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## Bacteria aid fight against blight

Botrytis blight is a common disease of greenhouse crops (pictured), caused by the fungus *Botrytis cinerea*. Writing in the *Journal of the American Chemical Society*, Götze *et al*. report bacterial compounds that are strongly active against *B. cinerea* (S. Götze *et al. J. Am. Chem. Soc.* https://doi.org/jt2n; 2023).

Götze and colleagues' discovery stemmed from their observation that the social amoeba *Dictyostelium discoideum* was unable to feed on a strain of *Pseudomonas* bacteria. They found gene clusters in the *Pseudomonas* genome that encode biosynthetic machinery for producing amoebicidal compounds, which the authors named keanumycins. Compounds that kill social amoeba often also act as antifungal agents, and *in vitro* screening revealed that keanumycins were indeed active against a variety of fungi.

Intriguingly, the compounds were particularly active against *B. cinerea*. The authors prepared a fermentation broth of the keanumycin-producing bacteria, and found that it strongly inhibited botrytis blight infection in a model plant (*Hydrangea macrophylla*). The findings suggest that keanumycins could be used to develop antifungal agents for protecting crops from *B. cinerea*.

**Andrew Mitchinson**

Condensed-matter physics

# Light tailors the properties of a model semiconductor

**Alberto Crepaldi**

When a semiconductor material called black phosphorus is hit with intense laser light, the behaviour of its electrons is found to change. The discovery opens a route to time-dependent engineering of exotic electronic phases in solids. **See p.75**

The atoms in a crystalline solid are arranged in space with a periodicity and symmetry that determine the physical properties of the material. These properties can therefore be modified by altering the crystal structure — for example, with pressure, strain or chemical substitution. But for many technological applications, controlling the properties of a crystal in time is just as important as changing them in space. Such temporal engineering has been successful in systems comprising groups of ultracold atoms arranged in lattices by means of intersecting laser beams[1], and in electrically conductive materials[2–4], but it is had not yet been achieved in semiconductors — until now. On page 75, Zhou *et al*.[5] report that the physical properties of black phosphorus (Fig. 1a), a model semiconductor, can be tailored through irradiation with intense laser light.

The behaviour of electrons in a periodic crystal was first described in 1929 by Swiss–American physicist Felix Bloch[6]. His theory reveals that the electrons have a range of allowed energy levels in the solid, owing to their wave-like nature, and the pattern of these levels is called the crystal's electronic-band structure. The forbidden range of energies between the 'valence' band (low energies) and the 'conduction' band (high energies) is known as the bandgap.

The way in which electrons occupy these bands determines how they can move through a material: metals have partially empty bands, whereas insulators have fully occupied bands with large bandgaps, and semiconductors have fully occupied bands with bandgaps that are small. Electrical conductivity can therefore be controlled by engineering the occupation of the band structure, and by manipulating bandgaps — and this can now be done in a time-dependent way (Fig. 1b).

The necessary mathematical tools for extending Bloch's theory to incorporate time had already been devised in the nineteenth century by French mathematician Gaston Floquet[7]. In the framework of Floquet's theory, when a solid is subjected to an intense

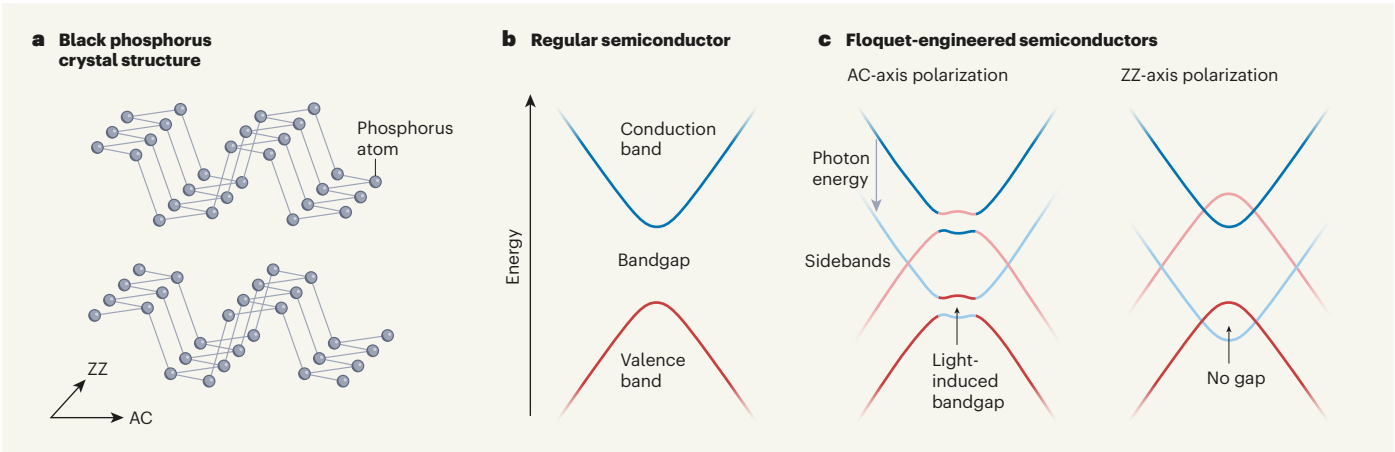


**Figure 1 | Modifying the electronic properties of black phosphorus. a**, Black phosphorus is a semiconductor material with a bilayer crystal structure that is 'armchair' shaped (AC) in one direction and zigzagged (ZZ) in the other. **b**, The energies of electrons in a regular semiconductor are restricted to a valence band and a conduction band, with a 'bandgap' in between. **c**, Zhou *et al.*[5] irradiated black phosphorus, and showed that the light induced new energy levels to appear at integer multiples of the photon energy, creating 'sidebands', as well as bandgaps at the crossing between the original bands and the sidebands. Light-induced bandgaps appeared when the light was polarized in the AC direction only, not in the ZZ direction. This type of modification is known as Floquet engineering, and it can be used to control the transport of electrons in a material and to realize new electronic phases. (Adapted from Figs 1 and 4 of ref. 5.)

electromagnetic field that oscillates in time, such as that associated with intense laser light, new energy levels appear at integer multiples of the photon energy[8], making the crystal band structure resemble a ladder of 'sidebands' known as the Floquet–Bloch states (Fig. 1c). Under certain conditions, gaps open up at the crossing between the original bands and the sidebands[9]. A 2009 prediction that such gaps would appear in irradiated graphene marked the birth of Floquet engineering of crystals[10], but the theory was confirmed experimentally in the material graphene only three years ago[2]. Zhou *et al.* have now broadened the scope of Floquet engineering by applying it in a semiconductor.

For real crystals, the first challenge is to track dynamical changes in the band structure while the solid is being optically excited with intense laser light, and the second is to distinguish the electronic states created by Floquet engineering from those arising from other effects. Zhou and colleagues overcame these challenges by using a technique called time- and angle-resolved photoemission spectroscopy. In doing so, they revealed a marked change in the shape of the valence band of black phosphorus when it is irradiated. They also found that they could manipulate the position and width of the light-induced bandgaps by varying the energy, intensity and polarization of the light.

Floquet theory is consistent with many of the authors' experimental findings, such as the dependence of the size of the bandgap on the laser fluence (a measure of its energy per unit area). Other effects were, however, unexpected. Zhou *et al.* found that the effects of Floquet engineering were largest when the energy of the photons was nearly equal to that of the material's bandgap. This finding is at odds with theoretical predictions suggesting that this 'resonant' excitation disrupts Floquet–Bloch states by allowing the laser to heat the material[1,11]. Intriguingly, Zhou *et al.* showed that the band structure changed even when impurities were added to black phosphorus to modify the occupation of the bands and to prevent electrons from traversing the bandgap by absorbing the energy of the photons. This indicates that the changes were not a result of the valence band being depleted of charge carriers, so must have arisen through Floquet engineering.

The physical properties of black phosphorus have a key role in the behaviour reported by Zhou and colleagues. The material has a large charge-carrier mobility and a bandgap that is easy to modify, and its crystal structure is a puckered honeycomb lattice comprising pairs of layers that are 'armchair' shaped (AC) in one direction and zigzagged (ZZ) in the other[12]. This asymmetry is known to be responsible for the direction-dependent optical properties of black phosphorus[13], but the authors found that the outcome of Floquet engineering also depends strongly on the relative orientation of the light polarization with respect to these directions. Specifically, the light-induced bandgap became substantially narrower when the direction of the laser light polarization was switched from the AC axis to the ZZ axis. This indicates that Floquet–Bloch states can be precisely adjusted by varying the properties of the electromagnetic wave with respect to the crystal orientation in space.

Zhou and colleagues' study demonstrates that near-resonance excitation is a viable strategy for tailoring the electronic properties of crystals, despite the detrimental effects of heating by laser. The approach is particularly successful when combined with the authors' careful use of impurities to pinpoint the effects of Floquet engineering. This strategy can now be extended to other families of semiconductor and insulator, such as transition-metal dichalcogenides and lead-halide perovskites, for example.

In addition to the possible technological advantages of optically controlling the electronic properties of solids in time, the authors' advance could motivate fundamental research designed to implement quantum-mechanical models in systems that can be easily tuned. Such efforts are typically undertaken in laser-controlled lattices of ultracold atoms, but solid-state systems offer a more versatile experimental platform. Zhou and colleagues' observation that Floquet–Bloch states are influenced by the crystal-lattice symmetry of black phosphorus is an example of the exotic electronic phases that emerge when optical perturbation is combined with solid-state materials.

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