Supporting Information

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

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AFM image and height profiles of WSe\textsubscript{2}/WTe\textsubscript{2} heterostructure

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

The thickness of the WSe\textsubscript{2} and WTe\textsubscript{2} flakes, which were confirmed through AFM analysis, were approximately 8 nm and 30 nm, respectively.
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 WTe₂ thicknesses

**Fig. S5.** (a) Conductivities of WTe₂ 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 WTe₂ thicknesses at (b) $V_{DS} = 3$ V and (c) $V_{DS} = -3$ V.

We fabricated various WSe₂/WTe₂ heterojunction transistors using WTe₂ flakes with different thicknesses (13 nm, 21 nm, 30 nm, and 57 nm), where we used WSe₂ flakes with similar thickness (approximately 10 nm) to minimize the channel thickness effect. We then conducted $I$–$V$ measurements in the WTe₂ flakes and the WSe₂/WTe₂ heterojunction transistors. Similar $I$–$V$ and $I_{DS}$–$V_{GS}$ characteristic curves were observed in the WTe₂ flakes (Fig. S5a) and the WSe₂/WTe₂ heterojunction transistors (Figs. S5b and S5c), respectively, regardless of the WTe₂ thickness.
Modified thermionic emission current for a heterojunction transistor with WTe$_2$ electrode.

The thermionic emission current is given by $J = A' T^2 \exp(-\frac{q\phi_0}{k_B T})$, where $J$ is the current density, $A'$ is the effective Richardson constant, $T$ is the temperature, $q$ is the elementary charge, $\phi_0$ 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 $k_B T (E_{F0} \gg k_B T)$.\(^2\) 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:\(^2\)

$$J = A' T^2 \exp(-\frac{q\phi_0}{k_B T}) \exp(-\frac{2\alpha E_{F0}}{k_B T}) \exp\left(\frac{80(\pi k_B T E_{F0})^2 + 7(\pi k_B T)^4}{960 k_B E_{F0}^4}\right)$$  \hspace{1cm} (1)

where $\alpha$ is the linear thermal expansion coefficient of WTe$_2$. Here, the $E_{F0}$ is

$$E_{F0} = \frac{\hbar^2}{2m} \left(\frac{3n}{8\pi}\right)^{2/3}$$  \hspace{1cm} (2)

where $\hbar$ is the Planck constant, $m$ is the effective mass of the WTe$_2$, and $n$ is the carrier concentration of WTe$_2$.

References