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Load-dependent energy dissipation induced by the tip-membrane friction on suspended 2D materials

Supporting Information

Content: Evolution of the E_{2g}^1 and A_{1g} modes in FL WS_2 (Figure S1), AFM tests of few-layer (FL) WS_2 (Figure S2), Determination of the lateral stiffness and torsional elastic potential energy of the cantilever, experiments considering the tilt compensation method (Figure S3).

Evolution of the E_{2g}^1 and A_{1g} modes in FL WS_2

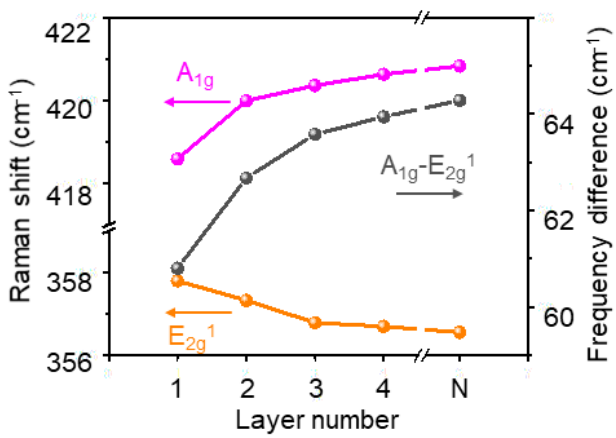

Figure S1. Evolution of the E_{2g}^1 and A_{1g} modes and their frequency difference with the number of layers.

AFM tests of FL WS_2

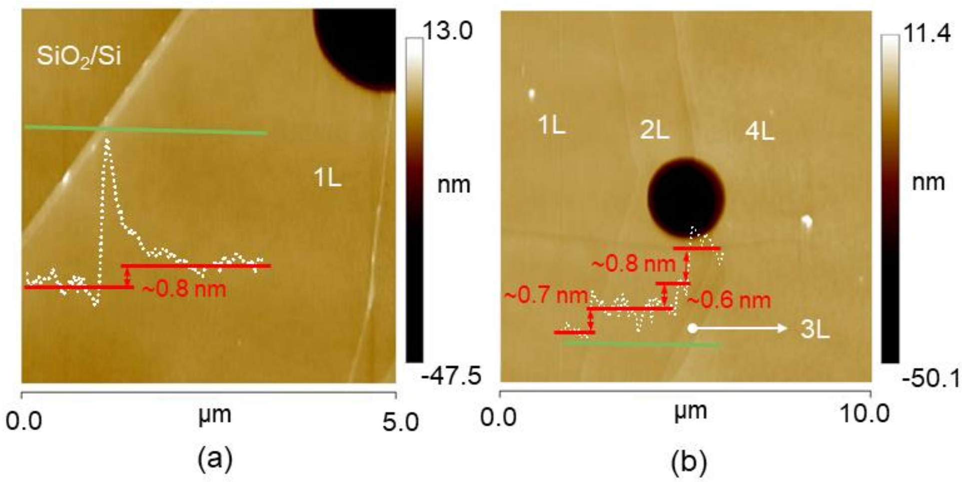

Figure S2. (a), (b) AFM tests of FL WS_2 from 1 layer to 4 layer. White dotted lines are the height profiles along the green solid lines.

To precisely determine the thickness of FL WS_2, a softer cantilever (vertical stiffness of ~0.2 N/m) was employed. As shown in Figure S2a and b, the thickness between individual layer was close to the theoretical thickness of ~0.7 nm, further confirming the effectiveness of the results from Raman spectroscopy.

Determination of the lateral stiffness and torsional elastic potential energy of the cantilever

The lateral stiffness (scaled by force/voltage) of the tip was firstly determined to be ~5000 nN/V via an improved wedge calibration method.[1] Since the optical sensitivity of the PSD could be viewed as the same in the vertical and lateral directions, the same amplitude voltage should result in the same variations in the vertical and lateral deflection angles.[2] Therefore, the lateral sensitivity S_L of the tip could be obtained by the following formula:

$$\frac{S_L}{H+t} = \frac{S_V}{L} \tag{S1}$$

where t and L are the length and thickness of the cantilever respectively, H is the tip height and S_V is the vertical sensitivity of the cantilever. When substituting the values of $t = 2.7\ \mu m$, $L = 100\ \mu m$, $H = 15\ \mu m$, and $S_V = 65.14$ nm/V into Equation (S3), the lateral sensitivity S_L was calculated to be ~11.53 nm/V. Thus, the lateral stiffness (scaled by force/displacement) of the cantilever was ~433.65 nN/nm. The maximum lateral deflection force F_L for 1L WS_2 in the Figure 3b was ~300 nN, corresponding to a lateral deflection displacement d_L of ~0.69 nm. This kind of the small displacement enabled the estimation of the torsional elastic potential energy stored in the cantilever to be ~103.5×10^{-18} J (equal to ~$\frac{1}{2} F_L \cdot D_L$).

Experiments considering the tilt compensation method

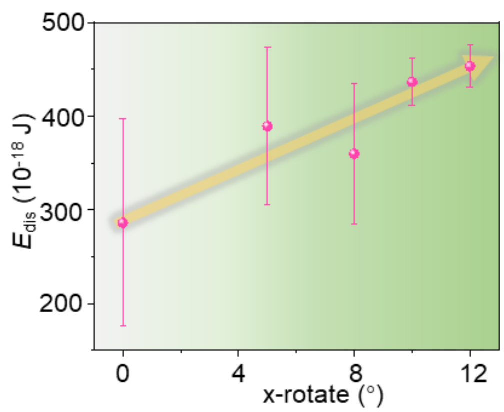

Figure S3. Variation of the energy dissipation (E_{dis}) with the x-rotate obtained from the indentation tests on suspended monolayer WS_2 with the load of ~540 nN.

Here we have conducted similar indentation experiments on suspended monolayer WS_2 membranes by varying the value of the x-rotate as shown in Figure S3. Theoretically, the method of the cantilever tilt compensation was proposed to reduce the extent of the side slip as demonstrated in related literatures.[3-5] However, it was even found that the energy dissipation would slightly increase with the increase of the x-rotate. This may be attributed to the complex situation favored by the ignorable bending stiffness of the ultrathin membrane, which distinguished our experimental results from the theoretical expectations. This may also demonstrate that the compensation method for the indentation on ultrathin membrane requires further investigation. On the other hand, the dependence of the energy dissipation on the x-rotate may indicate that the energy dissipation is related to the cantilever tilt (side slip).

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