Integrated Photonic Structure Enhanced Infrared Photodetectors

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The application fields of infrared photodetectors are quite extensive. Compared with traditional infrared photodetection materials such as IV and III–V semiconductors, newly emerging low-dimensional materials and quantum materials (e.g., 2D materials and quantum wells) have many advantages in different aspects, such as wide spectral range, low dark current, room temperature operation, and high processing compatibility. However, the performance of photodetectors based on low-dimensional materials is limited by the ultra small thicknesses, polarization selectivity, and the poor absorption efficiency. Therefore, improving the performance of infrared photodetectors based on low-dimensional materials has been a focus research task in recent years. The integration of photonic structures can improve the performance of infrared photodetectors, such as enhancing absorption efficiency, reducing the volume of active materials, and increasing polarization selectivity. Herein, different kinds of photonic structure integrated infrared photodetectors, roughly divided into two categories, namely, dielectric photonic structure integrated ones and metallic photonic structure integrated ones, are reviewed. The active materials include 2D materials, quantum wells, quantum dots, and carbon nanotubes.

1. Introduction

Infrared photodetectors (IRPDs)\cite{1,2,3} have been widely applied in many fields including telecommunication, surveillance, automotive, astronomy, and infrared imaging.\cite{4,5,6} Infrared radiation (IR) is a type of electromagnetic radiation with a frequency between microwave and visible red light, corresponding to a wavelength from 0.75 to 1000 μm. Matters above absolute zero (0 K, or −273.15 °C) can radiate infrared light. IR is divided into different wavebands, namely, near-IR (NIR, 0.75–3 μm), midwavelength IR (MWIR, 3–5 μm), and long-wavelength IR (LWIR, 8–14 μm).\cite{7} However, the method of classification varies from subject or technical field. Infrared detection was first used in the military field. Since the atmosphere is highly transparent to MWIR and LWIR light, infrared detection in these wavebands plays a critical role in many application fields such as night vision, meteorological monitoring, astronomy observation,\cite{8} and resources exploration.\cite{9} The performance of IRPDs is desired to be improved. The main bottleneck is to find feasible ways to improve the light absorption efficiency in a small volume of detection material, and thereby enhance the sensitivity.

According to the absorption law $\exp(-\alpha d)$,\cite{9} a large light–matter interaction length ($d$) is required to absorb the photons efficiently. As a result, the thicker the infrared detection material is, the higher the absorption efficiency is. However, thicker infrared detection materials usually lead to higher dark currents, higher material cost, and more defects for epitaxially grown quantum structures.\cite{6} In addition, since most infrared detection materials have high refractive indices, reflection loss becomes a serious problem for IRPDs. Integrating photonic structures\cite{10,11,12} with infrared detection materials seems to be a promising way to solve the aforementioned problems. The photonic structures integrated with infrared detection materials are able to increase the effective light–matter interaction length and producing an intensified local field at the infrared detection material while keeping the material in a small volume.\cite{13,14,15} Moreover, the photonic structures integrated with infrared detection materials can adjust the light coupling condition to a critical coupling status, where the reflection is zero and all the incident power is absorbed by the system. When anisotropic photonic structures are integrated with infrared
2. Infrared Photodetection Basics

The most basic principle of the detector is photoelectronic conversion, that is, to convert the absorbed photons into electron–hole pairs based on photoelectric effect.[20–22] The complementary metal oxide semiconductor (CMOS) image sensors and high-speed Si, GaAs photodetectors are constructed based on this effect. This conversion can also be achieved indirectly through other mechanisms, such as photovoltaic effect, the photothermoelectric effect, the bolometric effect, the photogating effect, and the plasma-wave-assisted mechanism.[23,24] In the following, we will describe the FOM that characterize the performance of IRPDs.

2.1. Figure of Merits

The performance of a photodetector can be gauged by some FOM, namely, the quantum efficiency, responsivity, NEP, and normalized detectivity.[6,24–26] Detectors in different applied fields emphasize different FOM, i.e., speed for optic communication, detectivity for astronomy,[4] and quantum efficiency for solar cell. In the following, these parameters are described in detail.

2.1.1. Responsivity

Responsivity (R) is a physical parameter that describes the photoelectric conversion efficiency of a device, which is related to device materials and wavelength (λ) of target light. The measurement of responsivity is the ratio of the output electrical signal in a photodetector to the incident power. The formula is expressed as: \[ R = \frac{I_{ph}}{P_{in}} \] or \[ R = \frac{V_{ph}}{P_{in}} \], and the unit is A W⁻¹. I_{ph} denotes photocurrent, and V_{ph} denotes photovoltage. Taking photocurrent as an example, it can be expressed by the formula: \[ I_{ph} = (P_{in} \eta \lambda)/(\hbar c) \], where e is the electron charge, \( \eta \) is the quantum efficiency (or external quantum efficiency, EQE), \( \lambda \) is the incident wavelength, \( \hbar \) is the Planck constant, and c is the light speed in vacuum. Therefore, the formula for responsivity also can be written as: \[ R = (\eta \lambda)/(hc) \]. \( \eta \) is defined as the ratio of the collected electrons to the number of all incident photons. The ratio of the generated electrons to the absorbed photons is the internal quantum efficiency (IQE).[23]

2.1.2. Noise Equivalent Power

The NEP is defined as the required incident IR power when the signal-to-noise ratio is unity, usually expressed in units of W * Hz⁻⁰.⁵. The NEP is also called the minimum power. Actually, the NEP is the minimum signal power that the detector can detect, and it marks the detectivity of a photodetector. The smaller the NEP, the higher the detectivity of a photodetector can reach.[4] One of the main causes of generating noises is the dark currents originate form thermal energy generated by carriers in devices.

2.1.3. Detectivity

Detectivity (D^0) is the quantity that characterizes the sensitivity of the photodetector, and it is proportional to the square root of the photosensitive area in a detector and the bandwidth. When the photosensitive area (A) of photodetectors is the unit area and the bandwidth (Δf) is 1 Hz, the signal-to-noise ratio obtained by the radiation of unit power is called the specific detectivity, which is recorded as D^s = (AΔf)⁰.⁵/NEP, in (cm²Hz)¹/² W⁻¹. For photodetectors, the higher the specific detectivity, the better the performance of the photodetectors. Considering that the noises in photodetectors primarily determined by dark current, the dark current measurement can be used to evaluate the detectivity of photodetectors.

3. Integrated Photonic Structures for Responsivity Enhancement

Low-dimensional materials, such as quasi quantum structures (e.g., quantum wells [QWs][27] and superlattice[28]), 2D materials (e.g., graphene and transition metal dichalcogenides [TMDs][23,29–35]), 1D materials (e.g., nanowires[36–40] and carbon nanotubes [CNTs][41,42]), and zero-dimensional materials (e.g., quantum dots [QDs][43,44]), are extensively studied for new infrared detection materials because they usually have extraordinary optoelectronic properties that are promising for high-performance infrared detectors.[45,46] However, the dimension mismatch between a low-dimensional material and the wavelength of infrared light results in poor light absorption. Integrating low-dimensional materials with photonic structures seems to be a promising way, since a properly designed photonic structure can efficiently couple the incident light into a subwavelength mode that concentrates the power inside the low-dimensional material and thus significantly enhance the responsivity. At present, infrared detectors of small volume and low dimensionality receive a lot of attention, and the rich active materials make the research of infrared detectors shine brilliantly. Some low-dimensional materials are promising for application in next-generation electronics and photodetection.[47–51] Typically, the photonic structures can be divided into...
two categories: metal photonic structures and dielectric photonic structures. Among them, the dielectric photonic structures can be subdivided into microcavity,\cite{52–56} photonic crystal (PhC), and waveguide,\cite{57–60} and the metal photonic structures can be subdivided into surface plasmon polariton (SPP) coupler, plasmonic cavity, and hot-electron injection structures. According to this classification, the photonic structures are reviewed as follows.

3.1. Dielectric Photonic Structures

3.1.1. Microcavity

Microcavities, as a type of microresonators, are able to confine light in a sub-micrometer region at a resonant wavelength, so they have been widely used to enhance the interaction between light and microscale objects.\cite{61–65} In this way, microcavities are proposed to enhance the absorptance and the photoresponse of infrared detection materials in microcavities. Graphene can respond to a wide spectral range of photons due to the zero bandgap,\cite{66} and have fast speed due to the high mobility.\cite{65} So graphene has been studied as a promising infrared detection material. However, the low absorptance of graphene is a bottleneck problem.\cite{52,66,67} It is naturally to use photonic structures to enhance the absorptance of graphene. Microcavities are one of the first type of photonic structures used to enhance the light–graphene interaction due to the relative simple design. Concerning the microcavity-graphene composite structure, when the graphene is placed at the strong local field created by the microcavity, optical absorption as well as thermal emission is significantly enhanced.\cite{61,67–70} As shown in Figure 1a, a graphene phototransistor is monolithically integrated with a microcavity consisting of distributed Bragg mirrors. It is demonstrated that the light absorptance of graphene integrated with the microcavity is increased to over 60% at the resonant wavelength (855 nm), which is 26 times of the light absorption in pristine graphene.\cite{52,67} this result can be observed from Figure 1b.

3.1.2. Photonic Crystal Slabs

PhC is a kind of periodic dielectric structures with properties of photonic bandgap (PBG).\cite{71–73} Photonic crystal slabs (PCSs) can couple the incident light into a localized mode confined in the slabs, and then enhance the interaction between light and the active materials integrated with the PCSs. By tuning the structure parameters to match the radiation loss to the absorption loss,\cite{71} highly efficient light coupling can be achieved and the absorptances of the active materials can be prominently enhanced. PCSs have been applied to QW infrared detectors (QWIPs)\cite{74} and graphene-based devices.

The PCS-integrated QWIP shown in Figure 2a is grown by molecular beam epitaxy, and its active region consists of 26 periods of QWs.\cite{75,76} This device showed excellent characteristics compared with a standard QWIP. As shown in the Figure 2b (solid line), photocurrent response of the PCS–QWIP has a sharp response peak at the resonant wavelength in the long-wavelength infrared range. The responsivity was enhanced by ten times due to the increased photon lifetime in the active region.\cite{75} Moreover, as a beneficial side effect, the truncated hole array in the slab reduced the volume of the active material and thus suppressed the dark current. On the basis of the enhanced responsivity and the suppressed dark current, the detectivity of the PCS–QWIP is 20 times higher than that of an ordinary QWIP (Figure 2c).

PCSs have also been used to improve the absorptance of graphene. PhC structures integrated with graphene can realize all-optical modulation.\cite{65} As shown in Figure 2d,e, Gan et al demonstrated that the light trapped in the subwavelength nanocavity in a PCS can significantly enhance the interaction between light and graphene. The absorptance of the graphene was increased to more than 45% under optimized conditions.\cite{53} In this way, the combination of graphene with PhCs is proposed for electro-optic modulation. By electrostatic gating a single layer of graphene on top of a PhC cavity, a ≈2 nm change in the cavity

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**Figure 1.** a) Schematic drawing of a graphene photodetector integrated with microcavity. The red part is graphene sheet, and the yellow parts are metal contacts. b) Spectral response of the single-layer graphene device. The dashed lines show calculation results: reflection R (red), transmission T (green), and absorption A (blue). The solid lines are measurement results: reflection (red), photocurrent (blue). A strong and spectrally narrow photoresponse is observed at the cavity resonance (855 nm wavelength). Inset: Theoretical result for normal incidence light. a,b) Reproduced with permission.\cite{43} Copyright 2012, American Chemical Society.
resonance line width and almost 400% (6 dB) change in resonance reflectivity was observed (Figure 2f).

3.1.3. Waveguide

Integrating low-dimensional active materials with waveguides is another good strategy to enhance light absorptance. When the light propagates along the waveguide, the light field continuously interacts with the active material. As a result, the length of interaction between light and the active material in this device is several orders of magnitude increased. In addition, waveguides are not resonant devices, so the bandwidth of the enhanced absorptance is much wider than that of microcavities and PCSs.

The successful integration of graphene and waveguides results in one to two orders of magnitude enhancement in absorptance. The coupled waveguide can absorb the evanescent optical wave propagating along the parallel plane of graphene, and enhance the graphene–light interaction, so as to achieve as high responsivity as possible. Figure 3a–c list three typical waveguide-integrated graphene photodetectors. Figure 3b is a waveguide-integrated graphene photodetector with a ground-signal electrode-ground (GND–S–GND) structure. Under the optimal condition, the responsivity of the device can reach 0.05 A W⁻¹. The waveguide can also be combined with chip-integrated graphene photodetector. Gan and his coworkers integrated a waveguide with a metal-doped graphene junction (Figure 3c), and the detector achieves a responsivity exceeding 0.1 A W⁻¹. Wang et al. also proposed a graphene/silicon-on-insulator (SOI) waveguide-integrated photodetector (Figure 3a) and achieved a responsivity of 0.13 A W⁻¹ in visible to midinfrared spectral range. The responsivity of above waveguide-integrated graphene photodetectors is one to two orders of magnitude higher than that of normal incidence graphene photodetectors.

In light of the excellent performances of waveguide-graphene composite photodetectors, waveguide structures were proposed to integrate with other 2D material photodetectors, such as MoS₂ and black phosphorus (BP) detectors. Figure 3d shows the cross section of a MoS₂ photodetector integrated with a silicon nitride photonic circuit, and the top of Si₃N₄ (Waveguide) is the MoS₂. The lateral excitation of waveguide can overcome the disadvantage of limited light absorption in 2D materials. The light–metal contacts interaction changes the light propagation.
The closer the metal contact is to the waveguide, the larger the photocurrent is realized in the photodetector. In Figure 3e, the responsivity of the waveguide-integrated MoS$_2$ photodetector can reach over 1000 A W$^{-1}$/C at low incident power. Youngblood et al. proposed a gated multilayer BP photodetector integrated on a silicon photonic waveguide, the structure of this device is shown in Figure 3f. As the 2D material, unlike graphene, BP has a finite and tunable bandgap, which enables the BP-based photodetectors to be applied in the visible to mid-infrared spectrum range. Moreover, the waveguide-integrated BP photodetector has the characteristics of high responsivity and low dark current. At the gate voltage $V_G = 0$ V and the bias voltage $V_{	ext{bias}} = 0.4$ V, the device achieves the optimal operation state, and the dark current is only 220 nA. It can be seen from Figure 3g that, the normalized photocurrent-to-dark-current ratio (NPDR) of BP photodetector is 85 mW$^{-1}$/C when the $V_{	ext{bias}}$ is equal to $-0.4$ V, which is four orders of magnitude higher than that of graphene photodetectors.

In addition to 2D materials, waveguides are also used to enhance the absorptance of GaAs/AlGaAs QWs. Tang et al. proposed the all-dielectric resonant waveguide (ADRW)-based QWIPs with high responsivity, fine spectral resolution, and a wide spectral range for infrared hyperspectral. This structure is shown in Figure 3a. The incident light is coupled into this structure to enhance the local field at the QWs, thus improving the responsivity of QWIPs. Most of the incident power is trapped in QWs with the top and the bottom contacts at the resonant wavelength (see Figure 3i), all the absorption peaks of the QWs are higher than 80%, the highest is around 95%.
Compared with plasmonic structure integrated QWIPs or PhC integrated QWIPs, the ADRW based on QW IRPDs has higher QW absorption efficiency and is easier to manufacture. In addition, the ADRW structure can expand the spectral detection range of single-color QWIRs without the assistance of various active materials [86].

3.2. Metallic Photonic Structures

3.2.1. SPP Coupler

SPPs are electromagnetic oscillations formed by the interaction of free electrons and photons on the surface of conductors and dielectrics [96]. When the optical wave (electromagnetic wave) is incident on the interface of metal and dielectric, the free electrons on the metal surface vibrate collectively. The electromagnetic wave and free electron on the surface of metals are coupled to form a near-field electromagnetic wave propagating along the surface of metals. If the oscillatory frequency of the electron is consistent with the frequency of the incident optical wave, there will resonate. In the resonant state, the energy of the electromagnetic field is effectively converted into the collective vibration energy of free electrons on the metal surface, and then a special electromagnetic mode is formed.

A SPP coupler can induce an intensified local field in a deep subwavelength scale due to surface plasmon resonance, and thus greatly enhance the interaction between light and active materials with small volumes. As a result, the photosresponse is improved due to the enhanced absorbance, and the dark current is reduced due to the small volume of the active material. Moreover, SPP coupler has frequency selectivity for excitation in SPP mode. Size of SPP coupler is designed to adjust the excitation wavelength of SPP mode, and select the frequency of photoresponse wavelength of detection materials. SPP couplers can be combined with graphene [97–99], MoS2 [100,101], BP [102], QDs [43], and QWs to improve EQE [103], responsivity, polarization selectivity [102], and so on. The corresponding Schematic illustration is shown in Figure 4a–e. Next, we will introduce these hybrid structures in detail.

Figure 4a is a schematic diagram of the integration of gold nanoparticles and graphene devices. This structure can achieve up to 15 times enhancement of photocurrent and EQE at 514 nm (wavelength) [97]. Similarly, the photocurrent of MoS2 transistors can be enhanced by threefolds at 632 nm with the help of gold nanoparticles (Figure 4b). Figure 4c shows a graphene device integrated with a typical grating coupler, which couples the incident light into a SPP wave at the metal–dielectric interface. By integrating the graphene layer at this interface, the graphene absorbance and thus the photosresponse are enhanced by 20 times [104].

![Figure 4](image-url)

**Figure 4.** a) A poly(methyl methacrylate) (PMMA) is dissolved away to leave gold nanoparticles on the surface of the graphene devices. Gray, blue, yellow, and white represent silicon, silicon dioxide, gold nanoparticles, and gold electrode, respectively. b) Schematic of few-layer MoS2 phototransistor with periodic Au nanoarrays. There is a 1 nm HfO2 layer between Au nanoarrays and MoS2 layer regarding as the passivation layer. It can protect the MoS2 layer from being damaged by Au nanoarrays deposition. c) Scanning electron microscopy micrographs of the graphene devices with plasmonic nanostructures. d) The structure of Bowtie antenna BP photodetector. e) A zoom-in SEM image of the 2DHA. The lattice constant is $a = 2.8, 3.0, \text{ and } 3.2 \mu m$, and the thickness of Au film is 50 nm. f) Summary of the enhancement times of the photosresponse of several kinds of photodetectors integrated plasmonic structure at resonant wavelength. The blue circles represent the SPP coupler integrated photodetectors, and the red circles represent the plasmonic cavity integrated devices. a) Reproduced with permission [103]. Copyright 2011, Springer Nature. b) Reproduced with permission [104]. Copyright 2015, Wiley-VCH. c) Reproduced with permission [105]. Copyright 2011, Springer Nature. d) Reproduced with permission [106]. Copyright 2018, American Chemical Society. e) Reproduced with permission [43]. Copyright 2010, American Chemical Society.
BP can be used for sensitive polarization photodetection in near-infrared due to its high mobility, low direct bandgap, and anisotropy. Venuthurumilli and his colleagues designed a plasmonic bowtie antenna structure, as shown in Figure 4d.[102] This design can enhance the absorption of the bowtie plasmonic structure, and then increase the photocurrent by 61% at the near-infrared wavelength of 1550 nm. Chang et al. combined the 2D hole array (2DHC) with the semiconductor InAs QDs (Figure 4e), and the infrared photoresponse of this hybrid structure is enhanced by 1.3 times at the plasmonic resonance wavelength (8.8 μm).[43] Similarly, Wu et al. reported a periodic hole array in gold film integrated with In_{0.53}Ga_{0.47}As/InP QWIP. Compared with other QWIPs, In_{0.53}Ga_{0.47}As/InP QWIP coupled with surface plasmon mode has narrower full width at half maxima (FWHMs) of responsivity spectrum and higher detectivity. The peak responsivity of the photodetector at 8 μm was ≈ 7 A W⁻¹.[95] We make a summary of the enhancement multiple of the optical response of several kinds of photodetectors integrated plasmonic structure at resonant wavelength, as shown in Figure 4f. Among them, refs. [62], [105], and [90] are about plasmonic cavity integrated infrared detectors. In principle, plasmonic cavities can lead to higher absorptance enhancement of infrared detectors than common SPP couplers.

### 3.2.2. Plasmonic Cavity (Integrated with QWIP, Graphene)

A plasmonic cavity is typically based on the metal–insulator–metal (MIM) structure with a limited lateral dimension that determines the cavity length (Figure 5). The two metal–insulator interfaces both support SPP waves. When the SPP waves at the two interfaces couple with each other, a plasmonic waveguide mode is formed. As it propagates laterally, it gets reflected at the boundaries so cavity resonances occur at certain wavelengths. At a resonance condition, an intensified local field is built up between the two metal pieces and within the insulator. If an active material is placed at the strong local field, a prominent absorptance enhancement is expected. Since the transmission is blocked and the radiation loss can be effectively tuned by adjusting the geometries of the MIM structure, perfect absorption can be achieved at a critical coupling condition. In this sense, a plasmonic cavity is more advanced than a normal SPP coupler to locally confine the light power and thus to enhance the absorptance of the active material. The hybrid structures of plasmonic cavity integrated with graphene, QWIP, and TMDs have various of advantages. In the following, we will focus on the first two cases.

The electrical field of a plasmonic cavity mode is mainly along the vertical direction, which can match with some anisotropic...
materials. For example, GaAs/AlGaAs QWs can only absorb the optical field whose electrical field is perpendicular to the QW plane.\[^\text{106}\] The direction of the electrical field of the incident light is parallel to the QW plane, and it is difficult to generate optical field with electrical field perpendicular to the plane of QW in general photonic structures. Therefore, plasmonic cavity is particularly suitable for QWs. As shown in Figure 5d, Sirtori et al. have studied a long-wavelength (9 μm) infrared QW photodetector with an absorption layer of GaAs/AlGaAs QWs.\[^\text{62}\] The absorbing region is inserted in an array of double-metal patch plasmonic cavities. The plasmonic cavities provide a subwavelength electric field limitation and they are used as antennas to improve the responsivity of the device by enhancing the local field in the thin layer semiconductor absorber. When the plasmonic cavities approach a critical coupling status, the photon collection area becomes much larger than its electrical area and there is little reflection. As a result, a very strong light absorption was achieved in the QWIP and the responsivity is enhanced by seven times, as shown in Figure 5e.\[^\text{62}\] In addition, the dark current of the device was greatly reduced since a large portion of the QW material was etched away. As a result, this plasmonic cavity integrated QWIP can operate at room temperature for 9 μm infrared light detection.

Plasmonic cavities are also effective to enhance the absorptance of 2D materials such as graphene. Compared with the general SPP coupler, one of the advantages of plasmonic coupling is that it can tune the critical coupling and achieve 100% complete absorption of incident light. Guo et al. demonstrated a hybrid structure which can overcome photoresponse cancellation at the two contacts and enhance the responsivity of the device.\[^\text{107}\] Figure 5b shows the metal–graphene–metal (MGM) structures integrated with plasmonic nanocavity and subwavelength metal grating, respectively. It is shown in Figure 5c that the responsivity of the plasma cavity integrated graphene is 11 times higher than that of the metal grating integrated graphene at their respective resonant wavelengths.

### 3.2.3. Hot-Electron Injection (Integrated with TMDs, Si)

The photonic structures related to hot-electron injection are different from SPP couplers and plasma microcavities. SPP couplers and plasma microcavities help to enhance the absorptance and thus the response of the active materials themselves, whereas hot-electron injection can give the materials without infrared response the ability to detect infrared signal. The hot-electron injection based infrared detection makes use of the high energy hot electrons from the nonradiative decay of the surface plasmon.\[^\text{105}\] These hot electrons can overcome the Schottky barrier between the metal and the semiconductor to produce photocurrent, whereas the electrons without plasmonic excitation do not have enough energy to pass over the Schottky barrier.\[^\text{108,109}\] The height of the Schottky barrier is adjusted to meet the requirements of response to the corresponding infrared signal. The infrared response has nothing to do with the energy band of the semiconductor itself, which is all due to the energy of the hot electrons and the Schottky barrier. This principle provides additional bandwidth for photodetectors and photovoltaic devices.\[^\text{110}\] The two most representative materials that can be integrated with the surface plasmon metal structure to produce hot-electron injection effect are TMDs and Si. Thus, this section mainly introduces the research works on the integration of surface plasmon metal structures with these two kinds of materials.

As shown in Figure 6a, for the first time, Wang et al. fabricated a plasma resonator integrated bilayer MoS\(_2\) film hot electrons injection device.\[^\text{110}\] The plasmonic resonance of the patches on the electrodes creates a lot of hot electrons with energy higher than the Schottky barrier. These hot electrons mainly contribute to the infrared photoresponse of the MoS\(_2\) device. Figure 6c shows the injection process of the hot electrons from a metal electrode into MoS\(_2\). The device produces obvious infrared response under 0.6 V bias (Figure 6b). Under 1070 nm light illumination, the responsivity is as high as 5.2 A W\(^{-1}\) with a photo gain of 10\(^5\).\[^\text{110}\] In comparison, a normal MoS\(_2\) detector cannot only respond to light with a wavelength shorter than 850 nm. Hong et al. studied plasmonic hot-electron induced photocurrent response at MoS\(_2\)–metal junctions.\[^\text{111}\] At the metal edge, the surface plasmon waves are much more efficiently excited by the light polarized perpendicular to the edge than excited by the light polarized parallel to the edge. Therefore, the photoresponse has an obvious polarization dependence as shown in Figure 6d.\[^\text{111}\]

Next, we will discuss Si-based hot-electron injection devices.\[^\text{108,112–114}\] As shown in Figure 7a, Knight et al. integrated Si-based photodiodes with active optical antennas to prepare Si-based hot-electron injection device.\[^\text{108}\] The nanoantenna and the photovoltaic conversion diode are combined to form a new type of photovoltaic detection device. Based on hot-electron injection and plasmonic resonance, this device can respond to infrared light with a wavelength as long as 1700 nm. In comparison, a normal Si device cannot respond to light with a wavelength longer than 1100 nm.\[^\text{108}\] Zhai et al. deposited a nanotin gold layer on the Si micro pyramid structure to form Si-based hot-electron injection device.\[^\text{114}\] Figure 7c shows the fabrication process of the gold film covered silicon micro pyramid. As shown in Figure 7d, either front side or back side illumination can produce a good response to infrared light.\[^\text{114}\] The principle of hot-electron injection devices is simple and the fabrication of the plasmonic coupling structures is mature. Therefore, these kinds of devices have a broad prospect for infrared detection in the near-to-midinfrared regime.

### 4. Light Coupling Optimization: Critical Coupling and Suppression of Power Loss in Photonic Structures

Although light coupling structures can significantly increase the total absorptance, they can also consume a big amount of light power. Especially for metallic light coupling structures, the ohmic loss is often higher than the power absorbed by the active material.\[^\text{115–118}\] In a photonic structure integrated photodetector, the absorption competition between the light coupling structure and the active material needs to be carefully manipulated. Otherwise, the performance enhancement would be very limited. Two specific studies about increasing the absorptance of the active material and suppressing the ohmic loss in a composite
of a plasmonic cavity and an active material are reviewed as follows.

Zhen et al. proposed a promising method to achieve this goal: increasing the volume of the active material in the plasmonic cavity, and meanwhile switching the cavity mode to a higher-order resonance or creating real facets as the cavity boundaries. The first action is to enhance the absorption rate of the active material, so the active material can overwhelm the metal in the absorption competition, and consequently the useful absorption is enhanced and the ohmic loss is suppressed. The second action is to prevent the radiation $Q$ factor from a too quick decline as the active volume increases, so the system is maintained close to the critical coupling status for efficient light capture.\cite{118} Figure 8a shows the typical plasmonic cavity structure for enhancing the photoelectron conversion process.\cite{118} Figure 8b shows the phase diagram of the total absorption of the device as a function of $Q_{rad}$ and $Q_{abs}$. The arrows from (b) to (c) on the phase diagram represent the optimization process: "(b) to (c)" corresponds to increasing the thickness of the active material; "(c) to (d)" corresponds to switching the plasmonic cavity resonance from the first order to the third order; "(d) to (e1)" corresponds to creating facets as the cavity boundaries; "(e1) to (e2)" corresponds to further increasing the thickness of the active material. For plasmonic cavity integrated QWIPs as an example, the optimization process increases the absorptance of the QWs to 82%, and suppressing the ohmic loss from 40% to 18%.\cite{118} Furthermore, the author applies this method to the plasmonic cavity integrated GaAs device, which can operate in the near-infrared band. After modification, the absorption capacity of the active material enhances to 78% and reduces the ohmic loss to 20% at the wavelength close to the forbidden band.\cite{118}

As shown in Figure 8c, Deng et al. proposed an absorption-enhanced all-semiconductor plasmonic cavity integrated THz QWIP on the basis of previous research work.\cite{119} In this system, both all-semiconductor plasmonic cavity and THz QW active material can be grown by molecular beam epitaxy simultaneously. Therefore, the optimal film quality and interface conditions can be ensured, the preparation process of plasmonic cavity can be simplified, meanwhile, the ohmic loss can be reduced also. In the same way as the former, the coupling effect between the all-semiconductor plasmonic cavity and active material is optimized. Through the optimization of the

Figure 6. a) Schematic of the asymmetric plasmonic device in which the yellow Au structures (RWS) are resonant whereas the green Au structures (NRWs) are nonresonant. b) Responsivity under $E_y$ polarization at 0.6, −0.6, and 0 V biases (red, blue, and green dots, respectively). The solid lines are the fit to the data. The inset is a zoom-in of the photocurrent and the fitting at 0 V bias. c) A schematic diagram of the injection of hot electrons from a metal electrode into a MoS$_2$. $E_g$ is the bandgap of MoS$_2$. d) Under the illumination of 850 nm, the normalized photocurrent intensity on the MoS$_2$–metal junction (200 nm wide metal electrode) is taken as a function of the polarization of the incident light. In the process of measurement, the gate voltage and source–drain bias are 0 V. a,b) Reproduced with permission.\cite{110} Copyright 2015, American Chemical Society. c,d) Reproduced with permission.\cite{111} Copyright 2015, American Chemical Society.
plasmonic cavity, the absorption competition between the QW and the doped GaAs is manipulated while the system is maintained around the critical coupling state. Thus, the absorptance of the QW is 13.2 times higher than that of the standard 45° facet device. Light coupling optimization improves the competitive absorption of the QWs and reduces the ohmic loss to achieve higher device performance. This light coupling optimization method pays more attention to the absorption enhancement of the active material and thus the device performance. It is an important way to improve the performance of infrared detectors, and worthy of more in-depth study in the field of infrared detection.

Figure 7. a) Representation of a single Au resonant antenna on an n-type silicon substrate. b) Polarization dependence of photocurrent for a 140 nm × 50 nm antenna excited at λ = 1500 nm (green points), exhibiting a cos^2 θ angular dependence (gray line). c) Schematic picture of the fabrication process of the gold film covered silicon micropyramid. d) In front illumination mode and back illumination mode, the responsivity spectrum of silicon micropyramid structure which is covered by gold film with 30 nm thickness. Illustration: schematic diagram of device structure and lighting direction. a,b) Reproduced with permission.[108] Copyright 2011, Science. c,d) Reproduced with permission.[114] Copyright 2020, American Chemical Society.

Figure 8. a) Sketch of the plasmonic cavity integrated with active material. h denotes the thickness of the active material, s is the metal patch width, and p is the period of the metal patches. b) Phase diagram of the on-resonance total absorption versus Q_rad and Q_abs. The white dashed diagonal shows the critical coupling status; the thickness of Au patches is 0.1 μm. c) Sketch of an all-semiconductor plasmonic cavity integrated QWIP. In which, h denotes the thickness of the QW, s is the GaAs stripe width, and p is the period of the GaAs stripe. a,b) Reproduced with permission.[118] Copyright 2019, WILEY-VCH. c) Reproduced with permission.[119] Copyright 2020, Optical Society of America.
5. Photonic Structures for Polarization Discrimination Enhancement

5.1. Deep Subwavelength Mode Volume Induced High Polarization Extinction Ratio

Once the antenna (i.e., the top metal piece) of a plasmonic cavity is shaped into an anisotropic geometry (such as a strip), the plasmonic cavity becomes polarization selective.\cite{63,91,120,121} For the incident light polarized perpendicular to the strip, the plasmonic cavity resonance can be excited and the light power can efficiently flow into the cavity mode. In this way, a strong local field is built up and the interaction between this field and the active material in the plasmonic cavity is prominently enhanced. In contrast, the incident light polarized parallel to the metal strip is mostly reflected, which suppresses the interaction between the light field and the active material. Since the plasmonic cavity mode is in the deep subwavelength scale, the polarization selectivity is not affected by light diffraction. Concerning the infrared polarization detection by a focal plane array, the light diffraction effects due to the limited pixel size (less than ten wavelengths) seriously reduce the polarization extinction ratio (PER).\cite{63} The integration of anisotropic plasmonic cavities and active materials seems to be a promising way to solve this problem, which is of great significance in infrared polarization detection. The specific examples are as follows.

Zhang et al. integrated an anisotropic plasmonic cavity array with a graphene phototransistor for polarization detection.\cite{121} In this device, as shown in Figure 9a, the plasmonic cavity is formed by a bottom metal plane, a dielectric ($\text{Al}_2\text{O}_3$) spacer, and a metal strip on the top. The graphene layer is set below the metal strip and on the $\text{Al}_2\text{O}_3$ spacer. The phototransistor is formed by connecting the graphene layer with two contacts. The bottom metal plane together with the dielectric spacer also functions as a gate for the transistor. This structure not only enhances the light absorbance of the graphene but also endows the graphene transistors with the ability of light polarization discrimination. As shown in Figure 9b, the plasmonic cavity enhances the photoresponse of the transverse magnetic (TM) wave, but suppresses the photoresponse of the transverse electric (TE) wave, and makes the PER as high as 30, which is 3–10 times higher than the all previously reported values for photonic structure enabling polarization detection by 2D materials.\cite{102,104} Meanwhile, for the selected polarization light, due to the enhancement of the local field by the plasmonic cavity, the light response intensity of the device is enhanced by 70 times.

As shown in Figure 9c, Zhou et al. integrated an anisotropic metal plasmonic cavity with a GaAs/AlGaAs QWIP to fabricate high-PER superpixel devices. A superpixel contains four subpixels with grating directions of 0°, 45°, 90°, and 135°, respectively.\cite{63} Figure 9d shows the photocurrent response of the subpixel with the 0° grating to different linearly polarized light,

![Figure 9](https://example.com/figure9.png)

Figure 9. a) Sketch of the plasmonic cavity integrated graphene phototransistor. b) Photoresponse spectra for TM and TE waves. c) SEM image of the super pixel of PMC–QWIP, including angle definition of the gratings. d) Photocurrent spectra versus wavelength at different polarization angles. a,b) Reproduced with permission.\cite{121} Copyright 2014, AIP Publishing. c,d) Reproduced with permission.\cite{63} Copyright 2018, Springer Nature.
the device shows good polarization sensitivity. The corresponding results are summarized and shown in Table 1 comparison of the data, the extinction ratios of the four polarization directions are all higher than 100, with a highest PER of 136. In comparison, previously reported PERs for integrated long-wave infrared polarization detection were lower than 10.\textsuperscript{[122]} There is no doubt that the plasmonic cavity integrated polarization QWIP is a significant progress in the field of infrared polarization recognition.

### 5.2. Improving Active Material Absorptance and Device Polarization Extinction Ratio by Double Polarization Selection

There are many infrared detection materials with anisotropic absorptivity. CNTs absorb the light polarized along the tubes more efficiently than absorb the light polarized perpendicular to them. Most 2D materials absorbs the in-plane polarized light much more efficiently than the out-of-plane polarized light.\textsuperscript{[123,124]} QWs only absorb the light polarized perpendicular to the growth direction. If the integrated photonic structure is carefully designed so that the local field polarization matches the main absorption axis of the active material, the absorptance of the active material can be efficiently enhanced.\textsuperscript{[42,125,126]} Furthermore, since the photonic structure and the active material are both polarization selective, the device polarization can be significantly enhanced once the double polarization selection is in operation. We will summarize the related work, as follows.

Guo et al. studied the MIM structure integrated 2D materials. Based on different geometric dimensions, the MIM structure can operate either in the magnetic resonator form (Figure 10a) or the metasurface Salisbury screen form (Figure 10b). The magnetic resonator provides a local field at the 2D material mainly perpendicular to it, whereas the metasurface Salisbury screen form creates a local field at the 2D material mainly parallel to it. As shown in Figure 10c, by changing the MIM structure from the magnetic resonator form to the metasurface Salisbury screen form, the absorptance of the graphene integrated with the MIM structure is enhanced by 4.2 times in the long-wavelength infrared range, the ohmic loss is suppressed by 7.4 times, and the detection bandwidth of the device is expanded by 3.6 times.\textsuperscript{[125]} In addition, Guo et al. also studied the performance improvement of MIM structure integrated monolayer BP and MIM structure integrated monolayer MoS\textsubscript{2}. For monolayer BP, by changing the MIM structure from the magnetic resonator form to the metasurface Salisbury screen form, the absorptance enhancement at the wavelength of 3.5 \textmu m is increased by 5.4 times, and the bandwidth enlarged by 1.8 times. For monolayer MoS\textsubscript{2}, the averaged absorptance in the visible–near-infrared range is enhanced by 4.4 times from 15.5\% to 68.1\%.\textsuperscript{[125]} It is revealed that the local field polarization with respect to the anisotropic active material can significantly influence the device performance.

In addition to 2D materials, CNTs are anisotropic for infrared absorption. As shown in Figure 11a, Chen et al. studied an optical antenna integrated aligned single-walled CNT (SWCNT) film as a far infrared detector.\textsuperscript{[42]} The film is shaped into a long belt and connected to two contacts at the two ends. The SWCNTs are aligned perpendicular to the electronic

**Table 1.** The experimental extinction ratio of the super pixel of PMC–QWIP. Reproduced with permission\textsuperscript{[63]} Copyright 2018, Nature Publishing Group.

| Grating orientation | Grating symbol | Measured extinction ratio |
|---------------------|---------------|--------------------------|
| 0\degree             | G0              | 136                       |
| 90\degree            | G90             | 131                       |
| 45\degree            | G45             | 116                       |
| 135\degree           | G135            | 122                       |

\textsuperscript{a}The grating angle is 0\degree. \textsuperscript{b}The grating angle is 90\degree. \textsuperscript{c}The grating angle is 45\degree. \textsuperscript{d}The grating angle is 135\degree.

![Figure 10](https://example.com/f10.png) **Figure 10.** a) Sketch of the MIM–graphene composite in the magnetic resonator form. $\rho = 183.5$ \textmu m, $w = 105.4$ \textmu m, and $h = 8.26$ \textmu m are the period, the metal strip width, and the insulator layer thickness, respectively. The red arrow represents the direction of polarization of incident light. b) Sketch of the MIM–graphene composite in the metasurface Salisbury screen form with $\rho = 35$ \textmu m, $w = 33$ \textmu m, $h = 30$ \textmu m. The metal strip thickness for both cases is 80 nm. The incident light is polarized along the x axis. c) The absorption spectrum of 2D material and metal in the device of (a) and (b). a–c Reproduced with permission.\textsuperscript{[125]} Copyright 2021, Optical Society of America.
transportation direction. The SWCNT film is diversely doped to form a p–n junction at the center. Once the incident light is focused at the junction, a photoresponse is created due to the photothermoelectric effect. The bowtie antenna integrated at the center of the film concentrates the incident light at the junction region. Since the bowtie antenna is aligned along the SWCNTs, the absorptance of the SWCNTs and the PER are both significantly enhanced. Over the range from 0.5 to 1.5 THz, the responsivity is enhanced by one to two orders of magnitude at different resonant frequencies and the peak

**Figure 11.** a) Sketch of the aligned SWCNT film. b) Sketch of the IRPD based on the aligned SWCNT belt. c) The sketch for the bowtie antenna integrated aligned SWCNT belt. d) Light response spectra of the two devices to the lights with different frequencies, the red line is polarized light parallel to the y axis, and the black line is polarized light parallel to the x axis. a–d) Reproduced with permission. Copyright 2020, The Royal Society of Chemistry.

**Figure 12.** a) Sketch of the asymmetric composite structure with QWs and GaAs contacts. b) Sketch of the asymmetric composite structure with HgCdTe. c) CPERs for the asymmetric composite structure with the QWs (magenta) and with HgCdTe (green). d) Sketch of the asymmetric composite structure with encapsulated InAsSb nanowire array. e) Sketch of the asymmetric composite structure with the InAsSb film. f) CPERs for the asymmetric composite structure with the encapsulated InAsSb nanowire array (magenta curve) and InAsSb film (green curve), respectively. a–f) Reproduced with permission. Copyright 2020, WILEY-VCH.
PERs are all bigger than 700, which are 16 to 320 times higher than that of the aligned SWCNT belt without the antenna. It is worth noting that the peak PER at 0.5 THz reaches 13608. [14]

The double polarization selection is not only effective to enhance linear PER but also effective to enhance circular PER (CPER). Chu et al. studied the CPER of the chiral metamaterial integrated QWs and that of the chiral metamaterial integrated HgCdTe (MCT). The device structures are shown in Figure 12a,b. [126] As shown in Figure 12c, the CPER of the QW absorptance is close to 14 at the wavelength around 1 μm, whereas the CPER of the MCT absorptance is less than 1.3. [126] The big contrast between the QWs and the MCT clearly shows that the double polarization selection from the photonic structure and the anisotropic active material can lead to higher CPERs. Except the common GaAs/AlGaAs QW, other anisotropic infrared absorption materials, such as InAsSb nanowires, CNT, and some monolayer 2D materials, present well application potential in the field of infrared detection. As shown in Figure 12d,e, vertical InAsSb nanowire arrays and InAsSb film are integrated with the chiral metamaterial to form circular polarization infrared detectors. As shown in Figure 12f, at the operating wavelength of 5 μm, the CPER of the device based on the InAsSb nanowire array (anisotropic) is 12.6, which is seven times higher than that of the device based on the InAsSb film (isotropic). [126] In comparison, the CPERs of the active material absorptance of the photonic structure empowered circular polarization infrared detectors are theoretically lower than 2.5 [127] and experimentally lower than 2. [128-130] Therefore, the double polarization selection is demonstrated to be a promising way to achieved circular polarization infrared detectors with high CPER.

6. Conclusion and Outlook

In this article, the related works on integrated photonic structure enhanced IRPDs are reviewed. The photonic structures are divided into two categories: dielectric photonic structures and metallic photonic structures. The dielectric photonic structure includes three kinds of structures: microcavities, PhCs, and waveguides. Since there is no metal structure integrated with the active region, there is no competitive light absorption with the active materials, which is a unique advantage of dielectric photon structure. Metallic photonic structures include SPP coupler and plasma cavities. Due to the ultra small mode volume in the deep subwavelength scale, metallic photonic structures are very effective to enhance the interaction between infrared light and the photodetection materials in small volume. The photonic structures can be integrated with the low-dimensional infrared photodetection materials appropriately. And, this is an important strategy to improve the performance of low-dimensional infrared photoelectric detection devices. According to the characteristics of different kinds of PhCs, they can be applied to improve the infrared detection performance of graphene, BP, TMDs, QWIP, etc. based infrared detectors. The introduction of PhCs can well break the barriers that limit the development of infrared detectors, such as large dark current noise, shrinking absorption layer leading to reduced light absorption, low sensitivity, and so on. How to design the integrated system of photonic structures and IRPDs to improve the overall performance of the device is a crucial problem that needs to be carefully considered. For this issue, the process of optimal coupling is described in detail, and some excellent photon structures are reviewed as well. At the end part of the review, we introduce in detail the important advantages of photonic structure in polarization discrimination, which can not only endow isotropic devices with polarization discrimination but also integrate with anisotropic devices to improve their polarization discrimination largely.

There is no doubt that it is an important way to integrate infrared detectors with photonic structures for detection performance improving. At present, to integrate photonic structures with infrared detectors, many kinds of photonic structures with different shapes have been designed. In the future, more attention should pay on the fabrication processes of photonic structure to fit different kinds of infrared photodetection materials, grown by epitaxy or chemical vapor deposition (CVD) for practical applications. Meanwhile, the essence of the photonic structures for IRPDs is to manipulate the light field to selectively enhance the interaction between the light and the photodetection materials based on frequency, polarization, photon spin, or even phase. In this sense, more novel and efficient regulation method of light field should be developed urgently in near future.

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Conflict of Interest

The authors declare no conflict of interest.

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