Localized bright luminescence of indirect excitons and trions in MoSe$_2$/WSe$_2$ van der Waals heterostructure

E. V. Calman, L. H. Fowler-Gerace, L. V. Butov, D. E. Nikonov, I. A. Young, S. Hu, A. Mishchenko, and A. K. Geim

1Department of Physics, University of California at San Diego, La Jolla, CA 92093, USA
2Components Research, Intel Corporation, Hillsboro, OR 97124 USA
3School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, UK

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Indirect excitons (IX) in semiconductor heterostructures are bosons, which can cool below the temperature of quantum degeneracy and can be effectively controlled by voltage and light. IX quantum Bose gases and IX devices were explored in GaAs heterostructures where an IX range of existence is limited to low temperatures due to low IX binding energies. IXs in van der Waals transition-metal dichalcogenide (TMD) heterostructures are characterized by large binding energies giving the opportunity for exploring excitonic quantum gases and for creating excitonic devices at high temperatures. IXs were observed at room temperature in TMD heterostructure. However, the obstacle for exploring IX quantum gases and IX devices in TMD heterostructures is disorder. In particular, high disorder is revealed in a broad IX luminescence linewidth that can exceed 100 meV. Here we report on the realization of IXs in MoSe$_2$/WSe$_2$ heterostructures with a luminescence linewidth of 4 meV. We observed an order of magnitude enhancement of IX luminescence intensity and the narrow linewidth in a localized spot. The narrow linewidth made possible resolving low- and high-energy features of IX luminescence identified as the charged and neutral IX. The experimentally found binding energy of the indirect charged exciton, indirect trion, is 26 meV.

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An indirect exciton (IX), also known as an interlayer exciton or a charge transfer exciton, is a bound pair of an electron and a hole confined in separated layers. The spatial separation between the electron and hole layers allows achieving long IX lifetimes, orders of magnitude longer than lifetimes of direct excitons (DXs) [1]. Due to their long lifetimes, IXs can cool below the temperature of quantum degeneracy [2]. The realization of IX quantum Bose gases in GaAs heterostructures led to finding of many phenomena, including spontaneous coherence and condensation of IXs [3], the spatially modulated exciton state [4, 5], the commensurability effect of exciton density waves [6], spin textures [7], and the Pancharatnam-Berry phase and long-range coherent spin transport in the IX condensate [8].

Furthermore, an IX has a built-in electric dipole moment, $ed$ ($d$ is the separation between the electron and hole layers) [9]. As a result, IX energy, lifetime, and flux can be effectively controlled by voltage that is explored for the development of excitonic devices, potentially offering energy-efficient computation and efficient coupling of signal processing to optical communication [10]. In GaAs heterostructures, experimental proof-of-principle demonstrations were performed for excitonic ramps [11–13], excitonic conveyers (excitonic CCD) [14], and excitonic transistors [15–17].

However, the IX range of existence in GaAs heterostructures is limited to low temperatures due to low IX binding energies. Excitons exist in the temperature range roughly below $E_{ex}/k_B$ ($E_{ex}$ is the exciton binding energy, $k_B$ is the Boltzmann constant) [18]. The IX binding energy in GaAs/AlGaAs heterostructures is typically $\sim 4$ meV [19]. The maximum IX binding energy in GaAs heterostructures is achieved in GaAs/AlAs coupled quantum wells (CQW) and is $\sim 10$ meV [20]. The temperature of quantum degeneracy, which can be achieved with increasing density before excitons dissociation to electron-hole plasma, also scales proportionally to $E_{ex}$ [21]. In GaAs heterostructures, quantum degeneracy was achieved at temperatures below few Kelvin [2] and the proof of principle for the operation of IX switching devices was demonstrated at temperatures below $\sim 100$ K [16].

Van der Waals heterostructures composed of atomically thin layers of transition-metal dichalcogenide (TMD) offer an opportunity to realize artificial materials with designable properties [22] and, in particular, allow the realization of excitons with remarkably high binding energies [23, 24]. IXs in TMD heterostructures are characterized by binding energies exceeding 100 meV making them stable at room temperature, the key requirement for the development of excitonic technology [21]. Indeed, IXs were observed at room temperature in TMD heterostructures [42]. This establishes the TMD heterostructures as a material platform both for exploring high-temperature quantum Bose gases of IXs and for creating realistic excitonic devices.

IXs are typically created using optical excitation in
FIG. 1: Van der Waals MoSe$_2$/WSe$_2$ coupled quantum well heterostructure. The heterostructure layer (a) and real space energy band (b) diagrams. The ovals indicate a direct exciton (DX) and an indirect exciton (IX) composed of an electron ($-$) and a hole ($+$). (c) Micrograph showing the layer pattern of the device. (d) Momentum space energy band diagram around the K point. Solid and dashed lines represent spin-up and spin-down bands. Optically active low-energy DX and IX states are indicated by arrows.

coupled electron and hole layers [2–21]. IXs can also appear in electron-electron (or hole-hole) bilayers in a collective electronic state in strong magnetic fields at the total Landau level filling factor 1. The latter was realized in GaAs heterostructures [25–30] and in graphene–boron-nitride–graphene van der Waals heterostructures [31, 32]. Optically excited IX systems allow creating IXs in a localized spot, controlling IX density by the excitation power, and probing IXs by optical methods, and are studied in GaAs heterostructures as outlined above [2–21]. The opportunity for exploring high-temperature IX quantum gases and devices in a material platform with a high IX binding energy instigated studies of IXs in optically excited TMD heterostructures with coupled electron and hole layers [33–47]. Although IXs in those studies were observed up to room temperature, high disorder (above 100 meV as revealed in a broad IX luminescence linewidth) has been an obstacle for exploring IX quantum gases and devices in such heterostructures [42].

Here we report on IXs in MoSe$_2$/WSe$_2$ heterostructure with a luminescence linewidth reaching 4 meV. The narrow linewidth has also made it possible to resolve low- and high-energy features of IX luminescence identified as the charged and neutral IXs and, in turn, to find the binding energy of the indirect charged exciton, i.e., indirect trion.

The van der Waals MoSe$_2$/WSe$_2$ heterostructure was assembled by stacking mechanically exfoliated two-dimensional crystals on a graphite substrate that acted as a global back gate (Fig. 1a). The top view of the device showing the contours of different layers is presented in Fig. 1c. The CQW is formed where the MoSe$_2$ and WSe$_2$ monolayers overlap. The MoSe$_2$ and WSe$_2$ monolayers are encapsulated by hexagonal boron nitride (hBN) serving as dielectric cladding layers. A graphene top layer is used for gate control: voltage $V_g$ applied between the graphene top gate and graphite back gate creates the bias across the CQW structure. The real-space energy-band diagram is shown in Fig. 1b. IXs are formed from electrons and holes confined in adjacent monolayer MoSe$_2$ and WSe$_2$, respectively. This type-II MoSe$_2$/WSe$_2$ heterostructure with staggered band alignment is similar to AlAs/GaAs CQW heterostructures where IXs are formed from electrons and holes confined in adjacent AlAs and GaAs layers, respectively [16, 20]. In the MoSe$_2$/WSe$_2$ heterostructure, due to the order of spin-up and spin-down states in valence and conduction bands the lowest energy DX state is optically active in MoSe$_2$ and dark in WSe$_2$, and the lowest energy IX state is also optically active (Fig. 1d) [47–52].

The excitons were generated by a semiconductor laser with excitation energy $E_{ex} = 1.96$ eV. Luminescence spectra were measured using a spectrometer with resolution 0.2 meV and a liquid-nitrogen-cooled CCD. The laser

FIG. 2: Bright spot in spatially indirect, i.e., interlayer, luminescence. (a) $x$–$y$ map of emission collected in the spectral range of 1.24–1.38 eV corresponding to indirect luminescence. Indirect luminescence intensity is strongly enhanced in a bright spot. The layer boundaries are shown as in Fig. 1c. (b) In-plane coordinate dependence of spatially indirect and direct luminescence in the bright spot region. The coordinate center is at the bright spot. (c) The luminescence spectrum in the bright spot. The laser excitation is defocused in (a) and focused at the bright spot in (b,c). $T = 1.7$ K, $V_g = 0$. 
was either defocused or focused to a spot with the radius \( \sim 2 \mu m \). The IX lifetime was measured using the laser pulses of a rectangular shape with the duration 20 ns, period 80 ns, and edge sharpness \( \sim 0.5 \) ns, the emitted light was filtered by an interference filter and detected by a liquid-nitrogen-cooled CCD coupled to a PicoStar HR TauTec time-gated intensifier. The IX lifetime measured at 2 K is about 10 ns, orders of magnitude longer than the direct exciton lifetime in single-layer TMD. The experiments were performed in a variable-temperature 4He cryostat at \( T = 1.7 \) – 293 K.

We observed two distinct regions in the heterostructure, a bright spot, which exhibits strongly enhanced IX luminescence, and the surrounding region of the heterostructure with weaker IX luminescence (Fig. 2a). The bright spot shows an order of magnitude enhancement of IX luminescence intensity (Fig. 2a). The IX luminescence in the bright spot is localized within the length smaller than the 1 micron resolution of the optical system used in the experiment as evidenced by the Airy diffraction pattern (Fig. 2b).

In contrast, the intralayer DX luminescence follows the laser excitation spot and does not show such localization (Fig. 2b). The DX luminescence intensity varies only slightly along the CQW heterostructure and does not show any intensity enhancement in the bright spot (Fig. S1 in Supplementary Information).

The bright spot forms naturally with no artificially designed IX confinement such as in electrostatic traps in GaAs heterostructures [53–59]. The presence of the luminescence bright spot for IXs with a built-in electric dipole and its absence for DXs with no electric dipole suggests that the bright spot originates from an accidental IX trapping due to the background electrostatic potential in the heterostructure.

Remarkably, the bright spot shows a very narrow IX linewidth (Fig. 2c). At the lowest excitation power tested, the IX linewidth in the bright spot reached 4 meV, the lowest value reported so far for IXs in TMD heterostructures.

Due to the IX electric dipole moment, \( e_d \), the IX energy shifts in the voltage-induced electric field in the \( z \) direction, \( F_z \), by \( \delta E = -e_d F_z \) [9]. The energy of two luminescence lines vs. temperature. The curves are guides to the eye. (c) Experimental (symbols) and simulated (lines) spectrally integrated luminescence intensity ratio \( IX^+ / IX \) (red) and \( DX^+ / DX \) (black) vs. temperature. \( P_{ex} = 1.25 \) mW, \( V_g = 0 \).

![Fig. 3: Gate voltage dependence. Indirect luminescence spectra in the bright spot in MoSe\(_2\)/WSe\(_2\) CQW at different gate voltages \( V_g \). Left inset: Luminescence peak energy vs. \( V_g \). IX and IX\(^+\) are indirect exciton and trion, DX and DX\(^+\) are direct exciton and trion. Right inset: Schematic of IX and IX\(^+\).](image)

![Fig. 4: Temperature dependence. (a,b) Spectra of (a) indirect and (b) direct luminescence in the bright spot in MoSe\(_2\)/WSe\(_2\) CQW at different temperatures. (c,d) The peak energy (c) and linewidth (d) of IX and IX\(^+\) luminescence lines vs. temperature. The curves are guides to the eye. (e) Experimental (symbols) and simulated (lines) spectrally integrated luminescence intensity ratio IX\(^+\)/IX (red) and DX\(^+\)/DX (black) vs. temperature. \( P_{ex} = 1.25 \) mW, \( V_g = 0 \).](image)
nescence lines is controlled by voltage (Fig. 3), indicating that both these lines correspond to IXs.

The IX line splitting of 26 meV (Fig. 3) is much smaller than the energy difference of the A and B excitons caused by the spin–orbit splitting of the WSe$_2$ valence band [60]. Therefore, both IX lines represent different species of A excitons. The calculated difference in the masses, 0.64 vs. 0.56$m_0$, and splitting of the conduction band spin states in MoSe$_2$ [61] result in a splitting of the optically active and dark IX states of the same order of magnitude [62]. However, the temperature dependence (Fig. 4a,e) indicates that the lower energy IX luminescence line corresponds to a charged IX, i.e., indirect trion (IX$^-$), and the higher energy IX luminescence line to neutral IX (Fig. 3 right inset). The relative intensity of the lower energy IX luminescence line decreases with temperature (Fig. 4a,e), consistent with the thermal dissociation of trions. The measured IX line splitting gives an estimate for the binding energy of the indirect trion of ~ 26 meV (Fig. 3 and 4a).

A similar temperature dependence is observed for spatially direct, i.e., intralayer, exciton and trion, DX and DX$^+$, luminescence (Fig. 4b,e). However, in contrast to IX and IX$^+$, the peak energy of DX and DX$^+$ practically does not change with voltage due to vanishing built-in dipole moment in the direction of applied electric field for direct excitons and trions (Fig. 3 left inset). DX and DX$^+$ luminescence was studied earlier in monolayer MoSe$_2$ [51, 52, 63–66].

Figure 4e presents also the simulated ratios of exciton and trion integrated luminescence intensities for the direct, DX$^+$/DX, and the indirect, IX$^-$/IX, cases. We simulated these ratios using their approximate proportionality to the densities of corresponding particles. The dependence of the densities on temperature is obtained from the mass action model following [64], details are presented in Supplementary Information. In these estimates, we assume the density of background charge carriers $n_B = 1.9 \times 10^{11}$ cm$^{-2}$ and the density of photoexcited electron-hole pairs $n_{ph} = 2 \times 10^{11}$ cm$^{-2}$. The simulations are in agreement with the experimental data (Fig. 4e). We also used the DX$^+$/DX and IX$^-$/IX density ratios to simulate the luminescence spectra (Fig. S4 in Supplementary Information).

The measured indirect trion binding energy of 26 meV is smaller than the direct trion binding energy of 32 meV (Fig. 4a,b) due to the separation between the electron and hole layers, consistent with the theory of indirect trions in GaAs and TMD heterostructures [67–69]. The measured indirect trion binding energy is also close to the calculated binding energy of 28 meV for negative indirect trions in MoS$_2$/WS$_2$ heterostructures [69].

As in the type-I MoS$_2$/hBN TMD heterostructure [42], IXs are observed at room temperature in our type-II heterostructures (Fig. 4a,c,d). The enhancement of IX intensity in the bright spot persists up to room tempera-

![FIG. 5. Excitation power dependence.](image)

The observed red shift of the lines with increasing temperature (Fig. 4c) originates from the band gap reduction, which is typical for semiconductors, the TMDs included [64].

The narrowest indirect luminescence linewidth is observed at the smallest excitation power $P_{ex}$ (Fig. 5a,d) and lowest temperature (Fig. 4d) in the experiment. With increasing temperature, the IX luminescence line broadens up to about 40 meV at room temperature (Fig. 4d). With increasing excitation power $P_{ex}$, the indirect luminescence also broadens (Fig. 5a,d) and shifts to higher energies (Fig. 5a,b). Similar line broadening and shift to higher energies were observed for IXs in GaAs heterostructures and described in terms of IX interaction [55]. The repulsive interaction between IXs originates from their built-in electric dipole moments [70–72]. Isolated IX$^+$ have substantial binding energy at low separation between electron and hole layers [67–69], relevant for the MoSe$_2$/WSe$_2$ heterostructure. However, the IX$^+$ binding energy is smaller than the IX binding energy that stabilizes the neutral system of IXs against the IX transformation to trions and charged particles. Therefore, we assume that IX$^+$ form by binding of electrons and holes created by excitation to background charge carriers which are present in the heterostructure due to unintentional doping. Increasing IX$^+$ and IX density with excitation power leads to the enhancement of interaction in the system of indirect excitons and trions and,
in turn, the enhancement of IX\textsuperscript{T} and IX energies.

Further lowering the disorder and IX luminescence linewidth as well as understanding the charged and neutral IXs is important both for exploring quantum Bose gases of IXs and for creating excitonic devices in TMD heterostructures. The development of tailored potential landscapes for IXs in TMD structures, as shown for the case of IXs in GaAs structures [53–59], in contrast to naturally formed IX traps resulting in bright luminescence spots, would be a subject for future work.

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* These two authors contributed equally
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Supplementary Information for
Localized bright emission of indirect excitons and trions in MoSe$_2$/WSe$_2$ van der Waals heterostructures

E. V. Calman,$^{1,}\ast$ L. H. Fowler-Gerace,$^{1,}\ast$ L. V. Butov,$^1$ D. E. Nikonov,$^2$
I. A. Young,$^2$ S. Hu,$^3$ A. Mishchenko,$^3$ and A. K. Geim$^3$

$^1$Department of Physics, University of California at San Diego, La Jolla, CA 92093, USA
$^2$Components Research, Intel Corporation, Hillsboro, OR 97124 USA
$^3$School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester M13 9PL, UK

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Map of indirect and direct luminescence

The spatially indirect (interlayer) luminescence intensity is strongly enhanced in the bright spot (Fig. 2a and Fig. S1a). In contrast, the spatially direct (intralayer) luminescence intensity varies only slightly in the CQW heterostructure and does not show an intensity enhancement in the bright spot (Fig. S1b).

Voltage dependence of luminescence in MoSe$_2$/WSe$_2$ CQW heterostructure outside the bright spot

As in the bright spot (Fig. 3), the IX energy outside the bright spot is controlled by voltage $V_g$ (Fig. S2). The neutral and charged indirect exciton peaks, IX and IX$^T$, are not resolved due to larger luminescence linewidth in this region of the sample (the indirect luminescence linewidth outside the bright spot is about 20 meV, Fig. S5e). The energy shifts with voltage in the bright spot (Fig. 3) and outside the bright spot (Fig. S2) are roughly the same, indicating that in both these regions the indirect luminescence lines correspond to IXs with the same $d$.

Temperature dependence of luminescence in MoSe$_2$/WSe$_2$ CQW heterostructure outside the bright spot

Figure S3 shows indirect and direct luminescence spectra outside the bright spot at different temperatures. The fit to indirect spectra in Fig. S3a and direct spectra in Fig. S3b is shown in Fig. S3c and Fig. S3d, respectively. In

FIG. S1: Map of indirect and direct luminescence. $x$-$y$ luminescence image of (a) the spatially indirect (interlayer) luminescence (measured in the spectral range 1.24–1.38 eV), and (b) the spatially direct (intralayer) luminescence (measured in the spectral range 1.24–1.91 eV). The layer boundaries are shown as in Fig. 1. Laser excitation is defocused. $V_g = 0$, $T = 1.7$ K.
FIG. S2: Voltage dependence of luminescence in MoSe₂/WSe₂ CQW heterostructure outside the bright spot. Indirect luminescence spectra outside the bright spot [at (15 µm, −4 µm), the coordinate center is at the bright spot] at different gate voltages \( V_g \). The neutral and charged indirect exciton peaks, IX and IX\(^T\), are not resolved due to larger luminescence linewidth in this region of the sample. The inset shows the peak energy of direct and indirect luminescence lines vs. \( V_g \). \( P_{ex} = 1.25 \) mW, \( T = 1.7 \) K.

contrast to the bright spot (Fig. 4), the neutral and charged indirect exciton peaks, IX and IX\(^T\), are not resolved outside the bright spot due to larger luminescence linewidth in this region (Fig. S3a). However, the fit to spectra (Fig. S3c) suggests that the temperature dependence of indirect luminescence outside the bright spot is similar to that in the bright spot: At low temperatures the indirect spectra are dominated by the IX\(^T\) luminescence (green Lorentzians in Fig. 3c), while the relative intensity of the high-energy IX luminescence (blue Lorentzian in Fig. S3c) increases with temperature, consistent with the thermal dissociation of IX\(^T\).

Both MoSe₂ and WSe₂ contribute to direct luminescence in the CQW heterostructure (Fig. S3b). As outlined in the main text, the lowest energy DX state is optically active (bright) in MoSe₂ and dark in WSe₂ (Fig. 1d) [1–6]. As a result, at low temperatures, the direct luminescence in the CQW heterostructure is dominated by MoSe₂. The intensity of direct luminescence of WSe₂ grows with increasing temperature due to thermal occupation of higher-energy conduction band states involved in the optically active DXs (Fig. 1d).

At the lowest tested temperatures, the direct spectra are dominated by MoSe₂ DX\(^T\) luminescence line (green Lorentzians in Fig. S3d). The relative intensity of the higher-energy MoSe₂ DX luminescence (blue Lorentzians in Fig. S3d) increases with temperature, consistent with the thermal dissociation of MoSe₂ DX\(^T\). The low-energy shoulders (magenta Lorentzians in Fig. S3c,d) are tentatively attributed to localized states.

WSe₂ DX\(^T\) luminescence line (cyan Lorentzians in Fig. S3d) and WSe₂ DX luminescence line (orange Lorentzians in Fig. S3d) appear in the spectrum around 60 K. The relative intensity of the higher-energy WSe₂ DX luminescence increases with temperature, consistent with the thermal dissociation of WSe₂ DX\(^T\). The red shift of the lines with increasing temperature (Fig. S3e) originates from the band gap reduction, which is typical in semiconductors, the TMDs included [7].

Measured and simulated temperature dependence of luminescence in the bright spot in MoSe₂/WSe₂ CQW heterostructure and in MoSe₂ and WSe₂ monolayers

The measured temperature dependence of indirect exciton and trion luminescence in the MoSe₂/WSe₂ CQW heterostructure as well as direct exciton and trion luminescence in MoSe₂ monolayer and in WSe₂ monolayer was compared with simulations based on the mass action model similar to [7]. The spectra of indirect luminescence were
FIG. S3: Temperature dependence of luminescence in MoSe$_2$/WSe$_2$ CQW heterostructure outside the bright spot. (a) Indirect and (b) direct luminescence spectra outside the bright spot [at (15 µm, −4 µm)] at different temperatures $T$. The fit to spectra in (a) and (b) is shown in (c) and (d), respectively. The spectra are shown by black lines. The fit Lorentzians are shown by green (IX and MoSe$_2$ DX$^T$), blue (IX and MoSe$_2$ DX), cyan (WSe$_2$ DX$^T$), orange (WSe$_2$ DX), and magenta (localized states) lines, their sums by red lines. (e) The peak energy of luminescence lines vs. temperature. The color of dots in (e) corresponds to the color of corresponding luminescence lines in (c,d). The curves are guides to the eye. $P_{ex} = 1.25$ mW, $V_g = 0$. measured in the bright spot in MoSe$_2$/WSe$_2$ CQW heterostructure (Fig. S4a). The spectra of direct luminescence in MoSe$_2$ monolayer (Fig. S4b) and in WSe$_2$ monolayer (Fig. S4c) were measured outside the CQW heterostructure region, namely in the monolayer MoSe$_2$ and in the monolayer WSe$_2$ regions of the sample.

The simulations set off with determining the densities of excitons and trions from the mass action model following [7]. The mass of an exciton is $m_X = m_e + m_h$ and that of a trion is $m_T = 2m_e + m_h$. The inputs are the density of background electron doping $n_B = 1.9 \times 10^{11}$ cm$^{-2}$ and the density of photoexcited electron-hole pairs $n_P = 2 \times 10^{11}$ cm$^{-2}$. The resulting densities of excitons $n_X$, trions $n_T$, and free electrons $n_e$ are determined from conditions

$$n_P = n_X + n_T,$$
$$n_B = n_T + n_e,$$
$$n_Xn_e/n_T = A k_B T \exp \left( \frac{-E_T}{k_B T} \right),$$
$$A = \frac{4m_e m_X}{\pi \hbar^2 m_T},$$

where $k_B$ is the Boltzmann constant, $T$ is the ambient temperature, and $E_T$ and $E_X$ are the trion or exciton binding energies, respectively. The trion binding energy is taken from the measured line splitting: $E_T = 26$ meV for indirect trion in CQW and $E_T = 32$ meV for direct trion in MoSe$_2$ (Fig. 4a,b). The above equations neglect the contribution of quantum degeneracy (fermion and boson nature of particles). These corrections are small for temperatures of 20 K and above at relevant particle densities. In the limit of vanishing temperatures, the equations give the physically correct result: all background electrons are bound into trions. This model gives the ratio of exciton and trion densities presented in Fig. 4e by black (for direct exciton and trion) and red (for indirect exciton and trion) lines.

Two species of both excitons and trions (bright and dark) were observed in direct luminescence of monolayer WSe$_2$ [5, 6]. In the monolayer WSe$_2$ studied here, three luminescence lines can be seen (Fig. S4c). The simulations of WSe$_2$ luminescence (Fig. S4f) include direct exciton and two species of direct trions with the binding energies taken from the measured line splitting $E_{T1} = 27$ meV and $E_{T2} = 52$ meV (Fig. S4c).

Figures S4d-f show luminescence spectra simulated using the following approximation. The ratio of exciton and trion luminescence intensities is taken equal to the ratio of exciton and trion densities. The estimation of the latter is described above. A phenomenological dependence of the bandgap on temperature is taken from the experiment (Fig. 4a-c) $\Delta E_g[\text{meV}] = -0.05T - 6 \cdot 10^{-4}T^2$, where temperature is in units of Kelvin. The peak energies of exciton
FIG. S4: Measured and simulated temperature dependence of luminescence in the bright spot in MoSe$_2$/WSe$_2$ CQW heterostructure and in MoSe$_2$ and WSe$_2$ monolayers. Measured spectra of (a) indirect luminescence in the bright spot in MoSe$_2$/WSe$_2$ CQW heterostructure, (b) direct luminescence in MoSe$_2$ monolayer, and (c) direct luminescence in WSe$_2$ monolayer at different temperatures. $P_{ex}=1.25$ mW, $V_g=0$. Simulated luminescence of (d) IX and IX$^T$ in MoSe$_2$/WSe$_2$ CQW heterostructure, (e) DX and DX$^T$ in MoSe$_2$ monolayer, and (f) DX and DX$^T$ in WSe$_2$ monolayer.

luminescence, i.e., the bandgap minus the exciton binding energy, at zero temperature are taken from the experiment (Fig. 4a-c) $E_g - E_X = 1425$ meV (IX in CQW), $E_g - E_X = 1636$ meV (DX in MoSe$_2$), $E_g - E_X = 1713$ meV (DX in WSe$_2$). The ratio of trion 1 and trion 2 densities in WSe$_2$ is approximated by the Boltzmann distribution. For temperatures of 20K and higher, the chemical potentials are lower than zero by more than the thermal energy, and the Bose and Fermi functions are approximately equal to the Boltzmann distribution. We do not specifically consider the effects of interaction, disorder, recoil, or light cone on the luminescence lineshape. Instead, we incorporate a phenomenological Lorentzian broadening dependent on temperature as $\Delta[\text{meV}] = 5 + 0.05T$ for the luminescence lines. The simulated spectra (Fig. 4d-f) illustrate the major features observed in the experiments (Fig. 4a-c).

Power dependence of luminescence in MoSe$_2$/WSe$_2$ CQW heterostructure outside the bright spot

As in the bright spot (Fig. 5), the indirect luminescence outside the bright spot shifts to higher energies with increasing excitation power $P_{ex}$ (Fig. S5). No such energy enhancement is observed for direct luminescence neither
FIG. S5: Power dependence of luminescence in MoSe₂/WSe₂ CQW heterostructure outside the bright spot. (a) Indirect and (b) direct luminescence spectra outside the bright spot [at (15 µm, −4 µm)] at different excitation powers $P_{ex}$. The energy (c), intensity (d), and linewidth (e) of the indirect (black circles) and direct (magenta squares) luminescence lines shown in (a) and (b) vs. $P_{ex}$.

$V_g = 0, T = 1.7$ K.

in the bright spot nor outside the bright spot.

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* These two authors contributed equally

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