# Research of Photodetectors Based On Two-Dimensional Materials

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**Abstract.** With the discovery of graphene, people have discovered that two-dimensional materials have unique properties and significance. Therefore, two-dimensional material-based photodetectors are also very valuable for research. This article first discusses the excellent properties of photodetectors based on two-dimensional materials, including high sensitivity, high modulation frequency, and wide spectral response capability. Then, recent research results on two-dimensional SnSe2/GaP type-II heterostructure photodetectors and photodetectors utilizing two-dimensional WSe2 were introduced. Additional representative studies, including two-dimensional layered materials-based valanche photodetectors and two-dimensional tin (II) sulfide (SnS) nanoflakes-based photodetectors, were also shown. The prospects and challenges of photodetectors based on two-dimensional materials were also discussed at the end of the article. They can be applied in fields such as video imaging, gas sensing, biological imaging, safety, night vision, optical communication, and motion detection. The issues of device stability, mass production, cost, and uniformity need to be addressed and find their more ideal commercial applications.

**Keywords:** Two-Dimentional; Photodetector; Heterostructure.

## 1. Introduction

Richard Feynman first posed the query, "What can we do in two-dimensional layered materials with controllable layers?" in the late 1950s. A wave of study on two-dimensional layered materials was started in 2004 when Novoselov et al. discovered graphene [1] and disclosed their intriguing physical phenomena. This discovery came about after several experiments and efforts by scientists. Afterwards, two dimensional materials are becoming increasingly familiar to people.

In materials with two dimensions, electrons can only travel freely in two non-nanoscale dimensions (1-100nm). Two-dimensional materials have several special features because heat diffusion and carrier migration are contained inside the two-dimensional plane. Its tunable bandgap finds extensive application in optoelectronics, thermoelectric, and field-effect transistors. Its controllability in terms of both spin and valley degrees of freedom has drawn extensive study in the valley electronics and spintronics domains. Therefore, two-dimensional materials have great research value and application prospects.

People have started researching photodetectors based on materials in two dimensions as a result of the development of two-dimensional materials. It may be widely used in many fields due to its great qualities, including high sensitivity, high modulation frequency, and wide spectral response capabilities. They might be important components of the spectrometers, fiber optic transceivers, image sensors, and photodetectors of the future. Motion detection, night vision, gas sensing, safety, biological imaging, optical communication, and video imaging are a few of its application areas. To illustrate the special capabilities and importance of two-dimensional photodetectors, this article will outline their characteristics as well as highlight current scientific developments in the field.

## 2. The properties of photodetectors based on two-dimentional materials

Using two-dimensional materials, photodetectors have many good properties, such as high sensitivity, modulation frequency, and spectral response ability. The following will introduce them one by one.

High sensitivity: Because of the thickness of their atomic layers, two-dimensional materials have a comparatively high surface area to volume ratio, which increases detector sensitivity and improves photon absorption. Moreover, two-dimensional materials have extremely high charge transfer rates, enabling them to convert optical signals into a significant quantity of photocurrent and enhance photodetectors' sensitivity even further. Furthermore, by optimizing material properties, two-dimensional material photodetectors can further increase sensitivity by dynamically modifying the structure and properties of materials during the manufacturing process. Finally, the high sensitivity of two-dimensional material photodetectors is also a result of their superior spectral detection capabilities, which extend from the ultraviolet to the far-infrared [2].

High modulation frequency: The unique material qualities and structure of two-dimensional material photodetectors contribute to their extremely high modulation frequency. First, two-dimensional materials can react to high-frequency optical signals because of their extraordinarily high carrier mobility and relaxation rate. Second, photons can travel through two-dimensional materials quickly due to their atomic thin layer structure, which speeds up photodetectors' reaction times. Wideband absorption is another property of two-dimensional materials that allows them to absorb light signals throughout a larger frequency range, thus increasing the modulation frequency. As a result, two-dimensional material photodetectors are appropriate for uses like data communication since they can obtain extremely high modulation frequencies [3].

Wide spectral response capability: Two-dimensional material-based photodetectors may respond to light in a broad spectrum of wavelengths, from ultraviolet to near-infrared (400-1575 nanometers). For example, in Arora et al.'s study, the foundation of this detector is a two-dimensional $Fe_3(THT)_2(NH4)_3$ metal organic framework (MOF) thin film, which exhibits strong carrier mobility and semiconductor properties and can operate in a photoconductive mode. During testing, the detector has shown good stability and dependability. Its photocurrent response has a high response speed and sensitivity and is linearly related to light intensity. In the meantime, the detector can do low-power photoelectric conversion and has a high voltage response value [4].

## 3. Types of photodetectors based on two-dimensional materials

### 3.1. Photodetectors based on a two-dimensional SnSe2/GaP type-II heterostructure

According to Wang et al.'s research, two-dimensional $SnSe_2$/GaP type-II heterostructure photodetectors have significant research value. An indirect bandgap of 0.439 eV is found in the type II heterostructure $SnSe_2$/GaP. It is possible to successfully separate electron-hole pairs produced by photolysis at the heterojunction contact. The two-dimensional $SnSe_2$/GaP type II heterostructure-based photodetector has many advantageous features. It has high absorption, to start. The light absorption coefficient of single-layer materials is greatly enhanced by the $SnSe_2$/GaP heterostructure, particularly in the UV area where some visible light wavelength bands can be partially absorbed. Because of this, it can absorb light very well in optoelectronic devices. It also performs exceptionally well optoelectronically. $SnSe_2$/GaP heterostructures may effectively separate photogenerated electron-hole pairs by controlling the energy levels of electrons and holes. This suggests that it has great potential in areas like ultraviolet detectors and extremely sensitive optoelectronic devices. It has an adjustable band structure as well. The $SnSe_2$/GaP heterostructure has an indirect bandgap of 0.439 eV, making it a type II heterostructure. Semiconductor metal transition can be achieved in heterostructures by tuning their band gap through strain, electric field application, and interlayer distance adjustments. These results in tunable transmittance and conductivity in the $SnSe_2$/GaP heterostructure. Lastly, it has a wider band absorption: the $SnSe_2$/GaP heterostructure has a markedly improved absorption capacity, particularly in the ultraviolet absorption area, with a wider light absorption range, as compared to two single-layer materials. To summarize, photodetectors that utilize two-dimensional $SnSe_2$/GaP type II heterostructures exhibit superior optoelectronic performance, wide band absorption, tunable band structure, and high absorption. This renders it

extensively relevant in domains like ultrasonic detectors and extremely sensitive optoelectronic devices (Fig. 1) [5].

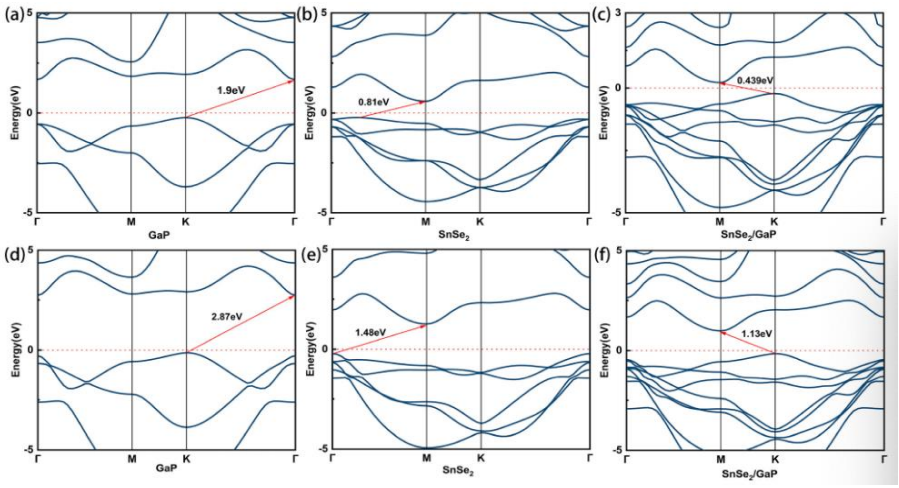



**Fig 1.** Projected energy band diagram of (a) GaP layer, (b) $SnSe_2$ layer, (c) $SnSe_2$/GaP heterostructure. Energy band structure based on HSE06 hybrid function calculations (d) monolayer GaP, (e) monolayer $SnSe_2$, (f) $SnSe_2$/GaP heterostructure [5].

### 3.2. Polarization sensitive photodetectors based on two-dimensional WSe2

Another useful material in the field of photodetectors is two-dimensional $WSe_2$. Guskov et al. imparted polarization sensitivity to two-dimensional $WSe_2$ thin films by using ordered silver triangular nanoprisms. The two-dimensional $WSe_2$ surface can be coated with ordered silver nanoprisms to boost the optical detector's optical sensitivity. This kind of nanoprism uses surface plasmon resonance to increase light absorption five times. The optimal circumstances of surface plasmon resonance have been discovered and its properties have been shown through theoretical simulations. By using this technique, a photodetector with spectral selectivity and polarization sensitivity that is based on two-dimensional graphene-like semiconductors is successfully created. This method has broad applications in biomedical, remote optical sensing, object recognition, polarization optical mapping, and optical sensing. Polarization-sensitive photodetectors of two-dimensional $WSe_2$ thin films are anticipated to play a significant role in optical applications and advance the advancement of optoelectronic technology in the future with more research on two-dimensional materials (Fig. 2) [6].

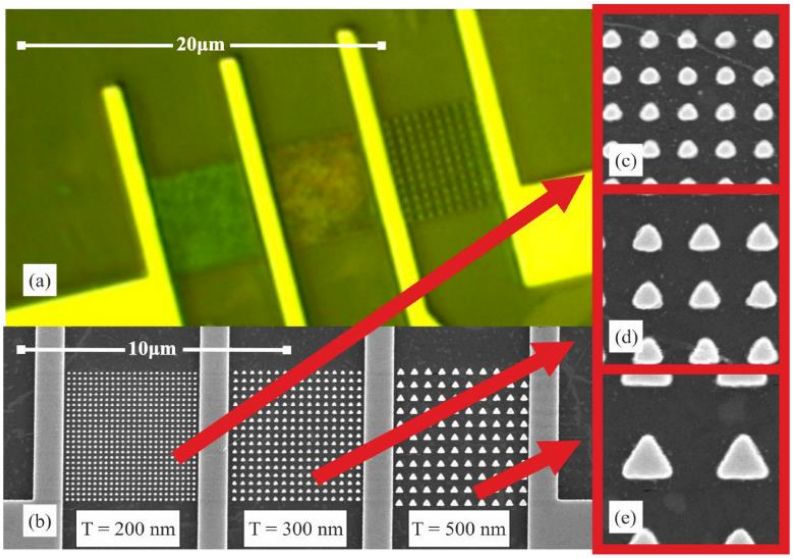



**Fig 2.** Image of the created photodetectors: (a) optical image, (b) structure-wide SEM image (c-e) nanoprism SEM images with T = 200, 300, and 500 nm, respectively [6].

### 3.3. Avalanche photodetectors based on two-dimensional layered materials

Low light absorption coefficients are a common issue with two-dimensional layered materials because of their atomic level thin film structure. A viable method for attaining carrier doubling is shock ionization, which can be applied to the creation of two-dimensional photodetectors with excellent detection efficiency. Miao et al. constructed avalanche photodetectors using their van der Waals heterostructures and two-dimensional layered materials. This allows for the realization of further possible uses for single photon counting technologies. These newly developed two-dimensional materials offer fresh approaches to developing sophisticated avalanche photodetectors by means of effective carrier doubling at the nanoscale. Time of flight measurement (ToF), intelligent robots, and light detection and ranging technology (LiDAR) are just a few of the expanding technical disciplines that are impacted by the deployment of two-dimensional material avalanche photodetectors (Fig. 3) [7].

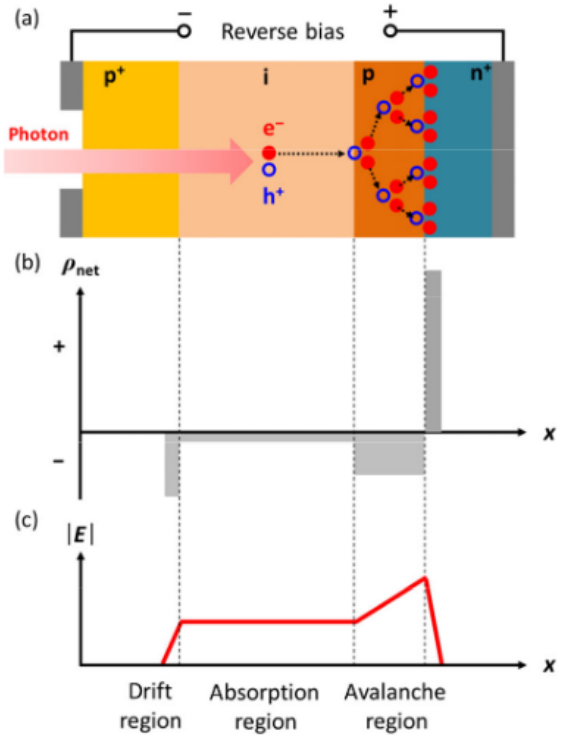



**Fig 3.** The working mechanism of avalanche photodiodes [7].

### 3.4. Photodetectors based on two-dimensional tin(II) sulfide (SnS) nanoflakes

Tin sulfide, a two-dimensional material that includes tin disulfide (SnS2) and tin sulfide (SnS), has drawn a lot of attention because of its abundant earth resources, affordability, and eco-friendliness. It is also seen to be a promising material for photovoltaic and photocatalytic applications. Using a novel precursor tin oxide (SnO) and the chemical vapor deposition (CVD) method, Liu et al. synthesized high-quality two-dimensional SnS. They then used optical microscopy (OM), scanning electron microscopy (SEM), atomic force microscopy (AFM), energy dispersive spectroscopy (EDS), Raman spectroscopy, and X-ray photoelectron spectroscopy (XPS) to characterize the morphology and properties of the material. In addition, photolithography pattern transfer (PPT) technology was used to create SnS based field effect transistors (FETs) and photodetectors. Under 405 nm laser irradiation, the grown SnS shows high responsiveness (156.0 A W-1) and standardized geochemical measurements (2.94), as well as external quantum efficiency (4.77 × 10^ 4%) and quick response time (5.1 ms). These results confirm that the generated SnS is, in fact, a p-type semiconductor [8].

## 4. Conclusion

This article first discusses the unique properties of photodetectors based on two-dimensional materials, including High sensitivity, High modulation frequency, wide spectral response capability, etc. Then this article mentions four representative achievements in recent years. Firstly, the photodetectors with two-dimensional $SnSe_2$/GaP II heterostructures have wide applications in fields such as ultrasound detectors and extremely sensitive optoelectronic devices, attributed to their excellent optoelectronic performance, broadband absorption, tunable band structure, and high absorption characteristics. Moreover, photodetectors sensitive to polarization utilizing two-dimensional $WSe_2$ are also important research achievements and are anticipated to be crucial in optical applications. Additionally, avalanche photodetectors built from stacked, two-dimensional materials can achieve carrier doubling through shock ionization. Finally, this article also discusses the advantages of two-dimensional tin (II) sulfide (SnS) nanoflakes-based photodetectors.

Building on these milestones, the future development of two-dimensional material-based photodetectors seems poised for transformative breakthroughs. The integration of such materials into flexible and wearable electronics could revolutionize personal devices, offering enhanced functionality with seamless human-machine interfaces. The potential for two-dimensional materials to be incorporated into large-area electronic and photonic devices also holds promise for the next generation of high-resolution imaging systems. Furthermore, with ongoing advancements in material synthesis and device fabrication techniques, we can expect a significant reduction in production costs, making these photodetectors more accessible for commercial and industrial applications. The versatility and superior properties of two-dimensional materials may well herald a new era in photodetection technology, with broad implications for sectors ranging from healthcare diagnostics to environmental monitoring.

## References

[1] Novoselov, K. S., Geim, A.K., Morozov, S.V., Electric Field Effect in Atomically Thin Carbon Films [J]. Science, 2004, 306 (5887), 666-669.

[2] Wang Jun, Han Jiayue, Chen Xiaoqing, et al. Design strategies for two-dimensional material photodetectors to enhance device performance. InfoMat, 2019, 1(1), 33-53.

[3] Konstantatos, G. Current status and technological prospect of photodetectors based on two-dimensional materials. Nat Commun, 2018, 9(1), 5266.

[4] Arora Himani, Dong Renhao, Venanzi Tommaso, et al. Demonstration of a Broadband Photodetector Based on a Two-Dimensional Metal–Organic Framework. Advanced Materials, 2020, 32(9), 1907063.

[5] Wang Jiaxin, Wei Xing, Xuan Jinzhe, et al. Theoretical design of a photodetector based on a two-dimensional SnSe2/GaP type-II heterostructure. CrystEngComm, 2023, 25(15), 2326-2338.

[6] Guskov Andrey, Lavrov Sergey, Galiev Rinat. Polarization Sensitive Photodetectors Based on Two-Dimensional WSe2. Nanomaterials, 2022, 12(11), 1854.

[7] Miao Jinshui, Wang Chuan. Avalanche photodetectors based on two-dimensional layered materials. Nano Research, 2021, 14(6), 1878-1888.

[8] Liu Gangzha, Li Yan, Li Bo, et al. High-performance photodetectors based on two-dimensional tin (II) sulfide (SnS) nanoflakes. Journal of Materials Chemistry C, 2018, 6(37), 10036-10041.