Semimetals are being explored for their unique advantages in low-energy high-speed photodetection, although they suffer from serious drawbacks such as an intrinsically high dark current. In this Perspective, we envision the exploitation of topological effects in the photosresponse of these materials as a promising route to circumvent these problems. We overview recent studies on photodetection based on graphene and other semimetals, and further discuss the opportunities created by topological effects, along with the additional challenges that they impose on photodetector designs.

Photodetectors (PDs) are pivotal optoelectronic components of modern communication and sensing systems that have become ubiquitous in our daily life. In the visible and near-infrared wavelength ranges, PDs with high performance, low cost and high level of integration with electronics have already been developed and widely deployed, mainly using elemental semiconductors such as silicon and germanium, and compound semiconductors such as gallium arsenide and indium phosphide. Currently, the main technological bottleneck of photodetection lies in the low-photon-energy range of the electromagnetic spectrum. Fast, highly sensitive PDs operated at room temperature are not widely available at low photon energies, despite the important role that they could play in a vast range of applications, such as autonomous driving, night vision, gas sensing, motion detection and bioassays, to name a few. Although there are commercially available technologies for this energy range, they suffer from considerable drawbacks. For example, HgCdTe technology has been widely adopted, but it involves high manufacturing costs, is difficult to integrate and requires cryogenic operation. Alternatively, microbolometers can operate at room temperature, but their speed of operation is usually low (<1 kHz). For applications such as high-throughput infrared spectrometry and high-speed imaging, innovative approaches will be needed to achieve fast, broad-band, room-temperature, integrated photodetection in the mid-infrared and terahertz spectral ranges.

PDs make use of different light-induced effects that are readable through electrical measurements. Figure 1 summarizes the most widely used photodetection mechanisms, classified according to the nature of the physical effect caused by the incident radiation: photon-type detectors rely on the direct production of photocreated electron–hole pairs, whereas thermal-type detectors rely on the change in electron and/or lattice temperature upon thermalization of those hot carriers. A comparison of the performance of different representative thermal- and photon-type PDs that are suitable for low-photon-energy detection is presented in Table 1. In a thermal-type detector, the absorbed incident radiation changes the material’s temperature, which in turn results in measurable changes of physical quantities that are probed electrically. Specifically, one can measure the temperature-induced variation of resistance in a bolometer, the modification of the voltage in pyroelectric materials and thermopiles, or even gas expansion in Golay cells. In general, thermal-type detectors are wavelength-insensitive, slow and usually less expensive than their photon-type counterparts. In contrast, in photon-type detectors, the electrical output signal comes directly from the charged photocarriers produced by the photoexcitation process, leading to improved signal-to-noise ratio and fast response; however, they are more expensive and usually require cryogenic cooling for low-energy photon detection to minimize thermally generated charge carriers, which otherwise compete with the targeted optically excited carriers by generating excessive noise.

In this Perspective, we focus on photon-type detectors because of their overall better performance relative to the thermal type. The most widely used photon-type detection scheme relies on the well-known p-doped-semiconductor/insulator/n-doped-semiconductor (PIN) structure illustrated in Fig. 2a. A reverse-biased PIN diode has a negligibly small dark current. When a photon of sufficient energy is absorbed in the depletion region of the diode, it creates an electron–hole pair. The reverse-biased field then sweeps these carriers away from that region, creating a photocurrent. Commercially available PIN photodiodes can reach quantum efficiencies of ~80–90% at the telecom wavelength (~1,550 nm); they are remarkably compact and highly integrable, and operate at high speed. In the mid-infrared, matured photon-type photodetection technologies are based on HgCdTe and InAs, with specific detectivity ($D^* = \sqrt{A\Delta f}/NEP$, defined in terms of the noise-equivalent power (NEP), the detection area A and the frequency bandwidth $\Delta f$) above $10^{11}$ Jones (1 Jones = 1 cm Hz$^{-1/2}$ W$^{-1}$) and operation response times in the nanosecond range. Nevertheless, as mentioned above, these detectors usually require cryogenic cooling, which makes them bulky, expensive, power-hungry and delicate. Therefore, it remains a challenge to develop high-performance, low-energy photon detectors that can perform well without cryogenic cooling.

Considerable effort is being invested within the materials science and optoelectronic communities to search for material platforms that enable better device performance and circumvent the technological bottlenecks. This Perspective portrays opportunities in photodetection enabled by semimetallic materials, which are promising candidates to achieve highly sensitive, low-energy photodetection with ultrafast operation.

Semimetals versus semiconductors

Semimetallic materials have not traditionally been considered candidates for photodetection because of the obvious drawback imposed by the high dark current traversing them when a bias

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Semimetals for high-performance photodetection

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Photodetectors (PDs) are pivotal optoelectronic components of modern communication and sensing systems that have become ubiquitous in our daily life. In the visible and near-infrared wavelength ranges, PDs with high performance, low cost and high level of integration with electronics have already been developed and widely deployed, mainly using elemental semiconductors such as silicon and germanium, and compound semiconductors such as gallium arsenide and indium phosphide. Currently, the main technological bottleneck of photodetection lies in the low-photon-energy range of the electromagnetic spectrum. Fast, highly sensitive PDs operated at room temperature are not widely available at low photon energies, despite the important role that they could play in a vast range of applications, such as autonomous driving, night vision, gas sensing, motion detection and bioassays, to name a few. Although there are commercially available technologies for this energy range, they suffer from considerable drawbacks. For example, HgCdTe technology has been widely adopted, but it involves high manufacturing costs, is difficult to integrate and requires cryogenic operation. Alternatively, microbolometers can operate at room temperature, but their speed of operation is usually low (<1 kHz). For applications such as high-throughput infrared spectrometry and high-speed imaging, innovative approaches will be needed to achieve fast, broad-band, room-temperature, integrated photodetection in the mid-infrared and terahertz spectral ranges.

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Semimetals versus semiconductors

Semimetallic materials have not traditionally been considered candidates for photodetection because of the obvious drawback imposed by the high dark current traversing them when a bias
voltage is applied, which reduces their detection sensitivity. However, the demonstration of a graphene-based field-effect transistor (FET) PD about a decade ago\(^{13}\) showed the feasibility of using \(n\)-metallic materials in high-speed photodetection applications over a broad wavelength range, despite their relatively high dark current. This work triggered much research on semimetal-based photodetection. Although the responsivities of \(p\)-semimetal-based detectors are usually far from optimal, their gapless electronic structures endow them with broadband photoresponse down to the far-infrared spectral region\(^{14-17}\), combined with extremely fast operation speed\(^{14,15,19}\), both of which directly address the aforementioned technological bottlenecks. As illustrated in Fig. 2 and d, the limitation on detectable photon energy imposed by an energy gap is absent in semimetals, and thus the detectable range extends naturally down to the low-energy end (Fig. 2e–g). Additionally, the transient lifetimes of the photoexcited carriers, which are relatively long in semiconductors and could compromise the operation speed of semiconductor-based PDs, are greatly reduced in the absence of a bandgap through rapid electron–electron scattering\(^{20}\), thus boosting the operation speed of semimetals (Fig. 2h).
Despite these advantages, semimetal-based PDs require unbiased operation in order to reduce the dark current, and therefore, in contrast to semiconductor detectors, charge separation cannot be achieved through the reverse bias approach discussed above for PIN diodes. Consequently, semimetal PDs operating in an unbiased mode (Fig. 2c) need to achieve charge separation through other, less efficient mechanisms, such as a built-in electric field, the photo-thermoelectric effect or the photo-Dember effect. The short transient lifetime of photoexcited carriers in semimetals further aggravates the charge-separation problem (that is, the time window for charge separation is reduced), rendering it rather inefficient and producing a low photodetection responsivity. The need for fast charge-separation mechanisms in semimetals is thus critical.

Two additional factors may further affect the performance of semimetal PDs. Dark noise in a typical metal–semimetal–metal FET device is dominated by thermal agitation of the charge carriers, even if its dark current is small in the absence of an external bias. Additionally, the photocurrent of an unbiased PD usually has a turn-on threshold (that is, the light intensity needs to exceed a certain threshold to produce a detectable photocurrent in an unbiased device; see Fig. 3c). With no external bias, this threshold power can be considerable, imposing a severe constraint on the lowest detectable light intensity of a semimetal-based PD.

Because of the above, the NEP that quantifies the sensitivity of a PD has to be defined differently. The NEP is now dominated by the turn-on threshold power, far exceeding the equivalent power converted from the dark noise and the device photoresponsivity according to the original definition of NEP. However, once the NEP is determined, other related figures of merit derived from NEP, such as the specific detectivity $D^*$, stay the same.

Development of semimetal-based PDs

Besides the advantages of fast and broadband operation, early developments of semimetal-based PDs benefited from several unique properties of graphene. The linear electron dispersion and atomically thin layered structure contribute to carrier multiplication, which increases the photodetection quantum efficiency and leads to a large photo-thermoelectric response with high mobility. Additionally, graphene is compatible with complementary metal–semiconductor (CMOS) technology, integrable with flexible electronics and amenable to hybridization with other materials. Over the past decade, these properties have been capitalized upon for photodetection, as summarized in recent reviews.

Despite these successful demonstrations, the semimetallic band structure and unbiased operation limit the photoresponsivity of graphene PDs. Solutions have been sought in using photonic and plasmonic cavities to boost the near-field enhancement, as well as hybridization in van der Waals material heterostructures. These approaches can improve the responsivity, but at the expense of reducing the broadband response and ultrafast operation. For example, boosting the responsivity through field enhancement in optical cavities generally relies on narrowband resonances that jeopardize broadband operation. Interestingly, in hybridizing with other materials, the latter not only act as light harvesters, but also provide interfaces and hetero-junctions that can aid the separation of photoexcited electron–hole pairs. A wide range of materials has been explored in this direction, including polymers, zero-dimensional quantum dots, one-dimensional nanorods and nanotubes, two-dimensional (2D) layered materials and bulk (3D) semiconductors, reaching measured responsivities as large as 435 mA W$^{-1}$ (ref. 39) but compromising the speed and spectral range—the main advantages of semimetals.

Beyond the responsivity, the sensitivity of the detector also depends on noise current and quantum efficiency (QE). Unfortunately, the noise current is underestimated in much of the literature by calculating the shot noise limit, instead of experimentally.
measuring it, as extensively discussed elsewhere.\textsuperscript{39} Compared with the responsivity, the QE provides a better characterization of how efficiently photons can be converted into an electrical current. A detector with low QE can reach very high responsivity if it responds slowly enough to integrate the generated current over a long period of time. The reported high internal QE reaching 30–60% in graphene PDs\textsuperscript{40,41} presumably originates in carrier multiplication, although in this case such improvement actually bears no connection with the topologically non-trivial band structure of Cd\textsubscript{3}As\textsubscript{2} (semimetal) by 3D Dirac semimetals, such as Cd\textsubscript{3}As\textsubscript{2}, which can improve the responsivity by about an order of magnitude without losing broadband response and ultrafast operation speed (Fig. 2h)\textsuperscript{14}, although in this case such improvement actually bears no connection with the topologically non-trivial band structure of Cd\textsubscript{3}As\textsubscript{2} and is simply produced by the enhanced absorption of the bulk material compared with the 2.3% value for monolayer graphene.

Recent advances in improving the responsivity are enabled by the rapid development of topological semimetals\textsuperscript{42–45},\textsuperscript{54} materials with semimetallic character possessing topologically non-trivial electronic band structures. The experimental realization of both Weyl and Dirac semimetals\textsuperscript{46–48} has brought the field to the forefront of quantum condensed-matter research, although early studies date back to the quantum-Hall effect in the 1980s\textsuperscript{49,50}, while topological insulators were extensively studied in the 2000s\textsuperscript{51–53}. A straightforward approach consists in replacing graphene (a 2D Dirac semimetal) by 3D Dirac semimetals, such as Cd\textsubscript{3}As\textsubscript{2}, which can improve the responsivity by about an order of magnitude without losing broadband response and ultrafast operation speed (Fig. 2h)\textsuperscript{14}, although in this case such improvement actually bears no connection with the topologically non-trivial band structure of Cd\textsubscript{3}As\textsubscript{2} and is simply produced by the enhanced absorption of the bulk material compared with the 2.3% value for monolayer graphene. Additionally, using the shift current response of Weyl semimetals, a boost of at least two orders of magnitude in responsivity is expected by leveraging the Berry field enhancement at the vicinity of Weyl nodes, which is a purely topological effect.\textsuperscript{54} We discuss this issue in more detail below and note that such enhancement should...
not affect the ultrafast operation speed and broadband response, although further experimental verification is needed.

**Topology and photodetection**

Certain topological properties of topological semimetals can greatly improve the photoresponse of PDs. We take Weyl semimetals as an example. These materials host Weyl fermions travelling along directions that are either parallel or antiparallel to their spin moment, which defines the chirality of a specific Weyl cone. The energy of a Weyl fermion is proportional to its momentum, forming a cone-like structure in energy–momentum space (Fig. 3a). Most importantly, each chiral Weyl node can be viewed as a 'monopole' of the Berry flux field, an effective magnetic field in momentum space (Fig. 3b)\(^5\). These magnetic monopoles have direct effects on the electron motion and result in various intriguing topological effects in the optical response\(^6\)–\(^8\). One such effect relates to the shift current response\(^9\), which results from the shift of charge centre during interband photoexcitation in non-centrosymmetric materials excited by linearly polarized light\(^1\), and constitutes an intrinsically different way of generating a photocurrent compared to that of semiconductor p–n junctions, where a built-in electric field separates electrons and holes. The shift of the charge centre can be expressed as a change of the Berry connection\(^10\), a vector potential that generates the Berry flux field and the phase of the velocity operator, and consequently, the corresponding conductivity tensor is expected to be greatly enhanced when the excitation takes place in the vicinity of Weyl nodes, where the Berry flux field diverges (Fig. 3c). Recently, this topological enhancement effect has been experimentally verified in both Lorentz invariance preserved type-I TaAs and Lorentz invariance violated type-II TaIrTe\(_4\) (Fig. 3d and e)\(^11\)–\(^13\).

Figure 3d shows the power dependence of the photoresponse to 4-μm light in a typical TaIrTe\(_4\)-based FET device\(^12\), which strongly differs from that of semiconductor PIN detectors. First, the TaIrTe\(_4\) detector shows a clear turn-on threshold at a low excitation power of \(~1.55\) nW (the turn-on threshold is usually overlooked in graphene PDs, owing to their much smaller responsivities). Second, above the turn-on threshold, the photocurrent experiences a marked change with excitation power, arising from the topologically enhanced photoresponse and quantified by a linear responsivity of \(130.2\) mA W\(^{-1}\). This giant response saturates at very low power, indicating a narrow linear dynamic range, but this should not affect its application in highly sensitive photodetection. Third, after the transitional power range, the response saturates and reaches a second linear dynamical range with a relatively low responsivity of \(21.8\) μA W\(^{-1}\). In this power region, the response is dominated by topologically trivial effects such as the photo-thermoelectric response.

The large responsivity obtained at low powers indicates that charge separation due to the shift current response is very efficient. As an additional advantage, this mechanism presents an intrinsically ultrafast behaviour, which could be useful to overcome the problem of low responsivity in semimetal-based PDs. However, the turn-on threshold, resulting from potential barriers in the device, as demonstrated in the prototype illustrated in Fig. 3, can become an issue that limits detectivity. Such barriers are primarily determined by the work-function difference at metal–semimetal interfaces in a FET device, but they can also relate to other factors such as impedance match with external circuits. The potential barrier can be lowered through device engineering by carefully matching the work function of a metal contact and the doping level of a semimetal, although constructing p–n junctions is perhaps a more feasible approach, because the doping levels of the p and n regions can be modified separately to achieve more flexible control over the junction. Even with fixed potential barriers, the turn-on threshold power can depend on the light wavelength, because higher-energy photons excite carriers with larger kinetic energy, for which barrier reflection is reduced, and consequently so is the turn-on threshold power.

**Technical challenges**

Despite the excitement created around topological enhancement leading to a large photoresponsivity in Weyl semimetals, several technical challenges need to be addressed. We discuss these below.

**Determination of the ideal type of photodetection material.**

Successful functional devices generally rely on high-quality material growth, but topological semimetals remain difficult to produce, and their wafer-scale CMOS compatibility is also a challenge. Recently, theorists have exhaustively explored topological candidates from the \(>26,000\) available non-magnetic crystalline compounds and compiled the results in the International Crystal Structure Database\(^1\)–\(^6\) (ICSD), where thousands of topological materials were proposed. Additionally, topological candidates can arise from engineering artificial structures based on existing materials, such as stacking of twisted layered materials\(^7\). It is infeasible to fully investigate such large numbers of material candidates experimentally. To narrow down the promising candidates, we provide some key considerations to profit from the advantages of the Berry phase enhancement effects on the shift current response. These considerations are in addition to the common requirements on wafer-scale epitaxial growth and general material properties, such as air stability, non-toxicity, CMOS compatibility and easy on-chip integration.

First, topological enhancement of the shift current response requires materials with inversion symmetry breaking, such as Weyl semimetals and chiral-fermion materials\(^8\)–\(^10\). Although a Dirac node is also a singularity point of the Berry curvature, similar to a Weyl node, inversion symmetry forbids shift current generation in Dirac semimetals. Consequently, Dirac semimetals do not share a similar topological enhancement. In contrast, chiral fermion materials are likely to be favourable for shift current generation compared with Weyl semimetals, because Weyl cones with opposite chirality are no longer energy-degenerate, so a wider photon energy region undergoing topological enhancement may be covered. Second, the Fermi level must be close enough to the nodal points to allow the topological effect to come into play with related optical transitions. If the nodal points are also far away from the topologically trivial bands, this further helps in unambiguously determining the response from the topological non-trivial bands. In addition, the cones should be well separated in momentum space, in such a way that it is possible to address them separately through optical transitions. Third, suitable dopants must be identified so that the material doping can be tailored. In fact, doping and its tunability are not only critical to optimize the potential barriers with metal electrodes (that is, to reduce the turn-on threshold power), but they also help to tune the wavelength range over which topological enhancement takes place\(^1\).

Fourth, layered materials can be conveniently integrated with other 2D layered materials for applications\(^1\): for example, boron nitride (BN) capping can be used to prevent degradation if the material is environmentally unstable. Incidentally, BN provides an ideal dielectric layer that can play the role of SiO\(_2\) in silicon technology\(^2\).

Lastly, we wish to remark briefly on the role of material quality. Uniform wafer-scale epitaxial growth with a well-controlled level of defects (dopants in most cases) is usually a prerequisite for applicable focal plane arrays. However, we expect that such requirements on growth may be slightly alleviated for topological semimetals. A key advantage of topological materials is that some of their properties are determined by the topology, and therefore protected against disorder and impurities. An established example is that the metallic surface state is protected by the topology of the bulk, so the surface state is immune to disorder and impurities\(^2\)–\(^4\). In addition, topological states have been verified to be protected by chiral spin texture from back scattering in topological insulators and semimetals\(^2\)–\(^4\). Although it is unclear so far whether the shift current responses of topological semimetals are defect-tolerant\(^2\), this is certainly an important research topic in the pipeline. The outcome could be a
The absence of an external bias and the involvement of topological effects demand special consideration in device designs. In particular, the absence of an external bias implies that one must minimize the turn-on threshold power of a FET PD to increase its sensitivity. This, in turn, requires an engineering effort to lower the semimetal-contact barrier by conventional approaches such as semimetal doping or choosing a metal contact with a suitable work function. Alternatively, one could combine optical approaches to solve this problem (for example, optically biasing the device just below the turn-on threshold). Furthermore, solutions may come from a topological effect, as we discuss below.

A second issue is also arising because of the unbiased device structure. Without an external bias, alternative efficient charge-separation mechanisms need to be found. Although the shift current response provides an efficient mechanism for charge separation, it imposes additional symmetry requirements, which demand careful device engineering. In this respect, the photoresponse observed in type-I TaAs is a second-order nonlinear optical effect, whereas the photoresponse observed in type-II TaIrTe4 is a third-order effect, equivalent to a shift current response under an in-plane direct current (d.c.) electric field. For second-order nonlinearities (for example in TaAs), the correct crystal facet with suitable symmetry must be selected to provide a non-vanishing shift current response. For third-order nonlinearities (for example, in TaIrTe4), a d.c. electric field is needed to produce a non-zero shift current response under normal incidence along the crystallographic c-axis, as otherwise the shift current response cancels owing to C2v symmetry in a C2v crystal. This limits the photocurrent response to a region in which a d.c. electric field exists after photoexcitation, such as along the semimetal–electrode interface. As a result, special device structures (such as the cross-finger geometry in Fig. 2c) need to be fabricated.

The third issue relates to engineering the photon energy range, and this can benefit from topological enhancement. In this respect, because the Berry field diverges at the Weyl nodes, the closer an optical transition is to a Weyl node, the more Berry field enhancement takes place in the shift current response. However, this argument is based on the assumption that the Fermi level goes through the Weyl nodes, whereas theory informs us that this applies only to type-II Weyl semimetals. Additionally, if the Fermi–Dirac carrier distribution is modified by either temperature or impurity doping, the divergence of the shift current response at a nodal point can be smeared out or truncated, and this modifies in turn the energy profile of topological enhancement. This implies that one can tune the range of topological enhancement by actively controlling the doping level. Incidentally, in this approach, the temperature needs to be stabilized to preserve a constant response.

**On-chip topological integration.** Given the wide range of existing layered species of topological semimetal, they can be conveniently integrated with waveguides or cavities to boost light–matter interactions. Alternatively, layered species could be artificially stacked to generate exotic hybrid materials, so that different functionalities...
could be added, instead of simply improving the optical and photodetection performances. Opportunities for topological materials might come from the rich phenomenology of surface states and interface effects, which make it possible to engineer edges and interfaces to achieve multiple functionalities.\textsuperscript{8,9,10} Integration is no longer simply a case of adding existing functions of multiple devices together, but, more importantly, generating previously non-existent functionalities. We anticipate that topological materials will define their own integrable platforms, resulting in radically improved optoelectronic devices.

**Opportunities in topologically enhanced photodetection**

Future solutions to the technical challenges of low-energy photodetection can greatly benefit from the opportunities opened up by topological physics in semimetals. For example, to address the important turn-on threshold problem in semimetal detectors, one could look for topologically protected dissipationless conducting channels to drive photoexcited carriers from the semimetal and the electrodes, instead of lowering the contact–semimetal potential barrier through work-function matching.\textsuperscript{11,12,13,14,15} In addition, the shift current response, which does not require an electric field built from a potential difference, would provide a suitable charge separation mechanism in such a design.\textsuperscript{16,17,18}

Symmetries in topological materials could also be exploited by carefully engineering their edges and interfaces. For example, with specific symmetry breakings on an edge fracturing along a certain crystallographic direction, a type-II Weyl semimetal with $C_2$ symmetry such as WTe\textsubscript{2} could efficiently realize charge separation to achieve a photocurrent response along the edge through the non-local Schottky–Rohm mechanism.\textsuperscript{19} Another possibility, yet to be verified, consists in using an exotic edge state (for example, the Fermi arc of a Weyl semimetal) to further enhance light–matter interaction on an edge. In particular, topological edge states not only add extra conducting channels on top of the bulk conductance, but also penetrate into the bulk, thus enlarging the charge separation region and the magnitude of the current response.

Additionally, topological effects may provide control mechanisms on specific quantum degrees of freedom, such as the chirality-related circular selection rule of Weyl cones, which can help to distinguish the helicity of the light to produce helicity-sensitive PDs based on Weyl semimetals and chiral-fermion materials.\textsuperscript{20,21}

As a blossoming field, topological effects of semimetals provide an encouraging platform for developments in photodetection. The interplay of chirality, quantum geometric effects, and exotic surface states with unconventional quantum degrees of freedom guarantees plenty of interesting optical effects to be discovered. Stacking of van der Waals materials offers an additional degree of freedom to customize semimetal materials. We illustrate several of these possibilities in Fig. 4. With the existing interest in the enhanced shift current response of Weyl semimetals by topology, we foresee topological solutions to acute technical issues in photodetection, which may become an early commercial application of topological physics.

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D.S. proposed the paper scheme and coordinated the work. All authors contributed to writing the manuscript.

Competing interests
The authors declare no competing interests.

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