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A Review of 2-dimensional Material in the Field of Quantum Hall Effect

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Abstract

The Quantum Hall Effect is one of the most important scientific discoveries in the field of condensed matter physics since the 20th century. The excellent performance of two-dimensional nanomaterials in quantum transport provides a superior research platform for the quantum Hall effect. As the most representative two-dimensional material, graphene has ultra-high mobility and a strict two-dimensional structure. However, due to its weak spin-orbit coupling, the band gap is zero, so it cannot be used to observe the quantum spin Hall effect at room temperature. Later, researchers found that two-dimensional transition metal dichalcogenides (TMDCs) have suitable band gaps, but their direct band gaps change to indirect band gaps as the number of layers increases and their carrier mobility at room temperature is low, which limits its further research development. Finally, black phosphorus has entered the field of vision of scientific researchers. Black phosphorus has high mobility and its direct band gap can be adjusted by the number of layers. The excellent adjustable performance shows that black phosphorus has great research potential and application prospects.

Keywords

2-D material; QHE; Graphene; MoS2; Black Phosphorus.

1. Introduction

In 1879, American physicist E. H. Hall discovered that when a current passes through a two-dimensional conductor perpendicular to the magnetic field, an electric potential difference perpendicular to the direction of the current and the magnetic field will be generated. This phenomenon is called the Hall Effect.

1.1 Integer Quantum Hall Effect

On February 5, 1980, German physicist von Klitzing found that in the state of a very low temperature and strong magnetic field (about 18T, 1.5K), the Hall resistance appeared as a quantized platform with the change of the magnetic field. These quantized Hall resistance values and e2/h maintain an exact integer multiple relationships, and the longitudinal conductance at this time will become an insulating state. This is called the Integer Quantum Hall Effect (IQHE).

1.2 Fractional Quantum Hall Effect

In 1982, Chee Tsui and Störmer further discovered in their research on GaAs heterojunction that when the temperature and magnetic field are lower and stronger than the integer quantum Hall effect (about 20T, 0.5K), it is observed that the transverse Hall resistance presents a plateau and the longitudinal resistance decreases to zero in some resistance and temperature ranges on the relationship curve of Hall resistance and magnetic induction intensity of the magnetic field. These platforms correspond to fractional values, so we call it the Fractional Quantum Hall Effect (FQHE).

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1.3 2-D material

The emergence of two-dimensional materials provides a brand new material basic system for the study of the Quantum Hall Effect. Two-dimensional materials have a quantum confinement effect in the direction of the thickness of the atomic layer, and electrons are confined in the two-dimensional plane of the material. In addition, the atoms in the particles occupy a considerable proportion at the surface and have high surface energy when observed at the nanoscale. This special effect is called the interface effect. The high exposure of surface atoms facilitates the manipulation of material properties using surface modification and element doping. This is of great help for the construction of corresponding material systems, so two-dimensional materials are ideal materials for basic research in condensed matter physics.

2. High Mobility and Zero-bandgap--graphene

2.1 Development of Quantum Hall Effect Research in Graphene System

Until 2004, graphene was considered a hypothetical material structure, but this idea was broken when Andre Geim and Konstantin Novoselov of the University of Manchester succeed in preparing graphene films by using methods of mechanical exfoliation. The experiment observed the "half-integer" quantum Hall effect of single-layer graphene, revealing that the carriers are Dirac fermions. Also, they surprisingly observed that single-layer graphene has extremely high mobility at room temperature without the need for extreme states. Philip Kim's lab followed, using electric field effects to adjust the chemical potential to observe the phenomenon, concluding that the phase shift measured in the magnetic oscillations can be attributed to the special topology of graphene's band structure with a linear dispersion relationship and the di Mass disappears near the Lack point, a conclusion that provides direct evidence for the Berry phase of massless Dirac fermions in graphene theory[1].

In 2014, the team of Philip Kim and Xiaomeng Liu at Harvard University and others observed fractional QHE states in bilayer graphene (BLG), which can be tuned by a transverse electric field. In bilayer graphene (BLG), coupling to electric and magnetic fields can force transitions between different spin and valley ordering, including different FQHE phases. Therefore, BLG provides a model system that is well suited to experimentally study phase transitions between different topologically ordered states[2].

The discovery of correlated insulator states, superconductivity and the Quantum Anomalous Hall Effect in the flat bands of magic-angle twisted bilayer graphene has led to a series of related explorations. In 2020, with the collaboration of Prof. Philip Kim from Harvard University and Liu Xiaoming's team, etc., the van der Waals isomerism of twisted two-layer bilayer graphene (TDBG) was used to demonstrate planar electrons that can be tuned by a vertical electric field within the twist angle range[3].

2.2 Structure of Graphene

Carbon atoms in graphene are connected by sp2 hybridization, each atom is covalently bonded to the surrounding three atoms through σ bonds, and π electrons in adjacent carbon atoms form delocalized large π bonds. The honeycomb lattice diagram of graphene is shown in the figure. Any adjacent atoms in each lattice unit are set to A and B, then each lattice point A or B is in the center of the corresponding equilateral triangle.

The electronic energy band structure of graphene is shown in the figure. The conduction band and valence band of graphene are very close to the Fermi level and are symmetrical about the Dirac point, and overlap in the six low-energy regions near the Brillouin zone, making graphene's bandgap is zero, which also makes graphene not have the properties of a semiconductor. Although it is said that the band gap of graphene can be opened by destroying the lattice of graphene, introducing doping, adatoms, etc., this will make the graphene's electronic properties affected seriously and reduce its mobility greatly. So currently, there are no effective methods to make the bandgap of graphene precisely controllable.

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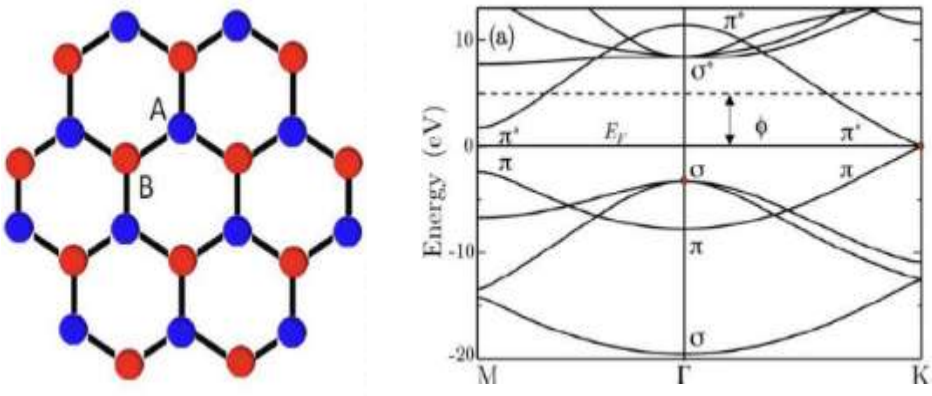

Figure 1. Honeycomb lattices of the graphene and energy band structure diagram

3. Molybdenum Disulfide

3.1 Structure of MoS_2

Compared with non-semiconductor graphene, molybdenum disulfide with a band gap is undoubtedly more advantageous than graphene. Two layers of sulfur atoms in a monolayer of molybdenum disulfide use van der Waals forces to sandwich a layer of molybdenum atoms, and the molybdenum atoms and sulfur atoms in the layers present a triangular prism-like structure, and the distance between each layer is about 0.65nm. Molybdenum disulfide has three crystal structures: 1T-type molybdenum disulfide, 2H-type molybdenum disulfide, and 3R-type molybdenum disulfide, of which 1T type is metallic and 2H type is semiconducting.

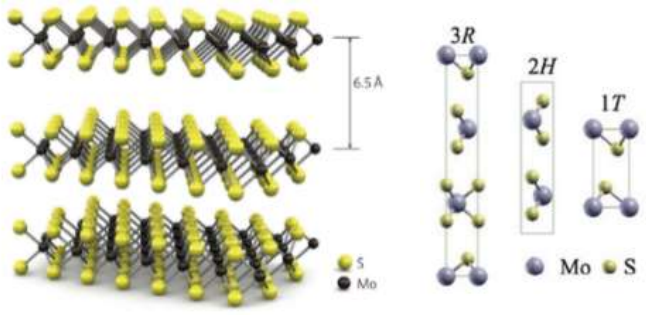

Figure 2. MoS2 entrainment structure and three crystal types

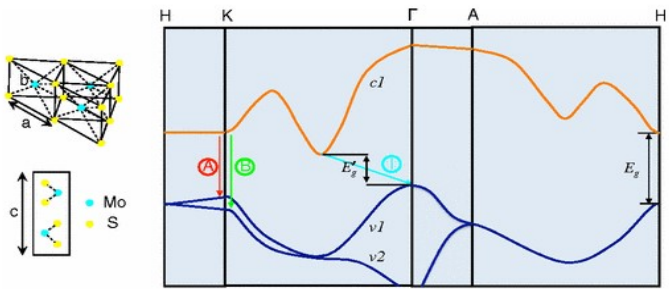

Figure 3. Expanded view of MoS2 in the first Brillouin zone

The figure shows the expanded view of molybdenum disulfide in the first Brillouin zone, where the conduction band c1 is the lowest and the valence bands v1 and v2 are the highest. A and B are direct transitions, and I is an indirect transition. E'g is the indirect band gap of the bulk and Eg is the direct

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band gap of the monolayer. The band gap of molybdenum disulfide is 1.89 eV for the monolithic layer and 1.29 eV for the bulk[4]. With the transformation of molybdenum disulfide from bulk to monolayer, its energy band structure also becomes a direct band gap, and the electronic transition is also vertical. It can be seen that monolayer molybdenum disulfide has superior electronic structure and electrical properties.

3.2 Development of Quantum Hall Effect Research of MoS_2

In 2011, Radisavljevic et al. constructed a single-layer MoS2 transistor with 270nm-thick layered silicon dioxide as the substrate and covered it with 30nm of HfO2, as shown in the figure. The carrier mobility of monolayer MoS2 is increased to 200cm2v-1s-1at room temperature with ammonium oxide gate dielectric and the room temperature switching ratio of monolayer molybdenum disulfide is increased to 1x108[5].

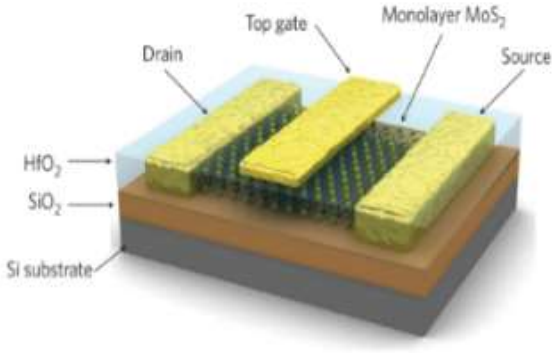

Figure 4. 3D pattern of MoS2 FET

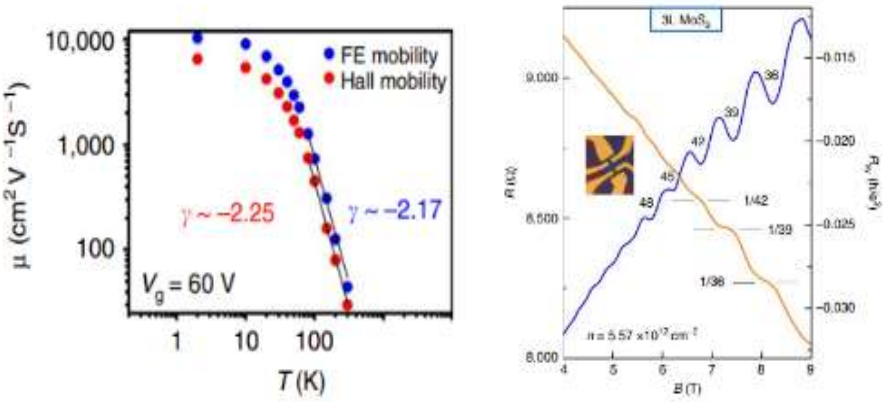

Figure 5. Schematic diagram of MoS2 mobility versus temperature and conductance showing a Hall platform

In 2016, Prof. Wang Ning and Fan Zhang et al. reported the experimentally observed quantum Hall platform of multilayer TMDCs, with hexagonal boron nitride (BN) encapsulated structures and metal contacts made by the selective etching process they report a magnetotransport study of both even- and odd-layer TMDCs. Experiments by measuring quantum transport in odd- and even-layer TMDCs reveal that unique electronic properties can be extended from single-layer TMDCs to multilayer TMDCs

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4. High Mobility and Controllable Bandgap--black Phosphorus

Above, we learned that graphene has high mobility and zero band gap. While molybdenum disulfide has a band gap, the carrier mobility is low. An emerging two-dimensional semiconductor material with a unique energy band structure and excellent properties, black phosphorus, stands out.

The black phosphorus crystal has the same two-dimensional layered structure as graphene, which is composed of folded phosphorus atomic layers. The distance between two adjacent monolayers is 0.53 nm. The phosphorus atoms are connected by covalent bonds. Individual phosphorus atoms are linked to three other phosphorus atoms.

Theoretically, the band gap of a single layer of black phosphorus is between 0.3 and 1.5 eV, which is just between the graphene's zero-bandgap and the band gap of molybdenum disulfide in value. As shown in the figure, when the number of layers of black phosphorus changes, its bandgap also changes gradually, and the relationship is inversely proportional, which led to the precise controllability of the black phosphorus band gap, which facilitates the study of quantum transport experiments.

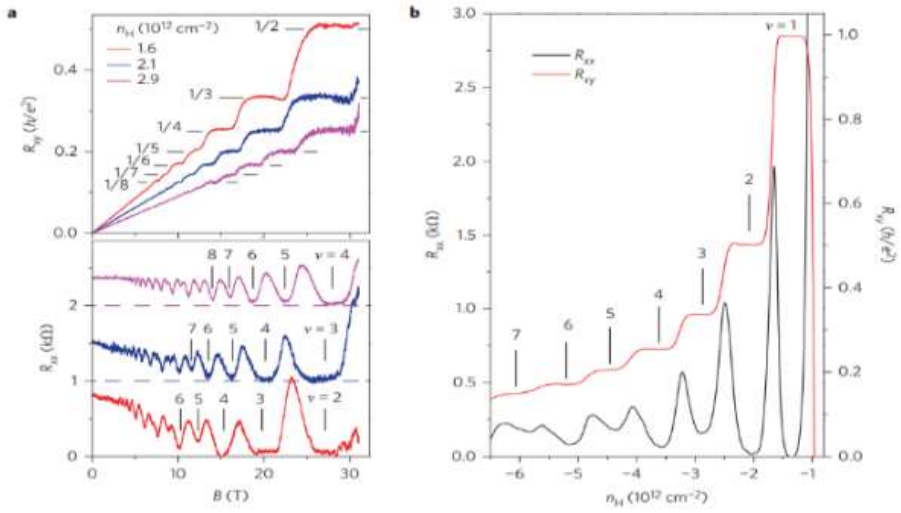

Figure 6. The Rx of black phosphorus exhibits a Hall platform. The experiment shows that the Hall resistance exhibits a Hall platform at B = 33 T and T = 1.7 K. The hole mobility of the sample is as high as 3000 cm2V-1s-1 at T = 1.5 K.

In 2016, Li et al. used hexagonal boron nitride (hBN) to wrap black phosphorus, graphene as the gate, and Si/SiO2 wafer as the substrate to build a heterostructure stack. By constructing a field-effect transistor (FET) of black phosphorus, the ultra-high carrier mobility of black phosphorus was achieved, and the integer quantum Hall effect was successfully observed.

5. Conclusion

Among many two-dimensional material systems, this review selects three representative two-dimensional materials, describes the corresponding material properties, and explores their excellent performance and shortcomings in the field of Quantum Hall Effect. The zero-bandgap and ultra-high mobility graphene system is the focus of current quantum transport experiments. Whether it can open a sufficiently wide-bandgap without affecting its electronic properties needs to be explored. In the two-dimensional transition metal dichalcogenides, molybdenum disulfide is used as an example to introduce its superiority compared to graphene, but its lower room temperature carrier mobility still has a lot of room for improvement. The emerging two-dimensional single-element crystal material black phosphorus already has a sufficient and tunable band gap width, but the research is still in a state of strong magnetic and low temperature. It is worthwhile to explore whether black phosphorus

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can also have the same superior performance at room temperature. In addition, whether it is experimental or industrial production, its inherently unstable nature also prompts us to find ways to make it stable and controllable.

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