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# Efficient carrier-to-exciton conversion in field emission tunnel diodes based on MIS-type van der Waals heterostack

Abstract

Van der Waals (vdW) heterostructures comprising of two-dimensional (2D) crystals offer promising prospects for realizing ultrathin electronic and photonic devices with precisely tailored functionalities.[1, 2] Efficient excitonic electroluminescence (EL) is a fundamental requirement for the realization of practical excitonic devices. Most EL devices reported to date require a large drive current density to trigger light emission, suggesting that that injected electrons and holes have low probability of forming a bound state during its transit across the active layer.[3, 4] We report on efficient carrier-to-exciton conversion and planer electroluminescence from tunnel diodes based on a metal-insulator-semiconductor van der Waals heterostack consisting of few-layer graphene (FLG), hexagonal boron nitride (hBN), and monolayer tungsten disulfide ($WS_2$). These devices exhibit excitonic electroluminescence with extremely low threshold current density of a few pA·μm$^{-2}$, which is several orders of magnitude lower compared to the previously reported values for the best planar EL devices. Using a reference dye, we estimate the lower bound of EL quantum efficiency to be ~ 1 % at low current density limit, which is of the same order of magnitude as photoluminescence quantum yield at the equivalent excitation rate. [5] Our observations indicate that the efficiency of our devices is not limited by carrier-to-exciton conversion efficiency but by the inherent exciton-to-photon yield of the material. The device characteristics indicate that the light emission is triggered by injection of hot minority carriers (holes) to n-doped $WS_2$ by Fowler-Nordheim tunneling and that hBN serves as an efficient hole-transport and electron-blocking layer. Our findings offer insight into the intelligent design of van der Waals heterostructures and avenues for realizing efficient excitonic devices.

## References

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## Figures

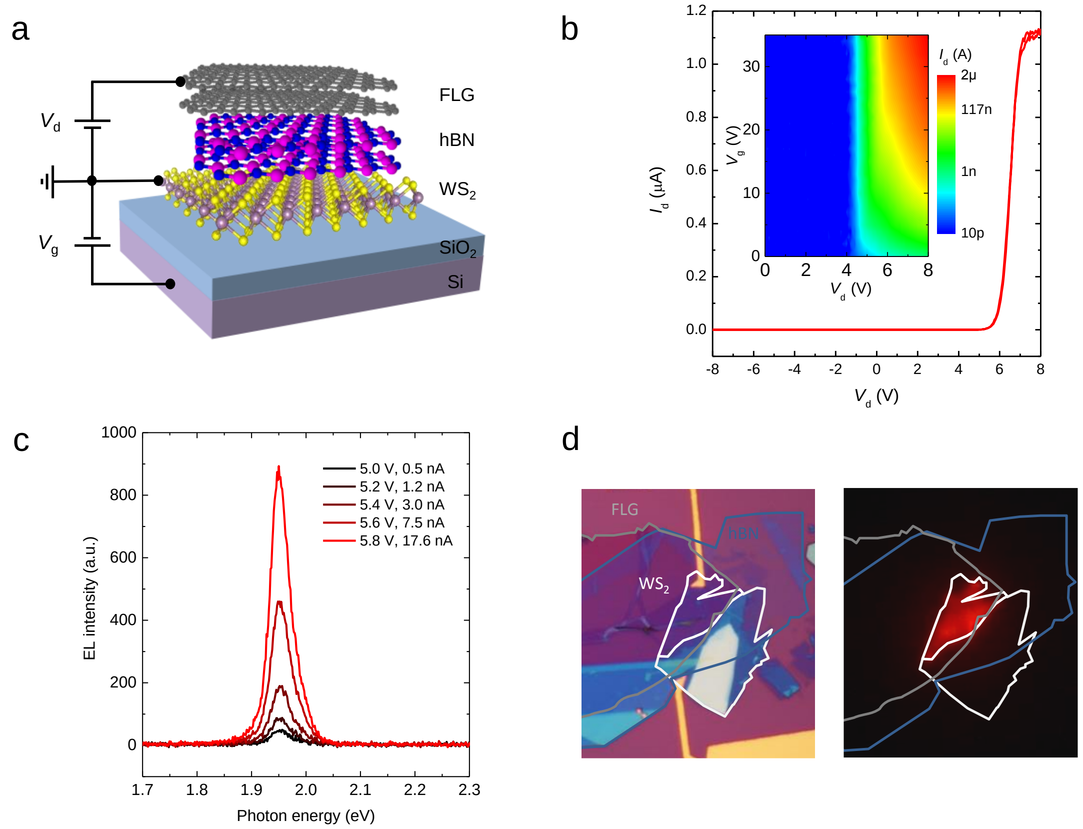


**Figure 1: Light emitting diode based on MIS-type vertical vdW heterostack.** (a) Schematic view of FLG/hBN/$WS_2$ light emitting diode. (b) $I_d$-$V_d$ characteristic at $V_g$ = 40 V. The inset shows the plot of tunneling current as a function of $V_g$ and $V_d$. (c) EL spectra of the MIS diode at different $V_d$ and $I_d$ at 100 K. (d) Bright-field optical image of the device and image of EL at an injection current of 100 nA at an accumulation time of 2 s.