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A study on two dimensional (2D) piezoelectric semiconductor materials: a review

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***Abstract*— This study explores the field of two-dimensional (2D) piezoelectric semiconductor materials, offering an in-depth analysis of their distinctive properties, synthesis techniques, and practical applications. Piezoelectricity, the generation of electric charge in response to mechanical stress is well-documented in bulk materials but has recently gained renewed attention with the development of 2D materials. These semiconductors exhibit unique characteristics, including exceptional mechanical flexibility, tunable electrical properties, and nanoscale control, which position them as promising candidates for advanced technologies. The paper examines the principles and mathematical models governing piezoelectric behavior, focusing on the distinctions between in-plane and out-of-plane effects in 2D systems. It further evaluates their potential applications in areas such as sensors, energy harvesting devices, and nanoelectronics. By synthesizing recent advancements, this study provides critical insights into the opportunities and challenges within this dynamic field, paving the way for the design of innovative devices and technologies.**

***Keywords*—Two-dimensional semiconductor, piezoelectric, optoelectronic devices, out of plane piezoelectric; exfoliation methods.**

I. INTRODUCTION

The exploration of two-dimensional (2D) materials has become one of the most prominent research areas in material science, owing to their extraordinary properties and wide-ranging applications. Among these, 2D piezoelectric semiconductor materials have garnered significant attention due to their unique combinations of electronic, mechanical, and piezoelectric properties. These materials exhibit the ability to generate an electric charge in response to applied mechanical stress, a phenomenon that has profound implications for energy harvesting, sensing, and flexible electronics. These materials are nowadays the focus of interest of researchers due to their unique physical and chemical properties[1].ultrathin geometry, unique electrical [2].optical[3],mechanical [4,5] properties, and their pliability, which is not found in their bulk nature [6]. Apart from these, two-dimensional (2D) materials are also lightweight and exhibit high performance in device applications. The interest in these 2D piezoelectric materials, which lack inversion symmetry or a non-centrosymmetric structure, is also increasing rapidly. This is due to their polarizations and potential applications as devices[7, 8].

Piezoelectricity is a material property generated by the application of strain and can be explain by the combination of mechanical and electrical activity in crystals lacking inversion symmetry. Piezoelectric materials are stated to create a dipole charge distribution on the material's surface that is opposite to the direction of polarization when subjected to mechanical strain[9]. This effect is known as the piezoelectric effect. Conversely, when an electric field acts on the material, the material is mechanically deformed[10]. This is called the reverse piezoelectric effect. Both the piezoelectric effect and the reverse piezoelectric effect are used in the design and construction of piezoelectric transformers to convert electrical energy [11-13]. A variety of two-dimensional (2D) materials have been experimentally demonstrated and theoretically predicted to be piezoelectric [14-24].These 2D materials include transition metal dichalcogenides[15, 25] (TMDCs, MoS_2, $MoSe_2$, WS_2, WSe_2), group II – V binary[19, 21, 26, 27] (AlSb, GaP, GaAs, InP, InAs, InSb), group IV monochalcogenides[17, 18, 22, 26] (GeSe, GeS, SnS, SnSe), hexagonal boron nitride[28], group III-IV buckled honeycomb[19]. etc.

Recent studies have expanded the family of 2D piezoelectric semiconductors, exploring materials with enhanced or tunable piezoelectric properties. For instance, a 2024 study demonstrated that monolayers of thorium oxytelluride (ThOTe) exhibit exceptional piezoelectric and ferroelectric characteristics when subjected to strain engineering, with a piezoelectric constant e_{11} reaching up to 13,181.19 pC/m under tensile strain [29]. Another study highlighted the potential of niobium oxydiiodide ($NbOI_2$) for high-performance wearable 2D energy harvesting devices, emphasizing its suitability for intelligent sensing applications[30]. Additionally, advancements have been made in integrating wide bandgap semiconductors with 2D materials, presenting new opportunities for device fabrication and performance enhancement [31].

The unique features of 2D piezoelectric semiconductors also enable significant advancements in mechanical flexibility

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and miniaturization, essential for modern applications in portable and flexible devices. Unlike traditional materials, the mechanical robustness of these 2D materials allows them to sustain high levels of strain, further amplifying their piezoelectric response [32]. Additionally, their reduced dimensionality ensures compatibility with nanotechnology, paving the way for their integration into nanoscale transducers, energy harvesting systems, and biomedical devices [33]. The tunable nature of these materials also allows for precise engineering of their properties, such as the piezoelectric coefficient and carrier mobility, by manipulating parameters like layer thickness, substrate interactions, and strain levels [34]. Despite the remarkable potential of 2D piezoelectric semiconductors, their practical implementation faces several challenges. Issues such as environmental stability, scalability of synthesis methods, and compatibility with existing semiconductor fabrication techniques must be addressed [35]. Furthermore, understanding the interplay between mechanical, electronic, and thermal properties in these materials requires continued theoretical and experimental exploration [36]. Although there have been many reports on 2D materials beyond graphene [37-40], the 2D piezoelectric materials have rarely been studied in details. This review aims to provide a comprehensive overview of the current state of research on 2D piezoelectric semiconductor materials. We will explore their intrinsic properties, synthesis methods, and the theoretical frameworks that describe their behavior. Additionally, we will discuss the latest advancements in their applications across various technologies, highlighting both the opportunities and challenges that lie ahead in this rapidly evolving field.

By synthesizing recent findings, this review seeks to offer valuable insights into the potential of 2D piezoelectric semiconductors, guiding future research and development efforts toward the realization of next-generation electronic and energy devices.

I. II. BASIC EQUATIONS GOVERNING TWO DIMENSIONAL (2D) PIEZOELECTRIC SEMICONDUCTOR

The basic equations guiding a plane n-type piezoelectric semiconductors with the absence of body force, electric charge, and the heat source can be given by [41]

$$\frac{\partial \sigma_{xx}}{\partial x}+\frac{\partial \tau_{xz}}{\partial z}=0$$
$$\frac{\partial \tau_{zx}}{\partial x}+\frac{\partial \sigma_{zz}}{\partial z}=0$$
$$\frac{\partial D_x}{\partial x}+\frac{\partial D_z}{\partial z}=q\left(N_D^+-n_o-n\right)$$
$$\frac{\partial J_x}{\partial x}+\frac{\partial J_z}{\partial z}=0 \tag{1}$$

where σ_{ij} is the stress tensor, D_i is the electric displacement vector, and J_i is the electric current, respectively, with $i, j = x, z.$ N_D^+ is the known donor density, $n_o + n$ is the total electron density, n is the deviation of the electron density from n_o. Since N_D^+ is uniform, then $N_D^+ = n_o$ and the charge equation (1c) becomes

$$\frac{\partial D_x}{\partial x}+\frac{\partial D_z}{\partial z}=-qn \tag{2}$$

From the deformation theory of electromechanical fields, the constitutive equations of a two-dimensional n-type piezoelectric semiconductor can be given by[42, 43]

$$\sigma_{xx}=C_{11}\frac{\partial u}{\partial x}+C_{13}\frac{\partial w}{\partial z}+e_{31}\frac{\partial \varphi}{\partial z}$$
$$\sigma_{zz}=C_{13}\frac{\partial u}{\partial x}+C_{33}\frac{\partial w}{\partial z}+e_{33}\frac{\partial \varphi}{\partial z}$$
$$\tau_{xz}=C_{44}\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)+e_{15}\frac{\partial \varphi}{\partial x}$$
$$D_x=e_{15}\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)-\varepsilon_{11}\frac{\partial \varphi}{\partial x}$$
$$D_z=e_{31}\frac{\partial u}{\partial x}+e_{33}\frac{\partial w}{\partial z}-\varepsilon_{33}\frac{\partial \varphi}{\partial z}$$
$$J_x=-qn_o\mu_{11}\frac{\partial \varphi}{\partial x}+qd_{11}\frac{\partial n}{\partial x}$$
$$J_z=-qn_o\mu_{33}\frac{\partial \varphi}{\partial z}+qd_{33}\frac{\partial n}{\partial z} \tag{3}$$

where u, and w, are the mechanical displacements in th e x and z direction, φ is the electric potential, and n is t he carrier density respectively. c_{ij}, e_{ij} and ε_{ij} are elastic , piezoelectric, and dielectric constants respectively. d_{ij} a nd μ_{ij} are the electron diffusion constant and mobility res pectively.

By substituting Equation (2) into Equation. (1), we can arrive at

$$\left(C_{11}\frac{\partial^2}{\partial x^2}+C_{44}\frac{\partial^2}{\partial z^2}\right)u+\left(C_{13}+C_{44}\right)\frac{\partial^2 w}{\partial x\partial z}+\left(e_{31}+e_{15}\right)\frac{\partial^2\varphi}{\partial x\partial z}=0$$

$$\left(C_{13}+C_{44}\right)\frac{\partial^2 u}{\partial x\partial z}+\left(C_{44}\frac{\partial^2}{\partial x^2}+C_{33}\frac{\partial^2}{\partial z^2}\right)w+\left(e_{15}\frac{\partial^2}{\partial x^2}+e_{33}\frac{\partial^2}{\partial z^2}\right)\varphi=0$$

$$\left(e_{15}+e_{31}\right)\frac{\partial^2 u}{\partial x\partial z}+\left(e_{15}\frac{\partial^2}{\partial x^2}+e_{33}\frac{\partial^2}{\partial z^2}\right)w+\left(-\varepsilon_{11}\frac{\partial^2}{\partial x^2}-\varepsilon_{33}\frac{\partial^2}{\partial z}\right)\varphi+qn=0 \quad (4)$$

$$-qn_0\left(\mu_{11}\frac{\partial^2}{\partial x^2}+\mu_{33}\frac{\partial^2}{\partial z^2}\right)\varphi+q\left(d_{11}\frac{\partial^2}{\partial x^2}+d_{33}\frac{\partial^2}{\partial z^2}\right)n=0$$

Also, equation (3) can be expressed as $D\left(u,w,\varphi,n\right)^T=0$ where

$$D=\begin{bmatrix} c_{11}\frac{\partial^2}{\partial x^2}+c_{44}\frac{\partial^2}{\partial z^2} & \left(c_{13}+c_{44}\right)\frac{\partial^2}{\partial x\partial z} & \left(e_{31}+e_{15}\right)\frac{\partial^2}{\partial x\partial z} & 0 \\ \left(c_{11}+c_{44}\right)\frac{\partial^2}{\partial x\partial z} & c_{44}\frac{\partial^2}{\partial x^2}+c_{33}\frac{\partial^2}{\partial z^2} & e_{15}\frac{\partial^2}{\partial x^2}+e_{33}\frac{\partial^2}{\partial z^2} & 0 \\ \left(e_{15}+e_{31}\right)\frac{\partial^2}{\partial x\partial z} & e_{15}\frac{\partial^2}{\partial x^2}+e_{33}\frac{\partial^2}{\partial z^2} & -\varepsilon_{11}\frac{\partial^2}{\partial x^2}-\varepsilon_{33}\frac{\partial^2}{\partial z^2} & q \\ 0 & 0 & -qn_0\left(\mu_{11}\frac{\partial^2}{\partial x^2}+\mu_{33}\frac{\partial^2}{\partial z^2}\right) & q\left(d_{11}\frac{\partial^2}{\partial x^2}+d_{33}\frac{\partial^2}{\partial z^2}\right) \end{bmatrix} \quad (5)$$

From the theory of matrix, the Determinant of D can be deduced as

$$|D|=a_1\frac{\partial^8}{\partial z^8}+b_1\frac{\partial^8}{\partial x^2\partial z^6}+c_1\frac{\partial^8}{\partial x^4\partial z^4}+d_1\frac{\partial^8}{\partial x^6\partial z^2}+e_1\frac{\partial^8}{\partial x^8}+ a_0\frac{\partial^6}{\partial z}+b_0\frac{\partial^6}{\partial x^2\partial z^4}+c_0\frac{\partial^6}{\partial x^4\partial z^2}+d_0\frac{\partial^6}{\partial x^6}, \quad (6)$$

Where $a_1,b_1,c_1,d_1,a_0,b_0,c_0$ and d_0 are constants obtained from equation (5) and shown in Appendix I

From equation (4), the general solution of a 2D piezoelectric semiconductor can be given as

$u=D_{31}F\left(x,z\right)$, w $=D_{32}F\left(x,z\right)$, $\varphi=D_{33}F\left(x,z\right)$, n $=D_{34}F\left(x,z\right)$, and $F\left(x,z\right)$ satisfies

$|D|F\left(x,z\right)=0$

II. TWO DIMENSIONAL (2D) PIEZOELECTRIC SEMICONDUCTOR MATERIALS

Piezoelectricity is an effect in which an electric potential is created in a substance when the pressure on the substance changes [44]. Piezoelectric substances are materials whose crystals do not have a center of symmetry. When such materials are compressed or bent, the electric charges align on the surface. Conversely, when voltage drops are applied to a piezoelectric material, the material is mechanically deformed. Examples of crystalline materials that exhibit piezoelectric behavior include quartz, PZT, ceramics, barium titanate, polymer film, and wurtzite-structured crystals, etc. When a voltage is applied to the crystal, the positive and negative charges are shifted to each other, as shown in Fig. 1. The difference in the displacement of the charge centers results in electrical polarization within the crystal.

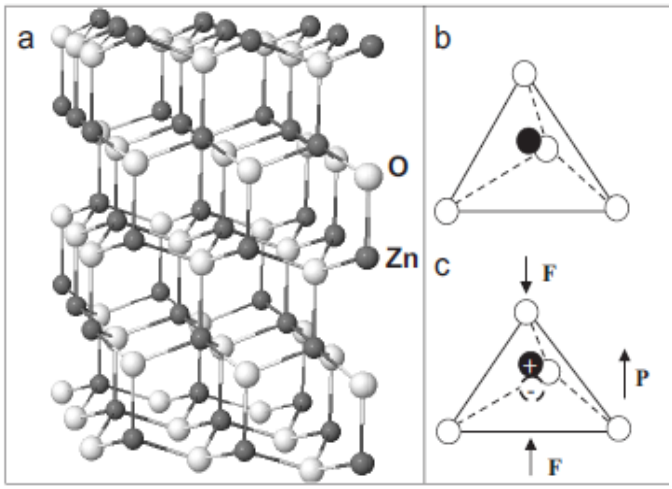

Fig. 1. a) Structural model of wurtzite ZnO. b) Tetrahedral coordination between Zn and oxygen. c) Distortion of the tetrahedral unit under the compression of an external force, showing the displacement of the center of positive charge from that of the negative charge (adapted with permission from Ref [45], Copyright © 2007, John Wiley and Sons).

A. In-plane and out-of-plane piezoelectric semiconductor

From the studies of Duerloo et al.,[15] it was found that the in-plane piezoelectric tensor d11 is higher for some TMDCs than for quartz. In this section, we will discuss experimentally and theoretically reported in-plane and out-of-plane piezoelectric 2-D semiconductor materials. Reed et al. reported on the basis of DFT calculations that the single-layer TMDCs are piezoelectric, but their bulk crystals are not. This prediction was experimentally confirmed by Wu et al [46], as shown in Fig.2(b) below, using a piezoelectric MoS_2 nanogenerator. The fact that single-layer MoS_2 has no inversion center, as shown in Fig.2(a), and that the crystal structure is not centrosymmetric is sufficient evidence that there is a piezoelectric effect in single-layer MoS_2.

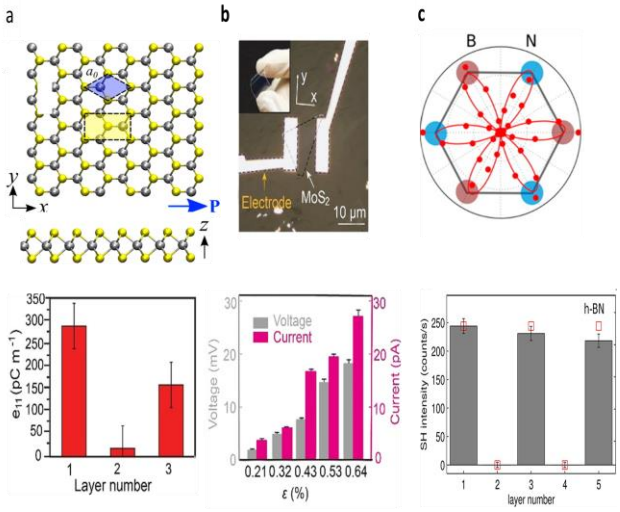

Fig. 2. a Top view and side-view geometries of trigonal prismatic molybdenum disulfide monolayer (2H-MoS2). The measured piezoelectric coefficient in one-, two-, and three-layer MoS2 are shown at the bottom panel (reproduced with permission ref. [15] Copyright © 2012, American Chemical Society, and ref. [47]) b. Optical graphs of a flexible monolayer MoS2 piezo-nanogenerator (up) and external strain dependence of the voltage and current outputs (bottom panel) (Adapted from ref.[46]). c. The orientation dependence for h-BN and layer dependence of SH intensity for layered h-BN(bottom panel) (adapted with permission from ref.[48] Copyright © 2013, American Chemical Society)

From the work of Wu et al [46], piezoelectric properties are only present in odd layers of MoS_2 but not in even layers as shown in Fig.2(a). Hexagonal boron nitride has also been described as piezoelectric, although it has a large bandgap, which designated it as an insulator [28, 49]. Unlike graphene, h- BN exhibits strong in-plane piezoelectricity. This can be explained by the alternating arrangement of the atoms of nitride and boron in a hexagonal vertex, as shown in Fig. 2(c). Their report also agrees with that of Wu et al. that piezoelectricity also present in odd layers, but not in even layers. A few years later, Heinz et al [48], experimentally proved the noncentrosymmetric nature of h- BN by using second harmonic generation (SGH), which somehow shows the piezoelectric nature of h- BN. From their experiment, it was concluded that the SGH signal in h- BN has a layer-dependent effect on the crystal structure.

A recent study by Zheng et al[50], showed that the group IV monochalcogenides (MX, M= Ge or Sn, X=Se, or S) exhibited the usual piezoelectric effect in their monolayer form. This study was carried out based on DFT calculations. From this study, the in-plane piezoelectric coefficient (d11) for this group of 2D monolayer semiconductors is in the range of 75pm/V to 250pm/V, which is much larger than the conventional piezoelectric materials comprising wurtzite structures. Moreover, Li et al. predicted the monochalcogenides of the III group such as GaS, GaSe, and InSe to be piezoelectric in their monolayer form by first- principal calculations. The determined piezoelectric coefficient for GaSe, GaS, and InSe are 0.06, 2.30, and 1.46 pm/V, respectively[51]. Also, Gan et al[52], used first-principles calculations discovered the in-plane piezoelectricity (d11) in various 2D materials in their monolayer form, including metal dichalcogenides (MX2, M=Cr, Mo, W, Ta, and X= S, Se, Te) materials of group III-IV (AXE, A= B, Al, Ca, In, and X= N, P, As, Sb), metal oxides of group IIA and IIB (MO, M= Be, Mg, Ca, Zn, Cd, Pb).

In 2017, Gao and Yiyuan investigated the elastic and piezoelectric properties of buckled monolayers of honeycomb group III - V such as GaP, GaAs, InP, InAs, and InSb by DFT calculations. They reported that these 2-D materials are not only piezoelectric but also ferroelectric. From their study, it was found that these materials have both in-plane and out-of-plane piezoelectric coefficients, with the in-plane coefficient ranging from 0.96 to 1.16 pm/V From their work, the piezoelectric coefficient exhibits a periodic trend for these groups of materials.

Among the experimentally reported 2-D, out-of-plane piezoelectric material is alpha-phase indium selenide (In_2Se_3). This is a semiconductor of group III-VI. From the experiment carried out by [53], it was found that this material has a stable and layered structure among the other five-phase materials at different temperatures. They also reported that this material exhibits out-of-plane piezoelectricity. This was found from TEM and SHG analyses. Also, many kinked hexagonal materials, such as the CdS membrane and ZnO nanofilm, retain their out-of-

plane piezoelectricity when reduced in size, but the introduction of certain chemical substrates, such as silicon dioxide, to form doped graphene. Their symmetry changes randomly, resulting in out-of-plane piezoelectricity[54]. Apart from experimental studies on out-of-plane piezoelectricity, the theoretical study of DFT also shows out-of-plane piezoelectricity in single layered materials of kinked group III-VI (AXE, A= Al, Ca, In and X = P, As, Sb) as reported by Blonsky et al, [21]. Some of these 2-D semiconductor materials are doubly ferroelectric. The existence of piezoelectric effect makes them promising candidates for future atomically thin piezoelectric applications such as sensors, transducers, energy harvesting devices and electromechanical devices.

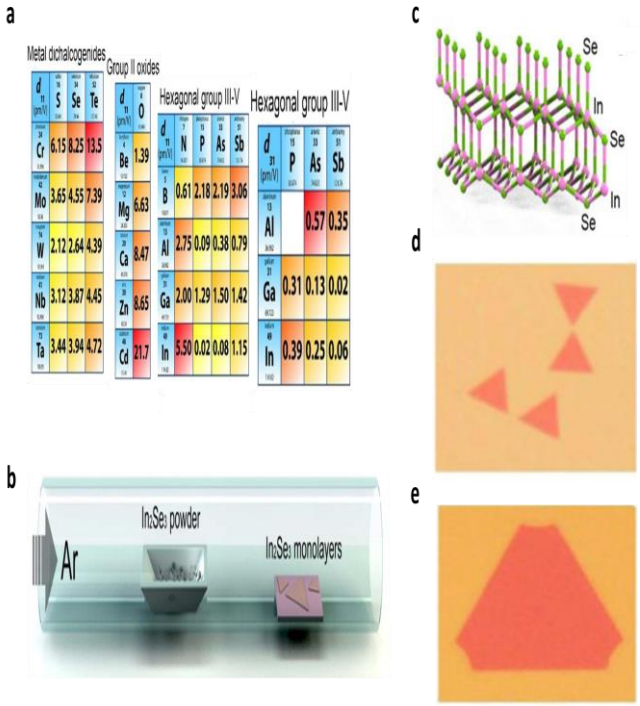

Fig 3 (a) Periodic trends for d_{11} in metal dichalcogenides, metal oxides, and group III–V semiconductors as well as for d_{31} in group III–V semiconductors (reproduced with permission from ref. [21] Copyright © 2015, American Chemical Society) b. Schematic illustration of the PVD process for In2Se3 layers with In2Se3 powders as precursors. b-e. Synthesis of 2D In2Se3 flakes by PVD method (adapted with permission from[55], Copyright © 2015, American Chemical Society).

Table 1 shows a summary of reported out of plane and in-plane piezoelectric properties

2D materials	Piezoelectric direction	Crystal structure	Piezoelectric coefficient	Methods	Notes
Monolayer MoS2	In-plane	Hexagonal	d_{11}=2.5–4 pm/V[56],[15]	Experiment	
Monolayer h-BN	In-plane	Hexagonal	e_{11} = 100 – 400C/m[15]	Experiment	
Doped graphene	Out of plane		d_{33} =1.4 nm/V[57]	Experiment	
α -In_2Se_3	Out of plane and in plane	Rhombohedral		Experiment	Indirectly confirmed by the ferroelectricity[58]
Group IV monochalcognides	In plane		d_{11} = 75 – 250pm/V[18, 59]	DFT	
GroupIII monochalcognides	In plane		d_{11} =1.46 – 2.30pm/V	DFT	
Buckled III-V semiconductor	Out of plane and in plane		d_{31}= 0.02 - 0.6pm/V[21] d_{11} = 1-1.2pm/V[19]	DFT	

III. FABRICATION OF 2D MATERIALS AND THEIR PIEZOELECTRIC CHARACTERIZATION METHODS

Many methods have been used in the fabrication of single and double layer 2D materials. In this section, we will talk about bulk crystal exfoliation and vapor deposition methods.

A. *Vapor deposition method:* this technique is the most cost effective for large scale fabrication of nanostructures and other 2D materials. It is also used for making atomically thin films or flakes. In this process, the thin flakes are deposited on the vapor phase compounds with or without the help of chemical substances to form a layer on the substrates. The main advantages of this method are: the material produced can be of good crystallinity, have a large area uniformity, and the layer can be well controlled. This method involves three [60] (3) steps: Metal transformation, thermal decomposition of precursors, physical vapor deposition (PVD), and chemical vapor deposition (CVD).

Many 2D materials have been prepared by this method, including: Zheng et al [61], used the PVD step to prepare In_2Se_3. They used powdered In_2Se_3 as precursor and mica as substrate under negative pressure to fabricate thin In_2Se_3 flakes for the first time. Later, Zhou et al, succeeded in fabricating high quality -In_2Se_3 material by atmospheric pressure PVD. In this work, Raman and PL signals were also observed in -In_2Se_3 for the first time, as shown in Fig. 3. Feng et al, [62] also used Se and In_2O_3 powders as precursors under the H_2/Ar atmosphere by the CVD method to prepare monolayer, bilayer and trilayer In_2Se_3 flakes. Moreover, Yu et al.,[63] in their study used the metal organic CVD method to fabricate polycrystalline In_2Se_3 films. Here, argon (Ar) was used as a carrier gas and the method was carried out at a pressure of 10 - 80 Torr. This method (CVD) also not only gives high yield but also shows a way to fabricate heterostructures with an interface free from impurities [60] which are needed for device applications. MoS_2 was prepared by Zhan et al.,[64] by depositing a thin Mo film on a SiO2 substrate followed by sulfurization to convert Mo to MoS_2. Using the same method, they first prepared a monolayer and then multiple layers of MoS_2

Song et al. also demonstrated for the first time the mass growth of h- BN on a large scale using ammonia-borane (NH3 - BH3) on a copper (Cu) substrate under low pressure[65, 66]. Later, Shi et al.,[67] used a similar approach by using borazine (B3N3H6) on a nickel (Ni) substrate to prepare h- BN. Recent studies show that single crystalline h- BN could be prepared by CVD under low pressure using Pt and Cu films as substrate [68- 69].

Table 2 shows the experimental preparation of some monolayers synthesized by the vapor phase method

Monolayer	Bandgap (eV)	Mobility on SiO2/Si ($cm^2V^{-1}s^{-1}$)
Graphene	0	16000[70]
MoS_2	1.8	7[64, 71]
WS_2	2.1	Hole =0.28, Electron = 0.46[72]
h-BN	6.0	-
WSe_2	1.7	Hole = 90, electron = 7[73]
$MoSe_2$	1.5	50[74]

B. *Exfoliation methods:* This is a method for fabricating atomically thin 2D materials by exfoliation from bulk crystal. This method was first applied to the preparation of graphene in 2004[75]. It involves both mechanical and chemical processes. It can also be used to fabricate monolayers and few layers of 2D materials. In this method, an adhesive tape is used to repeatedly exfoliate bulk crystals until the desired layer(s) are formed [76, 77]. It has been used to produce graphene, boron nitrides, TMDCs, etc. The advantage of this method is that the exfoliated material has high crystallinity and a clean surface. The only disadvantage is the low yield, which does not favor large scale production. The chemical method includes solvent assisted exfoliation [78-79] and ion intercalation assisted exfoliation[80]. The difference between the chemical exfoliation method and the mechanical exfoliation method is that the chemical method results in a better yield compared to the mechanical exfoliation method. However, the problem with chemical exfoliation is that the product may degrade due to the change in lattice structure [81].

IV. DEVICE APPLICATIONS OF TWO DIMENSIONAL (2D) PIEZOELECTRIC SEMICONDUCTOR MATERIALS

Due to the strong electron-hole confinement, high transparency, and pliability, two-dimensional (2D) piezoelectric semiconductor materials have attracted much attention in both practical applications and fundamental research [38,82]. In this section, we will review the application of 2D piezoelectric semiconductor materials in the field of optoelectronic and electronic devices.

Wu et al [46] have built for the first time a prototype nanogenerator based on MoS2 for mechanical energy harvesting. Its optical image is shown in Fig.2 (b). From their experiment, it was observed that the nanogenerator reaches its maximum voltage and current at a point of stretching and release. It was also observed that the voltage and current increased as the tensile load of the device increasesd. Kim et al[83, 84]., developed a piezoelectric nanogenerator from two-dimensional (2D) WSe2 monolayers. In Lee's experiment, the voltage reached a peak value of 45 mV at a strain of 0.39%. This is shown in Fig. 4(a). Moreover, the piezoelectric performance was enhanced by synthesizing a single-layer WSe_2 film by the CVD method and transferring it to another film.

Rahman et al[29, 85], fabricated a strain sensor based on a single-layer piezoelectric ZnO nanowire. For this purpose, a ZnO nanowire was glued to the side of a polystyrene substrate. The experiment revealed that the I-V characteristic of the device was regulated by the applied strain, which was due to an observed change in SBH. This is shown in Fig. 4 (b). The determined gauge factor was 1250, which was 25% higher than that demonstrated by carbon nanotubes. Moreover, Wu et al[86] fabricated piezoelectric ZnO nanowires under applied voltage for the first time. In their work, the logic gates such as NAND,

NOR and OR gates were demonstrated in performing piezotronic logic operations.

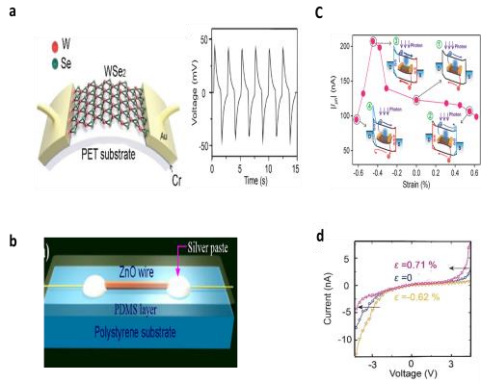

Fig 4. a. Schematics of the flexible monolayer WSe_2 piezoelectric nanogenerator and its piezoelectric voltage responses (adapted with permission from ref[83] Copyright © 2017, John Wiley and Sons). b. Schematic of a single ZnO PFW based train sensor device. C. Photocurrent as a function of the applied strain for the single-layer MoS2 flexible device and the correlated working mechanism (reproduced with permission from ref[87], Copyright © 2016, John Wiley and Sons). d. Piezoelectricity of monolayer MoS2 for the asymmetry modulation of the carrier transport in the electrical device as shown in fig.2.b (reproduced from ref [46]).

In addition, polarized charges as a result of the piezoelectric effect are used as gate voltages to regulate the charge carrier transport of the device. These types of devices are known as piezotronic devices. A two-dimensional (2D) material based on piezotronic devices was first implemented in MoS2 flakes by Wu et al, [46]. This is shown in Fig. 4(d). The rapid change of the curve can be explained by the piezoelectric effect regulating the metal-MoS_2 interface.

In the biomedical domain, 2D piezoelectric semiconductors have found many usages in implantable devices, biosensors, and tissue engineering. Their biocompatibility and ability to convert mechanical energy into electrical signals enable innovative applications such as powering implants using body motion and stimulating tissue regeneration through piezoelectric scaffolds[35]. Also, the combination of piezoelectricity and semiconducting behaviour in 2D materials has opened new pathways in optoelectronic device development. Devices such as photodetectors, light-emitting diodes (LEDs), and solar cells benefit from the direct bandgap and piezoelectric coupling effects in monolayer TMDs. Strain-engineered MoS_2 has been used to enhance the efficiency of LEDs and improve the performance of photodetectors[88, 89].

Moreover, the piezophotronic effect, which involves the use of polarized charges to modulate carrier generation, separation and recombination or diffusion at the interface, has also been applied to the development of monolayer MoS_2 photodetectors by[87, 90]. In their work, it was observed that the application of applied strain helped in regulating the charge carriers of the photo carriers. This is shown in Fig.4 (c). It was observed that the strain applied to the photodetector increased or decreased the photocurrent.

VI. CONCLUSION AND FUTURE OUTLOOK

The unique advantages of two-dimensional (2D) piezoelectric materials position them as promising candidates for high-performance optoelectronic and electronic devices. Despite this potential, their integrations into practical applications remains in its early stages. Although many 2D semiconductor materials, such as GeS, InP, and SnSe, have been theoretically were predicted to exhibit piezoelectric properties, experimental confirmation is still lacking for most of these materials. This gap is primarily attributed to the challenges in fabricating and characterizing 2D piezoelectric materials. Future research should prioritize experimental validation of the predicted piezoelectric properties in these materials. Additionally, the effects of strain and temperature on the structure and performance of 2D piezoelectric materials should be thoroughly studied, as these factors could significantly influence their efficiency and quantum yield in device applications. Enhancing the piezoelectric coefficient through innovative synthesis and preparation techniques also warrants attention. Finally, understanding and improving the environmental stability of 2D piezoelectric materials is crucial for ensuring their reliability in practical applications.

CONFLICT OF INTEREST

Authors declare that they have no conflict of interest.

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Appendix I

$$a_1 = -qd_{33}c_{44}\left(c_{33}\varepsilon_{33} + e_{33}^2\right),$$

$$b_1 = qd_{33}\begin{bmatrix} -c_{33}c_{44}\varepsilon_{11} - \left(c_{11}c_{33}\varepsilon_{33} + c_{44}^2\varepsilon_{33}\right) - c_{11}e_{33}^2 + \\ 2e_{33}\left(c_{11}e_{15} + c_{13}e_{31} + c_{44}e_{31}\right) + \left(c_{13} + c_{44}\right)^2\varepsilon_{33} - c_{33}\left(e_{15} + e_{31}\right)^2 \end{bmatrix} - qd_{11}c_{44}\left(c_{33}\varepsilon_{33} + e_{33}^2\right),$$

$$c_1 = qd_{11}\begin{bmatrix} -c_{33}c_{44}\varepsilon_{11} - c_{11}c_{33}\varepsilon_{33} - c_{11}e_{33}^2 + 2e_{33}\left(c_{13}e_{15} + c_{13}e_{31} + c_{44}e_{31}\right) \\ +c_{13}^2\varepsilon_{33} + 2c_{13}c_{44}\varepsilon_{33} - c_{33}\left(e_{15} + e_{31}\right)^2 \end{bmatrix} + qd_{33}\begin{bmatrix} -c_{11}\left(c_{44}\varepsilon_{33} + c_{33}\varepsilon_{11}\right) \\ -c_{44}^2\varepsilon_{11} - 2e_{15} \end{bmatrix}$$

$$d_1 = qd_{11}\begin{bmatrix} -c_{11}c_{44}\varepsilon_{33} - \varepsilon_{11}\left(c_{11}c_{33} + c_{44}^2\right) - c_{44}e_{15}^2 - 2c_{11}e_{15}e_{33} \\ +2\left(c_{13} + c_{44}\right)\left(e_{15}^2 + e_{31}e_{15}\right) + \left(c_{13} + c_{44}\right)^2\varepsilon_{11} - c_{44}\left(e_{15} + e_{31}\right)^2 \end{bmatrix} - qd_{33}c_{11}\left(c_{44}\varepsilon_{11} - e_{15}^2\right),$$

$$e_1 = -qd_{11}c_{11}\left(c_{44}\varepsilon_{11} + e_{15}^2\right),$$

$$a_o = q^2 n_o c_{33}c_{44}\mu_{33},$$

$$b_o = q^2 n_o\left[c_{33}\left(c_{11}\mu_{33} + c_{44}\mu_{11}\right) - \left(c_{13}^2 + 2c_{44}c_{13}\right)\mu_{33}\right],$$

$$c_0 = q^2 n_0\left[c_{11}\left(c_{44}\mu_{33} + c_{33}\mu_{11}\right) - \left(c_{13}^2 + 2c_{13}c_{44}\right)\mu_{33}\right],$$

$$d_0 = q^2 n_0 c_{11}c_{44}\mu_{11},$$