

Neutral Exciton Diffusion in Monolayer MoS₂

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ABSTRACT: Monolayer transition metal dichalcogenides (TMDCs) are promising materials for next generation optoelectronic devices. The exciton diffusion length is a critical parameter that reflects the quality of exciton transport in monolayer TMDCs and limits the performance of many excitonic devices. Although diffusion lengths of a few hundred nanometers have been reported in the literature for as-exfoliated monolayers, these measurements are convoluted by neutral and charged excitons (trions) that coexist at room temperature due to natural background doping. Untangling the diffusion of neutral excitons and trions is paramount to understand the fundamental limits and potential of new optoelectronic device architectures made possible using TMDCs. In this work we measure the diffusion lengths of neutral excitons and trions in monolayer MoS₂ by tuning the background carrier concentration using a gate voltage and utilizing both steady state and transient spectroscopy. We observe diffusion lengths of 1.5 μm and 300 nm for neutral excitons and trions, respectively, at an optical power density of 0.6 Wcm^{-2} .

KEYWORDS: MoS₂, exciton, trion, diffusion, transport, quantum yield

Due to strong Coulomb interaction, photogenerated carriers in TMDC monolayers form excitons with binding energy over an order of magnitude larger than in conventional semiconductors.^{1,2} These excitons can turn into positive or negative trions in the presence of background holes or electrons, respectively.³ Energy transport in monolayer semiconductors occurs mainly by the diffusion of these tightly bound quasiparticles. Therefore, the operation of a wide array of optoelectronic devices such as light-emitting diodes,^{4,5} solar cells⁶ and excitonic switches⁷ that utilize monolayer semiconductors is governed by exciton and trion diffusion.

Understanding and manipulating the exciton diffusion in these monolayers can improve device performance and lead to the development of next-generation room-temperature excitonic technologies.

While diffusion in monolayer semiconductors has been studied extensively,⁸⁻¹⁷ the effect of background carriers has been largely overlooked. Since almost all as-exfoliated monolayer semiconductors have some amount of unintentional doping,¹⁸ a mixture of excitons and trions are created after photoexcitation and previous approaches have produced an averaged diffusion length of both excitons and trions. In this work, we electrostatically tune the background carrier concentration of monolayer molybdenum disulfide (MoS₂), a prototypical monolayer semiconductor, to retrieve the separated exciton and trion diffusion length. Our findings demonstrate that excitons and trions in monolayer MoS₂ have very different diffusion lengths (1.5 μm and 300 nm at a power density of 0.6 Wcm^{-2} , respectively). This finding has wide implications for the design of excitonic devices utilizing monolayer semiconductors.

RESULTS AND DISCUSSION

We tune the background carrier concentration (electron and hole population densities) of the monolayer MoS₂ by varying the back-gate voltage (V_g) in a capacitor structure (Fig. 1A). The schematic of the device is shown in Fig. 1A, and an optical micrograph of a device is shown in the inset of Fig. 1A. We also tune the photocarrier generation rate by varying the incident pump power. MoS₂ monolayers are mechanically exfoliated on top of poly(methyl methacrylate) (PMMA, 100 nm), which is spin-coated on SiO₂ (50 nm)/Si substrate. The Au contacts (thickness 30 nm) are then transferred on the monolayer using a dry transfer technique.¹⁸ Exciton recombination in monolayer MoS₂ was probed spatially, spectrally and temporally in an inverted fluorescence

microscope (Fig. 1B). Photoluminescence (PL) was excited at $\lambda = 532$ nm wavelength by either a continuous wave (CW) laser or a 100 fs pulsed laser focused to a near-diffraction-limited spot with a full width at half maximum (FWHM) of $w_0 = 287$ nm. When excited by the CW laser, the resulting PL is either imaged or sent to a spectrometer. When excited by the pulsed laser, the PL is sent to a time-resolved single photon counting detector, which is then scanned across the image to obtain a map of the time-dependent exciton density as a function of position. All measurements reported in this paper are taken at room temperature, in an ambient lab environment.

We first discuss the results of CW excitation. The PL spectra (Fig. 1C) of a MoS₂ monolayer measured at $V_g = -20$ V and 0 V show a ~ 20 -fold difference in the PL peak intensity at a pump power of 10^2 Wcm⁻², with a peak energy shift of 30 meV. This difference in PL intensity and spectra has been attributed to the different photo-emitting quasiparticles in the monolayer³ (Fig. 2). The time-dependent concentrations of excitons, trions and background carriers in a monolayer semiconductor are locally determined by three dynamic processes: generation, recombination and transport (Fig. 2). At a specific location, exciton concentration increases if they are generated from a photon-absorption event or a trion-ionization at that location, or if excitons diffuse in from surrounding points. Concurrently, exciton concentration decreases through trion formation, radiative recombination and biexciton annihilation. Similar generation, recombination and transport processes also occur for trions. The ratio of exciton and trion concentration is determined by the local background carrier concentration, which can be controlled by the gate voltage.¹⁸ As-exfoliated monolayer MoS₂ is electron-rich due to substrate-induced doping and intrinsic chalcogenide vacancies.¹⁹ At $V_g = -20$ V, the background electrons are removed from the monolayer MoS₂ and it is close to intrinsic (Fermi level is at mid-bandgap). In this case, emission is observed primarily from neutral excitons which show high PL intensity. Positive V_g moves the

Fermi level closer to the conduction band, introducing a large number of background electrons that turn photogenerated excitons into trions. These negative trions show low PL intensity. As both neutral excitons and negative trions coexist at $V_g = 0$ V, previously reported diffusion lengths of as-exfoliated MoS₂ monolayers are a result of combined diffusion from both excitons and trions and do not reflect the true neutral exciton diffusion length in MoS₂.

PL images of a MoS₂ monolayer excited by a diffraction-limited CW laser at different V_g and different pump powers are shown in Fig 3. In the figure, images in the same row are captured at the same pump power, while images in the same column are captured at the same V_g . For the lowest pump power, we note that PL at $V_g = -20$ V is bright, while at $V_g = 20$ V it is below the noise floor, indicating neutral excitons are much brighter than the negative trions. For neutral excitons, ($V_g = -20$ V column) slight power dependence is observed in the measured diffusion map. Also, for all powers, neutral excitons diffuse much further than the negative trions. This is related to the difference in their effective lifetime. As neutral excitons have longer effective lifetime (~ 10 ns) compared to trions (~ 50 ps),¹⁸ they also diffuse to a larger distance compared to trions.

Photoluminescence quantum yield (PL QY) is defined as the ratio of the number of photons the material radiates to the number of absorbed photons. We first present the PL QY of monolayer MoS₂ in Fig. 4A as a function of pump power and V_g . The details of calibrated PL QY measurement and quantitative recombination kinetics at different V_g and pump have been discussed elsewhere.¹⁸ At $V_g = -20$ V all photogenerated carriers create neutral excitons, as there are no excess background carriers. We note that the PL QY vs. pump profile at $V_g = -20$ V has two distinct regions, indicated by different background colors in Fig. 4A. At low pump the PL QY does not change with pump. PL QY reaches near unity in this linear regime. At high pump the PL QY decreases with pump

power. This nonlinear droop has been attributed to the bi-exciton annihilation process at high exciton densities.²⁰ At $V_g = 20$ V a large concentration of excess electrons accumulates in the monolayer, and almost all photogenerated carriers turn into negative trions (Fig. 4B). Trions can non-radiatively recombine by transferring their excess energy into secondary electrons in an Auger-like process,²¹ so the PL QY is low.

We now present the diffusion length of monolayer MoS₂ in Fig 4C as a function of pump power and V_g . Throughout the manuscript, we define the squared width of the diffusion pattern as

$$w^2(t) = \frac{\int d^2r |r|^2 I(r, t)}{\int d^2r I(r, t)} \quad (1)$$

where $I(r, t)$ is PL intensity, r is the radial coordinate, t is time and the integrations are limited to the area of the monolayer. The steady state diffusion length (L_D) is then defined as the mean-square radius of the diffusion map deconvoluted by the laser spot size. At low pump we observe diffusion lengths of 1.5 μm and 300 nm at $V_g = -20$ V and 20 V, respectively. At $V_g = -20$ V, the diffusion length shows a slight increase over six orders of magnitude of pump power, while at $V_g = 20$ V the diffusion length is low at moderate pumps and increases by $\sim 5X$ at high pump. Note that we could not measure the diffusion length of trions at very low pumps due to low signal.

To extract the diffusion coefficient of neutral excitons, we extend the kinetic model of exciton recombination to incorporate diffusion. Considering only neutral excitons (at $V_g = -20$ V), we can write the time-dependent continuity equation as:

$$\frac{\partial n_X(r, t)}{\partial t} = \nabla \cdot [D_X(n_X, t)\nabla n_X] + G(r, t) - \frac{n_X}{\tau_X} - C_{\text{bx}}n_X^2 \quad (2)$$

where n_X and τ_X are the neutral exciton population density and lifetime, respectively, and C_{bx} is the bi-exciton annihilation coefficient. Both the exciton lifetime ($\tau_X \sim 10$ ns) and bi-exciton annihilation coefficient ($C_{\text{bx}} \sim 3.5 \text{ cm}^2\text{s}^{-1}$) have been experimentally measured previously¹⁸ and are known. At steady state, $\frac{\partial n_X}{\partial t} = 0$. We consider a Gaussian generation rate given by

$$G(r) = G_0 \exp(-2r^2/w_0^2) \quad (3)$$

where the peak G_0 is determined by pump intensity. The only unknown parameter in Eq. 2 is D_X . We extract an effective diffusion coefficient D_X at different pump intensity that gives the experimentally measured diffusion length shown in Fig. 4C. This extraction process is done by assuming a constant diffusion coefficient and numerically solving Eq. 2 for exciton concentration n_X . The extracted effective diffusion coefficient at different powers is shown in Fig. 4D. We note that the effective diffusion coefficient increases with pump power. This increase in effective diffusion coefficient has been observed in other excitonic systems such as 2D heterostructures and as-exfoliated WS₂ monolayers and is attributed to correlation driven diffusion.^{8,10,22} At the lowest pump density where neutral excitons recombine completely radiatively, a diffusion length of 1.5 μm and a diffusion coefficient of $2.1 \text{ cm}^2\text{s}^{-1}$ has been observed for neutral excitons.

Unlike the case of neutral excitons, extracting the trion diffusion coefficient is more complex due to its charged nature. Diffusion of trions would perturb the local charge neutrality, and the free carriers will respond to the resultant lateral electric field. Furthermore, the observed PL is a result of radiative recombination of both excitons and trions. Thus, we calculate an effective diffusion coefficient (L_D^2/τ_T^-) at $V_g = 20$ V using the known trion effective lifetime of $\tau_T^- = 50 \text{ ps}$ ¹⁸. At a pump power density of 0.6 Wcm^{-2} , we observe a trion diffusion length of 300 nm (Fig. 4C),

which corresponds to an effective diffusion coefficient of $18 \text{ cm}^2\text{s}^{-1}$. This large diffusion coefficient could be a result of strong Coulomb interaction between charged trions. We also note that, at very high pump, the diffusion length at any V_g will converge to the neutral exciton diffusion length. This is because the number of trions cannot be larger than the number of background carriers, and thus once the trion population saturates, recombination and diffusion must be dominated by excitons. This explains the increase of diffusion length with pump at $V_g = 20 \text{ V}$ and 0 V .

Now we discuss the results of pulsed excitation. Figure 5A, B, and C show the spatial and temporal evolution of the emission intensity distribution $I(r, t)$ after pulsed excitation at $t = 0$ at $V_g = -20 \text{ V}$, 0 V , and 20 V , respectively at a pump fluence of $75 \mu\text{Jcm}^{-2}$. We can see the neutral excitons spread further in time due to their considerably longer lifetime. The neutral exciton distribution variance can be obtained directly from the measured intensity distribution variance $\Delta w^2(t) = w^2(t) - w^2(0)$, which is shown in Fig. 5D, E and F for different optical pump fluences at $V_g = -20 \text{ V}$, 0 V and 20 V , respectively. $\Delta w^2(t)$ does not depend on the width of the initial distribution created by the laser pulse. In general, the variance can be written as

$$\Delta w^2(t) = At^\alpha \quad (4)$$

The exponent α characterizes the type of diffusion and A is the empirically observed proportionality factor which has fractional time units. For $\alpha = 1$, we get linear diffusion. In the case of $\alpha > 1$ and $\alpha < 1$ the transport is called superdiffusive and subdiffusive, respectively, which results from the concentration dependence of the effective diffusion coefficient.^{23,24} We note that in monolayer MoS_2 the nature of diffusion changes from linearly diffusive at low pump to subdiffusive at high pump (Fig. 5D). This could be because of exciton-exciton interaction at high

pump densities. At low fluence excitons recombine completely radiatively and diffuse linearly with $\alpha = 1$. For linear diffusion, the halved slope of $\Delta w^2(t)$ gives the diffusion coefficient. An effective diffusion coefficient of $\sim 1.2 \text{ cm}^2\text{s}^{-1}$ has been found at low fluence, which matches well with the steady state measurements. At high fluence, biexciton recombination dominates the recombination kinetics and subdiffusive ($\alpha < 1$) behavior is observed, indicative of a reaction-diffusion process. This could also be related to the relaxation of nonresonantly excited hot exciton gas by losing its excess kinetic energy²⁵ and further careful study is required to shed light on these mechanisms. At $V_g = 0 \text{ V}$ and 20 V , subdiffusive behavior ($\alpha < 1$) is observed (Fig. 5E, F). As previously discussed, this is a result of diffusion of both excitons and trions at high fluence.²⁶ The PL signal of trions is too low to measure diffusion at low pump.

Exciton diffusion length is not only of essential importance for understanding the energy transport physics in excitonic semiconductors, but also an imperative design consideration for optoelectronic applications.²⁷⁻³¹ The physical process of bi-exciton annihilation involves the diffusion of excitons and the rate of bi-exciton annihilation increases with diffusivity. In light emitting devices, the emission region must be located at least a diffusion length away from the injection region to avoid quenching. On the contrary, in energy harvesting devices the contacts must be closer to the absorption region to collect excitons. Materials with different diffusion coefficients can therefore be suitable for different applications. Some examples of different classes of excitonic materials with their diffusion lengths are shown in Table 1. Generally, quasi-0D systems such as molecular films and quantum dot films have very low diffusion lengths (1 nm – 50 nm) at room temperature, as the diffusion mainly occurs by site hopping.³² One dimensional excitonic semiconductors, such as semiconducting single wall carbon nanotube (SWCNT) have larger ($\sim 300 \text{ nm}$) diffusion lengths,³⁶⁻³⁸ depending on the chirality and dielectric environment. A

two-dimensional excitonic semiconductor, such as the monolayer MoS₂ discussed here can have an exciton diffusion length of ~1500 nm and a trion diffusion length of 300 nm at room temperature. In a three-dimensional bulk semiconductor, strong dielectric screening generally leads to low exciton binding energy, so excitons exist only at cryogenic temperatures. At those low temperatures they show the largest diffusion length (10 - 1000 μm), however the required operating temperature limits their practical usability. Therefore, among the classes of excitonic semiconductors discussed here, two dimensional materials such as monolayer MoS₂ achieve the highest diffusion lengths at room temperature and are particularly suitable for applications that require a large diffusion length.²⁷⁻³¹ Furthermore, excitons in MoS₂ achieve near-unity PL QY at room-temperature, even in the presence of defects. Exciton transport in MoS₂ can also be tuned by electrostatic doping, strain¹¹ and dielectric environment,^{8,50} further adding to their appeal. These qualities make two-dimensional semiconductors an ideal candidate for future room-temperature excitonic devices.

CONCLUSION

In summary, we have measured the diffusion length of neutral excitons in monolayer MoS₂. The steady state exciton diffusion length is found to be between 1.5 – 4 μm depending on the pump intensity. Our measurements demonstrate that with increasing exciton concentration the diffusion coefficient increases and transport of neutral excitons in MoS₂ changes from linear diffusion to subdiffusive. The diffusion coefficient of neutral excitons measured by steady state measurements and time resolved measurements are found to be in excellent agreement. These results are direct spatial and temporal observation of isolated neutral exciton diffusion in a monolayer semiconductor, which will be invaluable for the design and characterization of systems that rely on neutral and charged exciton diffusion at room-temperature.

METHODS

Device Fabrication. TMDC monolayers are mechanically exfoliated on top of poly(methyl methacrylate) (PMMA, 100 nm), which is spin-coated on SiO₂ (50 nm)/Si substrate. MoS₂ (SPI supplies), WS₂ (HQ Graphene), WSe₂ (HQ Graphene) and MoSe₂ (HQ Graphene) were mechanically exfoliated onto 50 nm SiO₂/Si p⁺⁺ substrates. Monolayers were identified by optical contrast. 40 nm thick Au contacts were evaporated on 280 nm SiO₂/Si, and then picked up and placed on the monolayer by a dry transfer method, using PMMA as the transfer medium. Electron-beam lithography was used to open a window in the transferred PMMA, allowing probe tip contact.

Electrical and Optical Characterization. Devices were charged from a Keithley 2410 Source Meter applied to the gate electrode, while the Au source contact was grounded. The PL QY was measured using a customized micro-PL instrument described in detail in previous study.^{18,20} For steady state measurements, a green diode laser was used as the excitation source.³⁵ Laser source was collimated and then focused to a diffraction-limited spot by a 100X 0.95 NA objective lens. The back aperture of the objective was overfilled to assure diffraction-limited performance. Emission from the sample was collected by the same objective and additionally magnified 5.3X for a total magnification of 530X and imaged on a camera (Andor Neo sCMOS 5.5, sensor size 16.6 mm x 14 mm, 2560 x 2160 pixels) with pixel size 6.5 μm, which provided an effective imaging pixel size of 8.63 nm. A long-pass dichroic filter and two long-pass edge filters (Semrock) were used to remove the excitation laser beam from the PL signal. To ensure no Fresnel broadening of the PL by the top PMMA, we compared the reflected laser profile from a thick reflective MoS₂ with and without top PMMA and found no significant broadening.

For time-resolved measurements, a Ti-Sapphire laser along with an OPO was used as the excitation

source. The laser beam was collimated and focused by a 100X 0.95 NA objective lens. The back aperture of the objective was overfilled to assure diffraction-limited performance. Emission from the sample was collected by the same objective and imaged on a single-mode fiber (P1-405P-FC-2, Thorlabs) attached to a translation stage (Attocube ECS series) that scanned the emission focal plane. The stage was moved in 5 μm steps corresponding to 50 nm at the sample. The signal was detected by a single-photon counting avalanche photodiode (MPD PDM-series) connected to a time-correlated single-photon counting unit (PicoHarp 300). The temporal resolution was approximately 50 ps, as determined by the FWHM of the instrument response function.

We simulated the processes of exciton generation and recombination by discretizing and solving the continuity equation (Eq. 2) in MATLAB. The spatial grid was sampled at 5 nm distances. Time was nonuniformly sampled, denser sampling points when concentration is higher to ensure convergence.^{23,24}

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Author Contributions

S.Z.U., H.K., A.W.B. and A.J. conceived the idea for the project and designed the experiments. S.Z.U., H.K. and M.L. performed optical measurements. S.Z.U., H.K. and M.Y. fabricated devices. S.Z.U., H.K. and M.L. analyzed the data. S.Z.U. performed analytical modeling. ML ESB AWB designed and built the exciton diffusion microscope. S.Z.U., H.K., M.Y. and A.J. wrote the manuscript. All authors discussed the results and commented on the manuscript.

Competing financial interests

The authors declare no competing financial interests.

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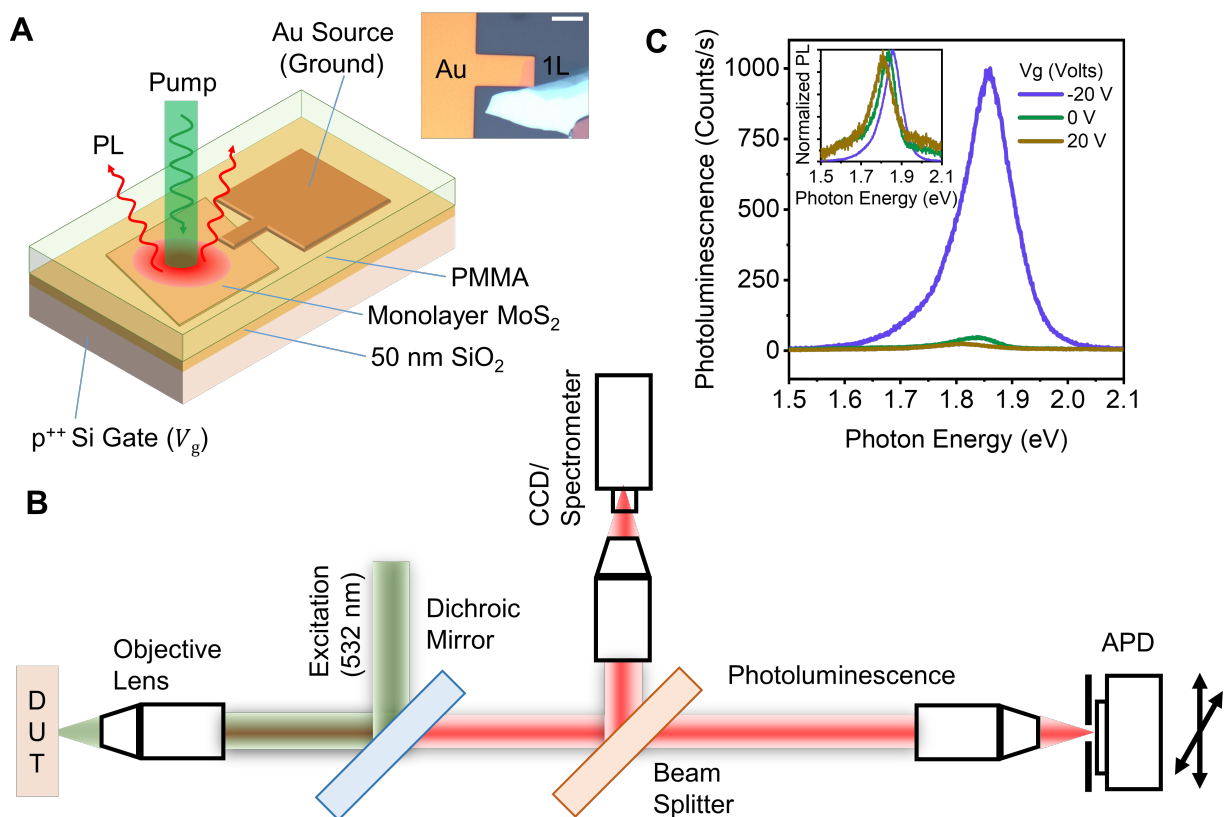


Fig. 1 | Neutral exciton transport in monolayer MoS₂. **A**, Schematic of the device, inset shows optical micrograph of the device (Scale bar 10 μm). **B**, Schematic of the exciton diffusion imaging setup. Photoluminescence excited by either pulsed or continuous wave excitation can be sent to a camera for imaging, a spectrometer for PL spectra or an APD for time-resolved single photon counting. The time resolved APD can be scanned across the emission spot to obtain a map of emission intensity as a function of position and time. **C**, PL spectra of the MoS₂ monolayer device under gate voltages $V_g = -20$ V, 0 V and 20 V at the pump density of 10^2 Wcm^{-2} .

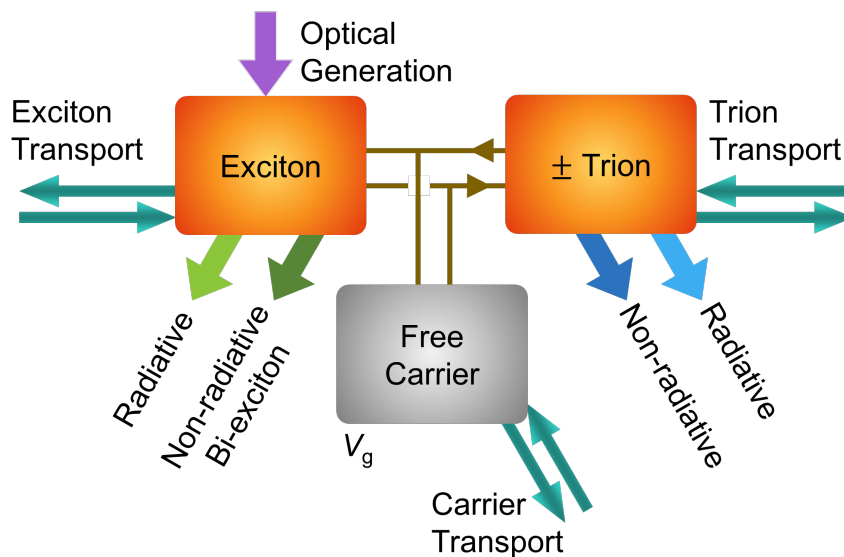


Fig. 2 | Local balance of various quasiparticles in monolayer MoS₂. In a differential area, exciton concentration increases by 1. generation upon absorption of a photon, 2. exciton transport into the area resulting from concentration or potential gradients, and 3. ionization of trions. Exciton concentration decreases by 1. trion formation, 2. radiative recombination and 3. bi-excitonic recombination. Similar generation and recombination processes occur for trions. The ratio of excitons and trions are controlled by the background carrier concentration, which also can drift and diffuse.

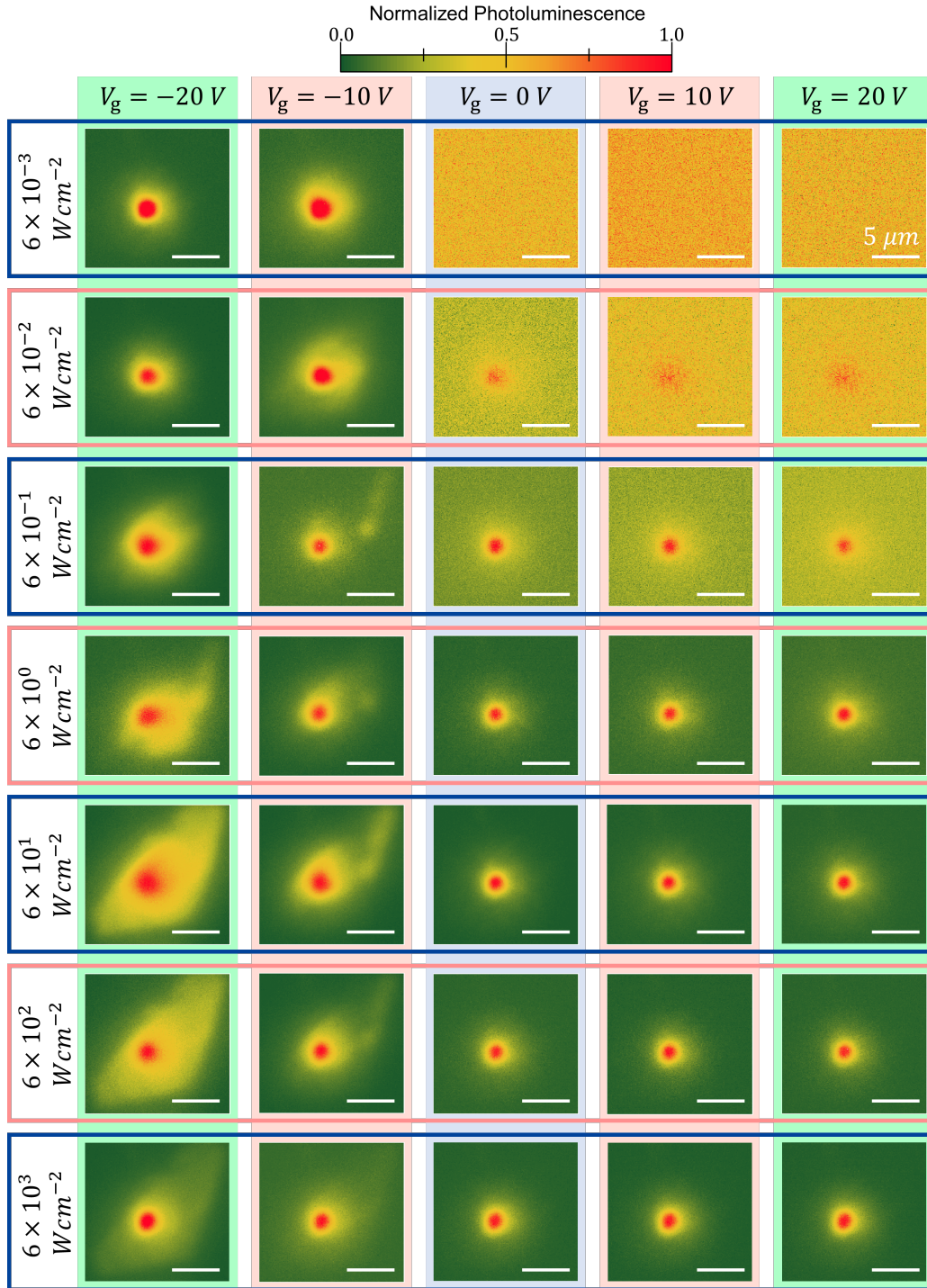


Fig. 3 | PL images at various pump powers and gate voltages. PL excited by a CW laser focused on a diffraction-limited spot for various pump powers and gate voltages. Images in the same row have the same pump power, and in the same column have the same gate voltage. Scale bar is 5 μm . Radial anisotropy arises from the finite size of the monolayer.

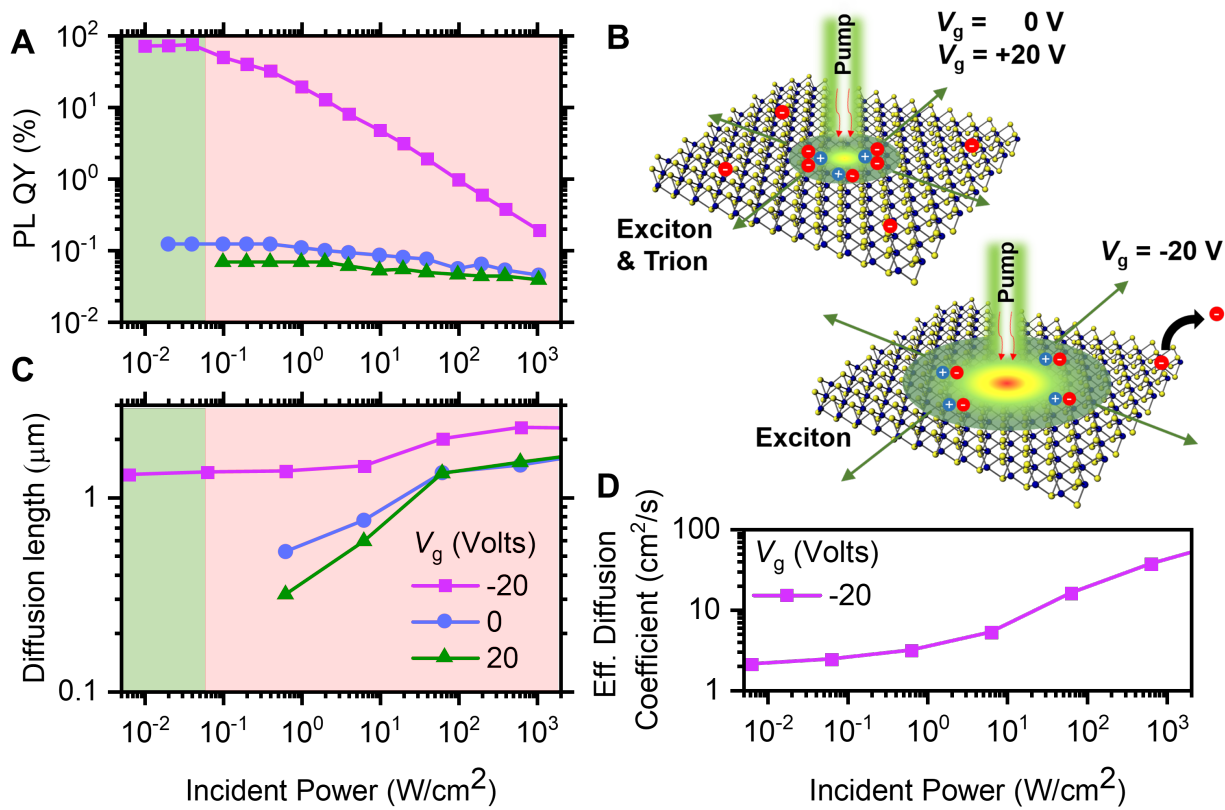


Fig. 4 | Diffusion of neutral excitons. **A**, Pump-power dependence of the PL QY for electrostatically-doped MoS₂. **B**, Exciton and trion diffusion in MoS₂. **C**, Diffusion length of a MoS₂ device under $V_g = 0$ V, $V_g = -20$ V and $V_g = 20$ V. **D**, Effective diffusion coefficient for neutral excitons in MoS₂ at different pump power.

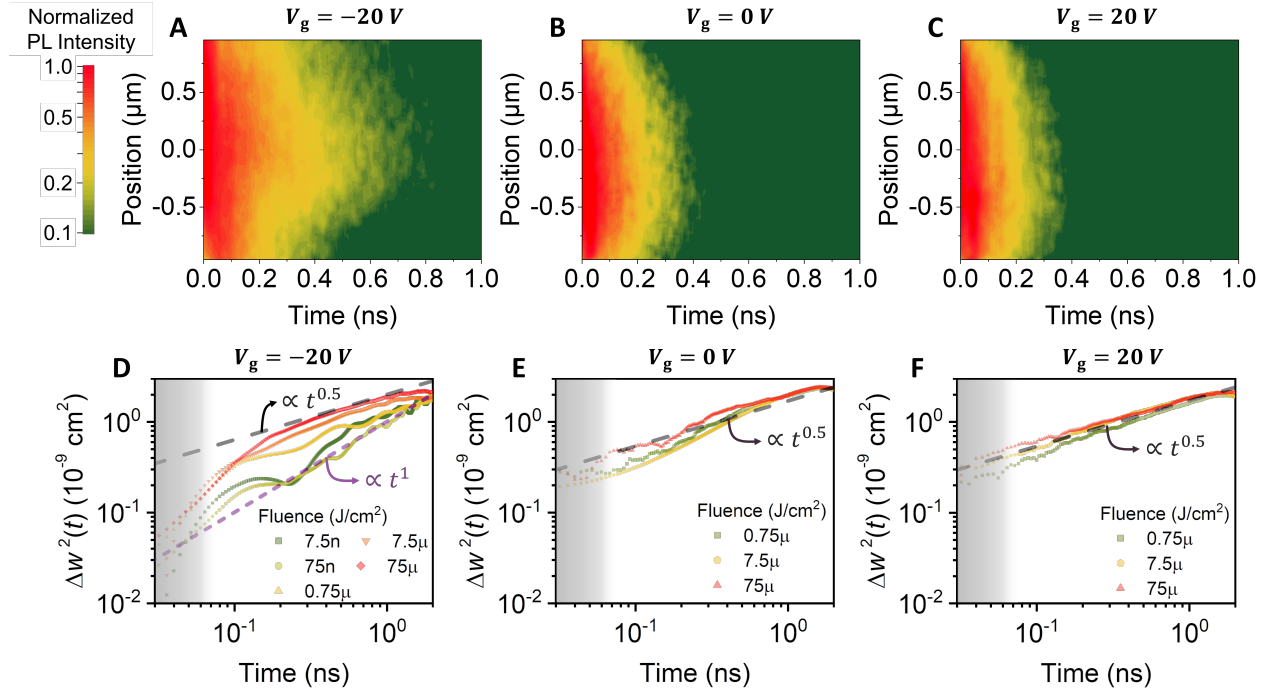
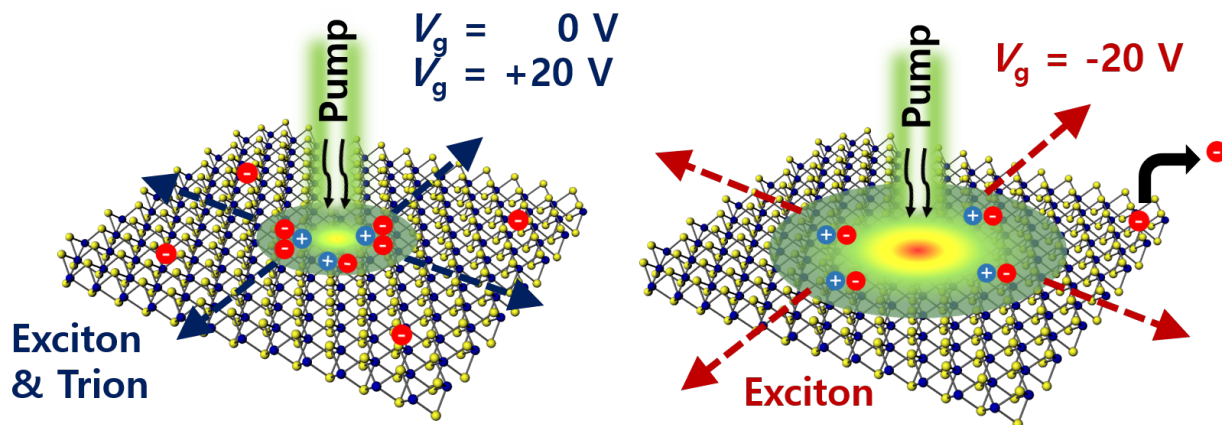


Fig. 5 | Temporal and spatial imaging of exciton transport in MoS₂. **A, B, C,** Map of emission intensity as it evolves in space and time at $V_g = -20$ V, 0 V, and 20 V, respectively at a pump fluence of $75 \mu\text{Jcm}^{-2}$. **D, E, F,** Time evolution of differential squared width for various pump fluence at $V_g = -20$ V, 0 V and 20 V, respectively. The instrument response function (IRF) has a FWHM of ~ 50 ps, which is shown as a shaded region.



ToC Graphic | ToC Graphic. Exciton and trion diffusion in monolayer MoS₂.

Table 1. Exciton diffusion in various materials. Exciton diffusion length and diffusion coefficient of various materials. All measurements are at room temperature unless specified.				
Dimension	Material	Diffusion Length	Diffusion Coefficient (cm ² s ⁻¹)	Reference
Molecules and 0D	Tris(8-hydroxyquinolinato) aluminum, Alq ₃	3 – 25 nm	(3 – 2000) × 10 ⁻⁶	[32,33]
	Spin-coated poly (p-phenylene vinylene) (PPV)	4 – 6 nm	6 × 10 ⁻⁴	[32,34]
	CdSe/CdS core/shell QD film	19 – 24 nm	2 × 10 ⁻⁴	[35]
	Cesium Lead Bromide perovskite nanocrystal film	200 nm	0.5	[36]
One Dimensional	Air suspended (9,8) SWCNT	290 – 610 nm	44	[37]
	Micelle encapsulated SWCNT	80 – 120 nm	2.5 – 10	[38]
	(6,5) single-wall carbon nanotube (SWCNT)	95 – 145 nm	10.7	[39]
	15 nm wide GaAs quantum wire (15 K)	4 μm	–	[40]
Two Dimensional	AlAs/GaAs coupled quantum well (200 K)	5 μm	3 × 10 ⁵	[41]
	As-exfoliated monolayer WSe ₂	500 – 1800 nm	0.6 – 2.2	[11,42]
	As-exfoliated monolayer WS ₂	360 – 750 nm	0.41	[8,43]
	As-exfoliated monolayer MoSe ₂	400 nm	9 – 15	[44]
	Monolayer 2D perovskite	160 nm	0.06	[45]
Three Dimensional	Undoped Si (11 K)	25 μm	100	[46]
	Doped Silicon (11 K)	24 μm	11	[47]
	Germanium (4.2 K)	900 μm	1000	[48]
	Cu ₂ O (1.2 K)	70 μm	1000	[49]