Site-selectively generated photon emitters in monolayer MoS$_2$ via local helium ion irradiation

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Quantum light sources in solid-state systems are of major interest as a basic ingredient for integrated quantum photonic technologies. The ability to tailor quantum emitters via site-selective defect engineering is essential for realizing scalable architectures. However, a major difficulty is that defects need to be controllably positioned within the material. Here, we overcome this challenge by controllably irradiating monolayer MoS$_2$ using a sub-nm focused helium ion beam to deterministically create defects. Subsequent encapsulation of the ion exposed MoS$_2$ flake with high-quality hBN reveals spectrally narrow emission lines that produce photons in the visible spectral range. Based on ab-initio calculations we interpret these emission lines as stemming from the recombination of highly localized electron-hole complexes at defect states generated by the local helium ion exposure. Our approach to deterministically write optically active defect states in a single transition metal dichalcogenide layer provides a platform for realizing exotic many-body systems, including coupled single-photon sources and interacting exciton lattices that may allow the exploration of Hubbard physics.
Point defects are important for a variety of physical phenomena in semiconductors. For example, they provide a means to engineer the equilibrium free-carrier density, which can serve as quantum emitters capable of hosting discrete quantum spin systems that can be optically addressed. A major challenge in several of these applications is that the defects need to be precisely positioned, which is particularly difficult for conventional three-dimensional semiconductors where defects are often buried deep within the bulk structure. One route to remedy this challenge is to reduce the physical dimensionality of the material. Over the last decade it became possible to fabricate and manipulate atomically thin two-dimensional (2D) materials that offer intriguing electronic and optoelectronic properties. In particular, the hexagonal transition metal dichalcogenides (TMDs), such as MoS2, MoSe2, WS2, and WSe2, are excellent candidates for photonic applications due to their exceptionally strong light-matter interaction resulting from weak non-local dielectric screening. The strong Coulomb coupling manifests itself in an exciton dominated spectral response and very large exciton binding energies. Beyond the response of mobile excitons, also quantum dot-like emission from localized excitons was recently demonstrated in WS2, MoSe2, and WS2, and the nature of the potential, which localizes the excitons is still not fully understood. The origin of such quantum emitters was hitherto considered to be caused by uncontrolled strain potentials that locally reduce the band gap, thus, funneling the recombination of excitons via a discrete recombination center. However, strain potentials are challenging to control, which limits the applicability of such quantum emitters for a prospective integration into quantum photonic circuits. In addition to the delocalized excitons, we observe spectrally sharper emission peaks X1 (FWHM = (8.3 ± 2.5) meV) and charged exciton −X1 (FWHM = (9.4 ± 2.9) meV) whose inhomogeneous linewidth is reduced due to the encapsulation with hBN62,32-34. Remarkably, for the helium ion exposed samples in addition to the neutral exciton, we observe spectrally sharper emission peaks X1 (FWHM ~ 0.5–6 meV) in a window of ΔEl ~ 100–200 meV red-shifted from X1 (spectral range highlighted by a dotted box in Fig. 1d). These features are superimposed on the so-called L-peak that is observed in monolayer MoS2 and has recently been attributed to the presence of sulphur vacancies. The sharp spectral features are spatially localized and require helium ion exposure of MoS2 and the subsequent encapsulation with hBN. Spectrally sharp peaks do not occur in unexposed hBN/MoS2/hBN heterostacks (cf. bottom spectrum in Fig. 1d), neither in exposed MoS2 without hBN encapsulation nor in exposed hBN (See Supplementary Fig. 1). To obtain further information on the origin of the sharp spectral emission, we statistically evaluate the energetic detuning ΔEl = E′(X1) − E(X1) of each localized emission peak E(X1) with respect to E′(X1). Figure 1d, top, shows a histogram of the localized X1 emission energies as a function of detuning ΔEl for ~3500 emitters for one representative sample (See Supplementary Fig. 5). The histogram shows that the spectral emitters possess a continuum of energies in the range of ΔEl ~ 100–220 meV below the neutral exciton. Intriguingly, we consistently observe that most of the helium ion induced emission peaks emit in a spectrally narrow (15) distribution at ΔEl ~ 193 meV (also see Supplementary Figs 4 and 5). We also show the spatial occurrence of emitters in three energy bins (cf. arrows in Fig. 1d), overlaid in Fig. 1c. So far, single-photon emitters have been found at sample edges or folds, where the bandstructure is strongly influenced by the crystal boundary, coupling of atomic-orbitals by local symmetry breaking or strain. By contrast, we find spectrally sharp emitters homogeneously distributed on the nanometer scale. Our study opens up new routes for inducing highly controllable defect emitters in ultrathin two-dimensional materials to create arrays of coupled single-photon sources, to study Anderson’s orthogonality catastrophe, and to realize lattices of interacting excitons similarly to optical lattices for ultracold atomic gases.
Fig. 1 Deterministically induced defect emitters in atomically thin MoS₂ realized by focused helium ions. a Schematic illustration of the exposed MoS₂/hBN van der Waals heterostructure. b Helium ion microscopy image taken at a dose of \( \sigma = 2 \cdot 10^{15} \text{cm}^{-2} \). The scale bar is 10 \( \mu \text{m} \). c Spatially resolved and spectrally integrated photoluminescence mapping. The colored pixels depict the occurrence of emitters within 500 \( \mu \text{m} \) wide energy bins (highlighted by colored arrows in d). d Bottom panel: typical low-temperature (10 K) \( \mu \)-PL spectra of the exposed (black) and unexposed (red) hBN/MoS₂/hBN heterostructure. The spectra of exposed MoS₂ feature emission from mobile excitons \( ^0X_{1s}^A \) and trions \( ^-X_{1s}^B \), as well as single emission lines \( X_i \) (open triangle) at lower energies. Top panel: a histogram of the emission energies detuned by \( \Delta E_L \) below \( ^0X_{1s}^A \). e Power dependence: \( ^0X_{1s}^A \) shows an expected linear power dependence, while the \( X_i \) emission saturates for higher excitation powers (data for the emitter highlighted by open triangle in d). f–i DFT calculated spin-up (black) and spin-down (red) density of states (DOS) of the neutral \( V_{Mo} \), single negatively charged \( V_{Mo}^- \), double negatively charged \( V_{Mo}^{--} \), and triple negatively charged \( V_{Mo}^{---} \) molybdenum vacancy. The DOS of \( V_{Mo}^{--} \) shows doublet \( e-p, e-pd \) and singlet \( a_1-pd \) defect states inside the band gap. The \( a_1-pd \) singlet state is situated within the valence band. The more electrons are added to the vacancy the closer the defect states and the DFT computed Fermi level energy \( E_F \) shift to the conduction band minimum (CBM) because of the on-site Coulomb repulsion.

distributed all over the 2D sample; this is a direct consequence of the helium ion exposure.

The sharp emission lines reveal a saturating behavior with a threshold power of \( P_{sat} \sim 10 \mu \text{W} \) (cf. Figure 1e), which is consistent with saturating a finite density of a single defect state as fitted by

\[
I \propto \frac{P}{P + P_{sat}}.
\]

By contrast, the 2D neutral exciton \( ^0X_{1s}^A \) shows the expected linear dependence with the excitation power. MoS₂ exhibits several defects, most prominently single sulfur vacancies and single molybdenum vacancies. So far, sulphur vacancies have not been demonstrated to be optically active, because they are very likely to be passivated with oxygen; although they are ubiquitous in exfoliated, unexposed MoS₂. Here, we concentrate on molybdenum vacancies \( V_{Mo} \), although we are aware that the discussed defect emitters might be of character that is more complex. Figure 1f–i show the ab-initio calculated density of states (DOS) for a neutral \( V_{Mo} \) as well as a single, double and triple negatively charged molybdenum vacancy \( V_{Mo}^- \), \( V_{Mo}^{--} \), and \( V_{Mo}^{---} \). The vacancy states have a trigonal and mirror symmetry.
between the two layers of the sulphur and the molybdenum layer\(^\text{40}\). In turn, two singlet (\(a_i\)) and two doublet (\(e\)) states are expected for all cases. The lowest \(a_{1s}-p\) \([-e-p\] level stems from the six adjacent sulphur \(p\) orbitals, and are found inside [above] the valence bands. The \(e-pd\) and \(a_{1s}pd\) states originate from the hybridization of the six sulphur \(p\) and six (second nearest neighbour) molybdenum \(d\) orbitals and are situated in the gap\(^\text{40}\). We find that all presented states are stable and relaxed within our DFT framework. Since \(\Delta E_i\) is significantly smaller than the quasi particle band gap in MoS\(_2\), we assume that the Fermi energy is close to the conduction band minimum (CBM). We interpret the experimentally observed sharp emission lines as resulting from excitons that also involve particle-hole excitations from the defect state orbitals\(^\text{42}\).

Figure 1f–i demonstrates that for instance, for \(V^{3-}_{Mo}\) and \(V^{3-}_{Mo}\), the DFT computed Fermi energy \(E^{\text{DFT}}_F\) is consistently close to the CBM. Taking the computed energy differences between each state and the CBM, our ab-initio calculation suggests that in this interpretation, the lowest unoccupied state in the \(V^{3-}_{Mo}\) the \(e-pd\) state, is likely to be involved in the photoluminescence signal \(X_i\) as in Fig. 1d (cf. Supplementary Figs 5 and 9). In particular, the computed energy difference \(\Delta E^{\text{DFT}}_i = E(CBM)^{\text{DFT}} - E(e-pd)^{\text{DFT}} = 0.22\) eV coincides with the highest experimental detuning \(\Delta E_i\) in the top panel of Fig. 1d. However, the DFT calculation does not consider the binding energy of the exciton that is comprised of the different electronic orbitals with a complex distribution of weights and varying momentum dependencies\(^\text{42}\).

**Site-selective creation of optically active defects by local helium ion irradiation.** In order to demonstrate the site-selective nature of our approach, we write a matrix of \(100 \times 100\) nm fields with a pitch of \(2\) \(\mu\)m onto monolayer MoS\(_2\) that is deposited on hBN. An optical micrograph of the flake prior to exposure is presented in Fig. 2a. Subsequent to exposure, the nano-structured MoS\(_2\) monolayer is fully encapsulated in hBN. We record a spatially resolved PL mapping of the treated areas with a small step size (250 nm). The corresponding spatially resolved and spectrally integrated PL mapping is presented in Fig. 2b (grayscale). Here, an integration range of \(\Delta E = (193 \pm 5)\) meV is chosen since, statistically (cf. Figure 1d), the localized emission is the strongest at these energies. Enhanced PL emission is clearly observed at the irradiated spots. Moreover, from the data, we extract and overlay the occurrence of localized emission \(X_i\) with the PL mapping (highlighted in orange). We find that localized emission is activated at all positions that are exposed by the HIM. Conversely, sharp line emission is not observed from the unexposed regions. Corresponding spectra of five exposed positions are presented in Fig. 2c. Each spectrum exhibits a small number (1–3) of emission lines that are completely absent in unexposed areas (cf. black spectra in Fig. 2c). Importantly, the site-selectively created defect emitters exhibit emission at \(\Delta E \sim 193\) meV in agreement with the distribution obtained from statistics in Fig. 1d (also See Supplementary Fig. 5). Since no annealing step is needed for emitter creation, the writing accuracy is expected to be predominantly limited by the helium ion beam, and is therefore expected to be on the nanometer scale. Near-field optical techniques and scanning tunneling microscopy can further be used to ultimately reveal the writing accuracy of atomistic defect states in the monolayer MoS\(_2\).

**Photoluminescence excitation spectroscopy and time stability of an individual single defect emitter.** To further corroborate the above interpretation of optically active defects, we perform photoluminescence excitation (PLE) spectroscopy to probe the energetic structure of the involved states. Figure 3a presents a false color plot for a typical PLE scan of an emission line \(X_1\) as the excitation energy is tuned across the \(0\) \(X^{1\text{A}}_1\). The emission occurs at \(E(X_1) = (1.76 \pm 0.01)\) eV energetically well below the \(0\) \(X^{1\text{A}}_1\). When measuring differential reflectivity \(\Delta R/R\) using a broadband supercontinuum source, we identify \(0\) \(X^{1\text{A}}_1\) at an energy of \(E(0X^{1\text{A}}_1) = 1.95\) eV (cf. Figure 3b). Upon resonant excitation of \(0\) \(X^{1\text{A}}_1\), the \(X_1\) emission is significantly increased. This is a consequence of the efficient creation of excitons, when the laser energy is in resonance with an exciton transition (See Supplementary Fig. 7 for excitation on \(0\) \(X^{1\text{A}}_1\) and \(0\) \(X^{1\text{B}}_1\)). Most significantly, we can excite \(X_1\) states also below the free exciton transitions. This is consistent with recently predicted absorbance spectra of single vacancy defects in 2D materials\(^\text{42}\) and in contrast to strain induced quantum dot-like emitters\(^\text{10–15,17–20}\).

Another key property of photonic emitters is their spectral stability. A stable time trace of a defect emitter is presented in Fig. 3c (with a spectrum acquired every second). Examples of two spectra highlighted in Fig. 3c are plotted in Fig. 3d. They demonstrate that the emitter exhibits a blinking behavior. This is an observed feature of various types of few-level systems\(^\text{48}\). In our case, the blinking behavior is not surprising since the defects are embedded in a two-dimensional plane with large surface-to-volume ratio and charges in the environment that are very likely to randomly fluctuate in position and time.

**Defect-phonon interaction and the independent boson model.** Measuring the temperature dependence of the \(\mu\)-PL spectra
allows us to determine the interactions between the involved electron orbitals and phonons. We gradually change the lattice temperature from 10 K to 300 K while recording µ-PL spectra (cf. Figure 4a). The spectra reveal emission from the defect emitters that are strongly red-shifted and simultaneously broadened at elevated temperatures (similar as for the $^0X_{1s}^A$). We analyze the evolution of the emitter $X_L$ in detail by utilizing the independent boson model that has been successfully applied to the lineshape of defect emitters recorded over long times. The integration time is set to 1 s while spectra are acquired every second. Two exemplary spectra taken from $\epsilon$ for the emitter being switched on and off exhibiting activation energies that are far below $k_B T$ (See Supplementary Fig. 10).

The temperature-dependent peak positions in Fig. 4a manifest in a polaron shift for all spectral features (cf. Figure 4c), as phenomenologically described by

$$E_G(T) = E_G(0) - S\langle h\omega \rangle \left[ \coth \left( \frac{\langle h\omega \rangle}{2k_B T} \right) - 1 \right],$$

with the emission energy $E_G(0)$ at 0 K, the Huang–Rhys factor $S$, the average phonon energy $\langle h\omega \rangle$, and the Boltzmann constant $k_B$. Fitting $X_L$ in Fig. 4c reveals average phonon energies of $\langle h\omega \rangle = (12.69 \pm 1.17)$ meV and an electron–phonon coupling of $S = 0.791 \pm 0.071$ (for $^0X_{1s}^A$; $\langle h\omega \rangle = (25.11 \pm 1.02)$ meV and $S = 2.135 \pm 0.061$). The experimentally observed value of $S_{\text{exp}} = 0.791$ is in very good agreement with $S_{\text{theory}} = 0.75$ as obtained from the independent boson model (See Supplementary Fig. 12). From our model, we can also distinguish between the fraction of photons emitted by the zero phonon line (ZPL) and the phonon sideband (PSB). Taking the relative spectral weight of ZPL and PSB, we find a Debye–Waller factor of $~0.2$ at 10 K, comparable to other few-level systems.

**Discussion**

To start the discussion, we point out that the emission peaks occur homogeneously across the whole basal plane of the...
exposed MoS₂ encapsulated into hBN (cf. Figure 1c). The sharp peaks neither occur in exposed hBN without MoS₂ nor in unexposed hBN/MoS₂/hBN (See Supplementary Fig. 1). This phenomenology suggests that the optically active defects can probably not be explained by sulphur vacancies, because the latter are ubiquitous in exfoliated, unexposed MoS₂\textsuperscript{37}, although they are very likely to be produced under helium ion exposure as well\textsuperscript{38,39,40}. However, sulphur vacancies are easily passivated by oxygen\textsuperscript{41}, which especially applies to the discussed nanofabricated TMDCs under ambient conditions. Figure 2b, c support this interpretation, since the emission \(X_2\) only appears at the exposed areas, while the unexposed areas show the broad L-peak attributed to the presence of sulphur vacancies\textsuperscript{36,37}. Equally, quantum emitters in hBN can be excluded for our sample (See Supplementary Figs 1 and 8)\textsuperscript{51}. Intriguingly, the beam energy of the HIM (30 keV) and also the excess energy of the secondary electrons (<10 eV) produced in the exposed materials are sufficient to form defects with a large formation energy, such as molybdenum vacancies\textsuperscript{40,52}, that are rare in pristine samples\textsuperscript{37,39}. This argument could explain why we observe optically active defect sites only after the helium ion exposure of the MoS₂ monolayers.

In our understanding, the influence of hBN is two-fold. On the one hand, the emission peaks \(X_2\) have the lowest emission energy of \(\Delta E_L\) of ~193 meV below \(0^+X_1\). Encapsulated in hBN, the excitonic emission energy is renormalized due to the dielectric environment\textsuperscript{6}. On the other hand, the emission linewidth is strongly reduced for both \(X_1\) and \(0^+X_1\). Encapsulated in hBN, the excitonic emission energy is renormalized due to the dielectric environment\textsuperscript{6}. The combination of the hBN-effects explain the sharp spectral features, which are spread across the broad energy window \(\Delta E_L \sim 100–220\) meV in Fig. 1d. However, most of the defects emit at an energy detuning of ~193 meV, which resembles the spectrally broad PL emission of helium ion exposed MoS₂ on SiO\(_2\)/Si substrate\textsuperscript{28} and on hBN (See Supplementary Fig. 2). This observation is also in good agreement with the emission properties of site-selectively activated defects in Fig. 2. From our consistent observations, we draw the conclusion that most of the emission indeed originates from the same helium ion induced defect that is deterministically created at designated positions in the MoS₂ monolayer. The defect emission at smaller detunings \(\Delta E_L < 180\) meV is most likely caused by dielectric effects, adsorbates or simply by another type of defect.

For all possibly created defects, the emission at \(\Delta E_L\) of ~193 meV must resemble the lowest unoccupied, optically active state. This interpretation is consistent with the saturating behavior as in Fig. 1e, and it also explains the blinking behavior in Fig. 3c, d. Furthermore, the PLE measurements in Fig. 3a are also consistent with this interpretation, since the expected joint density of states of localized electronic defect states opens exciting ways for possibly harnessing them as local nanometer scale sensors, investigating nuclear spin physics with wave functions only sampling a fraction of atoms or studying screening physics in the ultimate limit of a localized electronic defect state.

**Methods**

**Sample structure.** We employed the viscoelastic transfer method to transfer MoS₂ monolayer crystals and hBN multilayers onto 290 nm SiO\(_2\) substrates. The MoS₂ crystals used for exfoliation were purchased from SPI Supplies while high-quality hBN bulk crystals were provided by Takashi Taniguchi and Kenji Watanabe from NIMS, Japan.

**Helium ion microscopy.** We used MoS₂ monolayers transferred onto hBN/SiO\(_2\)/Si wafers by He\(^+\) irradiation. For the data shown in Fig. 1, a beam current \(I = 1\) pA and a beam energy of 30 keV are used. Large areas are exposed with a beam spacing of 5 nm. The dwell time was adjusted such that a dose of ~10\(^{17}\) He\(^+\) cm\(^{-2}\) is obtained, which is optimized for a high density of defect emitters (See Supplementary Fig. 6). For the data shown in Fig. 2, a low beam current of \(I \sim 20\) pA is used in order to obtain a low helium ion dose of ~10\(^{13}\) He\(^+\) cm\(^{-2}\) by accordingly adjusting the dwell time. Small areas of 100 x 100 nm are exposed. A beam spacing of 0.5 nm is used.

**Optical spectroscopy.** Confocal optical spectroscopy was performed in a helium flow cryostat with the sample kept at a lattice temperature of ~10 K. For cw \(\mu\)-PL experiments in Fig. 1, we used a doubled Nd:YAG laser with an excitation energy of 2.33 eV and typical excitation powers of less than 10 \(\mu\)W, which results in an excitation power density of 0.884 kW cm\(^{-2}\) at a laser spot diameter of 1.2 \(\mu\)m. The \(\mu\)-PL data in Fig. 2a are recorded with an excitation energy of 2.54 eV and an excitation power density of 900 nW (0.058 kW cm\(^{-2}\)) with a laser spot diameter of 0.7 \(\mu\)m.

For measuring differential reflectivity spectra a supercontinuum white light source was used that was focused with an optical microscope onto the sample kept at a lattice temperature of ~10 K. For all excitation energies, the excitation power was kept at 20 \(\mu\)W for all excitation energies. The excitation laser pulse was filtered with a sharp edge filter before being dispersed on a grating and detected with a charge-coupled device (CCD).
DFT calculations. The calculations were performed using density functional theory (DFT) as implemented in the Vienna ab-initio simulation package (VASP)23,24. The projected augmented wave method has been used25,26. The atomic and electronic structures were determined using the PBE functional. A plane wave basis with an energy cutoff of E\( _{\text{cut}} \)= 500 eV and a \( (6 \times 6 \times 1) \) Monkhorst-Pack k-point sampling has been used. The TMD layer has been modeled using a \( (9 \times 9) \) supercell containing 242 atoms.

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

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Author contributions
J.K., U.W., M.Ka., J.J.F. and A.W.H. conceived and designed the experiments, M.L. and M.F. performed the DFT and independent boson model calculations, F.S., J.K. and S.R. prepared the samples, K.W. and T.T. provided high-quality hBN bulk crystals, J.K., E.M. and P.Z. performed helium ion exposure of samples, J.K., L.S., J.W., J.C. and K.M. performed the optical measurements, J.K. analyzed the data, R.S. and M.Kn. contributed interpreting the data, J.K. and A.W.H. wrote the manuscript with input from all coauthors.

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