Mapping the Trap-State Landscape in 2D Metal-Halide Perovskites Using Transient Photoluminescence Microscopy

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Transient microscopy is of vital importance in understanding the dynamics of optical excited states in optoelectronic materials, as it allows for a direct visualization of the movement of energy carriers in space and time. Important information on trap-state dynamics can be obtained using this technique, typically observed as a slow-down of energy transport as carriers are trapped at defect sites. To date, however, studies of the trap-state dynamics have been mostly limited to phenomenological descriptions of the early time-dynamics. Here, it is shown how long-acquisition-time transient photoluminescence microscopy can be used to provide a detailed map of the trapstate landscape in 2D perovskites, in particular when used in combination with transient spectroscopy. An anomalous evolution of the studied exciton distribution is observed, which cannot be explained with existing models for trap limited exciton transport that only account for a single trap type. Instead, using a continuous diffusion model and performing Brownian dynamics simulations, it is shown that this behavior can be explained by accounting for a distinct distribution of traps in this material. These results highlight the value of transient microscopy as a complementary tool to more common transient spectroscopy techniques in the characterization of excited state dynamics in semiconductors.

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2D metal-halide perovskites have attracted significant attention as a more stable and versatile analog to their 3D bulk counterparts.[1–4] Efficient solar cells with improved stability have been made from 2D/3D mixtures, as well as phase pure 2D perovskites with efficiencies above 21% and 18%, respectively.[4–7] Moreover, 2D perovskites are a promising material platform for light emitting applications,[8–11] as they offer high photoluminescence quantum yields, tunable and spectrally pure colors,[12,13] and solution processability.[14] 2D perovskites are described by their general chemical formula L2[ABX3]nBX4, where L is a long organic spacer molecule, A is a small cation (e.g., Cs+, methylammonium, formamidinium), B is a divalent metal cation (e.g., lead, tin), X is a halide anion (chloride, bromide, iodide), and n is the number of inorganic octahedra that make up the thickness of the inorganic layer. The confinement of charge carriers into few-atom thick inorganic layers in 2D perovskites leads to strong quantum and dielectric confinement effects.[15] As a result, the optoelectronic properties of 2D perovskites are dominated by bound electron-hole pairs, called excitons.[16–18]

Understanding the spatial dynamics of the excitonic excited state is crucial in the optimization of device performance. For example, long diffusion lengths are required for solar harvesting as excitons need to reach charge separation sites, while short diffusion lengths are preferable for light-emitting technologies as they reduce the chances of encountering other excitons or non-radiative trapping sites.[19] Earlier this year, the first studies on exciton transport in these materials were reported using transient microscopy, directly visualizing the spatial displacement of the excitons as a function of time.[20–23] Deng et al. determined the diffusion constants of a set of 2D perovskites using transient absorption microscopy (TAM), showing how exciton transport improves on increasing inorganic layer thickness n.[20] In parallel, our own group reported on exciton transport in 2D perovskites with varying organic spacers and thicknesses using transient photoluminescence microscopy (TPLM), showing that exciton–phonon coupling is a key parameter in determining the intrinsic exciton transport
in these materials.\cite{21} Crucially, for bright materials like 2D perovskites, TPLM benefits from better signal to noise ratios as compared to, for example, TAM.\cite{24} As a result, we were able to follow exciton transport over several nanoseconds after excitation and in this way extract crucial information about the transition from purely diffusive to trap-state limited transport.\cite{23} This highlights the value of TPLM as a characterization tool for trap-states.

The ability to extract information on the trap-state dynamics from TPLM measurements was first reported by Akselrod et al., who observed a transition from normal diffusion to a regime of trap-state limited diffusion in organic single crystals.\cite{22} They described the deacceleration using a classical 1D diffusion model taking \( \text{MSD}(t) = 2Dt \), with MSD being the mean-square-displacement of excitons, \( D_0 \) a constant, and \( \alpha \) the diffusion exponent. For normal diffusion through a random walk one finds \( \alpha = 1 \) and a constant diffusivity: \( D(t) = \frac{1}{2} \frac{d\text{MSD}(t)}{dt} = D_0 \), where \( D_0 \) now corresponds to a constant diffusion coefficient. For a trap-state limited regime, an \( \alpha < 1 \) accounts for a diffusivity that slows down with time, representing a subdiffusive behavior. Unfortunately, this phenomenological model does not allow any quantitative characterization of the trap-state properties. More recently, our group\cite{21} and Folie et al.\cite{26} independently introduced a model that allows to describe the decrease in diffusivity in terms of a trap density \( 1/\lambda^2 \):

\[
\text{MSD}(t) = 2\lambda^2 \left( 1 - e^{\frac{-D_0 t}{\lambda^2}} \right)
\]

where \( \lambda \) is the average distance between traps. In this situation, excitons that fall into a trap are stuck and no longer diffuse \( (D(t) = 0) \), which in combination with the diffusing free excitons \( (D(t) = D_0) \) yields a lower effective diffusivity \( D(t) = D_0 e^{\frac{2}{\lambda^2} t} \). This model allowed us to describe exciton diffusion in 2D metal-halide perovskites for times up to 8 ns. Importantly though, this model assumes deep trapping sites that do not allow for detrapping of excitons. Shortly after, Delor et al.\cite{27} reported an empirical model which accounts for thermally activated detrapping of excitons:

\[
\text{MSD}(t) = 2\tau_{\text{turnover}} \left( D_0 - D_{\text{trapped}} \right) \left( 1 - e^{\frac{-t}{\tau_{\text{turnover}}}} \right) + 2D_{\text{trapped}} t
\]

where \( D_0 \) is the diffusivity of the free excitons, \( D_{\text{trapped}} \) is an average diffusivity that accounts for excitons being stuck at a trapping site for a certain time, and \( \tau_{\text{turnover}} = \frac{\lambda^2}{D_0} \) is the characteristic trapping time. For \( D_{\text{trapped}} = 0 \), the model with deep trapping sites that do not allow detrapping is recovered (Equation (1)).\cite{21,22,26} Importantly, Equation (2) allows for the extraction of both a trap density \( 1/\lambda^2 \) and the depth of the trap through \( \Delta E_{\text{trap}} = \ln(D_0/D_{\text{trapped}}) k_B T \).\cite{27}

In this report, we present transient photoluminescence microscopy (TPLM) measurements of exciton diffusion in (PEA)\(_2\)PbI\(_4\) 2D perovskites across extended time scales and show that existing models cannot account for the observed complex spatial dynamics at later times. While the early time dynamics is characterized by a rapid expansion and the previously observed transition to a trap-state limited regime,\cite{21} at later times, a full stagnation and even contraction of the MSD is observed. By combining our TPLM with transient spectroscopy and a continuous diffusion model, we show that the dynamics can only be explained by going beyond the conventional single-trap picture and accounting for a distinct distribution of trapping sites. This study highlights how the complementary use of spatial, spectral, and temporal information allows a more complete picture of the complex trap-state dynamics in 2D perovskites, reinforcing the position of transient microscopy as an increasingly important characterization tool for optoelectronic materials.

All measurements are performed on single crystalline flakes of phenethylammonium lead iodide (PEA)\(_2\)PbI\(_4\). We grow large (\( \approx 10–100 \) s of micrometers) single crystals of (PEA)\(_2\)PbI\(_4\) from a supersaturated precursor solution under ambient conditions (see Experimental Section for details).\cite{28,29} The single-crystals are then exfoliated and transferred to a microscope cover slip before each measurement to produce a freshly cleaved surface with minimal exposure to air. The cover slip on one side and the bulk of the crystal on the other side provide a form of self-passivation from oxygen and moisture during the measurements.\cite{21}

TPLM is performed using a near-diffraction limited pulsed excitation laser (\( \lambda_{\text{exc}} = 405 \) nm) to create a narrow initial exciton population. The image of the emission is projected outside the microscope with a total magnification of 330x. Spatially resolved photoluminescence lifetime measurements are then performed using an avalanche photodiode (APD) on a linear scanning stage. During measurements, the laser fluence is kept low (\( \approx 250 \) nJ cm\(^{-2}\)) to prevent second order effects (e.g., Auger recombination) from influencing the observed dynamics.\cite{21}

The isotropic exciton transport properties of the inorganic plane allow us to measure a 1D slice through the center of the exciton population and still capture the full exciton dynamics (see Figure 1a).\cite{20}

Figure 1b shows the resulting normalized diffusion map, illustrating the time-dependent spatial distribution of the exciton population. We can quantify this behavior by fitting each time slice with a Voigt profile (see Experimental Section for details) from which we extract the time evolution of the mean-square-displacement \( \text{MSD}(t) = \sigma(t)^2 - \sigma(0)^2 \) of the exciton population (see Figure 1c).\cite{30} The slope of this curve is proportional to the diffusivity \( D \), following \( D(t) = \frac{1}{2} \frac{d\text{MSD}(t)}{dt} \) (see Figure 1c, Supporting Information). We observe an early regime (<1 ns) of fast linear growth with a constant diffusivity \( D(t) = D_0 \) which is followed by a slower linear regime (\( \approx 1–20 \) ns). Interestingly though, after around 20 ns, we observe a full stagnation and even contraction after around 40 ns. The early expansion regime is consistent with our earlier studies on 2D perovskites, in which exciton transport up to 8 ns was reported and described with Equation (1).\cite{22} In the following, we will describe the shortcomings of the existing trap-state models and introduce a more rigorous one to account for our observations at times beyond 8 ns.

Figure 2 shows the early time dynamics of the MSD, focusing on the expansion regime. The linear expansion at time <1 ns is clearly visible, followed by a regime of a lower
Figure 1. a) Illustration of transient photoluminescence microscopy (TPLM): A narrow exciton population is excited with a near-diffraction-limited laser pulse in a (PEA)$_2$PbI$_4$ perovskite single-crystal (see inset for crystal structure). Recording the temporal evolution of the emission spot with a scanning avalanche photodiode allows to track both the spatial and temporal dynamics of the exciton population, which is proportional to the photoluminescence emission intensity at low fluences. The results of such a measurement is shown in b) map of normalized emission intensity showing the broadening of the exciton population in space and time. The white line represents the full-width-half-max of the population. c) Mean-square-displacement (MSD) of the exciton population as a function of time. Initially the MSD increases due to excitons diffusing outwards. After around 20 ns, the MSD stagnates and starts to decrease after around 40 ns.)

diffusivity, as excitons start getting trapped. In our previous work, we were able to successfully reproduce our experimental observations for early times ($t < 8$ ns) by assuming a simple model of deep traps that do not allow any detrapping of excitons (Equation (1), dashed line). However, acquiring data for longer delay times, we see that our exciton diffusion data agrees better with a model that accounts for shallow traps, which do allow for detrapping of excitons (Equation (2), solid black line). This model captures both the normal diffusion ($D_0$ for $t < 1$ ns) and the transition to slower diffusion at later times ($t \approx 1–20$ ns) where excitons get temporarily stuck at trapping sites, which is represented by the average diffusivity $D_{\text{trapped}} (< D_0$). For our (PEA)$_2$PbI$_4$ 2D perovskites, we find $D_0 = 0.223 \text{ cm}^2 \text{ s}^{-1}$, $D_{\text{trapped}} = 0.080 \text{ cm}^2 \text{ s}^{-1}$, and $\tau_{\text{turnover}} = 1.2$ ns. The diffusivity $D_0$ for free excitons is consistent with our previously reported value of (PEA)$_2$PbI$_4$ synthesized with the same method. Further, a Boltzmann ratio of 2.8 ($\approx D_0/D_{\text{trapped}}$) allows the estimation of a trap depth of $\Delta E_{\text{trap}} = 26 \pm 2 \text{ meV}$ ($\approx \ln(2.8) k_B T$).

Interestingly, the trap-state energy that we obtain from transient microscopy compares favorably to the spectral shape of the photoluminescence spectrum. As shown in Figure 3a, the emission peak has a tail toward lower energy, which is often attributed to trap-state emission. This tail is well reproduced using a fit with two Voigt functions with an energy difference of $23 \pm 2 \text{ meV}$, close to the trap-depth of $\Delta E_{\text{trap}} = 26 \pm 2 \text{ meV}$ from the diffusion measurement.

To gain more insight into the spectral dynamics of the exciton population, we resolve the photoluminescence spectrum in time using a streak camera. As shown in Figure 3b, we observe a clear transient redshift of the emission ($\Delta E = 25 \pm 1 \text{ meV}$), which can be interpreted as a shift in emission from free to trapped excitons. To confirm this, we fit each temporal slice to two Voigt functions, which allows us to extract the spectral weight of the two distributions at each point in time $t$ (Figure 3c). While the high-energy population displays prompt decay, the low-energy population shows an initial growth, consistent with an initially empty population of traps that are gradually being populated by diffusing free excitons. Importantly, we find excellent agreement between the time-scale of the transient red shift (double exponential fit in Figure 2b: $\tau_1 = 0.9$ ns and $\tau_2 = 23$ ns) and the transition from normal diffusion to trap-state limited diffusion obtained from our TPLM measurements ($\tau_{\text{turnover}} = 1.2$ ns and $\tau_{\text{stagnation}} = 20$ ns). The good agreement of both the trap-state energies and the characteristic time scales in both transient microscopy and transient spectroscopy measurements suggests that the dynamics have the same physical origin and highlights that the two techniques can be used complementarily to obtain a more complete picture of the exciton dynamics in semiconductors. We would like to note that, while the spectral weights do not allow a direct determination of the exact exciton densities, as the quantum yields of the free and
trapped excitons are unknown, they still allow to identify the relevant exciton dynamics.

While the shallow trap model of Equation (2) nicely reproduces the observed behavior for times up to 20 ns, it predicts a continuously increasing MSD(t) and therefore fails to capture our experimental observations at later time scales of stagnation (>20 ns) and contraction (>40 ns) of the MSD. To explain the observed stagnation and contraction regimes, we hypothesize that the MSD at later times is dominated by a sub-population of excitons that has been trapped for a prolonged amount of time. Longer trap-state lifetimes would correspond to deeper traps with slower detrapping rates. One important simplification of the shallow trap model (Equation (2)) is the assumption of a single well-defined trap-state energy $\Delta E_{\text{trap}}$. In addition, it assumes that the radiative lifetime of the free and trapped excitons is identical. The transient spectroscopy results presented in Figure 3b show that while the red shift fits reasonably well to a double exponential decay, a slow gradual red-shift persists at longer times. This suggests that a distribution of trap-states around $\Delta E_{\text{trap}}$ is present, rather than a single trap with a fixed energy of $\Delta E_{\text{trap}}$. Moreover, from the population dynamics presented in Figure 3c, trapped excitons appear to have a slower decay than the free exciton population.

To test the influence of a lower radiative decay rate for traps and a trap-state distribution on the MSD, we numerically solve the rate-equations and perform Brownian motion simulations (see Experimental Section and Supporting Information for details). We assume a Gaussian distribution of trap-state energies that is centered around $\Delta E_{\text{trap}} = 25$ meV and has a width of $\sigma_{\text{trap}} = 35$ meV, corresponding to the trap-state emission that we extracted from the steady-state photoluminescence in Figure 3a. The detrapping rate is modeled as a thermally activated process using the Arrhenius equation: $\mu(\Delta E_{\text{trap}}) = A e^{-\frac{\Delta E_{\text{trap}}}{kT}}$ (see Figure S2, Supporting Information for the resulting rate distribution). We fit the experimental data using the trapping rate $\nu$, the proportionality constant $A$, and radiative decay rates $\gamma_{\text{free}}$ and $\gamma_{\text{trap}}$ as the fitting parameters (see Figure 4a). The result of the simulation is shown in Figure 4b along with the experimental data. Indeed, we find that we can reproduce the observed stagnation and decrease in MSD up to 40 ns, by accounting for a distribution of trap-state energies (purple line with $D_0 = 0.223 \text{ cm}^2 \text{ s}^{-1}$, $\nu = 1.4 \text{ ns}^{-1}$, $A = 12 \text{ ns}^{-1}$, $\gamma_{\text{free}} = 1.1 \text{ ns}^{-1}$, $\gamma_{\text{trap}} = 0.7 \text{ ns}^{-1}$), rather than of a single trap-state energy (orange line with $D_0 = 0.223 \text{ cm}^2 \text{ s}^{-1}$, $\nu = 0.45 \text{ ns}^{-1}$, $A = 0.57 \text{ ns}^{-1}$, $\gamma_{\text{free}} = 1.1 \text{ ns}^{-1}$, $\gamma_{\text{trap}} = 0.7 \text{ ns}^{-1}$). We find that both a lower radiative decay rate of the traps ($\gamma_{\text{trap}} < \gamma_{\text{free}}$) and a distribution of trapping states ($\Delta E_{\text{trap}} = 25 \text{ meV}$, $\sigma_{\text{trap}} = 35 \text{ meV}$) is necessary to successfully reproduce the later time dynamics of the MSD (see Figures S3 and S4, Supporting Information).

The simulations suggest that the stagnation and contraction of the MSD is a result of a trap-state distribution with different decay dynamics. At early times, the MSD is dominated by quickly moving free excitons, that decay rather quickly and only get temporarily stuck in shallow traps, while the later times are dominated by excitons that are stuck in deeper traps that decay more slowly. We note that the final steep decay of the MSD observed in experiments (>40 ns) is not fully captured by the model. Moreover, the photoluminescence decay of the model is faster than the experimentally observed values (Figure S5, Supporting Information). This suggests that deeper traps beyond the Gaussian distribution or a distribution of radiative rates of the traps may need to be considered, both of which would lead to an emphasis of the contraction of the MSD. To illustrate this, we simulated a case where we introduced a small additional number of deep traps with an even slower radiative and minimized detrapping rate ($\gamma_{\text{deep}} = 0.5 \text{ ns}^{-1}$, $\mu_{\text{deep}} = 0 \text{ ns}^{-1}$, see Figure S6, Supporting Information for more details). These traps do not impact the early time dynamics but do matter at later times as they are still present when most other excitons have already decayed, allowing to reproduce the steep decay of the MSD at later times (black line in Figure 4b). The agreement between model and experiment is emphasized by the log–log representation of the MSD in Figure S7, Supporting Information, showing an excellent fit over almost three orders of magnitude.

Finally, we demonstrate how this model can be used to gain physical insight into the changes in the trap-state landscape...
upon degradation of the material. For this, we performed a series of TPLM measurements on a 2D perovskite flake that was sequentially photo-degraded between measurements using a high-intensity continuous wave blue LED (see Figure 4c). We find that the stagnation and contraction regimes are emphasized with increasing degradation, as excitons get more readily stuck at the additionally introduced trapping sites. Specifically, fitting the three curves with the model of a trap distribution including a rare deep trap (right panel of Figure 4a), we show that degradation leads to a higher trap-state density and introduces deeper traps, which is reflected in an increase of the trapping rates ($\nu$ and $\nu_{\text{deep}}$) and a broadening of the trap distribution ($\sigma_{\text{trap}}$), as well as a decrease in the radiative rate $\gamma_{\text{deep}}$ (see Table S1, Supporting Information for all fit parameters and Figure S8, Supporting Information for the broadening of the photoluminescence spectra for stronger degradation).

In summary, we have shown that TPLM is a powerful technique to study the exciton dynamics and material properties of semiconductors. Further, the good agreement of trap-state energies and characteristic time scales in both TPLM and transient spectroscopy suggests that the observed dynamics have the same physical origin and highlights that the two techniques can be used complementarily to gain a more complete picture of the exciton properties in semiconductors, with insights in both spatial and spectral dynamics. From our different measurements, we find that trap-states in (PEA)$_2$PbI$_4$ have an average depth of around $\Delta E_{\text{trap}} = 25$ meV. TPLM revealed an anomalous stagnation and contraction regime of the MSD of excitons for $t > 20$ ns, which cannot be explained with previous descriptions of trap-state limited exciton transport. Using a continuous diffusion model and Brownian dynamics simulations, we show that these dynamics can be explained by accounting for a trap distribution with a slower radiative decay than the free excitons.

**Experimental Section**

Sample Preparation: Chemicals were purchased from commercial suppliers and used as received. (PEA)$_2$PbI$_4$ single crystals were synthesized under ambient laboratory conditions following the over-saturation techniques reported previously.$^{[28,29]}$ In a nutshell, the precursor salts PEAI (Sigma Aldrich, 805904-25G), and PbI$_2$ (Sigma Aldrich, 900168-5G) were mixed in a stoichiometric ratio of 2:1 and dissolved in $\gamma$-butyrolactone (Sigma Aldrich, B103608-500G). The precursor solution was heated and kept at 70 °C for 2–3 days. The solution was cooled down to room temperature and drop cast on a glass slide, which was heated to 50 °C on a hotplate. After the solvent was evaporated, crystals with crystal sizes of up to several hundred microns were formed. The single crystals were mechanically exfoliated using the Scotch tape method and transferred to cover slips for the subsequent optical inspection in the microscope. Exciton diffusion measurements were performed following the same procedure as reported previously.$^{[25,30]}$ In short, a near-diffraction limited exciton population was created with a 405 nm pulsed laser (PicoQuant LDH-D-C-405, PDL 800-D) and a 100× oil immersion objective (Nikon CF1 Plan Fluor,
NA = 1.3) in a T2 inverted Nikon microscope. Photoluminescence of the exciton population was imaged on an avalanche photodiode (APD, Micro Photon Devices PDM, 20 μm × 20 μm) with a total magnification of 330x. As a result, the demagnified image of the APD had an effective area of around 60 × 60 nm (≈20 μm/330), which was scanned through the middle of the exciton population in 120 nm steps, recording a time trace in every point. A Pico-Harp 300 timing board was used for the synchronization of the laser and APD for time correlated single photon counting. To minimize laser induced degradation of the perovskite crystals, the perovskite flake was scanned using an x-y-piezo stage (MCL Nano-BIOS 100), covering an area of 5 × 5 μm. TPLM were performed with a laser fluence of around 250 nJ cm⁻² and a 10 MHz laser repetition rate for all measurements, with the exception of the measurements presented in Figure 4c where we used 50 nJ cm⁻² and 40 MHz. The time binning of the experimental setup was set to 4 ps and a nonlinear software binning was applied before analyzing the data. The bin size \( n_b \) was calculated according to \( n_b = \text{int}(0.3k^2 + 16) \rightarrow [16, 16, 17, 18, 20, 23, 26, 30, 35, …] \). The data was evaluated following the same procedure as previously reported by Seitz et al.[21] To model the dilute limit for excitons, Continuous Diffusion Model (Numerical Integration of Rate Equations) was compared to the experimental data.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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

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2D perovskites, exciton diffusion, exciton transport, metal-halide perovskites, transient photoluminescence microscopy, trap-states

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[1] I. C. Smith, E. T. Hoke, D. Solis-Ibarra, M. D. McGehee, H. I. Karunadasa, Angew. Chem., Int. Ed. 2014, 53, 11232.
[2] L. N. Quan, M. Yuan, R. Comin, O. Voznyy, E. M. Beauregard, S. Hoogland, A. Buin, A. R. Kirmani, K. Zhao, A. Amassian, D. H. Kim, E. H. Sargent, J. Am. Chem. Soc. 2016, 138, 2649.
[3] S. Yang, W. Fu, Z. Zhang, H. Chen, C. Z. Li, J. Mater. Chem. A 2017, 5, 11462.
[4] C. Ortiz-Cervantes, P. Carmona-Monroy, D. Solis-Ibarra, ChemSusChem 2019, 12, 1560.
