rates of the laser sources that currently produce few-cycle optical pulses, leading to poor statistics and thus requiring longer integration times. Maintaining long-term stable operating conditions will also be a difficult experimental challenge to solve.

Up to now, the main limitation affecting electron microscopes has been the intrinsic long temporal duration (on the order of hundreds of femtoseconds) of the generated electron bunches, which is still too far away from the desirable timescale for accessing electron dynamics. Although several schemes have been proposed in the past decade to compress the electron bunches — based on radio-frequency, microwave or terahertz-field technologies — faster timescales have been difficult to access.

Hassan et al. demonstrated the feasibility of mapping dynamics in a few tens of femtoseconds and proposed a route to achieve even shorter temporal resolution.

Future extensions of the gating approach will potentially be transformative for the entire scientific sector of ultrafast science. Beyond electron microscopes, different categories of coherent light sources will benefit from the gating approach, allowing access to faster timescales and a deeper knowledge of the fundamental electronic dynamics in materials, helping in the design of the next generation of devices. Furthermore, the community operating free-electron lasers is also looking for techniques that are able to achieve shorter pulses. The results reported by Hassan et al., besides setting a new limit for the state-of-the-art performance of electron microscopes, will open a larger debate in the ultrafast community, being a starting point for pushing the current technology.

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BLACK PHOSPHORUS

A new bandgap tuning knob

An external ‘tuning knob’ by means of applying a transverse electric field has been experimentally demonstrated to modify the bandgap of black phosphorus, making the two-dimensional material practical for integration in functional nanodevices.

Rafael Roldán and Andres Castellanos-Gomez

Tunability is integral to the function of electronic components. In field-effect transistors (FETs), for example, the charge-carrier density is tuned by means of an external voltage applied to the gate electrode. 2D materials hold great promise for the fabrication of novel functional devices because their inherent reduced thickness makes them extremely sensitive to external stimuli and thus highly tunable. In particular, the recently isolated black phosphorus (BP) has already demonstrated exceptional tunability of its electronic properties by different methods including quantum confinement (sample thickness)!, high pressure!, mechanical strain! and chemical doping$. Using these approaches, the bandgap of BP could be varied in the range of ~2 eV to 0 eV (Table 1). However, these tuning methods are not practical for integration in functional nanodevices.

Now, writing in Nature Communications, Bingchen Deng and co-workers have demonstrated a new tuning knob to modify the electronic properties of BP!. They fabricated dual-gate FETs with BP channels of different thicknesses and demonstrated that the bandgap can be tuned by means of a transverse electric field. This observation can be understood as the solid-state realization of the Stark effect, commonly observed in atomic and molecular physics. In fact, while the standard Stark effect leads to the splitting and deviation of atomic energy levels due to the presence of an external electric field, in crystalline semiconductors, the application of a bias voltage can modify the energy gap due to reconstruction of the band structure. Furthermore, due to reduced electric-field screening in quantum-confined systems, the Stark effect leads to stronger modulation of the electronic and optical properties in 2D crystals, such as few-layer BP flakes, than in their 3D bulk counterparts.

In 2015, the Stark effect in BP was studied theoretically using density functional theory calculations, and it was predicted that BP could exhibit a strong modulation of the bandgap in the presence of a perpendicular electric field!. This modulation has now been experimentally demonstrated by Deng and colleagues who, by using a four-probe dual-gate FET, have measured the

| Table 1 | The different methods used to manipulate the bandgap in BP. |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|
|         | Thickness       | Chemical doping | Controlled strain | High pressure   | Electrostatic gating |
| Gap modulation (eV) | ~1.7            | ~0.6            | ~0.7            | ~0.3            | ~0.3            |
| Reversibility | Fixed bandgap for a certain thickness | Not reversible | Reversible | Reversible |
| Prospective tunability speed | Fixed bandgap for a certain thickness | Slow | Fast | Very slow | Very fast |
| Reference | 2               | 6               | 5               | 3               | 7,10             |

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conductance of BP thin-films at different vertical bias voltages. The evolution of the bandgap is then obtained from the variation of the BP conductance at the charge neutrality point on application of the perpendicular electric field and from the quantitative analysis of its temperature dependence. The electrostatic potential and the charge distribution across the BP sample are controlled by the energetic balance between the induced interlayer capacitance and the kinetic energy terms, which strongly depend on the thickness of the sample. On the other hand, it is well known that there is a great dependence of the bandgap on the number of BP layers, which motivated Deng et al. to study samples of different thicknesses (~4 nm and ~10 nm). This allowed them to explore the scaling of the bandgap tunability in samples that present different electrostatic screening properties across them.

For thin samples of ~4 nm, which corresponds to ~7 BP layers, the authors observed, for a moderate displacement field of ~1 V nm⁻¹, a bandgap shrinkage of ~75 meV. For the 10-nm-thick samples, the authors found a large increase, of about 40 times, of the minimum conductance at the charge neutrality point when the bias voltage is maximized, indicating a bandgap modification of about 300 meV, much stronger than in the 4-nm-thick samples. The observed difference is expected because for thin samples and in the presence of a moderate electric field, the interlayer coupling dominates over the potential drop across the sample, limiting the tunability of the bandgap.

On the other hand, the effective potential difference between the top and bottom layers is stronger for thicker samples, leading to a potential drop across the sample that dominates over interlayer hopping, enhancing the Stark effect and therefore the bandgap tunability. The optimal tunability is found for samples with thickness comparable to that of the penetration length of the electric field in BP, which is ~10 nm.

Independently to the work of Deng et al., reporting in Nano Letters, Yanpeng Liu and co-workers also demonstrated the effect of an external electric field on the bandgap value of BP. Instead of measuring conductance in dual-gate FETs, Liu et al. obtained tunnelling spectra of few-layer BP flakes using a low-temperature scanning tunnelling microscope. Their set-up consists of a few-layer BP flake deposited on a SiO₂/Si substrate and contacted with a gold electrode. Interestingly, they also measured a reduction in the BP bandgap from ~310 meV to ~200 meV on application of a perpendicular electric field, in what can be considered additional confirmation of the tunable Stark effect in BP.

The two methods are complementary. The dual-gate device used by Deng et al. has the advantage to allow for effective compensation of the doping induced by the back gate, leading to an insulating behaviour at the charge neutrality point. In any case, the modulation of the optical and electronic properties of few-layer BP by external electric fields is clearly demonstrated. Another advantage of this method is reversibility, especially when compared with chemical doping or quantum-confinement tuning methods.

Furthermore, electric-field tuning of the bandgap can offer higher tuning speed than other tuning methods, such as high pressure or strain engineering.

The development of a tuning method to dynamically adjust the bandgap of BP over a wide range can have strong implications for the implementation of optical modulators and photodetectors operating in the mid-infrared. As shown in Fig. 1, unbiased BP is transparent to light of wavelength longer than the wavelength imposed by the bandgap, which is ~4 μm. The application of a bias voltage reduces, in a controlled manner, the size of the semiconducting bandgap (Fig. 1) and therefore makes BP optically active for a broad range of wavelengths, which subsequently can be used for infrared optoelectronic devices and optical modulators or switches.

Future work may aim at improving the electrostatic gating technique to achieve full closing of the bandgap. This would be of great interest because closing the bandgap in BP would enable a semiconducting-to-semimetal transition accompanied by a change in the topology of the material itself. In short, this transition can be understood in the following manner (Fig. 2). Unbiased BP is a trivial semiconductor with the direct gap at the Γ point of the Brillouin zone. For some critical value of the bias field, the paraboloidal valence and conduction bands merge, completely closing the bandgap. Applying higher values of the perpendicular electric field eventually leads to the generation of a pair of Dirac-like cones in the energy spectrum, which is accompanied by a change in the topology of the system due to the emergence of
of ±π Berry phases around the Dirac points. In fact, this transition has already been experimentally observed in chemically doped BP and in samples subjected to high pressure. However, electrostatic gating would allow for a dynamical control of this transition and for its possible use in nanodevices.

The independent experimental verification of the giant Stark effect in few-layer BP by Deng et al. and Liu et al. opens up exciting avenues to observe new physical phenomena and to fabricate functional devices based on BP using a moderate perpendicular electric field as an external tuning knob, which can be easily integrated with other existing device architectures.

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**Evolving X-ray science**

Reports of photon–photon interaction experiments, novel imaging schemes and state-of-the-art mirrors were highlights of the recent International Conference on X-ray Optics and Applications in Yokohama, Japan.

Noriaki Horiuchi

Given their high photon energy, X-rays are a valuable tool for probing fundamental science and are routinely exploited in particle physics and plasma physics. However, to improve the detection of X-ray signals with either better sensitivity or higher spectral resolution, further development is required. Researchers involved in X-ray optics recently met at Pacifico Yokohama, Japan to discuss this challenge and others at the International Conference on X-ray Optics and Applications (XOPT) 2017 (held 18–21 April 2017).

In an invited talk, Shoji Asai from the University of Tokyo explained how X-rays are being used in a vacuum experiment. “Our vacuum is not empty, but actually filled with various fields, such as the Higgs field. The vacuum therefore plays important roles for cosmology and particle physics,” he said.

Currently, one of the main goals for particle physicists is to discover whether there are still unknown quantum fields hidden in the vacuum. According to Maxwell’s equations, photons do not couple to other photons. However, if a photon–photon collision is observed in the vacuum, it would verify the existence of the so-called quantum electrodynamics (QED) field or an unknown new field. Asai’s research involves theoretically estimating the interaction cross-section between photons in various energy regimes and he has proposed two experiments to hunt for the existence of the QED field.

The first experiment is to investigate photon–photon collisions in the X-ray regime. To this end, Asai’s group built an experiment at the SPring-8 facility in Japan. X-ray beams from SPring-8’s Angstrom Compact Free Electron Laser (SACLA) with 6 × 10¹¹ photons per pulse at photon energy of 11 keV were used. The energy spectrum of the X-ray beam was narrowed from 50 eV to 60 meV by a monochromator. Then, the monochromated beam was collimated and shaped into a vertical beam (1 μm in the horizontal direction and 200 μm in the vertical direction) by a slit. The beam was subsequently sent to an interferometer installed in a vacuum chamber at a pressure of 10⁻³ Pa. The interferometer was designed so that two X-ray beams obliquely collided with a crossing angle of 10⁸°. A Ge detector was placed near the point of collision to measure the energy of the scattered X-ray beams.

Contrary to theoretical predictions, no signal was observed in the experiment and Asai believes that the reason for not detecting a signal might be an insufficient photon flux. “We believed that the monochromatic X-ray beam was suitable for the photon–photon collision experiment. However, in our case, the luminosity was reduced by 10⁹ times by the monochromator and the interferometer based on Bragg reflection. In order to maintain the high luminosity, a new type of interferometer like a multilayer Bragg reflector should be developed,” he said.

The second experiment he proposed was to investigate the photon–photon collision between an X-ray beam and an infrared laser, which is an ongoing project. Currently, a 500-TW laser synchronized with SACLA is being installed with a wavelength, pulse energy, pulse width and focused beam size of 800 nm, 12.5 J, 25 fs and 1 μm, respectively. The laser beam counter-propagates to the X-ray beam from SACLA.

In the collision between the X-ray beam and the laser beam, a fraction of the X-ray beam is expected to be diffracted by 30 μrad, if the theory is correct. To collect the signal relevant to the photon–photon collision, the direct X-ray beam should be suppressed by a slit. At present, the level of suppression is only a factor of 10⁴, and the diffracted photons at the edges of the slits contribute significantly to the measured signal. “If we can suppress [the diffracted photons at the edges of the slits] by 10⁴ using a new idea, for example diffracted photons can be cancelled by interference, I do believe that we can obtain experimental evidence of the QED field,” Asai told Nature Photonics.

Although many forms of X-ray imaging have already been demonstrated, Akio Yoneyama from Hitachi discussed a new design of phase-contrast X-ray imaging (PCXI), which makes it possible to visualize the temperature distribution of water. The temperature is determined by analysing the linear relation between the phase shift of the X-rays and the change in electron density of the sample, in other words, its refractive index. PCXI measures the phase shift of the