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Field Effect Transistors using Two - Dimensional Pnictogen

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Abstract: ***2D Pnictogen is emerging and a competitive candidate for next - generation logic devices due to its interesting physical and chemical properties, such as tunable midrange bandgap and controllable stability. There has been abundant research advancement on the fundamental properties, preparation methods, and related electronic applications of 2D pnictogen. This paper includes a brief understanding of crystal structure, electronic properties and applications of 2D pnictogen Field Effect Transistors (FET). And, the applications of 2D pnictogen in designing electronic devices including transistors, photodetectors, gas sensors, and chemical/ electrochemical sensors.***

Keywords: 2D pnictogen, electronic properties, Field Effect Transistors, chemical sensors, electronic devices

1. Introduction

Two - dimensional (2D) materials could lead to unique devices with new functions that standard semiconductors could never afford. Field - effect transistors (FETs) have been investigated as potential functional devices to meet this need, and a variety of 2D materials have been investigated, including semimetals, transition metal dichalcogenides, and many more. Following the successful demonstration of black phosphorus FET in 2014, there has been a surge in interest in new 2D - layered pnictogens such as phosphorene, arsenene, antimonene, and bismuthene in device research. Short channel effects, which present the scaling potentials for sub - 10 nm gate - lengths, are unaffected by these atomic - thin 2S semiconductor materials. Furthermore, 2D materials with a wide bandgap and carrier mobility could match the requirements of low - power, high - speed devices. The integration of 2D pnictogen materials into FETs is discussed in this study.

Rest of the paper is organised as follows:
Section 2 presents the electronic properties of 2D Pnictogen.
Section 3 Characteristics of 2D pnictogen FETs
Section 4 existing obstacles and future opportunities for 2D pnictogen FETs as a platform for innovative nanoelectronics.

2. Electronic Band Structure of 2d Pnictogen

2.1 Band Structure

The interesting electrical characteristics of 2D pnictogen materials have been investigated in recent research. The material's band structure controls its electrical and optoelectronic applications. Figure 1a shows that Black Phosphorus (BP), a member of the pnictogen group,

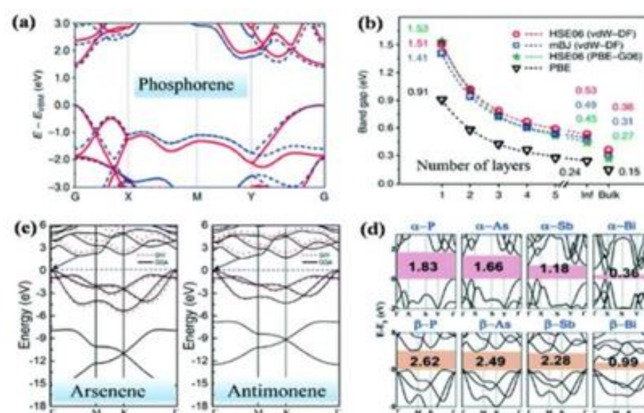

Figure 1: Band structure of BP. Red line - HSE06 functional, blue line - mBJ potential. (b) Bandgap as a function of number of layers. (c) Energy band structure of As and Sb calculated using PBE and GW theories. (d) Electronic band structure of the α and β phases of P, As, Sb and Bi using the HSE06 functional.

number of layers in BP, which is a key characteristic (figure1b). The other two materials present in pnictogen group are Arsenene and antimonene. These materials switch from indirect bandgap to direct bandgap by applying a small strain. The first - principals theory calculation showed indirect bandgaps of As (1.76eV) and Sb (1.65eV) in stable β phase (figure 1c). Wang et al. calculated the bandgap values of 2.47 and 2.38 eV for arsenene and antimonene respectively by using GW method. Another member of pnictogen is 2D monolayer bismuth. This member has semi - metallic properties in bulk form, it behaves as a narrow bandgap semiconductor as a single layer. Zhang et al. exclusively studied the band structures and energy levels of pnictogen monolayers (α and β phases) using the HSE06 band structure calculation. The summarized energy bandgaps of the α and β phases of phosphorene, arsenene, antimonene, and bismuthene are shown in figure 1d. The result shows that, (α - phosphorene (1.83 eV), (α - bismuthene (0.36 eV), and β - bismuthene (0.99 eV) exhibit a direct band - gap structure, while (α - arsenene (1.68 eV) and (α - antimonene (1.43 eV) exhibit a quasi - direct bandgap structure.

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2.2 Carrier Transport

$$\mu_2 D = \frac{2eh^3 C_2 D}{3kT_B |m^*|^2 E^2{}_1}$$

has direct bandgap values of 0.3 and 2.0 eV for bulk and monolayers, respectively. In comparison to other materials, the direct bandgap gives an advantage for future applications. Green's function and screening Coulomb interaction (GW) methods are used to determine the band gaps, which are then validated using scanning tunneling microscopy. The direct bandgap is easily tunable by adjusting the

The equation above represents carried mobility in 2D pnictogen.

The reduced Planck constant and the Boltzmann constant are de - noted by h and kB, respectively. The letter T stands for absolute temperature. The terms m* and C2D stand for effective mass and elastic modulus along the transport direction (zig - zag/armchair), respectively; the parameter E1 is the deformation potential constant of the valence - band minimum or conduction - band maximum along the transport direction. The elastic modulus can be calculated using the equation below.

$$C_2 D = \frac{1}{S_0} X \frac{d^2 E_s}{d\epsilon^2}$$

This explains us that the effective mass, elastic modulus and potential constant are important parameters in determining the carrier mobility in pnictogen.

2.3 Optical Properties

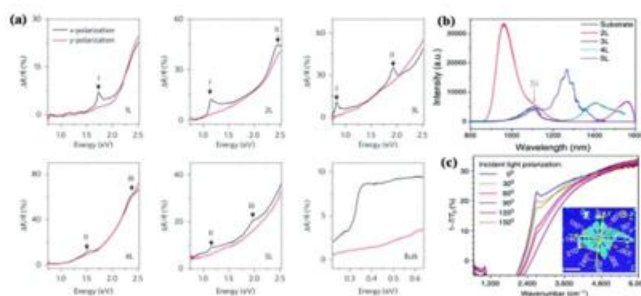

Figure 2: 2 (a) Reflection spectra along x, y directions for mono - layer to pentalayer and bulk phosphorene. black line is ban gap measured using lowest energy peak. the values are 1.73, 1.15, and 0.83 eV for monolayer, bilayer and trilayer phosphorene respectively. (b) Layer - dependent PL spectra of phospherene (2 - 5 layers). (c) Polarization - dependent infrared spectrum with six direction incident light polarizations.

Pnictogen has a variety of optical properties that make it a good choice for various sorts of optoelectronic devices. The thickness of BP's tunable bandgap is monitored using linear optical absorption spectra. The optical absorption peak at 77K has been explored by Li et al. Figure 2a shows that the absorption peaks for 1 L, 2 L, 3 L, and bulk samples were 1.73, 1.15, 0.83, and less than 0.75 eV, respectively. Zhang et al. confirmed that lowering the BP numbers causes the PL peak intensity to increase, as seen in figure 2b. In the MIR wavelengths, Chen et al. conducted a thickness - dependent PL analysis. For a 46 nm thick BP, increasing the temperature from 80 to 300K raises the bandgap from 0.308eV to 0.334eV. Zhang et al. also looked at the infrared fingerprints of BP, and their findings revealed that few - layered BP has a thickness - dependent distinctive infrared spectrum that reveals the elemental electronic structure progression. BP has plane anisotropy, which provides an enormous opportunity for new applications. The calculation pointed out the differentiation of optical absorption along the transport direction. In the armchair direction, the absorption peak decreases rapidly with increasing layer thickness, whereas in the zig - zag direction the intensity decrease much slower. This property of BP allows the electronic and optical determination of the crystalline orientation. The study by Tran et al. also demonstrated that BP absorbs light polarized along the armchair direction, and it's transparent to light along the zigzag direction in the same energy range. The polarization window can also be tuned by changing the number of layers in BP. This also points out that optical conductivity of BP is sensitive to layer thickness. Raman spectrum is one of the important parameters, which acts as a molecular fingerprint to identify a particular material.53, 54 Raman spectroscopy has been successfully used to study the layer numbers and temperature - dependent peak shifts for different 2D materials.

D. J Late et al. have performed the temperature - dependent Raman spectrum on BP and it resulted in a decrease in wave number when the temperature increased from 77 to 673 K.

3. Integration of 2D PNICTOGEN FET

FETs are the most widely researched semiconductor device since they are an essential component of modern integrated circuits. Due to the absence of dangling bonds, unwanted coupling with phonons, and the production of interface states, in 2D materials, using them in FETs could significantly increase its performance. Furthermore, the 2D channel topology is potentially resistant to short channel effects, allowing Moore's law to be extended below 10 nm indef - initely.2D pnictogen, as a novel family of nanomaterials, shares many of the same features as other nanomaterials, such as high elasticity and flexibility, making it ideal for flexible electronics. Their tunable bandgap and competitive mobility satisfy the need for high - performance power gain, analog amplifiers, and circuits, allowing for a larger on/off ratio and faster operation. In comparison to TMD - based FETs, 2D pnictogen transistors have a higher on - current and faster speed. The bandgap of black phosphorus might be inferred from an absorption spectrum ranging from visible light to infrared due to its direct bandgap structure. In comparison to mono - layer TMD materials, this characteristic allows black phosphorus to have better optoelectronic applications. Furthermore, with structural modification through encapsulation, the device performance of 2D pnictogen may improve significantly, reaching that of Bi2O2Se, a revolutionary 2D semiconducting material with tremendous potential for next - generation electronic applications. As a result, FETs based on 2D pnictogen have a lot of potentials.

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3.1 Device Behavior

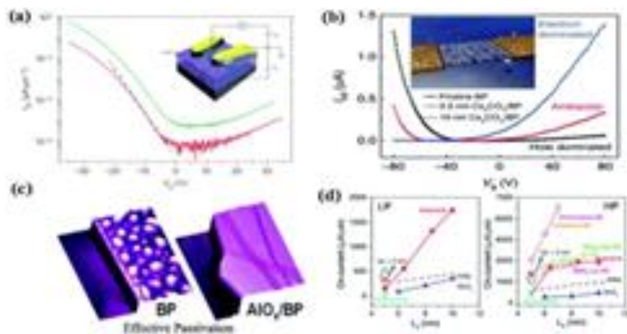

Figure 3: (a) DC conductivity and IR relative extinction (b) Transfer characteristics of BP FETs (c) Drain current Gate Voltage for black phosphorene FETs (d) Gate Sweep with L = 1000nm.

FETs based on few - layer black phosphorus were successfully manufactured in 2014. Black phosphorus nanosheets generated by mechanical exfoliation are placed onto doped silicon wafers with thermally grown silicon dioxide as gate dielectrics, as shown in Figure 3 (a). At normal temperature, typical black phosphorus FETs have substantial drain current modulation (105), as well as thickness - dependent field - effect mobility (1000 cm2 V - 1 s - 1). The carrier effective mass in the associated transport direction is closely correlated to direction - dependent on - state current and switching speed, according to Liu et al. Phosphorene FETs have a faster switching speed and create a higher current density than MoS2 FETs.

Black arsenic - phosphorus (AsP) was synthesized and manufactured as back - gate FETs with highly programmable chemical compositions. The semiconducting characteristics of black AsP materials and their potential uses in logic electronics are revealed by various transport measurements. FETs based on stable black arsenene crystals with strong carrier mobility and large Ion/Ioff ratios (Figure 3 (b)) were reported by Zhong et al. in 2018. Ji et al. used antimonene polygons with HfO2 as a top - gate dielectric to manufacture transistors whose channel materials were generated by van der Waals epitaxy. They pointed out that antimonene's competitive conductivity, along with its exceptional optical transparency, could lead to novel optoelectronic applications. Yang et al. recently disclosed centimeter - scale bismuth nanosheet - based FETs with significant carrier mobility.

3.2 Ambipolar

In charge transport, channel materials having ambipolar properties may exhibit symmetric n - and p - type behavior. Simplified and space - saving circuit designs are frequently required. Das et al. found that phosphorene FETs have increased electron and hole transport, with field - effect mobility of 172 and 38 cm2 V - 1 s - 1 for holes and elec - trons, respectively. Zhu et al. developed an ambipolar phosphorous amplifier with a voltage gain of 8.7 at symmetric DC bias of VGS = 1: 6 V and VDS = 2: 1 V, with the source or gate as the input terminal and the drain as the output terminal. Despite the presence of charge trapping sites on the surface, black phosphorus FETs can nonetheless exhibit intrinsic ambipolar properties.

Similarly, black arsenene FET demonstrated ambipolar charge transport behavior, which reveals higher or comparable electronic [42], thermal, and electric transport anisotropies between the arm - chair and zigzag directions than any other known 2D crystals. Similar to any other known 2D crystal, black arsenene FET showed am - bipolar charge transport behavior, revealing higher or comparable electronic, thermal, and electric transport anisotropies between the armchair and zigzag orientations.

3.3 Anisotropy

The anisotropic effects and peculiar features of pnictogen on device performances have been widely investigated in experiment and theory, inspired by a few preliminary research. For example, resolved polarization dependent photocurrent characterisation has been used to explore anisotropic photocurrent production in black phosphorus FETs. Anisotropic photocurrent response is found in the black phosphorus - electrode contact area in its FET devices due to crystal orientation - dependent absorption in black phosphorus. Figure 4a shows that black phosphorus has a substantial and anisotropic in - plane optical conductivity, as determined by polarization - resolved infrared spectroscopy and angle - resolved DC conductivity.

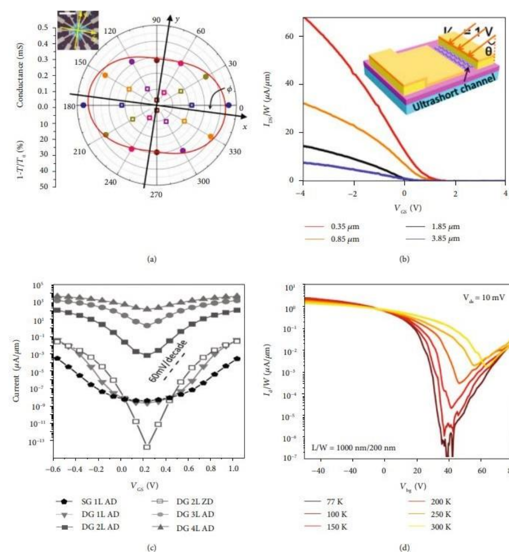

Figure 4: (a) Schematic of the device structure of a few - layer phosphorene FET (b) Transfer characteristics of monolayer arsenic device (c) Output characteristics of antimony devices (d) Transfer curve of FET based on 10 nm bismuthene flank.

3.4 Device Parameters

Many FET applications seek to reduce subthreshold swing, boost on - state current, and achieve well - defined drain current saturation in the high drain - source bias area. As a result, device parameters such as channel dimensions and contact resistance must be optimized.

3.5 Channel Length

Miao et al. used a combination of electron beam lithography and angle deposition to create top - gated black phosphorus FETs with excellent performance (figure4b). The evaporation

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angle control can be used to regulate the channel length of the FETs in the range of 20 to 70 nm. A vast variety of FETs with short channel lengths have been successfully manufactured thanks to advancements in device fabri - cation technology, including 5 nm carbon nanotube FETs [91], sub 10 nm even to 1 nm channel - length MoS2 FETs, and silicon - based MOSFETs. The transistors showed relatively mild short channel effects thanks to the configuration features of 2D black phosphorus. Meanwhile, even with a 20 nm channel, a comparable Ion/Ioff ratio of 102 is achieved. Lam et al. disclosed a black phosphorene with double gate field - effect transistors that was sub - 10 nm in size. Based on the nonequilibrium Green's function formalism and Ballis - tic device model, the transistors have a 50 fs inherent delay and a 104 Ion/Ioff ratio. The different performance metrics of the best sub - 10 nm phosphorene FETs expressly meet the ITRS high - performance device standards. Ion/Ioff can be increased by more than 108 by choosing the right transport route. Wang et al. also used ab initio methods to study the relationship between device performance and channel length of arsenene and antimonene FETs. The simulated MOSFETs with sub - 10 nm or even 4 nm channel exhibit outstanding electrical performances and can meet both the low power and high - performance application requirements in the ITRS.

3.6 Device Thickness

The thickness of 2D semiconductors is an important factor in determining their fundamental electrical properties as well as device performance. Because the bandgap of black phosphorus is a function of layer numbers, adjusting the performance of FETs in figure4c is a practical and efficient method. Das et al. found that the layer thickness has an impact on the current density and Ion/Ioff ratio of phosphorene FETs (102), which is confirmed by a robust technique based on the transfer characteristics. Yin and Yoon theorized that monolayer black phosphorus FETs might produce equivalent on - state current to bulk phosphorus while avoiding the disadvantage of lower density of states. Monolayer phosphorene FETs, on the other hand, may keep steep switching and resist gate - induced drain leakage.

With a 10 nm channel length, the Ion/Ioff ratio of monolayer - trilayer antimonene - based FETs may also be increased to 4: 87 108. Chang et al. recently suggested lateral monolayer - multilayer heterostructure - based antimonene and arsenene tunneling FETs. Gapless metallic states are introduced in the multilayer area, which significantly improve tunneling probability and drain - source current. Even a 1 nm scale multilayer can enhance current and enable abrupt device switching using ad initio electronic structure and quantum transport computing. Furthermore, strain and temperature are used to control the basic performance of 2D pnictogen FETs. Zhang et al. found that mechanical strain applied through flexible black phos - phorus FETs caused continuous bandgap modulation, as well as a significant piezo resistive effect in FETs at ambient temperature.

Yan et al. looked at the temperature - dependent transport parameters of phosphorene FETs. shown in figure4d. Off - state channel current increases when temperature rises, but on - state channel cur - rent drops, according to their findings, which can be linked to the charge conduction limiting mechanism. Decreased power consumption results from a lower off - state channel current, which is crucial for digital devices and integrated circuits. Black phosphorus (BP) is a good material for high - performance logic circuits because of its high mobility and gate modulation (Ion/Ioff ratio). In 2014, Wang et al. were the first to introduce the gigahertz frequency BP FET.

Mechanically exfoliated BP, Pd contact pad, and HfO2 gate di - electric are used to make the device. Standard RF characterisation, including a de - embedding technique, yields a practically operable cut - off frequency, f T, of 12 GHz. The first bendable gigahertz frequency BP transistors (f T up to 7 GHz) on polyimide substrate were reported by Zhu et al. in 2016, making BP the most promising candidate for flexible RF nanoelectronics. Te - doped BP or carbide BP FETs have recently been created to broaden the applicability of BP by providing a better balance of high carrier mobility with unaffected gate modulation.

Despite this, research into the limit of carrier mobility and on/off ratio for arsenene and bismuthene transistors is lacking. Further - more, the field - effect property of antimonene has yet to be reported, necessitating further research.

3.7 Doping

For 2D pnictogen, air - stability could be a major problem. It's notable that black phosphorus reacts irreversibly with O2 and H2O in the presence of oxygen and water over a short period of time to produce phosphoric acid or oxidized phosphorous compounds. As a result, it's critical to adjust the surface properties of 2D materials and avoid surface degradation using practical and controllable approaches like doping and passivation. Both methods might be used to control the electrical transport properties of 2D pnictogen, making it more suitable for electronic and optoelectronic applications.

Substitutional doping, charge transfer, and field induced doping are three methods for changing the carrier type of semiconductors. The traditional method of doping involves introducing dopants into the host semiconductor lattices, which is difficult to perform in ultrathin 2D materials. Metallic atoms, nonmetallic atoms, and molecules are all common dopants. Because of their low electron affinities, alkali metallic atoms are frequently used as dopants. Han et al. reported a FET based on gigantic electron doping of black phosphorene, demonstrating an ideal device performance with a near - unity ideality factor of 1.007 and around 104 Ion/I off ratio, using in situ surface functionalization with potassium (K). Specifically, K modification significantly improves the electron transport of black phosphorus. Not only metallic atom but also nonmetallic atom can achieve active surface functionalization Yang et al. investigated transport performances of black phosphorus FETs doped with tellurium (Te). The Te doping could dramatically suppress the degradation of black phosphorus, resulting in a high mobility (1850 cm2 V1 s1) of FETs at room temperature and pressure. As a result, a suitable element dopant can encourage the development of black phosphorus electronic devices as a potential approach to efficiently suppressing ambient

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degradation. Tan et al. also produced few - layer black phosphorus carbide FETs with a unique carbon doping approach, which displayed high hole mobility of 1995 cm2 V - 1 s - 1 at ambient temperature. A stable black phosphorus carbide with a lighter effective mass of carriers than its intrinsic ones was obtained using DFT calculations. Its absorption spectrum also includes the infrared range, which black phosphorus does not respond to.

4. Challenges and Conclusion

The essential structural and fundamental electronic features of 2D pnictogen, as well as its field - effect device configuration design and many performance enhancement strategies, were summarized in this paper.2D pnictogen has interesting physical features, such as a controllable moderate bandgap between graphene and TMDs, which means it has a lot of potential for new device applications that are both fast and energy efficient. In terms of devices, we discussed new research on 2D pnictogen transistors with great stability and performance, encompassing everything from fundamental properties to device topologies and integration engineering.

Nonetheless, there are still obstacles to overcome before 2D pnictogen FETs may be used in practical applications. The first is how to make large - area 2D pnictogen with excellent uniformity and quality, especially for monolayer applications. Second, air stability of 2D pnictogen FET devices is a major challenge in order to keep performance stable enough for practical applications. Another challenge is interfacial optimization for 2D pnictogen FET devices, which includes dielectrics and contact quality in a customized and optimized design.

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