Two-Dimensional Materials in Electronics

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***Abstract*—The following is a meta-analysis which delves into the field of two-dimensional (2D) materials within the realm of electronics. Key materials under scrutiny include graphene, molybdenum disulfide (MoS_2), and hexagonal boron nitride (hBN). This document and the research herein will then be used to generate an accompanying presentation.**

***Index Terms*—meta-analysis, two-dimensional materials, electronics, graphene, hBN, MoS_2**

I. Introduction

Two-dimensional (2D) materials are a mere one or two atoms thick but have a tremendous impact on the electronics industry. One of the more interesting aspects of these materials is that most allow for the transfer of electrons within them and, thus, are conductive. This holds tremendous promise within the semiconductor industry, which has primarily been a silicon-dominated industry. Though silicon has been revolutionary for the electronics industry, this next generation of semiconductors may stray from this silicon-based norm. Traditional semiconductors experience a host of imperfections as scaling continues to increase, including leakage currents, thermal dissipation issues, and short-channel effects [1]. Unlike their bulk material semiconductor counterparts, 2D materials have exceptional electrostatic control, which is a result of their thin atomic thickness. This has allowed for the construction of ultra-scaled field effect transistors (FETs) that are much more power-efficient than a silicon FET.

Discussed in this paper are a host of promising 2D materials pertaining to a wide range of applications. Graphene has a carrier mobility of $200,000[\mathrm{cm^2\,V^{-1}\,s^{-1}}]$ [2], which is significantly higher than that of silicon. This indicates the potential within a host of devices, including ultra-fast transistors, RF devices, and ultra-sensitive sensors with the capability to outperform the current market of devices due to its high carrier mobility. Hexagonal boron nitride (hBN) is another material that holds promise, specifically in deep-ultraviolet applications, due to its bandgap falling within that range. Other materials, such as silicene and MoS_2, may have uses within the ultra-fast transistor market and optoelectronics market, respectively. Silicene's high carrier mobility makes it a suitable candidate like graphene, but it is much simpler to synthesize. MoS_2 has a bandgap of $1.8[\mathrm{eV}]$ [3], thus making it viable for optoelectronics, including photodetectors and LEDs.

Another important attribute of 2D materials is the capability to create complex heterostructures, which are simply vertical stacks of different 2D materials. This allows for a customizable component, which facilitates device architectures such as tunneling FETs [1].

This creates various ways to manipulate these materials, such that they can be stacked, bent, twisted, etc., to create different effects. This attribute may allow for customizable electronic circuits, p-n junction uses, and computer memory applications. The main drawback for these heterostructures is the difficulty in replication and fabrication. There is a tremendous margin of error within these structures, but with upcoming hope for strides in fabrication processes, it is expected to stimulate the integration of 2D materials within heterostructures for devices [4], [5].

One of the detrimental challenges of 2D materials is the difficulty of synthesis, particularly in a consistent and scalable manner. This has limited the functionality and implementations of these materials, but the future holds promise in unlocking the full capability of these materials. A perpetuating challenge is achieving large-scale, uniform growth, as current processes often result in a surplus of defects, rendering the material unusable. Chemical vapor deposition is a process that is often used, but its scalability has been limited per current literature. This is due to its ability to produce the size required for a wafer, but these wafers introduce deleterious defects, such as grain boundaries that degrade the electronic performance [1]. The lack of control of layer thickness is another challenge, as monolayer films require tuning to control a host of parameters (temperature, pressure, etc.), while multilayer or heterostructures require even more. This is primarily due to material instability, which requires perfection in regard to the fabrication environment. Though synthesis remains one of the largest challenges in 2D materials, the promise these

materials hold is encouraging. With breakthroughs in the synthesizing process, such as with hBN in monolayer and multilayer applications [4], [5], the future appears bright for these materials.

II. Graphene — Michael Brodskiy

A. Material Structure

The atomic structure of graphene consists of a single layer of carbon atoms in the formation of a two-dimensional hexagonal lattice (shown in Figure 1). This structure makes graphene one of the most promising materials within the realm of electronics, as it allows for exceptional electrical, mechanical, and thermal properties [6]. These properties contribute to graphene's high carrier mobility and physical strength, which has led to its integration into transistors, and, subsequently, touch screen and energy storage devices [7]. The structure can be more thoroughly analyzed by breaking down the scope into three categories:

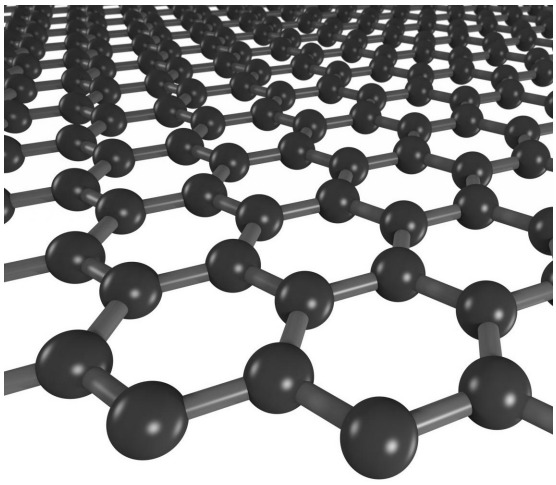

Fig. 1. Structure of Graphene

1) Atomic Arrangement — Each carbon atom in graphene is bonded to three other carbon atoms at 120° angles, forming a planar structure. This arrangement allows for a particularly stable formation while ensuring that the fourth valence electron of each carbon atom remains de-localized. The presence of these π-electrons leads to high electrical conductivity.
2) Band Structure — The band structure of graphene is characterized by a zero bandgap semi-metal property, effectively making it a unique material for electronic applications. The conduction and valence bands meet at the Dirac points, where electrons behave like massless Dirac fermions, enabling high mobility and speed in electronic devices.
3) Flexibility and Strength — Graphene is known for its extraordinary mechanical properties. It is approximately 100 times stronger than steel while being incredibly light and flexible. This resilience allows it to be integrated into various electronic materials without significantly affecting their other properties.

B. Electromagnetic Properties

The structure of graphene permits remarkable electrical conductivity (several orders of magnitude higher than silicon), with a carrier mobility of $200,000\left[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}\right]$ at room temperature [2]. The electrons within the graphene exhibit Dirac fermion behavior, which is the primary reason for such mobility [8]. Furthermore, graphene responds well to terahertz radiation — a crucial feature, especially considering the development of contemporary wireless technologies, including communications and imaging. This allows for tunable absorption across terahertz and infrared spectrum, which indicate graphene may be a suitable candidate for photonics and optoelectronic devices. Graphene is also highly useful for electromagnetic shielding, as its conductive properties inhibit electromagnetic interference (EMI) and radio frequency interference (RFI) [9].

C. Mechanical Properties

Due to the hexagonal lattice, graphene is ideal for electrical applications which require robust physical properties. The tensile strength of the material is approximately $130[\mathrm{GPa}]$ [10]; furthermore, graphene's flexibility makes it suitable for cases in which the device may experience stretching or warping [11].

D. Thermal Properties

In addition to its electrical conductivity and physical strength, graphene holds a high thermal conductivity. At room temperature, graphene commands a thermal conductivity of approximately $5,300[\mathrm{W\,mK}^{-1}]$. As such, it may be used for thermal management [12].

E. The Future of Graphene and Electrical Devices

Though the material itself is highly suitable for use within electronic devices, there are several challenges beyond aptitude which make the incorporation of graphene difficult. First and foremost is the difficulty of large-scale production. This, coupled with the difficulty of controlling the electrical properties and development of effect contact materials, make graphenes applicability within electronic materials uncertain [13]. The properties of graphene, however, have already proven quite promising for applications such as:

1) Transistors — The potential to create faster, more efficient transistors as a result of its high carrier mobility makes graphene a promising candidate in for replacing silicon transistors
2) Sensors — Graphene's large surface area and high conductivity allow for sensitive detection of various chemical substances, making it suitable for use in biosensors and environmental monitoring
3) Electrical Displays — Graphene's ability to conduct electricity while remaining transparent makes graphene an attractive alternative to materials like indium tin oxide (ITO), especially in electronic displays

III. Hexagonal Boron Nitride (hBN) — Jack Bergin

A. Structural Overview

Hexagonal Boron Nitride (referred to as hBN) is a covalently-bonded hexagonal structure that draws great similarity to graphite. hBN is typically found to be multi-layered, which can be imagined as a sheet. These layers are held together by rather weak van der Waals forces [14], creating peculiar properties when comparing single and multi-layered hBN sheets. Due to this structure, hBN exemplifies high chemical stability and high optical transparency. Though the physical structure of hBN is similar to that of graphite, unlike graphite, hBN is an insulator due to a lack of delocalized electrons and is free of dangling bonds. This marks hBN as one of the only insulating 2D materials. The surface of hBN is atomically smooth and lacking charge-trapping sites, thus making hBN a viable substrate for forming van der Waals heterostructures with graphene and other 2D materials [15]. Unlike typical substrates with insulating layers (SiO_2, for example), hBN substrates allow for the full electronic and optical properties of 2D materials to be exploited [14]. One of the most interesting material properties of hBN is its bandgap — a topic that continues to be debated. The first theoretical calculations allude to hBN having an indirect bandgap structure, but experimental results found utilizing optical microscopy suggest hBN having a direct bandgap, consequently allowing for the various optical qualities of the material. High purity crystals were observed to have an intense luminescence peak at $5.76[\text{eV}]$ [14], which initially was attributed to a direct bandgap. To resolve this, two-photon excitation was implemented, a fluorescence process that can reduce phototoxicity and allow for deeper tissue imaging. This technique requires a fluorophore (a molecule that fluoresces) to be excited by a simultaneous absorption of two photons, as opposed to one. With this implementation, it was discovered that multilayer hBN has an indirect bandgap at $5.955[\text{eV}]$ [15]. The curious aspect of hBN's bandgap structure is its dependence on the number of layers. Monolayer hBN has a direct bandgap, but with the addition of one or more layers, it exhibits an indirect bandgap [14]. Because of this structure, this allows for hBN having the capability to be applied to devices within the deep-ultraviolet (DUV) wavelength region, as well as monolayer hBN showing promise for applications within the UV region [14].

B. Synthesizing hBN

The synthesis of hBN is an ongoing challenge, in which its solution could provide a gateway for the commercialization of a variety of hBN sensors. Currently, one common method of synthesis is through chemical vapor deposition (CVD), a process in which a solid material is deposited on a substrate through chemical reactions involving a gaseous phase. This has been found to be the most consistent way to synthesize hBN, but large-scale production of hBN has not been achieved.

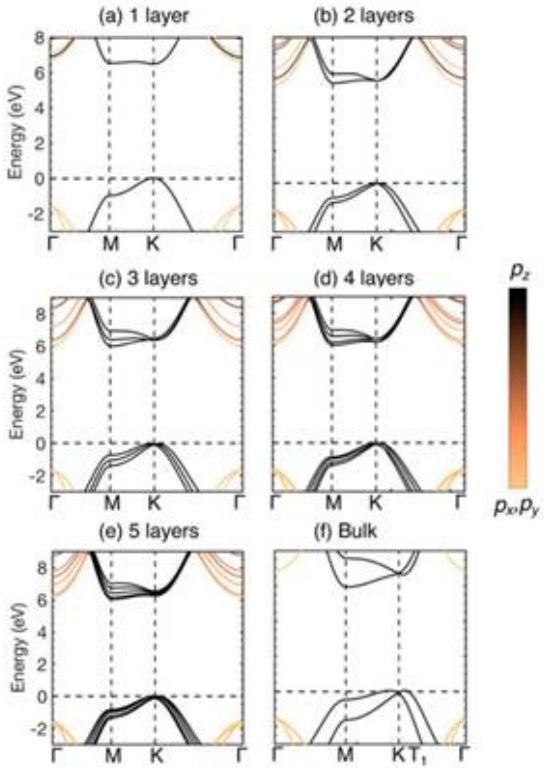

Fig. 2. The variations in the bandgaps of hBN for each layer count [14]

1) Monolayer Synthesis: Per Li et. Al, single-crystal hBN monolayers have been created, which is revolutionary for the future applications of hBN. To accomplish this synthesis, it is important to note the structure of the lattice of hBN. The structure of hBN suggests that a triangular lattice pattern is stronger than that of a hexagonal lattice, making for a more stable configuration on the metal substrates (Cu111 in this case) during synthesis [15]. Typical CVD synthesis of hBN involves the introduction of ammonia borane thermally decomposing and being introduced into a heated chamber ($\approx 1000[^\circ\text{C}]$) with argon carrier gas [15]. This then forms an hBN film of primarily triangular structures onto the Cu substrate. Interestingly, when a small amount of oxygen was diluted into the argon carrier gas, the hBN structures took the form of a hexagonal lattice [4]. This is critical as these hexagonal structures can form a quality hBN monolayer, whereas the triangular lattices typically seen cannot. This is important to future applications of hBN due to the capability of these monolayer sheets to create reliable wafers (similar to a Si wafer) of hBN van der Waals heterostructures, whose implementations will be seen in high-reliability electronic devices [14].

2) Multilayer Synthesis: As discussed in the previous section, monolayer hBN is able to be synthesized utilizing CVD onto a transition metal thin film, but creating multilayer hBN has proven challenging. The rationale for the desire of multilayer over monolayer comes from the effects that multilayer

hBN can produce, including improving optical properties of transition metal dichalcogenides, as well as for various DUV devices. Additionally, multilayer hBN films can reduce the influences of SiO_2 surfaces due to their thickness, while monolayers can not [4]. This is a crucial fact when considering the field-effect transistors being developed utilizing multilayer hBN alongside graphene and SiO_2 (substrate), such that the hBN screens the impurities of the SiO_2 (dangling bonds, charge impurities) to improve the intrinsic carrier mobility [15].

To synthesize multilayer hBN, Fukamachi et. al, reports successful growth on Fe-Ni alloy foils utilizing CVD. These multilayer stacks were then used to create heterostacks with graphene to create functional FETs, outperforming the SiO_2-based ones. The process to accomplish this proves to be scalable, thus creating a gateway for the mass production of more efficient FET devices. The FETs created through this process had very high carrier mobilities (a maximum hole mobility of $10,219[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$, with an average of $5,477[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$) and electron mobility of $9,571[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$ (with an average of $5,551[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$) [4]. This provides much hope for the future of 2D electronic devices, such that this observed high carrier mobility could reform the semiconductor industry in regard to 2D material implementation.

C. Applications

1) DUV LEDs: These LEDs are used in a plethora of applications, including sterilization, water purification, photocatalysis, and curing processes [15]. The current norm of these applications utilizes AlGaN semiconductors, but the issue is that these semiconductors emit light perpendicular to the surface of the plane. This makes for a weaker beam than if the light was emitted parallel to the plane, which is the case for an hBN DUV LED. This allows for a stronger beam, which in a process such as sterilization is crucial as it will be much more effective in neutralizing unwanted agents [14].

2) DUV PDs: Deep ultraviolet photodetectors, like DUV LEDs, are currently made with primarily AlGaN or GaN-based semiconductors, SiC semiconductors, amongst other similar 2D materials [14]. The purpose of these photodetectors applies to a range of applications including flare detection systems, air purification devices, and advanced communication technologies. hBN has been developed into multiple different DUV-PDs, which have been obtained due to its bandgap lying within the DUV region. It has been found that the addition of another material (such as copper whilst creating a Schottky junction), as well as the addition of graphene for heterostructures, allows for a much more responsive PD than that of a single-hBN-based PD [14].

3) Perfect IR Absorbers/Emitters: hBN holds much promise in the realm of photonic devices operating in the infrared (IR) region [15], for specific applications such as radiative cooling, IR sensors, and biosensing. hBN is a viable suitor for such devices due to its inherent hyperbolic properties, enabling strong light confinement and efficient emission/absorption. By adjusting layer count and thickness, the thermal radiation and absorption properties can be tuned, such as creating a device with exact specifications for a variety of applications [14]. The driving factor in utilizing hBN for these devices is its efficiency, as the current IR devices, although efficient, lack the tremendous efficiency seen by hBN within these applications. There is still much to be done in the form of research, but the future of IR appears to definitively have hBN involved.

IV. Silicene — Owen Chiu

A. Material Structure

Similar to graphene, silicene has a two-dimensional hexagonal structure, except with silicon atoms instead of carbon. Unlike graphene, silicene adopts a periodically buckled topology, where the atoms alternate being in the upper or lower positions (while still being a nominally 1 atom thick layer). This buckling behaviour is caused by differences in the sp hybridization of C and Si. For carbon, sp^2 is energetically favorable, while sp^3 hybridization is more favorable for silicon [5]. Many of the material structure properties, synthesis methods, and applications for silicene also apply to other Xenes (including stanene, germanene, and phosphorene) [16].

B. Synthesis

The majority of current manufacturing techniques revolve around thermally depositing a layer of Si atoms onto a Ag(111) substrate, which has appropriate surface characteristics to enable the self-organization of the Si atoms into silicene. A similar effect has also been observed with Ag(110) substrates, which can cause the self-organization of Si nanoribbons [3], [5]. There are a variety of further options for processing the grown silicene into useful forms, however most involve cleaving off a silicene layer and transferring it to a different substrate for further integration. This represents a substantial difference compared to how traditional bulk silicon semiconductors are manufactured.

Similar to bulk silicon, silicene easily oxidizes when exposed to normal atmospheric conditions, which can ruin its desired properties. Bulk silicon is normally put through a thermal oxidation process as part of the semiconductor manufacturing process, however this approach does not always work for 2D materials. Proposed solutions to this problem include complete encapsulation (likely with polymers or metal oxides) and passivation. Depending on the elements introduced in the passivation process, a variety of new behaviours could be introduced to the silicene [16].

C. Properties

One of the most notable properties of silicene is it's bandgap. Unlike pure graphene, with does not have a bandgap, silicene presents a bandgap of around $0.2[\mathrm{eV}]$ [16]. This is substantially smaller than pure silicon, which has a bandgap of $1.12[\mathrm{eV}]$. This bandgap can be modified with physical, chemical, or electromagnetic means.

In terms of physical modification, it has been demonstrated that geometry changes, such as the use of nanoribbons, impact the band structure of the Si [3]. The buckled nature of the silicene matrix leaves it more susceptible to bond changes from mechanical stress, which in turn results in changes in electrical properties [16]. For chemical modification of the bandgap, there will always be some substrate the Si is attached to that will have some impact on the bandgap. Other dopants could also be introduced to further increase the bandgap opening [5].

D. Applications

Silicene presents a variety of opportunities for novel device development and the improvement of current devices. Most prominent is the possibility of further miniaturization of transistors, as the 2D nature of silicene provides an inherent size reduction compared to 3D materials.

Similar to graphene, silicene's flexibility has the potential to unlock new possibilities in flexible computing devices. This application is supported by the requirement to grow the silicene on a dedicated substrate, so the process of bonding to a flexible substrate does not necessarily add additional manufacturing steps compared to bonding to traditional rigid substrates [16].

The inherently smaller size of silicene compared to bulk silicon can provide immediate benefits in the miniaturization of transistors, while the stacking of silicene layers provides opportunities for the stacking of multiple transistors, and the development of new types of transistors [5], [16].

Although the relatively high reactiveness of the raw silicene surface presents challenges during the manufacturing process, it also provides opportunities for the creation of new sensing devices [16].

V. Molybdenum Disulfite (MoS_2) — Oluwalaanu Adeboye

A. What is MoS_2?

Molybdenum disulfide (MoS_2) is an example of a transition metal dichalcogenide (TMDC). MoS_2 consists of Molybdenum (Mo), which is a transition metal from Group VI, and Sulfur (S), a chalcogen. As a TMDC, it has a layered structure where S atoms sandwich Mo atoms, and these layers are bounded by van Der Waal forces, which makes it easy for them to be separated into single layers, also known as monolayers [17].

B. Properties of MoS_2

In its single or monolayer form, MoS_2 behaves like a semiconductor with a direct bandage, making it ideal for use in photodetectors and transistors. It exhibits several exceptional properties in its monolayer form: It has strong light-matter interaction, making it ideal for use in devices like photodetectors, light-emitting devices, and solar cells, and it has large electron-hole pair binding energy, meaning it is more stable and less likely to dissociate, making it ideal for LEDs [18].

As MoS_2 gets thinner in its monolayer form, its carrier mobility improves because the electrons and holes can move more freely. Conversely, MoS_2's carrier mobility decreases as it thickens because more layers results in more scattering and interaction between layers, reducing overall mobility. The theoretical mobility of MoS_2 is said to be $354c[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$ in the monolayer form, but experimental mobilities are lower due to factors like contact resistance, substrate effects, and the quality of the provided MoS_2 [19]. In its bulk form, meaning several layers are in use, MoS_2 behaves more similarly like an indirect bandage semiconductor. In short, given the number of layers, so whether MoS_2 is in its bulk layer or monolayer form, that determines its usage since its different forms provide different electronic behavior.

C. Phase Transitions in MoS_2

A phase transition is a change in the state or phase of a material where the physical properties change depending on conditions like temperature and pressure. If a material undergoes a phase transition it can shift from being a semiconductor like material to a metal because of changes in its atomic or molecular arrangement.

For materials like MoS_2, phase transitions involve changes in its crystal structure. The two common crystal phases for MoS_2 are the 2H phase, where MoS_2 has a hexagonal crystal structure and has semiconducting behavior, and the 1T phase, which is a tetragonal structure. When MoS_2 is in the 1T phase, it exhibits metallic behavior, so it conducts electricity more freely than in the semiconducting 2H phase [20]. Both chemical treatment and laser irradiation, which involves shining a laser on the material, can initiate a phase change.

This is important because material properties like electrical conductivity, mechanical strength, and optical properties are largely dependent on the phase a material is in, so phase transitions allow MoS_2 to be used in a diverse range of electronics and in different ways. Notably, when MoS_2 undergoes a phase transition from the 2H phase top the 1T phase, it can be used in logic circuits, memory storage, or photodetectors [20].

D. Challenges Associated with MoS_2 Use

The intrinsic mobility of MoS_2 are limited by scattering effects from phonons, which are vibrations from the lattice that composes the material, and charge impurities from the base material or adsorbates, which are atoms or ions that attach to the surface of the material because of van der Waals forces, chemical bonds, or electrostatic forces. Figure 3 shows how temperature-dependent mobility can be influenced by factors like phonon scattering where decreases in mobility take place at higher temperatures when phonon scattering is present [21].

The carrier mobility in MoS_2 is influenced by both the base material as well as dielectric films, which are thin layers of material that are non-conductive, and the density of impurities in the material. In other words, the presence of non-conductive materials largely affects MoS_2's carrier mobility [22].

E. Optimizing MoS_2 Usage

The intrinsic mobility of MoS_2 could be achieved by using hexagonal boron nitride (hBN) as an encapsulation

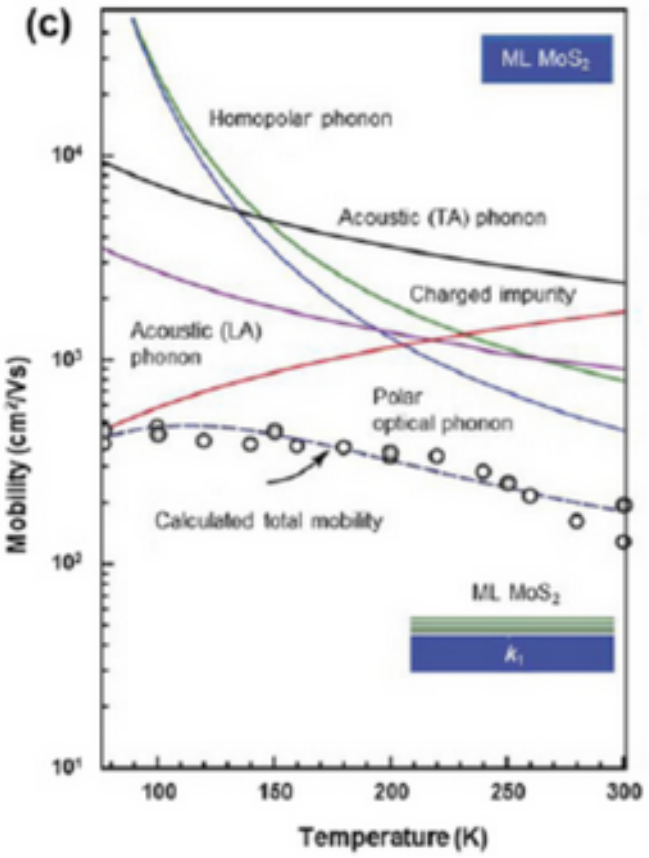

Fig. 3. Temperature versus Mobility for various MoS_2 characteristics [21]

layer, which is a protective layer that surrounds a material to enhance its stability or to prevent it from degrading or from environmental factors. The intrinsic mobility could also be achieved by using graphene as the contact electrode, meaning it would be used as the conductive material that provides a pathway for electric current to enter or exit the 2D material. In events where these optimization techniques have been employed, MoS_2 FETs have seen extremely high mobilities of $34,000[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$ at $5[\mathrm{K}]$ [23].

F. MoS_2 in Flexible and Optoelectronic Devices

An MoS2-based FET device was created on a polymer substrate consisting of hexagonal boron nitride (hBN), MoS_2, and graphene, which achieved a high electron mobility for trilateral MoS_2 FETs of $\approx 45[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$ while working with a low operating gate voltage of $10[\mathrm{V}]$ [24]. Notably, the devices capabilities are unaffected by physical strains up to 1.5%, demonstrating the flexibility and mechanical strength that MoS_2 provides in flexible electronics [24].

MoS_2 has been used as a photo absorbing layer in a phototransistor array. Uniquely, it generates photocurrent under visible light since it has a wide bandgap, which excludes infrared light, so it can be used for optical applications without the need for an infrared filter, unlike conventional silicon-based photodetectors [25].

When MoS_2 contains an odd number of layers, it exhibits piezoelectric properties. This is because the inversion symmetry of its 2H crystal structure in odd layers, which is when every atom or atom group at a certain position is paired with an identical atom or group at the opposition, as if reflected through a central point, is broken or asymmetric when inverted through the central point. As a result, the piezoelectric output decreases as the number of MoS_2 layers increases [26].

G. MoS_2 in 2D Tunnel Devices

Tunnel devices are alternatives to MOSFETs. They rely on quantum tunneling for the charge process, which allows for low leakage current and a high 'ON/OFF' ratio, or the ratio of the current when the device is on to when it is off. These attributes are important for achieving low-power, high efficiency electronics. Subthreshold swing is a parameter that represents the rate at which current turns on as the gate voltage is increased. MoS_2 has been involved in devices that surpass the theoretical minimum subthreshold swing limit for classical thermionic transport. An MoS_2 bilayer in a vertical heterostructure with degenerately degenerately doped p-type germanium (Ge) forms a tunnel FET, which allows quantum tunneling between the valence band of Ge and the conduction band of MoS_2, resulting in a subthreshold swing as low as $3.9\mathrm{mV/dec}$] [27]. Tunneling devices use bilayer MoS_2 as the channel, which allows for quantum tunneling to occur with a low subthreshold swing.

VI. 2D Materials in Electronics — Daniela Salazar

A. Semiconductor Integration

- Chemical Vapor Deposition (CVD)
  - Process were gas is in a reaction chamber, the gases then react and decompose in a heard surface which form a thin solid film
  - It is an essential for 2D material to synthesize thin layers and some of these steps include precursors, substrate preparation, and growth conditions
  - CVD is crucial in semiconductor manufacturing
    - Low Pressure CVD — this is used for highly uniformed films over large wafers
    - Metal Organic CVD
      - This is common in the growth of III-V semiconductors used for electronic devices
  - The importance of using CVD for 2D Materials and Semiconductors
    - Control of the thickness precisely
    - It can be scaled for large-area growth
    - Less defect with higher crystal quality
    - It is suitable for complex materials
  - Adhesive Wafer Bonding

        - This is a proces that is used to bond two wafers with an adhesive layer and it is valuable to integrate delicate materials
        - Adhesive wafer bonding functions:
            - Begins by preparing the surface & ensuring there isn't contamination
            - Then a polymer based adhesive is interested onto the wafers & then they are aligned and put in contact
            - The adhesive is then cured
        - Importance in Semiconductors
            - Integrating materials onto silicon for photonic devices
            - Enable 3D integration in advanced chip designs
            - It also facilitates temperature sensitive materials bonding without the need for excessive heat exposure
- Van der Waals Forces
    - A lot of 2D materials (graphene, MoS2 & h-BN) are composed of small layer that are held by these forces
    - The interactions are necessary for the structure
    - Importance in 2D Materials
        - Layered structure stability
        - Van der Waals Heterostructures
        - Clean interfaces
- Transfer Techniques

B. Applications

- Enhance electronic devices
    - Ultra thin channels for transistors
    - Improves mobility & conductivity
    - Flexible and transparent electronics
- Back end of line integration
    - Low-temperature processing
    - Atomic thinness for narrow spaces
    - Reduce capacitance
- Quantum computing
    - Topological insulators
    - Atomically shaped interfaces
    - Bandgaps that are tunable
- Buffer layer technique
    - Stress reduction
    - Interface quality is enhanced

VII. Flexible Electronics with 2D Materials — Thomas Czartoryski

Flexible electronics refer to devices and circuits that are printed on stretchable and bendable substrates. This in turn allows for the integration of electronic components in applications where rigid devices and circuits are impractical such as biomedical sensors and wearable devices. The multifunctional properties of 2D materials make them promising candidates for flexible electronics in applications ranging from sensing to wireless communication. These properties range from good carrier mobility, flexibility, electrostatic control, extremely high optical constants, and the ability to scale down to one atomic layer [28]. The materials that will be examined in this section for their usage in flexible electronics include graphene, black phosphorus (BP), and transition metal dichalcogenides (TMDs).

A. Black Phosphorus

Black Phosphorus (BP), is a popular 2D material used in flexible electronics. BP is an allotrope of phosphorus, and is phosphorus's most stable form, composed of layers held together by van der Waals forces. At a single layer it is called phosphorene and has a puckered honeycomb structure which results in direction-dependent electrical, optical, and mechanical properties [29], [30]. In addition, due to its puckered honeycomb structure, a monolayer of BP can sustain tensile strain up to 30% and has a bandgap that is tunable in a range of $0.3[\mathrm{eV}]$ in bulk and up to $2.0[\mathrm{eV}]$ in a monolayer [30]. One drawback of BP is that it oxides quickly which means that, unless it is encapsulated, it does not have long term stability. Part of the appeal of BP is its high speed and low energy consumption when compared to other 2D materials such as graphene and TMDs [29]. The zero bandgap of graphene results in low-field effect modulation and a high 'OFF' state current which makes digital or complementary metal-oxide-semiconductor (CMOS) logic implementations virtually impossible. TMDs, despite their large band gap and large 'ON/OFF' current ratio, have a room temperature carrier mobility range of $10 - 100[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$, which is less than ideal for high-frequency applications [31]. BP has a high room temperature carrier mobility ($\approx 1000[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$). Wang et al. [31] developed a top-gated transistor using BP which was found to have a cutoff frequency of up to $20[\mathrm{GHz}]$, and a saturation velocity of $6 \cdot 10^6[\mathrm{cm\,s}^{-1}]$. Additionally, the device, when tested under 1.5% stretch, still performed well which makes it ideal for flexible electronics, and particularly for flexible radio frequency (RF) devices such as wearable sensors or communication devices.

B. Graphene

Graphene is used in flexible electronics due to its mechanical and electrical properties. Graphene has fracture strains of 25%, good optical transmittance, high carrier mobility ($10,000[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$ at room temperature), and good piezoresistive sensitivity [28]. Graphene has been used in a variety of flexible electronic applications including logic devices, energy-harvesting devices, sensors for e-skin applications, and biomedical devices. E-skin are electronic systems able to mimic the properties of human skin, such as flexibility, stretchability, biocompatibility, and able to detect changes in pressure, temperature, and humidity. The application of graphene in E-Skin is particularly groundbreaking because it incorporates all the use cases of graphene including, but not limited to, pressure and temperature sensors, nanogenerators, and flexible transistors [28]. Graphene is used to develop tactile/pressure sensors due to its resistance to oxidation, high

electrical conductivity ($106[\mathrm{m}^{-1}]$), and its ability to be both thin and flexible. Zhu et. al [32] developed a tactile sensor with Graphene that was able to achieve response times of $0.2[\mathrm{ms}]$ and sensitivity to touch of up to $-5.53[\mathrm{kPa}^{-1}]$. Graphene has been used in the development of liquid crystal displays (LCDs), organic light-emitted diodes (OLEDs), and touch-screens due to its optical, electrical, and mechanical properties. Graphene is highly transparent with 97.7% of light transmission in a monolayer. Anagnostopoulos et al. [33] investigated the mechanical behavior of a graphene-based flexible touch display. Two layers of graphene were embedded within a polyethylene terephthalate film via chemical vapor deposition. This screen, when bent or stretched, started to deform into separated patches or 'islands', although this lowered electrical conductivity. The screen did not shatter like a traditional glass screen, and was able to withstand damage to the screen with up to 3% uniaxial tension, which is an improvement on tempered glass screens which can only withstand 0.2-0.3% uniaxial tensile strain before cracking [33]. Graphene has also been used to develop flexible graphene field-effect transistors (GFETs). By depositiving graphene onto flexible substrates via chemical vapor deposition, GFETs can be created that have favorable mechanical and electrical properties. GFETs have been shown to withstand strain of up to 1.75%, compared to traditional silicon field-effect transistors (FETs) which are brittle and can withstand less than a 0.1% strain. GFETs have an extremely fast carrier transport, theoretically up to $200,000[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$, which make them ideal for communication devices (RF). A weakness of GFET is that it has no bandgap and a low 'ON/OFF' ratio which makes them unsuitable for digital or CMOS logic [34].

C. Transition Metal Dichalcogenides (TMDs)

Another series of popular 2D materials used in flexible electronics are transition metal dichalcogenides (TMDs). TMDs are composed of a few atom polyhedral layers with transition metal atoms sandwiched between layers of chalcogen atoms. TMDs have been used in flexible FETs, flexible photodetectors, flexible sensors, and flexible memory devices [28]. TMDs are particularly useful in high-performance flexible nanoscale FETs. The most common TMDs in the development of FETs are molybdenum disulfide (MoS_2) and tungsten diselenide (WSe_2). Unlike graphene, which lacks a band gap and has low resistivity, which makes digital logic impossible, TMDs have band gaps similar to Silicon ($2[\mathrm{eV}]$), and have led to mobilities of up to $470[\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}]$ [35]. Daus et. al [35] utilized a new transfer process that resulted in the highest on-currents to date in $50[\mathrm{nm}]$ channels. High performance MoS_2 transistors were developed on flexible substrates that enabled channels of $50[\mathrm{nm}]$, which are the shortest to date in 2D material flexible electronics. Additionally, TMD FETs were able to withstand up to a 2% strain which makes them a perfect candidate for flexible electronics [35]. TMD nanosheets such as MoS_2 and $MoSe_2$ embedded in polymer matrices make for effective photodetectors due to their ability to absorb light across a wide spectrum. As a result, TMD can be particularly useful for foldable cameras and flexible optical sensors in applications such as robotics and wearables. Velusamy et. al [36] developed photodetectors by encapsulating TMD nanosheets in polymer matrices to prevent degradation. The $MoSe_2$ composite photodetectors achieved 'ON/OFF' photo current ratios of 105, which did not change even when bent at $200[\mathrm{m}]$. In addition to this, by blending MoS_2, which detects visible light, and $MoSe_2$, which detects near-infrared light, the device could selectively detect and cover both visible and near-infrared wavelengths. The photodetector was still able to maintain consistent performance even when under mechanical strain, which highlights its ability to be used in flexible electronics. The TMD composite photodetectors were subjected to 1,000 bending cycles at a radius of $1[\mathrm{mm}]$ and still worked without any deterioration in their performance [36].

VIII. Conclusion & Future Outlooks

As the field of 2D materials develops, it represents a transformative future for modern electronics by offering solutions to all the limitations faced by traditional technologies. Throughout this report various 2D materials, aimed at helping the future of electronics, have been explored. The materials — graphene, hexagonal boron nitride (hBN), silicene, molybdenum disulfide (MoS_2), and black phosphorus — all demonstrate unique properties which improve the performance of transistors, optoelectronics, sensors, and flexible devices.

Graphene's electrical conductivity and mechanical strength facilitate the development of high speed and flexible electronics. Though lacking a bandgap limits its applications, it allows for graphene to be used for sensing applications and much more. Graphene's ability to form clean interfaces allows it to be ideal for heterostructures especially when being paired with hBN. As such, graphene will continue to be a very useful material.

Molybdenum disulfide (MoS_2) will continue to be the most promising semiconducting 2D material. Its ability to have a direct bandgap with the monolayer form allows it to be useful for FETs and photodetectors. MoS_2 has also been shown to enable tunneling transistors and devices that at low power levels. As this material keeps being used, it will continue to demonstrate ways of being applied in semiconductors.

As development continues with silicene it will continue to offer the potential for seamless integration with CMOS technology. Silicene's compatibility with silicon will allow for it to continue being used in technologies that already exist. It holds promise in certain electronics like ultra scaled transistor or topological electronic devices despite its challenges.

The future for hexagonal boron nitride is extensive, and there will undoubtedly be much to see with this material in the coming years. Once multilayer synthesis of hBN is commercialized, there will be great strides within the sanitation and medical industries, due to the advantages a multilayer hBN DUV LED has over the current ones, such as a stronger and more direct illumination. Furthermore, a multilayer hBN and graphene FET have already been created; thus, we can expect to see the commercialization of this device, which has

been shown to improve the efficiency of the FET. Additionally, hBN is highly relevant in the RF realm in particular, as it has allowed for the development of an effective RF capacitor. Due to its tremendously low-loss dielectric properties at high frequencies, hBN is a viable option for future implementations within the RF realm. A summary of developing electronic material properties is summarized in Figure 4.

2D materials	Band gap (eV)	Conductivity	Ref.
Graphene	0	Semi-metal	50
BN	5.9	Insulator	90 and 91
2H-MoS_2	1.89	Semiconductor	92 and 93
2H-WS_2	1.98	Semiconductor	138 and 139
2H-$MoSe_2$	1.44	Semiconductor	140
1T-TiS_2	—	Metal	39
VS_2	—	Metal	83
V_2O_5	1.94	Semiconductor	89
Silicene	0	Semiconductor	94
Ti_3C_2	—	Metal	198

Fig. 4. Summary of 2D Electronic Material Bandgaps

The future of 2D materials being integrated into semiconductors is bright but presents many challenges. There will continue to be challenges, including working with large areas, synthesis without defects, and stabilizing air-sensitive materials. These challenges will continue to be studied and solved to work towards more efficient and adaptive electronic systems. Overall, the study of 2D materials will allow for a better future of electronics and help unlock the power 2D materials hold.

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Annotated Bibliography

A. Michael Brodskiy

1) Source [8]: This source provides in-depth insight into the properties and applications of graphene. This comprehensive paper discusses the fundamental aspects of graphene's electronic properties, including its unique band structure, and explores potential applications in electronic devices and materials science. The authors provide a detailed examination of experimental techniques for graphene synthesis and characterization, as well as future directions for research in graphene-based materials. This source serves as a foundational reference that helps to contextualize the transformative potential of graphene in modern electronics, and can possibly be dubbed one of the "father sources" of graphene's electrical applicability. By highlighting both theoretical and experimental perspectives, the authors create a comprehensive guide for researchers and industry professionals alike interested in graphene and its applications in electronic materials.

2) Source [9]: This source discusses the graphene's emerging applicabiity due to its versatile functions and potential applications across various fields, including energy, medicine, and the defense industry. Notably, graphene's role in electromagnetic wave absorption and shielding has been a focal area of research. The review explores the structures and electromagnetic properties of graphene hybrids while discussing relaxation, charge transport, magnetic resonance, and eddy currents (an important topic when considering losses). It emphasizes the importance of magnetic-dielectric synergistic effects and centers on various graphene-based systems. The review focuses specifically on flexible graphene, graphene hybrids, and three-dimensional graphene architectures (however only 2D graphene was of interest for our purposes). As an individual who has personally worked on electromagnetic shielding and interference testing within the defense industry, this source was especially of interest to me.

B. John Bergin

1) Source [14]: This paper provides significant insights into my research of hBN. The paper began with a general overview on the structure of hBN, allowing for an introduction to the material that was quite useful in the beginning of researching the material. It was particularly informative regarding the bandgap structure, showing how this bandgap holds promise in the IR and DUV ranges. Additionally, their explanation of the effects of van der Waals bonds within multilayer hBN permitted for further understanding of how heterostructures of hBN allow for increased stability and a higher bandgap. The paper continues to discuss the applications of hBN, which are primarily preliminary, as the synthesis of hBN on a large scale has still yet to be fully achieved. The section regarding its deep-ultraviolet applications was important to note, as it discussed in a very promising tone the strides made in this field. The LEDs and PDs discussed seem to hold much promise for the sanitation and detection fields, which aligns with my interests for my future career.

Regarding personal insights, the section on bandgap structure and how the number of layers of hBN can significantly affect the bandgap structure proved fascinating. This allowed for the conceptualization of how heterostructures of hBN, as well as other 2D materials, can significantly alter structure and properties based on how and how much they are layered. This allowed for obtaining a better understanding of the structure of hBN, as well as its potential applications, crucial for this project.

2) Source [15]: This paper focused primarily on the monolayer synthesis of hBN, particularly how they achieved a large-scale wafer with the usage of hexagonal hBN instead of triangular. This allowed for increased stability and mitigated many of the defects seen with the triangular islands. It is even more impressive to note that this was achieved from a singular hBN crystal, something that had not been accomplished up until this point. The paper dove deeply into how this was accomplished, which was summarized through this report due to a lack of necessity for this specificity. In short, they altered the substrate and added oxygen to argon gas such that the hBN would not stack when CVD was used. This allowed for the formation of the aforementioned hexagonal islands due to the tendency for the argon with oxygen to pull the hBN into this pattern.

This paper discussed the semiconductor industry extensively, as hBN seems to have the capability to disrupt silicon's dominance due to its potential in a host of devices and sensors. Though it was not used as frequently as my other source within this annotated bibliography ([14]), it required a great deal of time to fully understand how hBN is synthesized in a monolayer fashion. Thus, this paper served a great deal of purpose regarding furthering understanding of hBN synthesis.

C. Owen Chiu

1) Source [5]: This paper provides a broad overview of silicene, covering its discovery and journey to eventual manufacturing. There is a strong focus on the dynamics of atomic bonding during the process of growing silicene on different substrates. After covering the growing of silicene layers the authors discuss different approaches to moving it from the Ag growth substrate to other materials where it can be incorporated into devices. They also discuss the treatment of silicene to prevent environmental degradation, with the main threat being oxidation from atmospheric oxygen. Where applicable, this paper generalizes silicene's properties to other Xenes and demonstrates some key differences between them.

Although a bit on the old side, this paper helped me with my foundational knowledge of silicene and helped me relate what I already knew about graphene to it.

2) Source [16]: This paper provides an overview of silicene and the supporting processes that have been theorized to manufacture functional silicene devices. The authors also propose how their manufacturing processes could be modified to enable the growth of Group 13, 14, 15, and 16 Xenes, with

some elements working with the standard Ag(111) substrate, and some requiring more exotic substrates. The electrical properties of experimentally constructed silicene transistors were explored, with a focus on the electrical and mechanical benefits of multi-layer silicene devices. The use of topological modifications of silicene in a transistor, including the use of nanoribbons, was also theoretically explored. The electrical properties of silicene were also related to other Xenes where possible.

This paper really helped me understand the challenges involved with finding suitable substrates to grow 2d materials. It also introduced me to some ways that topological changes can be utilized to create practical devices from silicene.

D. Oluwalaanu Adeboye

1) Source [20]: This paper investigates the structural transformation between the semiconducting (2H) and metallic (1T) phases of single layer MoS_2 using situ scanning transmission electron microscopy. Regarding the component focused on MoS_2, this paper was useful for learning about how different crystal structures of 2D materials, specifically MoS_2, affect their properties and therefore their usability in electronics. Notably, the study mentioned in this paper demonstrated that areas of the 1T phase can be controllably induced within the 2D phase matrix using an electron beam, suggesting a method for controlling the electronic properties of MoS_2 at the nanoscale.

2) Source [24]: This paper presents the development of flexible and transparent FETs constructed on heterostructures of hBN and graphene using MoS_2 as the semiconducting channel, which were aimed at enhancing device performance and flexibility. Because of the 2D qualities and band gap of MoS_2, it provides advantages over traditional silicon-based materials. Notably, the paper touched on how the MoS_2-based FETs demonstrated high electron mobility and excellent current on/off ratios, showing of efficient charge transport and low leakage currents. This paper explained the flexible properties of MoS_2 that make it suitable for flexible electronics, and it provided insight on how the other properties are unaffected when a flexible device designed with MoS_2 undergoes physical strain.

3) Source [26]: This paper explains the piezoelectric properties of single-layer MoS_2 and how those properties make it a suitable candidate for energy conversion and piezotronic devices. Monolayer MoS_2 generates an electric charge in response to mechanical strain. Specifically, the paper touches on how strong transport measurements reveal a strong piezotronic effect in single layer MoS_2, whereas the effect is not observed in bilayer and bulk layer MOS2, emphasizing the unique properties of single-layer MoS_2. Also, odd layer numbers are favorable for both the piezoelectric and semiconducting properties of MoS_2. This paper provided insight on how the piezoelectric properties of MoS_2 make it a favorable candidate in several 2D electronic applications.

E. Thomas Czartoryski

1) Source [33]: This paper revolves around assessing the mechanical capabilities of a graphene based touch panel display. This is a key paper in flexible electronics because it highlights polymer-based touch panel displays incorporated with graphene as the future of optoelectronics. It provides clarity via Raman Spectroscopy on how stress is transferred by the embedded graphene layers, and how these new graphene-based displays hold up against fatigue tests. The authors detail the fabrication of these displays using various transfer techniques, the method on which they perform the mechanical tensile tests, and the role of Raman Spectroscopy in detecting structural changes in materials. This paper was then able to reach conclusions on the deformation of the graphene displays during loading and unloading cycles, thermomechanical responses of the displays, and functional fatigue behavior of the prototype display. The paper's experiments reveal via Raman mapping that the display is mechanically robust, under fatigue tests the max temperature recorded is below the glass's transition temperature, and the response to tensile strain is governed by graphene "islands" and the stress transfer efficiency was dependent on the size of these islands. By performing these comprehensive tests this paper was able to give an accurate portrayal on the robustness of graphene based screens and sets the groundwork for further development of screens.

2) Source [36]: This paper revolves around the development of band-selective photodetectors using flexible transition metal dichalcogenide (TMD) nanosheets. By liquid exfoliating TMD powders and binding them to amine-terminated polymers which were then deposited onto a flexible polymer substrate, the authors were able to create a micron-thick two-terminal photodetector. The authors were able to demonstrate that flexible photodetectors could be built with excellent photodetection and withstand bends of up to a $200[\mathrm{m}]$ radius. These devices selectively detect both visible and near infrared (NIR) light, through mixing two nanosheets of MoS_2, which detects visible light, and $MoSe_2$ which detects NIR light. The devices were also able to maintain performance after 1000 bending cycles, and were able to have $100[\mathrm{ms}]$ response times and were able to have detectivity up to $4 \cdot 10^{12}$ Jones. The author's novel design of a flexible photodetector opens the ability for the development of wearable health monitors, flexible imaging systems, and smart textiles.

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