Out-of-Plane Electromechanical Response of TMDs

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The electromechanical properties of materials are inherently interesting for sensors, actuators, and energy harvesters in which deformation is coupled with electronic or optical properties. 2D materials offer a promising platform for such devices because when atomically thin, they can withstand large strains and strain gradients. Theory [1] and experiments [2, 3] have revealed that transition metal dichalcogides (TMDs) are intrinsically piezoelectric in-plane due to their lack of centrosymmetry in or close to the monolayer limit. Recently, we have shown that MoS_2 also exhibits an out-of-plane electromechanical response, potentially a result of the flexoelectric effect [4]. Theory suggests that flexoelectricity may depend on lattice constant, allowing for the opportunity to study the fundamental nature of the effect by looking at similar TMDs with varying lattice constants.

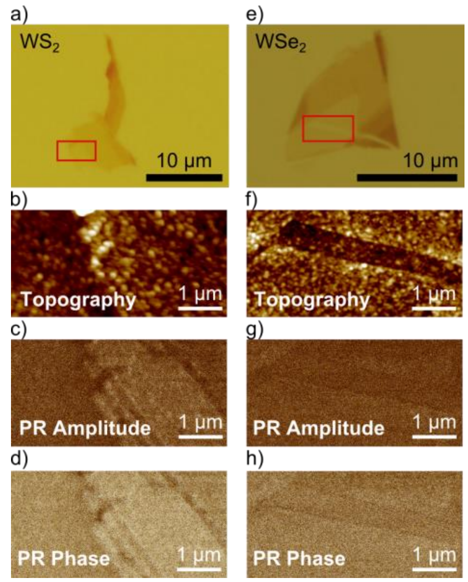

Figure 1. Optical images (a, e), and simultaneously captured topography (b, f), PR amplitude (c, g) and PR phase (d, h) images taken on WS_2 (a, b, c, d) and WSe_2 (e, f, g, h). The red box in a and e indicate the location of the PFM images taken below.

In this work, the out-of-plane electromechanical response of other monolayer TMDs is measured using piezoresponse force microscopy. A conductive atomic force microscope probe is used to apply an AC voltage across the sample and a lock-in amplifier is then used to measure the resultant deflection. Exfoliated WS_2 and WSe_2 are transferred onto gold for the measurements. Figure 1 shows optical images, topography, and piezoresponse (PR) amplitude and phase images for both WS_2 and WSe_2. Clear contrast between both TMDs and the underlaying gold in the PR images confirms that out-of-plane electromechanical coupling is present. Preliminary analysis suggests a correlation between the magnitude of the response and the lattice constant as indicated by the stronger contrast in the WS_2. A more detailed analysis of the results will be presented as well as their possible flexoelectric origin.

[1] Duerloo, K. A. N., Ong, M. T. & Reed, E. J., *J. Phys. Chem. Lett.* **3,** 2871–2876 (2012).
[2] Wu, W., Wang, L., *et al.*, *Nature* **514,** 470–474 (2014).
[3] Zhu, H., Wang, Y., *et al.*, *Nat. Nanotechnol.* **10,** 151–155 (2014).
[4] Brennan, C. J., Ghosh, R., *et al.*, *Nano Lett.* **17,** 5464–5471 (2017).
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Supplementary Page:
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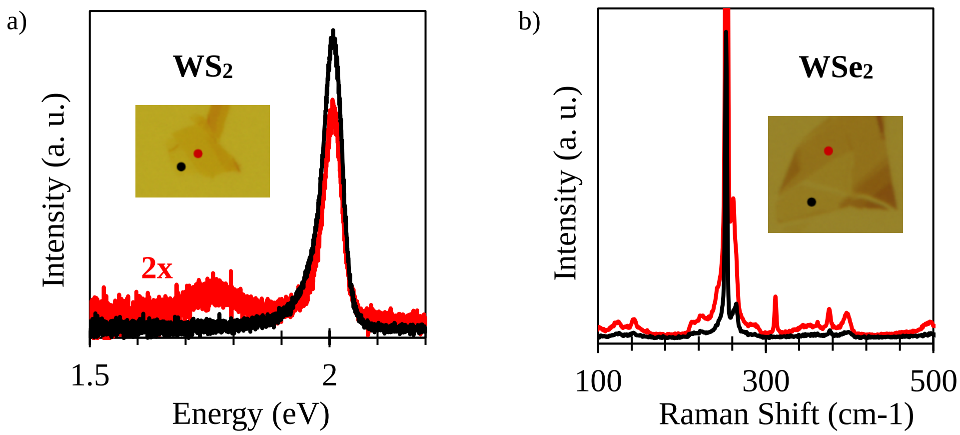

Figure S1. a) Photoluminescence (PL) measurements of WS_2 monolayer (black) and multilayer (red) regions scanned in Figure 1. The strong, single peak in the PL signal indicates that it is monolayer [S1]. b) Raman shift of WSe_2 monolayer (black) and multilayer (red) region scanned in Figure 1. The absence of the peak around 310 cm^{-1} in the black curve indicates that it is monolayer [S2].

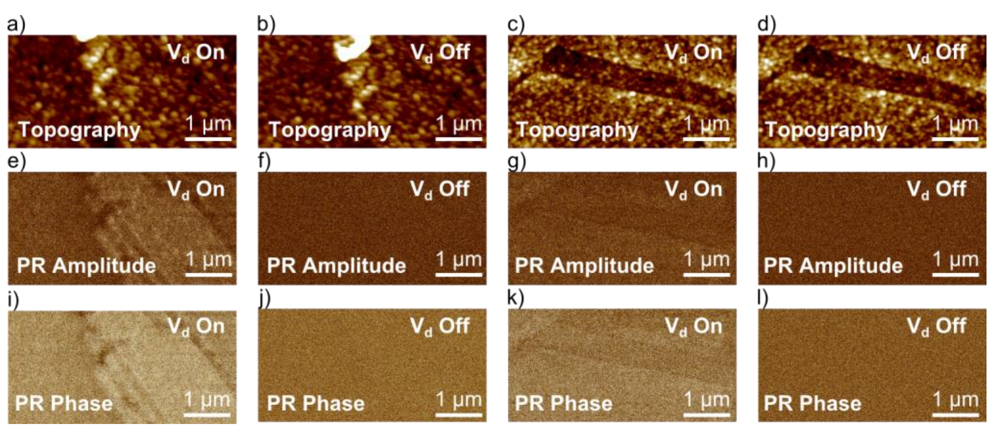

Figure S2. PFM images of WS_2 (a, b, e, f, i, j) and WSe_2 (c, d, g, h, k, l) taken with the drive voltage (V_d) applied (a, c, e, g, i, k) and not applied (b, d, f, h, j, l). The topography (a - d), PR amplitude (e - h) and PR phase (i - l) images in each case are taken simultaneously. The disappearance of the contrast when V_d is not applied indicates that there are no scanning artifacts.

[S1] Zhao, W., Ghorannevis, Z., *et al. ACS Nano* **7,** 791–797 (2013).
[S2] Zhao, W., Ghorannevis, Z., *et al. Nanoscale* **5,** 9677 (2013).