Dielectric Nanowire Hybrids for Plasmon-Enhanced Light–Matter Interaction in 2D Semiconductors

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ABSTRACT: Monolayer transition metal dichalcogenides (TMDs) with a direct band gap are suitable for various optoelectronic applications such as ultrathin light emitters and absorbers. However, their weak light absorption caused by the atomically thin layer hinders more versatile applications for high optical gains. Although plasmonic hybridization with metal nanostructures significantly enhances light–matter interactions, the corrosion, instability of the metal nanostructures, and the undesired effects of direct metal–semiconductor contact act as obstacles to its practical application. Herein, we propose a dielectric nanostructure for plasmon-enhanced light–matter interaction of TMDs. TiO₂ nanowires (NWs), as an example, are hybridized with a MoS₂ monolayer on various substrates. The structure is implemented by placing a monolayer MoS₂ between a TiO₂ NW for a photonic scattering effect and metallic substrates with a spacer for the plasmonic Purcell effect. Here, the thin dielectric spacer is aimed at minimizing emission quenching from direct metal contact, while maximizing optical field localization in ultrathin MoS₂ near the TiO₂ NW. An effective emission enhancement factor of ∼22 is attained for MoS₂ near the NW of the hybrid structure compared to the one without NWs. Our work is expected to facilitate a hybridized platform based on 2D semiconductors for high-performance and robust optoelectronics via engineering dielectric nanostructures with plasmonic materials.

KEYWORDS: transition metal dichalcogenides, dielectric nanowire, plasmonics, light–matter interaction, plasmonic hybrid structure

Manipulating light–matter interactions is a key requirement for engineering the performances of optoelectronics such as light-harvesting and light-emitting devices. Plasmonic metal nanostructures are widely used to improve the light absorption and emission performances of active materials. The localized surface plasmon resonance (LSPR) near metal nanostructures confines optical energies in the subwavelength scale volume. Thus, the local field enhancement and Purcell effects improve the absorption and emission performances of bulk semiconductors and quantum emitters such as quantum wells and quantum dots. Meanwhile, an emerging class of direct gap semiconductors, two-dimensional (2D) transition metal dichalcogenides (TMDs), offers advantages for optoelectronic and nanophotonic applications. Although the strong light–matter interactions at an ultimate atomic-scale thickness enable the application of TMDs in ultrafast photodetectors, ultrathin photovoltaics, optical communications, and light-emitting devices, their atomically thin characteristic limits the light absorption and emission capacities. Plasmonic hybridizations, including metal nanostructure array patterning and metal nanostructure decorations, have been studied extensively to improve the capacities of TMDs.

To maximize the benefits of plasmonic enhancement, metallic materials should be located close to semiconducting emitters. However, this causes emission quenching at the semiconductor–metal interfaces. In addition, the colloidal stability and corrosion of metallic nanostructures limit their utilization. Furthermore, the proximity effects of plasmonic nanostructures in contact with TMDs result in...
Figure 1. Enhanced light–matter interactions in MoS₂ on TiO₂ NW-embedded Ag films. (a) Schematic illustration of the device configuration. Monolayer MoS₂ is placed on a TiO₂-NW-embedded Ag film template. (b) OM (left) and PL (right) mapping image for the device. The PL map shows enhanced PL emission near the TiO₂ NW. The inset depicts the cross-sectional PL intensity in the blue-dashed line. (c) Comparative PL spectrum of On-NW and Off-NW. The PL intensity of the On-NW increases dramatically (nearly 50 times), compared to that of the Off-NW PL intensity. (d) Cross-sectional schematic of MoS₂ on TiO₂-NW-embedded Ag for FDTD simulation and electric field intensity map calculated using an FDTD method, implying optical mode confinement near the NW and edges of Ag.

issues such as band gap pinning,25 band renormalization,26 dielectric screening,37 emission quenching,29 phase transition,10,31 hot-carrier injection,10,31 and the typical charge transfer phenomena in metal–semiconductor junctions.52 Whereas such effects have not been adequately considered in bulk semiconductors and quantum dots, similar metal proximity effects are apparently more prominent and intricate in 2D semiconductors owing to the monolayer thickness.

The utilization of a dielectric nanostructure can potentially overcome similar problems arising from a 2D semiconductor–metal interface. Extensive studies have been conducted on the use of dielectric nanostructures for enhancing the light–matter interactions of bulk semiconductors and quantum dots by increasing the light trapping in active materials via Rayleigh scattering and resonance.27,28 Among the various dielectric nanostructures, dielectric nanowires (NWs) have been explored owing to their low loss and compatibility with a complementary metal–oxide–semiconductor.35,36 This has resulted in their application in waveguides and optical probes.37,38 In addition, notwithstanding their nanoscale size, dielectric NWs are stable and corrosion-resistant. Most importantly, they can overcome the emission quenching effect, which occurs at the semiconductor–metal interface and can be prevented. A titanium dioxide (TiO₂) NW is one of the representative dielectric NWs owing to its high refractive index and low loss in the visible light range. In addition, it exhibits exotic optical properties by combining with MoS₂.39

Here, we propose a hybridization method using dielectric NWs and plasmonic metal films for improving the light–matter interactions of 2D semiconductors. This is implemented by positioning monolayer MoS₂ between TiO₂ NWs for generating local photonic scattering and plasmonic metal substrates with a spacer for the Purcell effect. This hybrid is intentionally designed to prevent an unfavorable direct metal contact of 2D semiconductors and effectively utilize air-stable dielectric nanostructures. Such hybrids enable enhanced light absorption and radiative emission of MoS₂ near the NW arising from combined effects of the local field enhancement and promoted radiative decay due to the Purcell effect. For this structure, we demonstrate a reconfigurable usage of TiO₂ NWs for plasmonic hybrids and a modification process of the hybrid structure to prevent the quenching issues at the metal/MoS₂ interface, which has rarely been systematically discussed before.

RESULTS AND DISCUSSION

TiO₂-NW-Embedded Plasmonic Metal Nanogap. A metal nanogap is one promising way to construct plasmonic structures for 2D semiconductors.11 An emitter installed on a nanogap can enhance spontaneous emission by inducing the cavity effect. We propose a method to conveniently produce a metal nanogap by embedding a TiO₂ NW. Although MoS₂ hybridized with TiO₂ NWs was used for studying exotic optical properties of 2D semiconductors,34 our proposed structure has rarely been studied for plasmon-enhanced light–matter interactions of 2D semiconductors. TiO₂ NWs with a diameter of ~100 nm are dispersed in isopropyl alcohol (IPA), which is subsequently drop-casted on a Si wafer. Ag films deposited on this wafer are stripped off by adhesive tape. This causes the TiO₂ NWs to be embedded in the Ag film’s surface. Finally, monolayer MoS₂ synthesized via chemical vapor deposition (CVD) is transferred onto the substrate (see Methods). Figure 1a depicts a schematic illustration of TiO₂-NW-embedded MoS₂ hybrids. Figure 1b presents the optical micrograph (OM) and photoluminescence (PL) mapping images of the hybrid. A MoS₂ monolayer (yellow-dashed region) is placed on
top of the TiO2 NW (red-dashed region) embedded in the Ag film. The PL intensity map (Figure 1b, right image) reveals a considerably enhanced PL intensity near the TiO2 NW. Figure 1c shows a comparison of the PL spectra for On-NW and Off-NW collected from the PL mapping image of Figure 1b. The PL intensity for On-NW is ∼50 times higher than that for Off-NW. Here, the PL spectrum for On-NW was collected from the maximum intensity position on the TiO2 NW, and that for Off-NW was collected from the MoS2 on the Ag films. The peak position for Off-NW is ∼1.88 eV, whereas that for On-NW is ∼1.9 eV.40 We conducted a finite-difference time-domain (FDTD) simulation to investigate this phenomenon in detail. Figure 1d shows the cross-sectional illustration of the device structure and the corresponding normalized electric field |E|/|E0| distribution near the hybrid. Unlike the anticipated nanogap cavity effect, the main enhancement factor is the LSPR induced at two edge points: the orthogonial edge of the TiO2 film and the gap between the TiO2 NW and Ag film. The light confinement in the two local regions is verified by the PL intensity profile (blue-dashed line, shown in the inset of Figure 1b). It reveals two prominent peaks caused by the local field enhancement at the edge portions of the nanogap.

An additional aspect that needs to be considered is the quenching effect induced by the charge transfer across the Ag film–MoS2 interface. When MoS2 is in direct contact with the Ag film, optically excited charge carriers are transferred to the Ag film, resulting in a decrease in PL, which potentially limits optoelectronic applications. To systematically investigate this issue, we conducted comparative PL measurements for direct and indirect contact between the metal and MoS2.

**Figure 2.** Charge transfer effects in complex excitons at MoS2–metal contact. (a) Schematic diagrams of MoS2 on Ag film (100 nm) W/ and W/O a spacer (SiO2, 10 nm). (b) Corresponding PL intensity of the two configurations. For the W/O spacer, the PL intensity is magnified by 60 times for visualization. (c) Integrated PL intensity (top), peak position (middle), and fwhm (bottom) of MoS2 A exciton peak plotted as a function of laser power. (d) Schematic of the complex exciton formation and charge transfer for MoS2–metal contacts W/ and W/O an insulating spacer. (e) Schematic diagram of a MoS2 placed on a heterostructure. The regions, with which MoS2 is in contact, are glass (P1), Au (P2), and h-BN (P3). (f) OM image of the heterostructure. (g) PL spectrum from P1, P2, and P3 with examples of Lorentzian deconvolution for P2 (A′, trion; A0, neutral exciton; B, B exciton). Inset: Integrated peak intensities obtained from the deconvolution.
Films with and without a Spacer are summarized in Table 1.

Under a high excitation laser, multiexcitons such as trions are generally formed (Figure 2di). In direct metal Au/Cr (25/5 nm) layer on a glass substrate. Thereafter, the A exciton peak position for the W/O spacer is dramatically lower (∼1.87 eV) than that for the W/ spacer. The PL intensity has been magnified by 60 times in Figure 2b to visualize the PL spectrum for the W/O spacer case. Figure 2c summarizes the comparative PL characteristics as a function of the excitation laser power ($P_{\text{ex}}$). The integrated PL intensity curve for the W/O spacer is 2 orders of magnitude lower than that for the W/ spacer regardless of $P_{\text{ex}}$ (Figure 2c, top). As $P_{\text{ex}}$ increases, the A exciton peak position for the W/ spacer decreases dramatically from ∼1.9 to ∼1.87 eV, whereas that for the W/O spacer is not altered significantly from 1.86 eV (Figure 2c, middle). Moreover, the full width at half-maximum (fwhm) for the W/ spacer ranges from ∼110 to ∼130 meV, whereas that for the W/O spacer is significantly lower ranging from ∼60 to ∼100 meV (Figure 2c, bottom). For the W/ spacer, the dramatic red shift in the peak position and higher fwhm values than that of the W/O spacer with respect to $P_{\text{ex}}$ are consistent with the trion formation behavior in the representative PL characteristics of monolayer MoS$_2$ on a SiO$_2$/Si substrate. However, for the W/O spacer, the downshift of the peak position and fwhm curves as well as the PL intensity quenching are ascribed to the transfer of photoexcited charges from MoS$_2$ to Ag film. These results are summarized in Table 1.

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<th>$P_{\text{ex}}$-Dependent PL of MoS$_2$ on Ag Films with and without a Spacer</th>
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These phenomena are schematically summarized in Figure 2d. Under a high excitation laser, multie excitons such as trions are generally formed (Figure 2di). In direct metal—MoS$_2$ contact, the photoexcited carriers in the MoS$_2$ layer are transferred to the metal layer. This dramatically reduces the multie exciton formation and PL intensity (Figure 2dii). Conversely, for the W/ spacer, the oxide barrier significantly hinders the charge quenching. This results in neutral exciton and trion formation, as $P_{\text{ex}}$ increases without a reduction in the PL intensity (Figure 2diii).

We further verified the conformity of these phenomena with a mechanically exfoliated monolayer MoS$_2$. We deposited a Au/Cr (25/5 nm) layer on a glass substrate. Thereafter, mechanically exfoliated few-layered (∼5 nm) hexagonal boron nitride (h-BN) was transferred onto the substrate. Here, the h-BN layer functions as a 2D insulator with a band gap of ∼6 eV. We then align-transferred the mechanically exfoliated MoS$_2$ monolayer on the heterogeneous platform comprising the h-BN/Au/glass regions (Figure 2e). The PL was measured in each region, which is denoted as P1, P2, and P3. The OM image of the heterogeneous platform and the PL measured points are shown in Figure 2f. Moreover, the resulting PL spectra are plotted in Figure 2g. Each spectrum was deconvoluted by a neutral exciton ($A^0$) and trion ($A^-$). The result shows that the PL intensity is the lowest at P2, owing to the quenching effect, agreeing with our previous result. In particular, the PL intensity of the glass region (P1) is higher than that of the h-BN region (P3), which is possibly attributed to the charge transfer from MoS$_2$ to Au by the tunneling effect because of the low thickness of the h-BN barrier (Figure 2g).

MoS$_2$ NW Photonic Scattering Source for Plasmonic Hybrids. As discussed above, PL quenching effects should be prevented by utilizing 2D light emitters combined with plasmonic structures effectively. For this reason, we utilize TiO$_2$ NWs as a photonic scatter for localizing optical fields near MoS$_2$. The feasibility of this concept is verified using the heterostructure of Figure 2e–g. As shown in Figure 3, we placed a TiO$_2$ NW with a diameter of ∼100 nm on the heterogeneous substrate. The TiO$_2$ NW crosses the three substrate regions (denoted as R1, R2, and R3, which represent glass, Au, and h-BN/Au regions, respectively). The 3D schematic illustration of this structure is shown in Figure 3a, with an OM image background. Figure 3b shows the top-view OM image of this structure in bright-field (BF) and dark-field (DF). Three regions can be distinctively observed in the BF image. In the DF image of the same area, TiO$_2$ NW is well-defined owing to light scattering. Moreover, the TiO$_2$ NWs in R2 and R3 are brighter than that on glass (R1), owing to the enhanced light scattering near the TiO$_2$ NW. A topographic structure of this hybrid is visualized via atomic force microscopy (AFM), and the diameter of TiO$_2$ NW is verified as ∼100 nm (Figure 3c). Figure 3d shows the PL mapping image of the area shown in Figure 3b, where two wavelengths (514 and 633 nm) were used for the excitation laser. The three regions are distinctively defined by the color contrast to represent the PL intensity. As we observe the enhanced light scattering near the TiO$_2$ NW in the DF mode of the OM image (Figure 3b), the PL intensity on the TiO$_2$ NW is higher than those on the three substrates of R1, R2, and R3 for both the excitation wavelengths. Notably, the PL enhancement on the TiO$_2$ NW is observed at the R1 region even without plasmonic metal films, although such enhancement is not prominent. This is attributed to the enhanced light–matter interaction caused by the photonic scattering effect of the TiO$_2$ NW. Based on this feasible result, we conducted systematic studies on the proposed structure using Ag films and SiO$_2$ spacers.

Combining Photonic Scattering and Plasmonic Localization. In the above experiments, we systematically studied how dielectric spacers such as thin SiO$_2$ and h-BN effectively prevent PL quenching of MoS$_2$ for various excitation laser powers and substrates. Moreover, we demonstrated that a TiO$_2$ NW could be effectively utilized as a photonic scattering source for plasmonic hybrids. Based on previous results, we propose a representative hybrid structure, which is implemented by placing a monolayer MoS$_2$ between a TiO$_2$ NW for the photonic scattering effect and metallic film with a spacer for the plasmonic Purcell effect. Our structure aims to minimize emission quenching through the direct metal contact while maximizing the optical field localization in ultrathin 2D semiconductors near dielectric NWs. Such hybrids enable enhanced light absorption and PL emission of MoS$_2$ near the NW, arising from combined effects of the local field enhancement and promoted radiative decay due to the Purcell effect.

A CVD-grown MoS$_2$ monolayer is placed on the SiO$_2$ (10 nm)/Ag (100 nm) film. Figure 4b shows BF and DF OM
images of the sample. A prominent optical contrast is observed near the NW in the DF image owing to the strong light scattering by the NW. Figure 4c shows the cross-sectional illustration of the hybrid structure and the corresponding normalized optical field, \( |E|/|E_0| \), obtained by an FDTD simulation under plane wave illumination with a wavelength of 514 nm (see Methods). Notably, the optical field is strongly confined to the space near the NW. This strong light–matter interaction enables an absorption enhancement of MoS\(_2\), as shown in Figure 4d. The inset shows an OM (left) and absorption mapping image (right) of the hybrid. The overall absorption spectrum for On-NW increases compared with that for Off-NW in the visible range. Notably, the A, B, and C peak positions, which are typical absorption peaks for MoS\(_2\) monolayers,\(^{43}\) are not altered by hybridization. Figure 4e shows comparative PL spectra for On-NW and Off-NW collected from the PL mapping image. Here, the inset shows an OM (left) and PL intensity mapping image (right). The maximum PL intensity for On-NW is \( \sim 4 \) times higher than that for Off-NW. We calculated the empirical average PL enhancement factor, \( \langle EF \rangle \), using the following formula:\(^{18}\)

\[
\langle EF \rangle = \frac{I_{\text{On}}}{I_{\text{Off}}} \frac{A_{\text{Off}}}{A_{\text{On}}}
\]

where \( I_{\text{On}} \) and \( I_{\text{Off}} \) are the PL intensities for On-NW and Off-NW, respectively. \( A \) is the effective excitation area. \( A_{\text{On}} \) and \( A_{\text{Off}} \) are estimated from the NW dimension and the spot size of the laser beam, respectively: \( A_{\text{Off}} \sim \pi \times (348 \text{ nm})^2 \) for Off-NW (estimated size of laser spot), and \( A_{\text{On}} \sim 100 \text{ nm} \times 696 \text{ nm} \) for On-NW (the NW region within the laser spot). As a result, the estimated \( \langle EF \rangle \) attains a factor of \( \sim 22 \). The \( \langle EF \rangle \) or maximum PL enhancement of the TiO\(_2\) NW hybrids is lower than those of the metal-nanostructure-based hybrids fabricated by precise resonance tuning,\(^{11,13,14}\) whereas it is more or less comparable to\(^{31}\) or rather higher than those of other plasmonic hybrids.\(^{10,12,16}\)

The PL EF is also analytically determined using the following formula:\(^{18}\)

\[
\eta = \eta_0 \frac{QY}{QY_0}
\]

where \( \eta, \gamma, \) and \( QY \) are the PL collection efficiency, excitation rate, and quantum yield, respectively, for On-NW. The variables with the subscript “0” denote the corresponding quantities for Off-NW. We assume that \( \eta \) is constant\(^{19}\) and that \( \gamma \) is proportional to the electric field intensity \( |E|^2 \) for the On-NW under a vertically illuminated laser with the electric field \( (E_0) \) of an electromagnetic wave.\(^{19}\) Consequently, \( \langle EF \rangle \) is simplified to\(^{19}\)
EF = \left| \frac{E}{E_0} \right|^2 \frac{QY}{QY_0} (3)

where \( QY/QY_0 \) is determined by the radiative and non-radiative decay rates of excitons and the Purcell factor. Figure 4c shows the normalized electric field \( |E|/|E_0| \) distribution map for TiO2-decorated plasmonic hybrid, calculated by the FDTD method. Here, \( |E|/|E_0| \) is strongly confined (\( > 2.5 \)) to the space near the MoS2 layer under the TiO2 NW.

For low quantum yield systems such as monolayer MoS2 (\( QY_0 \approx 10^{-3} \)–\( 10^{-4} \)), \( QY/QY_0 \) for plasmonic hybrids is simplified as

\[
\frac{QY}{QY_0} = \frac{F_{\text{rad}}}{QY(F_{\text{rad}} + F_{\text{nonrad}} - 1) + 1} \approx \frac{F_{\text{rad}}}{QY F_{\text{nonrad}} + 1} (4)
\]

where \( F_{\text{rad}} \) and \( F_{\text{nonrad}} \) denote the Purcell factor regarding the radiative and non-radiative decay rate of the plasmonic hybrid, respectively. Moreover, in low quantum yield systems, \( QY \cdot F_{\text{nonrad}} \ll 1 \). Thus, eq 3 is approximated as

\[
EF = \left| \frac{E}{E_0} \right|^2 \frac{QY}{QY_0} \approx \left| \frac{E}{E_0} \right|^2 F_{\text{rad}} (5)
\]

This indicates that PL enhancement can be achieved via local field enhancement and radiative Purcell effects. In our case, \( EF \approx \langle EF \rangle \approx 22 \), as illustrated in Figure 4e. Given that \( |E|/|E_0| \) is estimated to be \( \sim 2.5 \) near the MoS2 layer based on the FDTD simulations (Figure 4c), the Purcell factor \( F_{\text{rad}} \) of the TiO2 NW hybrid is roughly approximated as \( \sim 3.5 \) using eq 5. Although the estimated Purcell factor is an order of magnitude lower than that obtained from precisely tuned plasmonic hybrids on Au nanogap substrates, \( 11 \) this value is comparable to that of a quantum dot hybridized with a Ag NW having a spacer of \( \sim 40 \text{ nm} \) \( 44 \) and higher than that of MoS2 hybrids based on dielectric ring resonators. \( 45 \) Conclusively, as observed in Figure 4d, overall absorption in MoS2 near the TiO2 NW increases due to the plasmonic local field enhancement combined with a photonic scattering effect. As a result, photon absorption of incident light and the generation rate of electron–hole pairs for On-NW increase compared to that for Off-NW. Such local field enhancement promotes the radiative decay rate due to the plasmonic Purcell effect, \( 16 \) resulting in effective PL enhancement for On-NW.

**Verifying Reconfigurable Architectures via FDTD Simulations.** The PL enhancement relies on several variables, such as the spacer thickness, refractive index, and dimension of dielectric NW. Figure 5a depicts the FDTD simulation geometry with the dielectric NW hybrid. \( |E|/|E_0| \) inside the MoS2 layer was monitored under illumination by a Gaussian laser beam (\( \lambda = 514 \text{ nm} \)). Here, \( d \) denotes the diameter of the dielectric NW, and \( t \) denotes the thickness of the SiO2 spacer. Figure 5b shows a lateral profile of \( |E|/|E_0| \) as a function of the refractive index of the NW for fixed SiO2 spacer thickness (\( t = 10 \text{ nm} \)) and NW diameter (\( d = 100 \text{ nm} \)). The variance effect of the refractive index of the NW is negligible on the field enhancement. This indicates the availability of a selection of materials with the refractive index of dielectric NWs spread over a wide range.

Figure 5c shows a lateral profile of \( |E|/|E_0| \) as a function of the emitter thickness (\( t \)) at a fixed diameter (\( d \)) of the TiO2 NW of 100 nm. Although the optical field is strongly confined...
to the space near the NW over a small range of \( t (t < \sim 5 \text{ nm}) \),
the field enhancement profile is laterally broadened at an intermediate \( t (t \sim 50 \text{ nm}) \). Furthermore, this broadness reduces at large \( t (t > \sim 60 \text{ nm}) \). Notably, the integrated \( |E|/|E_0| \) value is maximum at \( t \sim 55 \text{ nm} \) (see Supplementary Figures S1 and S2). We attribute this \( t \) dependence of the optical field enhancement effect to the hybridized contribution of plasmonic confinement\(^{46}\) and photonic scattering modes.\(^{33}\)

The plasmonic field confinement effect is dominant for a small spacer thickness.\(^{46}\) However, a photonic scattering effect near the NW is predominant at intermediate thicknesses, which is reduced at large thicknesses owing to the lower optical reflection from the metal reflector (see Supplementary Figure S3). The spacer thickness should be reduced as thin as possible to maximize the local field enhancement effect near the MoS\(_2\) layer, and it should be increased to minimize the PL quenching effect through charge tunneling. Therefore, our selection for the spacer thickness of 10 nm is reasonable because this thickness is normally used in various plasmonic hybrids.\(^{20}\)

Figure 5d shows a lateral profile of \( |E|/|E_0| \) as a function of the diameter (\( d \)) of the TiO\(_2\) NW. The optical field enhancement near the NW is maximum for \( d \) values ranging from 100 to 150 nm. Overall, the optical field enhancement effect can be realized for various values of \( n, t, \) and \( d \). This is advantageous for the selection of dielectric materials and substrate structures in terms of the optoelectronic device design. Moreover, these local field enhancement effects near NWs are feasible for various excitation wavelengths (see Supplementary Figure S4).

**CONCLUSIONS**

We herein proposed a hybridization method for enhancing the light–matter interaction of 2D semiconductors, using a dielectric TiO\(_2\) nanostructure. The TiO\(_2\) NW combined with various plasmonic substrates enables strong local field enhancement and Purcell effects near MoS\(_2\) via photonic scattering and plasmonic field confinement effects, thereby resulting in an enhancement of the absorption and emission of MoS\(_2\), which were verified through analytical models and FDTD simulations. Moreover, the enhanced light–matter interaction of the dielectric-based hybrids is also observed in metal-free substrates. This is advantageous for various optoelectronic device designs. Although the PL enhancement of TiO\(_2\) NW hybrids is still limited by precisely tuned metallic-nanostructure-based hybrids, it offers advantages in terms of flexibility in terms of material selection and hybrid architecture. The materials that can be applied for metallic nanostructures for conventional plasmonic hybrids are limited to noble metals such as Au and Ag to prevent corrosion and degradation. Meanwhile, the material library for dielectric nanostructures in our hybrids is significantly more versatile and robust for utilization under ambient conditions. For nanophotonic devices using our proposed hybridization concept, various fabrication methods of dielectric nanostructures will be applicable, such as conventional lithography patterning.
laser patterning, and nanoimprinting using inorganic oxide pastes. Our design diversifies hybridization libraries for high-performance optoelectronics based on 2D materials via manipulating dielectric nanostructures with plasmonic materials.

METHODS

Sample Preparation. Monolayer MoS2 flakes were synthesized on a SiO2 (300 nm)/Si substrate using CVD. The MoS2 flakes were transferred onto prepared substrates via the conventional poly(methyl methacrylate) (PMMA) support method. The PMMA A4 (Micro Chem, 4 wt % in anisole) was spin-coated onto the MoS2/SiO2/Si. The PMMA-covered TMD layer was detached from the SiO2/Si substrate in a hot 1 M potassium hydroxide (KOH) solution over several minutes to etch the SiO2 surface. The detached PMMA-covered MoS2 layer was rinsed using deionized water. Finally, the PMMA-covered MoS2 layer was transferred to various substrates and dried under ambient condition.

Characterization. The bright- and dark-field mode optical micrographs were obtained using optical microscopy (100× magnification, ZEISS, Axio Imager 2). The PL measurements at room temperature were performed using a lab-constructed confocal microscope equipped with 514 and 633 nm wavelength lasers and an objective lens with an NA of 0.9, as well as confocal PL and Raman spectroscopy (XperRam200VN, Nanobase) equipped with 532 nm wavelength laser. For the absorbance, we measured the differential optical reflectivity using the lab-constructed confocal microscope with a white light source (halogen lamp). The topography of the samples was observed using AFM (Nano Navi).

Simulation. An FDTD numerical simulation was conducted to calculate the optical fields of the hybrids. The designs of the device configuration for the numerical simulation are illustrated in Figure 5a. Here, the diameter of a TiO2 NW is 100 nm, and the thickness of a monolayer MoS2 is 0.7 nm. The minimum mesh size near the MoS2 makes were synthesized with a thickness of ~100 nm and SiO2 films with a thickness of ~10 nm were deposited on a SiO2/Si substrate using a thermal evaporator. The PMMA layer was removed using acetone, and the sample was rinsed with IPA. TiO2 NWs (TiO2, Sigma-Aldrich, 774510, nanowires, diameter × L ~ 100 nm × 10 μm) in IPA were dispersed on the MoS2 on various substrates and dried under ambient condition.

REFERENCES


