Electronic Supplementary Material (ESI) for Nanoscale.

Supporting Information

Exciton Dynamics and Annihilation in WS_2 2D Semiconductors

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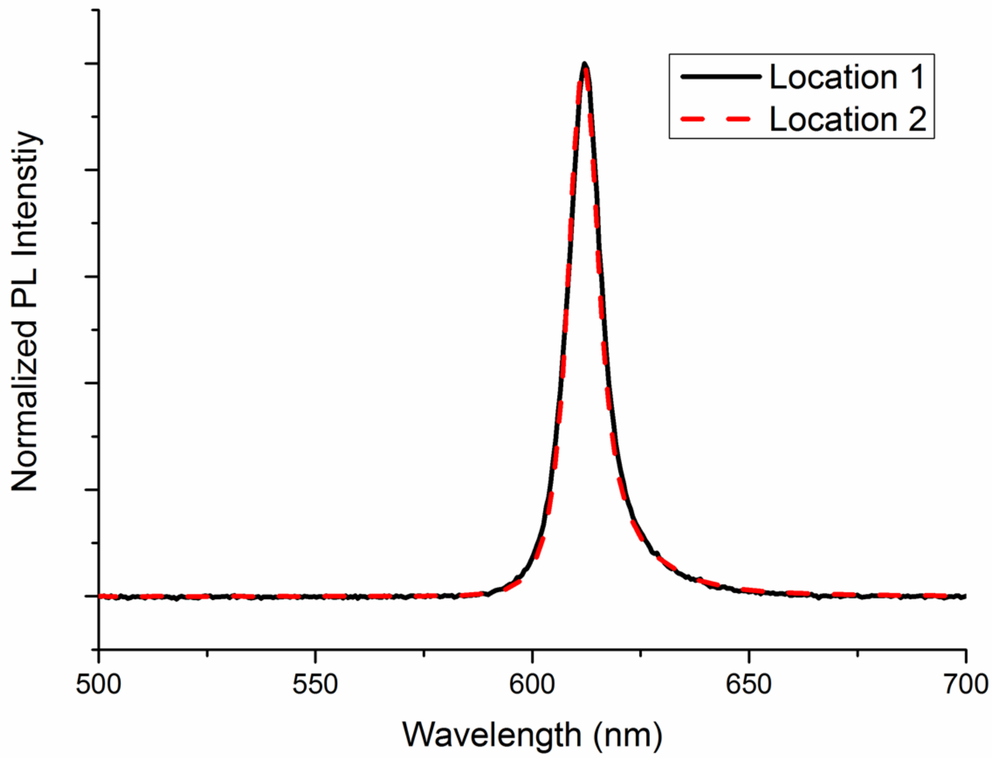

Fig.S1. *PL spectrum at different location for monolayer* WS_2.

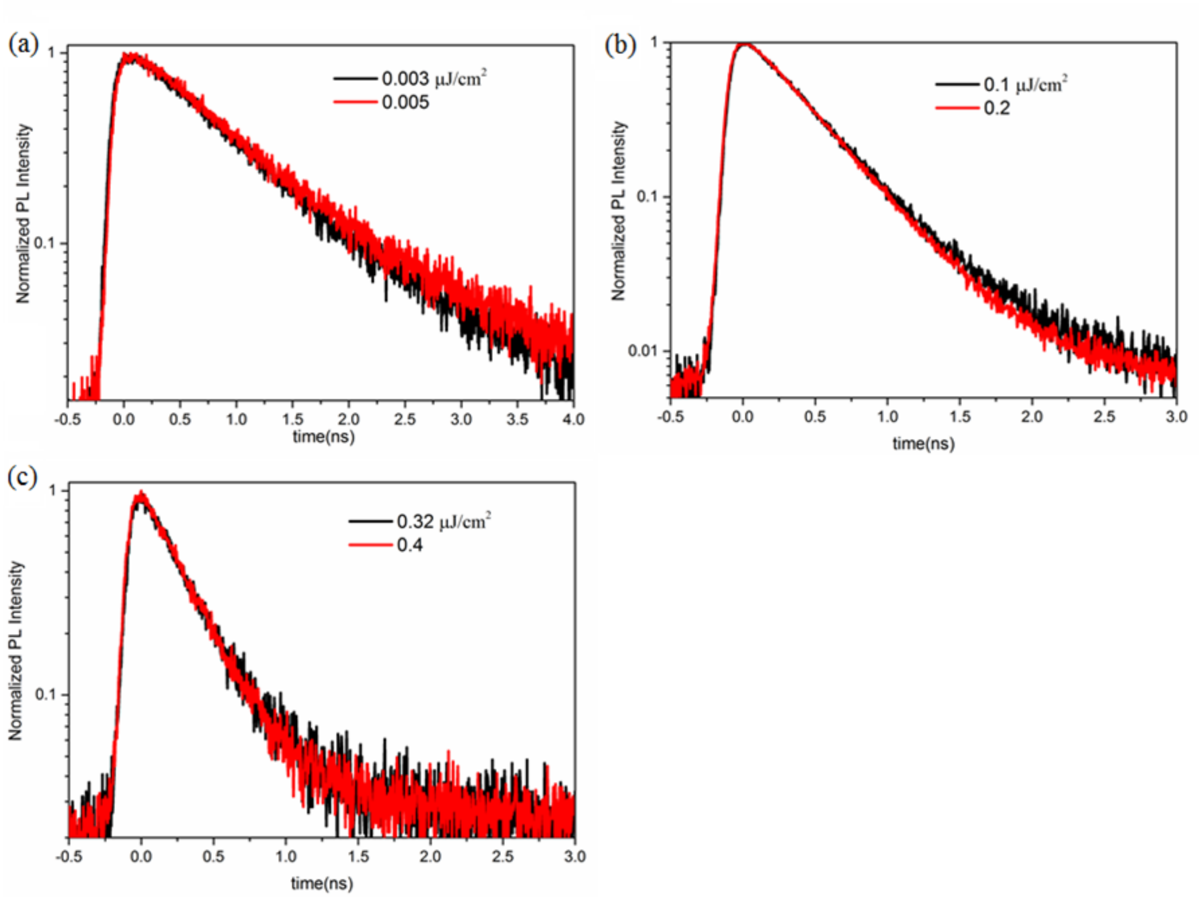

Fig. S2. *PL decay at two different low excitation densities to obtain the exciton lifetime without annihilation for* WS_2 *(a) monolayer, (b) bilayer, and (c) trilayer.*

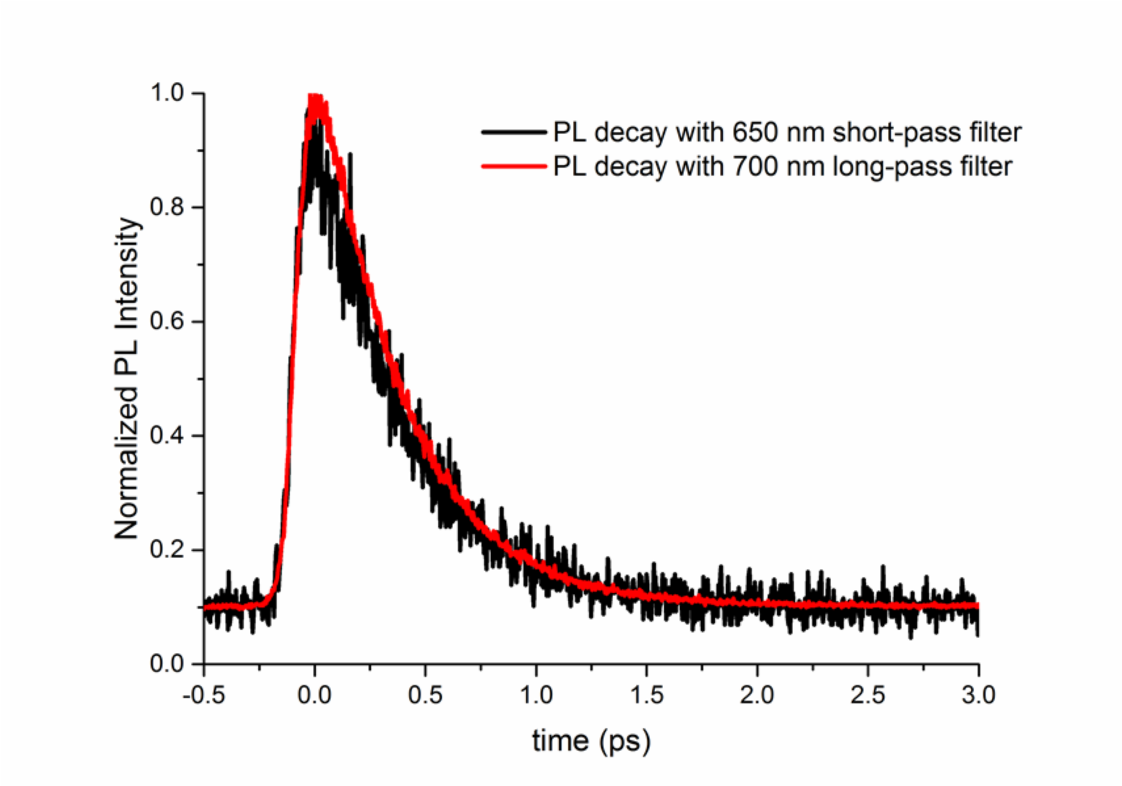

Fig. S3. *PL decay with 650 nm short-pass filter (black line) and 700 nm long-pass filter (red line) in WS_2 bilayer at pump intensity of 0.2 uJ/cm^2.*

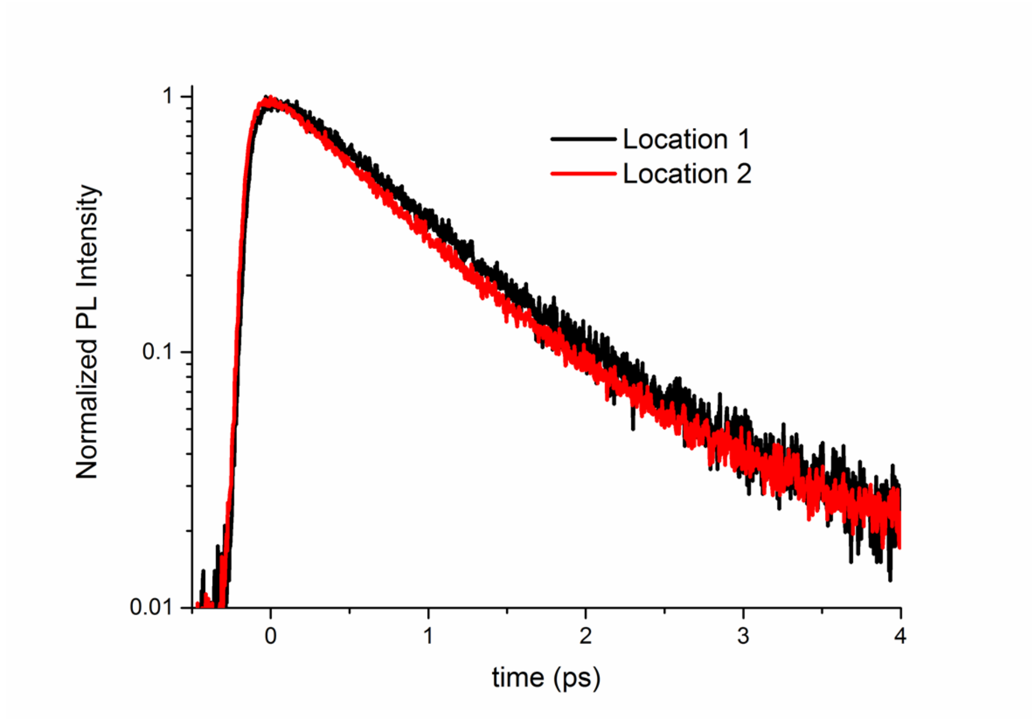

Fig. S4. *PL decay for WS_2 monolayer at different locations at pump intensity of 5 nJ/cm^2.*

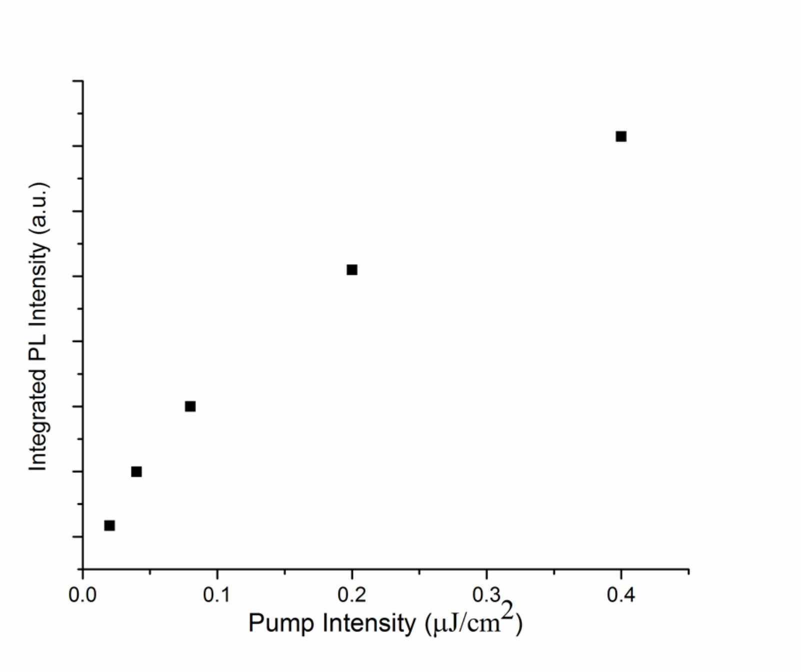

Fig. S5. Integrated PL intensity for monolayer WS_2 as a function of pump intensity.

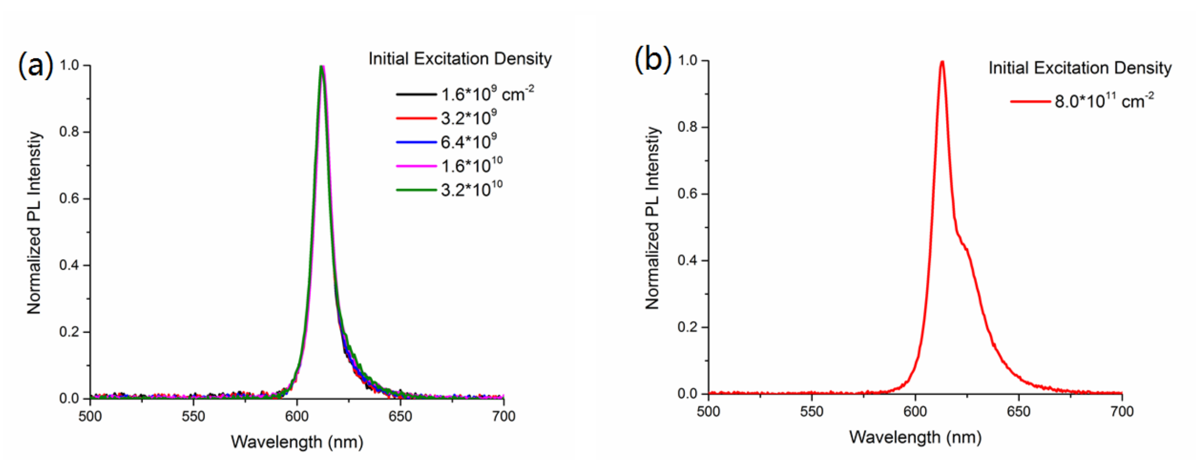

Fig S6. *Evolution of PL spectra in WS_2 monolayer with the pumping intensity. We observed an obvious biexciton emission peak only at pump intensity great than $8.0*10^{11}$ cm^{-2} (b).*

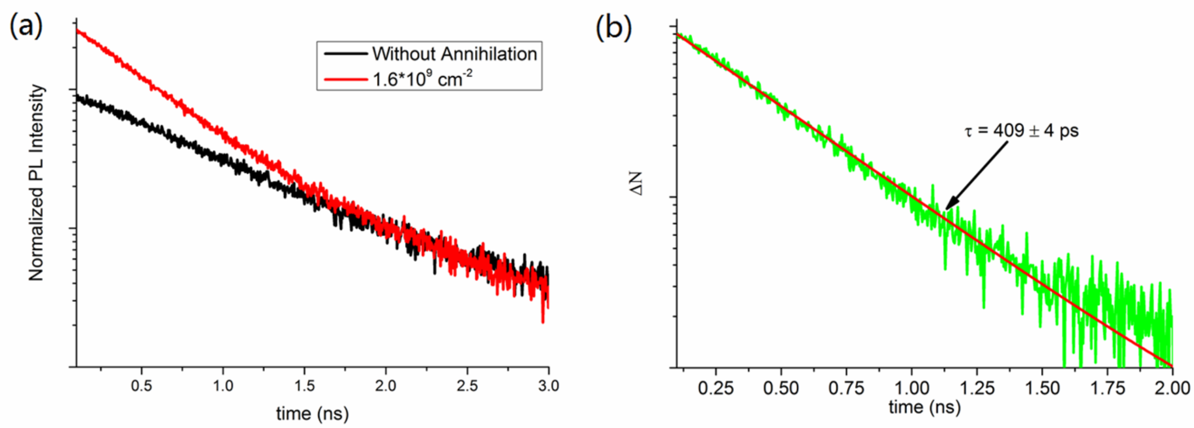

Fig. S7. (a)Normalize the decay curves at the low pump intensity (without annihilation) and high exciton density (1.6×10^9 cm^{-2}) at the long delay time of 2 ns. (b) The subtracted decay curve at the low pump intensity from the high pump intensity and fit the subtracted curve with a single exponential decay. The obtained annihilation time is ~ 400 ps.

Quantum yield measurements

We measured the quantum yield of WS_2 monolayer, bilayer, and trilayer following the method referring in previous study[1]. We used a calibrated reference consisting of a thin film of rhodamine-6G dye molecules. The films were prepared by spin coating a glass substrate with a concentrated methanol solution of rhodamine-6G. We firstly calibrated the absolute QY of our reference film using the methanol solution of rhodamine-6G, which has a quantum yield of 100%. With this reference, we then determined the QY of WS_2 films.

Reference

1. Mak, K. F. L., C.; Hone, J.; Shan, J.; Heinz, T. F., *Phys. Rev. Lett.* 2010, **105**, 136805.