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On-chip light control of semiconductor optoelectronic devices using integrated metasurfaces

Cheng-Long Zheng¹, Pei-Nan Ni^{1*}, Yi-Yang Xie^{2*} and Patrice Genevet^{3*}

Semiconductor optoelectronics devices, capable of converting electrical power into light or conversely light into electrical power in a compact and highly efficient manner represent one of the most advanced technologies ever developed, which has profoundly reshaped the modern life with a wide range of applications. In recent decades, semiconductor technology has rapidly evolved from first-generation narrow bandgap materials (Si, Ge) to the latest fourth-generation ultra-wide bandgap semiconductor (GaO, diamond, AlN) with enhanced performance to meet growing demands. Additionally, merging semiconductor devices with other techniques, such as computer assisted design, state-of-the-art micro/nano fabrications, novel epitaxial growth, have significantly accelerated the development of semiconductor optoelectronics devices. Among them, integrating metasurfaces with semiconductor optoelectronic devices have opened new frontiers for on-chip control of their electromagnetic response, providing access to previously inaccessible degrees of freedom. We review the recent advances in on-chip control of a variety of semiconductor optoelectronic devices using integrated metasurfaces, including semiconductor lasers, semiconductor light emitting devices, semiconductor photodetectors, and low dimensional semiconductors. The integration of metasurfaces with semiconductors offers wafer-level ultracompact solutions for manipulating the functionalities of semiconductor devices, while also providing a practical platform for implementing cutting-edge metasurface technology in real-world applications.

Keywords: optoelectronics; nanophotonics; metasurfaces; semiconductor

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Introduction

Since the initial demonstration of the first semiconductor laser in the early 1960s, semiconductor optoelectronic devices have achieved unparalleled commercial success and permeated every facet of human lives from communication, lighting, and entertainment to medicine¹. Furthermore, in response to the emergence of novel applications, such as the consumer electronics,

AR/VR displays, sensing, etc., continuous efforts have been devoted to further upgrade and enrich the performance and functionality of semiconductor optoelectronic devices. As a result, the ongoing trend towards device miniaturization, multi-functional operation and multi-tasking necessitates the integration of innovative engineering solutions. Artificially structured interfaces composed of nano-antennas, known as metasurfaces^{2–6}, are recognized as a disruptive enabling technology with the

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capability to control and manipulate the electromagnetic waves using ultra-compact and miniaturized optical interfaces. By manipulating the geometry and artificial arrangement of meta-atoms, metasurfaces can be used to precisely customize the amplitude, phase, and polarization of electromagnetic waves. This technology platform is positioned to replace bulky and heavy refractive optical components. Based on the physical properties of the materials, metasurfaces can be categorized into two main types: plasmonic metasurfaces and dielectric metasurfaces. Plasmonic metasurfaces exploit the plasmonic effect of metallic nanostructure to achieve enhancements in electric or magnetic fields, while dielectric metasurfaces made of high-refractive indices materials utilize near-field coupling to generate strong electrical and magnetic resonances simultaneously. For instance, local surface plasmon resonance refers to a collective yet non-propagating electronic oscillation phenomenon in a single metallic structure, occurring when the size of the metallic structure is smaller than the wavelength of the incident wave. In contrast, dielectric structures are capable of generating both electrical and magnetic resonances, which are known as Mie resonances.

Over the past decades, the metasurface technology has become well-established for achieving a large variety of functionalities, ranging from imaging^{7,8}, holographic display^{9–12}, and beam shaping to advanced display, and metrology, etc. The metasurface platform has been proven adequate for testing and proposing innovative functionalities, such as the general Pancharatnam-Berry phase^{13–15} and the topological phase¹⁶, thereby revealing new mechanisms for manipulating wavefront in the design of optical components. Although versatile meta-optics have been successfully developed into various forms and geometries using a rich family of materials, the need of supporting substrates, hundreds of times thicker than the metasurface itself, is still required for the majority of free-space applications where the meta-optics is deployed as a standalone device. On the other hand, the planar configuration of metasurface, along with its compatibility with the standard complementary metal oxide semiconductor (CMOS) fabrication techniques, makes it highly desirable for on-chip integration with semiconductor optoelectronic devices. Vertical integration of metasurfaces, directly on semiconductor devices, thus represents the ultimate implementation for ultracompact and integrated meta-optoelectronic systems.

In recent years, the integration of metasurfaces for on-

chip applications has been extensively utilized across various platforms, demonstrating significant success, in semiconductor devices, waveguides, optical fibers, and other areas. Specifically, integrating metasurfaces with semiconductor devices presents new opportunities for applications. This review provides a brief introduction and discussion of the recent advancements in controlling and manipulating semiconductor optoelectronic devices using integrated metasurfaces. The focus is on semiconductor lasers, semiconductor light emitting devices, semiconductor photodetectors and low-dimensional semiconductors as representative platforms. In conclusion, we are presenting our insights on the future directions and potential applications utilizing the direct integration of metasurfaces.

Wavefront shaping of semiconductor lasers

Semiconductor lasers have been well-known for their unique advantages, including compactness, high efficiency, long lifetime, superior controllability and reliability when compared to other types of lasers, such as, gas lasers, fiber lasers, and solid-state lasers. They can be categorized into two main groups, i.e. edge-emitting lasers, and surface-emitting lasers, based on their light emission characteristics and geometry. So far, the applications of semiconductor lasers have been extremely widespread from optical telecommunications, optical data storage, metrology, and spectroscopy, to material processing, medical treatments, and consumer electronics, etc., positioning them at the heart of modern optoelectronic technologies. On the other hand, the diverse uses of semiconductor lasers require increasingly precise laser beam properties, including minimal divergence angle, structured beam, polarization control, etc. Relying on the use of heavy and bulky conventional refractive optics to shape their laser wavefront has hindered the miniaturization and integration of these devices. To overcome these limitations, on-chip beam shaping of semiconductor lasers using integrated metasurfaces^{17–20} has gained considerable popularity over the past few years. The comparison of two types of semiconductor lasers integrating with metasurfaces is outlined in Table 1.

Edge emitting laser

Edge-emitting lasers (EELs), also known as in-plane lasers, are typically created by cleaving a waveguide ridge in a wafer and coating with high-reflectivity mirrors at

Table 1 | The comparison of two types of semiconductor lasers.

Emission type	Types of integrated metasurfaces	Functionalities
Edge emitting laser	Plasmonic metasurfaces	Improve beam collimation
	Plasmonic polarizer	Polarization conversion
Surface emitting lasers	Dielectric metasurface	Collimated emission, holographic display, vortex beam, beam splitter
	High-Contrast metastructure mirrors	Control the angular profile of the VCSEL beam

both ends to form a Fabry-Perot (FP) cavity that can confine and force laser oscillation parallel to the surface of the semiconductor wafer. EELs are well-established in the optoelectronic market. However, as a result of the asymmetric geometry of the emitting aperture, the output emission of the EEL takes on a slit-shaped beam, leading to strong divergence. In many applications, a tightly focused laser spot with circular shape is preferred. To address this issue, on-chip integration of metasurfaces with EELs has been demonstrated as an effective solution for improving its beam quality.

Plasmonic metasurfaces offer the advantages of both intriguing near field enhancement and simplified fabrication process, making them highly attractive for integrating with semiconductor lasers to alter their far field properties. To collimate the quantum cascade lasers (QCLs) with a lasing wavelength of 9.9 μm , Yu et al. directly fabricated plasmonic grating on the cleaved waveguide facet of the QCL, as shown in Fig. 1(a) and 1(b)²¹. Such integration was realized by first defining grooves pattern on the facet of the laser substrate through the focused ion-beam (FIB) milling. Afterwards, alumina and gold films were deposited onto the laser waveguide facet and substrate. Finally, a sub-wavelength slit aperture was create on the facet using FIB in order to both extract light from the cavity and facilitate the launch of surface plasmons on the laser facet. In their structure, the laser beam can be effectively coupled into surface plasmon waves and then scattered into the far-field by the plasmonic grating. Due to the coherent scattering of surface plasmon, the constructive interference among the scattered waves will form a collimated beam with a reduced divergence angle. By doing this, divergence angles as small as 2.4° were experimentally demonstrated. (Fig. 1(c)). Figure 1(e) shows the integration of metasurface waveguides with tapered terahertz (THz) QCLs for collimated beam emission²². In this design, part of the THz beam will be coupled into spoof surface plasmon (SSP) and propagate inside the metasurface waveguides, and then eventually scattered out perpendicular to the device surface by the SSP scatters. Meanwhile, the scattered SSP

light will interfere constructively with the uncoupled light, resulting in a collimated beam emission.

In addition to laser collimation, integrated metasurfaces can also be used to achieve other beam functions, such as the polarization conversion. Yu et al. designed a plasmonic polarizer integrated onto the facet of a $\lambda=9.9$ μm QCL, as shown in Fig. 1(e) and 1(f)²³. Since only the light of which the polarization is perpendicular to the grooves can be coupled to surface plasmons and propagate along the metallic grating, the orientation angle (θ) of the grating can be used to control the linear polarization direction of the output light. Figure 1(g) exhibits the measured output power as a function of observation angle, which proves the generation of a 45° linearly polarized light. Furthermore, by utilizing the plasmonic structure composed of two orthogonal grating-aperture structures, a superimposed polarization consisting of a linear polarization and circular polarization has been demonstrated.

Surface emitting laser

Surface-emitting lasers that emit an output laser beam perpendicular to the semiconductor wafer surface offer numerous advantages over their counterpart EELs, including higher beam quality, greater mode stability with reduced temperature dependence, lower fabrication cost and wafer-level testing, as well as scalability in 2D arrays. Surface-emitting lasers have been predominantly represented by vertical cavity surface-emitting lasers (VCSELs), in which the optical gain medium, consisting of multiple quantum wells, is sandwiched between two monolithically grown DBRs that confine the cavity modes along the growth axis. To date, VCSELs have steadily grown into the dominant laser source in various markets, ranging from optical communications and sensing to consumer electronic applications. Recently, the interest in VCSEL and associated arrays has seen a new surge due to their application in the emerging 3D sensing, light detection and ranging (LiDAR) applications. The surface emitting configuration of VCSELs allows for integration with metasurface for on-chip wavefront shaping.

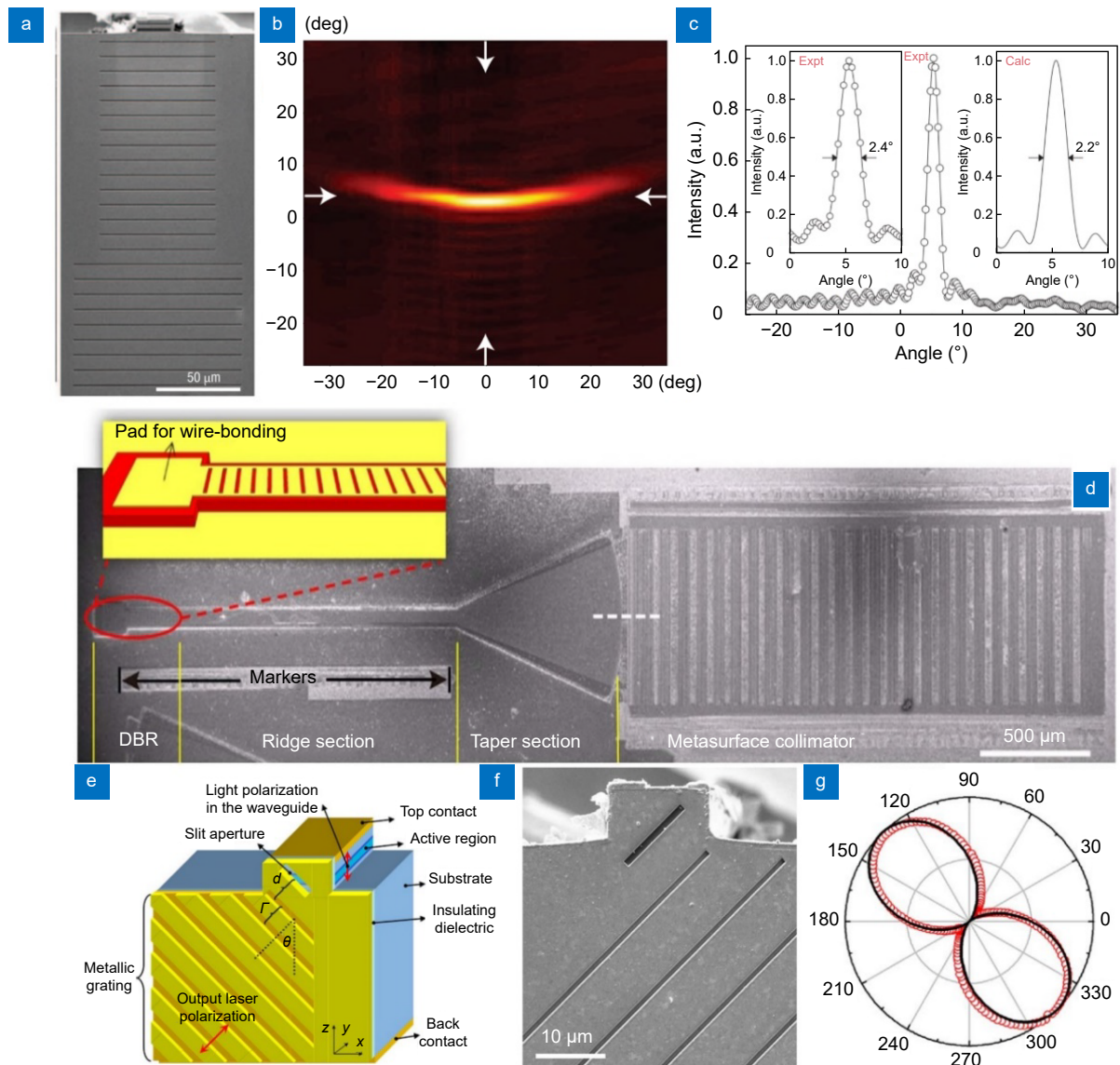


Fig. 1 | Integration of metasurface with edge emitting laser. (a) Scanning electron microscope (SEM) image the mid infrared QCL patterned with the slit-grating grooves. (b) Its measured two-dimensional (2D) far-field intensity distribution. (c) The experimental and calculated results of the intensity profiles along the vertical line indicated by the central arrow in (b). (d) SEM image of (a) THz QCL integrated with metasurface for collimated emission, the inset shows the schematic of the distributed Bragg reflector (DBR) structure. (e) The schematic and SEM image (f) of a QCL integrated with a plasmonic polarizer on its facet. (g) The measured emission power as a function of the linear polarization direction angle, confirming the generation of a 45° linearly polarized light. Figure reproduced with permission from: (a–c) ref.²¹, Springer Nature; (d) ref.²², Springer Nature; (e–g) ref.²³, AIP Publishing.

Xie et al. proposed and demonstrated a monolithic approach to integrate dielectric metasurface on the back-emitting facet of VCSELs by directly patterning and etching the substrate of laser wafer (Fig. 2(a))¹⁹. Their method provides several advantages. First, it fully leverages the thick and polished side of the wafer substrate, including its high crystalline property, high refractive index, and high optical transparency at the laser wavelength, which is ideal for the fabrication of metasurface.

Patterning the optical metasurface directly on the back of the VCSEL eliminates the need for additional material deposition and avoids the complexity of aligning and assembling the optical component with accurate vertical positioning and orientation control. Furthermore, due to the fact that the fabrication of metasurface can in principle be completed after all metallization steps, such integration is highly compatible with the standard processing of VCSELs, highlighting its suitability for mass

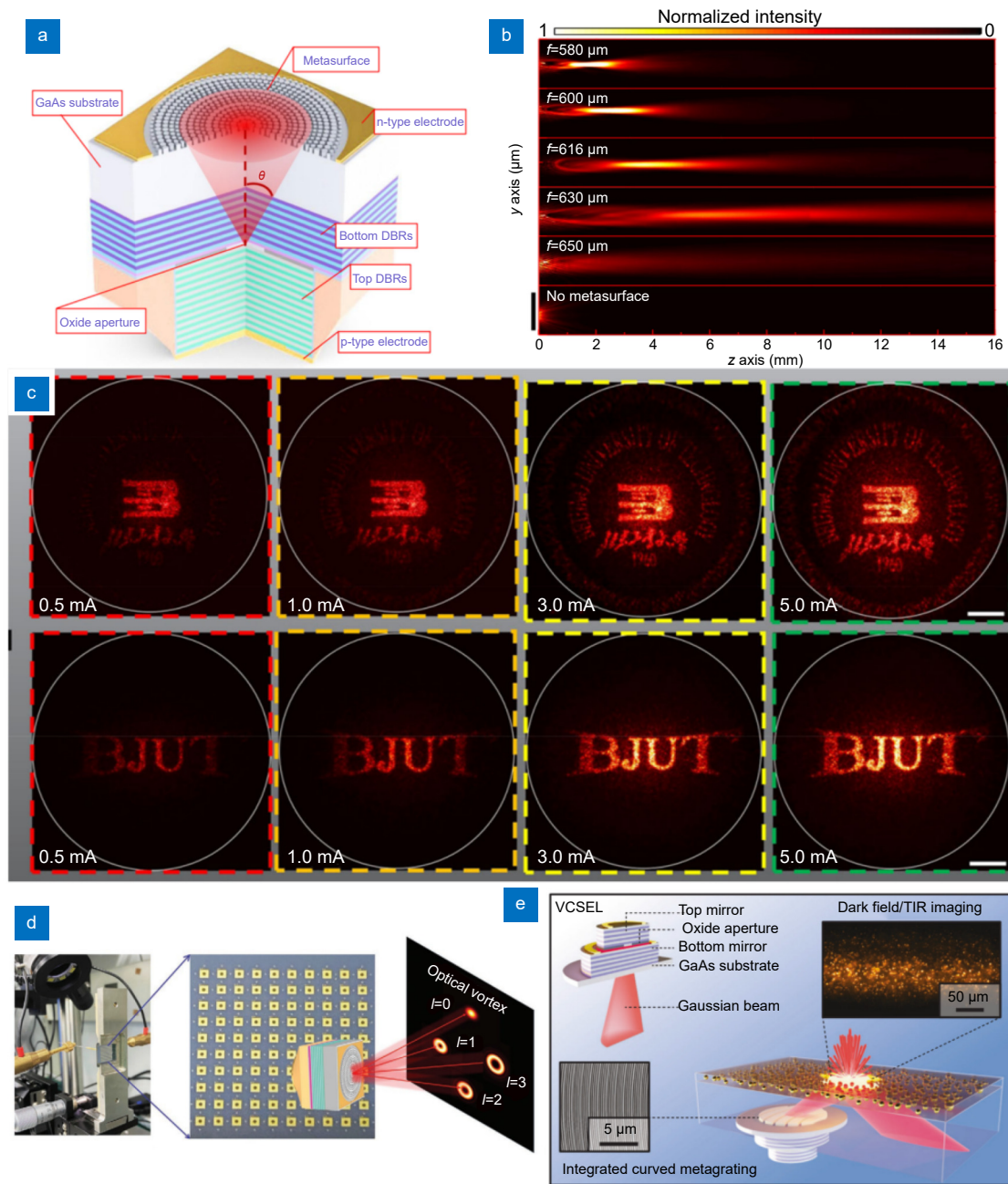


Fig. 2 | Integrating metasurface at the back side of surface VCSEL. (a) Schematic of the metasurface integrated VCSEL, where the metasurface was directly fabricated on the substrate of a back-side emitting VCSEL. (b) The measured laser intensity distribution along its propagation direction with and without metasurface integration, which shows that the VCSEL has been well collimated by the integrated metasurface. (c) The measured holographic images produced by the metasurface integrated VCSELs at different injection currents. (d) The optical image and the schematic of the VCSEL for the generation of multi-channel OAM beams with spatially varying topological charges. (e) The schematic of the VCSEL integrated with metasurface for off-axis emissions at high angles that can be used for high-contrast DF and TIR microscopy. Figure reproduced with permission from: (a, b) ref.¹⁹, Springer Nature; (c) ref.²⁴, (d) ref.²⁵, John Wiley and Sons; (e) ref.²⁷, Springer Nature.

production. Based on this approach, collimated emission with a divergence angle as small as about 0.83° was achieved by optimizing the focal length of the metasurface collimator, as summarized in Fig. 2(b), where the overall collimation efficiency is around 57%. This

method can be used for advanced beam shaping applications to realize complex wavefront modulations, such as holographic display with a large field of view (Fig. 2(c))²³, and multichannel generation of optical vortex beams that can carry spatially varying orbital angular

momentum (OAM) values (Fig. 2(d))²⁵. Moreover, this integration approach allows for both phase and polarization control of VCSELs on a chip. Polarization control is generally achieved using metasurfaces by employing birefringent nano-antennas such as nano-waveplates that can locally encode arbitrary phase and polarization profiles pixel-by-pixel at the emitting surface of a VCSEL²⁶. Additionally, through the integration of Jones matrix metasurfaces, it is possible to decouple the VCSEL beam while further adding specific and independent phase profiles on both spin-polarized output beams²⁰. Recently, Juodėnas et al. demonstrated that integrating curved metagratings on the substrate of a VCSEL in the back-emitting configuration can be used to effectively shape the VCSEL light into wide angular range wavefronts with high efficiency (Fig. 2(e))²⁷. Such large-angle off-axis emissions generated by the metagrating-integrated VCSELs will have important applications in total internal reflection (TIR) and dark field (DF) microscopy.

Wen et al. developed a fabrication method to integrate metasurface on the top-emitting facet of VCSEL²⁸. In their work, the mesas of VCSELs were first planarized by spin-coating a thick layer of SU8 (10 μm). Due to the high transparency of SU8 at the lasing wavelength of 850 nm and its chemical robustness, the SU8 layer acts as a beneficial flat platform for the metasurface fabrication. An amorphous silicon (a-Si) was then deposited onto the SU8 using plasma enhanced chemical vapor deposition (PECVD), followed by an e-beam lithography (EBL) and inductively coupled plasma-reactive ion etching (ICP-RIE) etching to define the metasurface pillar geometries (Fig. 3(a)). The a-Si metasurface was designed to work as a high conversion efficiency polarization beam splitter that provides different phase gradient to the left-handed circularly polarized (LCP) and right-handed circularly polarized (RCP) components of the VCSEL beam, respectively (Fig. 3(b)). In this way, the two orthogonal circularly polarized laser components can be separated and deflected to the opposite directions. Figure 3(c) schematically presents the measurement setup to characterize the diffraction angle and the polarization states of the VCSEL light passing through the metasurface.

A significant amount of research works has been devoted to controlling the optical feedback into the VCSEL cavity using High-Contrast Metastructure (HCM) mirrors, including broadband reflectivity^{29–31}. HCMs are closely related to metasurfaces and consist of a single layer of one-dimensional grating with subwavelength peri-

od. Li et al. demonstrated that HCM can also be used as a novel beam-shaping element for VCSELs (Fig. 3(d))³². For this purpose, the angular transmission characteristics of the HCM were leveraged to control the angular profile of the VCSEL beam, creating single-mode laser with various far-field emission patterns, including single-lobe, double-lobe, triple-lobe, “bowtie,” “sugar cone,” and “doughnut” shapes (Fig. 3(e)). The results proved that integration of HCM with VCSELs can work as a bi-functional optical element combining both a tunable mirror and beam shaping element.

Emission control of semiconductor light emitting devices

Semiconductor light emitting devices (LEDs) have been widely used in lighting and displays due to their unique advantages with respect to the other types of light sources, including low cost, high quantum efficiency, compactness, and long lifetime, etc. However, the light emissions of semiconductor LEDs typically exhibit a Lambertian-like beam profile with poor beam quality, such as unpolarized emissions, broad angular distributions and low emission directionality. Over the past few years, the integration of metasurfaces with semiconductor LEDs has been actively investigated to make significant progress in controlling their emission properties.

Wang et al. demonstrated that both the polarization extinction efficiency and the light extraction efficiency of InGaN/GaN green LEDs can be effectively increased by integrating nanostructures on both sides of the device³³. In their design, a top bi-layered wire grid polarizer has been integrated to determine the polarization of the emissions and a bottom metasurface has been utilized as a reflecting half waveplate that enhanced the extraction efficiency of the TM polarized emission. The experimental results showed that such design can effectively enhance the extraction efficiency of the linearly polarized light while keep the polarization extinction efficiency at a high level. To control the emission polarization and direction of LEDs, Part et al. patterned the top electrode of a quantum dots LEDs (Q-LEDs) into slot-groove array (Fig. 4(a))³⁴. It has been experimentally demonstrated that such metasurface-integrated electrode can convert the random polarized emissions from the bare LEDs into a linearly polarized beam and further deflect the beam in user-defined directions. Moreover, the slot-groove optical antenna can control the directions of light independently. For example, the LEDs emission of two

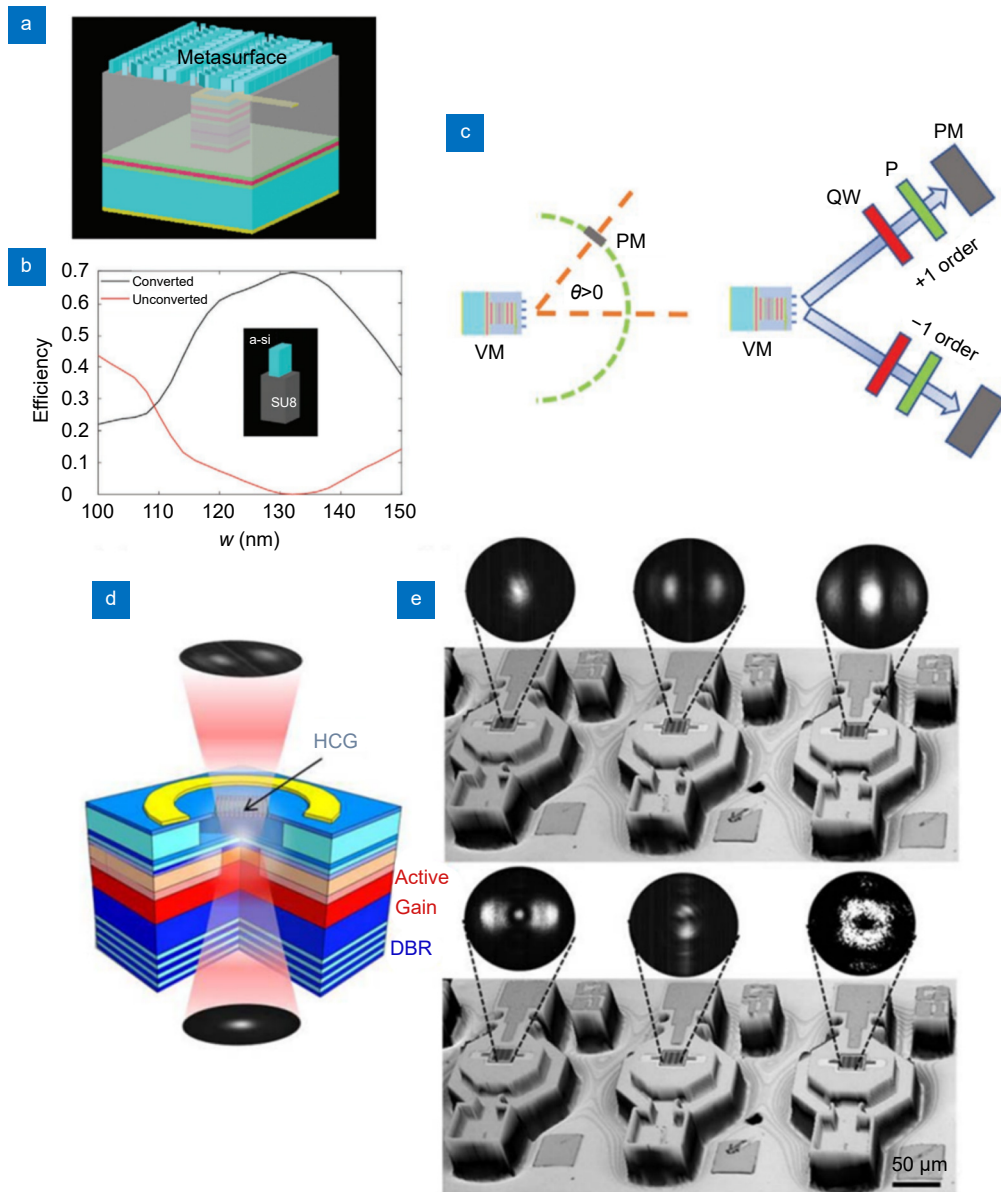


Fig. 3 | Integrating metasurface at the front side of surface VCSEL. (a) Schematic of the VCSEL integrated with metasurface at its front emitting side. (b) The simulated conversion efficiency of silicon nanopillar based meta-atom as a function of its width. (c) The setups to measure the angular distribution of the emission power (left) and the polarization state. (d) Schematic of the high-contrast grating (HCG)-VCSEL in which the top-surface beam was manipulated by the HCG designs. (e) The HCG-VCSEL arrays that emit single-mode laser with various far-field patterns. Figure reproduced with permission from: (a–c) ref.²⁸, John Wiley and Sons; (d, e) ref.³², Optica Publishing Group.

orthogonal polarization can be deflected into different directions by a metasurface composed of slot-groove array with two alternating directions (Fig. 4(b)). However, the overall light extraction efficiency from the metasurface integrated LEDs is rather low, about 4.5% compared to the electrode-free open space emission.

Low-loss dielectric metasurfaces have been considered as a promising solution for high-efficiency devices. However, the low spatial coherence of the LED emissions makes full wavefront control of the emission diffi-

cult, in particular when the distance separating the dielectric metasurface and the LED active region is smaller than several wavelengths. To overcome this limitation, Khaidarov et al. have proposed to increase the spatial coherence of a LED by introducing a FP cavity into the LED architecture³⁵. After that, dielectric metasurface consisting of amorphous silicon cylinders with a height of 350 nm is integrated at the output of the LED to perform the desired beam shaping functionality (Fig. 4(c)). Two different beam functionalities, including directional

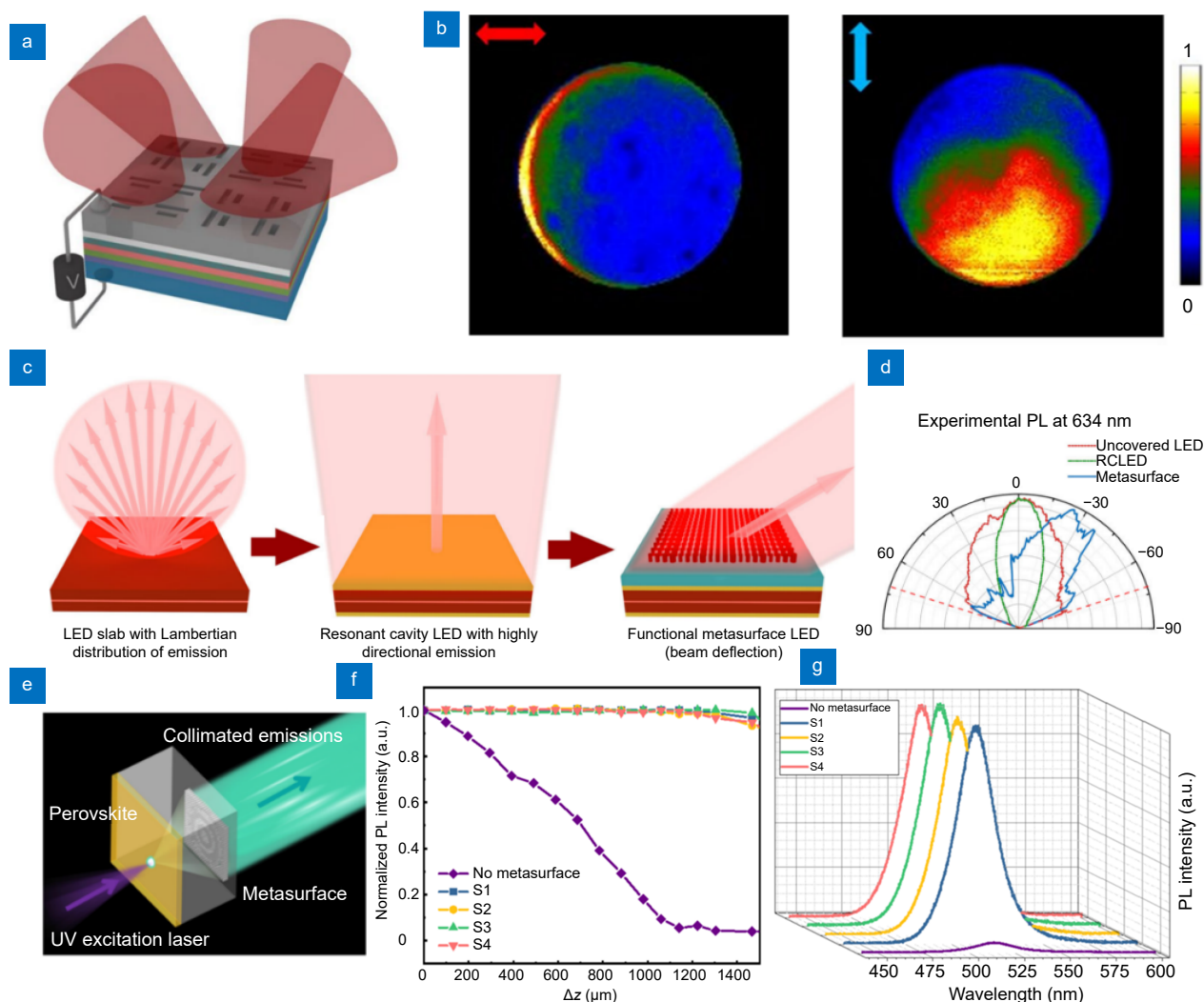


Fig. 4 | Integration metasurface with semiconductor LEDs. (a) Schematic of the QDs LED with metasurface-integrated electrode. (b) The emission direction of the metasurface integrated LED can be changed by changing the direction of the polarizer. (c) Integration of dielectric metasurface with resonant cavity LED (RCLED) for beam deflection. (d) Comparison of the emissions patterns from the uncovered LED, the RCLED, and the RCLED integrated with metasurface. (e) Integration metasurface with perovskite emitter for collimated emission. (f) The light emission intensity distribution of the emitter with and without metasurface as a functional of the propagation direction. (g) Comparison of the photoluminescence (PL) spectra of the sample with and without metasurface at $Z=1.3$ mm, showing that sample S3 integrate with metasurface has the best collimation performance. Figure reproduced with permission from: (a, b) ref.³⁴, Springer Nature; (c, d) ref.³⁵, John Wiley and Sons; (e, g) ref.³⁶, Springer Nature

emission at a desired angle and a vortex beam generation, have been experimentally demonstrated. (Fig. 4(d)). Alternatively, Li et al. have shown that by separating the integrated dielectric metasurface and the LED emitter across a relatively thick substrate (~ 430 μm) (Fig. 4(e))³⁶, the incoherent light from the LED beam could sufficiently expand through diffraction inside the substrate before being manipulated by the metasurface. Through diffraction over relatively thick substrate, the initial incoherent emission source can be treated as a point source emitting toward the metasurface. This approximation helps

to simplify the design of metasurface by alleviating the constraint of the low spatial coherence of LED. Figure 4(f) and 4(g) show that output emission of the metasurface integrated LEDs can be well collimated, creating a light beam with constant intensity profile along the propagation direction, up to 1 mm. In comparison, the light intensity distribution emitted by a bare laser quickly decreases, and quickly reaches background noise levels.

Besides integrating the metasurface and LED emitter as two separated elements, directly patterning the LED layer into nanostructures has also been proved feasible to

control the light emission properties. Liu et al. directly nano-structured the semiconductor layer containing epitaxial quantum dots into Mie-resonant metasurfaces with high quality factor (Fig. 5(a))³⁷. By overlapping the resonant modes of metasurface with the emission spectrum of the quantum dots, it is possible to enhance the PL (Fig. 5(b)) and directionally shape the far-field emissions (Fig. 5(c–e)). Metasurface based LEDs were also demonstrated from InGaN/GaN quantum-well structures (Fig. 5(f))³⁸. In this structure, the light emitter was strongly coupled to the metasurface, resulting in enhanced and unidirectional emissions (Fig. 5(g)).

Improving the performance of semiconductor photodetectors

Semiconductor photodetectors are typical optoelectronic devices that can receive and detect light radiation. They have been widely utilized in imaging, optical communication, biomedical science, environmental monitoring, and other fields, for converting optical information into electrical signals^{39–41}. Traditional semiconductor photodetectors can only distinguish information related to the variation of intensity of light. In recent years, several novel design strategies, including waveguides, two-dimensional material heterojunctions, quantum dots,

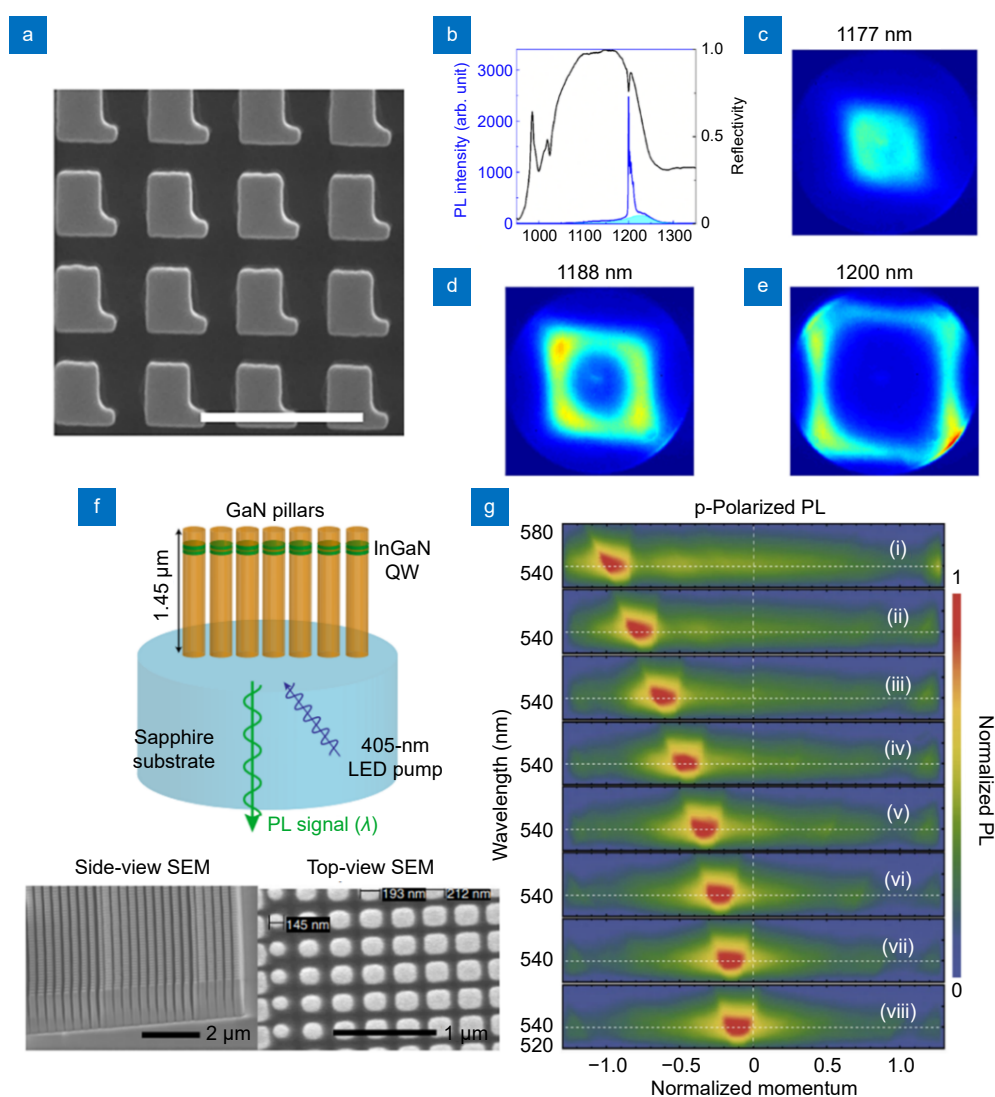


Fig. 5 | Directly fabricating metasurface into the LED layer. (a) SEM image of a symmetry-broken metasurface fabricated from III–V semiconductor QDs layer. (b) Measured optical reflectance and photoluminescence spectra for the symmetric metasurface sample, which shows the intensity enhancement for the symmetric design. (c–e) Measured back-focal plane images of emission from the symmetry-broken sample, showing the capability of reshaping the emission patterns. (f) Schematic and SEM images of the InGaN LEDs patterned into nanopillar arrays. (g) p-polarized PL as a function of normalized in-plane momentum for the eight different metasurfaces. Figure reproduced with permission from: (a–e) ref.³⁷, American Chemical Society; (f, g) ref.³⁸, Springer Nature.

and metasurfaces, have been developed to detect phase, polarization, wavelength, and even OAM^{42–44}, as outlined in Table 2.

Metasurface-enhanced photoresponsivity

The plasmon resonance or Mie resonances commonly used for the design of metasurfaces building blocks can provide local field enhancement, which significantly increases the light absorption. Combining nanoscale resonance with photodetector materials can thus improve considerably the photoresponsivity of photodetectors. Echtermeyer et al. demonstrated that plasmonic nanostructures could guide the incident energy directly to the p-n junction⁴⁵. By combining graphene with plasmonic nanostructures, local electric field enhancement in the p-n junction region can be realized at the graphene layer, and result in a photovoltage enhancement, with maximum amplification exceeding 20 folds at the plasmonic resonance. Similarly, a high-performance MoS₂ photodetector has been proposed through the integration of a gap-surface-plasmon metasurface. The photodetector is fabricated by integrating metallic nanostripe-arrays onto the MoS₂ flake (Fig. 6(a))⁴⁶. The gap-surface-plasmon resonance of the metasurface matches the exciton A resonance of the MoS₂ monolayer at around 650 nm, resulting in the selective enhancement of light-matter interactions.

The significant improvement in the responsivity of the photodetectors usually occurs at the plasmonic resonance frequency. To overcome this limitation, fractal metasurfaces with broadband absorption and multiple resonances are used to optimize the bandwidth of the photodetectors. Fang et al. integrated graphene photodetector with a snowflake-like fractal metasurface for realizing broadband and polarization-insensitive plasmonic enhancement⁴⁷. Figure 6(b) shows the SEM of the proposed photodetector sample and the enhancement factors at five measured wavelengths, exhibiting 8–13 folds

improvements over the entire visible spectrum. Active optical antennas, which combine the functions of nanoantennas and photodiodes, can convert hot electrons generated by plasmon decay into photocurrent, and by avoiding electronic resonant interaction, the bandwidth is no longer limited by the band gap of the semiconductor materials. Lin et al. proposed a concept of 3D antennas, which extended the band edge of silicon into the infrared regime and broadened the bandwidth of the photoresponse⁴⁸. The proposed active antenna structure consists of deep trench and thin metal, which utilizes surface plasmon resonance and 3D cavity effect to efficiently collect hot electrons and directly generate photocurrent. The responsivity of the devices remains hundreds of times higher than those of local-surface-plasmon-resonance-based active nanoantennas and displays high degrees of detection linearity under light both low (ca. 1 pW μm^{-2}) and high (ca. 40 $\mu\text{W} \mu\text{m}^{-2}$) intensity illumination conditions.

By integrating the metasurface absorbers with photodetectors, the absorption of incident light can be increased, and the photocurrent and signal-to-noise ratio of the photodetector can be improved. Li et al. demonstrated near-unity optical absorption using metamaterial perfect absorbers with thickness of 15 nm (Fig. 6(c))⁴⁹. A broadband and omnidirectional hot electron photodetector is demonstrated via integrating the absorber with a silicon substrate. The photoresponsivity is larger than 1.8 mA/W from 1200 nm to 1500 nm. Both the spectral bandwidth and polarization-sensitivity can be manipulated via proper engineering of the unit cell geometry. All-dielectric metasurfaces that support Mie resonances can also be used to absorb light for selected wavelengths. Zhou et al. proposed a Ge metasurface for achieving narrowband absorption at the telecommunication wavelength (Fig. 6(d))⁵⁰. The absorptance is shown to increase 6-fold compared to that of the unpatterned films, increasing the photocurrent by approximately 5 times.

Table 2 | Metasurface-enabled photodetectors.

Reference	Metasurface type/ principle	Photodetection
ref. ^{45–50}	Plasmonic resonance, Mie resonance	Enhanced photovoltage, photocurrent, responsivity
ref. ^{51–65}	Polarization-sensitive absorption, polarization filtering, polarization beam splitting, mode analysis of coded field	Linear, circular, and full-Stokes polarization detection
ref. ^{66–70}	Plasmonic resonance, Mie resonance, multi-foci metalens	Wavelength selective detection
ref. ^{77–81}	Plasmonic coupling, plasmonic grating, orbital photogalvanic effect, momentum transformation, spiral metalens	OAM detection

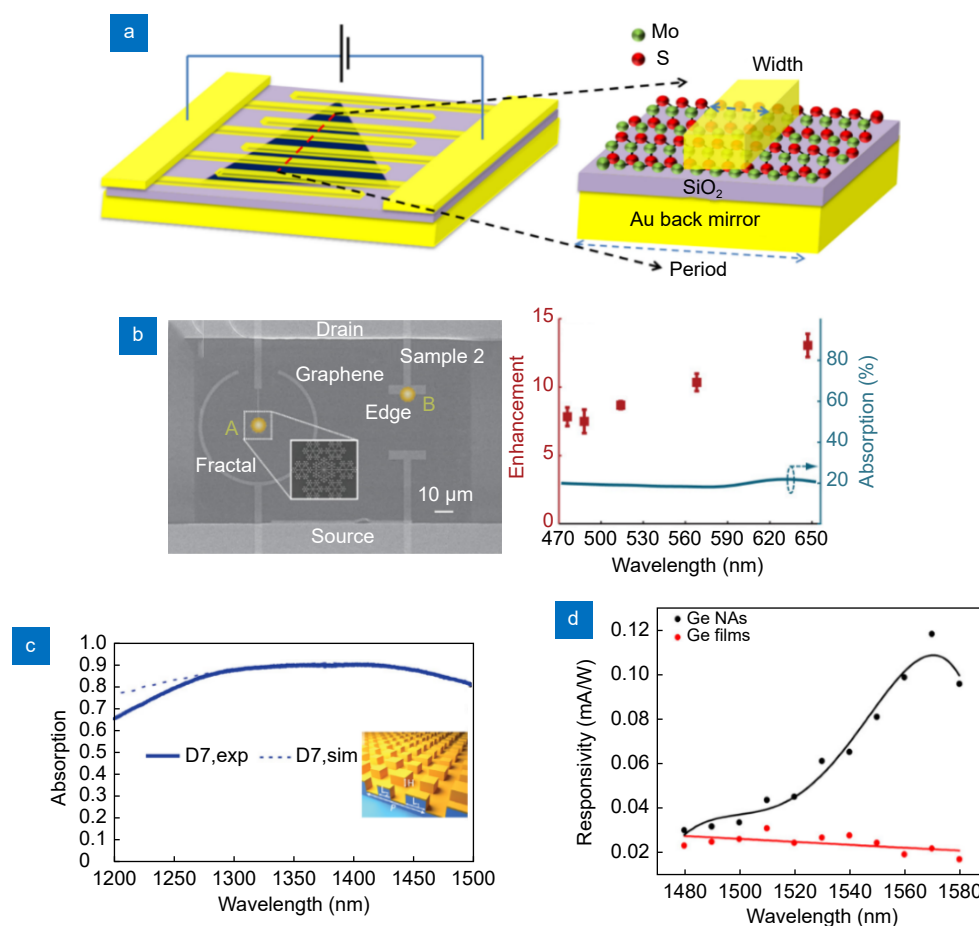


Fig. 6 | Metasurface-enhanced photoresponse. (a) The schematic of hybrid MoS₂ gap plasmon metasurface photodetectors. (b) SEM of fractal metasurface graphene photodetector, and measured enhancement of photovoltage generation and simulated absorption spectrum associated to the fractal metasurface. (c) Experimentally measured and simulated absorption spectra of the broadband metamaterial perfect absorbers detector. (d) Measured responsivity of the Ge nanoantenna arrays and the plane Ge film at different wavelengths. Figure reproduced with permission from: (a) ref.⁴⁶, IOP Publishing; (b) ref.⁴⁷, (c) ref.⁴⁹, (d) ref.⁵⁰, American Chemical Society.

Metasurface-enabled polarimetry

Polarization as a fundamental property of electromagnetic waves is widely used in optical communications, imaging, and biomedicine. Traditional photodetectors only detect the intensity of electromagnetic waves, requiring couples of additional polarization elements to access to the light polarization information. Combined with the anisotropy, chirality, and filtering capabilities of metasurfaces, ultra-compact linear, circular, and even full Stokes polarization detectors have been developed^{51–55}. Li et al. proposed an ultracompact circularly polarized (CP) light detector that benefits from the chirality in plasmonic nanostructures (Fig. 7(a))⁵¹. Chiral metamaterials are designed to selectively absorb a particularly polarized light while reflecting the other, and the circular dichroism can reach 0.9. The detector can distinguish LCP and RCP light without the use of addi-

tional elements. To achieve full Stokes polarization detection, it is necessary to obtain the intensity information of multiple polarization states. Li et al. reported an on-chip polarimeter comprising four metasurfaces (Fig. 7(b))⁵³. The chirality and anisotropy of the metasurfaces lead to circular and linear polarization-resolved responses. The full Stokes parameters including intensity, ellipticity, and orientation are obtained from the four metasurfaces, respectively. Furthermore, when combined with CMOS imaging sensors, the metasurface-based polarimeter can be used for polarization imaging. Zuo et al. presented a chip-integrated full Stokes imaging sensor by integrating a polarization filter array onto an imaging sensor⁵⁵. Polarization recognition was realized by double-layer metal grating and hybrid chiral metasurface with high polarization extinction ratios, and full Stokes polarization imaging of several objects was demonstrated.

Compared with Stokes imaging, Muller matrix imaging can extract rich information of target object or material. Zaidi et al. demonstrated a compact Mueller matrix imaging system, which consisted of two metasurfaces, one responsible for generating structured polarization illumination and the other for polarization analysis⁵⁶. The system can obtain the complete Muller matrix of the target object in a single shot, overcoming the limited time resolution of ‘division of time’ approach, and the volume and spatial resolution of other schemes.

Combined with the wavefront modulation ability of the metasurfaces, some polarization detection schemes using beam splitting, multi-focus metalens and vortex beam have been proposed^{57–64}. Wen et al. proposed a gradient metasurface for measuring the ellipticity and handedness of the polarized light (Fig. 7(c))⁵⁸. The LCP and

RCP components of the polarized beam are guided in two directions respectively, and the polarization information of the incident light is determined by measuring the intensity of the refracted spots. However, it is difficult for this method to measure arbitrary polarization states. To overcome this limitation, several other approaches using multi-focus metalenses have been proposed by spatially separating and focusing different polarization states. Yang et al. proposed a generalized Hartmann-Shack array based on 2×3 sub-arrays, supporting simultaneous measurement of phase and polarization profiles (Fig. 7(d))⁵⁷. Each sub-array comprising six metalenses to determine the Stokes parameters. And the phase-gradient profiles are detected by analyzing the foci displacements. Later, there are some works devoted to solving the problems of the working bandwidth and the

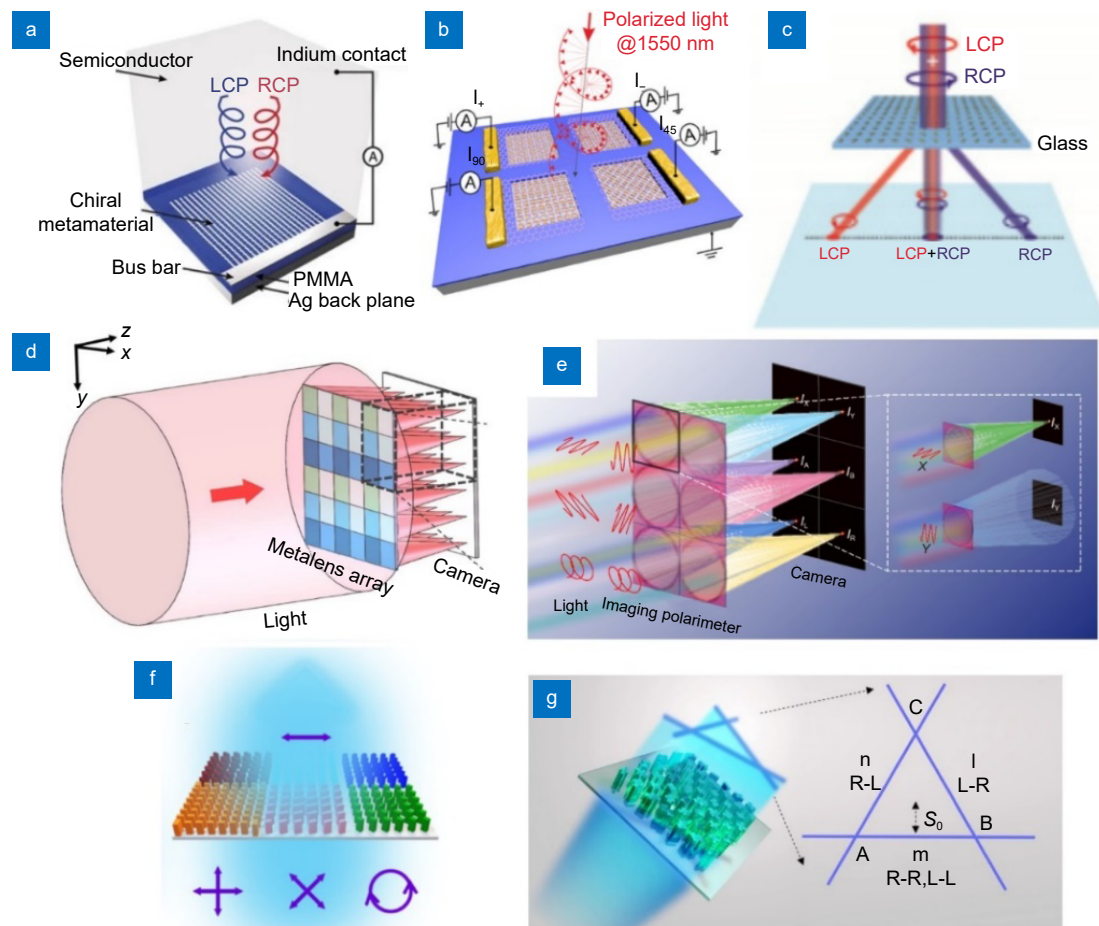


Fig. 7 | Metasurface-enabled polarimetry. (a) Schematic of the CP light detector consisting of a chiral metamaterial integrated with a semiconductor. (b) Schematic diagram of the plasmonic polarimeter. (c) Schematic to show the polarization of the refracted light after a polarized light beam passing through the metasurface. (d) Scheme of the generalized Hartmann–Shack array. (e) The schematic of the broadband achromatic imaging polarimeter. (f) Schematic of the multi-focus metalens for polarization detection. (g) Schematic illustration of the non-interleaved chiral metasurface for polarimetry. Figure reproduced with permission from: (a) ref.⁵¹, Springer Nature; (b) ref.⁵³, American Chemical Society; (c) ref.⁵⁸, Optica Publishing Group; (d) ref.⁵⁷, Springer Nature; (e) ref.⁵⁹, under a Creative Commons Attribution 4.0 International License; (f) ref.⁶⁰, Chinese Laser Press; (g) ref.⁶⁵, Springer Nature.

need for multiple measurements (Fig. 7(e)⁵⁹, Fig. 7(f)⁶⁰). In addition to these methods, Chen et al. proposed a non-interleaved, interferometric method to analyze the polarizations, which is based on a tri-channel chiral metasurface combined with a deep convolutional neural network (Fig. 7(g))⁶⁵. The metasurface can modulate the amplitude and phase profiles of the co- and cross- polarizations. The scheme is used to detect both spatially uniform and non-uniform polarization states.

Metasurface-enabled wavelength selective detection

By manipulating the resonance frequencies of the plasmonic nanostructures, it is possible to customize the spectrum responses of the devices in order to amplify the response at a specific wavelength, which can be used to distinguish the incident wavelengths of light. Liu et al. demonstrated a multicolor photodetector through integrating metallic plasmonic nanostructures with graphene photodetectors⁶⁶. Due to near-field enhancement, plasmonic nanostructures can locally increase the photoreponse at selected plasmonic resonance frequencies, resulting in a color-sensitive response for graphene photodetectors. By controlling the size, shape and periodicity of the structures, the plasmonic nanostructures with different resonance frequencies can be realized. Nanopillar arrays supporting Mie resonances and semiconductor nanowires can also be used for spectrum detection, and their resonant peaks can be tuned by adjusting the size of the pillars. Meng et al. demonstrated a spectrometer comprising an array of silicon nanowire photodetectors (Fig. 8(a))⁶⁷. These nanowire arrays sit on top of substrate photodetector and are used to filter the transmitted light, covering the entire visible spectrum. To enable spectrum detection, in addition to integrating photodetectors with plasmonic or dielectric structures, Wang et al. proposed a spectrometer with a multi-foci multiwavelength metalenses, mapping wavelength information into the different foci on the same focal plane (Fig. 8(b))⁶⁸. Furthermore, the concept of spectrometer has been further expanded, and some angle-resolved spectrometer⁶⁹ and spectroscopic ellipsometry (Fig. 8(c))⁷⁰ have been proposed successively, providing additional and powerful tools for optical imaging and spectral detection.

Metasurface-enabled OAM detection

The vortex beam carries OAM during propagation, which has been widely used in edge enhanced imaging, optical communication, optical trapping, and other

fields. By modulating the amplitude, phase, and polarization of the incident wave, metasurfaces can generate various vortex beams of different modes and different polarizations^{71–76}. Similarly, such capabilities can be used to separate different OAM modes in incident beams and to detect the OAM modes^{77–83}.

Genevet et al. demonstrated the integrated OAM selective detection using plasmonic detectors relying on selective coupling of propagation surface plasmon polariton (SPP) (Fig. 9(a))⁷⁷. Holographic surfaces can convert free-space beams with given topological charges into focused SPP waves. Chen et al. demonstrated an approach using nanograting to detect the topological charges of an OAM beam (Fig. 9(b))⁷⁸. The technique couples the OAM beam into two separated SPP beams according to in-plane wave vector matching process. This detection process is robust and without the strict alignment between incident light and the sample. The cylindrical vortex vector beam (CVVB), carrying both phase and polarization singularities, provides a higher degree of freedom for optical communication and microscopy. To simultaneously detect phase and polarization singularities of a CVVB, Feng et al. proposed a plasmonic spin-Hall nanograting containing double gratings and spin-Hall meta-slits (Fig. 9(c))⁷⁹. The incident vortex beams with different topological charges are coupled to SPP waves in different directions (in the y -direction). The topological charges of the incident beams can be calculated by measuring the propagation angles of the generated SPP. The chiral structure guides the SPP waves with opposite spins to propagate in opposite directions (in the x -direction), thus determining their topological charges and spin states. In addition to coupling vortex beams into SPPs to detect their topological charges, Ji et al. designed a photodetector based on tungsten ditelluride (WTe₂) to directly characterize the topological charges of OAM beams (Fig. 9(d))⁸⁰. The results show that the direction and amplitude of the photocurrent from OAM resulting from the phase gradient of optical fields directly reflect the OAM modes. In addition, some dielectric metasurfaces are proposed to separate the vortex beams with different topological charges into different spatial locations, to detect the topological charges of the incident vortex beams.

Manipulating light-matters interactions of low dimensional semiconductors

Low-dimensional semiconductors have emerged as a

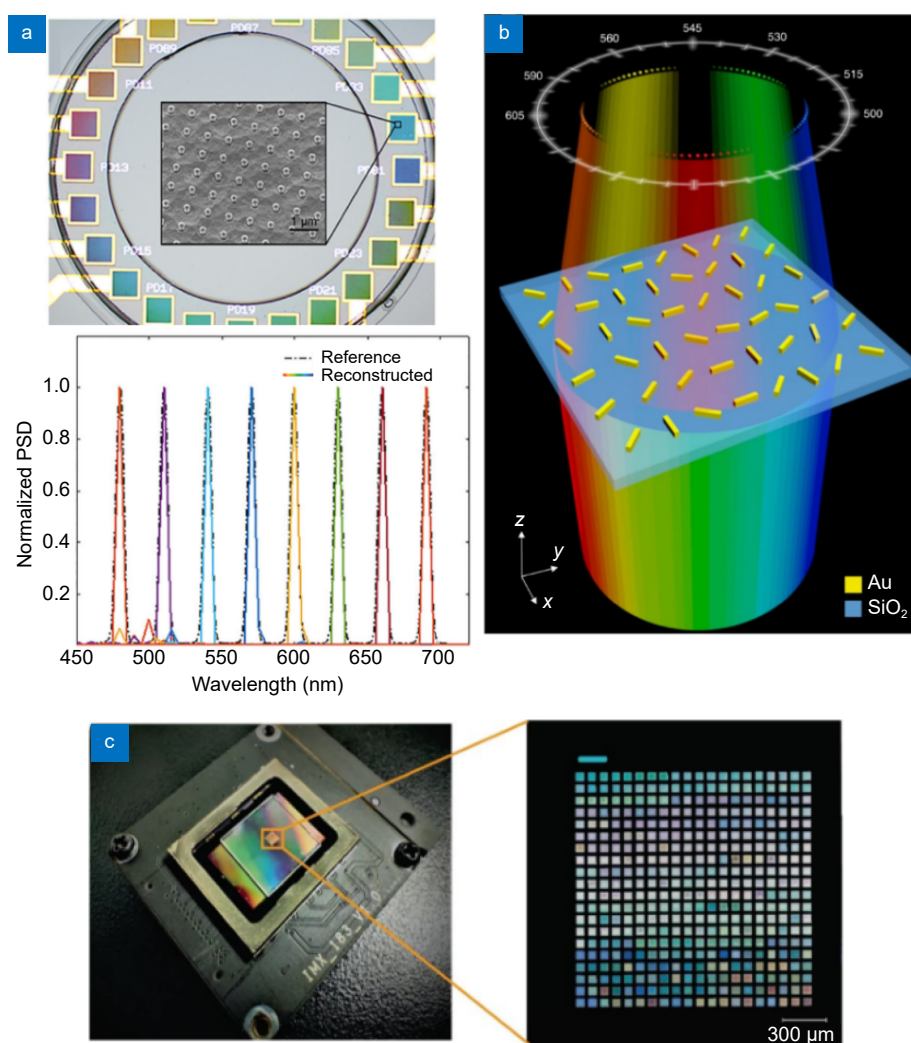


Fig. 8 | Metasurface-enabled spectrum detection. (a) Bright field optical microscope image of the silicon nanowire array photodetector, and reconstruction results for narrowband spectra. (b) A schematic diagram of the metasurface spectrometer based on wavelength dependent multi-foci metalens. (c) Photograph of the metasurface array-based spectroscopic ellipsometer. Figure reproduced with permission from: (a) ref.⁶⁷, American Chemical Society; (b) ref.⁶⁸, Springer Nature; (c) ref.⁷⁰, Springer Nature.

promising candidate for the development of new types of optoelectronic devices with intriguing properties, such as light emitters, photodetectors, modulators, etc. In this context, the capability of metasurfaces to confine the light, such as the near-field confinement using plasmonic metasurfaces around their plasmonic resonance, and the low-loss dielectric metasurface with high quality factor, provides a popular and powerful scheme to enhance the light-matter interactions inside low dimensional materials for optoelectronic applications. Table 3 summarizes the enhanced light-matter interactions of several typical low dimensional materials integrated with metasurfaces discussed in this review.

Graphene

Due to its high electron mobility, excellent mechanical

strength and thermal conductivity, graphene has great application potential in photonics and optoelectronics. In this section, we focus on graphene-integrated metasurfaces with improved functionalities, including tunable optical response (resonant frequency, absorption, and phase)^{84–92}, wavefront modulation^{93–95}, and enhanced nonlinear effect^{96,97}.

Mousavi et al. experimentally demonstrated that single-layer graphene can be used to tune the Fano resonances of plasmonic metasurfaces. The near-field coupling between the two vertical antennas results in the emergence of low-Q dipolar and high-Q quadrupolar modes (Fig. 10(a))⁸⁵. The interference between the two resonant paths leads to the typical asymmetric Fano feature in the spectrum. By placing a chemically doped

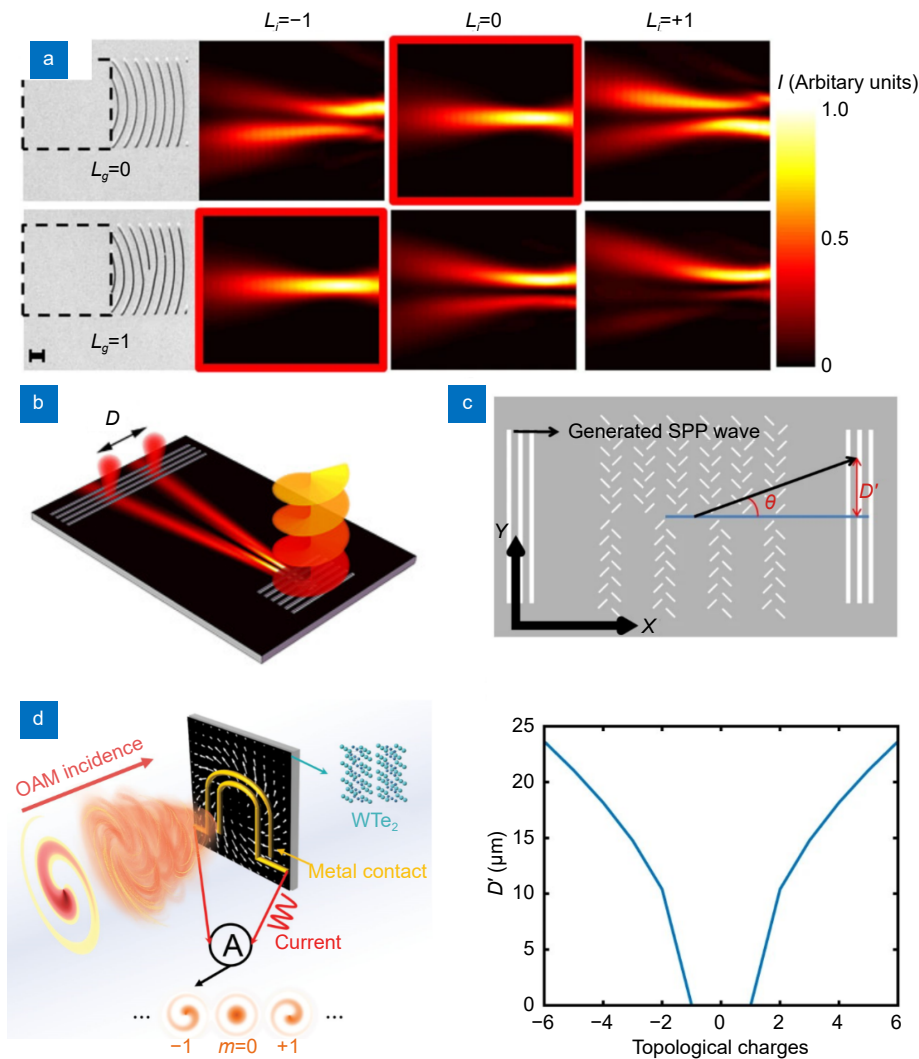


Fig. 9 | Metasurface-enabled OAM detection. (a) Numerical simulations of the generated SPP intensity distribution at normal incidence with a Gaussian beam or vortex beams of different topological charges. (b) Schematics of the on-chip OAM detection process. (c) Schematic of the plasmonic spin-Hall nanograting and calculated vertical displacement between the original and scattered beam spots on the output coupling grating. (d) Schematic of the photocurrent measurement based on WTe_2 photodetector. Figure reproduced with permission from: (a) ref.⁷⁷, Springer Nature; (b) ref.⁷⁸, John Wiley and Sons; (c) ref.⁷⁹, Springer Nature; (d) ref.⁸⁰, AAAS.

Table 3 | Metasurface-enabled light-matters interactions.

Material	Metasurface type/ principle	Integrated functions	Reference
Graphene	Fano resonance, plasmonic resonance, Fabry-Perot resonance	Tunable resonant frequency, absorption, and phase	ref. ^{84–93,99,100}
	Geometric phase, resonance phase	Wavefront modulation.	ref. ^{93–95}
	Plasmonic resonance, Fano resonance	Enhanced nonlinear effect	ref. ^{96,97}
Transition metal dichalcogenides	Plasmonic metasurface, Mie resonance, gap-surface-plasmon metasurface.	Enhanced photoluminescence	ref. ^{99–105}
	Surface plasmon polariton, bound states in the continuum, geometric phase	Second-harmonic generation enhancement, nonlinear wavefront shaping	ref. ^{106–111}
Hexagonal boron nitride	Hyperbolic phonon polaritons	Reconfigurable hyperbolic metasurface, broadband absorption	ref. ^{112,113}
Black phosphorus	Hybrid plasmon-phonon-polaritons	Tunable anisotropic plasmons	ref. ¹¹⁴
	Absorption-enhanced plasmonic metasurface, dielectric metalens	Enhanced photoresponsivity, photocurrent	ref. ^{115–117}

single layer of graphene on a Fano-resonant metasurface, a tunable blue shift is achieved in the mid-infrared band. The shift is caused by an inductive coupling between the metasurface and graphene, which can be controlled by electrostatic gating. A blue shift of the resonance of about 30 cm^{-1} has been experimentally demonstrated. Yao et al. demonstrated in situ control of antennas using graphene as an electrically tunable load⁹⁸. An equivalent circuit model was proposed to quantitatively analyze the tuning behavior. The tuning resonance ranges over 650 nm (140 cm^{-1} , $\sim 10\%$ of the resonance frequency) and over 30% intensity modulation ($\sim 100\text{ cm}^{-1}$, 8% of the center frequency) in the mid-infrared wavelength were demonstrated. Due to its relatively broad plasmonic resonances⁸⁴ and weak absorption, graphene has a limited modulation depth. To increase the modulation depth, Dabidian et al. integrated single-layer graphene with a high-Q Fano-resonant metasurface (Fig. 10(b)), achieving the modulation depth of the mid-infrared reflectance as high as 90% ⁸⁶. The enhancement of the electric field parallel to the graphene surface leads to a strong graphene/metasurface coupling that can shift the plasmon resonance by about half the spectral width, which in turn leads to an electronically controlled depth modulation of reflected infrared light. To increase the modulation speed, Zeng et al. demonstrated a hybrid graphene metasurface modulator based on a tunable metamaterial absorber (Fig. 10(c))⁸⁸. Only a few volts of gate bias are required to modulate the graphene conductivity, achieving a high modulation depth of up to 90% and a modulation speed larger than 1 GHz . The hybrid graphene metasurface modulator is formed into a pixel array, forming a prototype of a spatial light modulator with high frame rate, which provides the possibility for realizing wavefront engineering in the infrared region. Meanwhile, researchers have attempted to achieve terahertz modulation by coupling graphene with metasurface. Shi et al. demonstrated effective terahertz modulation by coupling graphene with a broadband terahertz metasurface (Fig. 10(d))⁸⁷. Using graphene as an active load with tunable conductivity, the local-field enhancement can be significantly enhanced, and the transmission of terahertz wave can be strongly modulated.

Graphene-integrated metasurface absorbers enable dynamically tunable absorption. Yao et al. demonstrated a high-speed tunable metasurface absorber with modulation depth up to 100% (Fig. 11(a)), which incorporates a metasurface on graphene into an asymmetric Fabry-Per-

ot resonator⁸⁹. The metasurface absorber consists of a metallic film, a dielectric layer, and an electrically tunable metasurface on graphene. Such a metasurface absorber does not require magnetic response, greatly reducing the complexity of the design. In addition to changing the gate voltage, Tasolamprou et al. experimentally demonstrated an ultrafast optically tunable absorption modulator (Fig. 11(b))⁹⁰. The absorber consists of a uniformly grown graphene sheet stacked on a SU-8 dielectric substrate, which is grounded by a metallic ground plate. A terahertz time-domain spectroscopy system coupled with an infrared-pump laser for photoexcitation can dynamically adjust the conductivity of the graphene sheet in the sample, with decay of 2.79 ps and absorption tuning of 40% . In addition to achieving tunable resonance frequency, amplitude, and absorption, the integration of graphene with metasurface can also be used to tune the phase, polarization, and other parameters of electromagnetic waves, such as realizing broadband tunable gate-controlled terahertz phase modulation and reconfigurable polarization conversion^{99,100}.

Graphene-integrated metasurface can be used to control the wavefront of light, including anomalous refraction, focusing lenses, and Airy beams, etc. By adjusting the size of the graphene structure, the dynamic adjustable amplitude and phase responses are verified by simulations. Wavefront control functions with dynamic tuning capability have been proposed^{93,94}. Except for these theoretical works, Kim et al. experimentally demonstrated a gate-controlled terahertz metasurface for modulation of anomalously refracted wave (Fig. 11(c)), which is formed by integrating a graphene onto a metasurface consisting of U-shaped apertures⁹⁵. By carefully designing the spatial phase distribution, the amplitude of abnormally refracted terahertz wave can be effectively modulated by varying the gate voltage.

Transition metal dichalcogenides (TMDs)

TMDs are a class of materials with layered structures, consisting of two atomic layers of chalcogenide elements (such as sulfur (S), selenium (Se) or tellurium (Te), etc. and a transition metal atomic layer (such as molybdenum (Mo), tungsten (W), etc.), forming an X-M-X sandwich structure. The chemical formula is usually expressed as MX_2 . Due to their direct bandgap electronic structure and strong light-matter interaction, TMDs exhibit strong excitonic effects, large spin-orbit splitting, and circular dichroism, showing excellent performance

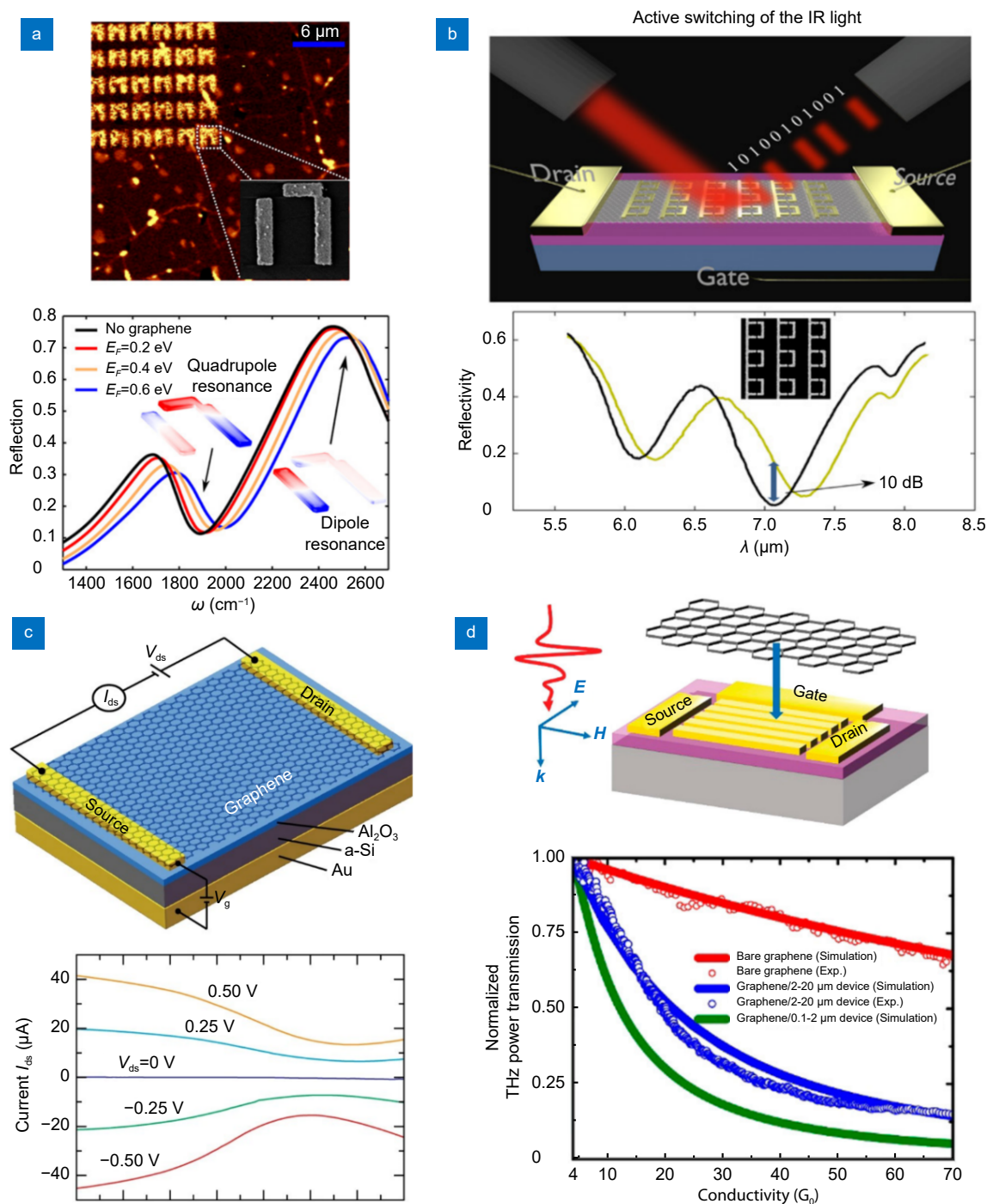


Fig. 10 | Graphene-integrated metasurface for modulation of the optical response. (a) Raman map of the graphene transferred onto a Fano-resonant metasurface, and the simulated reflectivity spectrum from the metasurface without and with graphene. (b) The schematic of a Fano-resonant metasurface integrated with graphene. Spectral shifting is achieved by back-gating of the graphene. (c) Schematic of the field-effect transistor structure, and the measured drain-source current across the graphene at different drain-source biases. (d) Schematic representation of the experiment setup for measurement as well as the hybrid device configuration, and terahertz power transmission modulation as a function of graphene conductivity. Figure reproduced with permission from: (a) ref.⁸⁵, (b) ref.⁸⁶, American chemical Society; (c) ref.⁸⁸, Springer Nature; (d) ref.⁸⁷, American Chemical Society.

in photoelectric applications such as PL, nonlinearity, wavefront modulation, etc.

TMDs-integrated metasurfaces are capable of manipu-

lating emissions of CP photon. Lin et al. demonstrated CP light emission from TMDs with thickness approximately 50 nm (Fig. 12(a)), where a monolayer WSe₂ is

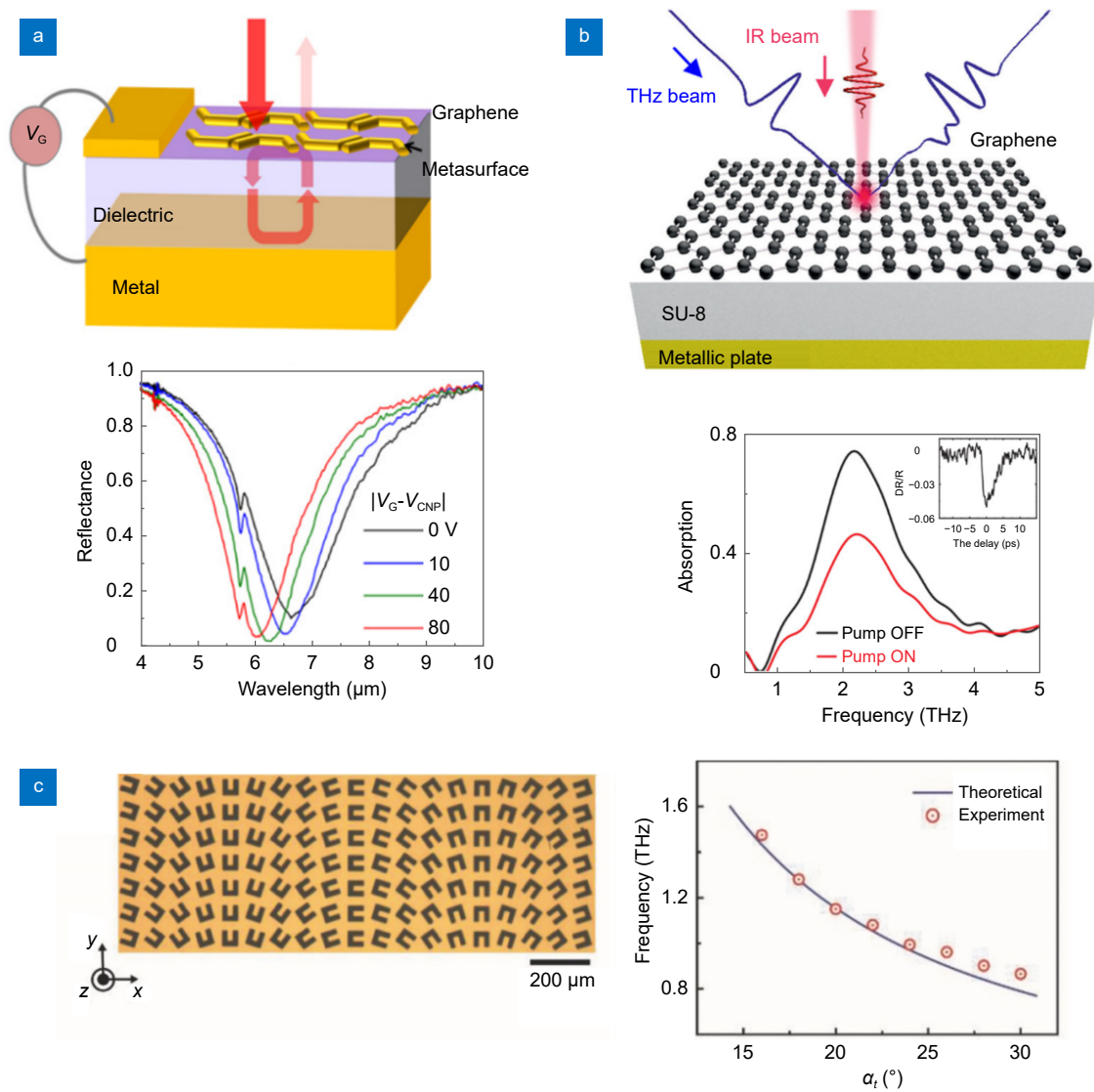


Fig. 11 | Graphene-integrated metasurface for dynamically tunable absorption. (a) Schematic of the optical modulator based on a tunable metasurface absorber, and the reflection spectra of metasurface absorbers for different gate voltages. (b) Schematic representation of the graphene absorber structure, and absorption spectra when the pump is ON or OFF. The inset presents optical pump induced terahertz relative reflectivity change. (c) Fabricated graphene metasurfaces for electrically tunable anomalous refraction. Figure reproduced with permission from: (a) ref.⁸⁹, American Chemical Society; (b) ref.⁹⁰, under a Creative Commons Attribution 4.0 International License; (c) ref.⁹⁵, John Wiley and Sons.

integrated with a plasmonic chiral metasurface¹⁰¹. The polarization states are controlled through the coupling between photons and chiral metamolecules. The circular dichroism of PL can be tuned from -26 to $+20\%$. Using the TMDs-metamolecules hybrid platform, the circular dichroism is enhanced from -6% to -26% , which is more than 4 times the enhancement in optical circular dichroism. Similarly, Ni et al. integrated gap-surface-plasmon metasurfaces with monolayer MoS_2 to enhance exciton-plasmon polariton emissions with controlled polarization (Fig. 12(b))¹⁰². Gate-tunable exciton plasmon polariton emissions are realized in MoS_2 under metal-

oxide-semiconductor configuration, demonstrating the capability of actively manipulating light-matter interactions through metasurface technologies. Some works have integrated TMDs monolayers with resonant dielectric nanostructures, controlling the emission directivity and/or enhancing directional emission^{103,104}. Bucher et al. explored the potential of all-dielectric resonant metasurfaces to manipulate light interactions inside the monolayers MoS_2 by changing their photonic and electric environment as well as the surrounding topography (Fig. 12(c))¹⁰⁵. An efficient platform for obtaining strong emission from an independent TMDs monolayer outside the

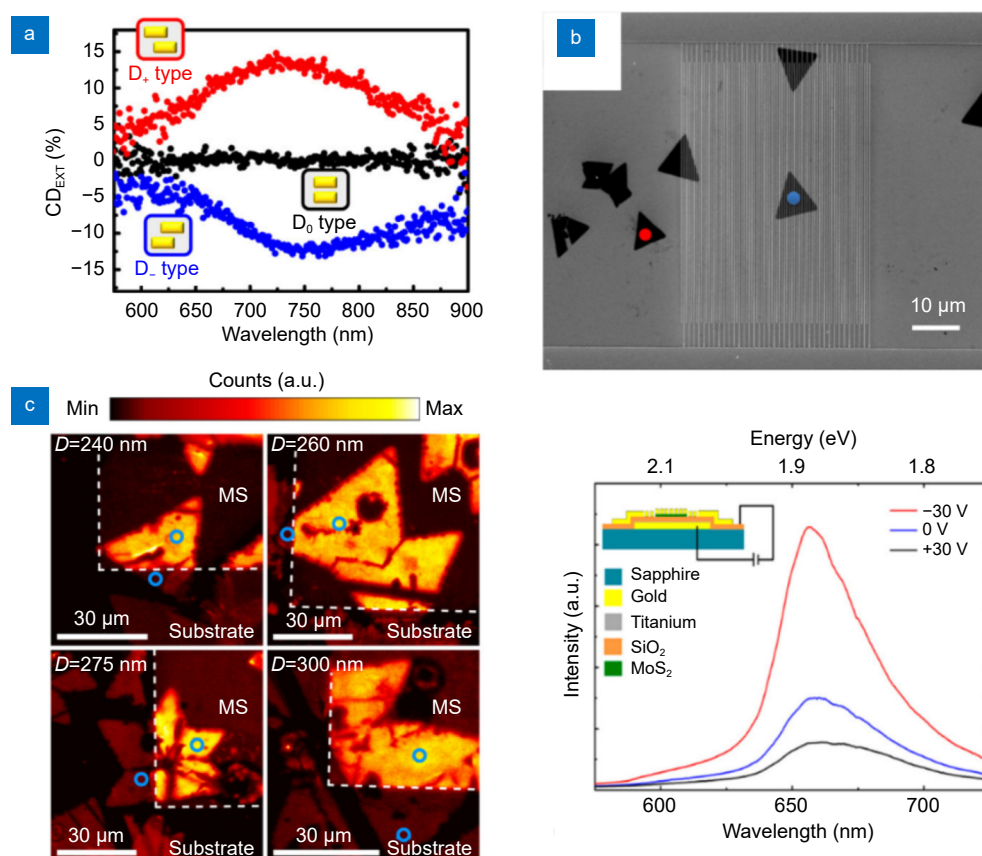


Fig. 12 | TMDs-integrated metasurfaces for manipulating PL. (a) The circular dichroism spectra of extinction of the achiral and chiral meta-molecules arrays. (b) The SEM image of the fabricated hybrid MoS₂ gap-mode metasurface and PL spectra under different applied voltages. (c) Spatial PL mappings of 1L-MoS₂ on silicon nanocylinder metasurfaces for different samples of varying diameters. Figure reproduced with permission from: (a) ref.¹⁰¹, (b) ref.¹⁰², (c) ref.¹⁰⁵, American chemical Society.

substrate plane has been demonstrated, allowing light collection using a simple low-NA optics.

TMDs-integrated metasurfaces provide an ideal platform for nonlinear photonics to potentially improve the weak nonlinear conversion efficiencies of monolayer TMDs limited by their atomic thickness. Many studies focus on enhancing the second harmonic emission of TMDs using optical microcavities, waveguides, and metasurfaces^{106,107}. Shi et al. demonstrated a two-dimensional frequency-doubling coherent light source and 400-fold second-harmonic generation (SHG) enhancement of monolayer WS₂ using the effective in-plane coupling of monolayer TMDs and resonator mode of surface plasmon polariton (Fig. 13(a))¹⁰⁸. The significant enhancement can be attributed to the strong confinement of the plasmonic field in the nanogrooves. By changing their groove depth, the resonance conditions and coupling strength can be adjusted. The concept of bound states in the continuum (BICs) opens a new way to achieve sharp resonances with high quality factors. Bern-

hardt et al. demonstrated a sharp enhancement of SHG from a two-dimensional material coupled to a quasi-BIC resonance in a dielectric metasurface (Fig. 13(b))¹⁰⁹. A WS₂ monolayer is placed on top of a silicon metasurface with a broken in-plane inversion symmetry to achieve a critical coupling state, balancing the radiation loss rates and other losses to provide the maximal field enhancement. A monolayer placed on a metasurface substrate exhibits at least 1140 times SHG enhancement relative to the monolayer placed on a bulk silicon substrate. Combining a monolayer TMD with locally rotated plasmonic nanorods to form a hybrid Pancharatnam-Berry phase metasurface has been used to add additional phase information to the SHG signal and achieve tunable geometric phases and field enhancement (Fig. 13(c) and 13(d))^{110,111}.

Hexagonal boron nitride (hBN)

hBN is a compound with a layered crystal structure, consisting of nitrogen and boron atoms arranged in a

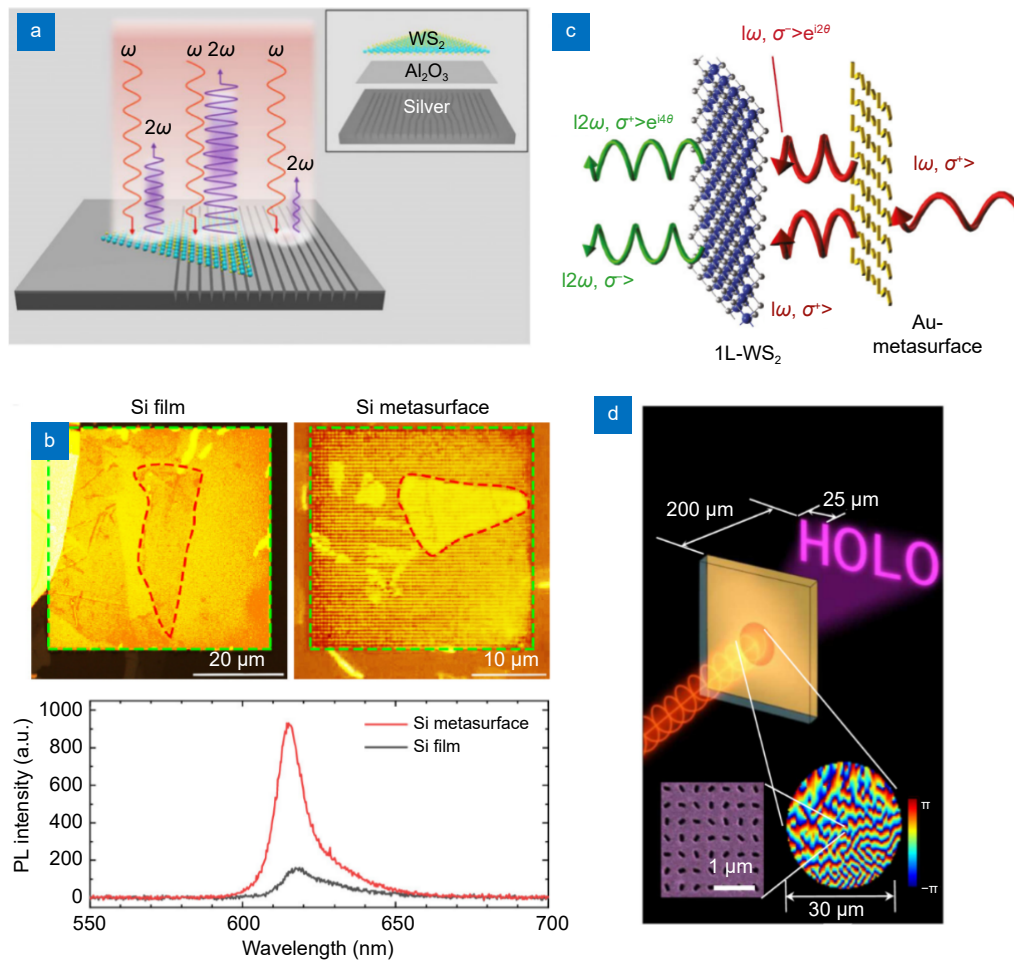


Fig. 13 | TMDs-integrated metasurfaces for nonlinear photonics. (a) Schematic diagram of the TMDs–plasmonic hybrid metasurface. (b) Optical microscopy images of the Si film and metasurface squares after the transfer of monolayer WS₂ flakes, and PL spectra of the WS₂ flakes. (c) Schematic illustration of the hybrid metasurface consisting of plasmonic Au nanorods and monolayer WS₂. (d) Schematic illustration of holographic imaging of the SHG beam. Figure reproduced with permission from: (a) ref.¹⁰⁸, John Wiley and Sons; (b) ref.¹⁰⁹, American Chemical Society; (c) ref.¹¹⁰, (d) ref.¹¹¹, under a Creative Commons Attribution International License.

hexagonal honeycomb pattern. It is a natural hyperbolic medium that supports low-loss hyperbolic phonon polaritons (HPPs), which significantly reduces the loss in polariton propagation. Folland et al. proposed a reconfigurable hyperbolic metasurface composed of hBN heterostructure in direct contact with single crystal vanadium dioxide (VO₂) (Fig. 14)¹¹². The metallic and dielectric domains in VO₂ provide spatially localized variations in the local dielectric environment, making it possible for HPP to emit, reflect, and transmit at the phase-change material domain boundary, and tuning the wavelength of HPP propagating in hBN by a factor of 1.6. This approach offers reconfigurable control of in-plane HPP propagation. To satisfy multi-spectral camouflage requirements, Buhara et al. proposed a hybrid nanoantenna architecture made of ITO-hBN grating¹¹³. Simulta-

neous excitation of plasma-phonon polaritons in ITO and hBN results in broadband absorption in the near-infrared range, and reflection in the mid-infrared and low-infrared ranges.

Black phosphorus (BP)

BP is a new two-dimensional direct bandgap semiconductor material with a layered structure, which has attracted much attention due to its unique photoelectric properties. Huang et al. developed a mid-infrared metasurface by nanostructuring a thin layer of BP carbide, realizing efficient excitation of hybrid plasmon mode at deep subwavelength-scale (Fig. 15(a))¹¹⁴. The hybrid plasmon mode displays an anti-crossing behavior of two splitting optical modes, which is attributed to the Fano resonance between plasmons and mid-infrared active

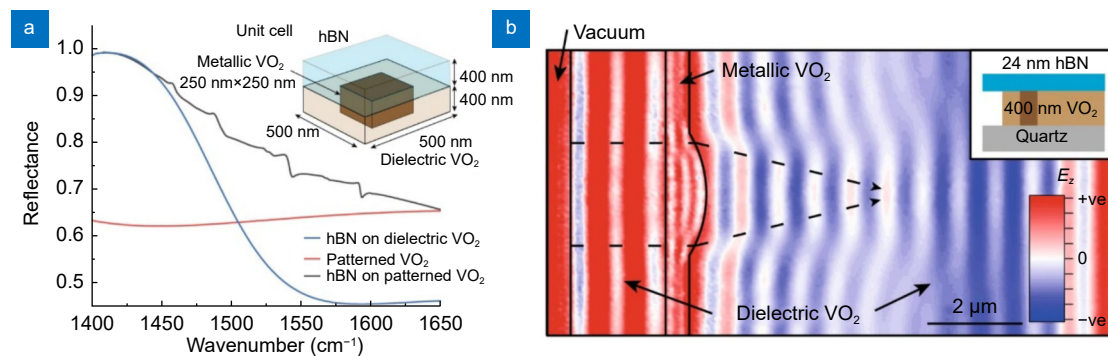


Fig. 14 | Schematic of refractive planar optics and reconfigurable resonators using hBN. (a) A tunable polariton metasurface of hBN and VO₂. (b) A simulation of a refractive polariton lens. Figure reproduced with permission from ref.¹¹², Springer Nature.

optical photons. These results show that the intrinsic in-plane anisotropy of BP carbide can provide a platform to engineer the plasmonic performance, leading to a new degree of freedom in which light-matter interactions can be manipulated in dynamically reconfigurable directions. Using the enhanced light absorption caused by the strong light-matter interaction, some hybrid photodetectors (Fig. 15(b) and 15(c)) have been proposed by combining the absorption-enhanced plasmonic metasurfaces with the BP photodetectors to improve the photoresponsivity^{115,116}. In addition, dielectric metalens can be directly fabricated at the substrate of the device to increase the collection of signals by BP photodetectors. The results show that the metalens increases performance at multiple testing wavelengths in the mid-infrared band (Fig. 15(d))¹¹⁷. Photocurrent and responsivity are approximately 6.65 times higher than that without metalens.

Conclusion and perspective

Metasurfaces offer a more compact and efficient means of modulating the amplitude, phase, polarization of light fields compared to the traditional refractive and diffractive optics, which enables a promising candidate for applications such as lenses, holograms, communication, sensing and display. In particular, metasurfaces have significant advantages, including ultra-compactness, high-efficiency, capability for wide-field applications, which holds great potential in promoting the development of wireless communications, wide field-of-view optics, next-generation virtual reality (VR) and augmented reality (AR) displays, multi-channel or even dynamic displays. Several reviews have thoroughly introduced and discussed the utilization of metasurfaces in these areas^{118–121}. In recent years, artificial intelligence (AI) has emerged as a powerful computational tool, offering an

efficient solution to optimize the design of metasurfaces and injecting new vitality into the development of nanophotonics^{122,123}. Inverse design methodologies, such as adjoint methods, evolutionary algorithms, and topological optimization, have successfully been implemented in the design of various photonic devices, such as power splitters, absorbers, dielectric nanoantennas, chiral metasurfaces. To handle design tasks with higher degrees of freedom and avoid some drawbacks of traditional optimization (such as the local minimum problem and expensive computations), neural network and deep learning have been alternative approaches to address the inverse design problem. Readers interested in nanophotonic intelligent designs can refer to recent reviews on this topic^{124–126}.

The integration of metasurface with semiconductor device has grown into a vibrant field over the past few years, and provide new opportunities to develop ultra-compact, integrated, and multifunctional optoelectronic devices with enhanced performance. Although this paper focuses on the semiconductor devices, it worth noting that integrated metasurfaces have been extensively explored and successfully combined with other platforms for on-chip applications with remarkable achievements, including solid-state lasers, waveguides, and optical fibers, etc. Transiting from the first generation of standalone photonic interfaces, metasurface integration in functional systems represents a significant transformation for this technology to closely and actively interconnect the optical, photonic and optoelectronic platforms. Compared to traditional optical and photonic systems that rely on bulky traditional optical components, integrated metasurfaces offer clear advantages in terms of ease of fabrication, compactness, lightweight, and scalability, etc. On-chip integration presents new and

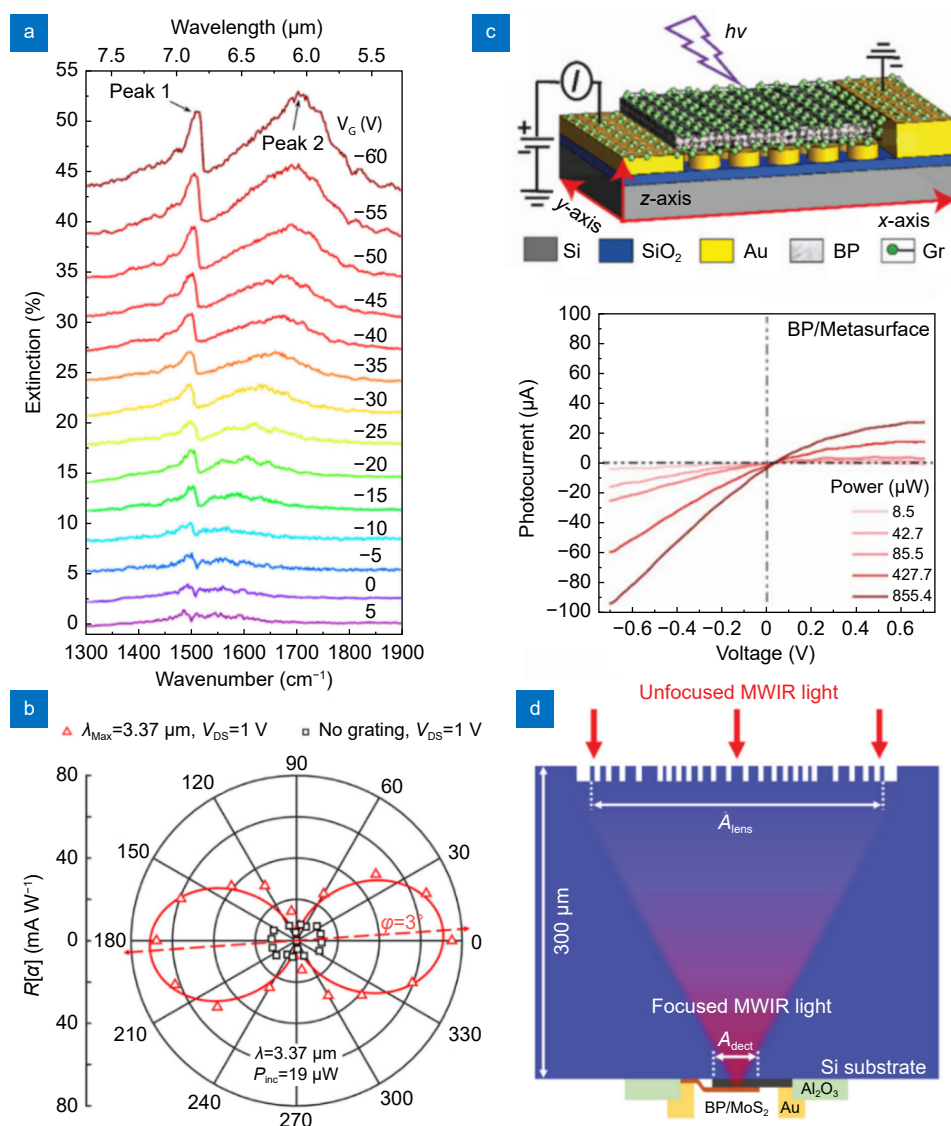


Fig. 15 | BP-integrated metasurfaces. (a) Gate-induced modulation of transmission through 80 nm wide BP carbide nanoribbon. (b) Polarization-resolved photodetector responsivity. (c) Schematic of the vertically stacked photodetector, and photocurrent with applied bias voltage at different illumination powers. (d) Conceptual diagram of a metalens-integrated BP photodiode. Figure reproduced with permission from: (a) ref.¹¹⁴, (b) ref.¹¹⁵, American Chemical Society; (c) ref.¹¹⁶, (d) ref.¹¹⁷, John Wiley and Sons.

coexisting challenges and opportunities. On one hand, the efficiency of integrated metasurfaces cannot compete with that of the conventional optical elements yet. On the other hand, a cost-effective and scalable solution for the integration of metasurfaces must be developed for practical use and commercialization. After witnessing a fantastic development pace over the last decade, metasurface technology is now facing the challenge of on-chip integration and, as such, we anticipate that considerable efforts in employing advanced design, optimization techniques and high-precision nanofabrication methods will be devoted to this endeavor.

So far, the integration of metasurfaces has been pri-

marily achieved through expensive and time-consuming nanofabrication techniques, such as EBL, FIB etching, which hinders the widespread use of on-chip metasurfaces. To tackle this issue, innovative manufacturing techniques for metasurfaces, including self-assembly growth, deep ultraviolet lithography, laser writing and nanoimprinting, etc, provide the advantages of large-scale and low-cost^{127–129}. However, there is currently no dominant “killer application” for metasurfaces that would dictate the most relevant fabrication approach in the industry. We envision that replacing the optoelectronic devices used in the current system with the emerging meta-devices will lead to the emergence of a new

version of meta-system, significantly impacting the development of future optoelectronic system with unprecedented advantages. Finally, the active metasurface, i.e. the holy grail of metasurface technology, has seen remarkable progress over the past few years^{130,131}. The combination of active metasurfaces with semiconductor devices would enable unmatched multiple functionalities encoding into single optoelectronic devices for future imaging, sensing, computing and LiDAR applications.

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Competing interests

The authors declare no competing financial interests.



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