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Floquet band engineering in action

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In a recent article in *Nature*, Zhou et al. [1] reported an impressive demonstration of Floquet materials engineering. In this field researchers aim at creating properties in materials that they do not usually exhibit in their equilibrium state. The scope ranges from inducing phase transitions in out-of-equilibrium that can otherwise only be achieved by pressure or doping, such as for example superconductivity [2], revealing hidden phases that can only be accessed out-of-equilibrium, to creating an altogether new phase of the material, such as a change in the topology of the electronic structure. This later case is often associated with the change of the electronic bandstructure that has attracted a great amount of attention of theorists because it can be readily described in the context of Floquet theory.

Floquet theory gives an elegant solution of the time-dependent Schrödinger equation of a material that is exposed to a continuous wave laser excitation. The solution of such a system, i.e., its time-evolution, can be fully described by the time-dependent but periodic eigenstates of the time-evolution operator and a set of real phases, the Floquet eigenvalues. Besides providing a convenient mathematical formulation for periodically driven systems by mapping the time-dependence into energy space, Floquet theory describes a particular regime of experiments. The Floquet eigenvalues can be interpreted as quasi-energy levels of the driven system corresponding to the light-dressed eigenstates. This means for materials that Floquet theory provides the concept of a quasi-energy bandstructure that can (and should) be different from the electronic band structure of the material in equilibrium.

Pioneering works in the field have shown that the emergence of a Floquet-bandstructure can be accompanied by a change in the topology of the electronic structure and have proposed concepts like the Floquet topological insulator [3] or the photovoltaic quantum hall effect [4]. Many more proposals of Floquet materials have since been put forward [5], not all being related to topology, but centered around the idea of creating a new bandstructure in materials. Thus the term Floquet band engineering was coined.

Despite the large number of theoretical proposals, experimental evidence for such control over the electronic bandstructure has been sparse. Early successes were made in optical lattices [6], where the conditions of continuous driving can be better achieved than in real materials. Floquet bands are, in principle, observable in time-resolved angular resolved photoelectron spectroscopy (ARPES) if the probe envelope is longer than the driving frequency. In practice however the conditions for the Floquet regime remained hard to achieve, due to several factors counteracting the formation of a coherently dressed electronic structure, such as for instance electron–phonon scattering. First-principles calculations have shown, that the condition of continuous driving can be somewhat relaxed, while still allowing for an interpretation of ARPES spectra in terms of Floquet theory [7]. However, evidence for Floquet band engineering and topology from ARPES has been reported in pioneering works by Nuh Gedik and collaborators, where they saw a modification of the Dirac bands at the surface of a topological insulator [8] and hybridization gaps between Floquet-Volkov states [9]. Even fewer works report transport signatures associated with a Floquet topological phase transitions [10].

This is why the work reported by Zhou et al. [1] is a big leap forward. Instead of focusing on a Dirac material, like previous reports, they show for the first time, that Floquet band engineering can be achieved in a semiconductor. They report a series of time-resolved ARPES measurements on black phosphorous. Owing to the relatively small band gap of the material of $E_g \approx 330$ meV the electronic excitation energy and hence the required laser frequency for Floquet engineering is much lower than the more commonly used 1.5 eV lasers. They show that when pumping with a mid-infrared laser close to resonance with the bandgap of the material Floquet replica bands of the conduction band hybridize with the valence bands leading to a characteristic avoided hybridization gap in the ARPES signal, c.f., Fig. 1. This hybridization between photo-dressed bands and bands of the equilibrium electronic structure is one of the fundamental predictions of Floquet band engineering [7]. It leads to an opening of the optical gap of the material that is observable in time-resolved optical absorption spectroscopy as a red shift [11] known as the optical Stark effect. It also results in an inversion of band character at the original band edge that is predicted to be accompanied with the formation of topological edge states [12].

Importantly, this work goes beyond previous proposals for Floquet band engineering in that it shows that the strong anisotropy

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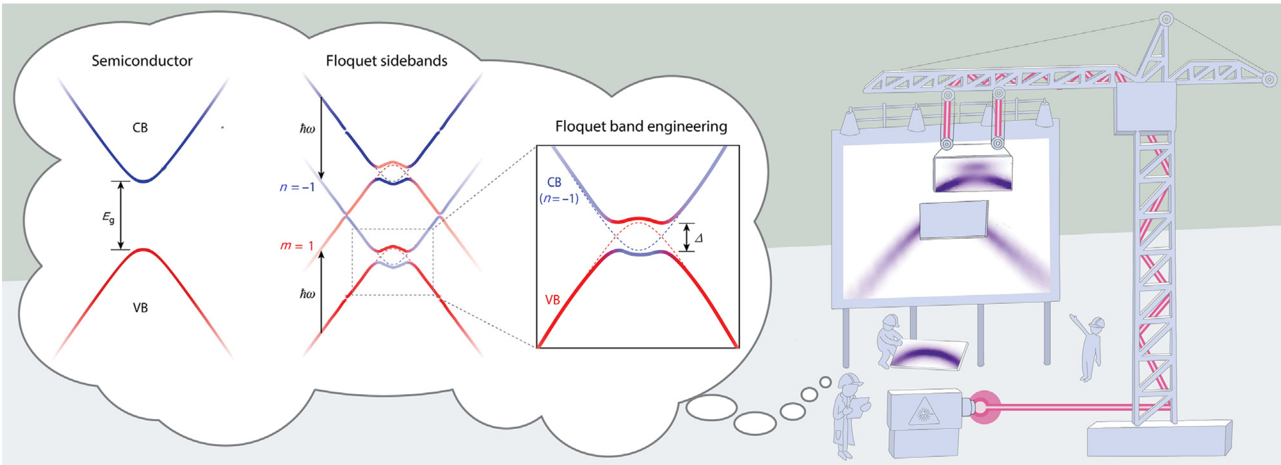

Fig. 1. Cartoonists impression of Floquet engineering. Figures adapted from Ref. [1] with Copyright © 2023 Springer Nature.

of the material can be used to selectively create and control Floquet bands. The equilibrium electronic structure of black phosphorous can be assigned a pseudospin texture that forms from binding and anti-binding superposition of sublattice states. The authors show that when the pump polarization is rotated in plane the interaction matrix elements that mediate the Floquet hybridization are modified. This can be assigned to lattice-symmetry-enforced pseudospin selection rules. Such selection rules provide an additional degree of freedom to control the strength of the Floquet interaction and hence the degree to which Floquet bands form and therefore allows to control their shape.

With this work by Zhou et al. [1], the feasibility and observability of Floquet engineered bands has been proven. Therefore the field is now open for the realisation of the many theoretical proposals available. A major next step forward would be the unambiguous confirmation of the Floquet-gap opening in Graphene under a time-reversal symmetry breaking laser. This would prove that the fundamental topological Haldane model can be realized with Floquet engineering and boost efforts to achieve optically switchable topological states [13]. This work also paves the way for a more flexible approach to Floquet band engineering, that employs specifically designed pulses [14] to tailor materials properties making the promise of manipulating and creating materials properties on demand and on utltrafast time scales, or indeed by other means of strong light-matter coupling such as in optical cavities [15], getting closer to fulfilment.

Conflict of interest

The authors declare that they have no conflict of interest.

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