 53-µm-long waveguide. Because of the spectrally flat absorption of graphene, they also observed a nearly flat photocurrent in spectrally resolved photodetection measurements with zero bias in the range 1,450–1,590 nm for a fixed optical input power. Pospischil *et al.*[1] break the symmetry of the electrodes even further by placing the source electrode entirely on the waveguide, but positioning the ground electrodes a few micrometres to the side of the waveguide (see Fig. 1). They achieved a responsivity of 0.05 A W^{-1} for a 24-µm-long waveguide. These results are on par with those for some of the best germanium photodetectors[8].

Graphene-based photodetectors are superior to germanium-based ones in terms of other parameters as well, especially the spectral bandwidth. The photocurrent of most semiconductor photodetectors drops off as the photon energy of the incident light approaches the material bandgap. Consequently, germanium photodetectors have lower efficiencies at wavelengths above 1.5 µm. Graphene, which is a zero-bandgap material, naturally overcomes this problem as its linear band structure ensures that its optical absorption coefficient is almost constant from visible to infrared wavelengths. It is thus not surprising that nearly flat optical responsivities are obtained over all optical communication bands. For instance, Pospischil *et al.*[1] achieved an almost completely flat photoresponse across all-optical communication windows (from the O to U band), which is well beyond the wavelength range of germanium or strained germanium detectors whose responsivities are limited by their bandgaps.

On the other hand, by employing a graphene–silicon heterostructure photodiode design formed by attaching graphene to a silicon optical waveguide on a silicon-on-insulator substrate, Wang *et al.*[3] extended the spectral bandwidth even further to the mid-infrared region, which is the territory of small-bandgap single-crystal compound semiconductors, such as HgCdTe and III–V quantum wells. Unlike most other mid-infrared detectors, their graphene photodetector does not require cooling by liquid nitrogen or a thermoelectric cooler; at room temperature, it has a photoresponsivity of 0.13 A W^{-1} and a photocurrent-to-dark current ratio as high as 3.9×10^7 W^{-1} for a 1.5-V bias and 2.75-μm-wavelength incident light. These specifications make it promising for applications such as environmental monitoring, on-chip infrared spectroscopy and chemical sensing.

Graphene has the highest carrier mobility of all known materials at room temperature, making it an ideal candidate for radiofrequency transistors. Such an ultrahigh carrier mobility also enables graphene photodetectors with extremely high operation speeds in excess of 640 GHz to be realized[4]. Gan *et al.*[2] examined the high-speed response of the device by monitoring the S_{21} parameter of a network analyser. They observed a degradation of only 1 dB at 20 GHz for 1.55-μm-wavelength optical signals. In addition, the device had a clear eye diagram at 12 Gbit s^{-1}. This speed can be further improved by reducing the device footprint.

To date, graphene photodetectors have been fabricated only on a laboratory scale. The major obstacle to realizing larger-scale production is the fabrication reliability. All three devices were fabricated from manually exfoliated graphene films[1–3]. Bilayer graphene was found to be better than monolayer graphene because its light absorption coefficient is twice as high and it may have a longer carrier lifetime owing to the existence of a bandgap at around 0.8 eV (corresponding to a phonon wavelength of ~1.55 μm) between the split π and π* orbitals (ref. 9). Chemical vapour deposition can be used to produce large-area graphene films, but such films usually have a lower carrier mobility than pristine graphene, and it can be difficult to precisely control the number of layers and the stacking configuration.

The studies by Pospischil *et al.*[1], Gan *et al.*[2] and Wang *et al.*[3] represent very important advances in graphene optoelectronics and silicon photonics. Their complementary metal–oxide–silicon (CMOS)-compatible graphene photodetectors complement the recently demonstrated CMOS-compatible graphene-based modulators[10], allowing for the development of scalable ultrahigh-bandwidth graphene-based optical interconnects. In addition to having a very wide wavelength detection range, high-speed operation, a low dark current, a good internal quantum efficiency and a small device footprint, this emerging technology also benefits from the mass production of graphene film, and its compatibility with CMOS and other aspects of the mature silicon industry. As these merits also apply to other graphene–silicon-based optoelectronic devices, this technology has the potential to usher in a new era of high-performance optical communications. ❒

Ming Liu and Xiang Zhang are at Nanoscale Science and Engineering Center, University of California at Berkeley, 3112 Etcheverry Hall, Berkeley, California 94720, USA. Ming Liu is also at the Department of Electrical Engineering, University of California, Riverside, California 92521, USA.
e-mail: ming@berkeley.edu, xiang@berkeley.edu

References

1. Pospischil, A. *et al. Nature Photon.* **7,** 892–896 (2013).
2. Gan, X. *et al. Nature Photon.* **7,** 883–887 (2013).
3. Wang, X., Cheng, Z., Xu, K., Tsang, H. K. & Xu, J.-B. *Nature Photon.* **7,** 888–891 (2013).
4. Xia, F. N., Mueller, T., Lin, Y.-M., Valdes-Garcia, A. & Avouris, P. *Nature Nanotech.* **4,** 839–843 (2009).
5. Engel, M. *et al. Nature Commun.* **3,** 906 (2012).
6. Liu, Y. *et al. Nature Commun.* **2,** 579 (2011).
7. Konstantatos, G. *et al. Nature Nanotech.* **7,** 363–368 (2012).
8. Wang, J. & Lee, S. *Sensors* **11,** 696–718 (2011).
9. Ohta, T., Bostwick, A., Seyller, T., Horn, K. & Rotenberg, E. *Science* **313,** 951–954 (2006).
10. Liu, M. *et al. Nature* **474,** 64–67 (2011).

Published online: 15 September 2013

FREE-ELECTRON LASERS

Fully coherent soft X-rays at FERMI

The Italian free-electron laser, FERMI, now generates coherent soft X-rays in the water window (2.3–4.4 nm) by two-stage frequency upconversion of ultraviolet seed laser pulses using the 'fresh bunch' technique.

Toru Hara

Scientists at the Free Electron Laser for Multidisciplinary Investigations (FERMI) in Trieste, Italy, report the generation of fully coherent soft-X-ray pulses by a two-stage high-gain harmonic-generation (HGHG) scheme[1]. The FERMI team not only generated the shortest wavelength for a HGHG free-electron laser (FEL) recorded to date, it also realized a stable, high-intensity light source, which will be attractive to scientists whose research suffers from noisy self-amplified spontaneous emission (SASE) spectra.

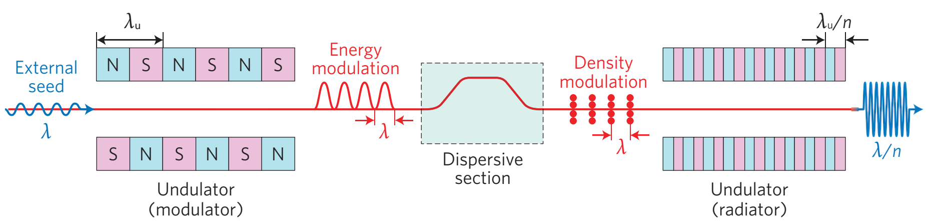

Figure 1 | Scheme for a single-stage HGHG. In a two-stage cascade, harmonic radiation from the first stage is used as an external seed for the second stage. λ, seed wavelength; λ_u, modulator period; n, harmonic number.