Supporting Information

Enhanced Field-Effect Control of Single-Layer WS_2 Optical Features by hBN Full Encapsulation

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Sample fabrication

Single-layer WS_2 and few-layer hBN flakes were mechanically exfoliated from bulk crystals with Nitto SPV 224 tape and transferred onto the surface of a Gel-Film (Gel-Pak WF ×4 6.0 mil) substrate. Then single-layer flakes of WS_2 were identified on the PDMS stamp with an optical microscope operated in transmission mode[1] and their thickness confirmed by differential reflectance.

Synthetic bulk WS_2 crystals were purchased from HQ Graphene.

Bulk hBN crystals were grown by K. Watanabe and T. Taniguchi.[2]

Raman characterization of the sample

Figure S1 shows the Raman signals coming from single-layer WS_2 (between 200 cm^{-1} and 500 cm^{-1}) and hBN (between 1200 cm^{-1} and 1500 cm^{-1}). The top panels have been recorded on bare WS_2 and bare hBN regions while the bottom panels have been measured in the hBN/WS_2/hBN stack region. The spectra collected on the WS_2 monolayer show typical Raman feature for this 2D material. [3] For laser excitation of 532 nm, the Raman spectrum is dominated by the 2LA mode at ~ 352 cm^{-1}, E^1_{2g} at ~356 cm^{-1} and A_{1g} at ~ 418 cm^{-1}.

Regarding hBN, the Raman spectrum is dominated by E_{2g} peak at 1362 cm^{-1}.

Gate dependent differential reflectance spectroscopy:

In order to verify the tunability of the optical properties by means of the electric-field, preliminary gate-dependent differential reflectance measurements were carried out on the devices.

For this measurements, the device is mounted under the objective of an optical microscope (Motic BA310 Met-T) system supplemented with a homebuilt micro-reflectance module based on a fiber- coupled CCD spectrometer (CCS200/M, Thorlabs).[4] The differential reflectance spectrum was calculated as (R-R0)/R, where R is the intensity reflected by the flake, R0 the intensity reflected by the substrate.[5] The absorbance spectra show two main peak features at 2.02 eV and 2.4 eV, respectively associated to direct band gap transitions at the K point of the Brillouin zone that generates excitons labelled A and B,[6] but Figure S2 focuses mainly on the characteristics of exciton A, which is also prominent in photoluminescence.[7]

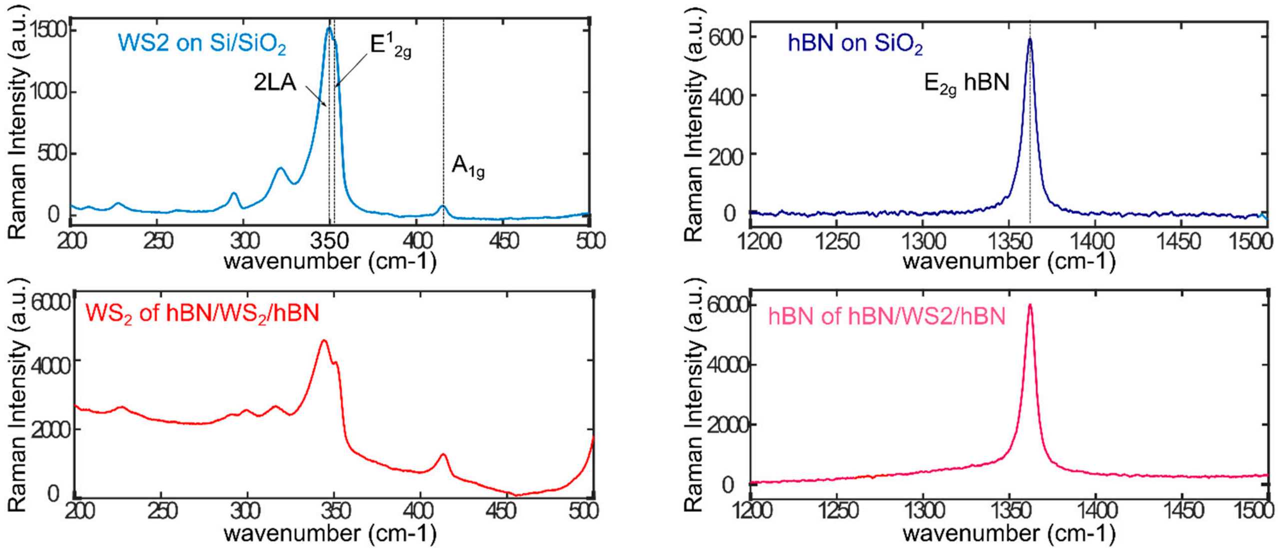

Figure S1. Room-temperature Raman spectra from the unencapsulated monolayer WS_2 region (top left), from the bottom hBN (top right) and from the hBN/WS_2/hBN stack region (bottom left and bottom right), using a 532 nm laser excitation. The main peaks due to WS_2 and hBN have been labeled.

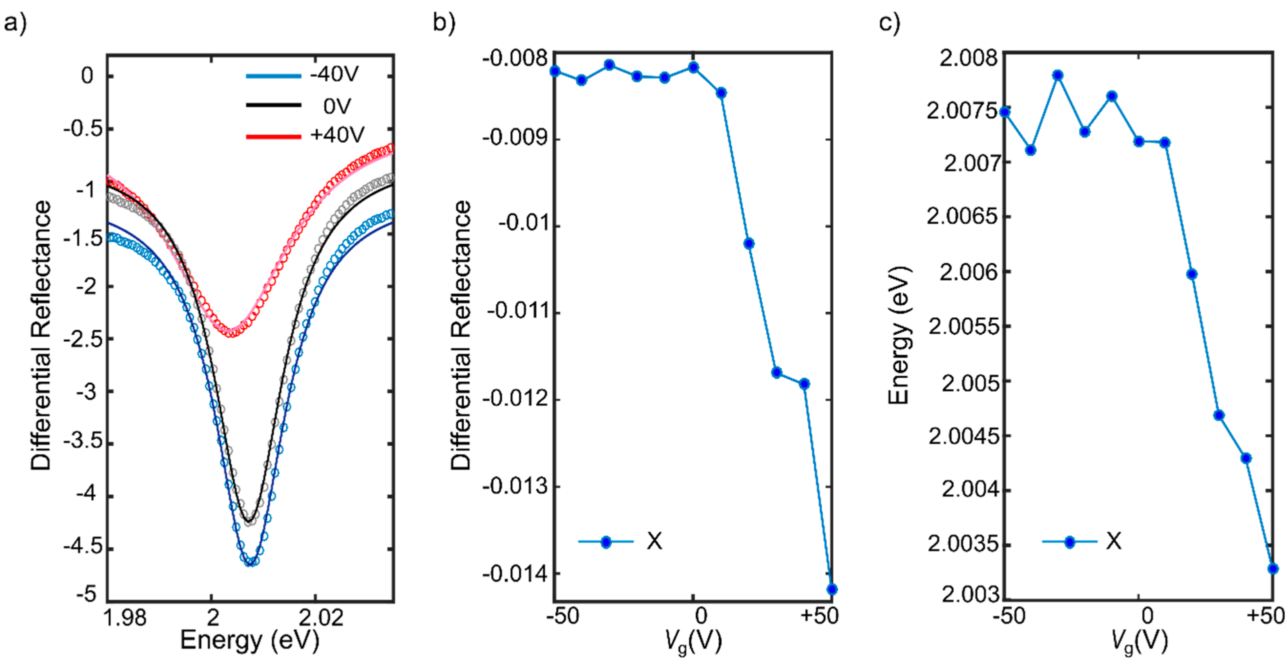

Figure S2. (a) Differential Reflectance spectra of the 1L-WS_2 sample at the back-gate voltages between -40V and 40 V. (b) Differential reflectance intensity of the A peak versus gate voltage. (c) Gate-dependent optical hysteresis the for A peak differential reflectance intensity in 1L-WS_2 FET.

Figure S2a shows the differential reflectance spectra of WS_2 FET under gate voltages, namely -40 V, 0 V and 40 V. We observed an overall reduction of the optical absorbance in correspondance of the A peak by increasing electron doping. Moreover, this effect is also accompanied by a red shift of the main peak. Fig S2b shows, the intensity variation of the peak as a function of voltage ranging from -40 V and 40 V with a step voltage of 10 V. We also observed the hysteresis behaviour in the differential reflectance performing a full gate sweep from -50 V to 50 V (Figure S2c). It is worth to note that was not possible to appreciate a reflectance signal on the WS_2 single-layer encapsulated with hBN, due to thin film destruvtive interference related to the thicknesses of hBN and SiO_2 that strongly influence the visibility of exciton resonances in absorption measurements.[8]

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