Supporting Information

Two- and four-probe field-effect and Hall mobilities in transition metal dichalcogenides field-effect transistors

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Atomic Force Microscopy

Atomic force microscopy (AFM) was performed to investigate the thickness and the surface morphology of WS_2 and MoS_2 films. Figs. S1a and S1b show the surface topology for WS_2 and MoS_2 flakes, respectively. AFM was conducted under tapping mode in ambient condition. Figs. S1c and S1d show height profiles, in which the thickness of WS_2 was ~10 nm and that of MoS_2 was ~14 nm. Both flakes were multilayer films.

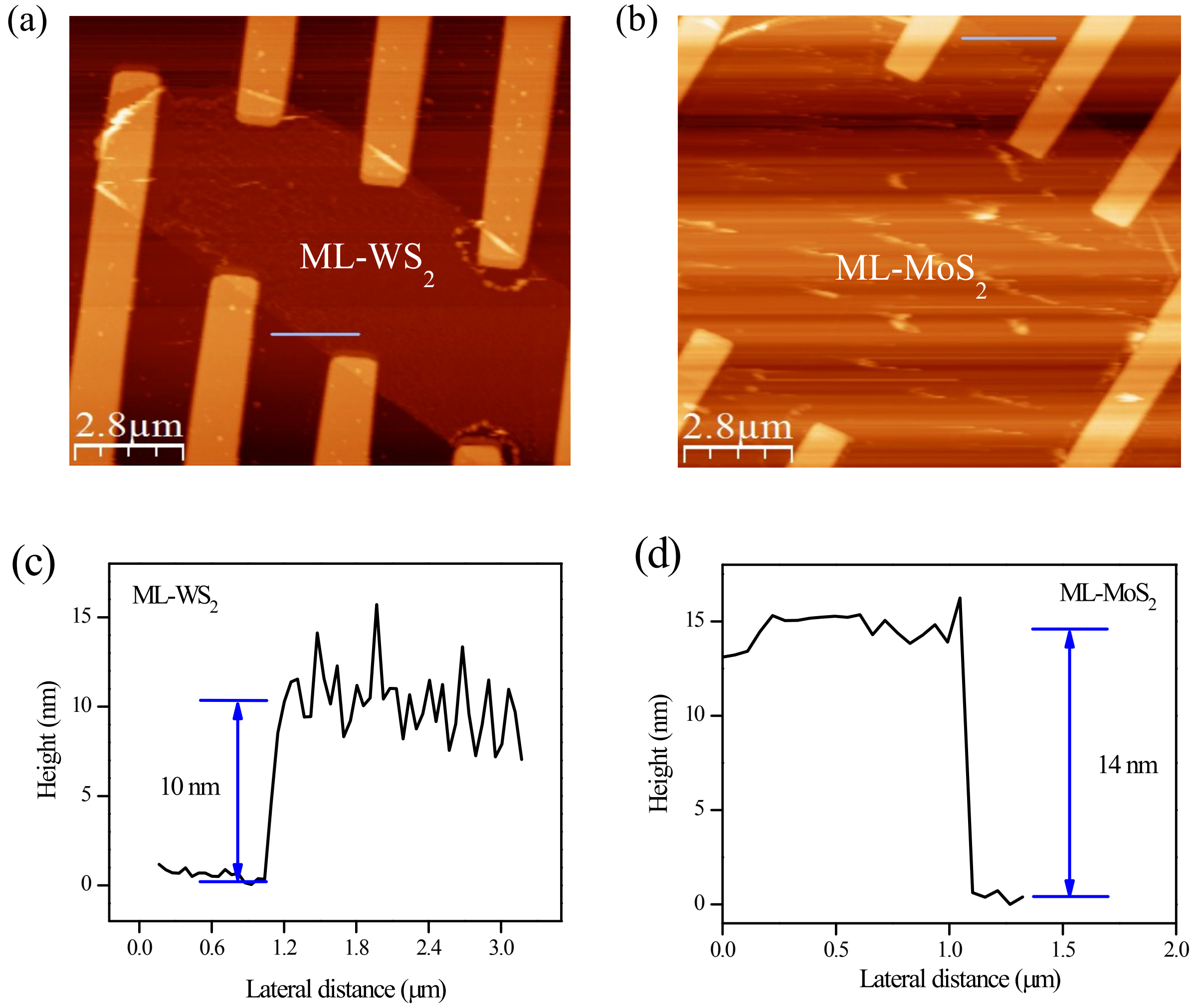

Fig. S1 Atomic force microscopy image of (a) WS_2 and (b) MoS_2 flakes. (c) Height profile along the gray line for WS_2 flake. (d) Height profile along the gray line for MoS_2 flake.

Raman spectroscopy

Raman spectroscopy provides very useful information about the number of layers of samples and the quality of films. Figs. S2a and S2b show the Raman shift for WS_2 and MoS_2 flakes. Both samples (WS_2 and MoS_2) showed two optical phonon modes for WS_2 at 352 and 420 cm^{-1} and for MoS_2 at 384 and 408 cm^{-1} for the in-plane E^1_{2g} and out-of-plane A_{1g} vibrations, respectively[1, 2]. The variation in relative peak intensity ratios E^1_{2g}/A_{1g} and the frequency difference between E^1_{2g} and A_{1g} modes strongly depend on layer thickness[1]. To analyze the spectra, Lorentzian curve fitting was conducted for both WS_2 and MoS_2 flakes to measure peak intensities and locations of E^1_{2g} and A_{1g}. The peak difference between A_{1g} and E^1_{2g} modes ($\Delta = A_{1g} - E^1_{2g}$) was nearly 68 cm^{-1} for WS_2 [1, 3] and 24 cm^{-1} for MoS_2 [1, 4, 5]; these results indicated that both samples were multilayer films.

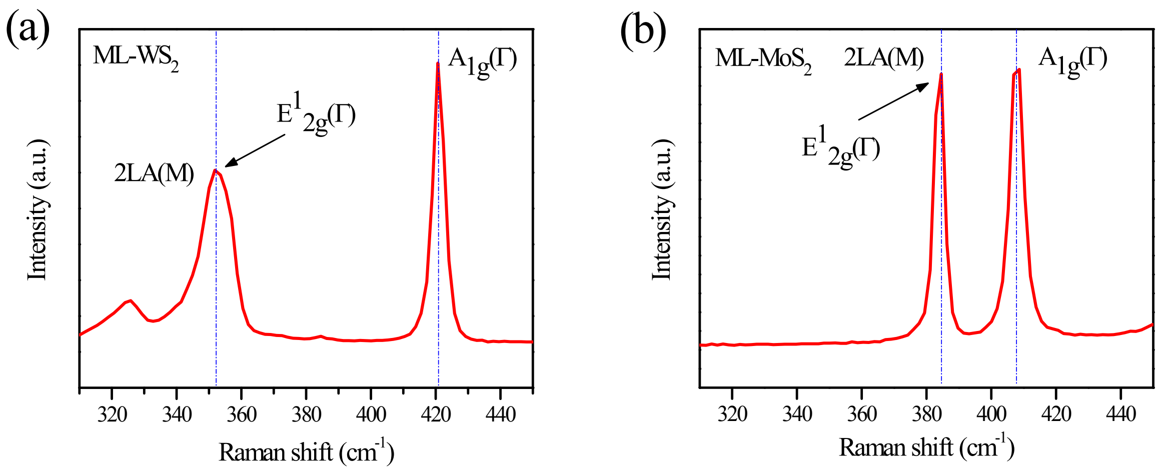

Fig. S2 Raman spectroscopy of (a) WS_2 and (b) MoS_2 flakes at room temperature using laser with wavelength of 514 nm.

Contact Resistance

We measured contact resistance for both WS_2 and MoS_2 samples using the transmission line method. Figs. S3a and S3b show the plots of specific resistance ($\rho= R\times W$) for WS_2 and MoS_2, respectively. Total specific resistance for the WS_2 or MoS_2 samples can be given by the following formula:

$$\rho_{total} = \rho_{channel} + 2\rho_c$$

where $\rho_{channel}$ indicates channel specific resistance, and ρ_c represents contact resistance at metal/semiconductor junctions for both devices. Specific contact resistance was measured by linear fitting the curve of $\rho_{channel}$ at a certain V_{bg}, which was set at 60 V. We measured the specific contact resistance for WS_2 and MoS_2 films at 3 and 13.5 kΩ.μm respectively[6, 7].

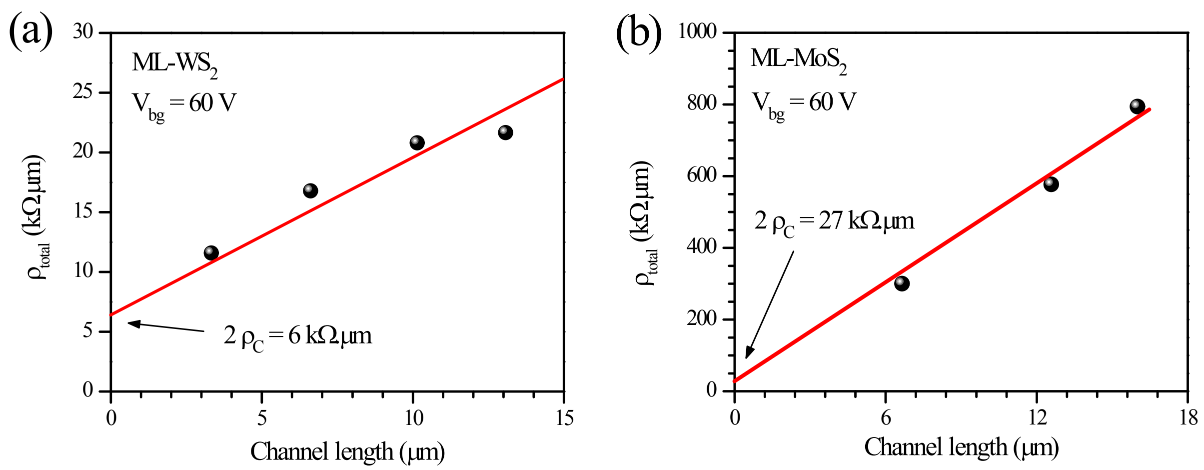

Fig. S3 Total specific resistance as a function of channel length for multilayer (a) WS_2 and (b) MoS_2 films using the transmission line method. The specific contact resistance is estimated as 3 kΩ.μm for WS_2 and 13.5 kΩ.μm for MoS_2.

References

1. W. Zhao, Z. Ghorannevis, K. K. Amara, J. R. Pang, M. Toh, X. Zhang, C. Kloc, P. H. Tan and G. Eda, *Nanoscale*, 2013, **5**, 9677-9683.
2. A. L. Elias, N. Perea-López, A. Castro-Beltrán, A. Berkdemir, R. Lv, S. Feng, A. D. Long, T. Hayashi, Y. A. Kim and M. Endo, *ACS nano*, 2013, **7**, 5235-5242.
3. H. Zeng, G.-B. Liu, J. Dai, Y. Yan, B. Zhu, R. He, L. Xie, S. Xu, X. Chen and W. Yao, *Scientific reports*, 2013, **3**, 1608.
4. D. Kiriya, M. Tosun, P. Zhao, J. S. Kang and A. Javey, *Journal of the American Chemical Society*, 2014, **136**, 7853-7856.
5. H. Li, Q. Zhang, C. C. R. Yap, B. K. Tay, T. H. T. Edwin, A. Olivier and D. Baillargeat, *Advanced Functional Materials*, 2012, **22**, 1385-1390.
6. H. M. Khalil, M. F. Khan, J. Eom and H. Noh, *ACS applied materials & interfaces*, 2015, **7**, 23589-23596.
7. S. Kim, A. Konar, W. S. Hwang, J. H. Lee, J. Lee, J. Yang, C. Jung, H. Kim, J. B. Yoo, J. Y. Choi, Y. W. Jin, S. Y. Lee, D. Jena, W. Choi and K. Kim, *Nature communications*, 2012, **3**, 1011.