data needs to be related to data obtained from established ensemble-averaging techniques. Second, it should be shown that the method is generally applicable and works for biorecognition reactions other than the extremely strong biotin–avidin interaction probed here. Protein antibodies are of particular importance as capture molecules, but they are considerably larger than biotin, which might impair sensitivity. Finally, it would be extremely valuable if the method could be parallelized, meaning that numerous nanoparticles are measured simultaneously whilst retaining single-molecule sensitivity. This would dramatically increase the speed and dynamic range of the approach, which could in turn lead to new and powerful methods for ultrasensitive medical diagnostics[7] and drug screening. Ultimately, the technique could help unravel the heterogeneity of biomolecular interactions[8], which is normally hidden by ensemble averaging, or it could be used to quantify molecular interactions in highly confined volumes, perhaps even inside living cells. ❒

Mikael Käll is at the Department of Applied Physics, Chalmers University of Technology, 412 96 Goöteborg, Sweden.
e-mail: mikael.kall@chalmers.se

References

1. Zijlstra, P., Paulo, P. M. R. & Orrit, M. *Nature Nanotech.* **7,** 379–382 (2012).
2. Atwater, H. A. & Polman, A. *Nature Mater.* **9,** 205–213 (2010).
3. Soukolis, C. M. & Wegener, M. *Nature Photon.* **9,** 523–530 (2011).
4. Homola, J. *Chem. Rev.* **108,** 462–493 (2008).
5. Stewart, M. E. *et al. Chem. Rev.* **108,** 494–521 (2008).
6. Ament, I. *et al. Nano Lett.* **12,** 1092–1095 (2012).
7. Giljohann, D. A. & Mirkin, C. A. *Nature* **462,** 461–462 (2009).
8. Henzler-Wildman, K. & Kern, D. *Nature* **450,** 964–972 (2007).

PHOTODETECTORS

A sensitive pair

A hybrid photodetector unites the electronic properties of graphene with the optical properties of colloidal quantum dots to achieve high sensitivity.

Edward Sargent

Graphene[1] has exceptional and easily controlled electronic properties, but in single-layer form it only weakly absorbs light, which is a disadvantage for applications such as photodetection. Colloidal quantum dots[2], on the other hand, absorb light strongly, but the low mobility of charge carriers in films of colloidal quantum dots limits the gain of photodetectors based on such films[3]. Writing in *Nature Nanotechnology*, Gerasimos Konstantatos, Frank Koppens and co-workers at the Institut de Ciències Fotòniques (ICFO) in Barcelona demonstrate a compelling combination of these two materials[4]: light absorption in a colloidal-quantum-dot film regulates the flow of charge in an underlying graphene field-effect transistor channel (Fig. 1). The electric tunability of the graphene channel is preserved, allowing simultaneous optical and electronic control over the device.

Graphene mobilities on substrates relevant to integrated circuits have been measured to be above 10^4 cm^2 V^{-1}s^{-1} (ref. 5), which is ~1–2 orders of magnitude higher than room-temperature mobilities in crystalline silicon. The conductivity of graphene channels can also be controlled through field-effect gating with high speed, which is useful for radio-frequency applications[6].

However, graphene absorbs light with about 2% efficiency, which may be remarkable for a single atomic layer, but is too low for practical photodetection. Absorption strength could be increased by stacking multiple graphene sheets together, but this would compromise both the transport properties and the bias-tunability of graphene. This points to the need for a sensitization strategy, one in which light is absorbed in a medium tailored for this purpose, and photogenerated charges are then transferred to a graphene transport layer.

Colloidal quantum dots make for an ideal sensitizing material. They can be easily synthesized in solution and deposited onto a substrate; and they have a custom-tailored bandgap that is programmed by setting the nanoparticle diameter at the time of synthesis. Konstantatos, Koppens and co-workers sensitized their graphene with quantum dots made from PbS, whose small bulk bandgap of 0.4 eV and large Bohr

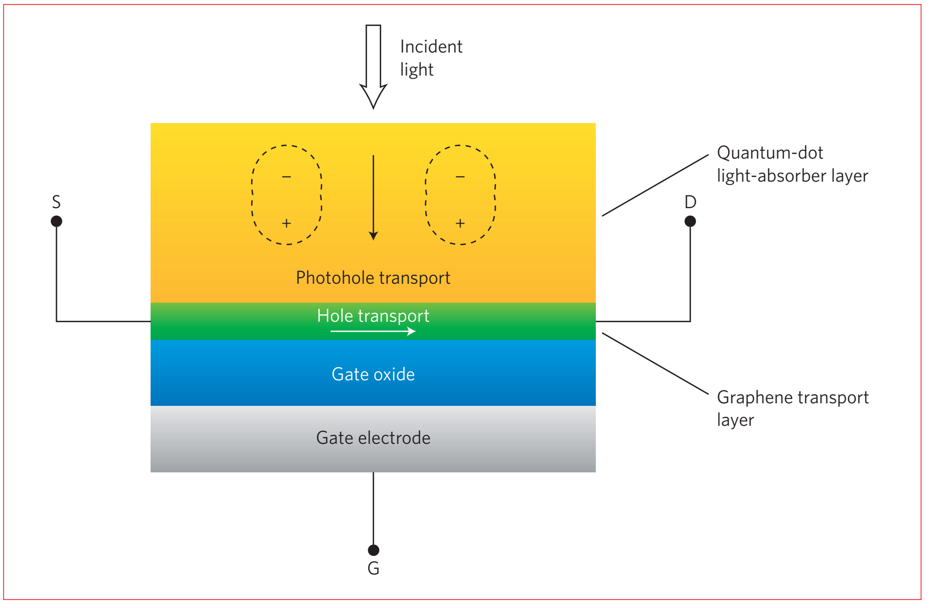

Figure 1 | The graphene–quantum-dot photo field-effect transistor. Light absorption by a sensitizing layer of quantum dots resulting in exciton (electron–hole pair) generation. Photoholes are transferred to a high-mobility, field-modulated graphene monolayer or bilayer, leaving behind photoelectrons in the quantum dots. Absorption and charge-transport processes are decoupled, with absorption occurring along the vertical axis and transport in the horizontal plane.

exciton radius of ~20 nm allows the bandgap to be tuned from the visible through to the short-wavelength infrared (0.7–2 μm) by varying dot diameter from 2 to 10 nm. Moreover, excitons in PbS colloidal quantum dots live for 1–10 μs before recombining radiatively, in comparison with picosecond lifetimes in graphene.

This means that photogenerated charge carriers in the quantum-dot film have time to travel vertically down to the graphene channel. Photoholes are injected into the graphene, and photoelectrons remain in the quantum-dot film. The hole carrier density in the channel is thus increased, and its lateral impedance decreased, as a result of photogeneration in the colloidal-quantum-dot layer. When a photohole exits the graphene channel at the drain contact, another takes its place at the source contact, and this circulation continues for the lifetime of the photoelectron trapped in the quantum dot.

Because of the long lifetime of these trapped photoelectrons, and the high mobility of graphene, the photodetector achieves a high gain of 10^8 electrons per photon, which compares very favourably to previously demonstrated graphene photodetector gains below unity. This leads to a high responsivity — the number of amperes of photocurrent that flow per watt of incident power — and a high sensitivity to light.

The ICFO team further elucidate the operation of their phototransistor[7] by investigating the dependence of the photocurrent on the gate bias. When the gate bias is chosen to minimize the density of free carriers in the graphene — corresponding to the Dirac point — the channel impedance is maximized. The voltage necessary to achieve this depends on the photoexcitation level, as stronger illumination means that more electrons are required on the gate to compensate photoinjected charges.

Fundamentally, coupling graphene and quantum dots opens up multiple new opportunities for photonic devices. The observation that holes can be selectively injected from colloidal quantum dots into graphene suggests that graphene can act as a high-conductivity, low-absorbance transparent conductive electrode for photovoltaics based on quantum dots, in place of indium tin oxide[8]. Further, these results suggest that quantum dots can be used as nanoscale optical probes to elucidate further the remarkable properties of graphene. Konstantatos, Koppens and co-workers have shown us the electronic and materials compatibility — and the functional synergy — of these two rapidly developing quantum materials. ❐

Edward Sargent is at the University of Toronto, 10 King's College Road, Toronto, Ontario M5S 3G4, Canada.
e-mail: ted.sargent@utoronto.ca

References

1. Geim, A. K. & Novoselov, K. S. *Nature Mater.* **6,** 183–191 (2007).
2. Sargent, E. H. *Nature Photon.* **6,** 133–135 (2012).
3. Konstantatos, G. *et al. Nature* **442,** 180–183 (2006).
4. Konstantatos, G. *et al. Nature Nanotech.* **7,** 363–368 (2012).
5. Berger, C. *et al. Science* **312,** 1191–1196 (2006).
6. Wang, H., Nezich, D., Kong, J. & Palacios, T. *IEEE Electron Dev. Lett.* **30,** 547–549 (2009).
7. Ghosh, S., Hoogland, S., Sukhovatkin, V., Levina, L. & Sargent, E. H. *Appl. Phys. Lett.* **99,** 101102 (2011).
8. Wang, X., Zhi, L. & Müllen, K. *Nano Lett.* **8,** 323–327 (2008).

Competing financial interests

E.S. is a shareholder in InVisage Technologies Inc.