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Research progress on metasurface-enhanced photodetectors: a review

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Abstract: The rapid development of technology has introduced new requirements for photodetector performance. The fabrication of high-performance multifunctional photodetectors with a broad spectral detection range and high detection accuracy has become an important research goal and development trend in photodetection. Metasurfaces, which are two-dimensional artificial materials with subwavelength-scale structural units, can flexibly regulate the basic characteristics of the light field, such as the amplitude, phase, and polarization. This further optimizes the performance of photodetectors and endows them with new functions, providing an effective and novel approach for developing high-performance, highly integrated multifunctional photodetectors. This paper reviews the latest progress in metasurface-based photodetectors in recent years, focusing on four aspects: light absorption enhancement, spectral response regulation, response speed improvement, polarization sensitivity and high-dimensional photodetectors. The development prospects and existing challenges are also discussed in this paper.

Keywords: metasurfaces; photodetectors; enhancement mechanism; performance optimization

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1 Introduction

Photodetectors are electronic devices that convert optical signals into electrical signals. Owing to their small volume, lightweight structure, fast response speed, and high sensitivity, they have extensive applications in fields such as communication, imaging, sensing, military, and medical care^{1–5}. Currently, reported photodetectors have achieved a responsivity of up to 91.24 A/W, a specific detectivity of 1.15×10^{11} Jones, a response time as low as the microsecond level^{6,7}, and a spectral detection range covering from the ultraviolet (UV) to the terahertz band^{8–12}, demonstrating excellent optoelectronic performance. However, with the rapid development of science and technology, the development of multifunctional photodetectors with high responsivity, wide spectral detection range, and high detection accuracy is crucial to meet the needs of different application scenarios^{13–16}. In recent years, researchers have continuously explored diverse material systems, structural design

schemes, and preparation processes in hopes of designing photodetectors that meet the requirements^{17–19}. Nevertheless, the design of high-performance photodetectors has become increasingly challenging owing to the inherent properties of materials, such as low light absorption efficiency, weak chirality or anisotropy, low carrier mobility, and limited response time. In particular, significant obstacles remain in the fabrication of broadband, high-dimensional, continuous photodetectors capable of acquiring multidimensional optical information^{20–22}.

Metamaterials are artificial materials with unique physical properties that are achieved through the design of their microstructures. When their thickness is smaller than the wavelength of the incident light, they are referred to as metasurfaces^{23,24}. By adjusting the geometric shape and material composition of periodic arrays in metasurfaces, it is possible to regulate the amplitude, phase, polarization, and spectral characteristics of light fields^{25–29}, thereby optimizing the key performance of photodetectors, such as responsivity

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and response speed. Moreover, the integration of metasurfaces can endow photodetectors with advanced functions, including polarization separation, efficient spectral analysis, and multidimensional light-field reconstruction²². In 2018, Xu et al.³⁰ achieved a relatively broadband enhancement of the efficiency of organic photodiodes using phase-gradient metasurfaces, verifying the feasibility of metasurfaces for improving the performance of low-absorption photodetectors and light-absorbing materials. In 2020, Li et al.³¹ reported a polarimeter composed of four graphene-silicon (Si) photodetectors integrated with metasurfaces. Through four metasurfaces with different geometric chiralities and anisotropies, discriminative optical responses to circular and linear polarizations can be realized, thereby enabling the acquisition of Stokes parameters of incident infrared light with arbitrary polarization states. Such studies indicate that the emergence of metasurfaces provides an effective and novel approach for the development of high-performance, highly integrated, and multifunctional photodetectors.

This review summarizes the latest research progress on the application of metasurfaces in photodetectors in recent years, aiming to provide a reference for future studies on the application of metasurfaces in optoelectronic devices. First, this study introduces the principle of light-field regulation using metasurfaces, followed by an overview of the main performance evaluation parameters of photodetectors. Then, it focuses on summarizing the latest research advances of metasurface-based photodetectors in recent

years around four aspects: light absorption enhancement, spectral response regulation, response speed improvement, polarization sensitivity and high-dimensional photodetectors (Figure 1). Finally, the future development prospects and trends of metasurface photodetectors are discussed in this review.

2 Principles and evaluation parameters

2.1 Principle of light field regulation by metasurfaces

Metasurfaces can achieve effective light manipulation through subwavelength periodic structural units, which induce resonant absorption, control diffraction, and generate localized field enhancement effects on the incident light^{32–34}. Furthermore, by optimizing the shape, size, and spatial arrangement of the microstructural units of metasurfaces, the processes of light absorption, reflection, and transmission can be precisely regulated^{35–37}, enabling customized modulation of parameters such as light amplitude, phase, and polarization.

When incident light irradiates a metasurface, resonance occurs between the metasurface and incident light, thereby altering the local field intensity. In metallic metasurfaces, resonance manifests as plasmon excitation, including localized surface plasmon resonance (LSPR) and surface plasmon polaritons (SPP)^{38,39}. Both resonance modes induce local field enhancement and energy dissipation⁴⁰, and thus

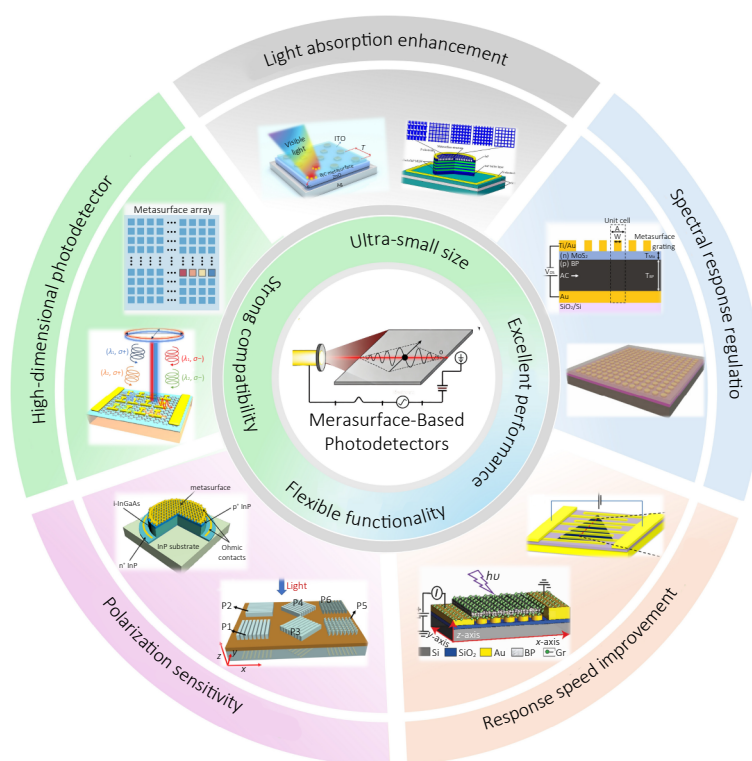


Fig. 1 | Overview of high-performance metasurface-based photodetectors.

can affect the amplitude of the transmitted or reflected light. In dielectric metasurfaces, resonance appears in the form of Mie scattering resonance⁴¹, which includes optical modes such as electric and magnetic dipoles. When the wavelength of the incident light matches the resonant wavelength of these resonance modes, resonantly enhanced absorption or scattering is generated, thereby changing the intensity of the transmitted or reflected light. Notably, the change in electromagnetic field distribution caused by the resonance between light and the metasurface structure can also lead to phase jumps during light reflection or transmission^{42,43}. Additionally, resonance exhibits different response characteristics to light of different polarization states, which can enhance the absorption, scattering, or transmission of light with specific polarization states while weakening the optical response of other polarization states^{44,45}.

In addition, when linearly polarized light passes through a metasurface with an anisotropic structure, its polarization direction rotates, thereby introducing a geometric phase related to the polarization rotation angle⁴⁶, and this geometric phase modulation can also achieve polarization state conversion⁴⁷. Meanwhile, by introducing a phase gradient on the metasurface and utilizing the differences in the phase responses of light with different wavelengths owing to dispersive properties^{48,49}, the separation or focusing of light with different wavelengths can be realized.

2.2 Performance evaluation parameters of photodetectors

Photodetectors are based on the photoelectric effect generated by the interaction between light and matter and can convert incident optical signals into measurable electrical signals⁵⁰. The basic principle is that when photons are absorbed by the photosensitive material in the device, the energy they carry excites electrons in the material, causing them to transition from a bound state to a free state, thereby generating freely movable charged particles, namely, electron-hole pairs. Photodetectors are primarily used to detect optical information, such as light intensity, spectrum, and optical pulses. The performance evaluation parameters of these devices are key indicators for measuring their detection capability, response characteristics, and operational stability, including responsivity, quantum efficiency, and response time^{51–53}.

Photoresponsivity (R) is an important parameter for evaluating photodetector performance. This reflects the efficiency which a photodetector converts optical signals into electrical signals. The higher the photoresponsivity, the higher is the detection sensitivity and efficiency of the detector^{54,55}. The calculation formula for R is shown in Eq. (1)

$$R = \frac{I_{\text{ph}}}{P_{\text{in}} \cdot S} \quad (1)$$

Wherein, R represents photoresponsivity; I_{ph} is the

photocurrent, with $I_{\text{ph}} = I_{\text{light}}$ (photocurrent under illumination conditions) – I_{dark} (dark current under dark conditions), P_{in} is the incident light power density, and S denotes the effective area illuminated by light. As mentioned earlier, metasurfaces can realize efficient light manipulation through subwavelength periodic structural units. The surface plasmon resonance or Mie resonance excited by them enables nanoscale light field localization and near-field enhancement, which, combined with perfect absorption, further improves the light absorption efficiency and photogenerated carrier density in the photosensitive region. In addition, the R can be further optimized by regulating carrier dynamics and extending the spectral response band.

External quantum efficiency (EQE) is one of the main performance indicators of photodetectors. When photons irradiate the surface of a photosensitive material, some photons excite the material to generate electron-hole pairs, which form an electric current. The ratio of the collected electrons to the total number of incident photons is called the external quantum efficiency. For photodetectors, a higher EQE value indicates a higher photon conversion efficiency of the device, and thus, a better detection performance^{56,57}. The expression for the EQE is shown in Eq. (2)

$$EQE = \frac{N_c}{N_i} = \frac{hc}{q\lambda} R \quad (2)$$

Wherein, N_c denotes the number of collected charge carriers, N_i is the number of photons generating the photocurrent, h is Planck's constant, c is the speed of light, q is the electron charge, λ is the incident light wavelength, and R is the photoresponsivity. After integrating the metasurface, the photodetector can achieve efficient light coupling and focusing, as well as light field localization and near-field enhancement via subwavelength structures, and improve the photon absorption efficiency of the photosensitive region in combination with perfect absorption. In addition, the metasurface introduces a localized electric field to regulate carrier transport and suppress carrier recombination, thereby effectively enhancing the EQE .

The response time reflects the response speed of a photodetector to changes in optical signals and is usually expressed as a comprehensive indicator of t_r (rise time) and t_f (fall time). Among them, t_r is the time required for the detector to rise from 10% to 90% of its steady-state value, reflecting the detector's response speed to the optical-signal rising edge. t_f is the time required for the detector to drop from 90% to 10% of its steady-state value, reflecting the detector's recovery speed at the falling edge of the optical signal. A shorter response time indicates that the detector can capture and respond to changes in optical signals more rapidly^{58–60}. Conventional photodetectors lack light field modulation structures, leading to large reflection and transmission losses of incident light, low photon utilization efficiency in the photosensitive region, and slow generation rate of photogenerated carriers. In the absence of localized

electric field modulation, the carrier transport path is random and the speed is low, which prolongs the relaxation time of carrier separation and transport and thus results in slow response speed. After integrating metasurfaces, the photon absorption efficiency of the photosensitive region can be greatly improved, enabling the rapid and high-density generation of photogenerated carriers and shortening the initial delay of electrical signal establishment. The localized electric field introduced by metasurfaces can efficiently separate carriers, suppress recombination and accelerate directional transport, reducing relaxation and collection time. Meanwhile, the optimized structure can reduce various types of delays, expand the spectral response range, and achieve fast optical response over a broad waveband.

In addition to the key performance evaluation parameters mentioned above, the noise equivalent power (NEP) directly reflects the noise level of a detector, and the lower its value, the lower the device noise. After integrating a metasurface with the photodetector, the NEP is effectively optimized by enhancing light absorption efficiency, suppressing the random thermal excitation of carriers, and reducing interfacial leakage current. The on/off current ratio is defined as the ratio of a detector's I_{light} to its I_{dark} , with a higher ratio indicating a stronger ability of the detector to identify optical signals and better anti-jamming performance. Following metasurface integration, its optical field localization and enhancement effects can significantly boost the photocurrent while suppressing I_{dark} generation, thereby optimizing the on/off current ratio. I_{dark} refers to the leakage current generated by thermally excited carriers, Schottky barrier leakage and other factors in the dark, a smaller dark current yields a lower detector noise level and a correspondingly higher on/off current ratio. Metasurfaces can optimize I_{dark} by improving interfacial properties, reducing carrier trapping by defect states, decreasing the number of thermally excited carriers, and mitigating barrier leakage current. For photodetectors with specific functions, it is necessary to introduce targeted and specific evaluation parameters^{61–67}. Among these, the extinction ratio (ER) is a core indicator for polarization-sensitive photodetectors, specifically referring to the ratio of the device's response signals to orthogonally polarized light. A higher ER value means higher accuracy of the detector in identifying the target polarization state and superior polarization selection characteristics. Metasurfaces can precisely regulate the absorption and transmission of light with different polarization states via the polarization-selective characteristics of their subwavelength structures, thereby optimizing the extinction ratio. The spectral response range defines the wavelength interval of incident light capable of eliciting an effective photoelectric response from the detector. This parameter is mainly determined by the intrinsic bandgap of the photosensitive material and directly defines the effective operating waveband of the device^{68,69}. Metasurfaces can break through the limitation of the intrinsic bandgap of photosensitive materials by

regulating the resonant waveband and combining the optical field enhancement effect, thus broadening the spectral response range.

3 Metasurface-based photodetector

3.1 Light absorption enhancement

The light absorption intensity is a crucial factor affecting the photoresponsivity of devices. Theoretical studies have shown that the introduction of metasurfaces can enhance the interaction between incident light and photosensitive materials, excite localized surface plasmon resonance (or Mie resonance in dielectric metasurfaces), or construct Fabry-Perot cavities, thereby improving the light absorption performance of photodetectors and further enhancing their photoresponsivity^{70,71}. For instance, in Si-based interconnection systems, traditional photodetectors exhibit weak light-trapping capabilities and can only excite simple resonance modes, which greatly limits their performance. However, when dielectric metasurfaces are integrated with photodetectors (Fig. 2(a)), a light absorption rate of up to 85.9% at specific wavelengths can be achieved by exciting the Mie resonance and light scattering processes (Fig. 2(b))⁷². In 2024, Chen et al.⁷³ reported a dual-band perfect absorber based on an arc-chamfered L-shaped chiral dielectric-metal metasurface (Fig. 2(c)). The rounded-corner L-shaped metasurface breaks mirror symmetry, allowing only right-handed circularly polarized (RCP) light to excite cavity resonance, and achieves efficient absorption through the plasmonic loss of gold (Au). Under RCP light incidence, the absorber achieved an absorption rate of over 90% at wavelengths of 1129 nm and 1148 nm (Fig. 2(d)). In contrast, under left-handed circularly polarized light incidence, the electromagnetic waves were almost completely reflected, demonstrating remarkable optical chirality. Importantly, the Au layer possessed a high photothermal conversion efficiency, with a temperature-difference circular dichroism of 1.0 K at 1129 nm, and the surface temperature of the thermosensitive material exhibited a positive correlation with the absorption rate. In addition to achieving absorption enhancement at specific wavelengths, the incorporation of metasurfaces can realize narrowband absorption enhancement. For example, a gallium oxide (Ga_2O_3) ultraviolet photodetector based on metasurfaces can achieve an absorption rate of up to 95% in the 200–220 nm wavelength range⁷⁴. In 2023, Zou et al.⁷⁵ proposed a metasurface-based pyroelectric detector, achieving an average optical absorption rate of 94.2% in the 3–5 μm mid-infrared band. As shown in Fig. 2(e), the top electrode of the detector was fabricated from an absorptive metasurface consisting of nanomesh patch units. The metal-insulator-metal (MIM) Fabry-Pérot (F-P) cavity integrated with the metasurface realizes uniform electric field distribution throughout the cavity via cavity mode resonance at 3.13 μm , thereby

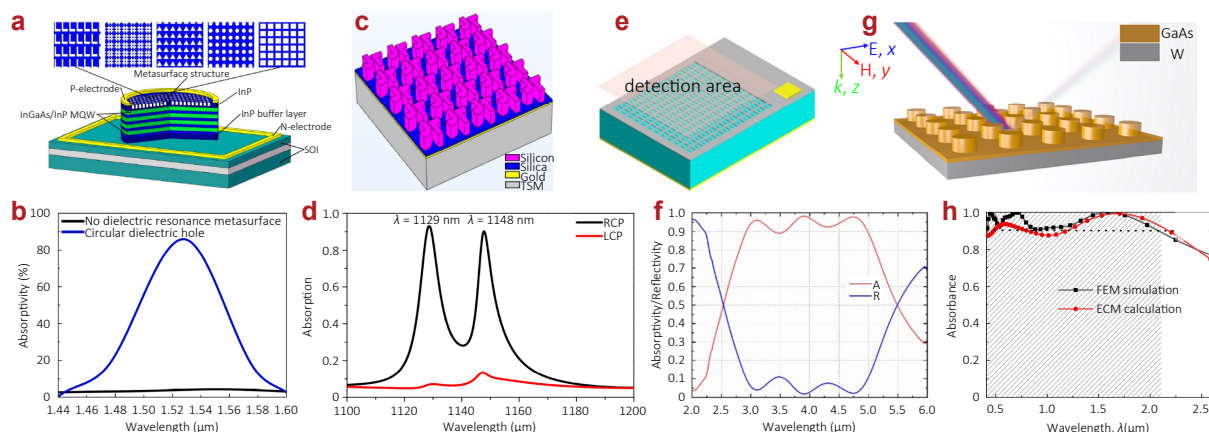


Fig. 2 | (a) Schematic diagrams of L-shaped, well-shaped, triangular, circular, and square metasurfaces. (b) Comparison of light absorption rates between photodetectors with and without circular dielectric metasurfaces. (c,d) Dual-band perfect absorber based on arc-chamfered L-shaped chiral dielectric-metal metasurfaces. (e) Schematic diagram of a metasurface-based pyroelectric detector (MPPD) with a top metasurface electrode composed of nanoantennas. (f) Absorption and reflectance of the MPPD. (g) Schematic diagram of an all-dielectric GaAs metasurface plasmonic light absorber. (h) Absorption spectra of the light absorber under normal incidence, obtained via finite element method (FEM) simulation and equivalent circuit model (ECM) calculation. Figure reproduced with permission from (a, b) ref.⁷², MDPI. (c, d) ref.⁷³, Optica Publishing Group. (e, f) ref.⁷⁵, IOP Publishing Ltd. (g, h) ref.⁷⁶, Elsevier B.V.

maximizing the coupling and energy capture of incident light by the LiTaO_3 pyroelectric layer. At $3.94 \mu\text{m}$, the electric dipole (ED) resonance of the Cr nano-grid, combined with the synergistic resonance effect of magnetic dipole (MD) and electric quadrupole (EQ), results in the electric field being highly localized at both ends of the nano-grid along the polarization direction, forming strong field enhancement regions that significantly improve the light absorption efficiency of this band. Moreover, the resonance peak position can be tuned by adjusting the MIM cavity gap and grid period. At $4.8 \mu\text{m}$, the ED resonance of the Cr nano-patches strongly localizes the electric field in the patch region, and precise tuning of the absorption peak is achieved by optimizing the geometric dimensions of the patches. The mutual coupling and complementarity of these three resonance modes enable absorption enhancement across the $3\text{--}5 \mu\text{m}$ mid-infrared band (Fig. 2(f)). However, the device achieves broadband absorption enhancement through the superposition of narrowband resonances and structural parameter tuning, which is essentially a compromise solution of multi-narrowband splicing and sacrifices narrowband resolution. In addition, under pulsed illumination at $3.94 \mu\text{m}$, its temperature response time ranges from 47 ms to 64.25 ms, belonging to a millisecond-level response that is much slower than infrared detectors based on quantum effects. In 2024, Cai et al.⁷⁶ demonstrated an ultra-broadband, wide-angle plasmonic light absorber based on an all-dielectric gallium arsenide (GaAs) metasurface (Fig. 2(g)). Propagating surface plasmon resonance (PSPR), LSPR, cavity resonance, and coupling effects between adjacent cylindrical resonators, all excited by the metasurface, enabled the device to achieve ultra-broadband strong absorption of over 90% in the wavelength range of

$0.39\text{--}2.09 \mu\text{m}$, with a relative bandwidth of 137.1% (Fig. 2(h)), indicating its enormous application potential in the field of photodetectors.

Experimental studies have also confirmed that the application of metasurfaces in photodetectors can enhance the light absorption of devices and achieve precisely controllable narrowband or broadband absorption enhancements^{77,78}. It has been found that adjusting the arrangement period of metasurfaces constructed from germanium (Ge) nanoantenna arrays can cause the overlap of electric dipole lattice resonance and magnetic dipole resonance, thereby generating localized electromagnetic fields inside and around the metasurfaces and further enhancing light-matter interactions (Fig. 3(a))⁷⁹. In 2024, Wang et al.⁸⁰ used dual-pore anodic aluminum oxide (BP-AAO) as a porous template and employed physical vapor deposition (PVD) technology to controllably deposit the deposited materials into or onto the template pores and surfaces. After template removal, they obtained ordered micro/nano array structures matching the pore channels of BP-AAO, and further designed and fabricated a plasmonic hot-electron photodetector based on the metasurface-semiconductor-metal structure. As shown in Fig. 3(b), the top metasurface of the detector consists of periodic silver nanoparticle arrays with two different shapes and sizes. Precise regulation of the size difference between the two types of nanoparticles can break the symmetry, forming quasi-bound states in the continuum (QBIC), which in turn excites gap surface plasmon resonance and achieves localized field enhancement, effectively improving the light-matter interaction efficiency (Fig. 3(c)). Moreover, near-perfect light absorption can be realized by optimizing the size difference to balance the radiative and non-radiative losses of the device. However,

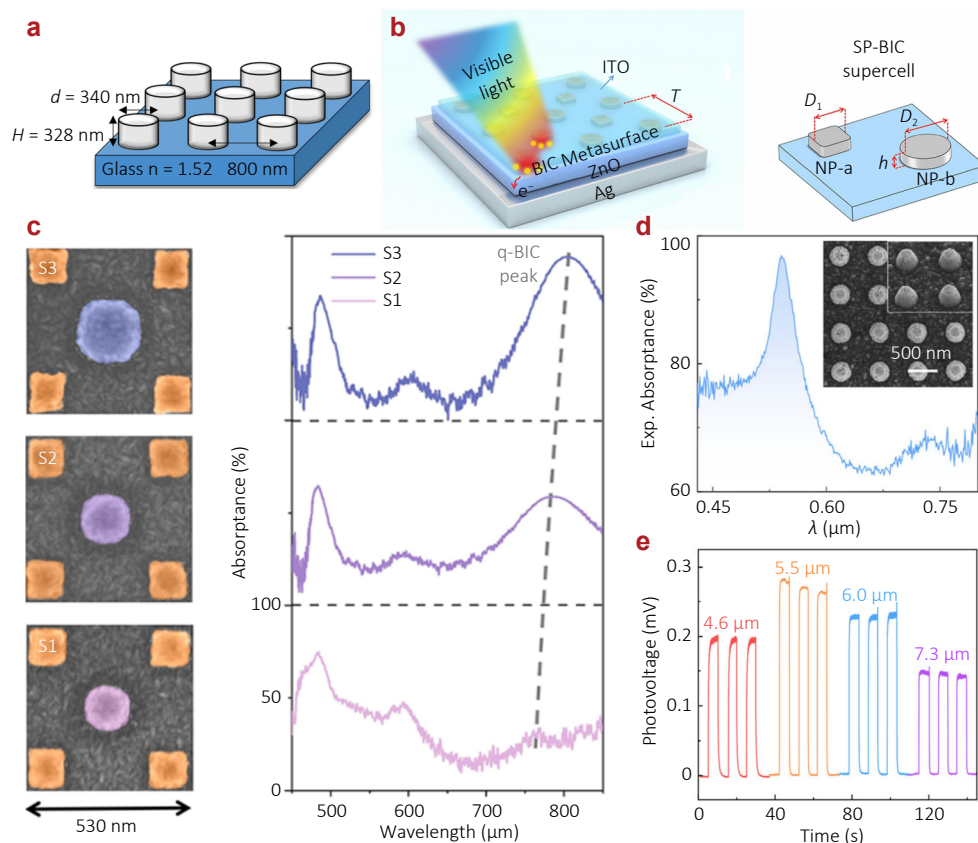


Fig. 3 | (a) Schematic of the Ge metasurface. (b,c) Schematic diagram of the bound states in the continuum plasmonic metasurface-semiconductor-metal structure, SEM images of silver binary nanoparticle arrays with different size differences and their corresponding absorption spectra. (d,e) Absorption spectra of the Sb_2Te_3 photodetector in the visible band; photogenerated voltage measured at an incident laser power of $4.5 \mu\text{W}$ under different wavelengths. Figure reproduced with permission from (a) ref.⁷⁹, American Chemical Society. (b, c) ref.⁸⁰, American Chemical Society. (d, e) ref.⁸², Wiley-VCH GmbH.

the light absorption of the device relies on the quasi-bound states in the continuum and gap surface plasmon resonance of the nanoparticles, while the resonance wavelength is determined by structural parameters such as the size difference of the nanoparticles and the thickness of the ZnO layer. Meeting the critical coupling condition limits the response spectral bandwidth. Nevertheless, the device achieves an approximate light absorption rate of 90% at a wavelength of around 800 nm, and a responsivity of 5.18 A/W under a 1 V bias and 780 nm light illumination. In 2024, Babicheva et al.⁸¹ grew a Ti_2O_3 active layer on a c-plane sapphire substrate via pulsed laser deposition (PLD) technology, and integrated a periodic silicon nanoantenna array on its surface as a resonant metasurface, fabricating an infrared photodetector with a "Si metasurface/ Ti_2O_3 /sapphire" structure. The Mie resonance excited by the metasurfaces enabled light modulation and improved the light absorption efficiency. Moreover, the lattice resonance formed by the coupling of the Mie resonance of individual antennas and the diffraction of the entire array significantly enhanced the interaction between light and Ti_2O_3 , increasing the light absorption of the Ti_2O_3 layer to over 80%. In 2025, Zhang et al.⁸²

fabricated an ultra-broadband photodetector based on antimony telluride (Sb_2Te_3) metasurfaces on a CaF_2 substrate via technologies including radio frequency (RF) sputtering, electron beam lithography (EBL), inductively coupled plasma (ICP) etching, and electron beam evaporation. Among these techniques, EBL, as an ultra-high-precision micro/nano fabrication technology, serves as a core process for fabricating the fine structures of metasurfaces. It enables nanoscale patterning through the selective exposure of photoresist with a focused electron beam and features an extremely high resolution. The device utilizes the interband plasmon resonance of chalcogenide Sb_2Te_3 in the visible band and Mie resonance in the mid-infrared band to localize incident light intensity in the Sb_2Te_3 metasurface region. The energy density of the localized light field is much higher than that of the incident light, thereby significantly improving the light absorption probability. As illustrated in Fig. 3(d,e), the device achieved approximately 97% resonant absorption under 532 nm laser irradiation, with an operating range from visible light to mid-infrared. In the visible band, the responsivity of the detector was 24 V/W , and the external quantum efficiency was approximately 56%. In

th mid-infrared band, the responsivity was 67 V/W, with an external quantum efficiency of approximately 30%. In addition, the device exhibited significant linear polarization selectivity.

To summarize, metasurface-integrated photodetectors can achieve high light absorption efficiency (up to 99% in some cases) across ranges from the ultraviolet to ultra-broadband, by adapting resonance mechanisms suitable for different wavebands. They can also synergistically enhance light-matter interactions through multiple mechanisms and are compatible with various photosensitive materials (Table 1), making them an effective approach to improving the light absorption performance of photodetectors. However, most current metasurface-based photodetectors are primarily based on simulation studies, and their enhanced light absorption is highly dependent on the structural parameters of metasurfaces-with complex structures posing significant fabrication challenges. Additionally, ultra-broadband light absorption enhancement relies on multi-narrowband splicing, which sacrifices spectral resolution and thus fails to meet the requirements of high-spectral-resolution application scenarios.

3.2 Spectral response regulation

The spectral response, which reflects the effective operating wavelength range and the sensitivity of the photodetectors, is a key indicator for evaluating their performance. However, the intrinsic photoelectric response capability of photosensitive materials makes it difficult for photodetec-

tors to achieve multiband spectral detection, which greatly limits the application scenarios of the devices^{83,84}. Metasurfaces with flexibly designable structures can significantly enhance multiband spectral responses by exciting multiple resonance modes^{85–87}, providing a feasible approach for designing broadband, high-sensitivity, and multifunctional photodetectors.

In previous reports, when metasurfaces composed of metal-dielectric-metal square cavities of different sizes were applied to quantum well infrared photodetectors (QWIPs), absorption covering the entire bandwidth of QWIPs was achieved by combining cavities with different resonance wavelengths. Calculations of localized asymmetric intrinsic state transitions (aISBT) showed that different cavities exhibit selective absorption characteristics at their resonance wavelengths⁸⁸. In addition, studies have found that adjusting the diameter and height of Ge disks can enhance the absorption of Ge at specific wavelengths. When Ge disks of different sizes are combined into a metasurface, uniform broadband absorption can be generated, thereby enabling photodetectors based on Ge metasurfaces to achieve a 3- to 100-fold photocurrent enhancement in the wavelength range of 1000–1550 nm⁸⁹.

In 2023, Lien et al.⁹⁰ fabricated a metal-insulator-metal (MIM) metasurface with a gold grating-black phosphorus (BP)-molybdenum disulfide (MoS₂)-Au structure via EBL and electron beam evaporation techniques (Fig. 4(a)). Furthermore, the resonant wavelength can be tuned by modulating the grating size of this metasurface; a 6.7-fold enhancement in the device's photocurrent is achieved

Table 1 | Summary of light absorption efficiency of metasurface-enhanced photodetectors across different wavebands.

Operating waveband	Metasurface type	Photosensitive material	Operating wavelength	Light absorption efficiency	Enhancement mechanism
UV (10–400 nm)	2D periodic diamond nanopillar array ⁷⁴	Ga ₂ O ₃	200–220 nm	95%	Mie resonance effect, optical path extension by the reflective layer
NIR (0.76–2.5 μm)	2D periodic GaAs cylindrical resonator array ⁷⁶	GaAs	0.39–2.09 μm	90%	PSP, LSP, cavity resonance, coupling effect of adjacent resonators
	Ag binary nanoparticle (BI-NPs) array ⁸⁰	Ag/ZnO	800 nm	90%	Plasmonic bound state in the continuum modulation
	Rounded L-shaped silicon chiral metasurface ⁷³	/	1129 nm, 1148 nm	90%	Mirror symmetry breaking and cavity resonance effect induced by chiral structures
	Ge nanoantenna array ⁷⁹	Ge	1480–1580 nm	75%	Resonance superposition of the lattice Kerr effect
	Au omega-shaped nanoantenna plasmonic metasurface ⁷¹	Graphene	1550 nm	99%	LSPRs, magnetic coupling resonance
MIR (2.5–5 μm)	Dielectric metasurface ⁷²	InGaAs	1550 nm	85.9%	Mie resonance enhancement, local field enhancement
	Si resonant metasurface ⁸¹	Ti ₂ O ₃	3–5 μm	86%	Light scattering and lattice resonance of resonant metasurfaces
	Chromium nanogrid-patch composite metasurface ⁷⁵	Cr	3–5 μm	94.2%	FP, ED, MD
LIR (5–15 μm)	MDM metasurface plasmonic cavity ⁷⁷	GaAs	6.0–7.4 μm	99%	Near-field resonant photon sorting mechanism, MDM cavity-enhanced light-matter interaction
Ultra-broadband	Sb ₂ Te ₃ metasurface ⁸²	Sb ₂ Te ₃	380 nm–8 μm	97%	Synergy of multi-band resonant absorption and pyroelectric conversion

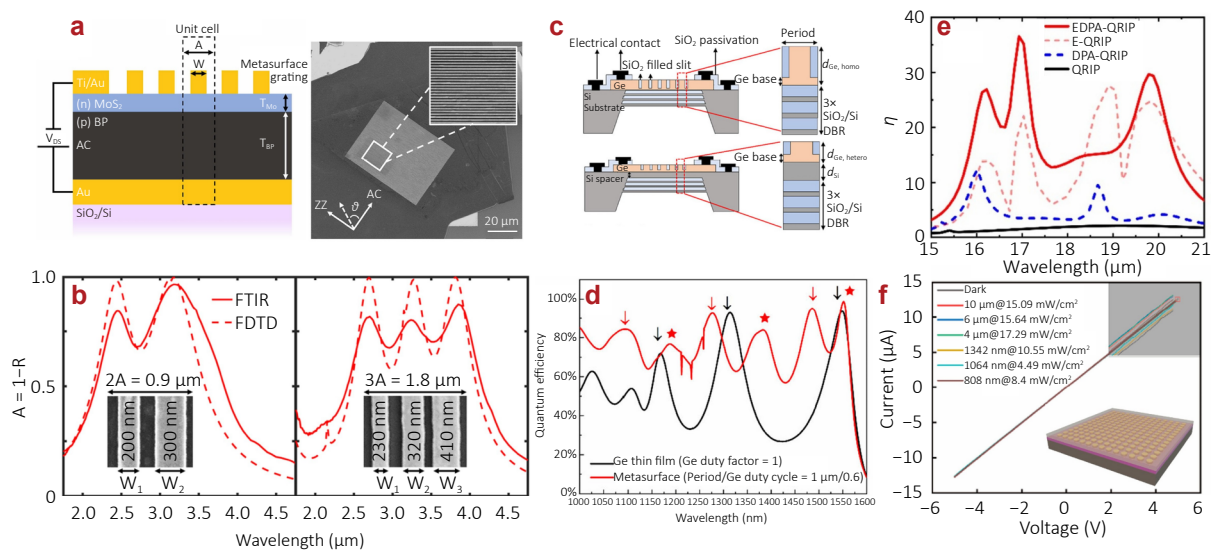


Fig. 4 | (a,b) Au grating-BP-MoS₂-Au metasurface. (c,d) SiO₂ nanoslit metasurface on a freely suspended resonator cavity-enhanced (RCE) Ge structure. (e) Size-optimized spectra of EDPA-QRIP (red solid line), E-QRIP (red dashed line), DPA-QRIP (blue dashed line), and QRIP (black solid line). (f) Schematic of the metasurface-enhanced MoS₂ photodetector (inset) and I-V characteristics of the photodetector in the dark and under illumination with light of different wavelengths. Figure reproduced with permission from (a, b) ref.⁹⁰, American Chemical Society. (c, d) ref.⁹¹, IEEE. (e) ref.⁹², IOP Publishing Ltd. (f) ref.⁹⁷, MDPI.

when light is incident along the armchair crystal axis of BP. Meanwhile, integrating multiple gratings with different widths within a single unit cell enables the construction of dual-resonator and triple-resonator architectures. By virtue of the coupling effect of multiple resonant modes and the localized optical field enhancement, combined with the anisotropic light absorption properties of BP, the response range of light absorption enhancement is extended from a single wavelength to a broader spectral band (Fig. 4(b)). In addition, the efficient carrier separation mechanism of the heterojunction formed by BP and MoS₂ further improves the photoelectric response performance of the device. However, this device exhibits a strong polarization dependence and can only efficiently detect infrared light with a specific polarization direction, which restricts the further expansion of its application scenarios. Figure 4(c) shows the silica (SiO₂)-filled nanoslit metasurface device fabricated by Hsu et al. in 2024 via a combination of EBL, dry etching and SiO₂ filling techniques, which is integrated on a freely suspended resonator cavity-enhanced (RCE) germanium-based structure. This device addresses the bottleneck of the narrow resonance linewidth in traditional Fabry-Perot cavity-based RCE devices. Moreover, it adopts silicon-compatible fabrication processes, which reduces the cost of system integration while endowing the device with excellent functional expandability. The diffraction effect induced by the nanoslit metasurface and the additional phase shift provided by its periodic structure for the resonator cavity enable phase matching between the incident light and horizontal guided modes, thereby enhancing the light coupling efficiency to the active region at wavelengths other than the

Fabry-Perot resonance wavelengths. As shown in Fig. 4(d), the device designed using this approach achieved an average quantum efficiency of 73.28% across the 1000–1600 nm spectral range, with a maximum of approximately 98.69% and a responsivity of 1.23 A/W⁹¹.

In 2025, Wang et al.⁹² found in their research on very long-wave infrared (VLWIR) detection that combining metal-dielectric-metal (MDM) resonant cavities with spliced metasurfaces can significantly improve the optical coupling performance and detection indicators of quantum ratchet infrared photodetectors (QRIPs). In the 16–20 μm VLWIR band (Fig. 4(e)), the broadband coupling efficiency of this structure is 20 times higher than that of traditional mesa reference devices, with a peak responsivity of 1.18 A/W, a minimum noise equivalent power (NEP) reduced to 0.6 pW·Hz^(-1/2), and a peak specific detectivity increased to 8.26 × 10¹⁰ Jones. Based on the Fabry-Perot resonance effect, the MDM resonant cavity can effectively confine the incident light field within the bimetallic region and achieve efficient absorption of optical signals by the active region by regulating the polarization state and amplitude distribution of the incident light. The diagonal arrangement of the spliced metasurface utilizes the near-field mutual perturbation between adjacent square patches to produce an equivalent modulation effect on the patch size, thereby broadening the spectral bandwidth of the resonance enhancement. In addition, the four-patch splicing unit strengthens the multi-cavity superposition effect through the collaborative optimization of the size and layout, significantly improving the broadband coupling efficiency and ultimately broadening

the spectral detection range and improving the performance of the detector in the VLWIR band.

Transition metal dichalcogenides (TMDs) have great potential in photodetection applications because of their tunable bandgaps, high carrier mobility, and strong light absorption capacity^{93–96}. However, owing to their intrinsic bandgaps, TMDs cannot effectively absorb photons with energies lower than the bandgap, resulting in a significant attenuation of their photoresponse in spectral regions outside the bandgap. The introduction of metasurfaces can break through the absorption limit by utilizing the LSPR effect, significantly improving the light absorption efficiency of TMD thin films. In 2025, Li et al.⁹⁷ fabricated a Au nanodisk array metasurface-enhanced MoSe₂ photodetector via a combination of EBL, electron beam evaporation, which integrates MoSe₂ with a surface-layer circular Au metasurface. By precisely regulating the structural size of the metasurface, the photoresponse was extended to a broadband in the mid-infrared spectrum. The subwavelength design of the Au metasurface, which matches the wavelength of the incident light, can effectively excite SPPs and LSPR, thereby confining and concentrating light on the material surface to enhance the localized electromagnetic field. In addition, the Schottky junction formed between the Au metasurface and the MoSe₂ layer, together with the LSPR effect at resonant wavelengths, will promote the injection of hot electrons into MoSe₂, thus effectively breaking through its intrinsic bandgap limit and expanding its photoresponse spectral range. The optimized metasurface-enhanced MoSe₂ photodetector had a broad spectral response range from 808 nm to 10 μm , with an R and specific detectivity (D^*) of 7.1 mA/W and 1.12×10^8 Jones, respectively, under 4 μm light illumination (Fig. 4(f)).

In summary, metasurfaces can effectively break through the spectral limitations of traditional devices and improve light coupling efficiency and detection performance by virtue of their flexible structural design and ability to excite multiple resonant modes. However, while the spectral detection range of photodetectors integrated with metasurfaces is broadened, certain adverse effects are also introduced. For instance, in the BP-MoS₂ optoelectronic device integrated with a gold grating, the influence of the metallic metasurface grating on the device conductance leads to a significant increase in its dark current. In the metasurface-enhanced MoSe₂ photodetector, the Schottky junction formed between the metasurface and MoSe₂, along with the interface characteristics, directly affects the response dynamic performance of the device and limits its response speed. In numerous optoelectronic devices, broad-spectrum detection is usually achieved through the superposition of multiple resonances, which results in non-uniform broadband enhancement and performance compromise in some spectral bands. Additionally, obvious polarization dependence exists, which greatly

restricts the application scenarios of the devices.

3.3 Response speed improvement

Two-dimensional MoS₂ is regarded as a highly promising new material for developing next-generation ultra-compact and lightweight optoelectronic devices, owing to its atomic-scale ultra-thin thickness and unique electronic structure. However, its extremely thin thickness weakens the light-matter interaction, resulting in a poor light absorption capacity. In addition, the large specific surface area of MoS₂ significantly limits its response speed. Metasurfaces can modulate the light properties in a compact and efficient manner, thereby enabling MoS₂ photodetectors with fast responses. In 2019, Ni et al.⁹⁸ fabricated a gap surface plasmon (GSP) metasurface with a Au nanobar array structure via a combination of EBL, electron beam evaporation, and integrated it with monolayer MoS₂ to construct a high-performance photodetector with fast response characteristics (Fig. 5(a)). The GSP metasurface achieves strong electromagnetic field localization through its structure, and its resonant mode can be designed to match the exciton A resonance of MoS₂. The synergy between the two promotes the enhancement of the photoluminescence. In addition, a tightly localized electromagnetic field can reduce the influence of surface trap states on the photogenerated carriers. Furthermore, the Au nanobar array can also serve as electrodes to shorten the carrier transport path, and the structural design matching the carrier diffusion length greatly improves the collection efficiency of photogenerated carriers. Under a 650 nm excitation light source, the photodetector maintained a large photocurrent even at high switching frequencies with only slight performance degradation, demonstrating excellent fast response capability.

Ge-based photodetectors are commonly used for near-infrared band detection; however, their unsatisfactory detection speed is a key factor limiting their applications. In contrast, photodetectors based on subwavelength Ge PIN diode array metasurfaces can achieve fast infrared photodetection (Fig. 5(b)) with a bandwidth of 65 GHz. Additionally, by designing optical resonance modes, light energy can be localized inside intrinsic Ge disks, resulting in a high quantum efficiency under near-infrared illumination⁹⁹. Similarly, BP has great application potential in mid-infrared band photodetectors because of its optical anisotropy and the adjustability of its direct bandgap with thickness. However, its performance is still limited by its small light absorption cross-section at room temperature. In 2023, Yadav et al.¹⁰⁰ designed a plasmonic metasurface with LSPR at 3.7 μm (Fig. 5(c)). The simulation results showed a field confinement effect at the edges of the Au disks. After integrating BP flakes onto the plasmonic metasurface, photoluminescence quenching was observed owing to the Förster resonance energy transfer effect induced by dipole-dipole coupling. The fabricated BP/plasmonic metasurface-

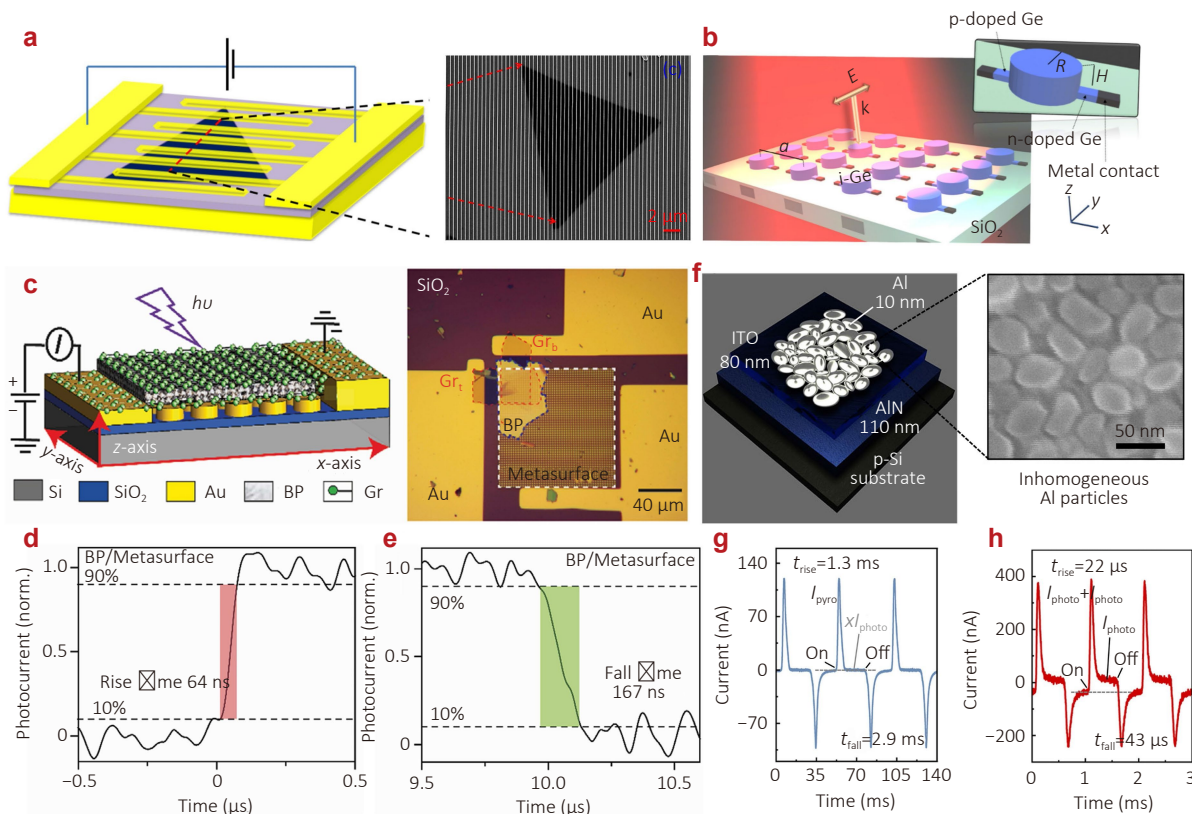


Fig. 5 | (a) Schematic diagram and SEM image of the MoS₂ gap plasmonic metasurface photodetector. (b) Schematic of the subwavelength Ge PIN diode array. (c) Schematic diagram and optical microscope image of the BP/plasmonic metasurface-based photodetector. (d) Rise response time of the black phosphorus/plasmonic metasurface-based photodetector. (e) Fall response time. (f) Structural schematic of the photon-enhanced (PE) detector and top-view SEM image of the aluminum particle metasurface. (g) Measured response waveform of the control sample without the integrated plasmonic metasurface. (h) Measured response waveform of the proposed detector with an integrated plasmonic metasurface. Figure reproduced with permission from (a) ref.⁹⁸, IOP Publishing Ltd. (b) ref.⁹⁹, MDPI. (c-e) ref.¹⁰⁰, Wiley-VCH GmbH. (f-h) ref.¹⁰¹, Springer Nature.

based photodetector achieved a peak responsivity of 495.85 mA·W⁻¹ and an ultra-high operating speed exceeding 10 MHz under an incident wavelength of 3.7 μm and power of 8.55 μW (Fig. 5(d,e)).

Pyroelectric detectors, whose photocurrent mainly originates from the change in spontaneous polarization intensity caused by temperature fluctuations in pyroelectric materials, are not restricted by the semiconductor bandgap and can thus achieve an extremely wide operating wavelength range. However, the pyroelectric signal requires a continuous energy conversion process from light to heat to electricity, resulting in an extremely slow response speed, typically on the order of tens of milliseconds. Metasurface-based pyroelectric detectors can improve the response speed and maintain wide-spectrum detection characteristics. In 2024, Lu *et al.*¹⁰¹ fabricated an ultrafast near-infrared pyroelectric detector based on an inhomogeneous plasmonic metasurface via a deposition self-assembly process, where a discontinuous and inhomogeneous particle structure is spontaneously formed. As illustrated in Fig. 5(f), the pyroelectric detector excites LSPR via an aluminum (Al) particle metasurface, accelerating the light-to-heat conversion process to the femtosecond

to picosecond level. This boosts the near-infrared response speed by to 2–4 orders of magnitude, with a rise time of 22 μs and a fall time of 43 μs (Fig. 5(g,h)). Furthermore, the random distribution characteristic of Al particles enables the generation of multi-wavelength LSPR resonances, realizing a broadband response covering the visible (550–700 nm) to near-infrared (1100–1800 nm) spectral ranges.

It can be seen that photodetectors integrated with metasurfaces can break through the bottleneck of low response speed of the original photosensitive materials and achieve high-speed photodetection of the devices by regulating the periodic structures of the metasurfaces. However, to optimize the response speed of the devices, the periodic structures of the metasurfaces require rigorous parameter design, which also severely restricts the spectral detection range of the devices. In addition, the signal attenuation rate accelerates as the devices achieve ultrafast response, and such rapid signal attenuation shortens the peak duration, thereby increasing the difficulty of capturing weak optical signals. Therefore, the design of irregular/composite metasurfaces, the synergistic regulation of optical field and carrier transport, the integration with novel device architectures,

or the adoption of reconfigurable metasurfaces can broaden the spectral detection range while maintaining high-speed response.

3.4 Polarization sensitivity

Light is a transverse wave, and the vibration directions of its electric and magnetic fields are perpendicular to the propagation direction. When the electric field vector of light waves vibrates only along a fixed direction or specific plane, the light exhibits polarization and is called polarized light. Polarized light is classified into linearly, circularly, and elliptically polarized light based on the vibration mode of the electric field vector. Among these, circularly polarized light is further divided into right-handed (clockwise) and left-handed (counterclockwise) circularly polarized light according to the rotation direction of the electric field vector. Notably, light polarization can carry various physical and structural information related to the light source, propagation medium, and material structure. Polarization-sensitive photodetectors are key to acquiring the information carried by polarized light, and they hold great significance in cutting-edge fields, including polarization imaging, quantum communication, and remote sensing^{102–107}.

Metasurfaces can sense and modulate light polarization through subwavelength structures by leveraging polarization-selective absorption, transmission, reflection, and beam control^{108,109}. Studies have shown that photodetectors integrated with metasurfaces can detect circularly polarized light and accurately measure light of any polarization state at specific wavelengths¹¹⁰. In 2024, Cheng et al.¹¹¹ proposed a circularly polarized photodetector with an extinction ratio (ER) of 21 : 1. Composed of a displaced double gold rod

chiral metasurface and an indium gallium arsenide/indium phosphide (InGaAs/InP) detector, the device exhibits excellent extinction ratio performance owing to the boundary states between its metal grating and InP substrate (Fig. 6(a,b)). In addition, Cheng et al.¹¹² reported a full-Stokes polarization mid-wave infrared detector fabricated via a one-step photolithography and thin-film deposition process, whose core structure consists of a silicon-based metasurface rotated 45° clockwise and a quantum well infrared photodetector (QWIP) (Fig. 6(c)). Among them, the Si cubic array metasurface rotated 45° clockwise can act as a polarization converter to realize the precise conversion of circularly polarized light to linearly polarized light, with an average transmittance higher than 0.98 and 0.975 for the transverse magnetic (TM) polarization and transverse electric (TE) polarization modes, respectively, and a phase difference of approximately 90° between the two modes at 4 μm. Left-handed circularly polarized light can be converted into linearly polarized light along the x-direction by the metasurface, while right-handed circularly polarized light can be converted into linearly polarized light along the y-direction, and there is a significant difference in the matching degree between the converted linearly polarized direction and the TM mode direction of the QWIP. Furthermore, by virtue of the Fano resonance effect of the Si/SiO₂ linear grating, the detector achieved a circular polarization extinction ratio (CPER) of 20 dB and an ultra-high linear polarization extinction ratio (LPER) of 60 dB at an operating wavelength of 4 μm (Fig. 6(d)). As a key metric for evaluating the capability of polarization photodetectors to discriminate circularly polarized light, a higher circular dichroism (CD) value indicates a more pronounced difference in the detector response to circularly polarized light

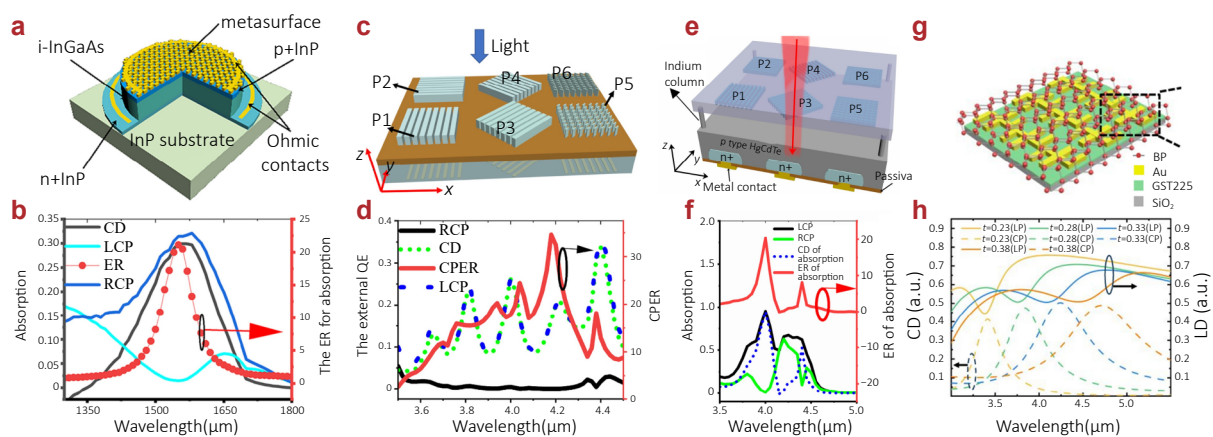


Fig. 6 | (a) Schematic diagram of the circularly polarized photodetector. (b) Absorption rate and ER spectra of the left-handed circular dichroism device. (c) Full-Stokes polarization mid-wave infrared detector composed of a Si metasurface and a QWIP. (d) External QE and ER of pixel P5. (e) 3D structural diagram of six small pixel unit cells. (f) Absorption and ER spectrum of the left circular dichroic device named the pixel P5. (g) Schematic of the proposed MPS detector. (h) Calculated CD (dashed line) and LD (solid line) spectrum for MPS detector with crystallization fraction of $m = 0.00$ (yellow), $m = 0.37$ (green), $m = 0.64$ (blue), $m = 1.00$ (orange), respectively, when $t = 0.28$. Figure reproduced with permission from (a, b) ref.¹¹¹, Elsevier Ltd. (c, d) ref.¹¹², Elsevier B.V. (e, f) ref.¹¹³, MDPI. (g, h) ref.¹¹⁶, Optica Publishing Group.

with opposite handedness. For the full-Stokes polarization mid-wave infrared detector integrated with a Si metasurface and QWIP, the CD of the circular polarization detection channel reached 0.25, whereas the linear dichroism (LD) of the linear polarization detection channel was 0.22. In 2024, Cheng et al.¹¹³ combined a displaced double-hole silicon chiral metasurface with a mercury cadmium telluride (HgCdTe, MCT) photodetector via lithography technology, and proposed a full-Stokes mid-wave infrared polarization photodetector (Fig. 6(e)). At 4 μm , the circular polarization pixels of this detector achieved an absorption CD of 95% and an ER of approximately 21 dB, whereas the linear polarization pixels exhibited an LD of 0.62 and an ER of approximately 22 dB (Fig. 6(f)). In addition, HgCdTe photodetectors integrated with silicon-based metasurfaces can realize linear polarization light analysis and circular polarization light discrimination via four linearly gratings with specific orientations and chiral symmetric silicon nanostructures¹¹⁴. In contrast, HgCdTe photodetectors integrated with Si/SiO₂ metasurfaces can achieve chiral design by breaking C₂ symmetry through geometric displacement, yielding a circular polarization extinction ratio of 18 dB and exhibiting excellent CO₂ monitoring performance¹¹⁵. In 2025, Kuang et al.¹¹⁶ reported a dynamically tunable black phosphorus (BP) photodetector, fabricated via lithography, thin-film deposition and lift-off processes, integrated with a germanium antimony telluride (GST225) plasmonic metasurface (Fig. 6(g)). Based on symmetry regulation, local field enhancement and phase-change modulation, combined with the SPP effect, the metasurface enables high-sensitivity detection and dynamic tuning of linear and circular polarized light in the mid-wave infrared band. For circular polarization detection, relying on symmetry breaking and selective local field enhancement, its metasurface unit cell uses an asymmetric structure of cross-shaped Au resonators and left/right rectangular Au strips to create artificial chirality, where the E_z component concentrates on rectangular Au strips for strong local fields under left-handed circularly polarized (LCP) light while gathering at the cross under RCP light. Constructive/destructive interference induces high circular dichroism, with detection selectivity enhanced by circularly polarized light decomposition and superposition. Linear polarization detection depends on BP's intrinsic anisotropy and the metasurface's mode selection, in which BP's armchair (AC) direction has 0.45 absorption for x-direction linear polarized light versus only 0.13 for y-direction in the zigzag (ZZ) direction, and their synergy significantly improves the linear polarization extinction ratio (Fig. 6(h)).

The high thermal loss of metallic materials is the primary obstacle limiting the application of metallic metasurfaces in optoelectronics. To address this challenge, Wilson et al.¹¹⁷ designed an ultra-thin pyroelectric photodetector integrated with a polarization-sensing metasurface via photolithography. Despite the active layer of the device being merely

290 nm thick, it exhibited an excellent response speed of 2 ns. The nanogap metasurface with asymmetric metallic units adopted in the device induced the gap plasmon resonance effect, which concentrated the electric field in the gap regions. Moreover, this resonance mode was highly sensitive to the polarization of incident light, with the light absorption efficiency reaching the maximum only when the linear polarization direction was aligned with the short axis of the nanounits, while absorption under the orthogonal polarization direction was almost completely suppressed, thus achieving a high polarization selectivity. The device achieved an extinction ratio of 19 for orthogonally polarized light, with the extraction error of Stokes parameters being less than 12% (Fig. 7(a,b)). In 2024, Bai et al.¹¹⁸ fabricated a multi-polarization-sensitive photodetector based on a plasmonic metasurface via EBL. Composed of H-shaped plasmonic nanostructures and a single-layer MoSe₂, the asymmetric structure of the H-shaped metasurface breaks mirror symmetry to form geometric chirality, thereby resulting in differences in the scattering and absorption between LCP light and RCP light (Fig. 7(c)). At a wavelength of 810 nm, the local electric field intensity excited by the metasurface under LCP light incidence is much higher than that under RCP light, which enhances the absorption of LCP light by the MoSe₂ layer to generate more photogenerated carriers. These carriers are then converted into polarization-dependent photocurrent through the photoconductive effect, leading to a photocurrent CD of 0.35. For linear polarization detection, the inherent anisotropy exhibited by the H-shaped metasurface due to the different structural dimensions in the *x* and *y* directions is utilized. At a wavelength of 633 nm, both the absorption efficiency and electric field enhancement effect of linearly polarized light in the *y* direction are significantly superior to those in the *x* direction. The MoSe₂ layer shows stronger absorption of *y*-polarized light and a higher concentration of photogenerated carriers, resulting in a higher photocurrent compared to *x*-polarized light, with a photocurrent linear polarization (LP) degree of 0.4 (Fig. 7(d)).

In 2025, Yu et al.¹¹⁹ designed an all-silicon hot-electron photodetector based on an embedded Au-Si nanogroove metasurface via EBL, which is suitable for high polarization-sensitive narrowband detection in the near-infrared (NIR) band. By embedding Au gratings into Si grooves, the device achieved a strong narrowband anisotropic absorption of 85%, along with self-powered characteristics and a tunable narrowband response. At 1450 nm, the responsivity reached 1.7 mA/W with a polarization ratio of 29 (Fig. 7(e,f)). The polarization ratio can be further improved to 130 by adopting a subwavelength-critical embedding structure. In the same year, Li et al.¹²⁰ proposed a metasurface-based room-temperature terahertz photodetector, consisting of Cs_{0.05}(FA_{0.85}MA_{0.15})_{0.95}Pb(I_{0.85}Br_{0.15})₃ (CsFAMA) perovskite and a metasurface. By constructing two structures (T-shaped

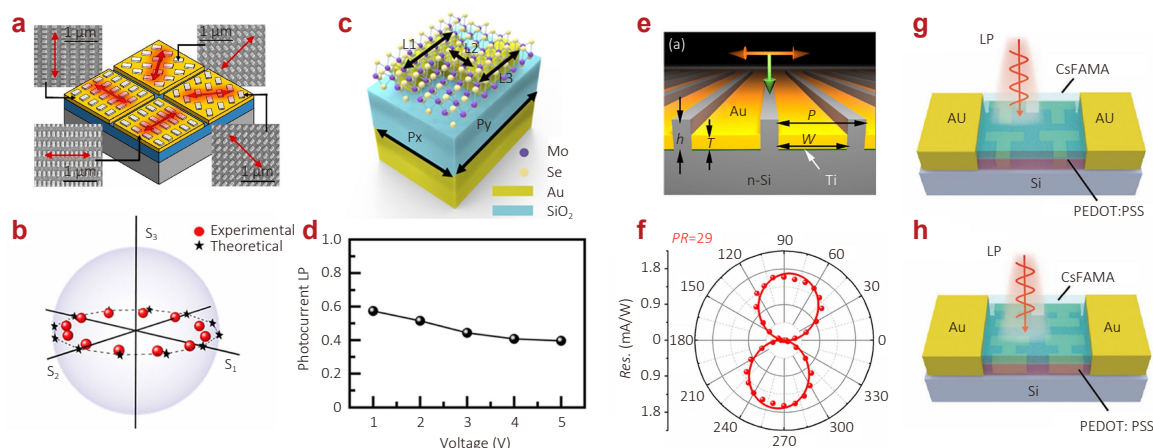


Fig. 7 | (a) shows a schematic of the four photodetectors. (b) Calculated Stokes parameters of the incident light with an angle of linear polarization (AoLP) ranging from 0° to 360°. (c) Schematic of the hybrid structure integrating a plasmonic metasurface with monolayer MoSe₂. (d) Photocurrent CD as a function of bias voltage. (e) Schematic of the hot-electron photodetector based on the embedded Au-Si nanotrench metasurface. (f) Polarization dependence of the responsivity of the photodetector, along with the corresponding sinusoidal fitted curve. (g, h) Schematic diagrams of the structures and dimensions of off-shaped and on-shaped photodetectors (PDs) respectively. Figure reproduced with permission from (a, b) ref.¹¹⁷, American Chemical Society (c) ref.¹¹⁸, Royal Society of Chemistry, (e, f) ref.¹¹⁹, American Chemical Society, (g, h) ref.¹²⁰, Wiley-VCH GmbH.

and I-shaped, Fig. 7(a,h)) and leveraging the photothermo-electric (PTE) effect, the device overcomes the limitations of traditional semiconductor energy bands. Among them, the I-shaped detector, benefiting from terahertz surface plasmon polariton (SPP) resonance and stronger boundary effects, achieves a responsivity of 94 V/W, a response time of 138 μs, a noise-equivalent power of 5.03 pW/Hz^{1/2}, an anisotropy ratio of 1.38 under 0.1 THz laser irradiation, and excellent stability.

The integration of metasurfaces into photodetectors endows the devices with polarization selectivity, enabling the detection of specific polarized light. This provides a core underpinning for the realization of high-resolution polarization imaging and narrowband polarization spectral analysis, while also overcoming the limitation of conventional photodetectors that require additional polarizers for polarization detection—greatly reducing device volume and lowering system complexity and power consumption. This intrinsic polarization recognition capability can be widely adapted to the precise detection requirements of special spectral bands such as the near-infrared and mid-infrared (Table 2), paving a brand-new path for the development of miniaturized, integrated, and high-performance polarization-sensitive photodetector systems.

3.5 High-dimensional photodetector

As mentioned earlier, photodetectors are widely used in optical sensing and communication, and extracting multidimensional optical information from light is key to expanding their applications. In previous studies, although multidimensional optical information detection has been achieved,

it usually requires the precise collaboration of numerous optical components^{121–125}. This significantly increases the volume and complexity of the system, which not only increases the manufacturing cost and assembly difficulty of the device but also reduces the detection accuracy owing to coupling losses between optical components, making it difficult to meet the application requirements of miniaturization and integration. In contrast, photodetectors integrated with metasurfaces can release spatial degrees of freedom, laying the foundation for the design of next-generation miniaturized optoelectronic chips^{126–128}.

Given that the polarization state and intensity of light fields can exhibit arbitrary variations over a broad wavelength range, there is an urgent need to develop high-dimensional photodetectors capable of comprehensively characterizing the three-dimensional parameter space of intensity, polarization state, and wavelength, as well as accurately describing the characteristics of arbitrary light fields. In 2024, Jiang et al.¹²⁹ proposed a broadband multidimensional photodetector based on metasurfaces, whose core structure consisted of dual-arm plasmonic meta-atoms integrated on top of graphene flakes (Fig. 8(a)). By encoding vector photocurrents with different polarities and amplitudes, the detector achieves multidimensional information decoupling of the polarization states and wavelengths. Combined with a multi-port architecture and machine learning techniques, it can simultaneously detect and distinguish multiple polarization states and wavelengths over an ultra-broadband range of 1–8 μm, with a wavelength prediction accuracy of 0.5 μm. In particular, for circularly polarized light, the device can effectively identify four combined signals of different wavelengths and circular polarization information, thus provid-

Table 2 | Polarization detection performance of metasurface-integrated photodetectors.

metasurface	Photosensitive material	Operating wavelength	Polarization sensitivity	polarization response performance	physical mechanism
Si metasurface ¹¹⁰	InGaAs	1550 nm	LP	LPER: 22.04 dB	Differential modulation of silicon gratings with specific orientations
offset double gold nanorod chiral metasurface ¹¹¹	InGaAs	1300-1600 nm	CP	CPER: 14.77 dB	Chirality-induced mode splitting and Fabry-Pérot (FP) cavity mode resonance
			LP	LPER: 19.03 dB	Modulation of the boundary state between the metal grating and the InP substrate
			CP	Absorption CPER: 13.22 dB; Transmission CPER: 15.44 dB;	Spin-dependent electric field loop excitation of the offset double gold nanorod chiral metasurface
single-layer offset double-hole silicon chiral metasurface ¹¹³	HgCdTe	4 μm	LP	LPER: 22 dB	Differential modulation of silicon linear gratings supported by CaF ₂ substrates
Si metasurface ¹¹²	GaAs/AlGaAs quantum well structure	4 μm	CP	Absorption CPER: 21 dB; Transmission CPER: 22 dB;	Structural asymmetry and the synergistic effect of multipolar resonance and cavity mode in metasurfaces
			LP	LPER: 60 dB	Fano resonance of Si/SiO ₂ gratings
			CP	CPER: 20 dB	Quarter-Wave Plate functionality of silicon metasurfaces
nanogap metal metasurface ¹¹⁷	Aluminum nitride	740 nm	LP	LPER: 12.79 dB	gap plasmon resonance
H-shaped plasmonic metasurface ¹¹⁸	Molybdenum diselenide	633 nm	LP	LP: 0.4	Anisotropy-enhanced electric field enhancement effect of metasurfaces
Embedded Au-Si nano-groove metasurface ¹¹⁹	Si+Au	810 nm	CP	CD: 0.35	LSPR
		1450 nm	LP	Polarization ratio: 29	SPR
		0.1 THz	LP	Anisotropy ratio(T):1.22; Anisotropy ratio (I): 1.38	olarization dependence of terahertz SPP resonance
Au T-shaped/I-shaped periodic nanostructured metasurface ¹²⁰	CsFAMA perovskite				

ing an innovative solution for ultra-compact, high-dimensional photodetectors (Fig. 8(b)).

In 2024, Wen et al.¹³⁰ proposed a compact spectroscopic ellipsometry system based on a Si nanopillar metasurface array. They integrated a 20 × 20 Si nanopillar metasurface array with an overall size of 1.5 mm × 1.5 mm onto a complementary metal-oxide-semiconductor (CMOS) image sensor and conducted an elaborate design on the metasurface units, endowing them with high anisotropy and diverse spectral responses (Fig. 8(c, e)). This design enabled one-time encoding of the full Stokes polarization spectral information of the light reflected from thin films into spatial light intensity distributions. Subsequently, combined with a pre-calibrated Mueller matrix and an iterative optimization algorithm, the full Stokes polarization spectra were reconstructed by minimizing the cost function and converted into ellipsometric parameters. Finally, the thin film thickness and refractive index were obtained by fitting the material models. Experimental verification demonstrated that the system exhibited excellent performance in the wavelength range of 500–700 nm. For spectral reconstruction with

narrowband light sources, the average peak wavelength error was 0.17 nm, and the root mean square error reached 1.87%, allowing the resolution of dual spectral peaks separated by 8.7 nm. When measuring SiO₂ thin films with thicknesses ranging from 100 nm to 1000 nm, the average relative thickness error was only 2.16%, with a measurement precision of 1.28 nm achieved within 10 min, and the average refractive index measurement precision was 0.84% (Fig. 8(f)). These results were highly consistent with those obtained using commercial ellipsometers. The entire reconstruction process took approximately 1 s, meeting the requirements for high-throughput detection. These findings highlight the potential application of the device in material characterization and demonstrate its capability to perform accurate optical measurements in a compact and efficient manner.

Overall, metasurfaces can achieve multifunctional detection capabilities without the need for collaboration with various optical components. Their designable subwavelength structures provide a new approach for the integration of polarization detection, spectral analysis, and multidimensional optical field manipulation, laying a solid

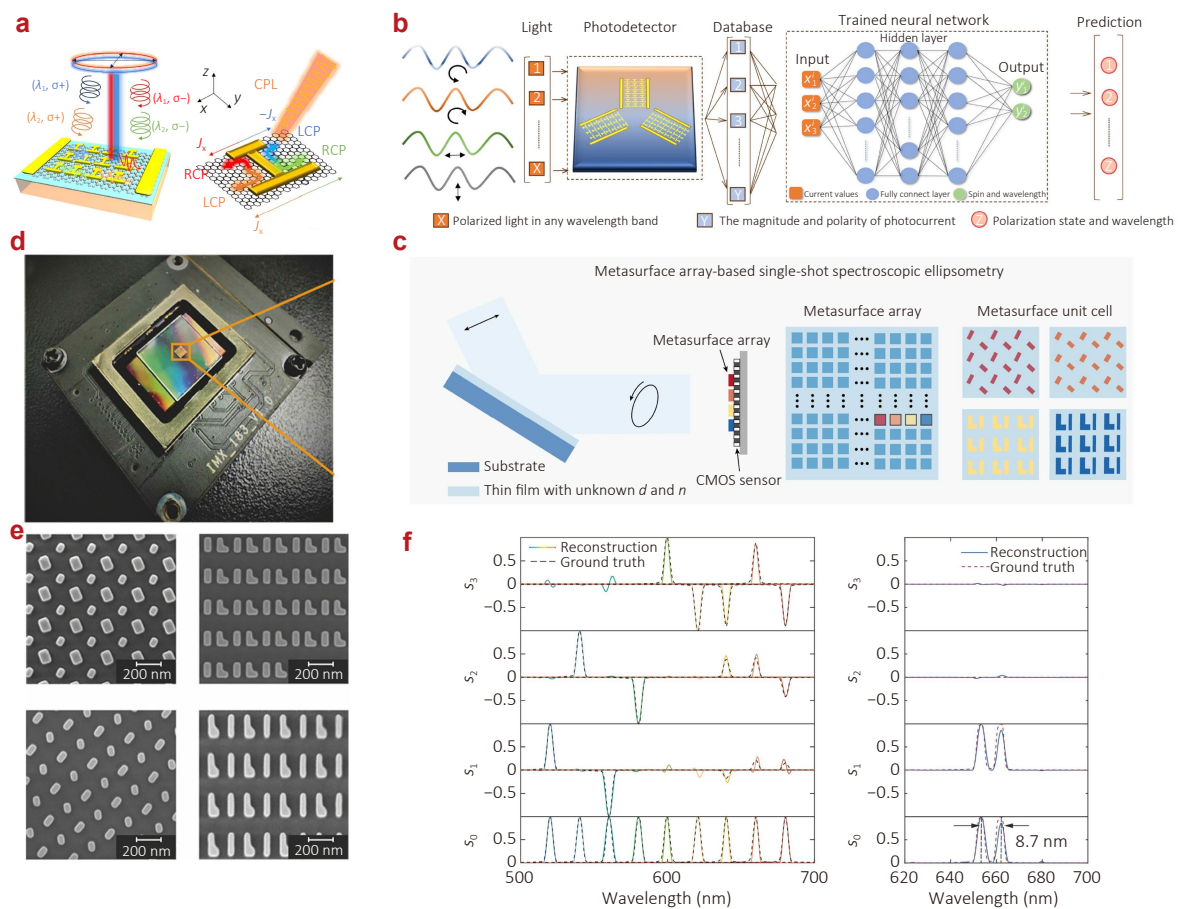


Fig. 8 | (a) The dual arm metasurface structure on graphene can localize light of different wavelengths and handedness on either side of the dual arms, generating vectorial photocurrents with different magnitudes and directions. CPL, LCP, and RCP represent circularly polarized light, left-handed circularly polarized light, and right-handed circularly polarized light, respectively. (b) Conceptual diagram of machine learning for the acquisition and identification of optical wavelength and polarization information using a three-port system. (c) Schematic of the metasurface array-based single-shot spectroscopic ellipsometry system. (d) Photograph of the metasurface array-based spectroscopic ellipsometer. (e) SEM image of the fabricated metasurface array. (f) Full Stokes polarization spectra of narrowband light sources measured with the metasurface array-based spectropolarimetric detection system and reconstructed full Stokes polarization spectrum of linearly polarized light with dual spectral peaks separated by 8.7 nm measured with the metasurface array-based spectropolarimetric detection system. Figure reproduced with permission from (a, b) ref.¹²⁹, Springer Nature, (c-f) ref.¹³⁰, Springer Nature.

foundation for the design and development of next-generation miniaturized, scalable, and high-dimensional optoelectronic devices.

4 Conclusion

As artificial structures, metasurfaces provide an effective and novel approach for enhancing the performance of photodetectors and realizing high-performance, highly integrated, and multifunctional photodetectors. This article reviews the latest research progress on metasurface-based photodetectors in recent years. First, it introduces the principle of light-field modulation by metasurfaces. Then, it presents the main parameters for evaluating photodetector performance. Finally, it focuses on the improvement of photodetector performance by metasurfaces from four aspects: light absorption enhancement, spectral response regulation,

response speed improvement, polarization sensitivity and high-dimensional photodetectors. As mentioned earlier, photodetectors integrated with metasurfaces can achieve enhanced light absorption, improved photoresponsivity, and response speed by adjusting the geometric shape and material composition of the periodic arrays in the metasurfaces. In addition, metasurfaces can regulate the spectral response range of photodetectors, thereby achieving multiband or broadband responses. Notably, the integration of metasurfaces can also realize polarization-sensitive photodetectors, which enables the detection and analysis of light with various polarization states. In addition, different types of metasurfaces exhibit distinct performance differences in enhancing the performance of photodetectors. For instance, plasmonic metasurfaces enable light field modulation by virtue of metallic plasmon resonance, demonstrating outstanding performance in light absorption enhancement and localized

field focusing, and thus hold evident advantages for application in photodetectors operating in the near-infrared band. All-dielectric metasurfaces, with low-loss dielectrics such as silicon as the substrate, achieve light modulation based on Mie resonance, featuring low optical loss, excellent broadband spectral adaptability and superior thermal stability. They can cover the visible to mid-infrared band and realize high-fidelity polarization and phase modulation. Hybrid-structured metasurfaces, by contrast, can integrate the advantages of the two aforementioned types. They realize synergistic modulation of light fields through metal-dielectric structures, not only achieving strong localized field enhancement to improve detection sensitivity, but also reducing metallic loss and broadening the spectral response range via dielectric layers while enabling flexible design of polarization and high-dimensional detection functions.

It is noteworthy, however, that plasmonic metasurfaces suffer from high metallic loss, which easily causes device heating and reduced quantum efficiency along with strong polarization dependence. All-dielectric metasurfaces, on the other hand, have weak light field localization capability, leading to limited light absorption enhancement effects. Although hybrid-structured metasurfaces can compensate for the shortcomings of the other two types, they involve complex structural design, great difficulty in interfacial matching of multiple components, high requirements for the compatibility of fabrication processes and a significant increase in preparation costs. In recent years, researchers have been continuously exploring the pathways for performance balance and optimization of these three types of metasurfaces, striving to break through their inherent limitations and give full play to their respective advantages so as to realize high-performance, low-loss and low-cost metasurface-integrated photodetectors.

Besides, metasurface-integrated photodetectors also face numerous challenges in their translation into practical applications. First, the performance of metasurfaces is highly dependent on the dimensional accuracy of subwavelength structures, with key performance metrics such as polarization response and resonant wavelength being extremely sensitive to structural parameter deviations, which typically require error control within 5%. At present, EBL is the dominant technique adopted in laboratories, while it can achieve nanoscale precision, it suffers from low processing speed, high cost and limited single-processing area, making it unable to meet the demands of industrial-scale mass production. Moreover, in large-scale production, the structural parameters of metasurfaces are susceptible to fluctuations in processing technology, leading to significant discrepancies in performance metrics such as polarization selection efficiency and extinction ratio across different regions of the array. For instance, during the inductively coupled plasma reactive ion etching of Si-based metasurfaces, an etching depth deviation of more than 10 nm will cause a shift in the resonant wavelength, thereby impairing

the consistency of polarization detection. In addition, the fabrication of high-performance metasurfaces usually involves multiple lithography steps, multi-material deposition and precise alignment, which further increases the complexity of large-scale production.

Second, the existing fabrication of metasurfaces mostly relies on dedicated micro-nano processing processes, which exhibit poor compatibility with the mature CMOS technology. Furthermore, processes commonly used in metasurface fabrication such as noble metal deposition may adversely affect the electrical performance of CMOS circuits. Meanwhile, the standardized processes of CMOS technology are unable to adapt to the customized structural design of metasurfaces, resulting in great difficulty in monolithic integration of the two on the same chip and thus limiting the miniaturization and system-level application of metasurface devices. In addition, the performance advantages of metasurfaces can only be fully exerted through integration with existing photonic systems such as fiber optic communication systems, imaging lenses and detector arrays. However, efficient mode matching between the optical field modes of conventional photonic systems and the subwavelength modes of metasurfaces is hard to achieve, which leads to substantial optical energy loss. What is more, polarization state distortion of optical signals tends to occur during transmission in the integration process, whereas metasurface-based polarization detection has extremely high requirements for the stability of the incident polarization state. A slight optical path deviation between the metasurface and the imaging lens will induce unpredictable changes in the polarization state of the incident light, which in turn degrades the measurement accuracy of Stokes parameters and causes reconstruction errors to exceed the acceptable range.

Currently, the development of low-cost, high-precision batch fabrication processes is the key to realizing industrial-scale mass production. Among existing technologies, nanoimprint lithography and roll-to-roll processes already possess batch fabrication capabilities; by optimizing template precision, improving process stability and expanding adaptability to large-size substrates, large-area, low-cost and high-precision replication of metasurfaces can be achieved in the short term, which serves as an effective solution to the large-scale production of metasurfaces. In addition, it is necessary to conduct in-depth research on the compatible design of metasurface fabrication with CMOS technology, so as to address core compatibility bottlenecks such as material selection, process temperature and patterning precision, and develop standardized metasurface fabrication processes that can be directly integrated into CMOS chips. Meanwhile, efforts should be made to explore wafer-scale large-area uniform fabrication technologies for metasurfaces, break through the limitations of substrate size and the challenges of in-plane uniformity control, and realize the monolithic integrated fabrication of metasurfaces with

CMOS photonic arrays, thus providing core technical support for the low-cost large-scale mass production and integrated performance upgrading of devices. To tackle the problems arising from the integration of metasurfaces with existing photonic systems, the development of high-efficiency optical coupling interfaces enables efficient mode matching between metasurfaces and photonic systems. In addition, the design of dedicated packaging schemes and standardized metasurface modules can improve the stability after integration and enhance the compatibility with existing systems.

In summary, metasurface-integrated photodetectors have broad application prospects but face certain challenges. Exploring high-precision and high-efficiency preparation processes and developing new material composite structures are the keys to realizing the application of metasurface-based photodetectors in actual production and daily life.

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Author contributions

Ai Wang wrote the initial draft. Yijia Huang proposed the original core idea and was responsible for the overall supervision of the project. Ling Li and Jianqi Zhu took charge of the funding acquisition. All authors contributed to the discussion of the results and commented on the manuscript.

Competing interests

The authors declare no competing financial interests.



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