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TWO-DIMENSIONAL MATERIALS

# An ambipolar homojunction with options

Circuits capable of reconfigurable logic and neuromorphic functions can be created by exploiting the electronic tunability of two-dimensional tungsten diselenide homojunctions.

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Two-dimensional (2D) semiconductors can be used to create transistors with the thinnest possible channels, and these channels can be electrostatically tuned with unprecedented versatility. In the areas beneath the metal contacts of the source and drain regions of such devices, the doping type and density in the semiconductor layer can be electrostatically modulated by a gate voltage (such as a global back gate or an overlapped local embedded gate). This differs from conventional physical doping, where the type and density of doping is fixed once fabrication is complete, and provides additional control over the carrier polarity of the device. As a result, the approach can determine whether the transistor operates as an n-type or p-type channel device, and can also affect the way the carriers are injected and flow. Writing in *Nature Electronics*, Shi-Jun Liang, Feng Miao and colleagues now show that reconfigurable logic and neuromorphic functionalities can be created in a homojunction device that uses 2D tungsten diselenide ($WSe_2$) — an ambipolar semiconductor — as the channel material by controlling the carrier polarity and current conduction with different voltages at the split-gate, source and drain terminals[1].

Previously, such electrostatic doping of $WSe_2$ has been employed to create p–n junctions for application in areas including non-volatile programmable memory[2], reconfigurable vertical diodes[3], and complementary logic gates[4]. More recently, tunnelling transistors based on electrostatically controlled ambipolar black phosphorus homojunctions have also been demonstrated with a sub-threshold swing below the thermionic limit of 60 mV dec$^{-1}$ (ref. [5]). Liang, Miao and colleagues — who are based at Nanjing university and the National Institute for Materials Science, Japan — further explore the multiple functionality of tunable homojunctions by building a field-effect transistor with two local gates side-by-side, each covering half of the $WSe_2$ channel and the areas of semiconductor layer under the source/drain metal contacts (Fig. 1a). In the contact regions, unlike in conventional bulk semiconductor, the ultrathin nature of the 2D material allows Fermi level tunability even with the metal above.

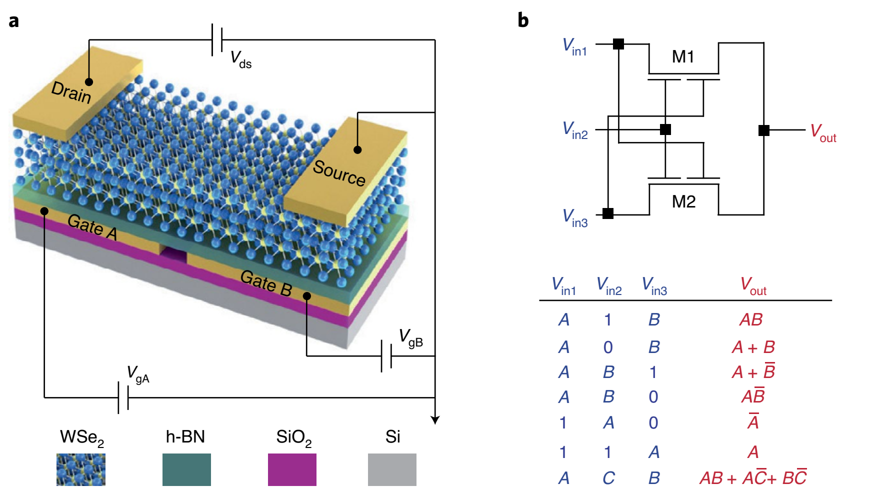


**Fig. 1 | Reconfigurable ambipolar $WSe_2$ homojunction devices and circuits. a**, Schematic of a $WSe_2$ homojunction device that consists of two polarity-control embedded gates. **b**, Using two of these devices, a reconfigurable circuit cell can be created (top) that has a multifunctionality controlled through combinations of gate voltage and drain voltage. The circuit has three input terminals, two of which connect to the polarity gate of one of the devices and the drain of the other device. Using different combinations of the three inputs, seven different Boolean functions can be achieved, including pass, inverter, two-input OR, AND, and borrow-out, as listed in the truth table (bottom). $V_{ds}$, drain–source voltage; $V_{gA}$ and $V_{gB}$, gate bias for partial gates A and B, respectively; $V_{in1}$, $V_{in2}$ and $V_{in3}$, input voltages for input terminals 1, 2 and 3, respectively; M1 and M2, homojunction devices 1 and 2, respectively; $V_{out}$, output voltage; *A*, *B* and *C* represent logic states of either '0' or '1'.

In the channel region of the devices, the carrier injection can be controlled by the two local gates to form four different polarity states: pn, np, nn and pp. Like a resistor, the same polarity (pp and nn) results in a high conductance. But when the polarity states are pn and np, the channel has an asymmetric energy band profile that is distinct from a conventional transistor. Normally, the switching-off operation occurs through the potential barrier modulation at the source end, which is controlled only by the gate voltage (as a convention, the gate voltage is always denoted as the sole input terminal voltage in more complex logic circuits starting with inverters). However, in the approach of Liang, Miao and colleagues, the gate voltage is no longer the only factor controlling the on-state and off-state of the device.

When the channel region is asymmetrically doped, the device behaves as classical rectifying diode, and the terminal voltage on the drain side determines whether it is forward or reverse biased. The homojunction exhibits exponentially increasing current at the forward bias condition and is turned off at the reverse bias condition. Hence, the device off-state is not controlled solely by the gate voltage, but in combination with the drain voltage. This type of device control cannot be realized using traditional transistor structures since the drain voltage is never used to switch the transistor off. Thus, rather than viewing of these devices as transistors, they can, fundamentally, be considered



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as electronically tunable p–n diodes, with much greater versatility.

Liang, Miao and colleagues also demonstrate more complicated functionalities by using the reconfigurable homojunctions as building blocks in larger logic circuits (Fig. 1b). In conventional logic circuits, and beyond a simple inverter (where the drain is always connected to the power supply, or cascaded into next input and the source grounded), there is only one input, the gate voltage. But here the drain voltage also acts as an additional input variable. Importantly, the different combinations of gates and drains can form entirely different functionalities with the same physical circuit configuration, and the researchers use the approach to create a 2:1 multiplexer, a D-latch and a 1-bit full adder/subtractor with the same circuit layout. The tunable homojunctions can also be used for reconfigurable neuromorphic functions, requiring fewer devices that would be needed with conventional silicon complementary metal–oxide–semiconductor technology.

The work of Liang, Miao and colleagues provides a new mechanism for controlling the operation of 2D devices using both polarity control and the combination of inputs from the gate and drain, benefiting from the high tunability of energy bands in ultrathin $WSe_2$. The approach has considerable potential for use in development of complex functionalities from 2D materials based circuits. However, further advances are still needed in order to increase the operation speed of these devices and to deliver larger-scale circuits, where rail-to-rail operations require robust and uniform devices. ❐

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