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Emerging Nanophotonics 2D Materials for Optoelectronic Applications: A Review

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Abstract
Recent advancements in Two Dimensional (2D) Material Nanophotonics design approaches, which involves techniques for light confinement at subwavelength scale using 2D material and optical structures based on desired characteristics, have reshape the landscape of structures available to nanophotonics. Here, we outline a cross-section of key developments in this emerging field of Nanophotonics: moving from a recap of 2D materials, nanophotonics, their structural classification, types, state-of-the-art designs and their advantages, to Practical applications.

Keywords: Nanophotonics, 2D materials, Graphene, hexagonal Boron Nitride, Black phosphorus, TMDCs.

INTRODUCTION
Nanophotonics is the study of the behaviour of light of wavelengths around 300 to 1200 nanometres (nm) that includes ultraviolet, visible, and near-infrared light, which interacts with structures at nm scale (≤100nm). It deals with the interactions between light and matter at a scale shorter than the wavelength of light itself. These interactions, taking place within the light wavelength at sub-wavelength scales, are determined by the physical, chemical, and structural nature of artificially or naturally nano-structured materials. Strong coupling

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between light and matter, efficient control of spontaneous emission, and enhanced non-linear phenomena are some of the interesting phenomena that can be observed when light and matter interact at the scale of nm (Datta and Munshi, 2017).

Two-dimensional (2D) materials are crystalline materials consisting of a single layer of atoms. They are strongly bonded within the same plane but weakly attached to sheets above and below by Van der Waals forces. This weak interlayer interaction makes the extraction of single or a few layers of their atoms possible, thus leading to explosion of research on 2D materials, including their Photonic properties and application(Xia *et al.*, 2014).

Several literatures have been reported on 2D materials for various applications. For instance, most recently,Zeng *et al.*(2018), reported a review on 2D materials toward next-generation circuits from monomer design and assembly. Clear guidelines on physical and chemical strategies for tuning their properties were outlined. Similarly, progress toward integrating 2D materials with silicon photonics for optoelectronics application was reviewed byYoungblood & Li(2016); focusing on lighting generation with TMDCs. Moreover,Tian *et al.*(2016), reported a review on synthesis of 2D TMDCs devices for optoelectronics applications. Most of these important reports and summaries focused on attractive properties of one section of 2D materials. Therefore, we find it expedient to systematically review 2D materials as a whole to better appreciate its contribution to the development of nanophotonics and its application. In this article, 2D materials, nanophotonics devices using 2D material and their practical application in the field of nanophotonics would be explored. The rest of the article is outlined as follows; section 2 is state-of- the-art in two-dimensional materials, section 3 is nano-photonic devices, section 4 is nano-photonic devices using 2D materials, section 5 future of information photonics from the perspective of 2D material, section 6 is conclusion and finally section 7 is references.

STATE- OF- THE-ART IN TWO DIMENSIONAL MATERIALS

Two-dimensional materials have been receiving great attention because of qualitative changes in their physical and chemical properties due to quantum size effect, which is related to their Nano-sized thickness. The family of 2D materials encompasses a wide selection of compositions including most elements of the periodic table. These include metals, semi-metals, insulators, and semiconductors with direct and indirect bandgap ranging from ultraviolet to infrared through the visible range (Zeng *et al.*, 2018).

2D materials exhibit many exceptional properties: First, quantum confinement in the direction perpendicular to the 2D plane leads to novel electronic and optical properties that are distinctively different from their bulk parental materials. Second, their surfaces are naturally passive without any dangling bond, which makes it easy to integrate 2D materials with photonic structures such as waveguides and cavities.It is also possible to construct vertical heterostructures using different 2D materials without the conventional 'lattice mismatch' issue.Third, despite being atomically thin, many 2D materials interact strongly with light. Finally, 2D materials can cover a very wide range of the electromagnetic spectrum because of their diverse electronic properties(Xia *et al.*, 2014).

While they exhibit these desirable properties, their innate thinness greatly limits light-matter interaction in free space. To solve this limitation and enhance light confinement, 2D material are inserted into external photonic structure such optical cavities, optical waveguide; or using Plasmon/localized Plasmon resonances(Youngblood, Li and Access, 2016).

2D materials are classified into two according to their structures; layered and non-layered materials. The layered structures provide the opportunity for the bulk counterparts to be removed into individual free-standing atomic layers. Vander Waals materials are the front-runners of layered material and enable their removal into mono- and few-layered nano-sheets. They exhibit strong in-plane covalent and weak interlayer Vander Waal bond, which can facilitate the removal of bulk parent crystals into nano-sheets. 2D non-layered material shave numerous dangling bonds on their surfaces, enabling their surface to be highly chemically active and enhance their capability of catalysis, sensing, and carriers transfer. Non-layered materials are mostly Group III-V semiconductors and have both high carrier mobility and direct bandgap(Zeng *et al.*, 2018). In this paper, the focus would be on 2D layered materials.

A. Graphene

The most appealing features of graphene for nanophotonics applications originate from its zero band-gap nature as depicted in figure 1e. Owing to its unique band structure, graphene offers a highly sensitive response to optical signals in a broad spectral range, from far infrared (IR) to ultraviolet (UV). The inter-band transition in graphene allows for the construction of detectors and modulators for many optoelectronic applications within the IR, visible, and ultraviolet spectral bands. However, graphene is not the best candidate for applications that require light generation owing to its short carrier lifetime, which originates from its zero-gap nature(Tian *et al.*, 2016).

B. Transition Metal Dichalcogenides

Transitions Metal Dichalcogenides (TMDCs) are another family of 2D materials. TMDCs are materials with the chemical formula MX_2,where M denotes a transition metal element (such as molybdenum (Mo), tungsten (W); while X is a chalcogen such as sulphur (S), selenium (Se), or tellurium(Te)(Tian *et al.*, 2016).2D layered TMDCs could be semiconductors (MoS_2, WS_2), semi-metals (WTe_2, $TiSe_2$), true metals (NbS_2, VSe_2), and superconductors ($NbSe_2$, TaS_2).This rich family of mono-molecular-layer semiconductors cover the energy range from under 1eV-2.5eV and beyond as displayed in figure 1c; thus overcome the key shortcomings of graphene for electronic applications and offering new opportunities for constructing devices that can realize light generation functions, such as light-emitting diodes (LEDs) and lasers (Tian *et al.*, 2016).

C. Hexagonal Boron Nitride

Hexagonal boron nitride (h-BN) known as "white graphene", has an extremely large direct bandgap of 5.97 eV as shown in figure 1b(Zeng *et al.*, 2018), which makes it an excellent insulator. h-BN could be incorporated into various heterostructures, as the 'lattice match' is not necessary in Van der Waals heterostructures (Xia *et al.*, 2014).

D. Black phosphorus

Black phosphorus (BP) exhibits a direct bandgap from 0.3eV - 2eV (Figure 1d) which increase with BP thickness and layer decrease (Xia *et al.*, 2014).

In summary, 2D materials can benefit applications in the electromagnetic spectral range from far and mid-infrared (IR) (by using zero-bandgap graphene) to the near IR and visible range (using the TMDCs) and potentially into the ultraviolet range(h-BN)(Tian *et al.*, 2016).

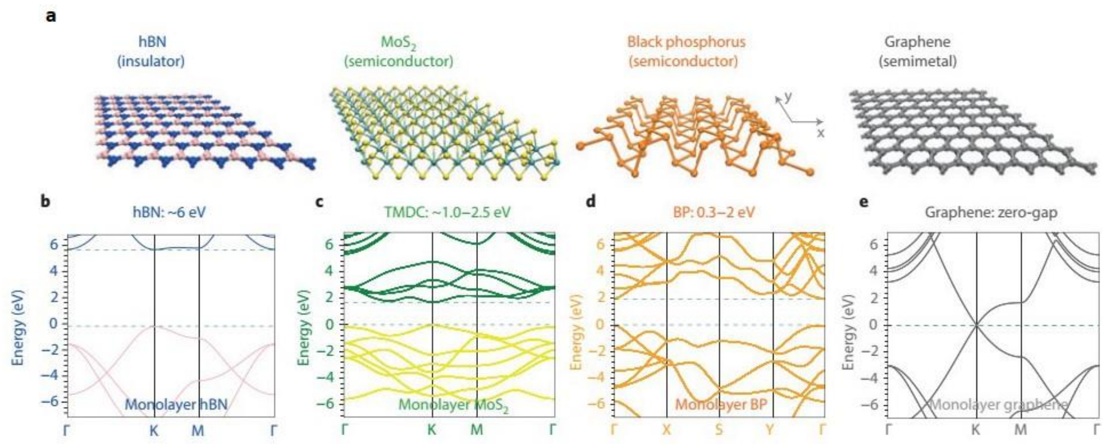

Figure 1.2D materials covering a broad spectral range. (a) Structures and Band of single-layer (b)h-BN, (c)MoS_2(d) BP and (e)graphene(Zeng *et al.*, 2018).

NANO-PHOTONIC DEVICES

The fundamental role of all nano-photonic devices is to increase the efficiency of transformation of energy from other forms to that of light. Devices can control the flow of light and sometimes localize or confine the light.Examples of Photonic devices used for localization of light are photonic crystals, optical wave guides, micro-resonators, plasmonics (Datta and Munshi, 2017).

The generation, detection, modulation and transformation of light are the major features in nano-photonic devices. For the generation, the main attention is focused on the development of nano-LEDs and ultra-compact lasers. For detection, the size has been dramatically reduced; the key issue lies in offering better solutions for enhanced sensitivity, bandwidth, and speed. In silicon nanophotonics, where functionalities are within ultra-compact integrated photonic chips; nano-photonic devices offer very useful solutions to the problem of light matter interaction and transformation taking place at the sub-wavelength scales(Datta and Munshi, 2017).

NANO-PHOTONIC DEVICES USING 2D MATERIALS

2D materials enable many important device applications in nanophotonics.

I. Photodetection

Photodetection using graphene: Graphene attracts significant attention for Photodetection because of its strong interaction with photons in a wide energy range and its high carrier mobility, making it a promising candidate for high-speed light detection applications in a broad wavelength range. Cakmakyapan *et al.*(2018) presented engineered photo-conductive nano-structures based on gold patched graphene nano-stripes, which enable simultaneous broadband and ultra fastphoto-detection with high responsivity(figure 2a).The key novelty that enables the superior performance of these photoconductive nanostructures is the confinement of most of the photocarrier generation and conduction to the graphene nano-stripes and gold patches, respectively.Through this approach, high responsivity Photodetection from the visible to infrared regime (0.6 A/W at 0.8 μm and 11.5 A/W at 20 μm), with operation speeds exceeding 50 GHzwas achieved. Benchmark for responsivity is in the order of mA/W (graphene photodetector typically is 0.2 mA/W).

Photodetection using TMDCs: While graphene is very attractive from the perspective of speed and broad optical sensitivity, it is fundamentally limited by its zero band-gap (Wang *et al*. 2016). Early reported TMDCs photodetectors had responsivity in order of mA/W using either mono or multi layer structures. Method to enhance their responsivity comes with drawback of decreased speed (Tian *et al.*, 2016). Recently, Ko *et al.*(2017) reported a High performance near-infrared photodetector based on few-layered back-gated $MoSe_2$. The device exhibits a high responsivity of 238 A/W (figure 2b).

Photodetection using BP: Black phosphorous (BP) is an exciting addition to the family of 2D materials, is ideal for photodetector applications due to its narrow but finite bandgap. Nathan *et al*. (2016) demonstrated a gated multilayer black phosphorus photodetector integrated on a silicon photonic waveguide operating in the near-infrared telecom band shown in figure 2c. In a significant advantage over graphene devices, black phosphorus photodetectors can operate under bias with very low dark current and attain an intrinsic responsivity up to 135 mA/W and 657 mA/W in 11.5nm and 100nm thick devices, respectively, at room temperature. The photocurrent is dominated by the photovoltaic effect with a high response bandwidth exceeding 3 GHz. While BP photodetectors have superior dark current performance compared to graphene detectors, there are also a few drawbacks. First of all, the best room temperature mobility in few-layer BP is two orders of magnitude less than that achievable in graphene. This limits the ultimate speed of BP photodetectors. Second, the absorption per layer of BP is less than graphene (about one-eighth) at near- and mid-IR wavelengths. Finally, BP suffers from oxidation and degradation when exposed to humidity and light. As there are approaches to overcome these drawbacks, BP photodetectors remain very promising for IR applications(Youngblood, Li and Access, 2016).

Photodetection in h-BN: Hexagonal boron nitride (h-BN), is an isomorph of graphene, has attracted great attention owing to its potential applications as an ultra-flat substrate or gate dielectric layer in novel graphene-based devices. Liu *et al.*(2018) reported a High performance deep ultraviolet photodetectors based on few-layer h-BN on a SiO_2/Si substrates (figure 2d). They found that the photocurrent increases with theh-BN thickness owing to the enhanced light absorbance. The photodetectors based on a 3nmh-BN layer exhibited high performance with an on/off ratio of >10^3 under deep UV light illumination at212 nm and a cutoff wavelength at around 225 nm.

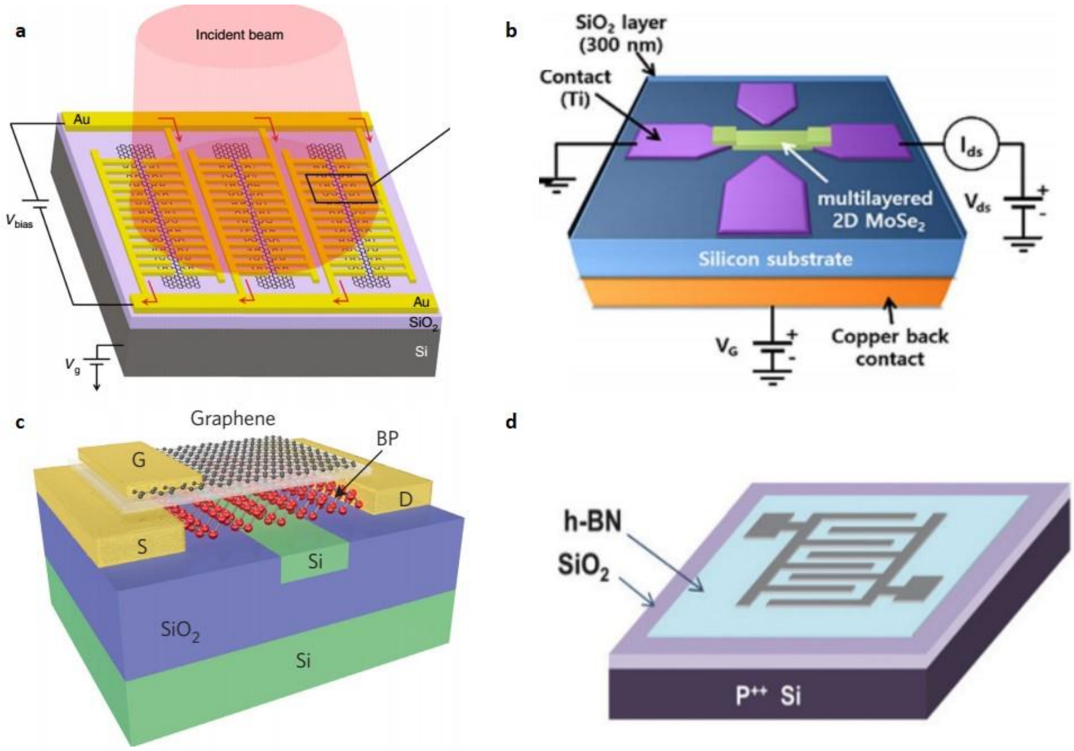

Figure 2. Schematic of: (a) a photodetector based on gold-patched graphene nano-stripes(Cakmakyapan *et al.* 2018). (b) High-performance near-infrared photodetector based on few-layered back-gated $MoSe_2$(Ko *et al.* 2017)(c) BP device featuring a few-layer graphene top-gate (Nathan *et al*.2016)(d) a h-BN photodetector (Liu *et al.* 2018).

II. Sources

In this section, recent progress toward generating light using 2D materials would be discussed.

Graphene LED: Graphene is an amendable platform who's electronic and optical properties can be tailored by chemical and electrical means. This property is particularly interesting as it potentially provides away to in situ control the color of LEDs. However, the development of graphene-based LEDs has been unsuccessful for some years owing to its vanishing bandgap. Hence, a method to fabricate a graphene-based device with a non-vanishing bandgap and charge injection capability is still lacking; until in 2015 when Wang *et al.*(2015) demonstrated a desirable combination of a band gap structure and a bipolar carrier injection in a special type of semi-reduced graphene oxide (GO) as shown in figure 3a. They reported a light-emission spectrum from blue (450 nm) to red (750 nm) by electrical gating or conditioning the environmental doping.

TMDC laser: TMDC family is true semiconductors with appreciable bandgap. In particular, molybdenum- and tungsten-based dichalcogenides exhibit optical bandgap in the range of 1–2 eV, which makes them suitable for near-infrared absorption and emission. The direct bandgap in TMDC monolayer occurs at the two unequalled corners(K and K`) of the hexagonal Brillouin zone, thereby endowing the electrons with a valley degree of freedom (Xia *et al.*, 2014).TMDCs based LED's suffer from low mobility, which hinders electrical performance, but have other properties that are highly desirable for optical applications(Youngblood, Li and Access, 2016). A TMDC monolayer placed on top of a Photonic crystal cavity (PCC) or disk resonator provides the optical feedback necessary for lasing. This is possible due to a strong overlap between the optical modes of the cavity through the evanescent field near the cavity-monolayer interface. Additionally, the use of a nanoscale optical cavity can greatly enhance spontaneous emission through the Purcell effect and reduce the lasing threshold of the gain material. Wu*et al.*(2015) used a GaP PCC to achieve lasing in a WSe_2 mono-layer (figure 3b). Through a 30-fold enhancement of the PCC quality factor, the Purcell effect was strongly enhanced, which enabled lasing at temperatures below 160 K.

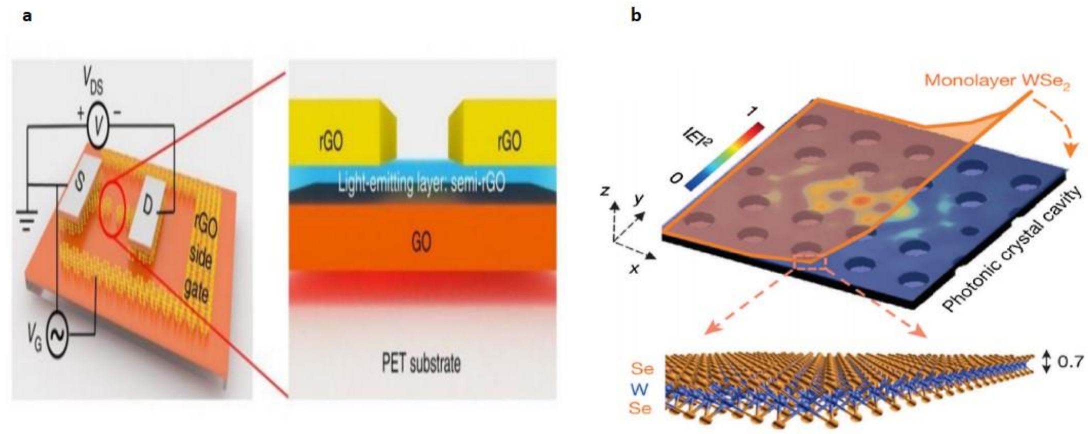

Figure 3. Schematic of (a) graphene-based field effect LED. A distinct semi-reduced graphene oxide (blue) at the interface between Graphene Oxide (orange) and reduce-graphene oxide (gold) is responsible for light emission (Wang *et al.* 2015). (b) Monolayer excitonic laser using WSe_2 on a PCC (inset scale bar 3 μm). Small mode volume and large overlap with the optical mode of the PCC contributed to the low lasing threshold (Wu *et al.* 2015).

III. Modulation

Optical modulators based on 2D materials include all-optical modulators, electro-optic modulators, thermo-optic modulators and others.

Graphene modulators: While the lack of a bandgap limits graphene's practical applications for photo-detectors, strong and broadband optical absorption makes graphene very promising for optical modulation. The principle behind optical modulation in graphene relies on the ability to tune the magnitude of its Fermi level to greater than (or less than) half the incident photon energy. At this point, graphene is no longer able to absorb incoming photons by inter-band transition as there are either no available carriers or excited states .The first functional graphene modulator was demonstrated by Liu et al. (2011). In this device, a sheet of CVD graphene was draped over a doped silicon waveguide, separated by a 7-nm-thick Al_2O_3 cladding as illustrated in Figure 3(a). The doped silicon waveguide was used as a back gate and controlled the Fermi level in the graphene. A modulation depth of around 4 dB and an RC time-limited bandwidth of 1 GHz were observed.This design suffers from some drawbacks which were later overcome. Subsequent improvements by the same authors show a modulation depth of 6.5-dB and 3-dB bandwidth of 3 GHz.(Li *et al.*, 2018) reported a Highly Efficient Graphene-Based Optical Modulator With Edge Plasmonics Effect by enhancing the gap plasmon mode and the edge plasmonic effect in a well-designed diagonal waveguide, a wedge-to-wedge surface plasmon polariton (SPP) mode is strongly confined in both horizontal and vertical directions in terms of a small mode area, which significantly improves the light-graphene interaction as shown in figure 3 (b). Modulation efficiency over 1.58 dB/μm with low plasmonics inserting loss of 0.2 dB/μmwas achieved.This research is an example of Electro-optic modulator.

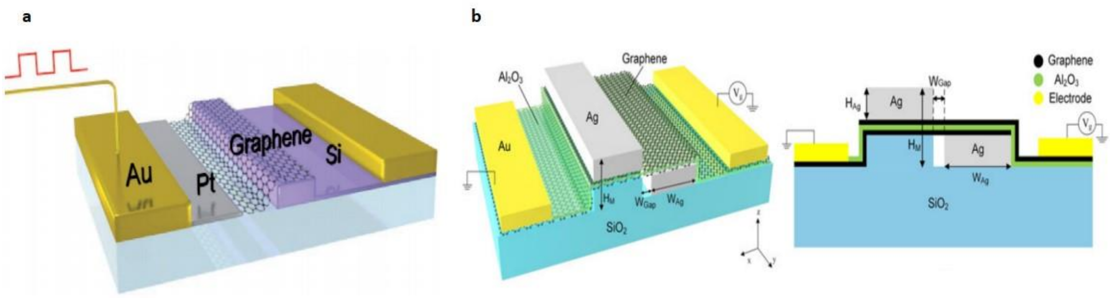

Figure 4. Schematic of: (a) First integrated graphene modulator using a doped silicon waveguide to gate the graphene layer. (b) 3D and cross-section of aelectro-absorption graphene modulator integrated with a diagonal plasmonics waveguide.

FUTURE OF NANOPHOTONICS FROM 2D MATERIALS PERSPECTIVE

The emerging field of 2D materials provides the optical community with many exciting new opportunities for exploration of sciences and technologies across a very wide electromagnetic spectral range(Xia *et al.*, 2014). 2D materials have enabled various functions such as sensor, photonic and optoelectronic functions, due to their diverse physical properties. 2D materials offers a significant benefit for electronics and photonics in terms of integration with an "all-in-one" solution, and also enables design of new devices with superior performance with simultaneous modulation and detection. However, the trade-off between performance and cost might make the commercial success of all-2D material systems challenging in the short term for nanophotonics applications. A more realistic success for 2D materials in the short term would build on the well-developed photonic technology platforms of silicon photonics and fiber optics(Sun, Martinez and Wang, 2016).

Moreover, the recent blossoming of artificial intelligence (AI), especially the sub-field of machine learning has revolutionized many realms of science and engineering, such as computer vision, speech recognition, and strategy making etc. Inspired by the biological neural networks, artificial neural networks dramatically changed the paradigm of information processing and powered the development of algorithms that can “learn” from data and perform functionalities to complete complex tasks. The associated technique of deep learning is thus considered a promising candidate for the inverse design of new materials, drugs, and nano-photonic devices.

CONCLUSION

In this paper, we tried to explore 2D material based on their classification, structure, devices and applications. The wide variety of available 2D materials have been used for very promising realization of novel devices such as light detection, emission, modulation, and manipulation, with many applications in communication, sensing, computation, and healthcare.

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