Integrated digital inverters based on two-dimensional anisotropic ReS₂ field-effect transistors

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Semiconducting two-dimensional transition metal dichalcogenides are emerging as top candidates for post-silicon electronics. While most of them exhibit isotropic behaviour, lowering the lattice symmetry could induce anisotropic properties, which are both scientifically interesting and potentially useful. Here we present atomically thin rhenium disulfide (ReS₂) flakes with unique distorted 1T structure, which exhibit in-plane anisotropic properties. We fabricated monolayer and few-layer ReS₂ field-effect transistors, which exhibit competitive performance with large current on/off ratios (~10⁷) and low subthreshold swings (100 mV per decade). The observed anisotropic ratio along two principle axes reaches 3.1, which is the highest among all known two-dimensional semiconducting materials. Furthermore, we successfully demonstrated an integrated digital inverter with good performance by utilizing two ReS₂ anisotropic field-effect transistors, suggesting the promising implementation of large-scale two-dimensional logic circuits. Our results underscore the unique properties of two-dimensional semiconducting materials with low crystal symmetry for future electronic applications.
The scaling down of conventional metal-oxide-semiconductor FETs is approaching the limit of miniaturization due to severe short-channel effects. One approach to solve this problem is searching for atomically thin semiconductors, such as semiconducting two-dimensional (2D) materials. Among the potential candidates, the family of transition metal dichalcogenides (TMDs) (MX$_2$, where M denotes a transition metal and X denotes a chalcogen) has attracted the most attention due to both its rich physics and tremendous potential for application. They are expected to exhibit a wide range of electronic structures and exotic transport properties arising from the various electron configurations of transition metals, such as superconductivity, half-metallic magnetism and charge density waves.

Lattice structure and symmetry are vital in determining materials’ fundamental properties. Most studied 2D TMDs exhibit isotropic behaviour due to high lattice symmetry; however, lowering the symmetry in TMDs could induce interesting anisotropic properties of both scientific and technological importance. For example, in WTe$_2$, which is a semi-metallic TMD with a distorted lattice structure, a large non-saturating magnetoresistance effect along a principle axis (the direction of W chain formation) has been recently reported and has attracted considerable attention. In contrast, semiconducting 2D TMDs with low symmetry have remained unexplored.

As the last stable element discovered in nature, the transition metal rhenium (Re) exhibits a wide range of oxidation states and crucial applications, such as superalloys and catalytic reforming. Its sulfide rhenium disulfide (ReS$_2$) is a semiconducting TMD with a distorted lattice structure, a large non-saturating magnetoresistance effect along a principle axis (the direction of W chain formation) has been recently reported and has attracted considerable attention. In contrast, semiconducting 2D TMDs with low symmetry have remained unexplored.

In this work, we systematically investigate the in-plane anisotropic properties of atomically thin ReS$_2$. In addition to highly competitive FET performance, we also observe a large anisotropic ratio along its two principle axes, which is the highest among all experimentally investigated 2D layered materials. We also successfully demonstrate a digital inverter with good performance by integrating two anisotropic ReS$_2$ FET devices. Our results suggest that the lattice orientation can be used as an alternative design variable to tune device properties and optimize circuit performance in future 2D integrated circuits based on the anisotropic semiconducting materials.

Results

Material characterizations and ab initio calculations. Figure 1a,b,c shows typical optical microscopy and atomic force microscope images of a monolayer ReS$_2$ film (see Methods for the material details), respectively. The inset of Fig. 1c shows that the thickness of the monolayer film is ~0.8 nm. In this study, we focus on monolayer and few-layer ReS$_2$, with thicknesses ranging from 0.8 to 5 nm (1–7 layers with interlayer spacing of ~0.7 nm). Micro Raman scattering experiments were performed on monolayer, five-layer and bulk ReS$_2$. Due to the low symmetry of ReS$_2$, 18 Raman modes were observed as shown in Fig. 1d. The peak positions of our three samples are close to each other, same to the reported results. In Fig. 1d, we labelled two low frequency A$_{g}$-like modes (located at 136.8 and 144.5 cm$^{-1}$) corresponding to the out-of-plane vibrations of Re atoms and four E$_{g}$-like modes corresponding to the in-plane vibrations of Re atoms. The rest 12 higher frequency Raman modes are vibrations mainly from lighter S atoms.

Figure 1 | Characterization and band structure of thin-layer ReS$_2$.

(a) Crystal structure of monolayer ReS$_2$ with a side view in the top panel and a top view in the bottom panel. Both directions of $a$ and $b$ axes are denoted by red arrows. (b) Optical image of a monolayer ReS$_2$ flake. Scale bar, 10 μm. (c) AFM image of a monolayer ReS$_2$ flake. Scale bar, 1 μm. Inset: height profile along the blue line indicating a single layer. (d) Micro Raman experimental results performed on monolayer, five-layer and bulk ReS$_2$. Six labelled Raman modes include two low frequency A$_{g}$-like modes corresponding to the out-of-plane vibrations of Re atoms and four E$_{g}$-like modes corresponding to the in-plane vibrations of Re atoms. The rest 12 higher frequency Raman modes are vibrations mainly from lighter S atoms. (e) Band structure of monolayer, trilayer and five-layer ReS$_2$ by ab initio calculations indicating band gaps of 1.44, 1.40 and 1.35 eV, respectively. AFM, atomic force microscope.
FET performances. We first examine the device performances of monolayer and few-layer ReS₂ FET devices (see Supplementary Note 1 for details). The inset of Fig. 2a presents the optical image of a typical monolayer device. The FET transfer curve was obtained by monitoring the source–drain current $I_{ds}$ while sweeping the back gate voltage $V_{bg}$. A fixed 100-mV source–drain bias voltage $V_{sd}$ was applied across the channel during all of the measurements. We first measured a couple of monolayer ReS₂ devices, all of which behaved as excellent n-type FET devices with the back gate swept between $-50$ and $+50\,\mathrm{V}$. As shown in Fig. 2a, the current on/off ratio reached $10^7$, which meets the requirement of many applications, such as digital logic computation. When the back gate voltage reached $+50\,\mathrm{V}$, the $I_{ds}$ approached saturation. Few-layer ReS₂ transistor devices, ranging from bilayer to seven-layer, were studied as well. Similar n-type FET behaviour but a slightly larger on/off ratio was observed. The results from a trilayer device with the same back gate sweep range are shown in Fig. 2a for comparison. We note that all of the above measurements were carried out under vacuum ($\sim 10^{-5}\,\mathrm{mbar}$) at room temperature, and ambipolar behaviour can be observed by introducing the ionic liquid gating technique (see Supplementary Note 2 for details). On the basis of the transfer curves, we can also measure the subthreshold swing. For the monolayer ReS₂ FET device shown in Fig. 2a, the subthreshold swing is $\sim 310\,\mathrm{mV}\,\mathrm{per}\,\mathrm{decade}$. The subthreshold swing becomes steeper for thicker flakes, reaching $\sim 100\,\mathrm{mV}\,\mathrm{per}\,\mathrm{decade}$ for the trilayer device shown in the same figure. The measured subthreshold swing values approach those measured in top-gated MoS₂ transistors⁷ and outperform black phosphorus devices⁵. This can be further improved by increasing the gate capacitance after introducing thinner high-κ dielectric materials.

The monolayer and few-layer ReS₂ FET devices (with Ti/Au electrodes) have also shown good contact behaviour. As shown in Fig. 2b, for a typical monolayer device, the source–drain current $I_{ds}$ varies linearly with the bias $V_{ds}$ in the $\pm 1\,\mathrm{V}$ range at different back gate voltages ($V_{bg} = -40, -20, 0, 20$ and $40\,\mathrm{V}$, respectively), indicating ohmic contact behaviour in the n-doped regime under consideration (see Supplementary Note 3 for more details).

We further extracted the mobility of all of the FET devices we measured and studied its dependence on the number of layers of the ReS₂. The mobility was determined by taking the steepest slope in the two-terminal $I_{ds}$–$V_{bg}$ curves. The results for 17 devices (from monolayer to seven-layer) are plotted in Fig. 2c. Similar to the reported results based on MoS₂ thin flakes²⁰,²¹, the device mobility generally increases with an increasing number of layers, implying that the electrons likely independently transport through different layers in thin ReS₂ flakes. The mobility of a monolayer device varies between 0.1 and $2.6\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$, and the highest mobility value obtained is $15.4\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$ for a six-layer device. These values were measured without any material treatment or device optimization. With further improvement in crystal quality, post-fabrication treatment²² and dielectric engineering⁷,²², considerable enhancement of mobility to approach application requirements should be expected. Here the scattering of mobility values for flakes with the same number of layers could be induced by device quality variations or the anisotropic property, as will be discussed below.

Anisotropic properties of ReS₂. We now focus on the in-plane anisotropic properties of monolayer and few-layer ReS₂ flakes induced by low lattice symmetry. As described in Fig. 1a, the $a$ and $b$ axes are the two directions with the shortest axes in the basal plane, thus differentiating them from other lattice orientations. Such a feature is often associated with the in-plane...
anisotropic properties of structural stiffness and electronic transport. Interestingly, during our experiments, exfoliated thin ReS₂ flakes commonly appear in a quadrilateral shape with inner angles of ~60° or 120°, as shown by a typical flake in Fig. 3a. Further results of all inner angles measured on over 20 thin flakes is shown in Fig. 3b, with >60% of the specimens showing these two angles. The inner angles of 60° and 120° match the angles between the a and b axes (118.97° or 61.03°) with high accuracy. This can be readily explained by the fact that the breaking strength is the weakest along these two axes, which are the two most strongly bonded orientations, and suggests that two sides of the quadrilateral shape with 60° or 120° inner angles correspond to the a and b axes, respectively.

The in-plane stiffness anisotropy-induced quadrilateral shape makes it feasible to determine the two axes of ReS₂ flakes via convenient transport measurements instead of other highly sophisticated tools, such as scanning tunnelling microscopy. Early studies on bulk materials reported that the b axis is more conductive than other crystalline orientations. We then patterned the electrodes to be perpendicular to two sides (A and B directions) of a quadrilateral-shaped five-layer ReS₂ with a 60° inner angle (as shown in the top inset of Fig. 3c). The transfer curves in two directions are shown in Fig. 3c, and anisotropic FET behaviour was observed. The B direction appears to be noticeably more conductive than the A direction, suggesting that the A and B directions correspond to the a and b axes, respectively. The conductance ratio of the two directions is gate dependent, with values of ~8.2 when V_{bg} = −50 V and ~2 when V_{bg} = 50 V. To evaluate the influence of contact resistance, we performed four-terminal measurements (see Supplementary Note 3 for more details). The four-terminal results of the same device are shown in the lower inset of Fig. 3c, indicating that the anisotropy arises from the intrinsic properties of ReS₂.

We further systematically studied the anisotropic properties of thin ReS₂ flakes through angle-resolved transport measurement. As shown in the inset of Fig. 3d, a six-layer device was fabricated with 12 electrodes (5 nm Ti/50 nm Au) evenly spaced at 30° apart. We measured the transfer curves of each pair of diagonally positioned electrodes separated by 4.5 μm at 180° apart and extracted the renormalized field-effect mobility of each direction, with the results plotted in Fig. 3d (red dots) in polar coordinates. Measurements on each pair of electrodes lead to two data points that are 180° apart by swapping source–drain current directions. Here we define the direction with the lowest mobility to be the 0° (or 180°) reference. The field-effect mobility is highly angle dependent, with the largest value in the direction of 120° (or 300°), which is 60° from the direction with the lowest value. The anisotropic ratio of mobility μ_{max}/μ_{min} is ~3.1, which is noticeably larger than that reported in other 2D anisotropic materials, such as 1.8 for thin-layer black phosphorus.

To fully understand our observations, we calculated the effective mass and mobility of monolayer ReS₂ along three

![Figure 3](image-url) Anisotropic properties of ReS₂. (a) Optical image of a typical thin ReS₂ flake with a quadrilateral shape. Scale bar, 5 μm. (b) The statistics of inner angles for over 20 thin ReS₂ flakes, showing the greatest prevalence for 60° and 120°. (c) Transfer curves of anisotropic ReS₂ FETs along two sides (A and B direction) of a quadrilateral-shaped five-layer flake (with an inner angle of 60° or 120°). Top inset: optical image of the devices. Scale bar, 10 μm. Low inset: the 4-probe resistance of the same devices with V_{bg} varying between 0 and 60 V. (d) Normalized field-effect mobility of a six-layer device along 12 directions evenly spaced at 30° apart plotted in polar coordinates (red dots with left axis). The direction with the lowest mobility was set to be the 0° (or 180°) reference. The optical image of the device is shown in the inset. The calculated mobility of monolayer ReS₂ along three orientations (a axis, b axis and perpendicular to the a axis) is plotted in the same graph (blue dots with right axis) for comparison. The lowest mobility (a axis) direction was set to be the 0° (or 180°) reference as well.
crystalline orientations ($a$ axis, $b$ axis and perpendicular to the $a$ axis) using an ab initio technique (see Supplementary Note 4 for details), with the results plotted in the same graph (blue dots with right axis). Here we set the direction with the lowest mobility ($a$ axis) to be the $0^\circ$ (or $180^\circ$) reference as well. By comparing with experimental data, the calculation results offer a qualitative explanation that for the device with polar coordinates, the direction of $0^\circ$ (or $180^\circ$) approaches the $a$ axis with the lowest mobility, $120^\circ$ (or $300^\circ$) approaches the $b$ axis with the highest mobility and $90^\circ$ (or $270^\circ$) approaches the direction perpendicular to the $a$ axis with a moderate mobility value between the two extremes. The quantitative discrepancies between the experimental and theoretical results imply that with continuous improvement of sample quality and material engineering, it is possible to achieve intrinsic properties that approach the real potential of ReS$_2$ in high-performance device applications.

Digital inverter based on anisotropic ReS$_2$ FETs. Anisotropic ReS$_2$ FET devices with expected high mobility could have important applications in future nanoscale electronics, especially on 2D logic circuits$^{27-31}$ with demanding requirements of scalability (<10 nm) and large-scale integration. In contrast to conventional complementary metal-oxide-semiconductor technologies, tailoring material properties and integrated circuit design variables (such as the channel width/length ratio)$^{32}$ to optimize circuit performance on such a rigorous scale will remain a significant challenge. In this context, the lattice orientation could be used as an alternate design variable to tune device transport properties and optimize circuit performance in future 2D integrated circuits based on anisotropic semiconducting materials.

As a simple example, we successfully demonstrated a ReS$_2$-based prototype logic device, a 2D digital inverter. As schematically shown in Fig. 4a, the inverter can be fabricated by combining two anisotropic ReS$_2$ FETs along the $a$ and $b$ axes (with a Re atomic chain highlighted in red). In our experiment, a quadrilateral-shaped few-layer ReS$_2$ flake with a $60^\circ$ inner angle was selected to fabricate two FETs along two axes. HfO$_2$ was then deposited with a thickness of 15 nm as the top dielectric, followed by the fabrication of two top-gate electrodes (30 nm Au). The optical image of a typical inverter device is shown in Fig. 4b. The transfer curves along the two directions are shown in the inset of Fig. 4c, which confirms the anisotropic behaviour and determines two axes as well. The circuit diagram is shown in the inset of Fig. 4b, where the top-gate voltage on the $a$ axis is fixed at $-2\,\text{V}$, the top-gate voltage on the $b$ axis is the input voltage $V_{\text{in}}$ and the middle shared electrode is the output voltage $V_{\text{out}}$. Figure 4c shows the voltage transfer characteristics with excellent logic-level conservation of our digital inverter, while $V_{\text{in}}$ varies between $-4$ and $2\,\text{V}$ for three different $V_{\text{DD}}$ values ($3, 2$ and $1\,\text{V}$ with different colours). When $V_{\text{in}}$ is above $-1\,\text{V}$, $V_{\text{out}}$ approaches $0\,\text{V}$, which denotes a digital 0. Similarly, when $V_{\text{in}}$ is below $-3\,\text{V}$, $V_{\text{out}}$ approaches $V_{\text{DD}}$, which denotes a digital 1. The output swing (defined as the largest difference of $V_{\text{out}}$) is close to the supply voltage $V_{\text{DD}}$. As the most important parameter of a digital

![Figure 4](image-url) Integrated digital inverters. (a) A schematic showing the structure of an inverter combining two top-gated anisotropic ReS$_2$ FETs. The left FET is along the $a$ axis, and the right FET is along the $b$ axis, where a Re atomic chain is highlighted in red. A quadrilateral-shaped few-layer ReS$_2$ flake with a $60^\circ$ inner angle was used to fabricate FETs along two axes covered by 15-nm-thick HfO$_2$ as the top dielectric and two top-gate electrodes (30 nm Au). Scale bar, 10 $\mu\text{m}$. Inset: the circuit diagram of the inverter, where the top-gate voltage along the $a$ axis is fixed at $-2\,\text{V}$, the top-gate voltage along the $b$ axis is the input voltage $V_{\text{in}}$ and the middle shared electrode is the output voltage $V_{\text{out}}$. (c) Transfer characteristics of an inverter operated at $V_{\text{DD}} = 1, 2$ and $3\,\text{V}$. Inset: The transfer curves of two FETs with $100\,\text{mV} V_{\text{GS}}$, confirming the anisotropic behavior. (d) The signal gain of the inverter extracted from c.
inverter, the gain is defined as $|dV_{\text{out}}/dV_{\text{in}}|$, which represents the sensitivity of $V_{\text{out}}$ to the change in $V_{\text{in}}$. For this device, the gain reaches 4.4 when $V_{\text{DD}} = 3\, V$ (as shown in Fig. 4d). The gain that we obtained is clearly larger than the unity gain (gain = 1), which is required in integrated circuits consisting of multiple cascaded inverters, such as ring oscillators, and is comparable to the MoS2 based inverters.28,30

In conclusion, we have systematically studied the anisotropic properties of atomically thin ReS2, a semiconducting 2D TMD with a distorted 1T structure. We fabricated monolayer and few-layer ReS2 FET devices that exhibit competitive performance, including a high current on/off ratio ($\sim 10^7$) and a steep subthreshold swing (100 mV per decade) at room temperature. We also obtained an anisotropic ratio along the two principle axes of ReS2 that is the highest obtained for all experimentally studied 2D materials. Finally, we successfully demonstrated a digital inverter device by integrating two anisotropic ReS2 FET devices. Our results underscore the unique properties of semiconducting 2D materials with low symmetry, which can be exploited for novel applications in future electronics.

During the preparation of this manuscript, we became aware of another work studying the FET properties of few-layer ReS2 (ref. 33).

Methods

Materials and devices. Single crystals of ReS2 were grown by the same Br2-assisted chemical vapour transport method described in ref. 17. We used a standard chemical exfoliation method to isolate monolayer and few-layer ReS2 films. The number of layers can be identified using the colour interference of a 285-nm-thick SiO2 wafer, and further confirmed by measuring the thickness of the films. The number of layers can be identified using the colour interference of a 285-nm-thick SiO2 wafer, and further confirmed by measuring the thickness of the films. The number of layers can be identified using the colour interference of a 285-nm-thick SiO2 wafer, and further confirmed by measuring the thickness of the films. The number of layers can be identified using the colour interference of a 285-nm-thick SiO2 wafer, and further confirmed by measuring the thickness of the films. The number of layers can be identified using the colour interference of a 285-nm-thick SiO2 wafer, and further confirmed by measuring the thickness of the films.

A conventional electron-beam lithography process (FEI F50 with Raith pattern generation system) followed by standard electron-beam evaporation of metal electrodes (typically 5 nm Ti/50 nm Au) was used to fabricate monolayer and few-layer ReS2 FET devices.

Ab initio calculations. Band structures for monolayer and few-layer ReS2 were calculated using the generalized gradient approximation Perdew–Burke–Ernzerhof functionals as implemented in the VASP code (Vienna ab initio Simulation Package) within the density functional theory (DFT)14,34. Projector-augmented wave potentials were adopted35. The kinetic energy cutoff for the plane-wave basis set was 550 eV. The few-layer ReS2 was simulated with a vacuum layer of 15 Å in the direction normal to the surface of the layer. The incident laser wavelength was 514.5 nm, and the power was <1 mW to minimize laser heating. Due to the limitations of the spectrometer, we only measured Raman modes above 100 cm$^{-1}$.

The conduction band structures for monolayer and few-layer ReS2 were calculated using the generalized gradient approximation Perdew–Burke–Ernzerhof functionals as implemented in the VASP code (Vienna ab initio Simulation Package) within the density functional theory (DFT)14,35. Projector-augmented wave potentials were adopted35. The kinetic energy cutoff for the plane-wave basis set was 550 eV. The few-layer ReS2 was simulated with a vacuum layer of 15 Å in the direction normal to the surface of the layer. The incident laser wavelength was 514.5 nm, and the power was <1 mW to minimize laser heating. Due to the limitations of the spectrometer, we only measured Raman modes above 100 cm$^{-1}$.

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electrical measurements. Y.F., H.L. and X.W. carried out the DFT calculations. W.Z. performed the Raman spectroscopy measurements and analysis. Y.S.H. and C.H.H. performed the ReS₂ single crystal growth. Z.C., L.W. and A.L. performed the HfO₂ growth. F.M., H.Y., B.W., E.L. and Y.F. performed the data analysis and interpretation. F.M., E.L., Y.F. and H.Y. co-wrote the paper, with all authors contributing to the discussion and preparation of the manuscript.

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