On page 223, McComas *et al.*[5] study detections of energetic ions and electrons, some of which are observed more often in the region just outside the corona than they are near Earth. These particles are accelerated by flares (eruptions of radiation) in the corona or by shock waves associated with coronal mass ejections (eruptions of plasma), which travel through interplanetary space. The authors identify particles corresponding to both types of source region.

Because energetic particles travel along the Sun's magnetic field, the difference in the time at which fast and slow particles arrive at the PSP can be used to estimate the path length of their trajectory along the field. McComas and colleagues find that this path length is longer than expected, which suggests that the magnetic field has a more complicated geometry than assumed. This finding could be accounted for by the S-shaped magnetic-field reversals.

The imaging instrument on board the PSP makes remote observations of light scattered by electrons and dust near the Sun. On page 232, Howard *et al.*[6] report that the intensity of the dust-scattered light decreases with distance from the Sun in almost the same way as it does when observed from Earth. However, the authors find some preliminary evidence for the existence of a hypothesized dust-free zone[8] near the Sun that has not been detected before. The detailed images from the PSP also show spatial variations in the solar wind that are consistent with variations in the Sun's magnetic field on its surface, and reveal small blobs of plasma that are ejected from the Sun and form part of the young solar wind.

These four papers show that, by going into an unexplored region of the Solar System, the PSP has already made great discoveries. In the near future, it will be important to combine all the available sources of information to develop a deeper understanding of the physics of the Sun and the solar wind. For instance, researchers should combine the measurements of the electric and magnetic fields with detailed observations of the plasma particles to determine how fields and plasma interact and drive instabilities[9]. They must also study the large azimuthal flow velocity further to confirm whether it is a persistent feature or just a one-time exception during these initial PSP measurements.

The use of magnetic-field models will enable scientists to learn more about the path of energetic particles between the Sun and the PSP, and, in turn, about space weather – the effects of the Sun and the solar wind on Earth and human technology. These energetic-particle studies must also be linked with remote observations of the Sun's surface and the corona. Examining the potential presence of the dust-free zone near the Sun must be another short-term goal, but might have to wait for closer approaches of the PSP to the Sun in the future.

It is expected that PSP data will guide our understanding of the Sun and the solar wind for many years. New models and theories will be motivated by the spacecraft's discoveries, and this knowledge will be transferable to other stars and astrophysical plasmas throughout the Universe. After all, the Sun is the only star that we can study up close using spacecraft. The orbit of the PSP will bring the spacecraft even closer to the Sun in the coming years, to just over 6 million kilometres from the surface[2]. During this time, the Sun will transition into a more active phase of its 11-year cycle, so we can expect even more-exciting results soon.

In 2020, the European Space Agency will launch the Solar Orbiter mission[10]. Although this spacecraft will not go quite as close to the Sun as will the PSP, its more extensive suite of scientific instruments will be used in combination with the PSP to reveal key information about the Sun. For example, Solar Orbiter will measure the elemental composition and charge states of ions and will take photographs of the Sun in different wavelengths of light. These joint measurements will certainly close some of the remaining gaps in our knowledge of the Sun and the solar wind. For now, however, the Sun has proved again that it still holds more secrets for us to discover.

Daniel Verscharen is at the Mullard Space Science Laboratory, University College London, Dorking RH5 6NT, UK.
e-mail: d.verscharen@ucl.ac.uk

1. Aschwanden, M. *Physics of the Solar Corona: An Introduction with Problems and Solutions* (Springer, 2005).
2. Fox, N. J. *et al. Space Sci. Rev.* **204**, 7–48 (2016).
3. Bale, S. D. *et al. Nature* **576**, 237–242 (2019).
4. Kasper, J. C. *et al. Nature* **576**, 228–231 (2019).
5. McComas, D. J. *et al. Nature* **576**, 223–227 (2019).
6. Howard, R. A. *et al. Nature* **576**, 232–236 (2019).
7. Horbury, T. S. *et al. Mon. Not. R. Astron. Soc.* **478**, 1980–1986 (2018).
8. Lamy, P. L. *Astron. Astrophys.* **33**, 191–194 (1974).
9. Marsch, E. *Living Rev. Sol. Phys.* **3**, 1 (2006).
10. Müller, D., Marsden, R. G., St. Cyr, O. C. & Gilbert, H. R. *Solar Phys.* **285**, 25–70 (2013).

Electronics

Graphene sees the light in wearable sensors

Deji Akinwande & Dmitry Kireev

Graphene coated with nanoparticles has been used to make wearable light sensors that measure the human pulse and blood oxygen levels from ambient light passing through tissue, offering a potential platform for health-care monitoring.

The popularity of wearable technology has risen enormously, with the US market projected to be in the tens of billions of dollars by 2022 (see go.nature.com/33tcein). However, the effectiveness of the most common wearable devices is hindered by the physical specifications of their components: although the device is often embedded in a flexible soft shell, the main parts, such as the sensors and electronics, are still rigid[1,2]. Now, writing in *Science Advances*, Polat *et al.*[3] report a class of truly flexible, transparent wearable device that is based on graphene covered with a layer of semiconducting nanoparticles known as quantum dots. Impressively, the devices measure various vital signs using only ambient light as a signal.

Materials that are just one or a few atoms thick are said to be two-dimensional. The best-known example is graphene, which consists of single sheets of carbon atoms arranged in a hexagonal lattice. 2D materials in general, and graphene in particular, have tremendous potential for the development of next-generation wearable, soft biosensors because they combine electrical conductivity, optical transparency and mechanical flexibility with outstanding biocompatibility[4] and stability to biological electrolytes. Graphene-based tattoo-like devices[5] have previously been used to record human health signals such as heart rhythm, skin hydration and body temperature. Their outstanding performance is associated with the subnanometre thickness of graphene, which allows it to bend and stretch with the skin, without affecting the sensor performance.

Polat *et al.* have now expanded the functionality of graphene in wearable devices by depositing light-sensitive quantum dots made of the semiconductor lead(II) sulfide (PbS) onto the graphene layer. When illuminated, the quantum dots generate pairs of charged particles: negatively charged electrons and

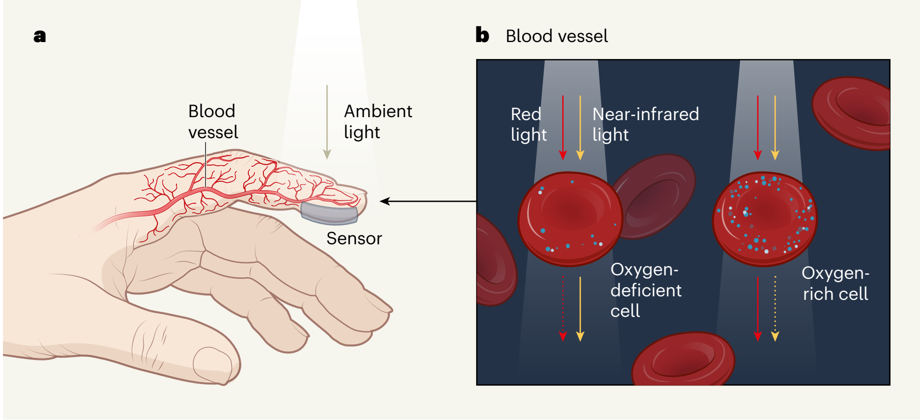

Figure 1 | A sensor that detects vital signs using light. a, Polat *et al.*[3] have used graphene coated with semiconducting nanoparticles (not shown) to make flexible, transparent devices that can detect the light transmitted through tissue. Ambient light passes easily through human skin and tissue, but is absorbed by the haemoglobin in red blood cells. By monitoring the modulation of ambient light as it passes through tissue, the sensors can thus monitor blood flow and heart rate. The rate of respiration can also be estimated from mathematical analysis of the blood-flow data. **b**, Moreover, absorption of red and near-infrared light by oxygen-rich red blood cells is significantly different from that by oxygen-poor cells. By monitoring the absorption of red and near-infrared light, the sensors can monitor the oxygen content of the blood.

positively charged holes (quasiparticles associated with the absence of an electron in an atomic lattice). The electrons stay trapped in the quantum dots, but the holes are transferred into the graphene layer and increase its electrical conductivity, producing a measurable electrical signal. The authors used this behaviour to construct light sensors from the quantum-dot-coated graphene.

The researchers observed that the responsivity (the electrical output per optical input) of their devices was remarkably large. The high responsivity is attributable to the fact that the holes in the graphene layer are recycled by the quantum dots, effectively increasing the number of charge carriers generated per absorbed photon in the devices — the devices are said to exhibit a photoconductive gain.

Previously reported light sensors typically do not have photoconductive gain, and therefore require an amplifier device to boost the electrical signal; this increases both power consumption and the size of the overall device[6]. Moreover, the amplifier must be in close proximity to the sensor, which can limit the ability of wearable devices to take on the contour of the skin. The intrinsic photoconductive gain of Polat and colleagues' devices eliminates the need for an amplifier, solving the above problems and making the sensors particularly suitable for real-life applications.

So how were the sensors used to measure vital signs? Light at certain wavelengths passes easily through human skin and adjacent tissue, but is absorbed strongly by blood[7] — more specifically, it is absorbed by haemoglobin, the molecule that transports oxygen in red blood cells. By continuously monitoring the intensity of light passing through tissue, sensors can produce readouts called photoplethysmograms (PPGs) that contain information about volumetric changes to blood vessels, which can be correlated to heart rate[8]. Polat and colleagues show that their wearable devices can, remarkably, use the ambient light that passes through tissue to measure human heart rates accurately. Moreover, the sensitivity of the devices allowed the researchers to estimate the rate of breathing by mathematically analysing the PPG data. Physical movements associated with breathing usually produce artefacts and noise in the PPG signals detected by rigid wearable devices[9], but the physical unobtrusiveness and flexibility of the new devices overcome this problem.

> **"Graphene has paved the way for other 2D materials to be used in sensors and mobile health-monitoring devices."**

Polat *et al.* report that their wearable devices can also monitor another vital health signal that is often checked by doctors: arterial oxygen saturation (SpO_2), which is the percentage of haemoglobin in blood that is loaded with oxygen (Fig. 1). Low SpO_2 levels can result in loss of consciousness, impaired mental functions, and respiratory and cardiac arrest. The absorption of red light and near-infrared light by oxygen-rich red blood cells is significantly different from the absorption by oxygen-free cells. The authors therefore estimated SpO_2 levels by using their devices to measure light absorption at these two wavelengths.

Finally, Polat and colleagues' reported a further application of their technology: the monitoring of ultraviolet light. Certain UV wavelengths can be harmful to the skin, and can potentially even cause cancer[10], making it desirable to measure UV levels in the environment. The authors show that their devices can be integrated with previously fabricated chips that enable the sensors to wirelessly transfer UV measurements to a mobile phone, thus enabling continuous and convenient monitoring of the environmental UV index.

The reported sensors are all designed to communicate wirelessly to any other electronics needed for a wearable device, clearly separating the soft sensor from any rigid components. But the wireless design requires a read-out device (such as a mobile phone) to be close to the sensor, which makes it difficult to perform long-term monitoring — as might be needed for heart-rate monitoring, for example. Establishing long-term, continuous communication between the wearable flexible sensors and conventional electronics will be essential for future applications. Alternatively, it might be possible to include components that enable memory storage and simple digital processing in the flexible platform. This could be achieved in the future using 2D materials other than graphene[11].

Graphene has now been used as a sensor and as a signal transducer in various prototypes for wearable and mobile health devices[12]. More importantly, however, graphene has paved the way for other 2D materials to be used in sensors and mobile health-monitoring devices. Thousands of such materials have been discovered, with as-yet unknown properties[13]. We think that the comprehensive study of those materials will be essential for the development of future biosensors that can be worn by, or even integrated into, humans.

Deji Akinwande and **Dmitry Kireev** are in the Department of Electrical and Computer Engineering, Microelectronics Research Center, The University of Texas at Austin, Austin, Texas 78758, USA.
e-mails: deji@ece.utexas.edu; d.kireev@utexas.edu

1. Huang, Z. *et al. Nature Electron.* **1**, 473–480 (2018).
2. Kim, D.-H. *et al. Science* **333**, 838–843 (2011).
3. Polat, E. O. *et al. Sci. Adv.* **5**, eaaw7846 (2019).
4. Fabbro, A. *et al. ACS Nano* **10**, 615–623 (2016).
5. Kabiri Ameri, S. *et al. ACS Nano* **11**, 7634–7641 (2017).
6. Kim, J., Kim, J. & Ko, H. *Sensors* **16**, E46 (2015).
7. Mannheimer, P. D. *Anesth. Analg.* **105**, S10–S17 (2007).
8. Allen, J. *Physiol. Meas.* **28** (3), R1–R39 (2007).
9. Shimazaki, T. & Hara, S. in *Proc. 2015 9th Int. Symp. Med. Inform. Commun. Technol.* 200–203 (IEEE, 2015).
10. Kuluncsics, Z., Perdiz, D., Brulay, E., Muel, B. & Sage, E. *J. Photochem. Photobiol. B* **49**, 71–80 (1999).
11. Akinwande, D. *et al. Nature* **573**, 507–518 (2019).
12. Huang, H. *et al. Front. Chem.* **7**, 399 (2019).
13. Ferrari, A. C. *et al. Nanoscale* **7**, 4598–4810 (2015).