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 $\mu$J/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 greater than $8.0 \times 10^{11}$ cm$^{-2}$ (b).
Fig. S7. (a) Normalize the decay curves at the low pump intensity (without annihilation) and high exciton density ($1.6 \times 10^9 \, \text{cm}^{-2}$) 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 $\sim 400$ 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