Supplementary Materials for

Quasi-1D exciton channels in strain-engineered 2D materials

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Published 29 October 2021, Sci. Adv. 7, eabj3066 (2021)
DOI: 10.1126/sciadv.abj3066

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1. **LOW-TEMPERATURE WSe\textsubscript{2} EMISSION SPECTRA UNDER STRAIN**

Under photo-excitation at low temperatures, excitonic interactions in the presence of a multi-valley band structure lead to a rich PL emission spectrum reported for high-quality encapsulated monolayers WSe\textsubscript{2}\textsuperscript{41–44}. The hBN encapsulation in our hybrid 1D-2D vdW heterostructures therefore allows us to monitor the impact of local strain on the emission of bright excitons ($X_0$), negatively charged trions ($X^-_1$ and $X^-_2$), neutral dark excitons ($D_0$), negatively charged bi-excitons ($XX^-$), dark trions ($D^-$), an unidentified peak ($T_1$), and phonon-assisted emission from dark states ($P_1$ and $P_2$) in energy and position resolved µ-PL scans. Analogous to the emission of bright $X_0$ excitons discussed in the main manuscript, all peaks show a position-dependent shift of the emission energy along the transverse $y$-direction (see Fig. S1A). A comparison between the two PL spectra from an unstrained (grey) and a strained (blue) region of our sample depicted in Fig. S1B demonstrates the peak shift towards lower energy. However, in the longitudinal $x$-direction of our device the PL emission energy varies only slowly, since the mechanical deformation in the vdW stack induced by the underlying semiconductor nanowire primarily creates uniaxial strain, as exemplary shown for bright $X_0$ excitons in Fig. S1C.

2. **FIRST PRINCIPLES CALCULATIONS OF STRAINED WSe\textsubscript{2}**

Recent studies have shown that experimentally observed excitonic transitions follow closely the strain dependence of the energy values calculated within the density functional theory (DFT) framework\textsuperscript{28,45,46}. The physical reason for such successful comparison of DFT and experiments is the following: although the single-particle energies experience strain effects more strongly, the effective masses and the dielectric screening are marginally affected. As a consequence, the exciton binding energy is almost independent of strain, especially in the presence of strong dielectric screening such as hBN encapsulation. Furthermore, strain calculations within the DFT framework remain consistent even when compared to more sophisticated theoretical approaches, for instance, that combine plain DFT to the effective Bethe-Salpeter equation (BSE)\textsuperscript{28} or even full GW-BSE calculations\textsuperscript{47}.

Here, we investigate strained WSe\textsubscript{2} monolayers within DFT and analyze the impact of different exchange-correlation functionals, namely local density approximation (LDA)\textsuperscript{48,49}, Perdew–Burke–Ernzerhof (PBE)\textsuperscript{50} and PBEsol\textsuperscript{51}. We also consider different orientations of strain since the relative alignment of the crystallographic axes of WSe\textsubscript{2} monolayer with respect to the nanowire axes is random in our samples.

In Fig. S2 we show the TMDC crystal structure and the unit cell for biaxial and uniaxial strain considered here. The in-plane lattice parameters are modified according to the type of strain applied. For biaxial strain,

\[ a = (1 + \varepsilon) a_0, \]
SUPPLEMENTARY FIGURE S1. Impact of local strain on the WSe$_2$ emission spectrum at low temperatures.

(A) In the transverse $y$-direction, all peaks of the WSe$_2$ emission spectrum recorded in a $\mu$-PL line scan shift to lower energy towards the center of the strain at $y = 0$. (B) Two exemplary PL spectra recorded in an unstrained sample position ($y = 3\ \mu$m, grey) and a highly strained region in the center of the deformation ($y = 0\ \mu$m, blue). (C) $\mu$-PL line scan in the longitudinal $x$-direction mapping the $X_0$ emission along the mechanical deformation. The blue dashed rectangle marks the sample position used for the time-resolved diffusion experiments shown in the main manuscript. Scans in (A) and (C) were recorded under 40 W/cm$^2$ and 400 W/cm$^2$ power density of 2.33 eV continuous-wave excitation, respectively.

for uniaxial strain along $x$ (armchair direction),

$$
L_x = (1 + \varepsilon_{xx}) \sqrt{3}a_0
$$

$$
L_y = (1 - \nu \varepsilon_{xx}) a_0,
$$

(S2)

and for uniaxial strain along $y$ (zigzag direction),

$$
L_x = (1 - \nu \varepsilon_{yy}) \sqrt{3}a_0
$$

$$
L_y = (1 + \varepsilon_{yy}) a_0,
$$

(S3)

with $\nu$ being the Poisson ratio that accounts for the in-plane crystal deformation in the perpendicular in-plane direction of the applied strain. We consider $\nu = 0.1849$, taken from Ref.\textsuperscript{52}.

The optimized lattice parameters and the conduction band splittings (at the K valley) for unstrained WSe$_2$ obtained from our calculations are summarized in Table I. Relaxing the WSe$_2$ atomic structure with different exchange-correlation functionals provides slightly different optimized lattice parameters and consequently different conduction band splittings; however, the band alignment remains unchanged following the well known ordering in TMDCs\textsuperscript{53}.

The extracted gauge factors for the different functionals and strain types are summarized in Table II. Since biaxial strain acts on both directions simultaneously, we divide the obtained values by a factor of 2 in order to properly compare them with the uniaxial strain calculations. For uniaxial strain, we show the average gauge factor obtained for strain applied along the armchair and zigzag directions (they differ only at the first digit after the decimal). We emphasize that our calculation results consistently confirm the experimentally observed linear reduction of $X_0 - D_0$ under tensile strain, regardless of the choice of exchange-correlation functional and of the type of strain. As a
SUPPLEMENTARY FIGURE S2. Primitive unit cells for biaxial (solid black lines) and uniaxial (shaded rectangle) strain used in the calculations.

TABLE I. Optimised lattice parameters, $a_0$ and $d_0$, and conduction band splittings at the K valley for the different exchange-correlation functionals considered in this study.

|                | LDA   | PBE   | PBEsol |
|----------------|-------|-------|--------|
| $a_0$ (Å)      | 3.2485| 3.3187| 3.2706 |
| $d_0$ (Å)      | 3.3343| 3.3632| 3.3516 |
| $\Delta_{CB}$ (meV) | 45.90 | 36.74 | 43.95  |

general trend, the individual gauge factors for $X_0$ and $D_0$ under uniaxial strain are smaller than the values for biaxial/2, whereas the $X_0 - D_0$ splitting is slightly larger.

3. ROLE OF DIELECTRIC SCREENING AND RESIDUAL DOPING

In order to exclude dielectric effects and to gain more insight into the role of background doping, we performed optical white light (WL) reflectance measurements using a spectrally broadband tungsten-halogen lamp in the same setup that we used for PL measurements. The reflectance contrast was calculated using $(R_{sample} - R_{ref})/(R_{ref} - R_{BG})$, where $R_{sample}$ and $R_{ref}$ spectra were acquired on the sample and in a reference position on the SiO$_2$/Si substrate in close proximity to the sample, respectively. Additionally, a background signal $R_{BG}$ was acquired without the light source. Resonance energies and linewidths were extracted using a transfer-matrix formalism with model dielectric functions based on a series of Lorentz resonances.$^{54,55}$ Exemplary reflectance contrast derivative spectra acquired at $T = 4$ K in a line-scan across the nanowire-induced deformation show the same strain-induced energy shift as the PL response (cf. Fig. S3A and B). The generally narrow linewidth of the reflectance resonances (less than 5 meV for both the strained and unstrained regions) highlights the absence of long-range disorder in the WSe$_2$ monolayer; only towards the edges of the strain-induced deformation, where the

TABLE II. Gauge factors (in meV/%) for $X_0$, $D_0$ and $X_0 - D_0$ for the different exchange-correlation functionals and types of strain considered in this study.

|               | LDA   | PBE   | PBEsol |
|---------------|-------|-------|--------|
| $X_0$         | -69.3 | -63.2 | -61.0  | -54.4 | -67.6 | -59.8 |
| $D_0$         | -64.9 | -56.8 | -58.0  | -50.5 | -63.4 | -54.2 |
| $X_0 - D_0$   | -4.4  | -6.4  | -3.0   | -3.9  | -4.2  | -5.6  |
SUPPLEMENTARY FIGURE S3. Impact of local strain on the reflectance contrast at \( T = 4 \text{ K} \). (A) Line scan across the nanowire-induced deformation in the \( y \)-direction with a step size of 0.3\( \mu \text{m} \). Reflectance spectra in the right part of the plot are multiplied by a factor of 10 to increase visibility. (B) Extracted energies of the ground state exciton resonance \( X_{0}^{1s} \) along the \( y \)-position (blue) in comparison to the \( X_{0} \) PL emission determined from the line scan in Fig. 1C (red). (C) Exciton binding energy as a function of the \( y \)-position demonstrates a uniform dielectric screening across the hybrid 1D-2D structure. (D) Energy separation of the bright exciton \( (X_{0}) \) and first negatively charged trion \((X_{1}^{-})\) as function of the \( y \)-position from a PL line scan.

white light spot of about 2\( \mu \text{m} \) collects signal from both unstrained and strained regions, we observe an additional broadening related to double peak features in the reflectance contrast.

The exciton binding energy \( E_{B} \) presented in Fig. S3C was estimated from the energy separation of the ground state and the first excited state by \( E_{B} = 1.3(X_{0}^{1s} - X_{0}^{2s}) \) according to the scaling for WSe\(_{2}\) monolayers from Ref.\(^{56}\). The resulting value of \( E_{B} \approx 175 \text{ meV} \) is nearly constant across the hybrid 1D/2D device and merely small variations of a few meV arise at the edges of the strain-induced deformation due to the aforementioned broadening of the signal, demonstrating a homogeneous dielectric screening in our hybrid 1D/2D structures. Generally, a change in the binding energy due to a different dielectric environment is partially compensated by a renormalization of the free-particle band gap, resulting in a reduced energy shift of the ground state compared to the binding energy. In addition, since the spatial fluctuation of the binding energy shows no correlation with the energy shift of the \( X_{0} \) peak, for which the maximum shift occurs in the center of the deformation, we exclude dielectric effects as reason for the position-dependent \( X_{0} \) energy shift.

Moreover, reflectance measurements show no signatures of trion/Fermi polaron reflectance features in both strained and unstrained regions of our sample, which demonstrates an overall low level of residual doping and additionally excludes any significant contributions from strain-induced local doping effects. We estimate the doping level in our sample based on the energy separation between the bright \( X_{0} \) exciton and the trion \( X_{1}^{-} \) peaks in PL: The comparison with a gate-tunable WSe\(_{2}\) field-effect transistor device\(^{57}\) determines an upper bound for the background electron density in our sample of \( n_{e} = 5 \times 10^{11} \text{cm}^{-2} \). Furthermore, a nearly constant energy separation, \( X_{0} - X_{1}^{-} \), confirms the absence of local doping in the strained region (see Fig. S3D). Merely the edges of the strain-induced deformation show broadening-induced features similar to the reflectance measurements.

4. DETERMINATION OF THE DEFORMATION-INDUCED STRAIN PROFILE

Based on the results presented in the previous section, the position-dependent \( X_{0} \) energy shift observed in \( \mu \)-PL is a direct result of strain in our sample and can be used to estimate its magnitude and spatial distribution. We also emphasize that, in addition to the absolute shift of the \( X_{0} \) energy, the relative shift between \( X_{0} \) and \( D_{0} \) exciton peaks (cf. Fig. 1E) in our experiments independently confirms the presence of tensile strain.

To derive the underlying strain profile from the spatially dependent \( X_{0} \) energy shift, we need to account for the
finite size of the \(\mu\)-PL collection spot. As demonstrated in Fig. 1 of the main manuscript and in Fig. S1 of the Supplementary Information, the emission energy of \(X_0\) excitons in our sample continuously decreases from 1.733 eV to 1.724 eV towards the point of maximum deformation, where it starts to increase again to the unstrained value, as expected for locally created strain. We note, that along the deformation created by the nanowire the \(X_0\) energy, and therefore also the strain, remains nearly constant. In this analysis, the absence of any additional spectral broadening in the \(X_0\) emission peak observed in the center of the deformation indicates a largely uniform strain distribution within the \(\mu\)-PL collection spot. We therefore assume a Super-Gaussian strain profile, which is shown in Fig. 1C. This profile accurately describes the spatial broadening of the \(X_0\) energy profile (dashed gray line in Fig. 1C-right panel) after convolution with a Gaussian to account for the finite resolution of the optical setup.

The magnitude of strain in our sample is estimated by calibrating the measured energy of the \(X_0\) exciton peak to the change of the band gap energy obtained from first-principles DFT-LDA calculations (cf. Supplementary Note 2). Based on the calculated \(X_0\) gauge factor of \(-63.2\,\text{meV/}\%\) strain, a line fitted to the experimental data points plotted in Fig. 1E determines a decrease of the \(X_0 - D_0\) separation by \(-6.6\,\text{meV/}\%\) strain, which excellently matches the corresponding calculated value of \(-6.4\,\text{meV/}\%\). For comparison, the same procedure based on first-principles DFT-PBEsol calculations, and thus a \(X_0\) gauge factor of \(-59.8\,\text{meV/}\%\) strain, renders a decrease of the \(X_0 - D_0\) separation by \(-6.3\,\text{meV/}\%\), which still agrees reasonably well with the DFT-PBEsol calculated value of \(-5.6\,\text{meV/}\%\), but does not match the agreement with DFT-LDA calculations (cf. table in Supplementary Note 2). Hence, the DFT-LDA calculated gauge factor of \(-63.2\,\text{meV/}\%\) strain is used for \(X_0\) throughout our study.

Previous experiments have reported comparable, albeit slightly lower scaling factors for \(X_0\) (for example \(-47.6\,\text{meV/}\%/^{25}\), or \(-49.0\,\text{meV/}\%/^{26}\)), while a recently published experimental study determined a gauge factor of \((-5\pm 4)\,\text{meV/}\%/^{27}\) that is very close to the scaling that we use. We note, however, that all of the reported gauge factors listed above were determined at room temperature in contrast to the low-temperature conditions studied here. It is thus, for example, not obvious whether exciton-phonon coupling that contributes to temperature-dependent band gap renormalization could change under strain. To avoid potential uncertainties that may result as a consequence, it seems reasonable to use the calculated scaling factor until this point is clarified in future studies. Moreover, the resulting match of the relative energy separation between bright and dark exciton states in theory and experiment provides additional, strong support for our choice of the scaling.

5. IMPACT OF LOCALIZATION AND FUNNELING ON EXCITON DIFFUSION

In general, spatial variations in the exciton potential landscape are expected to induce drift currents which can funnel excitons along the gradients of the potential and result in their localization. However, there are also reports that challenge the role of exciton funneling in the description of strain-induced changes in the spatially dependent PL.

Part of the apparent controversy in this regard might indeed relate to the different experimental realizations of the systems under study. More specifically, it appears crucial whether the samples exhibit a substantial amount of (dielectric) disorder inhibiting exciton movement, or whether the excitons can diffuse and drift more freely. Moreover, a careful spectral analysis of the detected resonance seems to be of particular importance. It thus seems likely that both experimental scenarios can exist: those in which funneling is present and those in which it will be largely suppressed.

In the following, we briefly discuss the potential role of exciton funneling in our experiments. In the hybrid 1D/2D systems, the length scale of the strain gradients relevant for exciton funneling is less than one micrometer, as determined by atomic force microscopy (see Fig. 1B and C of the main manuscript). Thus, directly resolving the exciton drift currents on such short length scales is difficult in optical diffusion measurements. Nevertheless, several observations in our experiments can be attributed to the occurrence of exciton funneling: when excitons are excited slightly off-center with respect to the strain-induced potential minimum, the resulting emission profiles show a small, transient shift of their center-of-mass towards the center of the deformation, as one would expect for the funneling of excitons. Figure S4A,B show normalized emission profiles at two different time delays for excitation on both sides of the 1D potential channel. The overall effect is small, yet the weighted arithmetic mean of the PL clearly shifts up to 50 nm towards the potential minimum (cf. Fig. S4C). The measurements are performed on both sides and the sign of the shift changes accordingly, supporting the interpretation of the observations as exciton funneling. In addition, we find strong indications of increased local density of the excitons that results in enhanced biexciton (\(XX^-\)) emission presented in Fig. 1C of the main manuscript. Finally, an overall higher PL intensity in the middle of the channel is consistent with funneling, even if it could also contribute to the observation of an effectively negative diffusion across the channel.
SUPPLEMENTARY FIGURE S4. Exciton diffusion measurements for excitation and collection at the side of the nanowire at $T=4K$. Normalized spatial PL profiles at early (10 ps) and later times (140 ps) after excitation on the left (A) and right (B) sides of the deformation. (C) Weighted arithmetic mean of the spatially resolved PL for the area -2 $\mu$m to 2 $\mu$m (shown in (A), (B)) shifts away from the excitation towards the middle for both sides of the strain-potential. Energy density per pulse was 5 $\mu$J/cm$^2$ of pulsed excitation at 1.77 eV. Dashed lines are guides to the eye.

6. REPRODUCIBILITY OF THE ANISOTROPIC EXCITON DIFFUSION MEASUREMENTS

Supplementing the results obtained from the nanowire-induced deformation in the vdW stack discussed in the main manuscript, we observe similar phenomena in several studied 1D-2D structures. Figure S5A exemplary depicts the position-dependence of the $X_0$ emission peak for a different sample. Similar to the measurements presented in the main text, the $X_0$ peak shifts towards lower energy upon approaching the apex of the deformation in a $\mu$-PL scan, reflecting the underlying strain-induced confinement potential. Correspondingly, time-resolved emission microscopy reveals a strongly anisotropic transport of excitons propagating along the longitudinal $x'$- and the transverse $y'$-direction of this hybrid 1D-2D structure (see Fig. S5B and C). Note that the value obtained in the transverse direction is likely to overestimate the diffusion coefficient since a certain contribution from the longitudinal component is expected due to a slight misalignment of the $y'$-axis relative to the detector slit in this particular measurement.

Additional hybrid 1D-2D devices, including nanowire-induced deformations in a second hBN/WSe$_2$ (1L)/hBN vdW stack, provide an average diffusion coefficient of $D = 1.2$ cm$^2$/s for excitons propagating either along the longitudinal direction of a hybrid 1D-2D device, or within an unstrained monolayer at $T = 4K$. In the transverse direction, we find an average value of $D = 0.1$ cm$^2$/s in a number of different hybrid 1D-2D devices, as demonstrated in Fig. S5D. Hence, our analysis demonstrates a strongly anisotropic propagation of excitons in 1D-2D hybrid structures with an average anisotropy ratio exceeding one order of magnitude.

7. LOW-TEMPERATURE EXCITON DYNAMICS

Exciton decay dynamics can play an important role in determining diffusion coefficients in time-resolved emission microscopy measurements. As the collected PL signal is monitored in both time and space domains, diffusion coefficients derived from such a spectrally integrated measurement inherently reflect the average propagation of all detected species at low temperatures. In addition to that, spatial variations of the emission lifetime could potentially alter the apparent diffusion coefficient determined in these experiments. For example, if the deformation-induced strain would locally modify the exciton lifetime, as reported in a recent room-temperature study$^{26}$, different lifetimes would be expected in the center of the deformation (maximum strain) as compared to the lifetimes at the edges and far from the deformation (minimal strain). Such a scenario could potentially lead to an apparent change of the diffusion coefficient measured in the direction perpendicular to the channel. For the comparably small values of strain present in our hybrid 1D-2D structures, however, effects of strain on the exciton decay are not expected$^{58}$. Most importantly, a comparison of the decay dynamics in a strained and an unstrained region of our sample further shows that the lifetime of the excitons does not change significantly under strain in our experiment, as demonstrated in Fig. S6A. Hence, the exciton decay itself cannot result in any anisotropy of the exciton diffusion under strain.
SUPPLEMENTARY FIGURE S5. Anisotropic exciton transport in additional devices. (A) µ-PL line scan showing the shift of the $X_0$ peak at 4 K for a second hybrid 1D-2D device obtained under 400 W/cm² power density and continuous-wave excitation with a photon energy of 2.33 eV. Pink circles indicate the peak energies determined from Gaussian fits. (B) and (C) Relative mean squared displacement from the spatially resolved exciton emission profiles, monitored at 4 K and 290 K in the longitudinal $x^*$- and transverse $y^*$-direction, respectively. These observations are characteristic for strongly anisotropic exciton transport. The energy density per pulse was set to 5 µJ/cm² and the photon energy to 1.77 eV. (D) Summary of the measured diffusion coefficients at 4 K. Values in brackets denote the average diffusion coefficient and its standard deviation, respectively.

In our experiments, the decay of the spectrally and spatially integrated total emission shows two regimes (see Fig. S3A): Initially, short-lived excitations dominate the PL signal (regime I, for $t < 50$ ps), which is subsequently characterized by a much slower, single exponential decay at later times (regime II, for $t > 50$ ps). By resolving the PL decay in both energy and time domains, we find that the weight of the total emission intensity dynamically shifts from short-lived bright $X_0$ excitons and negatively charged trions, $X^-_1$ and $X^-_2$, (regime I) to longer lived excitonic species (regime II), as apparent in Fig. S6B. For delay times exceeding 50 ps after the pulsed excitation, more than 65% of all detected photons arise from $D_0$, $XX^-$, and $D^-$ peaks. To avoid the effects of hot carrier transport and the subsequent cooling regime occurring within the first tens of ps, we focus our exciton propagation analysis in the main manuscript on delay times larger than 50 ps (regime II). Hence, the exciton diffusion coefficients determined in this time range primarily reflect the average propagation of dark $D_0$ excitons and their many-body excitonic complexes $XX^-$ and $D^-$. To confirm the hypothesis that the anisotropic transport in our hybrid 1D-2D structures is primarily carried by these excitons, we spectrally filtered the emission of each the $D_0$ and the $XX^-$ excitons from the spectrum recorded in the strained region, before measuring their diffusion in time-resolved emission microscopy (see Fig. S7). For $D_0$ excitons propagating along the longitudinal axis, we find a diffusion coefficient of $D^*_0 = (1.0 \pm 0.2)$ cm²/s and analogously determine a diffusion coefficient of $D^*_{XX^-} = (1.0 \pm 0.2)$ cm²/s for $XX^-$ excitons. These values derived from the isolated emission of $D_0$ and $XX^-$ compare reasonably well with the diffusion coefficient, $D_x^0 = (1.4 \pm 0.1)$ cm²/s, we obtain when spectrally averaging the emission of all peaks.

8. DENSITY-DEPENDENT MEASUREMENTS

We investigate the robustness of the anisotropic exciton transport in our hybrid 1D-2D structure by monitoring the exciton propagation in the longitudinal $x$- and the transverse $y$-direction for different exciton densities. The exciton density $n_X$ is calculated from the incident photon flux using
SUPPLEMENTARY FIGURE S6. Exciton decay dynamics at 4K. (A) Spectrally and spatially integrated PL transients recorded in strained and unstrained regions of the sample. The transients are essentially identical for the two regions, both featuring a fast initial decay and a slower decay in the regime, where the diffusion measurements are analyzed. (B) Spectrally resolved PL emission recorded in a strained region integrated from 0 ps to 50 ps (yellow) and from 50 ps to 1100 ps (blue) recorded in a strained region. Measurements were conducted under 5 µJ/cm² energy density per pulse of 1.77 eV excitation.

SUPPLEMENTARY FIGURE S7. Spectrally isolated diffusion of D₀ and XX⁻ at T = 4 K. (A) Prior to recording the (spectrally integrated) exciton propagation in time-resolved emission microscopy measurements, the PL emission obtained in the strained region was dispersed in a spectrometer to select a narrow spectral window by a combination of two tunable edge pass filters, indicated by the grey shaded areas. The upper and lower panel shows their selective transmission centered around the emission peak of D₀ excitons and charged XX⁻ biexcitons, respectively. The grey spectrum in the background represents the PL spectrum obtained without the two tunable filters. (B) A linear fit to the transient broadening of the emission profiles along the longitudinal x-direction determines a diffusion coefficient for D₀ and XX⁻ individually. Measurements were conducted under 5 µJ/cm² energy density per pulse of 1.77 eV excitation.

Here, \( \bar{P} \) is the time-averaged power density of the focused excitation laser and \( f_{\text{rep}} = 80 \text{ MHz} \) is the repetition frequency of the laser pulses. From the linear reflectance measurements shown in Section 3, we find an absorption \( \alpha(h\nu) \) of 0.8 % for an excitation energy of \( h\nu = 1.77 \) eV. Evaluating Eq. (S4) under the conditions indicated above results in an optically excited exciton density ranging from \( n_X = 1.3 \times 10^{10} \text{cm}^{-2} \) to \( n_X = 4.8 \times 10^{11} \text{cm}^{-2} \) in our experiments.

The two PL spectra obtained for the lowest and highest exciton density shown in Fig. S8A demonstrate a strongly non-linear dependence of the WSe₂ emission spectra under increasing excitation power. In our time and spatially resolved emission microscopy measurements, such substantial changes in the PL spectra directly imply a different excitonic composition of the spectrally integrated signals. Hence, different excitonic species contribute to the average...


SUPPLEMENTARY FIGURE S8. **Density dependent anisotropic exciton transport at T = 4 K.** (A) Time-integrated μ-PL emission spectra recorded in the strained region for two different exciton densities corresponding to the lowest and highest exciton density in (B). The spectrum at lower excitation density (purple) was multiplied by a factor of 40 to increase visibility. (B) Exciton density dependence of diffusion coefficients determined along the longitudinal x- and the transverse y-direction of the hybrid 1D-2D structure discussed in the main manuscript. At all densities, the exciton transport is highly anisotropic. Average diffusion coefficients in the longitudinal x- and transverse y-direction are \( (1.3 \pm 0.6) \text{ cm}^2/\text{s} \) and \( (-0.1 \pm 0.1) \text{ cm}^2/\text{s} \), respectively. Numbers in brackets denote the average value and the corresponding standard deviation.

diffusion coefficient extracted for each excitation density. Nonetheless, we find strongly anisotropic propagation at all exciton densities, as illustrated in Fig. SSB, demonstrating the robustness of anisotropic exciton transport in hybrid 1D/2D structures. This observation is a direct consequence of the universal impact of strain on the exciton energy, which creates a potential minimum for all excitonic species, as shown in Fig. S1.

9. **ESTIMATED OCCUPATION OF TRANSVERSE EXCITON MODES IN STRAIN-INDUCED CONFINEMENT CHANNELS**

In order to estimate the number of exciton states (quantized transverse modes) confined in strained channels, we neglect the complex multi-valley band structure giving rise to a manifold of excitonic species and instead evaluate only for \( X_0 \) and \( D_0 \) excitons the exciton center-of-mass motion in the presence of a confinement potential exemplary. The exciton levels are quantized in the direction perpendicular to the confinement potential channel whereas the exciton center-of-mass motion in the presence of a confinement potential exemplary.

The exciton levels are quantized in the direction perpendicular to the confinement potential channel whereas the exciton center-of-mass motion in the presence of a confinement potential exemplary. The exciton center-of-mass position is subject to a confinement potential, which is considered a barrier height \( V_0 \) in the main text. We emphasize that this approach is valid as long as the exciton radius is smaller than the spatial scale of the confinement potential we are considering. Particularly, excitons in WSe

\[
H(y) = \frac{\hbar^2}{2M} \frac{\partial^2}{\partial y^2} + V(y),
\]

in which \( M = m_c + m_v \) is the exciton center-of-mass, \( m_{c(v)} \) is the effective mass of the conduction (valence) band, \( V(y) \) is the confinement potential and \( y \) is the transverse direction of the hybrid 1D-2D structure (cf. Fig. 1B in the main text). We consider a finite square well with barrier height \( V_0 = 10 \text{ meV} \) and width \( L \).

Using the electron and hole effective masses provided in Ref. 53, we obtain \( M = 0.75m_e \) for \( D_0 \) and \( M = 0.64m_e \) for \( X_0 \), where \( m_e \) is the free electron mass. For the confinement potential, we consider a finite square well with barrier height \( V_0 = 10 \text{ meV} \) and width \( L \).

In Fig. S9 we show the number of confined states, which are populated by excitons with a thermal excitation energy below 0.35 meV (= \( k_BT \) at 4 K). For a potential width of 1 μm (similar to our experiments) only \( \sim 25 \) of the emergent quantized transverse exciton modes are populated. Given that confined excitons in our experiment still scatter frequently between different transverse modes (mode spacing \( \ll k_BT \)), the quasi-1D channels are ascribed to the transverse diffusive regime, opposed to transverse ballistic 1D systems. Decreasing the spatial scale of the confinement potential, we estimated a cross-over to the true 1D regime (in which a single-mode is populated) to
SUPPLEMENTARY FIGURE S9. Estimated number of quantized modes populated by excitons. For the values of L shown in the plot, the results are nearly identical if a barrier height of $V_0 = 5$ meV is considered or even if we consider the infinite square well limit $V_0 \rightarrow \infty$.

occur at 60-70 nm, which is still large enough to consider the center-of-mass description of the excitons presented here.

10. ANISOTROPIC EXCITON TRANSPORT AND POSITION-DEPENDENT SCATTERING AT ROOM-TEMPERATURE

Here we propose a modification to the exciton transport model, going beyond confinement-induced effects, to rationalize the experimentally observed strong anisotropy of exciton transport in hybrid 1D/2D structures at room temperature. However, we also note that due to complex exciton-phonon interactions in the multi-valley band-structure, exciton density-dependent Auger effects and the subtle equilibrium dynamics between excitons and the electron-hole plasma state, a quantitative transport description of excitons in TMDCs at room temperature requires considerations beyond the simplified picture of linear diffusion of a single exciton species.

Firstly, analogous to low temperatures, tensile strain creates a confinement potential $u = u(r)$ with a depth of 10 meV, which – while no longer fully suppressing the exciton transport – still significantly reduces the propagation of excitons in the $y$-direction (see discussion below). Secondly, local strain in WSe$_2$ causes a position-dependent exciton scattering rate at room temperature (evidenced in Fig. 4 of the main manuscript), equivalent to a spatially dependent diffusivity of excitons. This scattering rate determined from PL emission stems only from bright $X_0$ excitons, whereas the diffusion observed in our time-resolved emission microscopy experiments reflects the scattering of excitons populating different valleys. Indeed, this composite diffusion coefficient primarily contains contributions from excitons in spin and momentum-forbidden dark states, in addition to a significant contribution from the electron-hole plasma state. As a result, a realistic assessment of the strain-dependent exciton scattering rate required to quantitatively simulate our experiment is not straightforward.

Here, to demonstrate the general effect of position-dependent scattering on the propagation of excitons in WSe$_2$, we simulate Eq. (S6) based on a conservative estimate: a moderate increase of the diffusion coefficient from $D_{unstrained} = 9$ cm$^2$/s to $D_{strained} = 12$ cm$^2$/s is extracted from the calculations presented in Ref. for excitons in non-encapsulated 1L WSe$_2$. We thus replace the previously constant $D$ by a spatially dependent $D = D(r)$, which increases towards the center of the super-Gaussian strain profile in the $y$-direction, resulting in additional terms of the drift-diffusion model in Eq. (1) of the main manuscript:

$$
\frac{\partial n}{\partial t} = D \Delta n + \nabla D \cdot \nabla n + \frac{D}{k_B T} \nabla n \cdot \nabla u + n \nabla u \cdot \nabla \frac{D}{k_B T} + \frac{D}{k_B T} n \Delta u - \frac{n}{\tau}.
$$

We numerically calculate the time evolution of an initial Gaussian exciton density, $n(r,0) = n_0 \exp(-r^2/2\sigma_0^2)$ with $\sigma_0 = 0.43$ µm, a temperature of $T = 300$ K and an exciton decay time of $\tau = 40$ ps and analyse the fraction of excitons residing within the initially excited area of the strained region (cf. sketch in Fig. S10A). From the
Localization effect under the impact of position-dependent scattering at $T = 290\,K$. (A) Schematic of the extracted exciton profiles along $x$ and $y$. (B) Simulated exciton distribution profiles along $x$ and $y$ at 400 ps after the structure is excited with a symmetric Gaussian beam (grey dashed lines, $t = 0$ ps). Shaded area indicates the extension of the strained channel. (C) A $\mu$-PL line scan of the exciton energy is accompanied by a 1.5-fold increase of the integrated emission intensity in the center of the strain. The dashed line traces the energy-dependence of the emission peak along the $y$-direction. PL spectra were recorded in an unstrained ($y = 3\,\mu m$, grey) and strained ($y = 0\,\mu m$, blue) region of the vdW stack.

Data plotted in Fig. S10B, we find that after 400 ps less than 40% of the excitons are found in the initially excited area in the $x$-direction. Along $y$, however, approximately 90% of the carriers injected into the strained region are still localized in this part of the structure, even after 400 ps. In this case, the degree of anisotropy of exciton localization amounts to $\sim 40\%$, indicating a substantial direction-dependent exciton localization effect in our hybrid 1D/2D structure, which results in a strongly anisotropic transport of excitons. Note that if we remove the spatially dependent scattering from Eq. (S6), considering only the effects of the confinement potential on the transport of excitons with $D = 9\,cm^2/s$ at room temperature, we still observe a significant anisotropy in the transport of excitons, which is, however, characterized by a reduced degree of only 20%. Despite the conservative estimate of the position-dependent diffusion coefficient, we thus find a strong impact of strain on the room-temperature diffusion observed in our experiments.

In addition, Fig. S10C demonstrates a 1.5-fold increase of the integrated emission intensity in the strained region, qualitatively similar to the observations in a recent study on homogeneously strained WSe$_2$. In our structure, such a local enhancement in the PL emission intensity along the $y$-direction is consistent with the interpretation of funneling and the observed propagation.
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