Electronic Supplementary Material (ESI) for Nanoscale.
This journal is © The Royal Society of Chemistry 2019

Supporting Information

Polarity Control in a Single Transition Metal Dichalcogenide (TMD) Transistor for Homogeneous Complementary Logic Circuits

Jaewoo Shim,‡[a,b] Sung woon Jang,‡[a] Ji-Hye Lim,[a] Hyeongjun Kim,[a] Dong-Ho Kang,[a,c] Kwan-Ho Kim,[a] Seunghwan Seo,[a] Keun Heo,[a] Changhwan Shin,[a] Hyun-Yong Yu,[d] Sungjoo Lee,[e] Dae-Hong Ko,[f] and Jin-Hong Park[a,d]*

[a] *Department of Electrical and Computer Engineering, Sungkyunkwan University, Suwon 16419, Korea*
[b] *Department of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge, MA 02139, United States*
[c] *School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore*
[d] *School of Electrical Engineering, Korea University, Seoul 02841, Korea*
[e] *SKKU Advanced Institute of Nano Technology (SAINT), Sungkyunkwan University, Suwon 16419, Korea*
[f] *Department of Materials Science & Engineering, Yonsei University, Seoul 03722, Korea*

‡ These authors equally contributed to this work.
*) Correspondence to Jin-Hong Park (jhpark9@skku.edu)

AFM image and height profiles of WSe_2/WTe_2 heterostructure

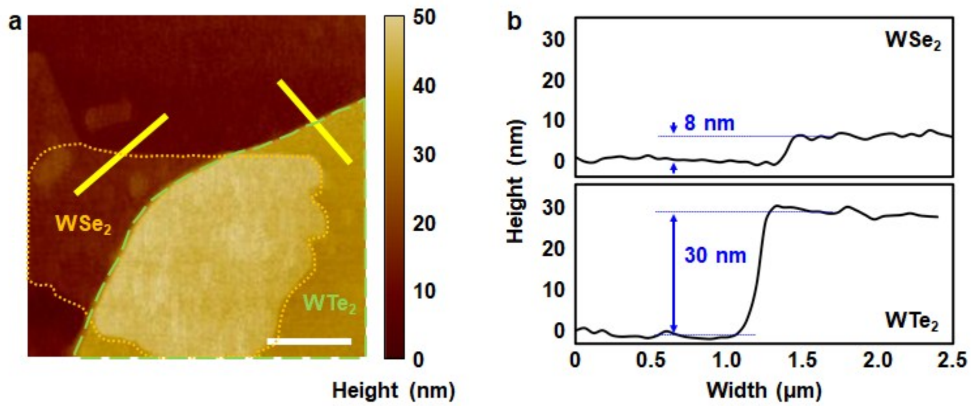

Fig. S1. (a) Atomic force microscope (AFM) image taken on the WSe_2/WTe_2 heterostructure sample. (b) Thickness of the WSe_2 (top) and the WTe_2 flakes (bottom) corresponding to the yellow lines marked in (a). The scale bar represents 2 μm.

The thickness of the WSe_2 and WTe_2 flakes, which were confirmed through AFM analysis, were approximately 8 nm and 30 nm, respectively.

I-V characteristics of the three different polarity controllable transistors

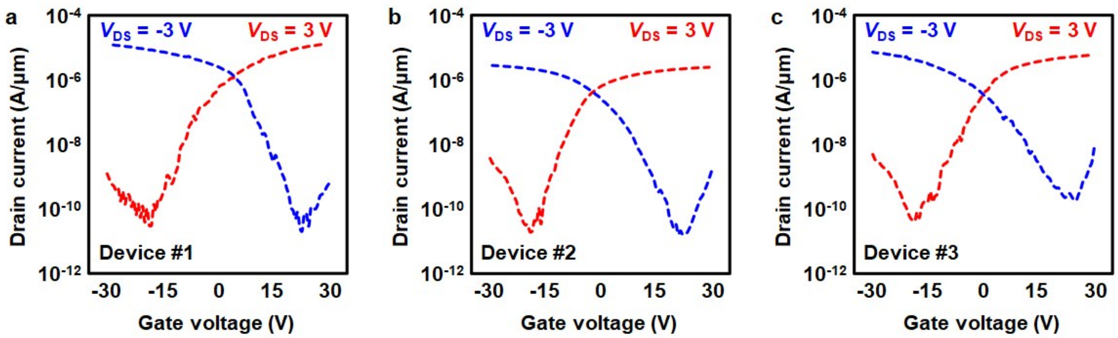

Fig. S2. (a)-(c) I_{DS}–V_{GS} characteristic curves of the WSe_2/WTe_2 heterojunction transistor at V_{DS} = 3 V (red dashed line) and V_{DS} = –3 V (blue dashed line).

We carried out current–voltage (*I*–*V*) measurements on three different polarity controllable transistors. As shown in Fig. S2, similar electrical characteristics were observed in all of the devices."

Electrical characteristics of WTe_2 at various measurement temperatures.

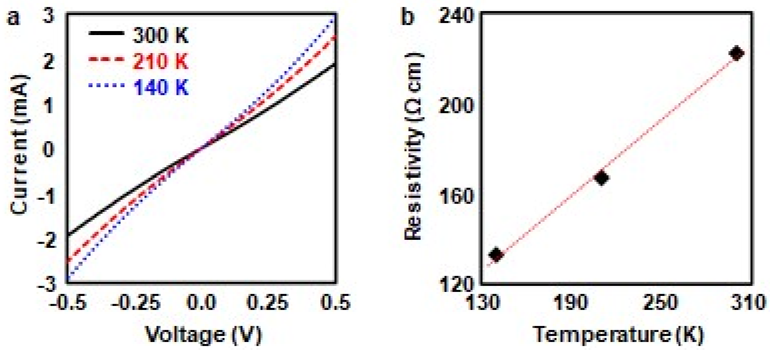

Fig. S3. (a) *I–V* characteristic curves of WTe_2 at various temperatures (140 K, 210 K, and 300 K). (b) Resistivity of WTe_2 as a function of measurement temperature, which was extracted from the *I–V* curves.

Two-terminal device was fabricated on the WTe_2 flake to investigate the electrical characteristic of the WTe_2. Fig. S3a shows the *I–V* characteristic curves of the WTe_2 device at different temperatures (140 K, 210 K, and 300 K). Then, the resistivity values of the WTe_2 were obtained from the slope of the *I–V* curves. As shown in Fig. S3b, the resistivity exhibited an increasing tendency with increasing a measurement temperature (i.e., the temperature coefficient of the resistivity was positive, indicating metallic nature of WTe_2).

Electrical characteristics of Pd/WSe_2/Pd and WTe_2/WSe_2/WTe_2 TFTs.

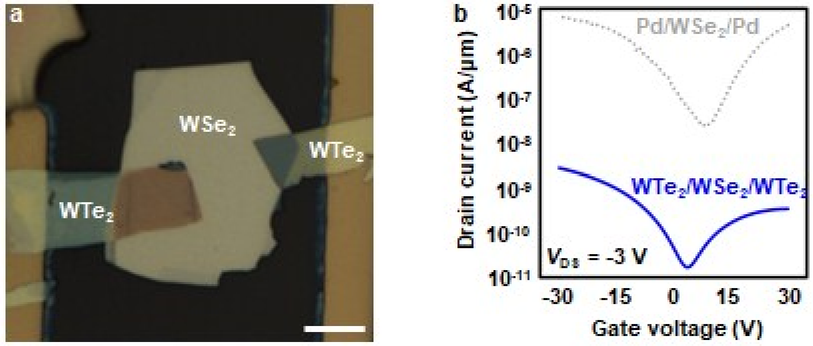

Fig. S4. (a) Optical image of WTe_2/WSe_2/WTe_2 transistor. (b) I_{DS}–V_{GS} curves of the Pd/WSe_2/Pd (gray dotted line) and WTe_2/WSe_2/WTe_2 (blue solid line) transistors at V_{DS} = –3 V. The scale bar represents 5 μm.

We fabricated a heterojunction transistor on WSe_2 using WTe_2 as electrodes, as shown in Fig. S4a. Here, the WTe_2 flakes were stacked onto the WSe_2 flake using a mechanical transfer process. Then, Pd/Au layers were deposited via e-beam evaporation to form the contacts for WTe_2. Fig. S4b shows the electrical characteristics of WTe_2/WSe_2/WTe_2 transistor with WTe_2 electrodes (blue solid line) and Pd/WSe_2/Pd transistor with metal (Pd) electrodes (gray dotted line), where V_{DS} = –3 V. The WTe_2/WSe_2/WTe_2 transistor operated at much lower current level (below 10 nA/μm) over the whole gate voltage range, compared to the Pd/WSe_2/Pd transistor.

Polarity controllable transistors with various WTe_2 thicknesses

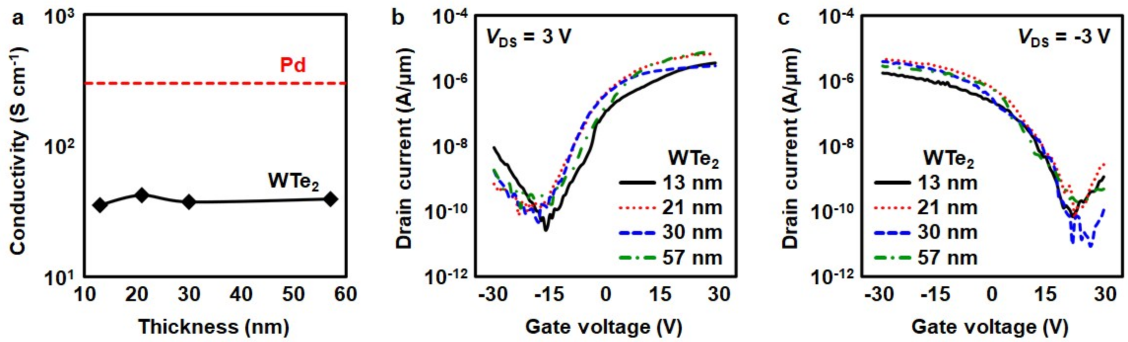

Fig. S5. (a) Conductivities of WTe_2 with various thicknesses (black symbol). Red dashed line indicates conductivity of Pd. (b,c) I_{DS}–V_{GS} characteristic curves of the polarity controllable transistors with various WTe_2 thicknesses at (b) V_{DS} = 3 V and (c) V_{DS} = –3 V.

We fabricated various WSe_2/WTe_2 heterojunction transistors using WTe_2 flakes with different thicknesses (13 nm, 21 nm, 30 nm, and 57 nm), where we used WSe_2 flakes with similar thickness (approximately 10 nm) to minimize the channel thickness effect. We then conducted *I*–*V* measurements in the WTe_2 flakes and the WSe_2/WTe_2 heterojunction transistors. Similar *I*–*V* and I_{DS}–V_{GS} characteristic curves were observed in the WTe_2 flakes (Fig. S5a) and the WSe_2/WTe_2 heterojunction transistors (Figs. S5b and S5c), respectively, regardless of the WTe_2 thickness.

Modified thermionic emission current for a heterojunction transistor with WTe_2 electrode.

The thermionic emission current is given by $J = A^{*}T^{2}\exp(-\frac{q\phi_B}{k_B T})$, where J is the current density, A^* is the effective Richardson constant, T is the temperature, q is the elementary charge, ϕ_B is the barrier height, and k_B is the Boltzmann constant.[1] The current equation is valid under the assumption that the Fermi energy at absolute zero temperature (E_{F0}) is much higher than k_BT ($E_{F0} \gg k_BT$).[2] Generally, high E_{F0} is observed in metals with lots of electrons. However, the electrode with relatively low carrier concentration like WTe_2 is expected to have much lower E_{F0} than metals. Thus, we modified the thermionic emission current equation for the heterojunction transistor using electrodes with low carrier concentration. The modified thermionic emission current based on the Richardson-Dushman equation is given by:[2]

$$J = A^{*}T^{2}\exp(-\frac{q\phi_B}{k_B T})\exp(\frac{-2\alpha E_{F0}}{k_B})\exp(\frac{80(\pi k_B T E_{F0})^2 + 7(\pi k_B T)^4}{960 E_{F0}{}^4}) \qquad (1)$$

, where α is the linear thermal expansion coefficient of WTe_2. Here, the E_{F0} is

$$E_{F0} = (\frac{h^2}{2m})(\frac{3n}{8\pi})^{2/3} \qquad (2)$$

, where h is the Planck constant, m is the effective mass of the WTe_2, and n is the carrier concentration of WTe_2.

References

1. SZE, S. M. *Physics of Semiconductor Devices*, Wiley: New York, 1981.
2. De, D. K.; Olawole, O. C. A Three-Dimensional Model for Thermionic Emission from Graphene and Carbon Nanotube. *J. Phys. Commun.* **2019,** *3*, 015004.