RESEARCH HIGHLIGHTS

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Anisotropic 2D materials for post-Moore photoelectric devices

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Since the discovery of two-dimensional (2D) graphene[1], 2D materials have been widely investigated due to their intriguing physical/chemical property and outstanding optoelectronic performance[1–3]. Generally, 2D materials can be divided into isotropy and anisotropy according to crystal structures. For isotropic 2D materials like graphene and hexagonal boron nitride, they have obvious lattice symmetry. Whereas, anisotropic 2D materials possess strong anisotropic crystal structure (Fig. 1(a)), providing new degree of freedom for exploring 2D materials. Currently, 2D materials with high anisotropy, due to their anisotropic electrical, optical, thermal, and phonon properties, are finding applications in polarization-sensitive photodetection, neural network construction, spin-polarized transport and other emerging fields[3–6].

In layered 2D materials, the in-plane atoms are held together by strong covalent bonds, while different layers are stacked by weak van der Waals (vdW) forces[7]. 2D materials can be easily exfoliated from layered crystals, and present a large surface-to-volume ratio. Interestingly, anisotropic 2D materials possess excellent polarized photodetection abilities because of their intrinsic sensitivity to polarized light[8]. A novel polarization-sensitive photodetector based on anisotropic 2D materials has recently been proposed (Fig. 1(b)). In such devices, the laser is set to pass through a polarizer, and then the direction of incident light can be controlled by a half-wave plate. 2D anisotropy phototransistor can convert polarization characteristics into electrical signals. Such polarization-sensitive photodetectors will find applications in optical communication, near-field imaging, navigation, and military fields[7–9].

In 2020, Pi *et al.*[4] reported a highly sensitive polarized photodetector based on 2D palladium diselenide ($PdSe_2$). $PdSe_2$ not only possesses high room-temperature mobility and high air stability, but also has a puckered pentagonal structure with highly anisotropic properties, which gifts it advantages in polarization detection. The strong anisotropic photoelectric properties of 2D $PdSe_2$ were revealed by azimuth-dependent reflectance difference microscopy. The polarized photodetector presented excellent performance with dichroic ratios as high as ~2.2 at 369 nm and ~1.8 at 532 nm, respectively (Fig. 1(c)). Moreover, their primary polarization orientations differed by 90°, which is due to the characteristic difference between *a*-axis and *b*-axis. This phenomenon was ascribed to the inherent linear dichroism of $PdSe_2$. Very recently, Li *et al.*[5] also demonstrated that $PdSe_2$ photodetector possesses excellent polarization sensitivity and high stability. The phonon anisotropy of $PdSe_2$ was confirmed by polarization-dependent Raman. Such polarization-sensitive photoresponse based on photothermoelectric effect was also demonstrated. These results indicate that anisotropic 2D materials can promote the development of next-generation high-performance polarized photodetection systems.

Compared with traditional 2D materials, anisotropic 2D materials like black phosphorus, ReS_2, and $PdSe_2$ show strong anisotropy in their crystal structure and photoelectric property[4–8]. The related devices can offer a high intrinsic heterogeneity for information transmission. In biological synapses, the heterogeneity of synaptic connections is the basis for the diversity of neural activity[6]. The realization of heterogeneity in synaptic plasticity is very crucial for constructing high-complexity neural networks. Therefore, the setup based on anisotropic 2D materials can bring intrinsic heterogeneity into new-generation neuromorphic electronics.

Tian *et al.*[6] realized the first anisotropic neuronal transistor based on black phosphorus. They used structure anisotropy of 2D materials to imitate the heterogeneity of synaptic behavior. The key characteristics of biological synapses were successfully emulated, such as long-term plasticity and spike-timing-dependent plasticity. More importantly, a simple axon-multi-synapse heterogeneity network was demonstrated. These devices can be regarded as the building blocks for future neuromorphic systems.

Recently, Qin *et al.*[9] used 2D trigonal selenium (t-Se) nanosheet to make an anisotropic electrolyte-gated synaptic transistor (EGT) (Fig. 1(d)). t-Se is a one-dimensional vdW material, where Se atoms are covalently bonded along *c*-axis direction while stacked together along the perpendicular plane via vdW interactions. 2D t-Se nanosheets tend to crystallize in an irregular quadrilateral. In the EGT devices based on t-Se nanosheets, the synaptic weight variation and temporal filtering capability showed a strong anisotropic response because of the inherent heterogeneity of channel conductance. Moreover, the complex axon-multi-synapse system with heterogeneous signal-transmission ability was also realized in multiterminal EGT devices (Fig. 1(e)). For the same stimulus input, the system exhibited an anisotropic filtering behavior (Fig. 1(f)). The devices based on 2D anisotropic materials can be used to build heterogeneous artificial neural networks.

Some isotropic 2D materials with special structures may

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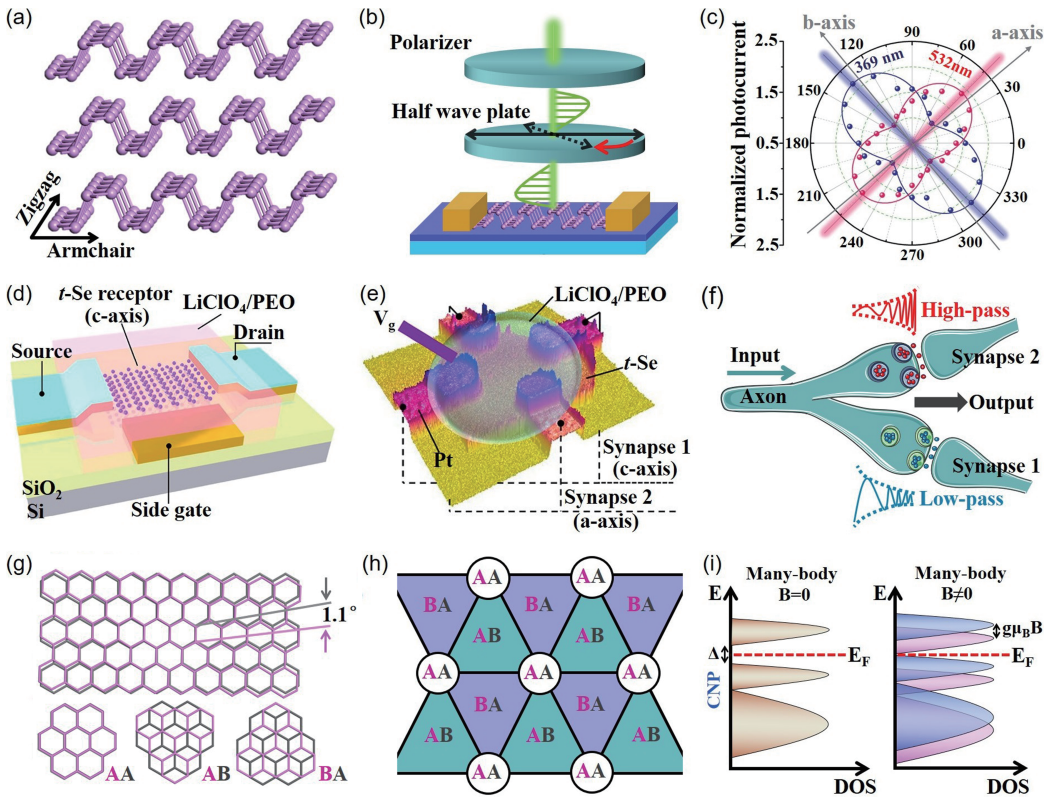

Fig. 1. (Color online) (a) Multilayer black phosphorus. (b) Schematic diagram of the polarization-sensitive photodetector based on anisotropic 2D materials. (c) Normalized photocurrents in the polar coordinates. Reproduced with permission[4], Copyright 2020, John Wiley and Sons. (d) Three-terminal EGT to mimic the synapse behavior. Reproduced with permission[9], Copyright 2020, American Chemical Society. (e) The EGT device with a pair of opposite electrodes. Reproduced with permission[9], Copyright 2020, American Chemical Society. (f) Biological axon-multi-synapse system. (g) Top: the Moiré pattern in TBG. Bottom: three different stacking in TBG. (h) A simplified model for the stacking order in TBG. (i) Density of states. Left: a spin-singlet Mott-like insulator ground state. Right: the excitations can be polarized and charge conduction occurs when the Zeeman energy exceeds the charge gap.

have anisotropic functions. A magic-angle graphene has been extensively studied due to its flat-band accessibility, bandwidth tunability, and superconducting phase[10–12]. Magic-angle twisted bilayer graphene (TBG) was made by stacking two aligned graphene sheets with a small twist angle of $\theta \approx 1.1°$ (Fig. 1(g)). The Moiré pattern can arise from a small twist angle or lattice mismatch between the sheets. A Hubbard model was used to explain the stacking order of TBG (Fig. 1(h)), in which each vertex of the trigonal lattice corresponds to A–A stacking of Moiré pattern. When applying a Zeeman field, the excitation can be further polarized. The charge conduction occurs when the charge gap is exceeded by Zeeman energy (Fig. 1(i)). Cao *et al.*[12] recently reported the identification of intertwined phases with rotational symmetry breaking in magic-angle TBG. A highly anisotropic phase was found in a "wedge" above the underdoped position of superconducting dome. This superconducting state exhibited an anisotropic response to a direction-dependent in-plane magnetic field. Both anisotropic 2D materials and isotropic 2D materials with special structures have a great promise in post-Moore photoelectric devices due to their atomic-level thin bodies and unique anisotropic feature.

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References

[1] Novoselov K S, Geim A K, Morozov S V, et al. Electric field effect in atomically thin carbon films. Science, 2004, 306, 666

[2] Conti S, Pimpolari L, Calabrese G, et al. Low-voltage 2D materials-based printed field-effect transistors for integrated digital and analog electronics on paper. Nat Commun, 2020, 11, 3566

[3] Dieny B, Prejbeanu I L, Garello K, et al. Opportunities and challenges for spintronics in the microelectronic industry. Nat Electron, 2020, 3, 446

[4] Pi L, Hu C, Shen W, et al. Highly in-plane anisotropic 2D $PdSe_2$ for polarized photodetection with orientation selectivity. Adv Funct Mater, 2021, 31, 2006774

[5] Li G, Yin S, Tan C, et al. Fast Photothermoelectric response in CVD-grown $PdSe_2$ photodetectors with in-plane anisotropy. Adv Funct Mater, 2021, 31, 2104787

[6] Tian H, Guo Q, Xie Y, et al. Anisotropic black phosphorus synaptic device for neuromorphic applications. Adv Mater, 2016, 28, 4991

[7] Du X, Tao L, Xu J, et al. Two-dimensional multibit optoelectronic memory with broadband spectrum distinction. Nat Commun, 2018, 9, 2966

[8] Xiang D, Liu T, Wang J, et al. Anomalous broadband spectrum photodetection in 2D rhenium disulfide transistor. Adv Opt Mater, 2019, 7, 1901115
[9] Qin J, Zhou F, Wang J, et al. Anisotropic signal processing with trigonal selenium nanosheet synaptic transistors. ACS Nano, 2020, 14, 10018
[10] Cao Y, Fatemi V, Demir A, et al. Correlated insulator behaviour at half-filling in magic angle graphene superlattices. Nature, 2018, 556, 80
[11] Park J M, Cao Y, Watanabe K, et al. Tunable strongly coupled superconductivity in magic-angle twisted trilayer graphene. Nature, 2021, 590, 249
[12] Cao Y, Rodan-Legrain D, Park J M, et al. Nematicity and competing orders in superconducting magic-angle graphene. Science, 2021, 372, 264

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