Bright Electroluminescence from Back-Gated WSe$_2$ P-N Junctions Using Pulsed Injection

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Abstract: We demonstrate bright electroluminescence in WSe$_2$ monolayers using pulsed injection, without the use of split gates, chemical doping, or heterostructures. Electroluminescence quantum efficiency approaches that of photoluminescence, indicating efficient exciton formation with injected carriers.

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1. Introduction
Next-generation optical interconnects require fast, efficient, nanoscale light sources [1–3]. Transition metal dichalcogenide (TMDC) monolayers are an attractive option due to their direct band gap, pristine surfaces, and ease of top-down fabrication. Tungsten diselenide (WSe$_2$) in particular shows ambipolar electrical characteristics, which is necessary for a light-emitting device. A variety of electrically-injected light emission schemes have been explored, including formation of P-N junctions using electrostatic gating with split gates [4] or ionic liquid gating [5], impact ionization [6], and vertical heterostructures [7]. These often require complex fabrication processes or measurement in vacuum or low temperature. Here, we demonstrate that bright electroluminescence can be achieved in WSe$_2$ using a simple back-gated field-effect transistor (FET) structure in pulsed voltage operation.

2. Fabrication Methods
Fabrication of WSe$_2$ FETs begins with an ITO-coated (280 nm) glass wafer (Thin Film Devices) with 20 nm Al$_2$O$_3$ gate oxide deposited by atomic-layer deposition (ALD). Chemical vapor deposited (CVD) WSe$_2$ is transferred atop the oxide using a PMMA-based pick-and-place method, followed by dissolution of PMMA in dichloromethane (DCM) at 50°C for 10 min. Flakes are patterned with e-beam lithography (EBL) and etched using XeF$_2$ vapor into ~10×10 µm$^2$ regions. A second EBL step defines contact regions, and 40 nm Au contacts are deposited with e-beam evaporation, followed by liftoff. The channel lengths are fixed at 1 µm for all devices. Fig. 1a shows a schematic of the device.

3. Experimental Results
Square-wave voltage signals are simultaneously applied to the source and drain contacts using two synchronized function generators, at frequencies ranging from 1 Hz – 1 MHz, and voltages ranging from 4 – 6 V. The back gate is

Figure 1. (a) Device schematic with bias conditions. (b) EL and PL spectra. EL is taken at $V_p = -V_n = 4$ V, $f = 5$ Hz. PL is taken at 330 nW pump power. (c) EL spatial map. Scale bar is 5 µm. (d) EQE versus equivalent current for EL and PL. EL is taken at $f = 1$ Hz.
grounded. One contact is designated as the p contact with \( V_p \) switching between 0 to \( |V| \), and the other with \( V_n \) from 0 to \(-|V|\). Duty cycle is fixed at 50%, but the phase between p and n is varied. Electroluminescence (EL) is collected from the top through a 20x objective and focused onto either a grating for spectral measurement, or mirror for spatial measurement, then onto a Si CCD. Photoluminescence (PL) spectra are also taken with etched flakes on the same chip, using a 532 nm pump laser. All measurements are performed in ambient conditions. The normalized EL and PL spectra in Fig. 1b show reasonable agreement, indicating the EL is due to excitonic recombination. The small discrepancy is likely due to spatial inhomogeneity, as PL is collected from a different etched region of the same large flake. Fig. 1c shows a spatial map of EL overlaid on an image of the device. Emission occurs in the channel region and is typically brightest in 1-3 localized spots. Fig. 1d compares PL and EL external quantum efficiency (EQE) versus equivalent current injected in the device, which takes optical absorption into account for PL. Electrical current is measured using a series resistor, with voltage bias at 1 Hz. We assume 6% absorption at 532 nm, as calculated from FDTD simulation. PL and EL EQE are comparable, indicating efficient exciton formation of the injected free carriers. Note that EQE is corrected for efficiency of the optical setup (~2x) but not for light trapping in the substrate, which adds a factor of \(~4\pi^2 \approx 10\) when calculating IQE. With EL injection at 1 Hz, we observed significant current fluctuation during pulsed operation, so only one point (average over many cycles) is plotted in Fig. 1d. We also note that the device is functional at DC voltage bias, but with lower efficiency, and with intensity and current decay on a timescale of 10s of seconds. Pulsed injection overcomes this issue.

Time-dependence of EL is measured with time-correlated single photon counting (TCSPC) at 1 MHz. Integrated emission for one period in shown in Fig. 2a and 2b, with the p voltage leading or lagging the n voltage respectively. Emission only occurs when both p and n voltages overlap. Thus, both hole and electron injection are necessary for EL. We observe \(~15\) ns EL rise and fall times (Fig. 2a inset), limited by the function generator and external parasitics. This is \(~20x\) faster than a recent report using vertical injection heterostructures [8], indicating strong potential for high-speed operation. In conclusion, we demonstrate efficient electroluminescence in monolayer WSe\(_2\) using pulsed injection. This bright emission using a facile process paves the way for future development of TMDC light emitters.

Figure 2. (a, b) Time-resolved electroluminescence measured with TCSPC, at leading and lagging voltage phase. Inset: close-up of fall time.

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4. References:


