Electronic Supplementary Material (ESI) for Nanoscale.
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Supporting Information

Electrically-tunable non-radiative lifetime in WS_2/WSe_2 heterostructure

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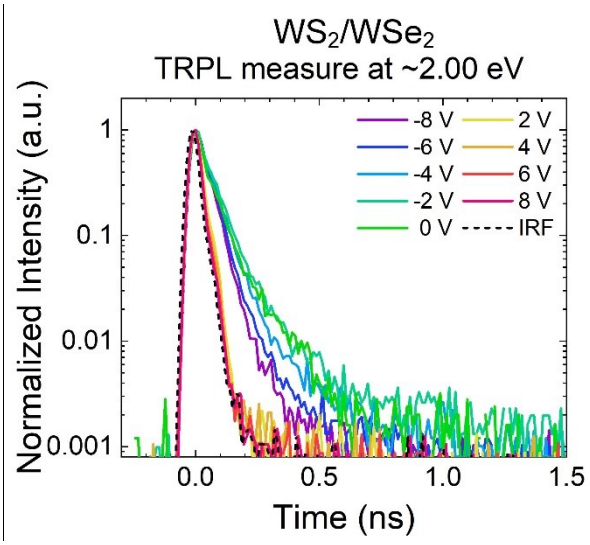
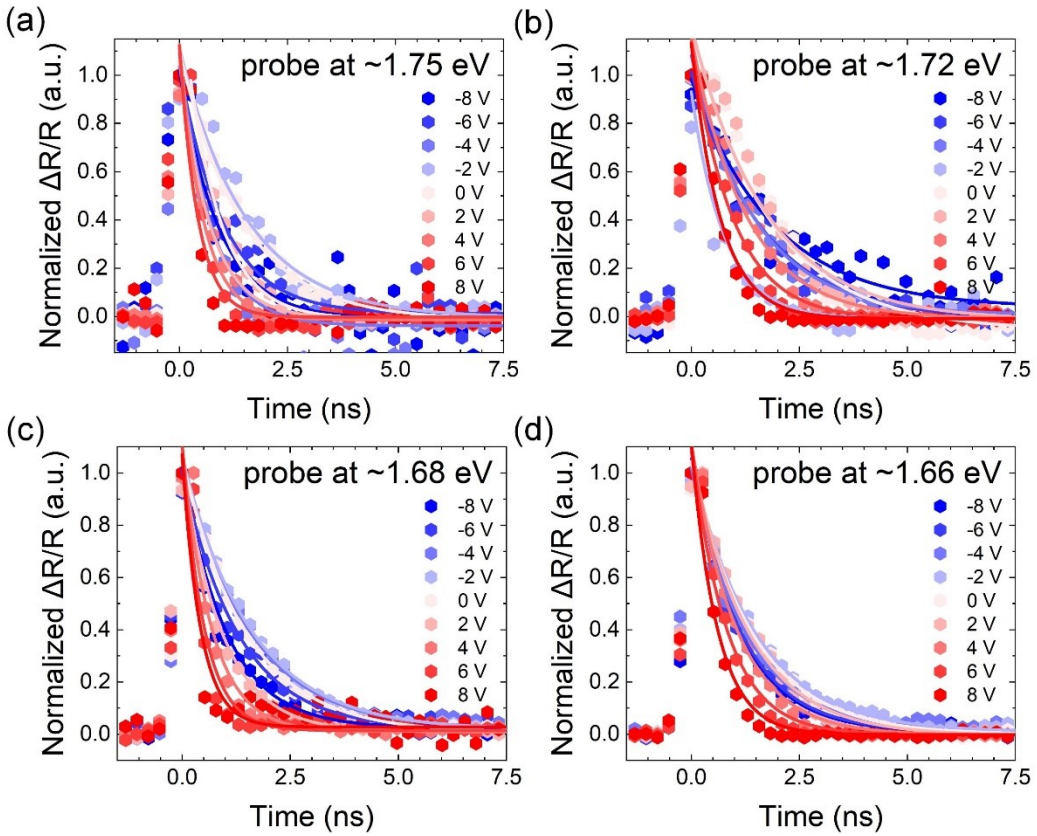
Supplementary Note 1. Back-gate dependent TRPL results of WS_2/WSe_2 at WS_2 resonant energy (~2.00 eV)



Supplementary Figure S1. Normalized time-resolved PL results of WS_2/WSe_2 heterostructure at WS_2 resonant energy (~2.00 eV) under different back-gate voltages. The black dashed line represents the IRF for the TRPL setup. All the measurements were performed at 7 K.

The TRPL of WS_2/WSe_2 heterostructure measured at WS_2 resonance (~2.00 eV) is shown in Supplementary Fig. S1. The PL lifetimes also exhibit clear gate-voltage dependence, with the longest lifetime at charge-neutrality point.

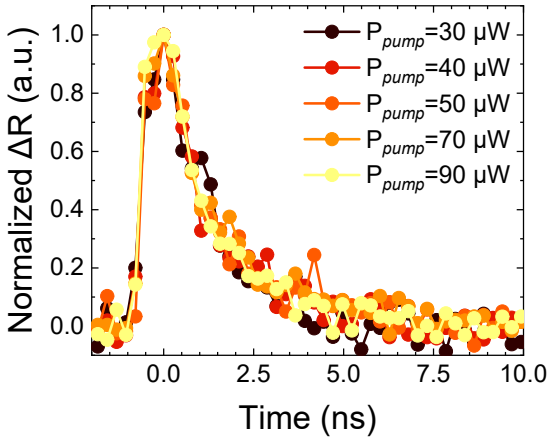
Supplementary Note 2. Back-gate dependent TAS results of WS_2/WSe_2 heterostructure across the A-exciton resonance range of WSe_2



Supplementary Figure S2. Normalized transient reflectance of WS_2/WSe_2 heterostructure at probe energy of (a) 1.75 eV, (b) 1.72 eV, (c) 1.68 eV and (d) 1.66 eV under different back-gate voltages. All the measurements were performed at 7 K.

To investigate the probe energy-dependence of the electrically-tuned non-radiative lifetimes of the WS_2/WSe_2 heterostructure, transient reflectivity has been measured varying the probe energy from 1.66 eV to 1.75 eV under different back-gate voltages. As is shown in Supplementary Fig. S2, the back-gate voltage dependence of dynamics can be observed across the A-exciton resonance range of WSe_2.

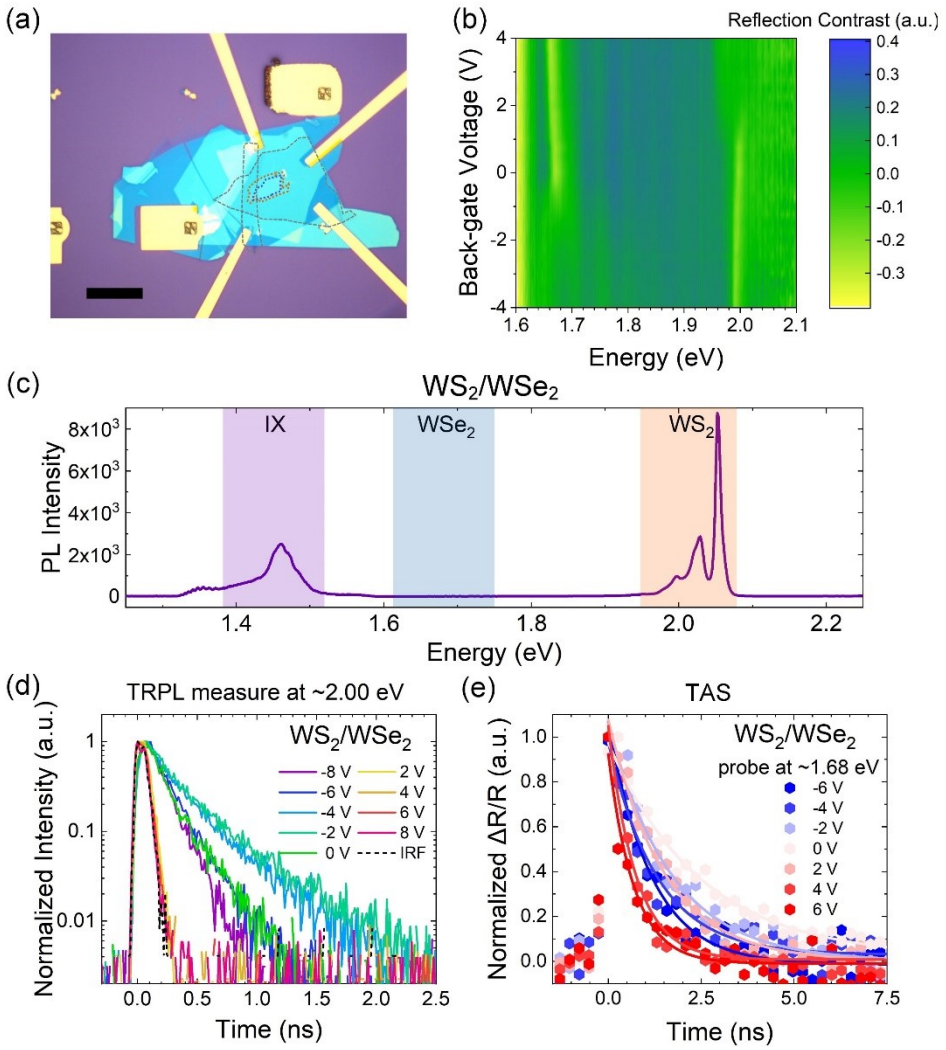
Supplementary Note 3. Pump-power dependent TAS results of WS_2/WSe_2 heterostructure



Supplementary Figure S3. Normalized transient reflectance of WS_2/WSe_2 heterostructure with probe energy of ~1.68 eV witout back-gate voltage under different pump power. All the measurements were performed at 7 K.

To investigate the effects of exciton-exciton annihilation (EEA) as the non-radiative recombination dynamics of WS_2/WSe_2 heterostructure, the pump-power dependent transient reflectance is shown in Supplementary Fig. S3. It is noticed that the non-radiative lifetimes exhibit trivial changes within the range of applied pump power, indicating the negligible effects of EEA.

Supplementary Note 4. Electrically-tunable non-radiative lifetimes in near-aligned WS_2/WSe_2 heterostructure



Supplementary Figure S4. (a) Optical microscopy image of near-aligned WS_2/WSe_2 heterostructure. The scale bar is 20 μm. (b) Back-gate-voltage-dependent reflection contrast of near-aligned WS_2/WSe_2 heterostructure. (c) Photoluminescence spectrum of the near-aligned WS_2/WSe_2 heterostructure. (d) Normalized TRPL dynamics of near-aligned WS_2/WSe_2 heterostructure at WS_2 resonant energy (~2.00 eV) under different back-gate voltages. (e) Normalized transient reflectance of near-aligned WS_2/WSe_2 heterostructure with probe energy of ~1.68 eV under different back-gate voltages. All the measurements were performed at 7 K.

To investigate the potential twist-angle-dependence of the electrically-tuned non-radiative lifetimes, we fabricated a near-aligned WS_2/WSe_2 heterostructure and studied

the back-gate modulation of exciton dynamics using transient photoluminescence and absorption spectroscopy at low temperature. The results are shown in Supplementary Fig. S4. The photoluminescence spectrum at 7 K exhibit strong emission of intralayer excitons of WS_2 and interlayer excitons, indicating that the stacking of this WS_2/WSe_2 sample is near aligned. As shown in Supplementary Fig. S4d, the PL lifetimes measured at ~2.00 eV show similar gate-voltage dependence. The different time constant from the manuscript sample may be related to the sample quality and different excitation power. In Supplementary Fig. S4e, the transient reflectance probed at ~1.68 eV exhibit strong back-gate dependence same as manuscript, suggesting that the electrically-controlled non-radiative lifetimes is not strongly influenced by the stacking of heterostructure.

Supplementary Table S1. Back-gate dependent TAS fitting results of monolayer WSe_2 and WS_2/WSe_2 heterostructure probed at ~1.68 eV

Back-gate Voltage [V]	TAS Lifetime [ps] of WSe_2	TAS Lifetime [ps] of WS_2/WSe_2
-8	692±14	1023±59
-4	670±12	1524±38
0	674±10	1472±29
4	773±15	675±34
8	783±19	422±41