Supporting Information

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Ambipolar MoTe$_2$ Transistors and Their Applications in Logic Circuits

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I. The preparation methods for the crystals and additional information on the elemental analysis.

Bulk MoTe$_2$ crystals were grown by chemical vapor transport, and the preparation method was described in detail elsewhere [1]. First, MoTe$_2$ powder was synthesized from stoichiometric Mo (99.9+ %, Nilaco) and Te (99.8 %, Sigma-Aldrich) powders. They were sealed in a fused-quartz ampoule (OD: 25 mm, ID: 22 mm, length: 190 mm) under the vacuum about $10^{-3}$ Pa, and made to react at 900 °C for 1 week. Then, typically 2.4 g of the MoTe$_2$ powder and 340 mg of Br$_2$ (transport agent) were vacuum-sealed in another fused-quartz ampoule with cooling the materials by liquid N$_2$ to avoid the loss of Br$_2$. The ampoule was set in a 2-zone horizontal electric furnace, and the temperature was raised from the room temperature (RT) up to 700 °C by a rate of 1 °C/min. Then the temperature of the source-side end of the ampoule was raised to 900 °C by 1 °C/min. After the heating for 1 week and natural cooling down to RT, bulk MoTe$_2$ single-crystals were found to grow at the opposite end of the ampoule. The experimental setup of a two-zone electric furnace for the growth of MoTe$_2$ crystals and as-synthesized bulk MoTe$_2$ crystals were displayed in Figure S1(a) and (b), respectively.

![Figure S1: (a) Experimental setup of a two-zone electric furnace for the growth of MoTe$_2$ crystal. (b) as-synthesized bulk MoTe$_2$ crystals.](image)

To get a fresh surface of MoTe$_2$ crystal, the bulk sample was cleaved in air by means of an adhesive tape before introducing into a vacuum apparatus and then was sputtered by Ar$^+$ cluster ion beam under an ultrahigh vacuum condition to remove any adsorbed contamination. Afterward, XPS inspection was carried out by using an AXIS Nova (Kratos analytical) system.
equipped with a monochromatized Al Kα X-ray source. On the other hand, XRD patterns were also examined by using a Bruker D2 Phaser powder X-ray diffractometer (Cu Kα radiation, wavelength ~ 0.15406 nm), employing an operation potential of 30 kV and a current of 10 mA. The XRD pattern of as-synthesized MoTe₂ crystals was presented in Figure S2. All of the observed strong and sharp peaks can be indexed to hexagonal α-MoTe₂, and they are compatible with the literature (JCPDS 73-1650), with a space group of $P6_3/mmc$ (the so-called “2H” structure). It must be noted that many MoTe₂ flakes were horizontally stacked on the XRD sample plate, so that observed (0 0 n) peaks are larger than others.

Figure S2: XRD pattern measured for as-synthesized MoTe₂ crystals.
II. Images of several layered triangular MoTe$_2$ flakes.

Figure S3: (a) AFM image of a few-layer MoTe$_2$ flake deposited on top of a silicon substrate with a 285-nm-thick SiO$_2$ layer. The corresponding optical image is shown in the inset. (b) The cross sectional profile is plotted along the dotted line of AFM image. The thickness of the flake is estimated to be about 2.9 nm, which agrees with a quadri-layer (4L) MoTe$_2$. 
III. Hysteresis loop of transfer characteristics.

**Figure S4**: RT transfer characteristics of a tri-layered MoTe$_2$ transistor under different $V_{ds}$ values on a logarithmic scale. The layered MoTe$_2$ transistor reveals nearly hysteresis-free at various back-gate voltage sweeping.
IV. The current on/off ratio and mobility as a function of temperature.

Figure S5: Current on/off ratio (a) and mobility (b) as a function of temperature for electrons and holes. The solid curves are guides to eye. An increase of two orders of magnitude in current on/off ratio was observed, whereas the mobility decreased more than one order of magnitude with decreasing temperature from 300 down to 100 K.
V. Modeling Schottky barriers.

An extensive description of modeling Schottky barriers is given here. The M-S-M structure has been successfully adopted in modeling a wide range of modern electronic devices [2-6] and is usually explained precisely with the help of the thermionic emission theory. In the model of the M-S-M structure, the current flow is caused by the transport of charge carriers from semiconductor to metal, which indicates that the $I_{ds}$-$V_{ds}$ characteristics are dominated mainly by the reverse-biased Schottky barrier in the model of thermionic emission. Due to the image force lowering, the Schottky barrier height can be further reduced with increasing $V_{ds}$.

According to the revised biased thermionic emission theory, the $I_{ds}$-$V_{ds}$ relationship is expressed by [7]

$$I_{ds} = A^* T^2 \exp \left( -\frac{q\phi_{eff}}{k_BT} \right)$$

with

$$\phi_{eff} = \phi_{bo} - \sqrt[4]{\frac{q V_{ds}}{4\pi\varepsilon_0\varepsilon_r}}$$

where $A$, $A^*$, $k_B$ and $q$ are the diode area, Richardson constant, Boltzmann constant, and elementary charge, respectively. $T$ is the absolute temperature in Kelvin and $\phi_{eff}$ is the effective Schottky barrier height. $\phi_{bo}$ is the ideal barrier height in the absence of image force. $\varepsilon_0$ and $\varepsilon_r$ are the permittivity of vacuum and relative permittivity, respectively. Taking the natural logarithm of both sides of eq(1), it can be rewritten as

$$\ln(I_{ds}) = \ln(A^* T^2) + \left( -\frac{q\phi_{eff}}{k_B T} \right) \frac{1}{T}$$

When plotting $\ln(I_{ds})$-1/T relation, the effective Schottky barrier height can be determined.

On the other hand, if the image force lowering takes place, such derived $\phi_{eff}$ versus $\sqrt{V_{ds}}$ plot should yield a straight line, where a value of $\phi_{bo}$ under a specific $V_{ds}$ can be extrapolated from the intercept.
VI. RT transfer characteristics of the MoTe$_2$ transistors with different metal contacts.

Figure S6: RT transfer characteristics of a few-layer MoTe$_2$ transistor with two Au metals as electrodes on a linear scale (a) and on a logarithmic scale (b). Obviously, instead of ambipolar behaviour, unipolar $p$-type manners are observed at different $V_{ds}$. 
Reference


