

Strain engineering of transient exciton diffusion in WSe₂ monolayers at cryogenic temperaturesRoberto Rosati^{1,*}, Mohammed Adel Aly^{2,3}, Robert Schmidt², Rudolf Bratschitsch², and Ermin Malic¹¹*Department of Physics, Philipps-Universität Marburg, Renthof 7, D-35032 Marburg, Germany*²*Department of Physics, University of Münster, Wilhelm-Klemm-Strasse 10, D-48149 Münster, Germany*³*Department of Physics, Faculty of Science, Ain Shams University, 11566 Cairo, Egypt*

(Received 3 August 2026; revised 27 September 2026; accepted 29 September 2026; published 16 October 2026)

Tungsten-based transition metal dichalcogenides exhibit dark excitons as the energetically lowest states. These are crucial for exciton thermalization and propagation and they dominate low-temperature photoluminescence via the emergence of pronounced phonon sidebands. After a resonant excitation, highly mobile hot dark excitons are formed, which quickly thermalize into an equilibrium distribution. The application of strain modifies the exciton energy landscape and, in particular, the relative energy separation between bright and dark exciton states. The impact of strain on the transient photoluminescence and diffusion of nonequilibrium excitons has remained largely unexplored so far. In this work, we investigate the spatiotemporal exciton dynamics in strained WSe₂ monolayers under encapsulation in hexagonal boron nitride at cryogenic temperatures. We demonstrate that tensile strain abruptly increases the excess energy of hot excitons, thereby accelerating their transient diffusion. We trace this back to suppressed phonon-mediated scattering from bright to dark excitons. Furthermore, we predict a periodic modulation of the transient exciton diffusion in the presence of a compressive strain resulting from strain-driven emission of M phonons. The gained microscopic insights illustrate how strain can be used to engineer transient photoluminescence and exciton diffusion in technologically promising two-dimensional semiconductors.

DOI: [10.1103/rvb3-tn15](https://doi.org/10.1103/rvb3-tn15)**I. INTRODUCTION**

Two-dimensional semiconductors, such as transition metal dichalcogenides (TMD), are characterized by tightly bound excitons. The charge neutrality of these Coulomb-bound electron-hole pairs inhibits their control by external electric fields [1]. Only in vertical [2–4] or lateral heterostructures [5–9], the appearance of spatially separated dipolar excitons allows electrical control. The application of external mechanical strain presents a strategy to overcome this limitation and obtain directional control of exciton propagation even in TMD monolayers. Strain modifies the exciton energy landscape in a valley-dependent way [10–20]. In particular, the energy of bright excitons shifts to the red with tensile strain, allowing funneling of excitons toward spatial, high-strain regions [21–26], where intense photoluminescence (PL) is observed [27–29]. Recently, it was demonstrated that, interestingly, strain can even result in exciton *anti*-funneling toward spatial, low-strain regions in tungsten-based TMDs [30]. This is driven by dark KA excitons, which shift blue with strain—opposite to bright KK excitons. Similarly, strain has been shown to accelerate exciton diffusion at equilibrium [31,32] as well as to enhance PL intensity [33] and polarization [34]

or to modify exciton *g* factors [35] by bringing dark and bright excitons in resonance.

Dark excitons also have a crucial impact on the transient spatiotemporal exciton dynamics through the formation of *nonequilibrium* dark excitons [36–38]. In tungsten-based TMD monolayers the optically excited bright KK excitons scatter into the energetically lower dark states by emitting intervalley phonons [see Figs. 1(a) and 1(b)]. Due to the spectral mismatch between the bright-dark exciton separation and intervalley phonon energies [39], *hot* dark excitons are formed with a finite excess energy. Subsequently, they gradually lose their energy by scattering with quasielastic intravalley phonons, whose efficiency decreases linearly with decreasing temperature. As a result, the thermalization time of hot dark excitons increases from tens of femtoseconds to tens of picoseconds when moving toward cryogenic temperatures [36]. In WSe₂ under hexagonal boron nitride (hBN) encapsulation, this gradual thermalization has been directly tracked via time-resolved PL [38]. Since hot excitons have a higher group velocity, their formation leads to a transient diffusion which is orders of magnitude faster than the equilibrium diffusion [30]—similar to the behavior demonstrated in two- and three-dimensional perovskites [40–42].

Strain can be used to tailor the dark-bright exciton energy landscape and to control the excess energy of hot dark excitons and thereby the transient exciton PL and exciton diffusion in TMDs. This strain engineering of the ultrafast spatiotemporal exciton dynamics at cryogenic temperatures has remained largely unexplored so far. In this work, we bridge this knowledge gap by performing a material-specific and predictive theoretical study on the impact of tensile and

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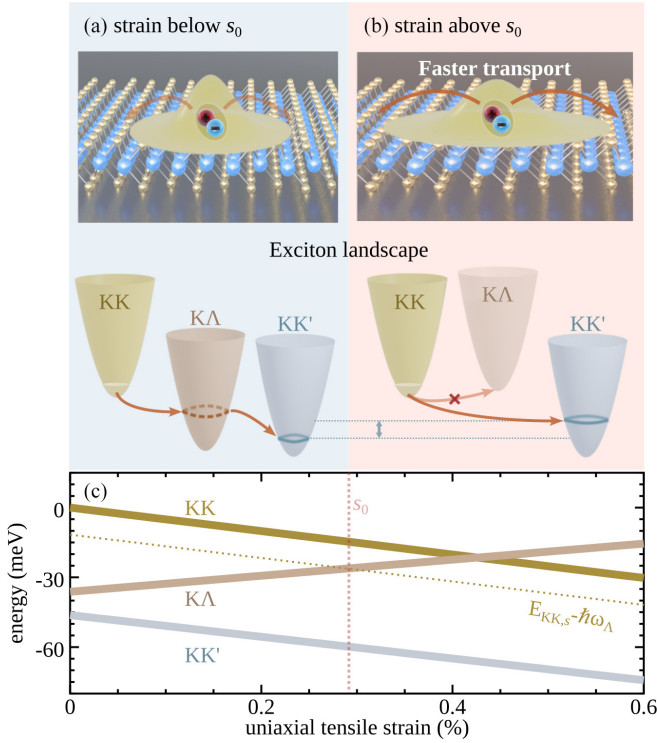


FIG. 1. Strain engineering of the exciton landscape in WSe₂ monolayers. (a), (b) Tensile strain leads to a speedup of exciton transport due to a spectral reordering of KK, KΛ, and KK' excitons. Strain particularly modifies possible scattering channels and exciton thermalization. Strain larger than the critical value $s_0 \approx 0.3\%$ deactivates the phonon-mediated KK-to-KΛ scattering resulting in a direct formation of hot dark KK' states with a large excess energy. (c) The state reordering is a result of opposite strain gauge factors for KK (KK') and KΛ excitons.

compressive strain on the transient PL as well as on the temporal exciton thermalization and the spatial exciton propagation in the exemplary case of strained, hBN-encapsulated WSe₂ monolayers. We show how tensile strain leads to an abrupt increase in the excess energy of hot dark KK' excitons resulting in a speedup of exciton diffusion for strain values larger than the critical strain $s_0 \approx 0.3\%$. This can be traced back to the deactivation of phonon-mediated scattering channels into KΛ excitons. While intervalley scattering with optical phonons is already closed in only weakly strained TMDs due to their large energies in the range of 27–33 meV [39], intervalley scattering with acoustic phonons with energies of about 12–14 meV is energetically not allowed for strain values with $E_{KK,s} - \hbar\omega_\Lambda < E_{K\Lambda,s}$, where $E_{v,s}$ is the minimum energy of excitons in valley v at strain s and $\hbar\omega_\Lambda \equiv \hbar\omega_0^{\text{TA},\Lambda}$ is the energy of the intervalley TA acoustic Λ phonons. As shown in Fig. 1(c), this takes place at $s_0 \approx 0.3\%$ for hBN-encapsulated WSe₂ monolayers, while larger s_0 values are expected for lower dielectric screening due to a generally increased energy separation between KK and KΛ excitons [24,33]. Furthermore, we predict a qualitatively different behavior in the presence of compressive strain that is characterized by a strain-induced periodic modulation of exciton diffusion due to the activation of

M-phonon emission. Overall, our microscopic study sheds light on the impact of tensile and compressive strain on exciton thermalization and transient exciton diffusion in TMD monolayers.

II. THEORETICAL APPROACH

First, we evaluate the strain-dependent exciton energy landscape. Starting from the unstrained single-particle dispersion relation [43] and strain-induced variations of effective masses and band extrema [15], we apply a continuum approach to solve the Wannier equation [44–47] with a nonlocal Coulomb screening [48]. In this way, we obtain a set of excitonic states $|\mathbf{Q}, v; s\rangle = \hat{X}_{v,\mathbf{Q},s}^\dagger |0\rangle$ with the strain-dependent energy $E_{\mathbf{Q},s}^v = E_{v,s} + \hbar^2|\mathbf{Q}|^2/(2M_{v,s})$, where $\mathbf{Q}$ denotes the center-of-mass momentum and $M_{v,s}$ the total exciton mass in valley v at strain s . Here, we have introduced $\hat{X}_{v,\mathbf{Q},s}^\dagger$ as the exciton creation operator. Due to a considerable energetic separation to higher excitonic states and the limited range of considered strain values, we restrict our investigations to the lowest 1s state of the bright KK as well as of momentum-dark KK' and KΛ excitons [49]. Note that other valleys, such as ΓK and $\Gamma\text{K}'$, become only relevant at larger strain values $s \gtrsim 1\%$ [31].

Now, we introduce the excitonic intravalley Wigner function $N_{\mathbf{Q},s}^v(\mathbf{r}, t) = \sum_{\mathbf{Q}'} \langle \hat{X}_{v,\mathbf{Q}+\mathbf{Q}'/2,s}^\dagger \hat{X}_{v,\mathbf{Q}-\mathbf{Q}'/2,s} \rangle_t e^{i\mathbf{Q}'\cdot\mathbf{r}}$ with $\mathbf{r}$ indicating the center-of-mass position while $\langle \hat{X}_{v,\mathbf{Q},s}^\dagger \hat{X}_{v,\mathbf{Q},s} \rangle_t$ is the time-dependent single-exciton density matrix after tracing out the other degrees of freedom [50]. We then numerically determine the evolution of $N_{\mathbf{Q},s}^v(\mathbf{r}, t)$ within the continuum approach. Exploiting the Heisenberg equation, in the low-excitation [51,52] and undoped regime [53–56] the associated spatiotemporal exciton dynamics reads [36,57]

$$\begin{aligned} \dot{N}_{\mathbf{Q},s}^v(\mathbf{r}, t) = & \left(-\frac{\hbar\mathbf{Q}}{M_{v,s}} \cdot \nabla - \gamma\delta_{\mathbf{Q},0}\delta_{v,\text{KK}} \right) N_{\mathbf{Q},s}^v(\mathbf{r}, t) \\ & + \Gamma_{0\mathbf{Q},s}^{\text{KK}v} |p_{0,s}(\mathbf{r}, t)|^2 + \dot{N}_{\mathbf{Q},s}^v(\mathbf{r}, t)|_{\text{sc}}. \end{aligned} \quad (1)$$

The first term indicates the free spatial evolution of excitons, while the second term takes into account the losses due to the radiative recombination of bright excitons $|\text{KK}, 0; s\rangle$ within the lightcone via a strain-independent rate $\gamma_s \approx \gamma$ corresponding to a radiative linewidth of $\hbar\gamma = 2.5$ meV [15]. The second line of Eq. (1) provides the effects induced by exciton-phonon scattering. The first contribution describes the formation of incoherent excitons due to phonon-driven transfer from excitonic polarization $|p_{\mathbf{Q}\approx 0,s}(\mathbf{r}, t)|^2$ (referred to in literature as coherent excitons [46]). This polarization follows the spatiotemporal laser profile, for which we take a Gaussian with a full width at half maximum of 0.2 ps in time and 850 nm in space, as realized in a previous experiment [38]. The last term in Eq. (1) provides the scattering-induced dynamics, which we describe with the conventional Markov approach as a local Boltzmann collision rate $\dot{N}_{\mathbf{Q},s}^v(\mathbf{r}, t)|_{\text{sc}} = \Gamma_{\mathbf{Q},s}^{\text{in},v} N_{\mathbf{Q},s}^v(\mathbf{r}, t) - \Gamma_{\mathbf{Q},s}^{\text{out},v} N_{\mathbf{Q},s}^v(\mathbf{r}, t)$ in the Boltzmann transport equation with $\Gamma_{\mathbf{Q},s}^{\text{in},v}(\mathbf{r}, t) = \sum_{v',\mathbf{Q}'} \Gamma_{\mathbf{Q}'\mathbf{Q},s}^{v'v} N_{\mathbf{Q}',s}^{v'}(\mathbf{r}, t)$ as well as $\Gamma_{\mathbf{Q},s}^{\text{out},v} = \sum_{v',\mathbf{Q}'} \Gamma_{\mathbf{Q}\mathbf{Q}',s}^{vv'}$. Both terms depend on the exciton scattering coefficients $\Gamma_{\mathbf{Q}\mathbf{Q}',s}^{vv'} = \frac{2\pi}{\hbar} \sum_{\alpha,\pm} |G_{\alpha\mathbf{Q}'-\mathbf{Q},s}^{v'v}|^2 \eta_{\alpha\mathbf{Q}'-\mathbf{Q}}^\pm \delta(E_{\mathbf{Q}',s}^{v'} - E_{\mathbf{Q},s}^v \pm \hbar\omega_{\mathbf{Q}'-\mathbf{Q},s}^\alpha)$, which

describe the scattering from exciton $|v, \mathbf{Q}; s\rangle$ to $|v', \mathbf{Q}'; s\rangle$ via interaction with phonon modes α with the energy $\hbar\omega_{\mathbf{Q}-\mathbf{Q}}^\alpha$ (neglecting the weak variation of phonon energy with strain [15,58]). Here, $G_{\alpha\mathbf{Q},s}^{vv'}$ are the coefficients of the exciton-phonon Hamiltonian, derived from the analogous electron-phonon coefficients [39] through the excitonic form factors [47], while $\eta_{\alpha\mathbf{Q}}^\pm = (\frac{1}{2} \pm \frac{1}{2} + n_{\alpha\mathbf{Q}})$ are the factors for the emission (+) and absorption (−) of phonons with the Bose-Einstein occupation $n_{\alpha\mathbf{Q}}$. Exciton-phonon scattering crucially depends on strain, mostly via the modification of energies of the involved initial and final exciton states [14,15,58,59]. In particular, strain-induced energy shifts can open or close specific intervalley scattering channels, which strongly affects the formation of hot excitons and their excess energy [see Figs. 1(a) and 1(b)].

The resulting spatiotemporal dynamics can be experimentally accessed via space-, time-, and energy-resolved photoluminescence $I_s(E, \mathbf{r}, t)$. Extending the generalized Elliott formula introduced in Ref. [60] and adapted for time-resolved PL in Ref. [37], this can be described as

$$I_s(E, \mathbf{r}, t) = \frac{2|M|^2[I_{d,s}(\mathbf{r}, t) + I_{\text{ind},s}(E, \mathbf{r}, t)]}{(E_{\text{KK},s} - E)^2 + \hbar^2(\gamma + \Gamma_{0,s}^{\text{out},\text{KK}})^2} \quad (2)$$

including the direct $I_{d,s}(\mathbf{r}, t) = \gamma N_{0,s}^{\text{KK}}(\mathbf{r}, t)$ and the phonon-assisted indirect contribution to the emission $I_{\text{ind},s}(E, \mathbf{r}, t) = \sum_{\mathbf{Q}, v, \alpha, \pm} |G_{\alpha\mathbf{Q},s}^{v\text{KK}}|^2 \eta_{\alpha\mathbf{Q}}^\pm N_{\mathbf{Q},s}^v(\mathbf{r}, t) \frac{2\Gamma_{\mathbf{Q},s}^{\text{out},v}}{4(E_{\mathbf{Q},s}^v \mp \hbar\omega_{\mathbf{Q}}^\alpha - E)^2 + (\hbar\Gamma_{\mathbf{Q},s}^{\text{out},v})^2}$. The coefficient $|M|^2$ is the squared modulus of the exciton-photon matrix element in the lightcone [60] and it directly relates to the radiative rate γ [41]. The spatiotemporal dynamics of Eq. (1) allows us to track excitonic diffusion, which induces a spatial broadening of the squared width of the PL profile $\sigma_s^2(t) = \iint \mathbf{r}^2 I_s(E, \mathbf{r}, t) d\mathbf{r} dE / 2 \iint I_s(E, \mathbf{r}, t) d\mathbf{r} dE$. At equilibrium, this evolves linearly in time, while in the transient nonequilibrium regime, the effective diffusion coefficient is given by $D_s(t) = \frac{1}{2} \partial_t \sigma_s^2(t)$ [see Sec. 1 in the Supplemental Material (SM) [61] for more details]. While Eq. (2) describes the local photoluminescence as a well-established technique for measuring spatiotemporal exciton dynamics [22,30,51,62,63], the more general Eq. (1) can be adapted to other experimental approaches, such as local pump-probe [24,64,65], raster scanning [66–68], transient gratings [69,70], and space- and time-resolved angle-resolved photoemission spectroscopy [71–78].

III. RESULTS

A. Strain engineering of transient exciton optics

The direct radiative recombination of bright excitons gives rise to a peak in the PL spectrum at the energy $E_{\text{KK},s}$. The phonon-assisted recombination of dark excitons dominates the PL at low temperatures, although the efficiency of this process is orders of magnitude smaller. This is compensated for by the much higher occupation of the energetically lowest dark states at cryogenic temperatures. The resulting phonon sidebands appear energetically below $E_{\text{KK},s}$ and allow to track dark excitons. In unstrained hBN-encapsulated WSe₂ monolayers, phonon sidebands have been demonstrated to

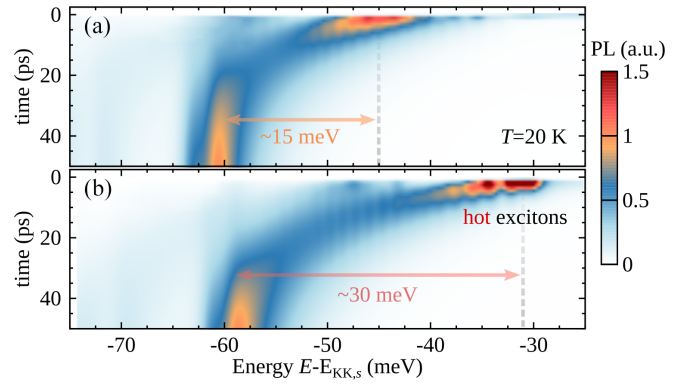


FIG. 2. Strain tuning of exciton thermalization. Time- and energy-resolved photoluminescence of hBN-encapsulated WSe₂ at $T = 20$ K under an external uniaxial tensile strain of (a) $s = 0.15\% < s_0$ and (b) $s = 0.5\% > s_0$, with $s_0 \approx 0.3\%$ being the critical strain value [see Fig. 1(c)]. An initial high-energy signal redshifts toward the equilibrium emission within a few tens of picoseconds. This is a hallmark of the thermalization of hot dark excitons [Figs. 1(a) and 1(b)]. The energy separation between the initial and the equilibrium resonance increases abruptly from 15 to almost 30 meV at the critical strain value of s_0 reflecting the suppression of the scattering channel from KK to K Λ excitons [Fig. 1(b)].

provide direct optical access to the thermalization of nonequilibrium hot dark excitons [38]. In a recent study, it was shown that strain can be used to fingerprint the dark exciton landscape via the emergence of their phonon sidebands [33,34,79]. However, the interplay of strain and nonequilibrium exciton dynamics has remained unexplored so far.

In Fig. 2, we show the energy- and time-resolved emission of a hBN-encapsulated WSe₂ monolayer at $T = 20$ K under an external uniaxial tensile strain of $s = 0.15\%$ and 0.5% , respectively. In both cases, an initially higher emission energy gradually redshifts on a timescale of a few tens of picoseconds. The final equilibrium resonance lies approximately 60 meV below $E_{\text{KK},s}$ [37,60]. Similarly to the case of unstrained WSe₂ [37], such a redshift indicates the initial formation of hot dark excitons and their subsequent thermalization to their equilibrium distribution. Following an optical excitation of bright excitons, hot dark excitons in the KK' valley are generated on a subpicosecond timescale via emission of intervalley phonons [see Figs. 1(a) and 1(b)]. The energy separation between bright and dark excitons does not match the energy of the involved phonons resulting in the formation of *hot* dark excitons with an excess energy with respect to band minimum at $E_{\text{KK},s}$. The excess energy is smaller than the energy of intravalley optical phonons, whose emission is hence energetically forbidden. As a consequence, hot dark excitons lose their energy by scattering with intravalley acoustic phonons. Since the latter carry only a small amount of energy, this relaxation requires multiple scattering events resulting in a gradual loss of excess energy within a few tens of picoseconds. This is directly visible in the calculated time-resolved PL spectra via a temporal redshift of the excitonic resonance (see Fig. 2), in agreement with a recent joint theory-experiment study on unstrained WSe₂ monolayers [37].

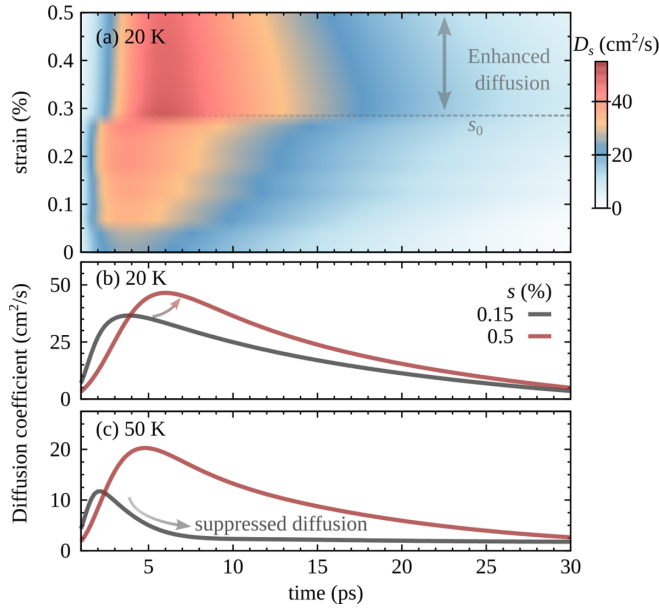


FIG. 3. Strain engineering of exciton propagation. (a) Time-resolved transient exciton diffusion coefficient of hBN-encapsulated WSe₂ as a function of tensile strain at 20 K. We find an abrupt enhancement above the critical strain value of $s_0 \approx 0.3\%$. (b), (c) Cuts at two specific strain values below and above s_0 at 20 and 50 K, respectively. Interestingly, at the larger temperature, the duration of the enhanced transient diffusion is considerably shortened to only a few picoseconds for strain values smaller than s_0 . This is due to the thermal activation of phonon absorption inducing the KK'-to-K Λ backscattering.

In unstrained TMDs and for strain values up to $s_0 \approx 0.3\%$, the optically excited bright excitons first form hot K Λ excitons before they scatter into the energetically lowest KK' states [see Fig. 1(a)]. Above the critical strain value s_0 , the relative separation between bright and dark excitons changes such that the KK-to-K Λ scattering channel is turned off [see Fig. 1(b)]. A direct consequence is that optically excited KK excitons can only scatter directly into KK' excitons forming hot dark excitons with a much larger excess energy. Therefore, we find an abrupt increase in the energy of the initial PL signature in Fig. 2(b). In Fig. S1 of the SM [61], we show more strain values in the range below and above s_0 . When energetically allowed, the scattering process from KK into KK' through K Λ is faster than the direct scattering from KK to KK'. This occurs mostly due to the threefold degeneracy of K Λ states together with the very efficient scattering between K Λ and KK' excitons via M phonons [31,39]. However, strain closes this fast channel by inducing a blueshift of K Λ excitons [Fig. 1(c)].

B. Strain engineering of ultrafast exciton diffusion

Since hot excitons exhibit larger group velocities, they typically give rise to a faster transient diffusion than at equilibrium [38,41,42]. As strain can be used to control the excess energy of excitons (Fig. 2), strain engineering of exciton diffusion is possible. Figure 3 shows the time-resolved effective exciton diffusion coefficient $D_s(t)$ at $T = 20$ K for different

values of strain. We find that the maximum effective diffusion coefficient abruptly increases from approximately 35 to about 45 cm²/s above the critical strain value $s_0 \approx 0.3\%$. This maximum diffusion appears shortly after the optical excitation, before gradually decreasing as excitons thermalize via quasielastic scattering with acoustic phonons. The diffusion coefficient decreases on a timescale of a few tens of picoseconds [Fig. 3(b)], reflecting the gradual reduction of the excess energy shown in Fig. 2.

The connection between the transient diffusion and the exciton excess energy can be understood from a generalized Fick's law [41], which neglecting the occupation of the high-energy valleys results in $D_s(t) \approx \frac{\tau_s}{M} \langle E_s \rangle_t$ with the scattering time $\tau_s = 1/\Gamma_{0,s}^{\text{out},\text{KK}'}$, exciton mass $M \equiv M_{\text{KK}',s}$, and the averaged exciton energy $\langle E_s \rangle_t$. This relation follows under the assumption of a weak spatial inhomogeneity of $N_{\text{Q},s}^{\text{KK}'}(\mathbf{r}, t)$. This implies timescales larger than τ_s , where first scattering even takes place and randomizes the momentum distribution [80,81]. Furthermore, in the simplified equation we neglect effects stemming from an intervalley bottleneck or backscattering [80] and assume a negligible momentum dependence of the scattering rate $\Gamma_{\text{Q},s}^{\text{out},\text{KK}'} \approx \Gamma_{0,s}^{\text{out},\text{KK}'}$ [41]. The averaged exciton energy depends on the spatiotemporal exciton occupation via $\langle E_s \rangle_t = \int d\mathbf{r} \sum_{\text{Q}} E_{\text{Q},s}^{\text{KK}'} N_{\text{Q},s}^{\text{KK}'}(\mathbf{r}, t) / \int d\mathbf{r} \sum_{\text{Q}} N_{\text{Q},s}^{\text{KK}'}(\mathbf{r}, t)$. For times t larger than the thermalization time t_{th} , excitons equilibrate in a local Boltzmann distribution with $\langle E_s \rangle_{t_{\text{th}}} = k_B T$, leading to the well-known conventional diffusion coefficient $D_s = \tau_s k_B T / M$ [41]. In contrast, before thermalization, the averaged energy $\langle E_s \rangle_t$ is determined by the excitonic excess energy. This is approximately one order of magnitude larger than the thermal energy at 20 K, leading to considerably faster transient exciton diffusion. The abrupt increase of the excess energy for tensile strain values above s_0 (Fig. 2) is reflected by an abrupt enhancement of the maximum diffusion above this critical strain value [see Fig. 3(a)]. Interestingly, the opposite trend is found during the first 2–3 ps, when diffusion becomes slower at larger strain values [see Fig. 3(b)]. This can be traced back to the suppressed scattering into K Λ excitons, thereby slowing down the formation of KK' excitons, i.e. the direct KK-to-KK' scattering process is slightly slower, hence requiring more time until highly mobile hot KK' excitons become crucial. Note that there is also an enhancement in diffusion for strain values above $s \approx 0.05\%$ due to the suppression of a phonon bottleneck between KK' and K Λ excitons [37] (see Fig. S1 in the SM [61] for more details).

Higher temperatures slow down the transient exciton diffusion due to the increased efficiency of exciton-phonon scattering. Surprisingly, we find that this occurs in a highly asymmetric way for strain values larger and smaller than s_0 . For $s = 0.5\% > s_0$, the evolution of $D_s(t)$ is qualitatively similar at 20 and 50 K [see the red lines in Figs. 3(b) and 3(c)]. The two results differ only by the expected quantitative reduction of the maximum diffusion by a factor of approximately 2.5. This originates from the linear increase of the exciton-phonon scattering rates with temperature, which at large strain are dominated by the interaction with acoustic Γ phonons. For the smaller strain $s = 0.15\% < s_0$, at 50 K the transient diffusion is strongly suppressed already after

5 ps—contrary to the case at 20 K [see the gray lines in Figs. 3(b) and 3(c) as well as the surface plot in Fig. S2 of the SM [61]]. This results from the thermal activation of the intervalley scattering from hot KK' into KA states via absorption of acoustic M phonons. These modes have low energies (15–16 meV [39]) and strongly couple the KK' and KA excitons. Their thermal activation, already significant at 50 K, rapidly transfers hot KK' excitons back to the KA states, suppressing the transient diffusion. Note that the same mechanism also governs the strain dependence of the equilibrium diffusion at room temperature [31]. For larger strain values with $s > 0.4$ – 0.5% , no thermal activation of M phonons is possible and the enhanced transient diffusion is preserved for a longer time, since here KA excitons are shifted too far away from KK' states [Fig. 1(c)]. In the intermediate range of strain values $s_0 \lesssim s \lesssim 0.4$ – 0.5% , the scattering from KK to KA is energetically suppressed, while hot KK' excitons can still scatter into KA states. Together with the larger thermal broadening of transient distributions, this leads to a variation of the transient diffusion with strain that is less abrupt at $T = 50$ K than at 20 K. In particular, the maximum diffusion smoothly increases from 10 to 20 cm^2/s for strain values going from s_0 to 0.4 – 0.5% (see Sec. 1 of the SM [61] for more details).

C. Periodic strain modulation of exciton diffusion

In conventional semiconductors, the excess energy of photoexcited electrons can be tuned simply by changing the excitation energy. When the excess energy exceeds the optical-phonon energy $\hbar\omega_{\text{op}}$, successive phonon-induced scattering reduces the energy by multiples of $\hbar\omega_{\text{op}}$ [82,83]. In contrast, in TMD monolayers the exciton oscillator strength is strongly centered at the bright-exciton energy, which cannot be tuned by laser energy. As a result, exciton excess energy is largely insensitive to excitation energies close to resonance. Here, we show how compressive strain allows a continuous tuning of exciton excess energy—in analogy to the effect of laser excitation energy on electrons.

Recently, compressive strain has been experimentally realized using piezoelectric support [84,85] or thermal expansion of the substrate [86,87]. The key qualitative difference between tensile and compressive strain is that the lowest state changes from KK' to KA for uniaxial strain smaller than $s_{\text{cr}} \approx -0.1\%$. This change has two important consequences: First, KA excitons are threefold degenerate, contrary to KK' states. This opens up new scattering channels for hot excitons. While hot KK' excitons can only interact with intravalley Γ phonons, hot KA excitons can also interact with M phonons and scatter between degenerate KA valleys [see Fig. 4(a)]. Second, in contrast to only a small change in the energy separation between bright KK and dark KK' excitons with tensile strain [88] [see quasiparallel strain-dependent lines for KK and KK' excitons in Fig. 1(c)], compressive strain induces a large variation of bright-dark energy separation. This is comparable to the variation of the energy separation $E_{K\Lambda,s} - E_{KK',s}$ between the two energetically lowest valleys, which decreases with compressing strain with a gauge factor $d_{\Lambda-K'} \approx 80 \text{ meV}/\%$ [see Fig. 4(b)]. This is due to the opposite strain-induced energy shift of KK and KA excitons [see Fig. 1(c)]. These

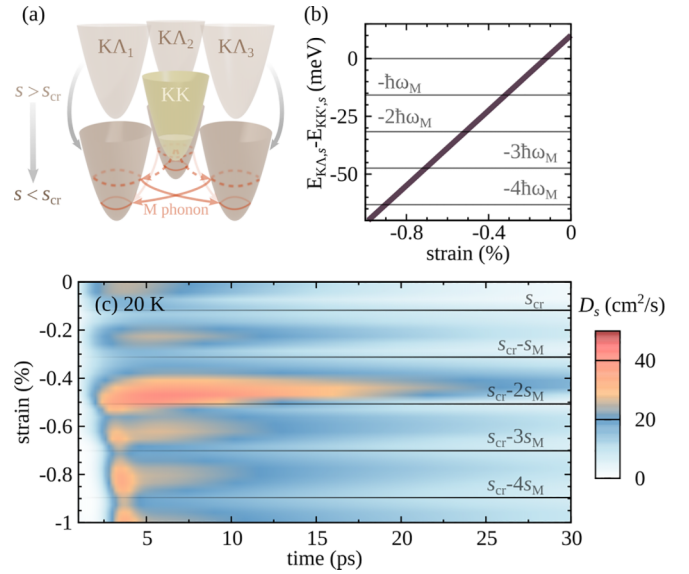


FIG. 4. Strain-induced periodic modulation of exciton diffusion. (a) Activation of KA excitons in the presence of compressive strain. Here, hot dark excitons scatter between the three degenerate KA valleys by emitting acoustic M phonons with the energy $\hbar\omega_M$. (b) For strain values smaller than $s_{\text{cr}} \approx -0.1\%$, KA excitons become energetically lower than KK' excitons. The large strain gauge factor of $E_{K\Lambda,s} - E_{KK',s}$ allows emission of acoustic M phonons with a multiple of $\hbar\omega_M$ (horizontal lines), which corresponds to a strain periodicity of $s_M \approx 0.2\%$. (c) The resulting periodic strain modulation of the transient exciton diffusion.

two qualitative changes lead to drastically different transient exciton diffusion with compressive and tensile strain.

At the critical strain value $s_{\text{cr}} \approx -0.1\%$, KA and KK' excitons are quasidegenerate [Fig. 4(b)], leading to a small transient diffusion due to the enhanced intervalley scattering, similar to the case of equilibrium diffusion at high temperatures [31]. Here, hot KK' excitons are formed with an excess energy of approximately 15 meV [Fig. 2(a)], which is in the range of the energy of M acoustic phonons [39], and hence hot KK' excitons can relax into KA states by emitting an M phonon. This leads to a suppressed diffusion for $s \approx s_{\text{cr}}$. A tuning of compressive strain beyond this critical value induces a periodic change of fast and slow exciton diffusion [see Fig. 4(c)]. This indicates a cyclic variation of exciton excess energy. The initial excess energy corresponds to the energy separation between the two lowest dark excitons, hence it increases with compressive strain with the gauge factor $d_{\Lambda-K'}$. Once a certain excess energy is reached, emission of intervalley M phonons drives the system back to the initial excess energy. At first approximation, this process is quantized in multiples of the average acoustic phonon energy $\hbar\omega_M \equiv 0.5\hbar(\omega_0^{\text{M,TA}} + \omega_0^{\text{M,LA}}) = 15.8 \text{ meV}$, because exciton scattering scales with one over the phonon energy and acoustic M phonons possess the smallest energy. The horizontal lines in Fig. 4(b) indicate when the energy separation between the two dark valleys is large enough to activate the emission of M phonons. This takes place with a strain periodicity $s_M = \hbar\omega_M/d_{\Lambda-K'} \approx 0.2\%$. Interestingly, the same periodicity appears in the strain- and time-dependent exciton diffusion

in Fig. 4(c). First, increased compressive strain induces a higher excess energy of hot dark excitons resulting in a larger exciton diffusion. Whenever the condition is reached for the emission of M phonons inducing scattering between the three K Λ valleys, the diffusion is significantly reduced. This results in a phonon-induced periodic modulation of exciton diffusion. Note that there is a deviation from this expected periodicity at higher compressive strain values, which can be ascribed to the small contribution of other phonon modes and exciton valleys, in particular other M phonons and KK' excitons. For large compressive strain $s \lesssim s_{\text{cr}} - 2s_{\text{M}}$ there is even a competition between two- and one-phonon processes.

IV. CONCLUSIONS

Based on a microscopic, material-specific and predictive approach, we study the possibility of strain engineering of exciton emission and diffusion in hBN-encapsulated WSe₂ monolayers at cryogenic temperatures. We predict an abrupt increase of the excess energy of hot dark KK' excitons above the critical strain of $s_0 \approx 0.3\%$. This is explained by the deactivation of the phonon-mediated scattering to K Λ excitons, which considerably slows down exciton thermalization and increases the energy of transient phonon sidebands that can be monitored in time-resolved photoluminescence spectra. Furthermore, we show that the maximum exciton

diffusion coefficient increases abruptly from about 35 to about 45 cm²/s above the critical strain s_0 , which is one order of magnitude faster than equilibrium diffusion. The enhanced transient diffusion reflects the suppressed phonon-mediated scattering from bright to dark K Λ excitons. Finally, we predict a qualitatively different diffusion behavior in the presence of compressive strain that is characterized by a periodic strain modulation. This can be traced back to an interplay of a strain-induced increase in the excess energy of hot dark excitons and its abrupt release via emission of M phonons. Overall, our work provides microscopic insights into strain engineering of exciton emission and propagation in strained two-dimensional semiconductors.

ACKNOWLEDGMENTS

We acknowledge financial support by the Deutsche Forschungsgemeinschaft via Project No. 512604469. We thank A. Chernikov for discussions.

DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

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- [1] E. Malic, R. Perea-Causin, R. Rosati, D. Erkensten, and S. Brem, Exciton transport in atomically thin semiconductors, *Nat. Commun.* **14**, 3430 (2023).
 - [2] D. Unuchek, A. Ciarrocchi, A. Avsar, K. Watanabe, T. Taniguchi, and A. Kis, Room-temperature electrical control of exciton flux in a van der Waals heterostructure, *Nature (London)* **560**, 340 (2018).
 - [3] A. Ciarrocchi, D. Unuchek, A. Avsar, K. Watanabe, T. Taniguchi, and A. Kis, Polarization switching and electrical control of interlayer excitons in two-dimensional van der Waals heterostructures, *Nat. Photonics* **13**, 131 (2019).
 - [4] N. Leisgang, S. Shree, I. Paradisanos, L. Sponfeldner, C. Robert, D. Lagarde, A. Balocchi, K. Watanabe, T. Taniguchi, X. Marie, R. J. Warburton, I. C. Gerber, and B. Urbaszek, Giant Stark splitting of an exciton in bilayer MoS₂, *Nat. Nanotechnol.* **15**, 901 (2020).
 - [5] K. W. Lau, Calvin, Z. Gong, H. Yu, and W. Yao, Interface excitons at lateral heterojunctions in monolayer semiconductors, *Phys. Rev. B* **98**, 115427 (2018).
 - [6] R. Rosati, I. Paradisanos, L. Huang, Z. Gan, A. George, K. Watanabe, T. Taniguchi, L. Lombez, P. Renucci, A. Turchanin, B. Urbaszek, and E. Malic, Interface engineering of charge-transfer excitons in 2D lateral heterostructures, *Nat. Commun.* **14**, 2438 (2023).
 - [7] E. Vandoolaeghe, F. Fortuna, S. K. Chakraborty, B. Nayak, T. Taniguchi, K. Watanabe, P. K. Sahoo, T. Chervy, and P. A. Murthy, Dipolar excitonic quantum wires at atomically sharp lateral interfaces, *Nano Lett.* (2026), doi:10.1021/acs.nanolett.6c02624.
 - [8] K. Sonowal, D. Erkensten, E. Malic, and R. Rosati, Coulomb-mediated interactions of charge-transfer excitons in TMD lateral heterostructures, *Phys. Rev. B* **114**, L171407 (2026).
 - [9] R. Kitaura, Electrically switchable one-dimensional quadrupolar excitons in lateral double heterojunctions, *arXiv:2609.32392*.
 - [10] A. Castellanos-Gomez, R. Roldán, E. Cappelluti, M. Buscema, F. Guinea, H. S. J. van der Zant, and G. A. Steele, Local strain engineering in atomically thin MoS₂, *Nano Lett.* **13**, 5361 (2013).
 - [11] H. J. Conley, B. Wang, J. I. Ziegler, R. F. Haglund, Jr., S. T. Pantelides, and K. I. Bolotin, Bandgap engineering of strained monolayer and bilayer MoS₂, *Nano Lett.* **13**, 3626 (2013).
 - [12] C. R. Zhu, G. Wang, B. L. Liu, X. Marie, X. F. Qiao, X. Zhang, X. X. Wu, H. Fan, P. H. Tan, T. Amand, and B. Urbaszek, Strain tuning of optical emission energy and polarization in monolayer and bilayer MoS₂, *Phys. Rev. B* **88**, 121301(R) (2013).
 - [13] M. Ghorbani-Asl, S. Borini, A. Kuc, and T. Heine, Strain-dependent modulation of conductivity in single-layer transition-metal dichalcogenides, *Phys. Rev. B* **87**, 235434 (2013).
 - [14] I. Niehues, R. Schmidt, M. Drüppel, P. Marauhn, D. Christiansen, M. Selig, G. Berghäuser, D. Wigger, R. Schneider, L. Braasch, R. Koch, A. Castellanos-Gomez, T. Kuhn, A. Knorr, E. Malic, M. Rohlfing, S. Michaelis de Vasconcellos, and R. Bratschkitsch, Strain control of exciton-phonon coupling in atomically thin semiconductors, *Nano Lett.* **18**, 1751 (2018).
 - [15] Z. Khatibi, M. Feierabend, M. Selig, S. Brem, C. Linderälv, P. Erhart, and E. Malic, Impact of strain on the excitonic linewidth in transition metal dichalcogenides, *2D Mater.* **6**, 015015 (2019).

- [16] R. Schmidt, I. Niehues, R. Schneider, M. Drüppel, T. Deilmann, M. Rohlfing, S. M. de Vasconcellos, A. Castellanos-Gomez, and R. Bratschitsch, Reversible uniaxial strain tuning in atomically thin WSe₂, *2D Mater.* **3**, 021011 (2016).
- [17] T. Deilmann and K. S. Thygesen, Finite-momentum exciton landscape in mono- and bilayer transition metal dichalcogenides, *2D Mater.* **6**, 035003 (2019).
- [18] E. Blundo, M. Felici, T. Yildirim, G. Pettinari, D. Tedeschi, A. Miriametro, B. Liu, W. Ma, Y. Lu, and A. Polimeni, Evidence of the direct-to-indirect band gap transition in strained two-dimensional WS₂, MoS₂, and WSe₂, *Phys. Rev. Res.* **2**, 012024(R) (2020).
- [19] L. L. Li, R. Gillen, M. Palummo, M. V. Milošević, and F. M. Peeters, Strain tunable interlayer and intralayer excitons in vertically stacked MoSe₂/WSe₂ heterobilayers, *Appl. Phys. Lett.* **123**, 033102 (2023).
- [20] P. E. Faria Junior and J. Fabian, Signatures of electric field and layer separation effects on the spin-valley physics of MoSe₂/WSe₂ heterobilayers: From energy bands to dipolar excitons, *Nanomaterials* **13**, 1187 (2023).
- [21] D. F. C. Leon, Z. Li, S. W. Jang, C.-H. Cheng, and P. B. Deotare, Exciton transport in strained monolayer WSe₂, *Appl. Phys. Lett.* **113**, 252101 (2018).
- [22] H. Moon, G. Grosso, C. Chakraborty, C. Peng, T. Taniguchi, K. Watanabe, and D. Englund, Dynamic exciton funneling by local strain control in a monolayer semiconductor, *Nano Lett.* **20**, 6791 (2020).
- [23] M. G. Harats, J. N. Kirchhof, M. Qiao, K. Greben, and K. I. Bolotin, Dynamics and efficient conversion of excitons to trions in non-uniformly strained monolayer WS₂, *Nat. Photonics* **14**, 324 (2020).
- [24] H. Su, D. Xu, S.-W. Cheng, B. Li, S. Liu, K. Watanabe, T. Taniguchi, T. C. Berkelbach, J. C. Hone, and M. Delor, Dark-exciton driven energy funneling into dielectric inhomogeneities in two-dimensional semiconductors, *Nano Lett.* **22**, 2843 (2022).
- [25] R. J. Gelly, D. Renaud, X. Liao, B. Pingault, S. Bogdanovic, G. Scuri, K. Watanabe, T. Taniguchi, B. Urbaszek, H. Park, and M. Lončar, Probing dark exciton navigation through a local strain landscape in a WSe₂ monolayer, *Nat. Commun.* **13**, 232 (2022).
- [26] H. Lee, Y. Koo, J. Choi, S. Kumar, H.-T. Lee, G. Ji, S. H. Choi, M. Kang, K. K. Kim, H.-R. Park, H. Choo, and K.-D. Park, Drift-dominant exciton funneling and trion conversion in 2D semiconductors on the nanogap, *Sci. Adv.* **8**, eabm5236 (2022).
- [27] A. Branny, S. Kumar, R. Proux, and B. D. Gerardot, Deterministic strain-induced arrays of quantum emitters in a two-dimensional semiconductor, *Nat. Commun.* **8**, 15053 (2017).
- [28] C. Palacios-Berraquero, D. M. Kara, A. R.-P. Montblanch, M. Barbone, P. Latawiec, D. Yoon, A. K. Ott, M. Loncar, A. C. Ferrari, and M. Atatüre, Large-scale quantum-emitter arrays in atomically thin semiconductors, *Nat. Commun.* **8**, 15093 (2017).
- [29] J. Kern, I. Niehues, P. Tonndorf, R. Schmidt, D. Wigger, R. Schneider, T. Stiehm, S. Michaelis de Vasconcellos, D. E. Reiter, T. Kuhn, and R. Bratschitsch, Nanoscale positioning of single-photon emitters in atomically thin WSe₂, *Adv. Mater.* **28**, 7101 (2016).
- [30] R. Rosati, R. Schmidt, S. Brem, R. Perea-Causín, I. Niehues, J. Kern, J. A. Preuß, R. Schneider, S. Michaelis de Vasconcellos, R. Bratschitsch, and E. Malic, Dark exciton anti-funneling in atomically thin semiconductors, *Nat. Commun.* **12**, 7221 (2021).
- [31] R. Rosati, S. Brem, R. Perea-Causín, R. Schmidt, I. Niehues, S. Michaelis de Vasconcellos, R. Bratschitsch, and E. Malic, Strain-dependent exciton diffusion in transition metal dichalcogenides, *2D Mater.* **8**, 015030 (2021).
- [32] S. Z. Uddin, N. Higashitarumizu, H. Kim, J. Yi, X. Zhang, D. Chrzan, and A. Javey, Enhanced neutral exciton diffusion in monolayer WS₂ by exciton–exciton annihilation, *ACS Nano* **16**, 8005 (2022).
- [33] A. M. Kumar, D. Yagodkin, R. Rosati, D. J. Bock, C. Schattauer, S. Tobisch, J. Hagel, B. Höfer, J. N. Kirchhof, P. H. López, K. Burfeindt, S. Heeg, C. Gahl, F. Libisch, E. Malic, and K. I. Bolotin, Strain fingerprinting of exciton valley character in 2D semiconductors, *Nat. Commun.* **15**, 7546 (2024).
- [34] A. M. Kumar, D. J. Bock, D. Yagodkin, E. Wietek, B. Höfer, M. Sinner, A. Dewambreches, P. H. López, S. Kovalchuk, R. Dhirga, S. Heeg, C. Gahl, F. Libisch, A. Chernikov, E. Malic, R. Rosati, and K. I. Bolotin, Strain control of valley polarization dynamics in a 2D semiconductor via exciton hybridization, *Nano Lett.* **25**, 15164 (2025).
- [35] E. Blundo, P. E. F. Junior, A. Surrente, G. Pettinari, M. A. Prosnikov, K. Olkowska-Pucko, K. Zollner, T. Woźniak, A. Chaves, T. Kazimierczuk, M. Felici, A. Babiński, M. R. Molas, P. C. M. Christianen, J. Fabian, and A. Polimeni, Strain-induced exciton hybridization in WS₂ monolayers unveiled by Zeeman-splitting measurements, *Phys. Rev. Lett.* **129**, 067402 (2022).
- [36] R. Rosati, R. Perea-Causín, S. Brem, and E. Malic, Negative effective excitonic diffusion in monolayer transition metal dichalcogenides, *Nanoscale* **12**, 356 (2020).
- [37] R. Rosati, K. Wagner, S. Brem, R. Perea-Causín, E. Wietek, J. Zipfel, J. D. Ziegler, M. Selig, T. Taniguchi, K. Watanabe, A. Knorr, A. Chernikov, and E. Malic, Temporal evolution of low-temperature phonon sidebands in transition metal dichalcogenides, *ACS Photonics* **7**, 2756 (2020).
- [38] R. Rosati, K. Wagner, S. Brem, R. Perea-Causín, J. D. Ziegler, J. Zipfel, T. Taniguchi, K. Watanabe, A. Chernikov, and E. Malic, Non-equilibrium diffusion of dark excitons in atomically thin semiconductors, *Nanoscale* **13**, 19966 (2021).
- [39] Z. Jin, X. Li, J. T. Mullen, and K. W. Kim, Intrinsic transport properties of electrons and holes in monolayer transition-metal dichalcogenides, *Phys. Rev. B* **90**, 045422 (2014).
- [40] J. D. Ziegler, J. Zipfel, B. Meisinger, M. Menahem, X. Zhu, T. Taniguchi, K. Watanabe, O. Yaffe, D. A. Egger, and A. Chernikov, Fast and anomalous exciton diffusion in two-dimensional hybrid perovskites, *Nano Lett.* **20**, 6674 (2020).
- [41] R. Rosati, J. K. König, S. Terres, J. J. P. Thompson, M. Baranowski, P. Płochocka, A. Chernikov, and E. Malic, Microscopic insights into magneto-optics and magneto-transport in 2D perovskites, *Nano Lett.* **26**, 5468 (2026).
- [42] S. Saris, R. Rosati, V. Bruevich, T. J. Sheehan, M. Roman, V. Podzorov, E. Malic, and W. A. Tisdale, Nonequilibrium transport in epitaxial CsPbBr₃ single crystals, *arXiv:2606.02460*.
- [43] A. Kormányos, G. Burkard, M. Gmitra, J. Fabian, V. Zólyomi, N. D. Drummond, and V. Fal'ko, *k*·*p* theory for two-dimensional transition metal dichalcogenide semiconductors, *2D Mater.* **2**, 022001 (2015).

- [44] H. Haug and S. W. Koch, *Quantum Theory of the Optical and Electronic Properties of Semiconductors*, 5th ed. (World Scientific, Singapore, 2009).
- [45] M. Selig, G. Berghäuser, A. Raja, P. Nagler, C. Schüller, T. F. Heinz, T. Korn, A. Chernikov, E. Malic, and A. Knorr, Excitonic linewidth and coherence lifetime in monolayer transition metal dichalcogenides, *Nat. Commun.* **7**, 13279 (2016).
- [46] M. Selig, G. Berghäuser, M. Richter, R. Bratschitsch, A. Knorr, and E. Malic, Dark and bright exciton formation, thermalization, and photoluminescence in monolayer transition metal dichalcogenides, *2D Mater.* **5**, 035017 (2018).
- [47] S. Brem, M. Selig, G. Berghäuser, and E. Malic, Exciton relaxation cascade in two-dimensional transition metal dichalcogenides, *Sci. Rep.* **8**, 8238 (2018).
- [48] S. Brem, J. Zipfel, M. Selig, A. Raja, L. Waldecker, J. D. Ziegler, T. Taniguchi, K. Watanabe, A. Chernikov, and E. Malic, Intrinsic lifetime of higher excitonic states in tungsten diselenide monolayers, *Nanoscale* **11**, 12381 (2019).
- [49] E. Malic, M. Selig, M. Feierabend, S. Brem, D. Christiansen, F. Wendler, A. Knorr, and G. Berghäuser, Dark excitons in transition metal dichalcogenides, *Phys. Rev. Mater.* **2**, 014002 (2018).
- [50] R. Rosati, R. C. Iotti, F. Dolcini, and F. Rossi, Derivation of nonlinear single-particle equations via many-body Lindblad superoperators: A density-matrix approach, *Phys. Rev. B* **90**, 125140 (2014).
- [51] M. Kulig, J. Zipfel, P. Nagler, S. Blanter, C. Schüller, T. Korn, N. Paradiso, M. M. Glazov, and A. Chernikov, Exciton diffusion and halo effects in monolayer semiconductors, *Phys. Rev. Lett.* **120**, 207401 (2018).
- [52] R. Perea-Causín, S. Brem, R. Rosati, R. Jago, M. Kulig, J. D. Ziegler, J. Zipfel, A. Chernikov, and E. Malic, Exciton propagation and halo formation in two-dimensional materials, *Nano Lett.* **19**, 7317 (2019).
- [53] F. Gao, Y. Gong, M. Titze, R. Almeida, P. M. Ajayan, and H. Li, Valley trion dynamics in monolayer MoSe₂, *Phys. Rev. B* **94**, 245413 (2016).
- [54] T. Kato and T. Kaneko, Transport dynamics of neutral excitons and trions in monolayer WS₂, *ACS Nano* **10**, 9687 (2016).
- [55] F. Cadiz, C. Robert, E. Courtade, M. Manca, L. Martinelli, T. Taniguchi, K. Watanabe, T. Amand, A. C. H. Rowe, D. Paget, B. Urbaszek, and X. Marie, Exciton diffusion in WSe₂ monolayers embedded in a van der Waals heterostructure, *Appl. Phys. Lett.* **112**, 152106 (2018).
- [56] M. Titze, B. Li, X. Zhang, P. M. Ajayan, and H. Li, Intrinsic coherence time of trions in monolayer MoSe₂ measured via two-dimensional coherent spectroscopy, *Phys. Rev. Mater.* **2**, 054001 (2018).
- [57] O. Hess and T. Kuhn, Maxwell-Bloch equations for spatially inhomogeneous semiconductor lasers. I. Theoretical formulation, *Phys. Rev. A* **54**, 3347 (1996).
- [58] A. M. Dadgar, D. Scullion, K. Kang, D. Esposito, E. H. Yang, I. P. Herman, M. A. Pimenta, E.-J. G. Santos, and A. N. Pasupathy, Strain engineering and Raman spectroscopy of monolayer transition metal dichalcogenides, *Chem. Mater.* **30**, 5148 (2018).
- [59] B. Aslan, M. Deng, and T. F. Heinz, Strain tuning of excitons in monolayer WSe₂, *Phys. Rev. B* **98**, 115308 (2018).
- [60] S. Brem, A. Ekman, D. Christiansen, F. Katsch, M. Selig, C. Robert, X. Marie, B. Urbaszek, A. Knorr, and E. Malic, Phonon-assisted photoluminescence from indirect excitons in monolayers of transition-metal dichalcogenides, *Nano Lett.* **20**, 2849 (2020).
- [61] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/rvb3-tn15> for additional details on the microscopic evaluation of photoluminescence and diffusion as well as for additional time-resolved spectra and diffusion at temperature $T = 50$ K or with artificially stronger bright-to-KK' scattering.
- [62] D. F. C. Leon, Z. Li, S. W. Jang, and P. B. Deotare, Hot exciton transport in WSe₂ monolayers, *Phys. Rev. B* **100**, 241401(R) (2019).
- [63] N. S. Ginsberg and W. A. Tisdale, Spatially resolved photogenerated exciton and charge transport in emerging semiconductors, *Annu. Rev. Phys. Chem.* **71**, 1 (2020).
- [64] L. Yuan, B. Zheng, J. Kunstmann, T. Brumme, A. B. Kuc, C. Ma, S. Deng, D. Blach, A. Pan, and L. Huang, Twist-angle-dependent interlayer exciton diffusion in WS₂-WSe₂ heterobilayers, *Nat. Mater.* **19**, 617 (2020).
- [65] G. Lo Gerfo Morganti, R. Rosati, G. D. B. Vazquez, S. Varghese, D. Saleta Reig, E. Malic, N. F. van Hulst, and K.-J. Tielrooij, Transient ultrafast and negative diffusion of charge carriers in suspended MoSe₂ from multilayer to monolayer, *Nat. Commun.* **16**, 5184 (2025).
- [66] D. Beret, I. Paradisanos, H. Lamsaadi, Z. Gan, E. Najafidehaghani, A. George, T. Lehnert, J. Biskupek, U. Kaiser, S. Shree, A. Estrada-Real, D. Lagarde, X. Marie, P. Renucci, K. Watanabe, T. Taniguchi, S. Weber, V. Paillard, L. Lombez, J.-M. Pomirol, *et al.*, Exciton spectroscopy and unidirectional transport in MoSe₂-WSe₂ lateral heterostructures encapsulated in hexagonal boron nitride, *npj 2D Mater. Appl.* **6**, 84 (2022).
- [67] H. Lamsaadi, D. Beret, I. Paradisanos, P. Renucci, D. Lagarde, X. Marie, B. Urbaszek, Z. Gan, A. George, K. Watanabe, T. Taniguchi, A. Turchanin, L. Lombez, N. Combe, V. Paillard, and J.-M. Pomirol, Kapitza-resistance-like exciton dynamics in atomically flat MoSe₂-WSe₂ lateral heterojunction, *Nat. Commun.* **14**, 5881 (2023).
- [68] R. Rosati, S. Shradha, J. Picker, A. Turchanin, B. Urbaszek, and E. Malic, Impact of charge-transfer excitons on unidirectional exciton transport in lateral TMD heterostructures, *Nano Lett.* **25**, 11319 (2025).
- [69] L. Rieland, J. Wagner, R. Bernhardt, T. Wang, O. Abdul-Aziz, P. Stein, E. A. A. Pogna, S. Dal Conte, G. Cerullo, H. Hedayat, and P. H. M. van Loosdrecht, Ultrafast optical control of exciton diffusion in WSe₂/graphene heterostructures revealed by heterodyne transient grating spectroscopy, *Nano Lett.* **24**, 9824 (2024).
- [70] Z. Bi, Y. Bai, Y. Shi, T. Sun, H. Wu, H. Zhang, Y. Cui, D. Zhu, Y. Wang, M.-L. Lin, Y. Wang, D. Ma, P.-H. Tan, S. Meng, Q. Xiong, and L. Yang, Intrinsic exciton transport and recombination in single-crystal lead bromide perovskite, *ACS Nano* **19**, 19989 (2025).
- [71] D. Schmitt, J. P. Bange, W. Bennecke, G. Meneghini, A. AlMutairi, M. Merboldt, J. Pöhls, K. Watanabe, T. Taniguchi, S. Steil, D. Steil, R. T. Weitz, S. Hofmann, S. Brem, G. S. M. Jansen, E. Malic, S. Mathias, and M. Reutzel, Ultrafast nano-imaging of dark excitons, *Nat. Photonics* **19**, 187 (2025).
- [72] J. Madéo, M. K. L. Man, C. Sahoo, M. Campbell, V. Pareek, E. L. Wong, A. Al-Mahboob, N. S. Chan, A. Karmakar,

- B. M. K. Mariserla, X. Li, T. F. Heinz, T. Cao, and K. M. Dani, Directly visualizing the momentum-forbidden dark excitons and their dynamics in atomically thin semiconductors, *Science* **370**, 1199 (2020).
- [73] D. Schmitt, J. P. Bange, W. Bennecke, A. AlMutairi, G. Meneghini, K. Watanabe, T. Taniguchi, D. Steil, D. R. Luke, R. T. Weitz, S. Steil, G. S. M. Jansen, S. Brem, E. Malic, S. Hofmann, M. Reutzel, and S. Mathias, Formation of moiré interlayer excitons in space and time, *Nature (London)* **608**, 499 (2022).
- [74] S. Aeschlimann, A. Rossi, M. Chávez-Cervantes, R. Krause, B. Arnoldi, B. Stadtmüller, M. Aeschlimann, S. Forti, F. Fabbri, C. Coletti, and I. Gierz, Direct evidence for efficient ultrafast charge separation in epitaxial WS₂/graphene heterostructures, *Sci. Adv.* **6**, eaay0761 (2020).
- [75] S. Dong, M. Puppini, T. Pincelli, S. Beaulieu, D. Christiansen, H. Hübener, C. W. Nicholson, R. P. Xian, M. Dendzik, Y. Deng, Y. W. Windsor, M. Selig, E. Malic, A. Rubio, A. Knorr, M. Wolf, L. Rettig, and R. Ernstorfer, Direct measurement of key exciton properties: Energy, dynamics, and spatial distribution of the wave function, *Nat. Sci.* **1**, e10010 (2021).
- [76] J. P. Bange, D. Schmitt, W. Bennecke, G. Meneghini, A. AlMutairi, K. Watanabe, T. Taniguchi, D. Steil, S. Steil, R. T. Weitz, G. S. M. Jansen, S. Hofmann, S. Brem, E. Malic, M. Reutzel, and S. Mathias, Probing electron-hole Coulomb correlations in the exciton landscape of a twisted semiconductor heterostructure, *Sci. Adv.* **10**, eadi1323 (2024).
- [77] F. Boschini, M. Zonno, and A. Damascelli, Time-resolved ARPES studies of quantum materials, *Rev. Mod. Phys.* **96**, 015003 (2024).
- [78] G. Meneghini, M. Löwe, R. Perea-Causin, J. P. Bange, W. Bennecke, M. Reutzel, S. Mathias, and E. Malic, ARPES signatures of trions in van der Waals materials, *Nano Lett.* **26**, 5866 (2026).
- [79] P. Hernández López, S. Heeg, C. Schattauer, S. Kovalchuk, A. Kumar, D. J. Bock, J. N. Kirchhof, B. Höfer, K. Greben, D. Yagodkin, L. Linhart, F. Libisch, and K. I. Bolotin, Strain control of hybridization between dark and localized excitons in a 2D semiconductor, *Nat. Commun.* **13**, 7691 (2022).
- [80] R. Rosati, F. Lengers, C. Carmesin, M. Florian, T. Kuhn, F. Jahnke, M. Lorke, and D. E. Reiter, Electron dynamics in a two-dimensional nanobubble: A two-level system based on spatial density, *Nano Lett.* **21**, 9896 (2021).
- [81] J. M. Fitzgerald, R. Rosati, and E. Malic, Polariton transport in 2D semiconductors: Phonon-mediated transitions between ballistic, superdiffusive, and exciton-limited regimes, *Sci. Adv.* **11**, eaea3495 (2025).
- [82] T. Kuhn and F. Rossi, Monte Carlo simulation of ultrafast processes in photoexcited semiconductors: Coherent and incoherent dynamics, *Phys. Rev. B* **46**, 7496 (1992).
- [83] R. Rosati, F. Dolcini, and F. Rossi, Electron-phonon coupling in metallic carbon nanotubes: Dispersionless electron propagation despite dissipation, *Phys. Rev. B* **92**, 235423 (2015).
- [84] O. Iff, D. Tedeschi, J. Martín-Sánchez, M. Moczala-Dusanowska, S. Tongay, K. Yumigeta, J. Taboada-Gutiérrez, M. Savaresi, A. Rastelli, P. Alonso-González, S. Höfling, R. Trotta, and C. Schneider, Strain-tunable single photon sources in WSe₂ monolayers, *Nano Lett.* **19**, 6931 (2019).
- [85] Z. An, P. Soubelet, Y. Zhumagulov, M. Zopf, A. Delhomme, C. Qian, P. E. Faria Junior, J. Fabian, X. Cao, J. Yang, A. V. Stier, F. Ding, and J. J. Finley, Strain control of exciton and trion spin-valley dynamics in monolayer transition metal dichalcogenides, *Phys. Rev. B* **108**, L041404 (2023).
- [86] P. Gant, P. Huang, D. Pérez de Lara, D. Guo, R. Frisenda, and A. Castellanos-Gomez, A strain tunable single-layer MoS₂ photodetector, *Mater. Today* **27**, 8 (2019).
- [87] E. Henríquez-Guerra, H. Li, P. Pasqués-Gramage, D. Gosálbez-Martínez, R. D'Agosta, A. Castellanos-Gomez, and M. Reyes Calvo, Large biaxial compressive strain tuning of neutral and charged excitons in single-layer transition metal dichalcogenides, *ACS Appl. Mater. Interfaces* **15**, 57369 (2023).
- [88] F. Dirnberger, J. D. Ziegler, P. E. Faria Junior, R. Bushati, T. Taniguchi, K. Watanabe, J. Fabian, D. Bougeard, A. Chernikov, and V. M. Menon, Quasi-1D exciton channels in strain-engineered 2D materials, *Sci. Adv.* **7**, eabj3066 (2021).