TOPOLOGICAL MATERIALS

Lighting up Weyl semimetals

By measuring the photocurrent from illuminated Weyl semimetals, an optical signature of topological properties arising from Weyl fermions has been revealed, highlighting nonlinear optical effects and applications of Weyl semimetals.

Hongming Weng

In 1929, Hermann Weyl proposed a fermion whose mass is zero but has definite right- or left-handed chirality[1]. Such a chiral fermion, termed a Weyl fermion, travels parallel or anti-parallel to its spin momentum. In this sense, it is very similar to circularly polarized light, whose angular momentum is also parallel (right circular polarization) or anti-parallel (left circular polarization) to the light propagation direction. The energy of a Weyl fermion is proportional to its momentum, forming a Dirac cone-like band structure in momentum–energy space (Fig. 1). Weyl fermions have never been found in nature, but recently they have been realized as quasiparticles — low-energy collective excitation of electrons — in so-called Weyl semimetals (WSMs)[2]. The typical Dirac cone-like band structure indicative of Weyl nodes has been well identified in angle-resolved photoemission spectroscopy by shining X-rays on WSMs. Each chiral Weyl node can be viewed as a 'monopole' of Berry flux field, a magnetic field in momentum space. The magnetic charge is determined by chirality. These magnetic monopoles have direct effects on the motion of electrons and result in various intriguing properties, such as an anomalous Hall effect, negative longitudinal magnetoresistivity and large second harmonic generation. Now, writing in *Nature Materials*, Gavin Osterhoudt et al.[3] and Junchao Ma et al.[4] report their independent observations of a greatly enhanced photovoltaic effect in two typical WSMs by mid-infrared light illumination. They attribute their observations to the presence of Weyl nodes. These discoveries suggest a new way to control chiral Weyl fermions and may spark applications of WSMs in sensing and energy conversion at arbitrary wavelengths of light.

Osterhoudt et al. studied the first experimentally discovered WSM TaAs. They made devices with different TaAs facets using focused-ion beam fabrication techniques. These devices are smaller than the spot size of light to minimize the influence of non-uniform illumination.

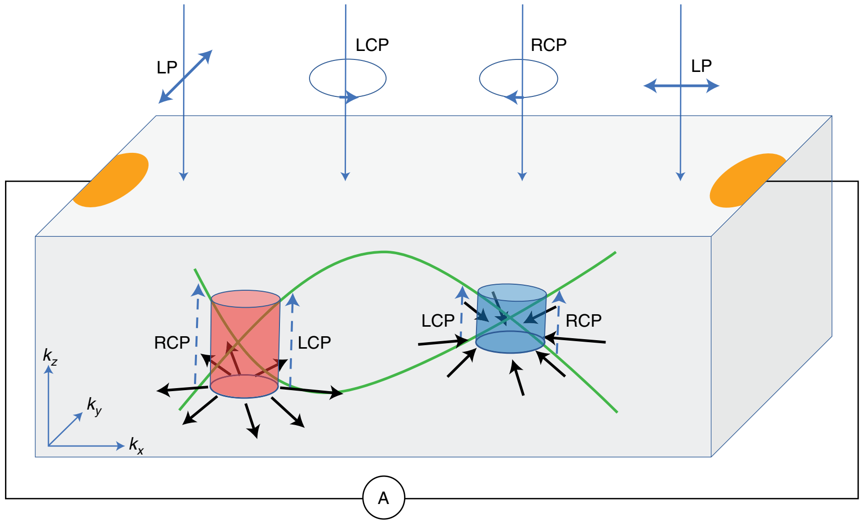

Fig. 1 | Shining light on a Weyl semimetal to generate photocurrent through the interaction of light with Weyl nodes. Light can be adjusted to have different linear polarization (LP), right or left circular polarization (RCP, LCP), and various wavelengths. Weyl nodes in a Weyl semimetal come in pairs with opposite chirality and generate an outgoing or ingoing hedgehog-like Berry flux field (black arrows). These Weyl nodes are represented in momentum space in the figure near the crossing of the two green bands. The coloured cylinders enclose different chiral Weyl nodes. The vertical dashed arrows indicate the excitation of different chiral Weyl Fermions by absorbing different helical photons. The yellow areas are the electrical contacts with an ammeter in the circuit to measure the photocurrent. The momentum space represented by k_x, k_y and k_z is a reciprocal lattice space of the Weyl semimetal crystal. The coordinates of the real-space experimental setup can be related to momentum space once the facet of the sample is known.

This allows the authors to determine that the observed mid-infrared response arises from an intrinsic bulk photovoltaic effect (BPVE) and an extrinsic photothermal effect (PTE). The BPVE is a second-order optical response of a single material without centrosymmetry. It converts linearly polarized light into electrical currents through the shift of charge centre during the interband photoexcitation. Thus, it is called shift current and is expected to be greatly enhanced when the excitation is around Weyl nodes where the Berry flux field diverges when approaching monopoles (Fig. 1). This natural connection with the band topology[5] of Weyl nodes is further supported by theoretical calculations and symmetry analysis. Generation of photocurrent in this way is totally different from that in heterostructural p–n junctions of semiconductors, where the built-in electric field separates the photoinduced electron and hole carriers.

Ma et al. have chosen another WSM $TaIrTe_4$. Distinct from the type-I WSM TaAs, it is a type-II WSM since its Dirac cones are largely tilted along one direction so that the two branches of the cone have the same sign of slope. The band topology around the Weyl nodes is nearly the same, while the tilting gives rise to additional circular photogalvanic effect (CPGE) with injection current[6]. This current comes from the asymmetric injection of charge carriers into opposite momenta generated by circularly polarized light nonlinearly. It reverses sign when the helicity of the light flips. TaIrTe$_4$ has a layered structure and the device is straightforward to fabricate, with current flowing in the layer plane and light shining perpendicular to the plane. They find that the planar photocurrent from the second-order response is forbidden, while the combination of the third-order response and the built-in electric field due to electrode–substrate contacts or PTE contributes to the observed shift current and injection current. Both currents are substantially enhanced due to the Berry flux field singularity around Weyl nodes.

Light can have different linear polarization, helicity and wavelength, while Weyl cones in WSMs are tunable in chirality, valley and tilting. Throwing light on WSMs yields interesting phenomena and novel physics. In addition to the above shift and injection current, there have been many theoretical proposals closely related to the combinations of these factors. For example, the proposed anomalous photocurrent[7] is due to anomalous velocity caused by the Berry flux field and is sensitive to light helicity. The quantized CPGE[8] can be realized through circularly polarized photoexcitation of only one valley of a pair of Weyl cones and the width of the quantized plateaus in wavelength can be controlled in this valley selection. In WSMs, the high mobility of the carriers is another reason for the observed giant photocurrent response. The fast motion of carriers — that is, ultrafast photocurrent — also results in prominent optical responses. For instance, in TaAs, giant terahertz wave emission was recently found by excitation of femtosecond laser pulses[9,10]. Here, the terahertz wave can be elliptically polarized[10], and its ellipticity and chirality can be controlled on a femtosecond timescale via changing the polarization of the incident light. These effects are attributed to ultrafast colossal chiral photocurrents via BPVE and CPGE associated with the unique band structure of WSMs. There are many routes to explore toward more exciting properties and applications of Weyl semimetals. ❐

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BIOELECTRONICS

Neuron-like neural probes

Neural probes that mimic the subcellular structural features and mechanical properties of neurons assimilate across several structures of the brain to provide chronically stable neural recordings in a mouse model.

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Over the past 10–15 years, academics and companies have been attempting to redefine how we use our brains. Brain–computer interfaces (BCIs) can be used to control toys, reach a 'better' meditative state, control robotics, and as part of a system to rehabilitate paralyzed limbs[1]. Several companies and federal agencies have even promised the ability to accelerate learning, enable telepathy, expand and transfer memory, or become symbiotic with AI-enabled machines.

Arguably, higher-order tasks require more invasive BCI devices to communicate with finer populations of neurons within the brain. Neural recordings from individual or small populations of neurons within the brain come at a cost of not just invasiveness, but also self-destructive inflammatory responses that are both damaging to the implanted device and neurodegenerative, ultimately causing the BCIs to fail prematurely[2]. In fact, implanting BCI probes in the region of the brain associated with fine motor skills can actually cause a decline in the performance of fine motor tasks in healthy rats[3]. Therefore, numerous teams have attempted to develop strategies to circumvent the neuroinflammatory response to chronically implanted neural probes within the structures of the brain[4]. Writing in *Nature Materials*, the team led by Charles Lieber at Harvard University reports on neural probes that attempt to mimic the cellular structural features and mechanical properties of neurons, enabling these devices to evade the typical inflammatory process[5]. The researchers build on the often-tested hypothesis that smaller, more flexible devices will reduce the neuroinflammatory response and improve the functional recording performance of brain-dwelling electronics.

Lieber's team used photolithography to develop their 'neuron-like electronics' (NeuE) with an impressive size scale of only ~0.9 μm in total thickness, comparable to a myelinated axon (Fig. 1a). Utilizing their previously published methods for insertion[6], they were able to successfully implant ~80% of their animals across several brain structures. Full three-dimensional mapping of implanted NeuE devices displayed the intimate integration between the NeuE devices and native neurons (Fig. 1b), complete with triangulated positioning of the presumptive neuron believed responsible to the units recorded across electrode contacts.

Recently, fabrication techniques to create micro- and nanosized electronics have been refined by several groups[7]. For example, carbon-based probes with diameters of ~8–10 μm have been used to demonstrate stable chronic neural recordings with