Electronic Supplementary Material (ESI) for Nanoscale.

Supporting Information for

Ultra-low Friction and Patterning on Atomically Thin MoS_2 via Electronic Tightly Binding

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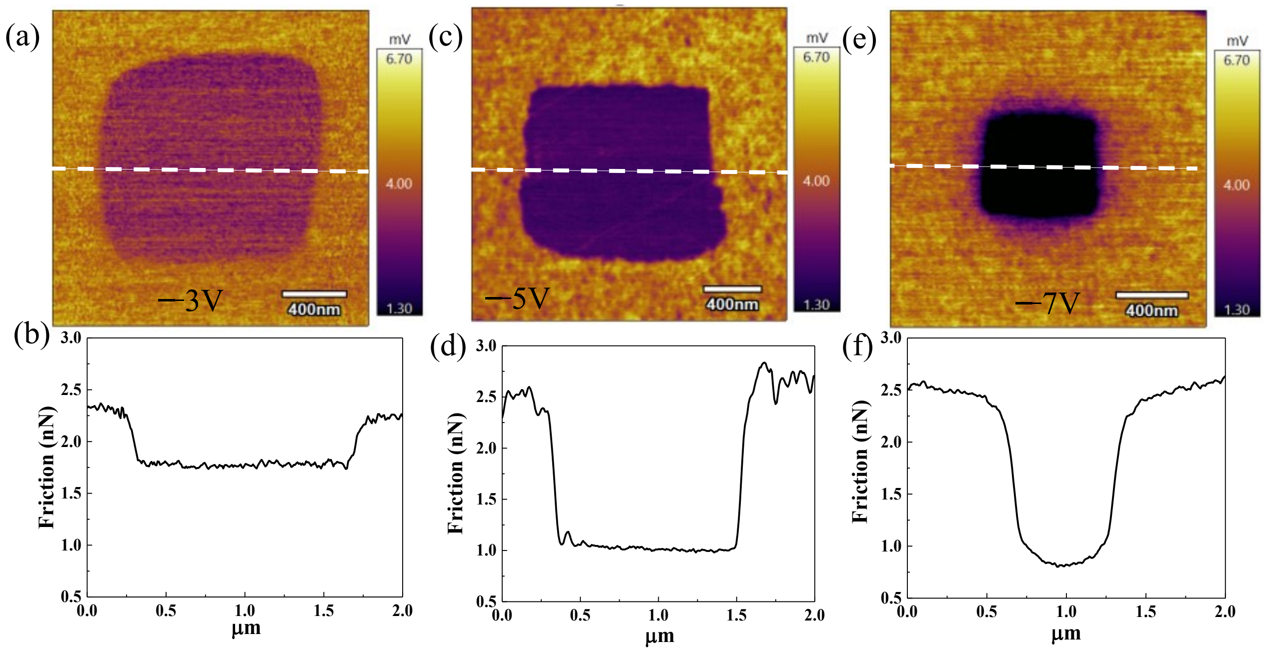

Figure S1. Friction maps of atomically thin MoS_2 after rubbing with different gate voltages and corresponding friction profiles with the applied load of 20 nN. (a, c, e) Friction maps of atomically thin MoS_2 after rubbing with gate voltages of −3 V, −5 V and −7 V, respectively. (b, d, f) Corresponding friction profiles along the white dotted lines.

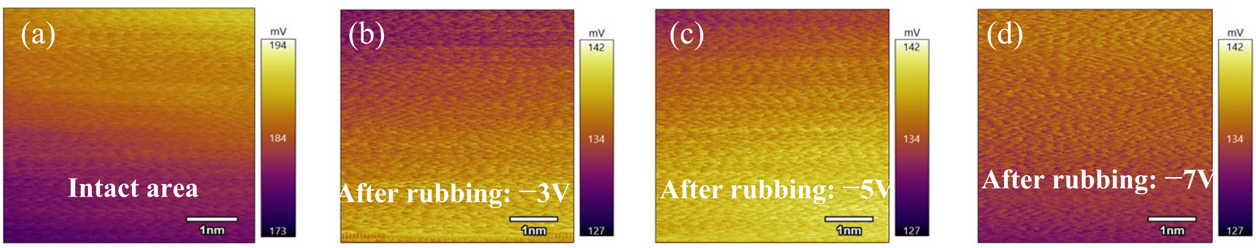

Figure S2. Lateral force maps measured on the intact area and the rubbed area of atomically thin MoS_2. (a) Lateral force map measured on the intact area of atomically thin MoS_2. (b, c and d) Lateral force maps measured on the rubbed area with gate voltages of –3V, −5V and −7V, respectively.

Calculation of the contact area between the atomically thin MoS_2 and AFM tip based on DMT model: AFM tip (Multi-75AL-G) used for friction tests was characterized using SEM (HITACHI S-4800) to measure the tip radius. The frictional values of MoS_2 in Figure 1(e) were used as the fitting data.

The general equation is [1]:

$$\frac{a}{a_0(\alpha)} = \left(\frac{\alpha + \sqrt{1 - L/L_c(\alpha)}}{1 + \alpha}\right)^{\frac{2}{3}} \qquad (1)$$

Where L is the load, L_c is the pull-off force, a and a_0 represent the contact radius at load L and at zero load, respectively. α is a parameter which can be obtained from the fitting. F_0 and L_c are acquired from DMT model. The values of F_0 are 0.71±0.08, 0.9±0.02, 1.51±0.014, 1.68±0.02, respectively.

In DTM model, $L_c = -2\pi\gamma R$. where R is the tip radius (~ 30 nm) and γ is the work of adhesion. At zero load, a_0 is given by:

$$a_0 = \left(\frac{2\pi\gamma R^2}{K}\right)^{\frac{1}{3}} \qquad (2)$$

where K is the combined elastic modulus of the tip and the sample, given by

$$K = \frac{4}{3}\left[\frac{1 - \nu_t^2}{E_t} + \frac{1 - \nu_s^2}{E_s}\right]^{-1} \qquad (3)$$

where E_t and E_s represent the Young's modulus of the tip and sample materials, ν_t and ν_s represent the respective Poisson ratios (E_t~130 GPa, E_s~270 GPa, ν_t~0.27, ν_s~0.25).[3,4] Combining eqs 1, 2, and 3, the calculated contact area at zero load at V_g = 0 V, −3 V, −5 V, and −7 V are 22.05±0.39nm^2, 20.09±0.31 nm^2,16.46±0.28 nm^2 and 13.9±0.22 nm^2, respectively.

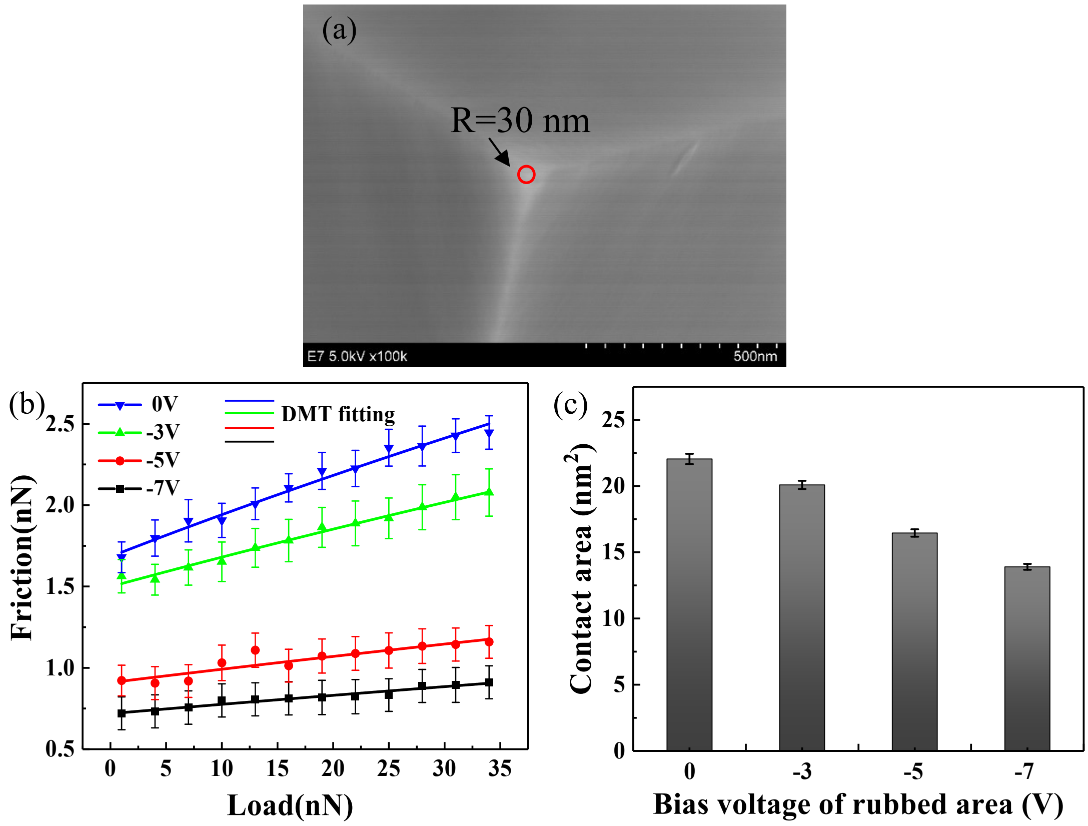

Figure S3. SEM image of the Si tip and friction as a function of load with different gate voltages. (a) SEM image of the Si tip used for friction tests. (b) Plot of the friction versus the applied load on the rubbed area of atomically thin MoS_2 with different gate voltages. Variation of the true contact areas during the tip sliding on atomically thin MoS_2 with different gate voltages based on DMT fit.

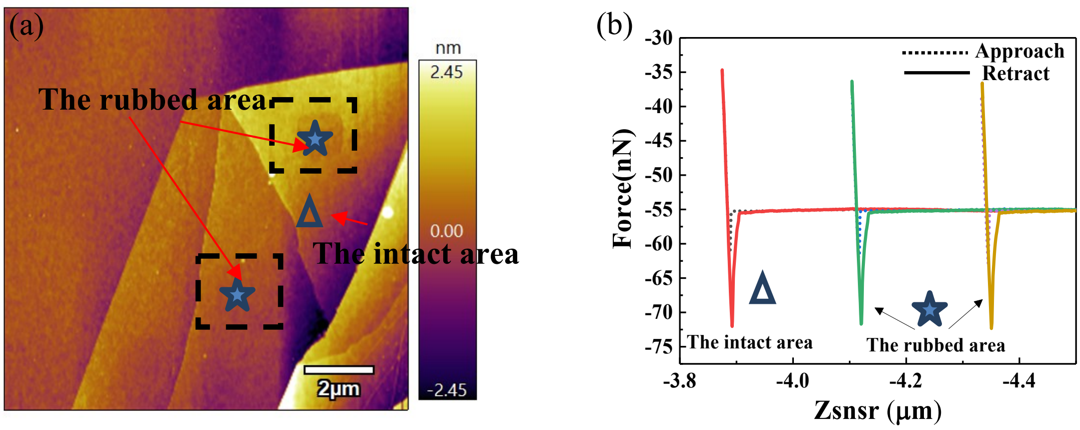

Figure S4. Pull-off force measurements on the rubbed area and the intact area of atomically thin MoS_2. (a) AFM topography image of atomically thin MoS_2 after rubbing at the gate voltage of −6V. (b) Corresponding pull-off force curves acquired on the regions as marked on the rubbed area and the intact area by star and triangle in (a). Little difference in the pull-off force curves is observed between the two representative regions.

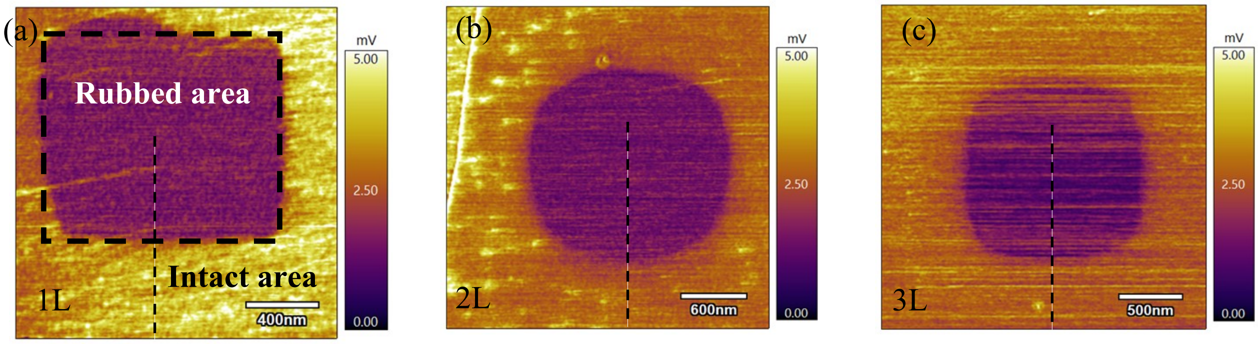

Figure S5. (a, b, c) Frictional maps measured on MoS_2 with different layer thicknesses under the applied load of 10 nN.

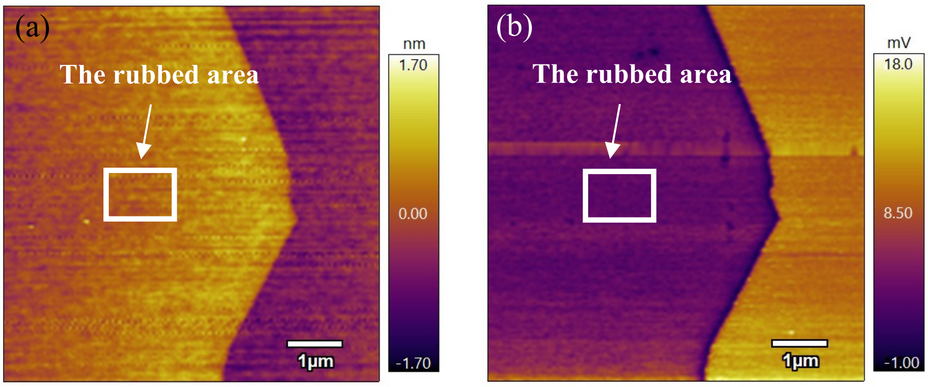

Figure S6. AFM topography image of atomically thin MoS_2 and friction map after rubbing. (a) The AFM topography of the atomically thin MoS_2 after rubbing at the gate voltage of +6V. (b) Friction map of atomically thin MoS_2 on SiO_2/Si substrate (applied load of 25 nN) after rubbing at the gate voltage of +6V. The results indicated that the friction of the atomically thin MoS_2 does not show observable change after rubbing with the positive gate voltage.

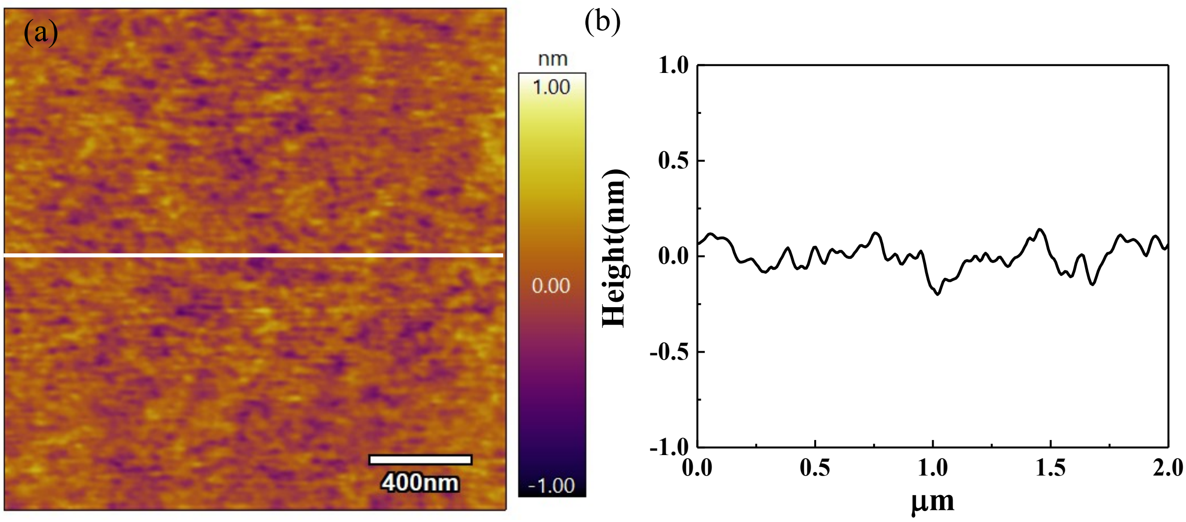

Figure S7. AFM topography image of SiO_2/Si substrate. (a) Topographic image of SiO_2 surface. (b) The height profile of SiO_2 along the white line in (a). The surface roughness values Ra on a representative SiO_2/Si substrate is 0.172 (±0.006) nm.

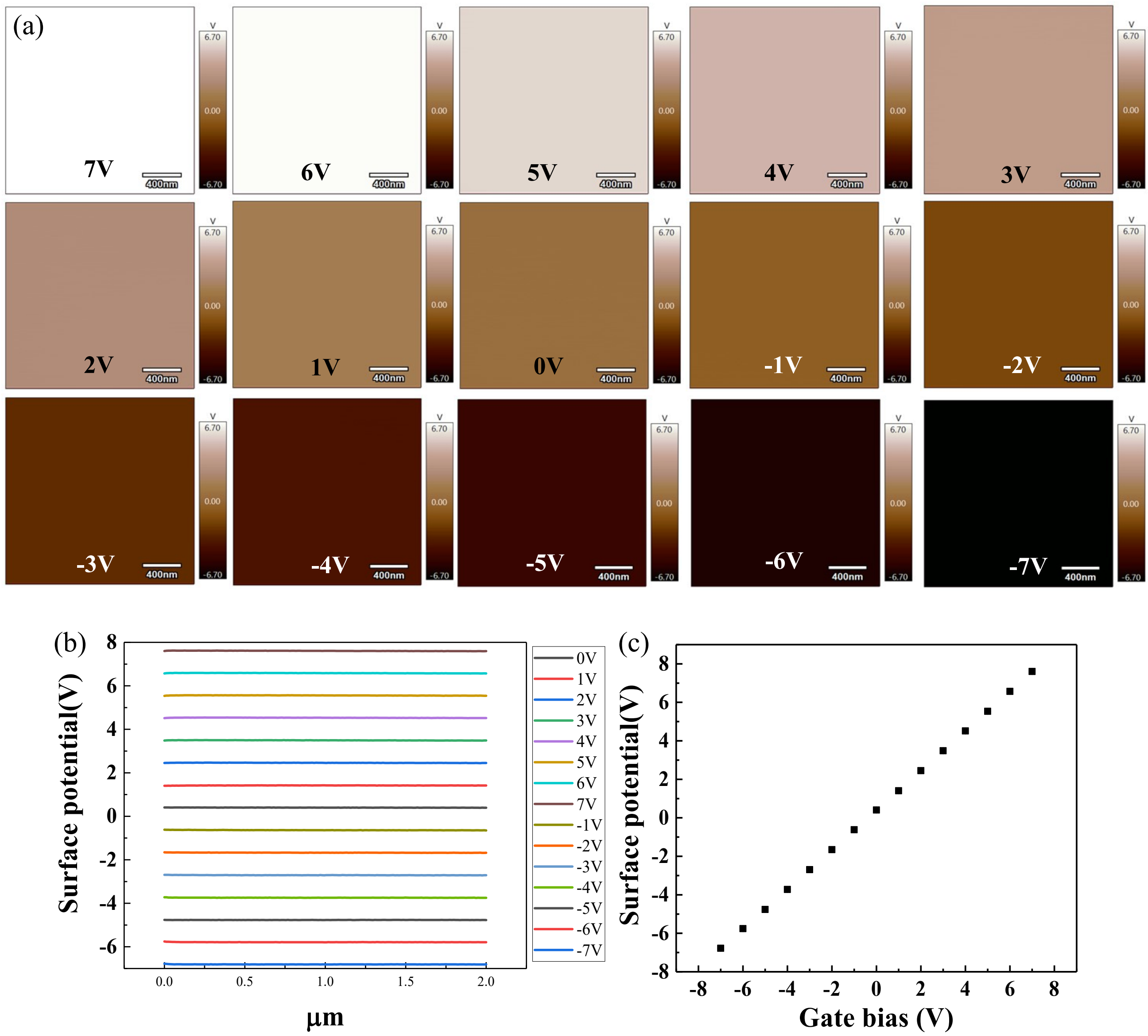

Figure S8. SKPM characterization and corresponding profiles with different gate voltages. (a-o) The surface potential images of SiO_2/Si substrate with gate voltages from −7 V to +7 V. (p) The line profiles of the surface potentials along the conductive tip and SiO_2/Si substrate with different gate voltages. (q) Surface potential difference between the conductive tip and SiO_2/Si substrate as a function of different gate voltages.

References

[1] Ni Z. H., Wang H. M., Kasim J., et al. Graphene thickness determination using reflection and contrast spectroscopy. Nano Letters **2007**, 7(9):2758-2763.

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[3] Castellanos-Gomez A., Poot M., Steele G. A., van der Zant H. S. J., Agrait N., Rubio-Bollinger G. Mechanical Properties of Freely Suspended Semiconducting Graphene-Like Layers Based on MoS_2. Nanoscale Research Letters **2012**, 7:233.

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