Manipulating the interlayer carrier diffusion and extraction process in organic-inorganic heterojunctions: from 2D to 3D structures

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Interlayer carrier transfer at heterointerfaces plays a critical role in light-to-electricity conversion using organic and nanostructured materials. However, how interlayer carrier extraction at these interfaces is poorly understood, especially in organic-inorganic heterogeneous systems. Here, we provide a direct strategy for manipulating the interlayer carrier diffusion process, transfer rate and extraction efficiency in tetracene/MoS₂ type-II band alignment heterostructure by constructing the 2D–3D organic–inorganic (O–I) system. As a result, the prolonged diffusion length (12.32 nm), enhanced electron transfer rate ($9.53 \times 10^9$ s$^{-1}$) and improved carrier extraction efficiency (60.9%) are obtained in the 2D O-I structure which may be due to the more sufficient charge transfer (CT) state generation. In addition, we have demonstrated that the interlayer carrier transfer behavior complied with the diffusion mechanism based on the one-dimensional diffusion model. The diffusion coefficients have varied from 0.0027 to 0.0036 cm$^{-2}$ s$^{-1}$ as the organic layer changes from 3D to 2D structures. Apart from the relationship between the carrier injection and diffusion process, temperature-dependent time-resolved spectra measurement is used to reveal the trap-related recombination that may limit the interlayer carrier extraction. The controllable interlayer carrier transfer behavior enables O-I heterojunction to be optimized for optoelectronic applications.

RESULTS AND DISCUSSION
Construction and energy level arrangement of organic-inorganic heterojunction
To study the interlayer carrier transfer process, O-I layered heterostructures were selected as the research platform for the

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interlayer carrier diffusion and transfer process because of their type-II band alignment, which was further confirmed by using UV–vis absorption, ultraviolet photoelectron spectroscopy (UPS) measurements. As shown in Supplementary Figs. 1–2, by extrapolating the linear portion of the Tauc plot \((\alpha h\nu)^2\) versus \(h\nu\), where \(\alpha\) was the absorption coefficient and \(h\nu\) was the photon energy, the optical bandgap energy of monolayer MoS\(_2\) was experimentally determined to be 1.84 eV, which was consistent with the theoretical prediction. In addition, Fig. 1a shows plots of the secondary electron cut-off in the UPS spectra for the MoS\(_2\) and tetracene layer, where the work function was extracted from the difference between photon energy (21.2 eV for He I photons) and photoemission onset (17.62 eV for MoS\(_2\) and 17.88 eV for tetracene). The values obtained from this analysis were 3.58 and 3.32 eV for MoS\(_2\) and tetracene, respectively. Besides, from linear extrapolation of the onset of the low binding energy presented in Fig. 1b, the energy difference between the valence band edge \(E_V\) and \(E_C\) can be estimated at 1.76 eV for MoS\(_2\) and 1.85 eV for tetracene. The \(E_V\) position of MoS\(_2\) is close to the edge of the conduction band, indicating highly electron-doped characteristics. As summarized in Fig. 1c, the energy band diagram of the monolithically formed O-I heterojunction exhibited typical features of type-II band alignment. Figure 1d, e show the energy bandgap of 1 L MoS\(_2\) and tetracene by first-principle density functional theory (DFT) calculations, proving that the O-I heterostructure of tetracene and MoS\(_2\) was type-II band alignment. The calculation results confirmed that the tetracene/MoS\(_2\) organic-inorganic heterostructure was Type-II band alignment.

Building of multidimensional organic-inorganic heterostructures and their exciton dynamics

Because the thickness of the donor tetracene layer in the heterostructures directly defined the length of the interlayer carrier transfer and diffusion process, building multidimensional O-I heterostructures with various thicknesses is a straightforward approach to systematically understand the interlayer carrier transfer behavior. O-I heterostructures with varied thicknesses (keeping the MoS\(_2\) as monolayer, Supplementary Fig. 3) were controllably prepared by a two-step method (detailed information was shown in Methods). All the organic layer thicknesses in this work were measured using atomic force microscopy (AFM) images, which were shown in Fig. 2a-c. The tetracene with a thickness of ca. 0.6 nm was referred to as 1 L, while the 10 nm thick film was referred to as bulk. As a result, the increased organic layer thickness changed the O-I heterojunction from 2D structure to 3D structure. In addition, Raman spectroscopy was further carried out to confirm the TMDC\(_x\) and organic components of the heterojunctions (Supplementary Fig. 4a).

The steady-state absorption spectra of the heterojunction and the isolated components of the junction were shown in Fig. 2d. The three absorption maxima of the tetracene film, which were located at 443, 474 and 522 nm, can be attributed to the absorption from H- and J-aggregates, CT states, and associated vibrational sidebands, respectively. The isolated MoS\(_2\) spectrum included the B and A excitons at 605 nm and 651 nm, respectively. Distinctly, absorption enhancement was observed in the O-I heterojunction due to the higher absorption coefficient of the inorganic layer. Typical PL spectra collected from various organic layers were compared in Fig. 2e, the increased PL intensities owing to the increment of absorption (Supplementary Fig. 4b). The PL spectra acquired from tetracene and MoS\(_2\) peaked at 532 nm and 668 nm, respectively (Supplementary Fig. 4c). In general, carriers in the donor layer can be efficiently extracted by the extraction layer during its lifetime which brings about dramatic quenching of the PL (Supplementary Fig. 5). Comparing the spectral changes of the organic layer from 2D (0.6 nm) to 3D (bulk), no obvious peak broadening and shift are observed, indicating that the multi-dimensional organic structure has no obvious change of crystallinity affecting the optical properties (Supplementary Fig. 6a-b). Furthermore, the full width at half maxima measurement was also performed to exclude the
Possibility that the PL intensity quenching originates from the defect states in tetracene layers of various thicknesses due to the laser irradiation-induced thermal decomposition. These results proved that the defect states do not change significantly with the thickness change. Distinct PL behaviors in different tetracene layers can be well interpreted by the excitonic dynamics processes. The TRPL measurements based on neat tetracene with different thicknesses were performed to accurately verify the potential CT process in the O-I heterojunction (Fig. 2f). The lifetime data were fitted with the biexponential Eq. (1). For the O-I heterostructures, \( \tau_1 \) and \( \tau_2 \) are considered to be nonradiative and radiative lifetimes. The detailed information was shown in Table 1 (Supplementary).

\[
I = A \exp\left(\frac{-t}{\tau_1}\right) + B \exp\left(\frac{-t}{\tau_2}\right) + C
\]  

(1)

Interlayer exciton diffusion and carrier transfer process with various organic layer thickness

For these type II O-I heterostructures, electron carriers transfer from the upper layer (tetracene) to the bottom layer (MoS\(_2\)) after excitation. The DFT charge distribution calculations of 2D and 3D O-I heterostructures were shown in Fig. 3a, which proved that the organic tetracene layer was an excellent charge donor. Compared to the isolated tetracene with different thicknesses, the average lifetimes of tetracene (donor layer) in O-I heterostructures were decreased, which validates the CT process in the O-I system. For the 2D O-I heterojunction, significant lifetime and fluorescence quenching were observed (green and red lines in Fig. 3b). While, after the tetracene layer changed to the 3D structure (yellow and purple lines in Fig. 3b), the corresponding lifetime decreased from 318 ps to 294 ps at 532 nm and slight fluorescence quenching was observed in Supplementary Fig. 5b. These results indicated that the existence of the faster and more efficient electron transfer process may originate from the 2D O-I system with the optimized nanoscale exciton separation. The related electron transfer rates \( k_{ET} \) of these blends were calculated using Eq. (2):

\[
k_{ET} = \frac{1}{\tau_{HS}} - \frac{1}{\tau_{neat}}
\]  

(2)

where \( \tau_{neat} \) and \( \tau_{HS} \) are the lifetime of neat tetracene and O-I heterostructures, respectively. For the 2D O-I heterojunction, the \( k_{ET} \) value of \( 6.07 \times 10^9 \text{ s}^{-1} \) was obtained, which was much longer than that of 3D structure (\( 2.57 \times 10^8 \text{ s}^{-1} \)), as presented in Fig. 3c, which manifests the more efficient exciton dissociation and thus more sufficient CT state generation at the donor/acceptor interfaces. To further study the interlayer carrier transfer process, the carrier extraction efficiency was calculated as \( \eta = \frac{\tau_{HS} - \tau_{neat}}{\tau_{neat}} \times 100\% \) (Fig. 3c). To make a fair comparison of O-I structures, we used 4.0–10.21 μW excitation light to explore the variation of extracted parameters. The results showed that the electron transfer rates and extraction efficiency remain stable with the change of excitation power (4.0–10.21 μW) for both 2D and 3D O-I structures (Supplementary Fig. 7). Supplementary Fig. 8a exhibited the significant overlap between the normalized absorption spectrum of tetracene and PL spectrum of MoS\(_2\), demonstrating the potential existence of Förster resonance energy transfer (FRET) in theory. In addition, we also probed the fluorescence decay time at 668 nm that was longer in the 2D O-I system than that in neat tetracene film, shown in Supplementary Fig. 8b. Therefore, we speculated that FRET occurred between the tetracene layer and MoS\(_2\) layer.

To further study the relationship between the carrier transfer and extraction, the carrier diffusion dynamics of tetracene layer in O-I heterostructure was modeled by calculating the population and distribution of the carriers in tetracene layers using a one-dimensional diffusion equation as following.
equation (Eq. 3):\[ \frac{\partial n(x,t)}{\partial t} = D \frac{\partial^2 n(x,t)}{\partial x^2} - \frac{n(x,t)}{\tau} \tag{3} \]

where \( D \) is the diffusion coefficient of tetracene, and \( \tau \) represents the exciton lifetime across the sample, which was obtained by fitting the TRPL curve. \( n(x,t) \) is the carrier population at \( x \) nm depth in the tetracene layers (\( x = 0 \) at the upper surface), \( t \) the time delay, \( n(0,t) = 0 \). Theoretical calculation of carrier density in the organic layer was shown in Note 1 (Supplementary). Based on this model, the TRPL curves of tetracene in heterostructures with different thicknesses were well fitted. The fitting results of \( D \) ranged from 0.0027 to 0.0036 cm\(^2\) s\(^{-1}\) (Supplementary Fig. 9), which were consistent with the consequences of conventional organic materials. To better explore the relationship between the exciton diffusion and the organic layer thickness, we further investigated the diffusion length in 2D-3D O-I heterostructures as Eq. (4):\[ L_D = \sqrt{D\tau} \tag{4} \]

The diffusion length \( L_D \) was defined as a function of the diffusion time \( \tau_D \) and the diffusion coefficient \( D \). In addition, the diffusion time \( \tau_D \) was the effective value of the intrinsic tetracene carrier lifetime, which can be obtained by fitting the TRPL curve of tetracene in the heterostructure with a bulk thickness (>40 nm, Supplementary Fig. 10). When the thickness of the O-I heterostructure increased over 40 nm, the carrier extraction effect can be ignored. The results showed that the effective value of \( \tau_D \) was 422 ps. On the basis of Eq. (4), the results of diffusion length ranged from 10.7 nm to 12.32 nm were obtained (Fig. 3d). For the 20 nm organic layer thickness of heterojunction, the shortest diffusion length (10.7 nm) was observed. It was worth noting that for the 3D O-I heterojunction, the diffusion distance was significantly smaller than the thickness of the upper donor layer, which results in the unbalanced interlayer carrier diffusion and the extraction process, in good agreement with the results proved in Fig. 3c. In addition, the exciton-exciton annihilation effect may be increased as the thickness of the organic layer increased, which may limit the exciton diffusion and carrier transfer process in the O-I system. Thermal field regulated interlayer carrier transfer behaviors

The interlayer carrier transfer behavior was also sensitive to the temperature. By decreasing the temperature, the intensities of PL characteristics increased due to the decreased phonon interaction. In the temperature-dependent PL spectra of MoS\(_2\) (Supplementary Fig. 11a), an obvious blue shift was observed, which may be attributed to the broadening of the energy bandgap and exciton confinement by the weak phonon interaction. The temperature-dependent energy bandgap extension can be described as \( E_g = E_{0g} - aT^2/(T^2 + \beta) \), where \( E_{0g} \) was the energy bandgap, \( E_0 \) was its value at 0 K, \( a \) and \( \beta \) were proportionality constants. Figure 4a, b show the temperature-dependent steady-state PL spectra of the pristine 1 L (0.6 nm) tetracene and 3D tetracene, respectively. For the pristine tetracene structure, new PL peaks in the range of 700–760 nm were observed, indicating the formation
of trap states at low temperature (Supplementary Fig. 11b). The bound excitons originated from trap states were caused by impurities and defects on the surface, resulting in the broadening of the PL spectrum.

To better analyze the influence of the trap states of different O-I structures, the temperature-dependent time-resolved spectra were measured, as shown in Fig. 4c, d. Compared with the tetracene lifetime at room temperature, a significant lifetime increase was observed for all organic layer thickness under low-temperature conditions. Besides, clearer biexponential decay was observed with the temperature decreased due to the trap-related recombination. Compared to the isolated tetracene with different thicknesses, the average lifetimes of tetracene in O-I heterostructures were decreased at the same temperature, which proves the CT process in the O-I system. For the O-I structure with the 2D tetracene layer, we observed a more significant lifetime quenching phenomenon of the donor layer, which is consistent with the aforementioned results at room temperature (Fig. 3b). In addition, the increased lifetime of the organic layer may be originated from exciton fission, which is expected to slow the electron-hole recombination. Like Eq. (2), the related electron transfer rates of these hybrid O-I heterojunctions were measured to describe the temperature-dependent CT process (Fig. 4e). By changing the temperature from 160 to 340 K, the electron transfer rates increased from $2.60 \times 10^8$ s$^{-1}$ to $9.53 \times 10^9$ s$^{-1}$ for the 2D O-I heterostructure. For all thicknesses of heterojunctions, the lowest electron transfer rates were obtained at 160 K. Besides, the trap states also limited the carrier transfer and carrier extraction at the donor/acceptor interfaces leading to the decreased carrier extraction efficiency at lower temperatures (Fig. 4f). The detailed information about the temperature-dependent lifetime with various organic layer thicknesses was shown in Table 1 (Supplementary).

In summary, we have observed the controllable interlayer carrier transfer and extraction process successfully in multidimensional type-II band alignment vdW heterostructures with tetracene and monolayer MoS$_2$. Apart from the controllable carrier transfer research, the thickness-dependent exciton diffusion
process was also observed by ultrafast spectroscopy. Due to the balanced interlayer carrier diffusion and injection process, the highest electron transfer rate \((9.53 \times 10^{9} \text{s}^{-1})\) was obtained in the 2D O-I structure. Furthermore, the electron transfer process was also sensitive to the temperature due to the formation of trap states at low temperatures, which caused the trap-related recombination and limited carrier extraction. Our findings provide a facile and general way to manipulate the light-matter interaction in 2D materials and to control the CT across O-I interfaces in hybrid systems, enabling new possibilities and innovations in future optoelectronic applications.

**METHODS**

**Materials**

Monolayer MoS\(_2\) on SiO\(_2\)/Si substrates was purchased from SixCarbon Technology Shenzhen Inc. Tetracene was purchased from tetracene TCI (Renishaw plc).

Preparation of organic-inorganic heterostructures

Tetracene/MoS\(_2\) O-I heterojunction was fabricated in two steps. The monolayer MoS\(_2\) that we used in this work was grown on a 300 nm Si/SiO\(_2\) substrate by the chemical vapor deposition (CVD) method. The tetracene films with different thicknesses were subsequently grown on the monolayer MoS\(_2\) via the physical vapor deposition method. The deposition rate was 0.01 nm s\(^{-1}\) and the vacuum was held at \(2.0 \times 10^{-4}\) Pa at 215 °C. The thickness of bulk-tetracene was over 10 nm. All the tetracene layer thickness in this work were measured using the AFM images.

DFT calculation

DFT calculations were carried out using the Quantum Espresso package. Projector-augmented-wave potentials were adopted to describe the electron-ion interactions, and the generalized gradient approximation in the form of the Perdew–Burke–Ernzerhof functional was employed to treat the electron exchange-correlation. The energy cut-off for plane-wave basis set was set to 500 eV. The convergence threshold for the iteration in the self-consistent field and the maximum force component for geometry optimizations were set to \(10^{-6}\) eV and \(0.01\) eV Å\(^{-1}\), respectively. The calculation used a 3 × 3 × 1 and 7 × 7 × 1 k-point grid for structural optimizations and energy calculations, respectively.

Characterization

The absorption was characterized with the TU-1900 UV–vis dual-beam spectrophotometer (PG Instruments, Ltd.). The absorption spectra of MoS\(_2\) were obtained by transferring the monolayer MoS\(_2\) to the quartz substrate. The steady-state PL spectra and TRPL spectra were acquired through a confocal optical microscope (Nanonfider FLEX2, Tokyo Instruments, Inc.) equipped with time-correlated single-photon counting (TETRACENESPC) module (Becker & Hickl, SPC-150). All the PL spectra were measured using a charge-coupled device sensor (DU420A-OE, Andor) to select the different regions across the samples. Topography images were obtained using AFM in tapping mode (Solver P47 PRO, NTMDT Co.). Raman measurement was conducted using Micro Raman spectrometer LabRAM HR8000 (Renishaw plc).

**DATA AVAILABILITY**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**REFERENCES**

1. Cai, Z., Liu, B., Zou, X. & Cheng, H. M. Chemical Vapor Deposition Growth and Applications of Two-Dimensional Materials and Their Heterostructures. Chem. Rev. 118, 6091–6133 (2018).
2. Von Klitzing, K. Essay: quantum hall effect and the new international system of units. Phys. Rev. Lett. 122, 200001 (2019).
3. Canonico, L. M., Rapportor, T. G. & Munitz, R. B. Spin and Charge Transport of Multiorbital Quantum Spin Hall Insulators. Phys. Rev. Lett. 122, 196601 (2019).
4. Gao, T. et al. Talbot Effect for Exciton Polaritons. Phys. Rev. Lett. 117, 097403 (2016).
5. Pei, J. et al. Excited State Biexcitons in Atomicsinly Thin MoSe\(_2\), ACS Nano 11, 7468–7475 (2017).
6. Liu, B., Abbas, A. & Zhou, C. Two-dimensional semiconductors: from materials preparation to electronic applications. Adv. Electron. Mater. 3, 1700045 (2017).
7. Zong, X. et al. Black phosphorus-based van der Waals heterostructures for mid-infrared light-emission applications. Light. Sci. Appl. 9, 114 (2020).
8. Park, H. J. et al. Hybrid Characteristics of MoS\(_2\) Monolayer with Organic Semi-conducting Tetracene and Application to Anti-Ambipolar Field Effect Transistor. ACS. Appl. Mater. Interfac. 10, 32556–32566 (2018).
9. Wang, H. et al. Van der Waals Integration Based on Two-Dimensional Materials for High-Performance Infrared Photodetectors. Adv. Funct. Mater. 31, 2103106 (2021).
10. Zheng, W. et al. Direct Vapor Growth of 2D Vertical Heterostructures with Tunable Band Alignments and Interfacial Charge Transfer Behaviors. Adv. Sci. 6, 1802204 (2019).
11. Roy, T. et al. 2D-2D tunneling field-effect transistors using WSe\(_2\)/SnSe\(_2\) heterostructures. Appl. Phys. Lett. 108, 083111 (2016).
12. Hong, X. et al. Ultrafast charge transfer in atomically thin MoS\(_2\)/WS\(_2\) heterostructures. Nat. Nanotechnol. 9, 682–686 (2014).
13. Lee, J. Y., Shin, J. H., Lee, G. H. & Lee, C. H. Two-Dimensional Semiconductor Optoelectronics Based on van der Waals Heterostructures. Nanomaterials-basel 6, 193 (2016).
14. Geim, A. K. & Grigorieva, I. V. Van der Waals heterostructures. Nature 499, 419–425 (2013).
15. Jia, C. et al. Ultrafast dynamics in van der Waals heterostructures. Nat. Nanotechnol. 13, 994–1003 (2018).
16. Zhang, L. et al. Efficient and Layer-Dependent Exciton Pumping across Atomically Thin Organic-Inorganic Type-I Heterostructures. Adv. Mater. 30, 1803986 (2018).
17. Li, Z. et al. Intercalation Strategy in 2D Materials for Electronics and Optoelectronics. Small Methods 5, 2100567 (2021).
18. Parveen, S., Paul, K. K. & Giri, P. K. Precise Tuning of the Thickness and Optical Properties of 2D Monolayer MoS\(_2\) by Humidity in Heterostructures. RSC Adv. 6, 99717–99721 (2016).
19. Lopez-Sanchez, O., Lembke, D., Kayci, M., Radenovic, A. & Kis, A. Ultrasparsitve photodetectors based on monolayer MoS\(_2\). Nat. Nanotechnol. 8, 497–501 (2013).
20. Lin, Y. et al. 17% Efficient Organic Solar Cells Based on Liquid Exfoliated W\(_5\), as a Replacement for PEDOT:PSS. Adv. Mater. 31, 1902965 (2019).
21. Wu, B. et al. Multifunctional MoS\(_2\) Transitors with Electrolyte Gel Gating. Small 16, 2000420 (2020).
22. Cheng, C. H., Li, Z., Hambarde, A. & Deotare, P. B. Efficient Energy Transfer across Organic-2D Inorganic Heterointerfaces. Adv. Mater. Interfac. 10, 39336–39342 (2018).
23. Wang, S. et al. MoS\(_2\)/PTCD A Hybrid Heterojunction Synapse with Efficient Photoelectric Dual Modulation and Versatility. Adv. Mater. 31, 1806227 (2019).
24. Kakavelakis, G. et al. Size-Tuning of WSe\(_2\) Flakes for High Efficiency Inverted Organic Solar Cells. ACS Nano 11, 3517–3531 (2017).
25. Lyu, C. K. et al. Functionalized Graphene Oxide Enables a High-Performance Bulk Heterojunction Organic Solar Cell with a Thick Active Layer. J. Phys. Chem. Lett. 9, 6238–6248 (2018).
26. Pei, K. & Zhai, T. Emerging 2D Organic-Inorganic Heterojunctions. Cell Rep. Phys. Sci. 1, 100166 (2020).
27. Han, J. et al. Graphene/Organic Semiconductor Heterojunction Phototransistors with Broadband and Bi-directional Photoresponse. Adv. Mater. 30, 1804020 (2018).
28. Hu, F. et al. Tailored Plasmons in Pentacene/Graphene Heterostructures with Interlayer Electron Transfer. Nano Lett. 19, 6058–6064 (2019).
29. Li, H. et al. Recent progress and strategies in photodetectors based on 2D inorganic/organic heterostructures. 2D Mater. 8, 012001 (2020).
30. Wu, H. et al. MoS\(_2\)/CNC nanofiber with double-layer carbon coating for high cycling stability and rate capability in lithium-ion batteries. Nano Res. 11, 5866–5878 (2018).
31. Habib, M. R. et al. Tunable photoluminescence in a van der Waals heterojunction built from a MoS\(_2\) monolayer and a PTCDA organic semiconductor. Nano Res. 10, 16107–16115 (2018).
32. Bettis Homan, S. et al. Ultrafast Exciton Dissociation and Long-Lived Charge Separation in a Photovoltaic Pentacene-MoS\(_2\) van der Waals Heterojunction. Nano Lett. 17, 164–169 (2017).
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AUTHOR CONTRIBUTIONS

J.W.Q., L.F., and X.T.H. conceived the idea and performed the data analysis. J.W.Q., F.Z., C., and Y.H. conducted the characterization and measurement of the materials. W.Q.Z. provided the first principle DFT calculation. J.W.Q., L.F., and X.T.H. Hao co-wrote the paper. All authors discussed the results and commented on the paper.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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