Review

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Monolayer MoS₂ for nanoscale photonics

<https://doi.org/10.1515/nanoph-2019-0533>

Received December 18, 2019; revised January 8, 2020; accepted January 12, 2020

Abstract: Transition metal dichalcogenides are two-dimensional semiconductors with strong in-plane covalent and weak out-of-plane interactions, resulting in exfoliation into monolayers with atomically thin thickness. This creates a new era for the exploration of two-dimensional physics and device applications. Among them, MoS₂ is stable in air and easily available from molybdenite, showing tunable band-gaps in the visible and near-infrared waveband and strong light-matter interactions due to the planar exciton confinement effect. In the single-layer limit, monolayer MoS₂ exhibits direct band-gaps and bound excitons, which are fundamentally intriguing for achieving the nanophotonic and optoelectronic applications. In this review, we start from the characterization of monolayer MoS₂ in our group and understand the exciton modes, then explore thermal excitons and band renormalization in monolayer MoS₂. For nanophotonic applications, the recent progress of nanoscale laser source, exciton-plasmon coupling, photoluminescence manipulation, and the MoS₂ integration with nanowires or metasurfaces are overviewed. Because of the benefits brought by the unique electronic and mechanical properties, we also introduce the state of the art of the optoelectronic applications, including photoelectric memory, excitonic transistor, flexible photodetector, and solar cell. The critical applications focused on in this review indicate that MoS₂ is a promising material for nanophotonics and optoelectronics.

Keywords: MoS₂; monolayer; excitons; photonics; optoelectronics.

1 Introduction

In addition to the composition and structure of materials, physical dimensionality also plays a significant role in the determination of their fundamental properties. Monolayer MoS₂ was exfoliated by intercalation with lithium in 1986 [1]. The advantage of monolayer MoS₂ complementary over graphene is the layer-dependent band-gap tunability. The band structure of graphene exhibits a linear dispersion and the charge carriers act as massless Dirac fermions [2]. Monolayer graphene and few-layer MoS₂ can be act as saturable absorbers for mode-locked lasing [3, 4]. For semiconducting MoS₂, it undergoes a transition from an indirect band-gap (1.3 eV) in the bulk form to a direct band-gap (1.8 eV) in the single-layer form [5]. This indirect-to-direct band-gap transition that occurs during the MoS₂ bulk is thinned down to MoS₂ monolayer, thus significantly enhancing light emission and optical absorption in the monolayers. The direct band-gap can induce photoluminescence (PL) from monolayer MoS₂, providing the opportunity to device applications on photonics and optoelectronics [6]. In addition, the electronic structure of monolayer MoS₂ can also enable valley polarization for device applications on valleytronics [7].

There are two types of excitons in monolayer MoS₂, one is propagating excitons and another is localized excitons [8]. The propagating excitons exhibit large oscillation strength and high binding energy, resulting in the resonant coupling with incident photons [9]. The localized excitons are tightly bound to the defects and behave as single-photon emitters with narrow spectrum linewidths [10]. The photons emitted from propagating and/or localized excitons are preferred to be properly collected and efficiently guided for integrated photonic applications. Practically, the photonic applications of monolayer MoS₂ are always limited by their low quantum yield. Therefore, achieving high quantum yield of monolayer MoS₂ remains a challenge and is a hot topic [11]. It is anticipated that rapid developments would occur in monolayer MoS₂ photonics during the next years. In fact, the exfoliation of bulk MoS₂ into monolayers preserves most of their bulk properties and also results in additional characteristics originated from quantum confinement effects. Moreover, different types of monolayers could be stacked

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by van der Waals interactions to realize two-dimensional hetero-layers without the problem of “lattice mismatch,” providing an easy and flexible method to design intriguing properties [12]. In this review, we highlight some interesting properties of monolayer MoS₂ and how they are applied in nanoscale photonics and optoelectronics.

2 Monolayer MoS₂

2.1 Characterization of monolayer MoS₂

Figure 1A shows an optical micrograph of the monolayer MoS₂. It can be seen that most of the monolayers are in the shape of equilateral triangle with side lengths ranging from 10 to 25 μm , indicating the high level of crystallinity. The inset shows an enlarged triangle-shaped MoS₂ monolayer with a side length of 16.7 μm , indicating their high

crystallinity. Figure 1B shows the atomic force microscope (AFM) micrograph. The inset presents the height profile along the white dotted line, crossing one side of the monolayer, which indicates that the thickness of the MoS₂ monolayer is about 0.75 nm. This is in agreement with the thickness for S-Mo-S atomic structures [14]. Both Raman scattering and PL spectra were also obtained at room temperature under an excitation wavelength of 514 nm. The Raman spectrum of the monolayer MoS₂ (Figure 1C) shows two peaks for the in-plane (E_{2g}^1) and out-of-plane (A_{1g}) vibrational modes at 384 and 403 cm^{-1} , respectively. The peak-to-peak distance between those two modes is $\Delta = 19 \text{ cm}^{-1}$, which is another characteristics for monolayer MoS₂. Figure 1D shows the PL spectrum of the monolayer MoS₂ with a peak wavelength of 673 nm, which originated from the direct-gap excitonic transition [15]. Excellent excitonic features of monolayer MoS₂ interacting with incident photons offer a promising platform to construct multifunctional hybrid structures. Li and colleagues have

Figure 1: Optical and microscopic characterization for monolayer MoS₂.

(A) Optical micrograph of monolayer MoS₂ with shape of equilateral triangle. Inset: a typical monolayer MoS₂ with a 16.7- μm -long side.

(B) AFM micrograph of a monolayer MoS₂. Inset: the height profile along the dotted line. (C) Raman spectrum of the monolayer MoS₂. The distance between E_{2g}^1 and A_{1g} peaks is 19 cm^{-1} . (D) PL spectrum of the monolayer MoS₂ with peak wavelength of 673 nm. Reprinted with permission of Ref. [13].

fabricated two types of hybrid structures, demonstrating the resonance energy transfer between monolayer MoS₂ and CdSe/ZnS quantum dots [13], decorating MoS₂ monolayers with silver nanostructures for surface-enhanced Raman scattering applications [16].

2.2 Exciton modes in monolayer MoS₂

Nanoscale photonics applications of transition metal dichalcogenide is limited by weak light absorption, and their exciton modes are perturbed easily by varying excitation conditions since they are inherent as atomically thin layers. Lee et al. proposed a cavity-free configuration to enhance the exciton emission of two-dimensional semiconductors at varying laser excitation power with good peak shape and quality [17]. In their study, the silver (Ag) nanowire (NW) and monolayer MoS₂ hybrid structures were experimentally used. The Ag-NW was overlapping partly on the monolayer MoS₂ with a 10-nm-thick SiO₂ spacer to avoid doping, band-pinning, and PL quenching due to the direct contact of metal and semiconductor [18]. Figure 2A gives a schematic diagram and cross-sectional

view of the experimental setup and the hybrid structures. The representative exciton modes of monolayer MoS₂ are indicated as the primary A exciton (A⁰, ~1.88 eV), A⁰ multi-exciton (A', ~1.84 eV), and B exciton (B, ~2.02 eV) [15, 19, 20]. The Ag-NW and MoS₂ overlapped region (NMOR) is indicated as “on NW” and the bare MoS₂ is indicated as “off NW”. The PL image in Figure 2B shows a strong red emission at the laser excitation spot but a weak red emission at the NW-end, indicating that MoS₂ excitons were coupled into surface plasmons and propagated along the Ag-NW [21]. Figure 2C gives the normalized PL spectra that were de-convoluted by using a Lorentzian function. The X peak observed in the off NW case is assumed as a localized state due to impurities or defects [22]. At all five excitation power levels of 5–500 μW, only the A⁰ peak observation for on NW is significantly different from the three peaks observed for the off NW. For the case of on NW, the A⁰ peak position is ~1.88 eV and the full width at half maximum (FWHM) is ~50 meV, remaining unchanged and independent of the excitation power. But for the off NW case, as the excitation power increases, the A⁰ peak redshifts because the A' peak dominates, and the intensity of A' and B increases.

Figure 2: Typical exciton modes for monolayer MoS₂.

(A) Schematic diagram for the experimental setup with a side view of the structure. PL signals were excited by an incident laser and then collected from the region on/off Ag-NW. (B) Bright field optical micrograph (top) shows the laser excitation spot (green arrow) and dark field PL image (bottom) shows the spectrum collection position (white arrow) for the PL signals. The effective length from the excitation spot to the NW end is about 3 μm. (C) Normalized PL spectra vs. the excitation power for on/off NW, with examples for Lorentzian de-convolution at excitation power of 5 μW. (D) Two PL spectra for on/off NW at excitation power of 100 μW. (E) The logarithmic scale PL intensity vs. the excitation power for the off NW case. (F) Two PL spectra for the off NW case at excitation power of 5 nW and 100 nW, with the single Lorentzian fit at 5 nW indicated as A⁰ (red line). Reprinted with permission of Ref. [17].

Figure 2D compares the PL spectra for the two cases of on NW and off NW at an excitation power of 100 μ W. The peak intensity (I_A) for on NW containing only the A^0 is notably enhanced as compared with that for off NW containing the A' and A^0 (Figure 2C). The A-peak enhancement factor (ε) is defined as the ratio between the maximum I_A for on NW and off NW, and the factor ε can reach up to ~ 20 . Figure 2E gives the logarithmic scale intensity-power relationship for A and B peaks in the off NW case. The integrated PL intensity of I_{PL} is approximately equal to (excitation power) ^{m} , where m indicates exponent. For the I_A , $m \sim 0.9$ with excitation power ranging from 5 to 100 nW, in which only the A^0 peak is verified by using a single Lorentzian fit (Figure 2F). However, for excitation power larger than 100 nW, the I_A was saturated and m was degrading to ~ 0.6 since the A' begins to evolve and dominate the A peak (Figure 2C, off NW). As the A peak begins to be saturated over 100 nW, the B-peak intensity (I_B) also begins to occur and increase, giving $m \sim 1.3$. Thus, for the off NW case, the exclusive occurrence of the A^0 peak at an extremely low level of laser excitation power (Figure 2F) is strongly different from the exciton modes (A' and B) at a high level of excitation power (Figure 2C), which resulted from the exciton band-filling effect [23, 24]. Furthermore, because the FWHM of ~ 50 meV for off NW at low excitation power (Figure 2F) is the same as that for on NW (Figure 2C), the origin of PL enhancement for on NW (Figure 2D) could not be related to the cavity resonance [25].

2.3 Thermal excitons in monolayer MoS₂

Transition metal dichalcogenide undergoes an indirect-to-direct band-gap transition as the thickness thins down, resulting in the strong excitonic PL and electroluminescence in monolayers. Dobusch et al. demonstrated that a monolayer MoS₂ suspended in vacuum across a 150-nm-distance emits visible light due to Joule heating [26]. The narrow-band visible light emission from thermally excitonic states was located spatially into a 50-nm-wide area in the device center. Figure 3A shows the schematic diagram of the device. Figure 3B gives the corresponding optical micrograph for the device. The monolayer MoS₂ flake was suspended freely over a pre-defined trench with a gap of 150 nm. The MoS₂ was chosen since it can allow driving large currents for thermal emission; in fact, the device concept could be extended to any other two-dimensional semiconductors. The chosen distance between the electrodes ($L_{\text{channel}} = 4 \mu\text{m}$) was relatively large to successfully determine the spatial location for the resulting excitonic emission and distinguish

it from the contacts emission [27]. As can be seen from the inset of Figure 3A, the calculation shows that (under large bias) a large fraction of the applied drain-source voltage (V_{DS}) descends at the trench (i.e. $V_{\text{trench}}/V_{\text{DS}} \approx 0.5$), even though $d/L_{\text{channel}} \approx 0.04$, leading to effective heating in the suspended monolayer MoS₂. The SEM image in Figure 3C presents the suspended MoS₂ monolayer, in which neither bends (strains) nor cracks can be seen. The thickness of a monolayer MoS₂ is verified by Raman scattering signals [28], which was measured before the MoS₂ flake transfer process (see the following Figure 3F). The silicon (Si) substrate was acted as a backgate with a 100-nm thick dielectric Si₃N₄. From the transfer characteristics, shown in Figure 3D, a field effect mobility ($\mu \approx 175 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) at a substrate temperature ($T_0 = 80 \text{ K}$) was clearly extracted, where the short channel effects were neglected because of the short screening length of λ (i.e. $\lambda \sim 6 \text{ nm} < d \sim 150 \text{ nm}$) [29, 30]. The extracted mobility agrees well with previous devices. At low V_{DS} , the self-heating effects could be neglected; thus, the electron temperature (T_{el}) is equal to T_0 .

Optical micrograph can reveal that the origin of light emission was the suspended area for the MoS₂ flake, where the heat dissipation via the substrate was completely eliminated. Figure 3G presents the light emission intensity (upper) and the respective current I_{DS} (lower) vs. applied voltage of V_{DS} . The onset for the thermally excitonic emission was in the negative differential conductance regime under a high level of biasing, which indicates strong self-heating and scattering for electrons by hot optical phonons. The self-heating was caused from the Joule power dissipation ($P \approx V_{\text{trench}} \times I_{\text{DS}}$), in which the hot electrons can emit optical phonons, then decaying via an-harmonic coupling to the acoustic modes that carried the heat away [31]. Under the operation of light emission, the high T_{el} results in a significant thermal population for excitonic states and the visible light emission originated from the radiative recombination of electron-hole pairs. Figure 3H shows the thermal emission spectra with V_{DS} ranging from -17 V to -20 V and V_{BG} of 18 V , which was plotted on a logarithmic scale. The well-appreciable peak around $\sim 1.7 \text{ eV}$ corresponds to the A-exciton. The second, weaker peak at the higher energy corresponded to the B-exciton, which originates from the spin-orbit coupling for the valence band, corresponding to the lower spin level transition. In contrast to the low-temperature PL spectra, as shown in Figure 3E, the thermally excitonic emission spectra are relatively broader and shifted in energy (eV).

To extract the applied bias-related T_{el} , the spectra were numerically fit by Planck's law, shown as dashed

Figure 3: Thermally excitonic emission in monolayer MoS₂.

(A) Schematic diagram for the device structure with monolayer MoS₂ suspended freely over a gap (width $d \sim 150$ nm). The monolayer MoS₂ was contacted with Ti/Au (2/60 nm) electrodes and separated from the Si substrate (backgate) via a 100-nm-thick dielectric (Si₃N₄). The inset gives the calculated channel potential (V_{channel}), when $V_{\text{BG}} = 18$ V and $V_{\text{DS}} = -20$ V. The small potential (~ 0.5 V) descends at $x = 0$ and $x = L$ because of the contact resistance. (B) Optical and (C) scanning electron micrographs for a representative device. Scale bars in (B) are 10 μm and in (C) are 400 nm. (D) Transfer characteristics measured at $V_{\text{DS}} = -5$ V and $T_0 = 80$ K with $W = 4.5$ μm and $L = 4$ μm . (E) Offset PL emission from monolayer MoS₂ at different temperatures, ranging from 20 K to 300 K. (F) Raman scattering spectrum of monolayer MoS₂. The frequency difference of ~ 18.5 cm⁻¹ between the E_{2g}^1 and A_{1g} Raman modes verifies a thickness of one monolayer. (G) Integrated light emission intensity (upper plot) and the corresponding current I_{DS} (lower plot) vs. applied voltage of V_{DS} for V_{BG} ranging from 14 to 20 V. (H) Logarithmic scale thermal emission spectra with $V_{\text{BG}} = 18$ V and V_{DS} ranging from -17 to -20 V. The T_{el} was extracted via using the Planck's law (dashed line). (I) Thermal emission intensity vs. T_{el} , plotted with logarithmic scale. Inset: the shift of the A-exciton peak with respect to T_{el} . Reprinted with permission of Ref. [26].

lines in Figure 3H. Under a V_{BG} of 18 V, the T_{el} of 1597 K was extracted. Plotting the emission intensity vs. the extracted T_{el} (as symbols of Figure 3I) shows good agreement with the theoretical expectation (dashed line of Figure 3I) according to Planck's law. The observed red shift may be mainly attributed to a lattice heating. By plotting the peak position of A-exciton vs. the extracted T_{el} (as inset of Figure 3I), a linear relationship is found at a slope of -0.2 meV K^{-1} . To compare this result with the PL shift at the studied temperatures, Varshni's relation [32] was used and extrapolated from PL measurements conducted below room temperature (Figure 3E). Using Varshni's relation, a reduction in the band-gap energy with respect to the increasing lattice temperature can be described. A red shift of $-0.25 \pm 0.03 \text{ meV K}^{-1}$ was obtained, which was similar to the value extracted from the thermally excitonic emission.

2.4 Band renormalization in monolayer MoS₂

The Coulomb potential of monolayer semiconductors could result in a strong renormalization for energy band-gap (E_g)

and large exciton binding energy (E_b) by carriers. The former is difficult to determine since a cancellation occurs for alterations in E_g and E_b , leading to little alteration in the optical transition energy under different densities of carriers. Liu et al. quantified the band-gap renormalization in single-crystal MoS₂ monolayer on SiO₂ substrate by using angle- and time-resolved photo-emission spectroscopy [33]. Figure 4A and B presents the electron energy distribution curve (EDC) maps showing the conduction and valence band photo-emission signals, respectively, vs. the pump-probe delay (Δt). Because of the low electron population in the conduction band, these electrons were assumed to reside near the conduction band minimum (CBM), and the CBM position was taken as the intensity-weighted average for CB photoelectron energy. For the valence band maximum (VBM), each valence band EDC from the *K* valley can be described with a Gaussian function, and the VBM position can be represented by the high-energy cutoff at ($E_a + 2\sigma$), where E_a stands for the intensity-weighted average of the VB photoelectron energy and σ stands for the variance of the Gaussian fitting. Figure 4C gives the CBM and VBM positions vs. the delay Δt . Notably, the photo-excitation inducing band-gap renormalization was exclusively reflected in the upper shift of the VBM and the CBM remained a

Figure 4: Dynamics of band renormalization in photo-excited monolayer MoS₂.

All as a function of pump-probe delay: (A) and (B) are intensity (false color) plots of EDC individually collected for conduction and valence bands, respectively. (C) CBM and VBM positions obtained from EDC scans of (A) and (B). (D) Energy band-gap E_g (gray) with bi-exponential fitting (black). (E) photoelectron intensities of the conduction (blue) and valence (red) bands. (F) Width (FWHM) of the valence band. Reprinted with permission of Ref. [33].

constant, indicating that the CBM was fixed to the Fermi level for the metal contact, in agreement with the findings of Radisavljevic et al. [34]. The difference between VBM and CBM presents the band-gap E_g with time dependence. In the E_g calculation, the CBM was fixed to be 0.223 eV above the Fermi energy. Figure 4D shows the measured E_g of 2.19 ± 0.10 eV without photo-excitation ($\Delta t < 0$), which is about 0.4 eV lower than that of undoped MoS₂ monolayer [35, 36]. This difference clearly reflects the band-gap renormalization in the intrinsic n -type doping with $n_0 = (4.9 \pm 1.0) \times 10^{12} \text{ cm}^{-2}$. When $\Delta t = 0$, the photo-excitation across the band-gap further decreases E_g by ΔE_g of (-0.36 ± 0.04) eV.

The photo-induced large band-gap renormalization originated from the strong many-body interactions and deficiently screened Coulomb potential in the MoS₂ monolayer. The band-gap was initially renormalized by $\Delta E_g = -0.36 \pm 0.04$ when $\Delta t = 0$, then recovered with the increasing Δt because of the carrier recombination. The recovery could be described with a biexponential fitting (as black line of Figure 4D), with a decay time τ_d of 2 ps and 80 ps, respectively. The time-dependent E_g was consistent with the population decay for the CB photoelectron intensity (blue curve of Figure 4E), also in the recovery for VB width (Figure 4F). In comparison, the VB photoelectron intensity (red curve of Figure 4E) remains stable, as anticipated from the small VB depletion ($\sim 1\%$) of photo-excitation. At the high density of photo-excitation, the fast decay τ_d of 2 ps probably originates from the Auger recombination [37], while the slow decay τ_d of 80 ps may be a result of the intrinsic radiative and/or nonradiative decays in the monolayer MoS₂ [38]. Here, the electronic interaction with or without screening by the SiO₂ dielectric substrate was minimal and the photo-excited carrier populations at room temperature lived for about 400 ps. This is in contrast to previous experiments on polycrystalline MoS₂ monolayer on metallic substrate showing that the lifetime is shorter by four orders of magnitude [39]. Therefore, the determined band-gap renormalization closely reveals the intrinsic many-body interactions in monolayer MoS₂ [40].

3 MoS₂ photonics

3.1 Monolayer MoS₂ laser

The realization of low-consumption lasers based on atomically thin transition metal dichalcogenides is highly important for the development of nanoscale photonics [41–45], but most of them are achieved via an exfoliation

method accompanied by poor controllability and low reproducibility. Zhao et al. reported that a controllable strategy for obtaining large-scale lasing from chemical vapor deposition (CVD) achieved MoS₂ monolayer [46]. Figure 5A presents the schematic configuration for MoS₂/microsphere cavity lasing. Arrays of SiO₂ microsphere were placed on top of monolayer MoS₂ with a 285-nm-thickness SiO₂/Si substrate. The substrate was chosen to enhance absorption and emission efficiency because of constructive interference and reducing lattice distortion [47, 48]. The microsphere acts as a whispering-gallery-mode microcavity (Q factor of 10^8) with low absorptions both in the excitation and emission wavebands [49]. Furthermore, the microcavity lens can locally focus the excitation laser onto monolayer MoS₂, enhancing the spatial overlap between excitation energy and gain material (Figure 5B). In addition, because of the higher screening of the microcavity compared with the atmosphere, the MoS₂ below the microspheres exhibits smaller band-gap (E_g) compared with the surrounding MoS₂, which further increases the carrier localization and thus enhances effective gain in the MoS₂/microsphere coupling region [50]. An optical micrograph for the MoS₂/microsphere arrays (Figure 5C) indicates good controllability and reproducibility for MoS₂ lasers [51–53]. A scanning tunneling microscopy (STM) image of CVD-grown MoS₂ on a pyrolytic graphite (HOPG) substrate is shown in Figure 5D. The microsphere exhibits a smooth and clean surface according to the SEM image presented in Figure 5E. The spontaneous emissions of MoS₂/microsphere lasing devices are investigated by optical excitation under a 532-nm continuous-wave laser at power density of 980 W/cm^2 . Figure 5F shows that the PL intensity of MoS₂/sphere (red) is larger than that of MoS₂ monolayer (olive), indicating the microsphere lensing effect and increasing excitation efficiency [54]. The PL peak position of the MoS₂ below microspheres is red-shifted by ~ 30 meV compared with the surrounding MoS₂, indicating a smaller band-gap. The red-shifts could be attributed to strain and screening effect caused by microspheres [55]. Multiple oscillation peaks appear above the A exciton and B exciton emissions of monolayer MoS₂, indicating the optical feedback of whispering-gallery-mode microcavity [56].

3.2 Exciton-plasmon coupling

Atomically thin films of transition metal dichalcogenides are rising as a new system to investigate exciton-plasmon coupling [57–59]. Two-dimensional excitons in monolayer MoS₂ are strongly bound, strictly oriented in-plane, and

Figure 5: Optically pumped lasing from monolayer MoS₂ with microsphere.

(A) Schematic diagram for microsphere cavity on top of monolayer MoS₂, with red lasing under 532 nm excitation. (B) Lasing principle shows the localized carriers and the strong coupling between gain medium and cavity modes. (C) Optical micrograph of microsphere arrays on monolayer MoS₂. Scale bar, 15 μm . (D) Moiré-scale STM image of monolayer MoS₂ transferred on pyrolytic graphite (HOPG) substrate; scale bar, 4 nm. Inset gives the magnified view; scale bar, 0.8 nm. The arrows lie along moiré pattern (blue) and the S atoms (green) for MoS₂ monolayer, respectively. Rhombus shows the unit cell for moiré pattern giving a period of about 1.06 ± 0.05 nm. (E) SEM image for a representative microsphere showing the clean and smooth surface; scale bar, 2 μm . (F) Lasing spectrum of MoS₂/sphere and PL spectrum of monolayer MoS₂ on SiO₂/Si substrate, under 532 nm laser excitation at power density of ~ 980 W/cm². Reprinted with permission of Ref. [46].

exhibit large oscillator strength [60, 61]. The mechanical robustness of monolayer MoS₂ allows the ease of integration with plasmonic nanostructures, providing possibilities to engineer light-matter interaction [62, 63]. Zhao et al. reported on plasmonic modification of light-matter interaction in monolayer MoS₂ hybridized with Ag nanoparticles (Ag-NPs) [64]. The hybrid structures were obtained by thermal evaporation of a metallic film on top of monolayer MoS₂ and then annealing. Figure 6A and B shows optical micrographs of monolayer MoS₂ on quartz substrate without and with Ag-NPs, respectively. Figure 6C shows an AFM micrograph of 10-nm-thick Ag-NPs with sizes of 20–120 nm, uniformly distributed on MoS₂ surface, giving dozens of nanometers of interparticle spacing. Electric field distributions for different excitation wavelengths were simulated by finite-difference time-domain (FDTD). The obtained morphology of the nanodisks (Figure 6C) was used for the FDTD simulations. Figure 6D presents the simulated field distribution.

A large field enhancement of 50 times occurred in hotspots (narrow gaps), where dipole-dipole interactions between adjacent particles are highly strong [65]. For comparison, the preparation method was modified to obtain smaller-sized Ag-NPs. The large nanodisks (average size of 57 nm) and small semispheres (average size of 34 nm) are referred as LNP and SNP, respectively. The FDTD simulation of Ag SNP (Figure 6H) shows interparticle hotspots with large field enhancement but smaller overall enhancement. Experimental extinction spectra for monolayer MoS₂ with and without Ag-NPs are given in Figure 6I and J, along with the FDTD simulated spectra for Ag LNP and Ag SNP, respectively. The extinction spectra of the hybrid MoS₂/Ag-NP system consist of optical features attributing to MoS₂ excitons and localized surface plasmons of Ag-NPs. Specifically, broad peaks centered on 700 and 500 nm for MoS₂/Ag-LNP and MoS₂/Ag-SNP are attributed to localized surface plasmon resonances of Ag-NPs, which agrees well with FDTD simulations. The observed PL enhancement

Figure 6: Exciton-plasmon coupling in monolayer MoS₂ hybridized with Ag-NPs.

Optical micrographs of monolayer MoS₂ on quartz without (A, E) and with (B, F) Ag-NPs. AFM micrographs (C, G) of monolayer MoS₂ with Ag-NPs and FDTD simulations (D, H) for localized field enhancement of indicated area in AFM. The Ag LNP were simplified as 10-nm-thick nanodisks with various diameters, while Ag SNPs were simplified as semi-spheres with various diameters. The maximum field enhancements for Ag LNP and Ag SNP are 52 and 40 times, respectively. The scale bars are 5 μm and 200 nm for the optical and AFM micrographs, respectively. (I, J) Experimental (red, green) and FDTD simulated (orange) extinction spectra for monolayer MoS₂ with Ag LNP and Ag SNP, respectively. Experimental extinction (dashed blue) of bare MoS₂ are shown as references. As comparison, FDTD simulated extinction were normalized to experimental extinction. Reprinted with permission Ref. [64].

originated from the enhancement of both spontaneous emission rate and excitation optical field. The spontaneous emission enhancement depends on the extinction spectra of localized surface plasmons [66]. Thus, tunable coupling between excitons and plasmons from weak to strong coupling regimes is of fundamental interest.

3.3 PL tailoring

Monolayer MoS₂ exhibits PL in the visible waveband as its direct band-gap. Compared with zero- and one-dimensional emitters, the absence of interlayer interactions in monolayer shows great flexibility and functionality [67, 68]. However, monolayer MoS₂ suffers from low absorption due to the sub-nm thickness, resulting in low

PL yields. To enhance the emission from monolayer MoS₂, Gao et al. demonstrated the localized PL manipulation of monolayer MoS₂ by using single shaped Ag nanoantenna [69]. Single Ag nanoantennas with different morphologies were used to control the spectral overlap between the localized surface plasmons of Ag and the band-gap of MoS₂. The PL of monolayer MoS₂ can be continuously tuned from a weakened emission to an enhanced area. Individual Ag nanoantennas were sparsely distributed on monolayer MoS₂, with an interparticle distance $>1 \mu\text{m}$ to avoid plasmonic coupling between adjacent Ag nanoantennas (Figure 7A), where NC is nanocube, SP1 is large-sized nanosphere, SP2 is small-sized nanosphere, and OCT is octahedral. The large interparticle distance also ensures that only single Ag nanoantennas were excited within the volume from laser excitation. Incident 532-nm excitation

Figure 7: PL tailoring of monolayer MoS₂ by single shaped Ag nanoantennas.

(A) Dark-field optical micrograph of monolayer MoS₂ deposited with single shaped Ag NC (i), Ag SP1 (ii), Ag SP2 (iii), and Ag OCT (iv). Insets present the SEM micrographs of single nanoantenna, and scale bars in (i–iii) are 100 nm and (iv) are 200 nm. (B) PL intensity maps of monolayer MoS₂ deposited with single shaped Ag nanoantenna at 680 nm (A1 peak). (C) PL spectra of monolayer MoS₂ with and without the Ag nanoantenna. (D) Intensity profile of A1 peak along the dashed line in (B). Reprinted with permission ref. [69].

was used to control the exciting efficiency for the localized surface plasmons of Ag nanoantennas. The excitation intensity was kept below 1×10^5 mW/cm² to avoid photo-damage of monolayer MoS₂. PL intensity maps in Figure 7B demonstrate the localized manipulation over PL from monolayer MoS₂ as the presence of Ag nanoantennas. For the case of Ag NC, both the wavebands around B1 (625 nm) and A1 (680 nm) peaks exhibit strong PL enhancement in the areas deposited with single Ag NC (Figure 7C-i). For the areas without Ag NC, the PL intensity returns immediately to that of bare monolayer MoS₂ (Figure 7D-i). The similar PL enhancements can also be observed in the PL spectra of Ag SP1 (Figure 7C-ii and D-ii), but almost no PL enhancements were observed for Ag SP2 (Figure 7C-iii and D-iii). On the contrary, PL quenching was observed from Ag OCT (Figure 7C-iv and D-iv). In the case of Ag NC, the localized surface plasmons completely overlap with both the 532-nm excitation and the 680-nm band-gap, leading to significant field enhancement at both excitation and emission wavelengths. Since the nanoantennas change from NC to SP1 and SP2, the spectral overlaps decrease, resulting in lower efficiency for exciting the surface plasmons. This off-resonant excitation progressively gives the smaller PL enhancements. On the other hand, PL weakening of monolayer MoS₂ with Ag OCT originates from both the emission quenching and complex antenna effects, such as the nonradiative nature of the high-order surface plasmons. Such PL manipulation is promising for the integration of monolayer MoS₂ photonics.

3.4 Integration with NWs

A monolayer semiconductor exhibits fascinating nonlinear optics, such as second harmonic generation (SHG) [70]. However, nonlinear utilization of monolayer MoS₂ is a challenge because of the poor field confinement and the weak light-matter interaction, which limits the conversion efficiency. Integration of monolayer MoS₂ with dielectric NW offers an opportunity to achieve enhanced SHG. Li et al. reported a hybrid structure of monolayer MoS₂/TiO₂ NW that shows anisotropic and enhanced SHG compared to the bare MoS₂ monolayer [71]. To fabricate the hybrid structure (Figure 8A), TiO₂ NW suspension was spin-coated onto a SiO₂ substrate. After drying, monolayer MoS₂ was transferred onto a TiO₂ NW via an optical microscopy. Figure 8B gives a false-color SEM image of a hybrid structure, confirming that the monolayer MoS₂ (purple) was successfully integrated with the TiO₂ NW (green). Figure

8C shows the AFM topography of the hybrid structure, where the diameter of TiO₂ NW is about 75 nm. Figure 8D shows a cross-sectional high-resolution transmission electron microscopy (HR-TEM) image, which confirms the high crystallinity of TiO₂ NW, the monolayer characteristic of MoS₂ flake, and the smooth MoS₂/TiO₂ interface. Interestingly, an air gap was observed between the MoS₂ and SiO₂ substrates, indicating a suspended MoS₂ monolayer locally formed on each side of the TiO₂ NW. Manipulation of SHG from a hybrid structure of monolayer MoS₂/TiO₂ NW (Figure 8E) was exploited. Figure 8F shows the SHG mapping of the hybrid structure in Figure 8E, where the monolayer MoS₂ was coupled partially onto the TiO₂ NW with a diameter of 100 nm (dotted line). The SHG emission from the bare MoS₂ monolayer exhibits a relatively weak signal, while the SHG emission from the hybrid structure exhibits a significantly enhanced signal with two orders of magnitude enhancement. The enhanced SHG signals from the hybrid structure shows an inhomogeneous distribution (Figure 8F), which resulted from the nonuniform distribution of diameter in the same TiO₂ NW. This diameter-sensitive response can be used to well control the SHG enhancement. The method could be extended to other nonlinear processes, such as Kerr effect, nonlinear absorption, and refraction in few-layer quantum dots and black phosphorus [72–74].

3.5 All-dielectric metasurfaces

Single dielectric nanocavities provide moderate manipulation of fluorescence emission as compared with plasmonic nanocavities. Dense arrangement of dielectric nanocavities in a resonant metasurface exhibits strong collective responses, which can be well controlled to manipulate the emission behaviors [75]. Fano resonances in dielectric nanohole arrays were used to enhance the absorption and emission of MoS₂ monolayer, then achieving unidirectional emission [76]. Bucher et al. explored the potential manipulation of all-dielectric metasurfaces on light emission from MoS₂ monolayer [77]. By a wet-transfer process, monolayer MoS₂ was placed on top of Si nanocylinder metasurfaces. Figure 9A shows a typical sketch of the monolayer MoS₂/Si metasurface structures. Figure 9B shows an optical micrograph of monolayer MoS₂ flakes with the shape of triangles. The monolayer MoS₂ clusters come from merging of adjacent MoS₂ monolayers by either grain boundaries or an overlapping bilayer. The color impression of the monolayer MoS₂ flakes originates

Figure 8: Monolayer MoS₂ integrating with TiO₂ NW for enhanced SHG.

(A) Schematic diagram of a monolayer MoS₂ integrated with single TiO₂ NW and excited by the fundamental wave ω , where scattered SHG signal 2ω can be collected. (B) False-color SEM micrograph and (C) AFM topography for hybrid structure of monolayer MoS₂/TiO₂ NW on SiO₂ substrate. Inset shows the height profile. (D) Cross-sectional HR-TEM micrograph (right) and overlapped energy-dispersive X-ray spectrometry mapping (left) for the same structure in (B). (E) Optical micrograph of MoS₂/TiO₂ hybrid structure on a SiO₂ substrate with (F) the SHG mapping. Reprinted with permission of Ref. [71].

from thin film interferences in the growth substrate, and the blue color is determined by the layer thickness. The Si nanocylinder metasurfaces were fabricated on glass by using electron-beam lithography. The metasurfaces consist of square arrays of Si nanocylinders with a constant height of 188 nm, lattice constant of 560 nm, and varying diameters of 200–350 nm. Figure 9C shows a SEM image of a typical metasurface, which supports the optical resonances in visible range covering the 660 nm emission band of monolayer MoS₂. For transferring the monolayer MoS₂ to the metasurfaces, MoS₂ grown Si wafer was immersed into weak KOH solution to separate the SiO₂ layer and the PMMA. The wafer sank down, making the

PMMA layer with MoS₂ monolayers float on the surface. The transfer layer was fished from the surface by catching it with the metasurfaces. The PMMA layer was removed using acetone solvent and supercritical CO₂ fluid [78]. Figure 9D shows a top-view optical micrograph of target Si metasurface (dark square) with good transfer of monolayer MoS₂ (cyan triangles), indicating that the structural integrity of monolayer MoS₂ was relatively preserved. To analyze the placement of monolayer MoS₂ on the Si metasurface, Figure 9E takes the cross-sectional SEM through the hybrid structure by focused ion beam milling. The monolayer MoS₂ is lying flat on top of the Si metasurface, giving direct contact with the nanocylinders, and freely

Figure 9: Monolayer MoS₂ integrating with all-dielectric metasurface.

(A) Sketch of MoS₂ monolayers placed on top of Si nano-cylinder metasurface on a glass substrate. Inset shows the crystal structure.

(B) Real-color optical micrograph of MoS₂ monolayers on the Si wafer. (C) Top-view SEM micrograph of a Si metasurface on glass. (D) Real-

color optical micrograph of MoS₂ monolayers on a Si metasurface. (E) Cross-sectional SEM micrograph of the same sample in (D), where an area covered by monolayer MoS₂. Reprinted with permission of Ref. [77].

suspended between adjacent nanocylinders. PL mappings were performed by using a laser confocal scanning microscope (MicroTime 200, PicoQuant), showing a uniformly enhanced PL signal in the region of the Si nanocylinder metasurfaces with typical enhancement factors of 5–8. This work takes a crucial step for integrating semiconductor monolayers into photonic applications.

4 MoS₂ optoelectronics

4.1 Optoelectronic memory

Atomically thin nanomaterial has emerged as a hot topic since the stable graphene monolayer was isolated perfectly [79–81]. Alternatively, monolayer MoS₂ with an obvious band-gap has emerged as an efficient channel material for various electronic devices [82, 83]. The 1.8 eV of direct band-gap at 689 nm makes monolayer MoS₂ unique for practical device applications in optoelectronics [84, 85]. Lee et al. developed a multibit nonvolatile memory, which

synergistically combines the rational device designs and the efficient transfer for large-area MoS₂ monolayers [86]. Figure 10A presents a schematic illustration for the monolayer MoS₂ optoelectronic memory device, in which the gold NPs (AuNPs, diameter ~9.7 nm) act as a charge-trapping layer. High-quality large-area monolayer MoS₂ flakes were fabricated by using a transfer method with an adhesive-strained metal layer. Figure 10B gives the transfer procedures for transferring a monolayer MoS₂ flake. The transfer yield was optimized by testing other metallic layers (i.e. Al and Ni) with different thicknesses and demonstrated to be the best using a 100-nm-thick gold layer. Figure 10C gives an optical micrograph for a transferred MoS₂ monolayer with size more than 150 μm . The large-area MoS₂ monolayer could be well transferred with minimal wrinkles or defects, and the memory device was prepared by depositing drain and source electrodes via metal shadow mask. The channel length (L) and width (W) were 30 and 60 μm , respectively. The height profile for the MoS₂ monolayer was measured by AFM and presented as the inset of Figure 10C. The thickness of the MoS₂ monolayer was experimentally measured to be ~0.78 nm,

Figure 10: Optoelectronic memory with monolayer MoS₂.

(A) Schematic diagram for the monolayer MoS₂ optoelectronic memory device configuration. (B) Schematics of the transfer procedure for the high-quality large-area monolayer MoS₂ flakes. (C) Optical micrograph of the monolayer MoS₂ flakes transferred by adhesive-strained metallic layer. Inset: cross-sectional height profile obtained by AFM. (D) Raman signal mapping of the energy difference between the E_{2g}^1 and A_{1g} modes for monolayer MoS₂ flakes. The inset gives a typical Raman scattering spectrum. (E) PL spectrum of the monolayer MoS₂. (F) Optically and electronically controlled memory functionalities of the monolayer MoS₂ optoelectronic memory device. Reprinted with permission of Ref. [86].

corresponding to that of previous work [87]. Figure 10D gives the Raman spectrum mapping for the energy difference between the two vibrational modes over the same area imaged by optical microscope (Figure 10C). A relatively uniform color distribution was measured over the imaged area. The above results ensured that the transferred MoS₂ monolayers were in uniform thickness. Figure 10E gives the steady-state PL spectrum for monolayer MoS₂. The PL spectrum shows a single exciton peak at 668 nm, resulting from the interband direct recombination of the photo-generated excitons [88]. For the dynamic behaviors of the monolayer MoS₂ optoelectronic memory, Figure 10F presents the light-controlled and voltage-controlled storage characteristics of the memory device for multilevel data. As seven programming pulsed gate biases were applied from −20 V to −100 V, the level of drain current increased stepwise (red area). The stored data were fully erased upon application of a gate bias of +100 V. Pulsed light at seven different powers was optically applied, and eight-level data storage was realized with a drain current level spanning seven orders of magnitude (blue area). Importantly,

only voltage-controlled operation yielded a drain current ratio of programming/erasing similar to that achieved under light-illumination operation. A considerable light-controlled programming/erasing current ratio larger than 10⁷ would enable the data states in the memory devices to be exactly read.

4.2 Excitonic transistor

Two-dimensional semiconductors have received great attention in optoelectronics due to the band-gap tunability, tightly bound excitons, and strong exciton-plasmon interactions. Young et al. demonstrated an exciton field-effect transistor (FET) through exciton-plasmon interconversions in Ag-NW overlapping onto monolayer MoS₂ transistor [89]. Figure 11A shows the operation principle, where monolayer MoS₂ was located in the middle of Ag-NW. The surface plasmon polariton (SPP0) coupled from λ_0 was absorbed in the MoS₂ monolayer and then generated an exciton λ_1 . The generated exciton λ_1 was

Figure 11: Long channel excitonic transistor.

(A) Long Ag-NW overlapped on the monolayer MoS₂ FET. The input λ_0 was converted into SPP0. The SPP0 propagating along the Ag-NW was absorbed in monolayer MoS₂, and the exciton λ_1 was generated at the overlapped region between NW and MoS₂. The exciton λ_1 was recoupled into SPP1 near the Ag-NW and then scattered into free space from another end of the Ag-NW. The λ_1 exciton flux was modulated by gate voltage (V_G). (B) Optical micrograph overlapped with false-colored MoS₂ monolayer (top) and PL micrograph (bottom) for the excitonic transistor. D (drain) and S (source) for electrodes of the transistor. Green and red arrows are for λ_0 position and λ_1 emission, respectively. Blue circle is the position for PL collection. Scale bar: 10 μm . (C) PL spectra of *On* (red, −100 V) and *Off* (blue, +100 V) states. (D) Schematic shows the MoS₂ FET operation. OS (optical source) and OD (optical drain) are for λ_0 input and λ_1 output, respectively. Channel: Ag-NW and the overlapped region. Reprinted with permission of Ref. [89].

recoupled into SPP1 and then propagated along Ag-NW. Finally, the SPP1 was converted into free space (λ_1) via scattering at another end of Ag-NW. Figure 11B presents an optical image and PL micrograph of the excitonic FET device. The green arrow is the input λ_0 illumination, the red arrow near the overlapped region (NW-MoS₂) is the output λ_1 emission, and the red light spot (blue circle) at another end of Ag-NW is a position for PL collection in Figure 11C. In the output λ_1 emission area, the propagating SPP0 along Ag-NW was converted into SPP1 through exciton-plasmon interconversion, and the subsequent SPP1 propagation was detected by the λ_1 scattering at another end of Ag-NW. Figure 11C shows the clear on ($V_g = -100$ V) and off ($V_g = +100$ V) states for the PL spectra. Particularly, the channel length was demonstrated up to ~ 32 μm at room temperature, which was about 10 times longer than (~ 32 μm) of quantum well transistors [90, 91]. For the SPP in Ag-NW, the $1/e$ propagation lengths were calculated to be of 12–31 μm at 620–760 nm visible band, which agrees well with experimental results. An even longer propagation length of about 50 μm at visible band has also been demonstrated in Ag films via the CMOS process [92]. These length scales are compatible with nanoscale optoelectronics, merging electronics, and photonics at nanometer scale [93]. Furthermore, two-dimensional semiconductors with smaller band-gaps for longer wavelengths could allow even longer propagation length on metallic SPP. The principal concept of the excitonic FET was schematic presented in Figure 11D, where the input λ_0 is the optical source, the output λ_1 is the optical drain, and the channel is the Ag-NW and overlapped region. The above results show the unique advantages of monolayer MoS₂ for building reconfigurable architectures in integrated optoelectronic circuits.

4.3 Flexible photodetector

Dynamic manipulation of electrons and photons in optoelectronics is generally realized by electrostatic biasing [94]. However, wearable device applications require that flexible optoelectronics can be modulated by mechanical strains [95, 96]. Wang et al. reported strain-modulated flexible optoelectronics based on monolayer MoS₂ using piezophototronic effect [97]. The electrical transport of a monolayer MoS₂ photodetector under mechanical strain without light illumination is shown in Figure 12A, giving strong dependence of the dark current on mechanical strain. Mechanical strain can also modulate the photocurrents under different power intensities of 3 $\mu\text{W}/\text{cm}^2$ and 4.297 mW/cm². The changes in transport behaviors

and photocurrents by mechanical strain originated from two effects: the piezophototronic effect [98], where the photo-generated carriers are effectively separated by strain-induced charges at the Schottky barriers; and the piezoresistive effect, where the band structure and density of states for carriers are changed by mechanical strain [99]. Figure 12B shows the changes in dark current and photocurrent with different strains under a drain bias (-2 V). For the case without light illumination, dark current of the detector increases with increasing tensile strain and decreases with increasing compressive strain (top of Figure 12B). For the case with light illumination (middle, bottom of Figure 12B), the photocurrent decreases with the increasing tensile strain, while the photocurrent increases first and then decreases with the continuous increase in compressive strain. The parameter $S = (I_{\text{strain}} - I_0)/I_0$, defined as the relative change of photocurrent by strain under certain power intensity, is plotted as Figure 12C, where I_{strain} and I_0 are the equilibrium photocurrents with and without strain, respectively. The values of S decrease with increasing power intensity, suggesting that the strain-induced polarization of photogenerated carriers is more effective at low power intensity. This results from the screening of piezoelectric polarization charges because of finite carrier density in monolayer MoS₂ [100]. Figure 12D shows the photocurrent mapping of monolayer detector under different strains and power intensities. The photocurrents first increase to a maximum as the compressive strain is small and gradually decrease as the compressive strain continually increases, whereas the photocurrents always decrease with the increasing tensile strain. Furthermore, the compressive strain for the photocurrent maximum shifts up to a higher value as the power intensity increases. Piezoelectronics merging with photonics in monolayer MoS₂ could enable the development of flexible ultrathin optoelectronics.

4.4 Solar cell

For practical applications of solar cells, it is highly important to develop low-cost devices. This could be realized by either lowering the device cost or enhancing the efficiency. Both have been achieved in Si-based heterojunction solar cells because Si has dominated the photovoltaic market due to mature Si technologies and considerable power conversion efficiencies [101, 102]. Tsai et al. fabricated a solar cell with an intact monolayer MoS₂ on a p-Si substrate [103]. Ultraviolet photoemission spectroscopy was applied to show the band structures of p-Si and MoS₂ for a type II heterojunction, achieving a 5.23% power

Figure 12: Piezophototronic effects of monolayer MoS₂ photodetector.

(A) Electrical transport of photodetector in the dark under different strains (top). Photocurrents of the detector under strains with illumination intensity of 3 $\mu\text{W}/\text{cm}^2$ (middle) and 4.297 mW/cm^2 (bottom). (B) Strain-dependent dark current (top) and photocurrents (middle, bottom) for the detector under drain bias of -2 V. (C) Relative change of photocurrents by strain modulation under different power intensities. (D) Piezophototronic mapping of photocurrents in the detector under different strains and power intensities. Reprinted with permission of Ref. [97].

conversion efficiency. Figure 13A presents a schematic diagram for the device structure of monolayer MoS₂/p-Si solar cell. Figure 13B gives an optical photograph of monolayer MoS₂ transferring onto p-Si substrate, indicating the uniform distribution around 1 cm $\times$ 1 cm. The solar cell was fabricated following the steps in Figure 13C. The p-Si substrate was first immersed into the buffered oxide etchant to remove native oxide layers. Layers of Cr/Ag (5 nm/300 nm) were deposited as back electrodes. Monolayer MoS₂ was transferred onto the top of p-Si substrate. The samples were cut into an area of $\sim$ (1 cm $\times$ 1 cm) with full coverage by monolayer MoS₂ on p-Si (Figure 13B). Semitransparent Al of 15 nm and finger-patterned Al of 100 nm were successively deposited as the top electrodes. The 15-nm-thickness Al layer was used to create an Ohmic contact with monolayer MoS₂ for facilitating carrier collection at the top electrodes. Figure 13D gives the J - V characteristics of the MoS₂/p-Si heterojunction device. Compared with Al/p-Si Schottky device, the MoS₂/p-Si

heterojunction device exhibits improved J_{sc} from 21.66 to 22.36 mA/cm^2 , V_{oc} from 0.38 to 0.41 V, and fill factor from 56.02% to 57.26%, achieving an efficiency of 5.23%. Figure 13E presents the external quantum efficiency (EQE) for the MoS₂/p-Si heterojunction device. Compared to the Al/p-Si Schottky device, the MoS₂/p-Si heterojunction device exhibits broadband enhancement due to increased absorption and improved carrier collection efficiency. Monolayer MoS₂ integrated into the silicon process shows great promise for optoelectronics.

5 Conclusion

Monolayer excitons in MoS₂ offer an ideal platform for exploring the two-dimensional physics and enable device applications in nanoscale photonics. We presented the current advances on the manipulation of PL from monolayer MoS₂ by plasmonic nanostructures and all-dielectric

Figure 13: Monolayer MoS₂ heterojunction solar cell.

(A) Schematic diagram for the device structure. (B) Photograph of monolayer MoS₂ transferred on p-Si with size of 1 cm × 1 cm. (C) Fabrication flow chart for the MoS₂/p-Si solar cell. (D) *J-V* characteristics and (E) EQE of the solar cell. Reprinted with permission of Ref. [103].

metasurfaces. For the practical light-emitting applications, it is highly urgent to beat the limits of low quantum yield in monolayer MoS₂. High band-gap, environmental stability, flat geometry, fast mobility, optical transparency, and mechanical flexibility are the main advantages of MoS₂ monolayer for nanophotonics and optoelectronics. The combination of monolayer MoS₂ with low-dimensional nanostructures could enable the new discovery of optical sciences and technology for light generation, transmission, modulation, and detection applications [11, 104–112]. The reviewed device applications based on these advantages focus on the photonic and electronic properties of MoS₂ monolayers, while their valley- and spin-related properties may be highly potential for future applications in exciton-polariton interactions, quantum photonics, information valleytronics, and nonlinear optics [12, 113–120]. We believe that the fundamental physics and device applications of monolayer MoS₂ in nanophotonics and optoelectronics will open up an avenue for other transition metal dichalcogenides monolayers.

Acknowledgments: We thank the financial supports provided by National Natural Science Foundation of China (grants 11804120 and 61827822, Funder Id: <http://dx.doi.org/10.13039/501100001809>), the Natural Science Foundation of Guangdong Province (grant 2017A030313026), the Fundamental Research Funds for the Central Universities

(grant 21617334), and the Research Projects from Guangzhou (grant 201804010468).

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