The Basic Category and Application of Graphene-based Hybrid Photodetector

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Abstract. A photodetector is an optoelectronic device that can be divided into inorganic photodetector, which consists of traditional semiconductors, and organic photodetector, the recent direction of researching that made of organic semiconductors with the help of organic dye molecular or other organic compounds. The core of the improvement of photodetector is graphene, a single layer of the two-dimensional (2D) carbon crystalline structure, which provides the property with wide spectral bandwidth and considerably high response speed. This review focuses on the basic knowledge about graphene-based hybrid photodetector, because the hybrid photodetectors have the advantages of breaking the limitation of light absorption and shortening the recombination time of electrons and holes to increase photoresponsivity. Photodetectors can also behave differently when lights are in the infrared, ultraviolet, and terahertz region, so that the selection of materials based on graphene to detect the specific wavelengths of light becomes a challenge. In order to explain the complicated advanced technology briefly, this review can be regarded as two main parts. The first one is the basic properties of inorganic and organic photodetectors with the addition of perovskite, a new material that has been extensively studied recently, and the second part is about how photodetectors can be applied in a different wavelength of lights.

Keywords: Graphene, Hybrid photodetector, Perovskite, Infrared, Ultraviolet, Terahertz

1. Introduction
With the rapid development of electronic technology, optoelectronic products play an increasingly important role in human society and are widely used in social life, industrial production, and scientific research in various fields. Among them, as one of the members of optoelectronic devices, the photodetector has made great contributions to the field of optoelectronics, especially the wide-spectrum photodetectors, and plays an essential role in various applications of optical detection. Graphene is a potential and promising material for photodetector for the reason that it possesses the property of zero-energy bandgap, and its high carrier mobility contributes to the ultrafast photoresponse, which is the requirement for advanced photodetectors. The development of photodetector, nevertheless, cannot be achieved with graphene itself, because the limitation of light absorption inhibits the photoresponsivity, and the performance will be compromised. By combining graphene with other materials, not only the traditional inorganic materials can be used in the
photodetector, such as Germanium, but also the organic dye molecules, for example, Rhodamine-based dye molecules, are extensively used as the core of the photodetector. Recently, the popularity of the perovskite-graphene photodetector, such as CH$_3$NH$_3$PbC$_3$, an inorganic-organic halide perovskite, also contributes a lot to the development of improving detecting speed and response performance. Photodetectors cannot be designed to detect all the light with different wavelengths, so the specific detector should be designed for assigned light. For example, infrared light could be detected faster and more accurately by enhancing Photovoltaic Effect (PV), Photothermoelectric Effect (PTE), and Photo-thermionic Effect (PTI), and ultraviolet light could be detected more efficiently by attaching specific material on the surface of graphene/silicon device, such as Bi$_2$, to change the irregular surface, which hinders the absorption of light to smooth surface. Indeed, since graphene as a 2D material, other 2D materials are also promising in this area. Hexagonal boron nitride (h-BN) is a good example that h-BN with its brilliant performance on thermal conductivity and stable mechanical characteristic have been widely used as a detector.

2. Mechanism and Characterizing for Graphene-based Hybrid Photodetector

Basically, the structure of light detectors is generally relatively simple, including a semiconductor material and two ohms. When the energy of light is higher than the bandgap, it is converted to electricity and displayed on the detector’s dashboard.

2.1. Operating Mechanisms

The basic principle of photodetector is based on the photoelectric effect. When the photon strikes a light-sensitive substance if the electron absorbs the energy of the photon, the kinetic energy increases immediately. While if the kinetic energy increases enough to overcome the gravitational pull of the nucleus, it can escape from the metal surface, which will become a photoelectron and form a photocurrent. By detecting the different wavelengths of light, the detector will show different values, which can be compared to the known values of the currents to determine the category of lights.

Since the principle is to contact semiconductors with other materials, when graphene is combined with semiconductors, different Fermi energy levels will cause the energy band to move to make sure that the Fermi energy levels are aligned. Figure 1a shows the difference between the n-type and p-type semiconductors combined with graphene. In such a situation, the energy barrier ($\Phi_e$), and the energy required for electron transfer, exist to make a balance that electrons cannot transfer from graphene to semiconductor easily. Therefore, different energy causes different types of effects. When the energy is in the range from $\Phi_e$ to semiconductor bandgap ($E_g$), the minimum energy that is required to excite an electron up to a state in the conduction band where it can participate in conduction, the electrons are moving from graphene to semiconductor. While the energy is larger than $E_g$, the depletion layer of semiconductor is generating electron-hole pairs. [1] Figure 1b represents a basic scheme of the core structure of the photodetector that consists of the battery, resistance, semiconductor and graphene material, and a display panel. The mechanism of photodetectors is evident and easy; the challenge is advancing to detect lights in different wavelengths.
2.2. Figure-of-merit for characterizing photodetectors

2.2.1. Photoresponsivity ($R$). Photoresponsivity is defined as the ratio of the photocurrent or photogenerated voltage to the light power that incident to the photodetector. The formula can be written as $R_i = \frac{I}{P}$, which corresponds to photocurrent, or $R_v = \frac{V}{P}$, which corresponds to the photogenerated voltage, and $P$ is the incident light power. [2]

2.2.2. External Quantum Efficiency (EQE). The external quantum efficiency is defined as the ratio of the number of the collected charge carriers to the number of photons that produce the photocurrent. It can be written as $\text{EQE} = \frac{N_c}{N_i} = \frac{hc}{q\lambda} R$, where $N_c$ is the collected charge carriers, $N_i$ is the number of photons illuminating the device, $h$ is the Planck constant, $c$ is the speed of light, $q$ is the electron charge, $\lambda$ is the wavelength of the incident light, and $R$ is photoresponsivity.

2.2.3. Detectivity ($D^*$). Detectivity represents the sensitivity of a photodetector that the weakest level of light can be detected and defined by the responsivity and the noise of the photodetector. It can be expressed as $D^* = \frac{\sqrt{AE}}{B_i}$, where $A$ is the effective area of the photodetector, $B$ is the electrical bandwidth, and $I_{N_i}$ is the noise current. Besides, the value of $D^*$ is restricted by three reasons, the thermal fluctuation noise, Johnson noise, and dark current. [3]

2.2.4. Noise Equivalent Power (NEP). Noise equivalent power is defined as the signal power that gives a signal-to-noise ratio of one in a one-hertz output bandwidth. [4] It can be expressed as $\text{NEP} = \frac{E}{I}$, so the unit of NEP is W Hz$^{-1/2}$.

2.2.5. Response Time and Cutoff Frequency. Response Time includes the rise time $\tau_r$ and fall time $\tau_f$, which are usually considered from 10%/90% to 90%/10% of the measured time of the net photocurrent. The photoresponsivity is often determined by the light modulation frequency as $R(f) = \frac{R_0}{\sqrt{1+(2\pi f)^2}}$, where $R_0$ is the photoresponsivity under the condition of static illumination.
2.2.6. Linear Dynamic Range (LDR). Linear Dynamic Range describes a range of illumination intensity, and the current response of photodetector is linearly dependent on the light intensity, which can be expressed as \( LDR = 20 \log \frac{I_P}{I_{d,\text{dark}}}, \) where \( I_P \) is the photocurrent density measured at a light intensity of \( 1 \text{ mW/cm}^2 \) and \( I_{d,\text{dark}} \) is the dark current. Moreover, Larger LDR can be used more widely because of its good ability of detecting the weak and intense light with the same device.

3. Graphene-based hybrid photodetector

Graphene is a 2D material, which is chemically passivated to support free binding to any substrates. This inherent integrity makes it easy for the performance of integrated photonic devices to benefit from the interesting properties and functions of two-dimensional materials and their van der Waals heterojunctions. [5] Besides, due to its lack of bandgap, ultra-high electron mobility, resistivity lower than that of silver and copper at room temperature, and high thermal conductivity, graphene has high application value in phototransistors, biochemical sensors, battery electrode materials, and composite materials. Moreover, because of its low resistivity and extremely high carrier mobility, the properties that photodetector exactly needed, that graphene-based hybrid photodetector can perform better than traditional semiconductor-based photodetector, which the energy gap of semiconductor inhibits carriers to transfer as quickly as possible.

3.1. Inorganic-graphene based hybrids

The first photodetector based on Germanium semiconductor was invented by Shive in 1950, when it can be used to detect from visible light to infrared, but the response to visible light is weak. [6,7] Later in 1965, planar silicon photodiode was invented, and its response spectrum can range from 190nm to 1100nm, which means that it can range from ultraviolet and cross visible light to near-infrared. [8] Certainly, the development made by hybrid photodetectors is huge that improving the transmission capacity of carriers which results in a better performance of graphene-based inorganic photodetector to have higher photoresponsivity and response speed. Until 2016, Zheng and his group prepared large transparent wide spectrum photodetector based on two-dimensional material WSe\(_2\), with the average transmission rate of the device in the visible spectrum being up to 72% and the spectrum response range being 370nm-1064nm. Photoresponsivity (R) and external quantum efficiency (EQE) were 0.92A/W and 180%, respectively. Figure 2a and 2b show the results of the inorganic photodetector, WSe\(_2\)-based photodetector, under different lighting conditions, that the photodetector's light response changes with time when the bias voltage is 0.2V. [9] Scientists are focusing on how to integrate graphene-based photodetectors to improve the characteristics of photodetectors to get faster responses and a wider range of wavelengths of light. The result is that integration with optical cavities, or silicon waveguides, is the proper way. As for improving by utilizing the optical cavity, in order to enhance the ability to absorb light, embedding graphene into optical or photonic crystal cavities is the method that is usually used. An optical resonator usually consists of a thin dielectric layer enclosed by two mirrors. The thickness is configured for a quarter of the resonant wavelength. Consequently, the light field is trapped in the cavity, so light passes through the embedded graphene sample several times. Thus, in a compact device, the absorption of light increases significantly. Figure 2c schemes the appearance of the cavity, which could improve light absorption. Alternatively, by integrating a graphene photodetector with a low-loss optical waveguide, the light absorption of graphene can also be improved. In this case, the evanescent mode of the photofield is limited and guided by the waveguide and propagates parallel to the graphene channel. As a result, the light propagates in the waveguide interacts with graphene, causing graphene to absorb light throughout the plane. [5] Besides, the graphene-based hybrid photodetector can also be advanced by forming graphene/silicon heterostructure, just as Figure 2d shows. The experiment was done by Wang et al. and it showed that the extension of the spectral range of the photodetector working at the room temperature is wider. Figure 2e shows the responsivity of graphene silicon and metal silicon Schottky photodetector under the condition of negative bias voltages. [10] Graphene-based hybrids can perform better in many
situations, for example, combining graphene with quantum dots can extend the lifetime of induced photon carriers, which can contribute to high responsive photo detect assignment. [11] Therefore, the photodetectors used in nowadays are mainly based on inorganic graphene integrated photodetector.

Figure 2. (a) and (b) The photo response change of $\text{WSe}_2$-graphene photodetector with a bias voltage of 0.2V. [9] (c) Schematic of a graphene microcavity photodetector [5] (d) Scheme of integrated silicon/graphene heterostructure photodetector [5] (e) The relationship between responsivity and a negative bias voltage of graphene silicon and reference metal silicon Schottky photodetector [5]

3.2. Organic-graphene based hybrids

Improved by organic substances. Graphene itself cannot contribute a lot to the photodetector because of its zero-band gap and limited optical absorption. [12] Therefore, how to improve the graphene-based photodetector becomes a problem. Organic substances can advance the whole field. Recently, people have tried to solve this problem by decorating the graphene surface with efficient light-collecting materials. It is well known that the conjugated structure of organic dye molecules can produce strong interaction with graphene, which can promote the photoexcited charge to transfer between dye molecules and graphene, thus enhancing the gain of the light guide in devices. Thus, take an organic dye as an example; the performance of graphene photodetectors can be significantly improved by forming hybrid structures with gold nanoparticles-based plasma resonators, colloidal quantum dots, metal halide perovskite, and other absorbers. Organic dye molecules can provide a way to solve these problems. [13] To be more specific, the ways that can deal with the current predicament are gaining mechanism in optical gain, integrating the device, and progressing the applications of hybrid films in photodetectors. [14] Improving the sensitization mechanism of the graphene-based photodetector and fabricating the devices are concentrating on graphene itself so that the organic-graphene hybrid photodetector progress should be emphasized. According to the research, organic dye molecules, such as rhodamine 6G (R6G), can be combined with graphene to improve the photodetector. This is because, basically, the $\pi - \pi$ stacking [17] between aromatic components of R6G can make the assembly of the molecules, which is on the surface of the graphene, more stable to assure the photodetector working, as shown in Figure 3a. Besides, the structure switching molecules: spiropyran, which can switch states when the wavelengths reach the required standard, can be used as a photonic input to control the electrical device. By synthesizing a spiropyran derivative bearing an 18-
carbon alkyl chain, it can atomically form precise superlattice at the surface of graphene, which is made from photochromic molecules. [14] Figure 3b [13] represents the scheme of photodetectors that combined graphene channel layer hybrids with three different Rhodamine-based dye molecules. Each dye molecule shows different absorption behavior in the visible range. For example, Rh110, Rh101, and Rh800 show absorption peaks at 499, 565, and 685 nm, which correspond to the direct transition of each dye from the highest occupied molecular orbital to the lowest unoccupied molecular orbital. When the dye concentration was fixed at $100 \times 10^{-6}$ M, it was found that the Rh101 dye solution had the highest absorption strength, indicating that the absorption coefficient of Rh101 was greater than that of the other two dyes. [15,16] Therefore, by utilizing different Rhodamine-based dye molecules with the particular process, the photodetector can be designed to detect required light with different wavelengths.

**Figure 3.** (a) The structure of a single $\pi$ stacking. [17] (b) Core of photodetectors that combined graphene channel layer hybrids with Rh110, Rh101, and Rh800 Rhodamine-based dye molecules. [13]

Besides, two-dimensional covalent organic frameworks (COF) is another possible strategy to facilitate charge carrier to separate in the surface COFs-graphene hybrids, which settle the problem that graphene itself has low absorption of light. COFs are 2D organic material, as shown in Figure 4a, with $\pi$—conjugated structure attached on the surface of SiO2/Si/Gr traditional device. Cao et al. conducted an experiment with COFs as shown in Figure 4b that represents the relationship between the responsivity of the devices and the thickness of the films. Figure 4c is the condition when the concentration is 0.003 mg/g [18]. It is apparent that the response time has a distinction so the choice of which kind of COF matters.
3.3. Perovskite-graphene based hybrids

Perovskite-graphene based hybrids have the advantages of possessing ample and tunable optoelectronic properties, like high EQE, and enough surface area to improve the range of electronic and optical applications. [19-22] In the past few years, halide perovskite has emerged as a candidate material for a new and revolutionary field of optoelectronics. These materials are made up of general chemical formulas $ABX_3$, representing organic or inorganic cations; B means a divalent metal (such as lead, tin or germanium) cations, halogenated; and X represents a monovalent (such as chlorine, bromine or iodine) anions. The huge benefits of exploring metal halide perovskite led to the first use of perovskite in photovoltaic equipment as a solar cell with a light absorption efficiency of less than 4% in 2009, followed by a rapid increase in efficiency of more than three times to 10-11% in solid perovskite in 2012 for solar cells.[23-26] Figure 5a [14] shows the research did by Chen et al. that the visible light sensitive BGTC phototransistor made good use of the lead-free perovskite $(\text{PEA})_2\text{SnI}_4$ thin film with the spin-coating process.[27] Under the bias voltage, the inorganic charged sheet of 2D $(\text{PEA})_2\text{SnI}_4$ may extend to the carrier transport direction, leading to the effective charge injection under light illumination. Due to the excitation gate modulation, when VGS = 16 V and VDS =−40 V, the visible light signal can obtain a $1.9\times10^4$ AW$^{-1}$ ultra-high light response rate. [28] However, the ability to release trapped electrons result in a slow rate of recombining trapped electrons and holes that have the potential to improve, which can be better in fabricating ultrasensitive 2D perovskite phototransistors and light-triggered memory devices. [29]. Figure 5b [21] schemes the change in Fermi level of graphene in photodetector illuminate under different power density and it is the special feature results from the perovskite-based graphene photodetector.
Recently, mixed organic-inorganic halide perovskite was found capable of collecting light for a highly efficient of 19.2% [65] so that the special family of the perovskite material is still $ABX_2$. To be more specific, $A = \text{CH}_3\text{NH}_3^+; B = \text{Pb}^{2+}; X = \text{Cl}^-/\text{I}^-/\text{Br}^-$. [66] To get the properties of the perovskite-graphene photodetector compared with single perovskite photodetector, Figure 6a and 6b represent the relationship between absorption, wavelength, and photoluminescence (PL). With the combination of graphene, the perovskite-graphene photodetector can absorb the light more, and the intensity of photoluminescence can be lower, which is beneficial to developing the performance of photodetector.

**Figure 5.** (a) Scheme of $\text{(PEA)}_2\text{SnI}_4$ perovskite phototransistor [14] (b) The Fermi level changed in photodetector illumination under different power density. [21]

**Figure 6.** (a) The relationship between absorption and wavelength in the range of UV-visible light under a single and combined situation. [66] (b) The relationship between PL intensity and wavelength of light under perovskite and combined with graphene situation. [66]
4. Application of Graphene-based Hybrids Photodetector

Light can be roughly divided into three parts, which are infrared, visible light, and ultraviolet, just as Figure 7 shows. Light with different wavelengths represents distinct properties, so how the photodetector can detect the specific wavelength of light matters.

![Optical spectrum from terahertz to ultraviolet.](image)

Figure 7. Optical spectrum from terahertz to ultraviolet. [69]

4.1. UV

The frequency of ultraviolet rays can vary from $10^{15}$ to $10^{16}$. If sensitizing the graphene and related materials (GRMs), the sensitivity will cover the range from ultraviolet to visible light, which can make a breakthrough in a sensitive area and large-scale production problems, because GRMs can treat the dark current to readout circuitry and speed up the whole device. [30] However, the ultraviolet light is not easy to detect, so a high-sensitive photodetector should be designed to detect. Nowadays, scientists found that bismuth iodide (BiI$_3$) could be properly used in photovoltaic applications because of its strong optical absorption with a wide bandgap of 1.8eV. Figure 8a shows the difference that BiI$_3$ used in photodetector with and without graphene. [39] It is evident that BiI$_3$ films grew better on graphene with larger grain sizes. In Figure 8b, the tendency of the absorption is less than 400nm, which means the ultraviolet region is considerable, compared to the infrared region, so BiI$_3$ films can also improve the detector in UV detection. Respectively, not only graphene could be used as UV photodetector, and Table 1 gives a sample of some properties of photodetectors based on different materials. Briefly take two materials as examples to explain the problem that the black phosphorus (BP) has on storage; hexagonal boron nitride (h-BN), because of its thermal conductivity, perfect mechanical characteristics and stability in chemical properties, has become popular, but the low conductivity that causes the high burden in operating voltage needs to be considered.

| Materials | Absorption coefficient ($cm^{-1}$) | Carrier mobility ($cm^2V^{-1}s^{-1}$) | Bandgap (eV) | Ref. |
|-----------|---------------------------------|---------------------------------|-------------|-----|
| BP        | 1.13-3.49                       | 100-7000                        | dir.0.3-2   | [31,32] |
| BN        | $10^{15}$                       | ---                             | Dir.6.0     | [33]  |
| SnO2      | $10^4$                          | 80                              | Dir.3.6     | [34]  |
| SnSe      | $10^4$                          | $10^4$                          | Ind.0.9     | [35]  |
| GaTe      | $10^4$                          | 4.6                             | Dir.1.6     | [36,37]|
4.2. IR

Photogating is significant to the two-dimensional materials in the photodetector. Due to the presence of a heterogeneous interface, the optical electron-hole can be separated into different raw materials, making an excess carrier life longer, and having the potential of regulation and control on the channel. Similarly, if a single material or substrate has a wealth of defects and defects can capture some light carrier, it can also lead to light raw potential regulation and control channel conductance phenomena. [39-41] A new type of high-performance infrared detector can be obtained by coupling ferroelectric materials with low-dimensional materials. The traditional ferroelectric materials have excellent dielectric, ferroelectric, pyroelectric, transparency, and flexibility. [42] By using the ferroelectric materials, the provided electric field intensity is larger because of its high dielectric constant, and it can also adjust carrier concentration of channel materials so that the detected range of wavelength can be wider. Besides, there is no suspension bond on the surface of these new two-dimensional materials; the layer is bonded by van der Waals force, and the thin layer sample can be obtained by mechanical stripping. Meanwhile, the fabrication of heterogeneous junction is not limited to the lattice matching required by the interface of the heterogeneous junction and can be stacked at any angle. [43,44] Graphene with high mobility can be used as a channel material for devices with wideband light absorption and fast response. However, graphene devices have the problem of large dark current, which can be effectively suppressed through the built-in electric field of the heterogeneous junction. The built-in electric field can effectively separate photogenerated carriers, thus obtaining a highly sensitive room temperature infrared detector. [45,46] Photogating was first used on photodetector in 2012 with a combination of graphene and quantum dots (QDs) to get an ultrahigh gain detector. Based on this mechanism, graphene-based detector structures are usually phototransistors made of graphene/semiconductor materials, such as Figure 4.2a [54] shows where graphene is used as a channel conductance material due to its high mobility.

Besides photogate to control photodetector, PTE, BE, and PTI effects can also contribute to the photodetector. In 1821, German physicist Seebeck discovered that in a closed-loop composed of two different metals, when light was in the contact area, photothermal carriers would form a potential difference due to temperature difference diffusion. This photoelectric conversion phenomenon is called the Seebeck effect or PTE. In 2010, Xu et al. found that this effect was also important in different doped graphene. [47-51] Figure 4.2b [55] shows the phenomenon that generates photocurrent, because the incident light causes the carrier temperature change, and the photothermal carrier diffuses due to the temperature gradient. Although eigen phonon scattering can only exists in limited phase space with weak graphene electron-phonon coupling, the hot carrier through and acoustic phonon scattering between the hot electron and the lattice can reach the temperature balance in a few seconds so that PET effect can be used for the production of the super-fast response of graphene detector.
Similarly, Figure 4.2c [56] shows the BE effect based on Wheatstone bridge structure. The basic principle is that when radiated by the electromagnetic wave, the resistance of thermosensitive material changes, due to the temperature change, and the radiated electromagnetic wave work rate can be obtained by measuring this resistance change. Moreover, Figure 4.2d [57] illuminates the PTI effect, which refers to the physical process where the light-generated carrier and the carrier in the metal are scattered. The temperature of some thermophoretic electrons and the energy are higher than the potential barrier so the incident low-energy photon can also excite the electrons to the conduction band and form the photocurrent. In the case of conventional graphene-based infrared detectors, these photo conversion effects are often not independent. For example, the PV effect and the PTE effect both are diode structures, and often occur at the same time. Their common feature is the increase in the concentration of photo-induced carriers. Both can generate hot electrons through electron-phonon interactions that persist after photoexcitation, and both rely on electron-electron scattering to dominate the energy relaxation of photo-induced carriers. [52,53]

**Figure 9.** (a) A phototransistor made of graphene/semiconductor materials based on photogating effect [54] (b) The scheme of the phenomenon that incident light generates the photocurrent. [55] (c) The BE effect based on the Wheatstone bridge structure. [56] (d) Scheme of PTI effect. [57]

Based on special optical and electrical properties and energy band structure, graphene-based infrared detectors have made progress in high responsiveness, fast response, and wide spectral detection. At present, the performance of graphene infrared detectors based on various device structures in terms of responsiveness and band is shown in Table 2, and some of their indicators have reached or exceeded the level of traditional detectors (Gr is graphene).
Table 2. The parameters of typical IR sensitive materials for photodetector

| Device structure | Mechanism       | Responsivity/ $A \cdot W^{-1}$ | Wavelength/ $\mu m$ | Response time | reference |
|------------------|-----------------|---------------------------------|--------------------|---------------|-----------|
| Metal/Gr/Metal   | PV              | ---                             | 1.55               | 2.1ps         | [58]      |
| Gr/PbS QDs       | Photogating     | $10^7$                          | 0.3-1.6            | 10-20ms       | [59]      |
| WS2/Gr/MoS 2     | PV              | >$10^4$                         | 0.4/2.4            | 53.6/30.3μs   | [60]      |
| Gr/Si/Gr         | PTI+Photogating | 1.9/1.1                         | 2.1/3.2            | ---           | [61]      |

4.3. Terahertz

Terahertz electromagnetic waves can detect the inherent chemical and physical characteristics of substances, and the low energy terahertz wave can be used to detect the organism without damage. Moreover, Terahertz technology may bring a significant technological revolution to the field of telecommunication. Due to the resonance enhancement of terahertz waves with plasmas, graphene terahertz surface plasmas can be used in many fields, such as terahertz lasers and terahertz antennas. [62] Figure 10a [64] shows an antenna-coupled graphene bolometer designed by Martin Mittendorff et al. in 2013, which was operated at room temperature. [63] Based on this fundamental device, scientists advanced it with other 2D materials to get a broader range of broadband photodetection, faster response time as short as 50ps, and other characteristics. Due to the tunability of graphene, strong localization and the ability of interacting with terahertz electromagnetic waves, graphene can also be used to make other tunable plasma devices. In 2012, Tamagnone et al. proposed to construct the Terahertz plasma antenna by using the graphene /Al2O3 / graphene laminated structure. Figure 10b is the schematic diagram of the structure of the graphene dipole antenna. [65] The substrate in the figure is GaAs. The two parts of the dipole are composed of graphene /Al2O3/graphene laminates. The purpose of the intermediate insulation layer is to control the conductivity of graphene. The antenna width $W$ is 7 m; the length $L$ is 11 m, and the 2 m gap in the middle represents the terahertz photoelectric mixer. Silicon lenses are used to improve the directivity of terahertz antennas. The construction of terahertz antenna can lay a foundation for the research of high efficiency and high integration of the graphene terahertz apparatus.

![Figure 10.](image)

In addition, graphene's plasma can also be coupled to photons. In 2011, Wang et al. etched graphene grown by chemical vapor deposition into a $2.5 \times 2.5 \text{mm}^2$ micron band array using standard lithography technology explored the coupling effect between plasma and light in graphene, and
pointed out that graphene could be used as a terahertz metamaterial. Experiments show that the plasma resonance can be controlled by changing the size of the micron band and the value of the gate pressure. The resonance frequency is inversely proportional to the square root of the micron band bandwidth, i.e., $\propto -1/2$, and is inversely proportional to the fourth square root of the carrier concentration, i.e., $\propto -1/4$. Figure 11a shows an atomic force microscope (AFM) image of an array of three-micron bands 1, 2, and 4 m wide. [67] Figure 11b shows the transmission spectrum of graphene micron bands with different widths when the carrier concentration is $1.5\times 10^{13} \text{ cm}^{-2}$. When the micron bandwidth decreased from 4 m to 1 m, the resonance frequency of the plasma increased from 3 THz to 6 THz. Figure 11c shows the transmission spectrum of graphene micron bands under different gate pressure regulation conditions. With the increase of the absolute pair value of negative gate pressure, the plasmon resonance also redshifts.

**Figure 11** (a) AFM scan of graphene micron band arrays. (b) When carrier concentration is $1.5\times 10^{13} \text{ cm}^{-2}$, the normalized transmission spectrum of graphene micron bands with different widths. [67] (c) When the square direction of incoming excitation light is perpendicular to the micrometer band, the penetration spectrum of the micrometer band with different gate pressure control bars is shown in the diagram when the square direction of incoming light of terahertz is parallel to the nanometer band. [68]

5. Conclusion
Photodetectors have evolved quite rapidly and changed quite a bit over the last few decades, whether in the infrared range, the ultraviolet range, or even the terahertz range. Traditional photodetectors that based on single inorganic material or inorganic materials combined with graphene are widely used now, but the result is not as good as required because of the poor performance in many essential indices, which reflects the quality and practicality. Therefore, alternative high-efficiency materials, such as graphene, that can be used in photodetector is significant. The potential of graphene is enormous because of its particular 2D structure and other excellent ability to combine with other materials, which can improve the critical characteristics of photodetectors, just like responsivity and EQE, to get higher-efficiency and higher-quality photodetectors. Graphene is not the only choice where many other 2D and 3D materials, such as h-BN, perovskite, and others, can be applied with the combination of graphene to break the limits.

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