Two-dimensional (2D) materials are promising for next-generation photo detection because of their exceptional properties such as a strong interaction with light, electronic and optical properties that depend on the number of layers, and the ability to form hybrid structures. However, the intrinsic detection ability of 2D material-based photodetectors is low due to their atomic thickness. Photogating is widely used to improve the responsivity of devices, which usually generates large noise current, resulting in limited detectivity. Here, we report a molybdenum-based phototransistor with MoS$_2$ channel and $\alpha$-MoO$_{3-x}$ contact electrodes. The device works in a photo-induced barrier-lowering (PIBL) mechanism and its double heterojunctions between the channel and the electrodes can provide positive feedback to each other. As a result, a detectivity of $9.8 \times 10^{16}$ cm Hz$^{1/2}$ W$^{-1}$ has been achieved. The proposed double heterojunction PIBL mechanism adds to the techniques available for the fabrication of 2D material-based phototransistors with an ultrahigh photosensitivity.
Photodetectors based on two-dimensional (2D) materials usually have a low responsivity and detectivity because atomically-thin 2D layered materials have weak light absorption. The photogating mechanism has been widely used to provide a photo gain to improve device performance, which is basically achieved either by a trap-assisted photoconductive effect or by a photovoltaic effect. For example, charges were transferred from the channel to the bound water molecules on the SiO₂ surface in pristine MoS₂ phototransistors, and the poor charge separation ability of water molecules leads to a relatively low detectivity. In a hybrid MoS₂/PbS quantum-dot photodetector, photogenerated electrons were transferred to a MoS₂ layer, while photogenerated holes stayed in the quantum-dots, and a leakage path was inevitably formed and resulted in a large dark current. An all-2D MoS₂ phototransistor achieved a detectivity as high as 9.8 × 10¹⁶ cm Hz¹/² W⁻¹ at a low bias voltage has not been reported. Results (Methods, Supplementary Fig. 1), and the channel material was dark current. An all-2D MoS₂ phototransistor achieved a detectivity as high as 3.5 × 10¹⁴ cm Hz¹/² W⁻¹ under a high bias voltage of 10 V, in which a MoS₂ P–N homojunction played the roles of charge separation and a sensitive layer. Overall, a phototransistor with high responsivity, low-noise current and working at low bias voltage has not been reported.

Here, we report a molybdenum-based double-heterojunction phototransistor with a MoS₂ channel and two α-MoO₃-x contact electrodes. Using the energy band combination of the MoS₂/α-MoO₃-x junction, the formed double heterojunctions are able to provide a positive feedback to each other with the help of light. And we proposed a working mechanism named photo-induced barrier lowering (PIBL) for this phototransistor. As a result, a high detectivity of 1.7 × 10¹⁴ cm Hz¹/² W⁻¹ was achieved. However, because the intrinsic noise of the device is too low to be measured, the detectivity of this device is seriously underestimated. Through the reasonable estimation of the intrinsic noise, the detectivity of our device is as high as 9.8 × 10¹⁶ cm Hz¹/² W⁻¹. At the same time, this device maintains a response speed with a rise time of 95 μs and a fall time of 105 μs.

Results

Device design and characterization. A phototransistor with a back-gate structure was fabricated by a layer transfer method (Methods, Supplementary Fig. 1), and the channel material was a few- or multi-layer MoS₂ flake which was stacked on the patterned multilayer α-MoO₃ electrodes (Fig. 1a, b and Supplementary Fig. 2). Thermal annealing at 350 °C was carried out to introduce oxygen vacancies which changed the structural and electrical properties of α-MoO₃ (Methods). For the resulting α-MoO₃-x (0 < x < 1), the crystal lattice constant decreased slightly due to the formation of oxygen defects (Supplementary Figs. 3–5), but the conductance of α-MoO₃-x was dramatically increased by more than 4 orders of magnitude (Supplementary Fig. 6). Figure 1c shows the cross-section of the phototransistor that has a high-quality van der Waals heterojunction of MoS₂ and α-MoO₃-x covered by a 5-nm-thick HfO₂ passivation layer. The thin HfO₂ capping layer causes the n-type doping on MoS₂, which narrows the interfacial energy barrier between α-MoO₃-x and MoS₂ (Supplementary Fig. 7). The transfer characteristics of the α-MoO₃-x/MoS₂/α-MoO₃-x phototransistor show a strong optoelectronic response using a monochromatic light source with a wavelength of 405 nm (Fig. 1d), which is similar for 516 and 638 nm wavelengths (Supplementary Fig. 8).

The detailed optoelectronic performance of the fabricated phototransistor is evaluated to obtain its figure of merit in Fig. 2 at Vₛₒ₃ = 1 V. The noise density spectral (S) as a function of frequency (f) at different gate voltage (Vₛₒ₃) is shown in Fig. 2a, all these low-noise spectra exhibit a typical 1/f power density. As shown in Fig. 2a, the S around the OFF state (Vₛₒ₃ ~ from −30 to −40 V, in blue and red) dwrons with background noise (in black). It is well-known that the 1/f (flicker) noise is mainly dominated by fluctuations of carrier density or mobility. So that the intrinsic noise of the device can be inferred from the normalized noise power density (SI/Dark)² as a function of frequency. Except around the OFF state, the S/Dark² of our device is almost a certain value at different frequency (f), so we can extract the real noise which dwrons with background noise using $S = \left(S/Dark²\right) \times \left(Dark²\right)$ (Supplementary Fig. 8). When the device is in the OFF state (Vₛₒ₃ = −35.2 V), the S of the channel can be as low as 9.7 × 10⁻³² A²/Hz. The responsivity (R) first increases with the increase of Vₛₒ₃ since the photocurrent (Ipḥ) increases with Vₛₒ₃ (Supplementary Fig. 9), and then decreases slightly and becomes stable (Fig. 2b). The external quantum efficiency (EQE) follows the changing tendency of R with Vₛₒ₃ (Fig. 2c). The highest values of R and EQE of this device in the OFF state are 1.9 × 10⁸ A/W and 5.9 × 10⁻⁶ respectively, reached at P_in = 0.46 mW/cm² (Fig. 2b, c). The light–dark current ratio (I_Dark/I_P) reaches a maximum value of 1.4 × 10³ at P_in = 4.78 mW/cm² (Fig. 2d). The detectivity (D*) increases slightly from Vₛₒ₃ = −40 V to Vₛₒ₃ = −35.2 V and reaches a peak value around 9.8 × 10¹⁶ cm Hz¹/² W⁻¹ at P_in = 0.46 mW/cm² because of the increasing of R. From Vₛₒ₃ = −35.2 V to Vₛₒ₃ = 0 V, the D* decreases dramatically for the significant increase of S. In the range of Vₛₒ₃ > 0 V, the D* is flat because the R and S are both stable (Fig. 2e). The D* calculated using measured S shows the same tendency with the estimated S, and reaches a peak value of 1.7 × 10¹⁴ cm Hz¹/² W⁻¹ at Vₛₒ₃ = −30 V (Fig. 2e, inset). The time-dependent photo response of the device was measured at bias voltage (Vᵦₒ₃) of 1 V and Vₛₒ₃ = 0 V (Supplementary Fig. 10, Fig. 2f), the rise (Tᵣ) and fall (Tᵣ) time of photocurrent are measured to be 95 μs and 105 μs, respectively. The devices fabricated with different scale also show a stable high performance (Supplementary Fig. 11, Table 1).

To benchmark our device, we compared 2D material-based high-performance phototransistors using MoS₂, graphene, Ga₅₃, WSₑ³₅, PbS, InSₑ₅, InₙSe₉, and SnₙSe₄, comprehensively (Fig. 2g). Compared with those of reported pure or engineered 2D materials based phototransistors using various strategies, including surface plasmon enhancement, charge transfer assistance, impurity/energy band engineering, negative capacitance, gate engineering, and contact-engineering, the D* of our device is highest among all previous results, while response speed is approaching to the highest previously reported value.

Photo-induced barrier-lowering mechanism. To reveal the origin of the ultrahigh detectivity of our devices, we first pull out the photo response of α-MoO₃-x itself or Ti/Au/α-MoO₃-x junctions (Supplementary Fig. 12). Then we compared the performance of four phototransistors using a shared MoS₂ channel but different electrodes, marked as T1, T2, T3, and T4 (Fig. 3a). The transfer characteristics measured under dark and light conditions showed obviously different optoelectronic responses when the cathode and anode of the phototransistor were replaced by α-MoO₃-x from Ti/Au (Fig. 3b). When one α-MoO₃-x/MoS₂ heterojunction formed at the cathode, $I_D/S_{Dark}$ increased to more than 10 times that with a Ti/Au cathode, and for T4 using double α-MoO₃-x/ MoS₂ heterojunctions, $I_D/S_{Dark}$ dramatically increased more than 1000 times. The output characteristics ($I_D − V_{DS}$) also indicate that $I_D$ increased for the device using one heterojunction as the cathode compared with the Au electrode case, while using double heterojunctions increased $I_D$ significantly (Supplementary Figs. 13, 14). On the basis of the scanning photocurrent maps (Fig. 3c), it is found that photon absorption occurs at the α-MoO₃-x/MoS₂ heterojunction near the cathode.
Based on the above results, a double-heterojunction PIBL mechanism was proposed to explain the ultrahigh detectivity of the α-MoO$_3$,$\alpha$/MoS$_2$/α-MoO$_3$$_x$ phototransistor. Two heterojunctions exist between the channel and electrodes in the device, namely a source heterojunction (α-MoO$_3$,$\alpha$/MoS$_2$) and a drain heterojunction (MoS$_2$/α-MoO$_3$$_x$$_x$). The relative positions of the conduction band minimum ($E_c$) and the valence band maximum ($E_v$) of α-MoO$_3$$_x$ and MoS$_2$ are critical to analyze the energy band structure of the heterojunctions, which are determined by experimental characterizations such as absorbance spectrum, ultraviolet photoelectron spectroscopy (UPS) and photoluminescence spectrum (PL) (Fig. 4a, b and Supplementary Fig. 15) and theoretical techniques (Supplementary Fig. 16). Bandgaps of α-MoO$_3$ and α-MoO$_3$$_x$ are 3.28 and 3.24 eV, respectively, were obtained from the absorption spectra (Fig. 4a). The work function of α-MoO$_3$$_x$$_x$ was obtained from the cutoff region, which is 5.32 eV. The difference between the Fermi level and the valence band maximum was calculated to be 3.05 eV from the valence region (Fig. 4b). Particularly, Fig. S15 shows the PL spectrum (red line) of the α-MoO$_3$$_x$$_x$ flakes. The peak at 560 nm induced by oxygen vacancies determines the defect band is 2.21 eV above valence band maximum ($E_v$), corresponding to the density function theory (DFT) calculations (Supplementary Fig. 16), which is responsible for the 4 orders-of-magnitude increase in the conductance of α-MoO$_3$$_x$ after annealing (Supplementary Fig. 6). Besides, compared with the MoS$_2$ flakes, the luminescent intensity of the α-MoO$_3$$_x$$_x$/MoS$_2$ heterojunction is significantly reduced, which means that excitons are efficiently dissociated at the α-MoO$_3$$_x$/MoS$_2$ interface (Supplementary Fig. 15, black and green lines).

If combined with the well-known MoS$_2$ band structure obtained by spectroscopic measurements\cite{40} (Supplementary Fig. 17), the band diagram of α-MoO$_3$$_x$/MoS$_2$ heterojunction can be determined to clarify the mechanism of the photo-carrier induced feedback effect. In the dark, two $n$–$n^+$ junctions are formed at the vdW heterointerface. The alignment of the Fermi level leads to charge transfer between α-MoO$_3$$_x$$_x$ and MoS$_2$, which naturally results in two space-charge regions. Our device is generally operated at OFF state of the phototransistor, where MoS$_2$ is almost fully depleted. At this region, MoS$_2$ present very small density of states. Figure 4c shows a schematic of the energy band of α-MoO$_3$$_x$/MoS$_2$/α-MoO$_3$$_x$$_x$ when a positive bias is applied to the drain of the phototransistor in the dark. The major source of dark noise of our device is flicker noise (Fig. 2a, Supplementary Fig. 8), which is caused by carrier density fluctuations attributed to traps associated with contamination and crystal defects. The electrons at the source side faces a large Schottky barrier at a low gate voltage which blocks the traps with the energy below the barrier. We have quantitatively characterized the Schottky barrier height as about 0.55 eV at $V_{GS} = -36$ V in dark (Fig. 4d, Supplementary Fig. 18a–f, m), which is five to ten times than the Ti contact case\cite{41,42}, resulting in such low flicker noise (around $10^{-29}$ A$^2$/Hz, Supplementary Fig. 11). As shown in process (1) in Fig. 4e, by light illumination, electron-hole pairs are dynamically generated at the reversely biased source junction and subsequently separated by the built-in filed. Or in other words, there is an equivalent charge transfer between α-MoO$_3$$_x$$_x$ and MoS$_2$, which rapidly modifies the Fermi level at the source and leverages the carrier density. The process causes an increase in the $E_f$ of the source and a decrease in the barrier at the source heterojunction, making it much easier to inject electrons from the source. In the MoS$_2$ channel, the injected electrons will raise the concentration of charge carriers, which narrows the space-charge region and lowers the barrier at the drain side. As a feedback of this barrier lowering, more voltage drops...
at the Source junction. Therefore, the double heterojunction enables a positive feedback to each other in one phototransistor. We also have quantitatively characterized the Schottky barrier height as about 0.042 eV at $V_{GS} = -36$ V under a 405 nm light ($P_{in} = 0.6$ mW/cm$^2$) (Fig. 4f, Supplementary Fig. 18g–l), which is much lower than that in dark, resulting in such high responsivity (around 10$^5$ A/W, (Fig. 4f, Supplementary Fig. 18g–l). When a Ti/Au contact is used, an electron Schottky potential barrier is expected for the Ti/Au-MoS$_2$ junction. Comparing with vdW junction, metal junction presents obvious Fermi-level pinning effect. Due to the strong pinning effect, the transfer of photogenerated carriers can not lower the barrier at the Source and Drain contact. The weak photo response mainly comes from the MoS$_2$ itself (Fig. 4g). When $\alpha$-MoO$_{3-x}$ is used as the anode in T2, there is also no electron injection at the Source junction. The photogenerated electrons of MoS$_2$ itself will raise the anode in T2, there is also no electron injection at the Source junction. The weak photo response mainly comes from the MoS$_2$ itself (Fig. 4g).

**Fig. 2 Optoelectronic performance of the phototransistor.** a) Density spectral ($S$) as a function of frequency at $V_{DS} = 1$ V with different gate voltage $V_{GS}$ of 0 V, −15 V, −20 V, −25 V, −30 V, and −35 V as well as the background noise from top to down. b) Responsivity ($R$) as a function of $V_{GS}$, $R = (I_{DS} - I_{Dark})/P_{in}$, where $P_{in}$ is power density of light. c) $V_{GS}$-dependent external quantum efficiency (EQE), EQE $= h\nu R/2e I_{DS} V_{DS}$. d) $V_{GS}$-dependent light-dark current ratio ($I_{DS}/I_{Dark}$). e) $V_{GS}$-dependent detectivity ($D^*$), which was calculated using intrinsic $S$. $D^* = (AB)^{1/2}R/S^{1/2}$, where $A$ is the active area of ~2.5 $\mu$m$^2$, $B$ is the bandwidth (1 Hz). Inset: $V_{GS}$-dependent $D^*$, which was calculated using measured $S$. f) Response speed of the phototransistor showing the rise time of 95 $\mu$s and the fall time of 105 $\mu$s. g) Benchmark of the phototransistor in this work demonstrating a high $D^*$ compared to previously reported 2D materials based photodetectors. The $D^*$ represented by hollow polygon were calculated by estimated noise, and represented by solid polygon were calculated using measured noise.
contact is only slightly lower than for Ti/Au in T1, resulting in a slightly better photo response (Fig. 4i). When α-MoO$_3$-x is used as the cathode in T3, barrier lowering at Source appears, resulting in a large electron injection and a large photo gain. Due to the strong pinning effect, the injected photocurrent can not lower the barrier at the Drain contact. The Source built-in field is thus invariant and no feedback occurs (Fig. 4i).

Discussion

In conclusion, we have designed and fabricated a molybdenum-based phototransistor with one MoS$_2$ channel and two α-MoO$_3$-x contact electrodes. A double-heterojunction PIBL mechanism is proposed, in which double heterojunctions enable positive feedback to each other in one phototransistor, leading to a high detectivity of 9.8 × 10$^{16}$ cm Hz$^{-1/2}$ W$^{-1}$. A fast response speed was also achieved, because our device employs the PIBL mechanism without trapping photogenerated carriers and can be intrinsically fast. Based on this mechanism, a series of 2D material-based phototransistors with high performance can be expected since the 2D material family keeps growing to enable various energy band combinations, and van der Waals heterojunctions are typically free of a lattice mismatch. 2D material phototransistors with double-heterojunction PIBL mechanism provide new technologies and shed light on the fabrication of high-performance 2D photodetectors.

Methods

Preparation of α-MoO$_3$ flakes. Bulk α-MoO$_3$ crystals were grown by chemical vapor deposition in air environment. Commercial MoO$_3$ powder (Alfa Aesar, 99.95%, metals basis) was placed in a quartz boat that was put in the center of a horizontal tube furnace (Lindeberg Blue M, TFS5035KC-1). The furnace was heated to 750 °C at a rate of 25 °C/min and this temperature was maintained for 60 min until the MoO$_3$ powder was completely volatilized. When the furnace cooled to room temperature, the bulk α-MoO$_3$ was synthesized on both ends of the quartz tube. The bulk α-MoO$_3$ crystals were exfoliated using Scotch® tape and multilayer α-MoO$_3$ flakes were placed on the surface of a 280-nm-thick SiO$_2$ layer grown on a heavily p-doped silicon (p$^+$) wafer.

Transfer of the MoS$_2$ flakes. Polydimethylsiloxane (PDMS) was used as the medium to transfer the MoS$_2$ flakes onto the target α-MoO$_3$ electrodes. The PDMS was prepared by stirring a mixed solution of the base and its curing agent (10:1 in weight) and baking at 65 °C for 6 h. Few-layer MoS$_2$ flakes were exfoliated from the bulk MoS$_2$ crystals using Scotch® tape, and transferred onto the PDMS substrate, and finally released onto the target α-MoO$_3$ electrodes using a home-made electrostatic van der Waals transfer station.

Vacuum annealing of the fabricated stacks. To produce the transition from α-MoO$_3$ to α-MoO$_3$-x, the fabricated stacks were annealed in a vacuum. The number of oxygen defects in the crystal could be controlled by the temperature and time. The annealing furnace was heated to 350 °C from room temperature in 30 min, where the temperature was maintained for 120 min. The samples were removed after the furnace cooled to room temperature. This process has no significant effect on MoS$_2$ (Supplementary Fig. 21).

Device fabrication. Multilayer α-MoO$_3$ flakes were exfoliated onto a SiO$_2$/Si substrate and patterned by RIE. A few-layer MoS$_2$ flake was exfoliated onto a PDMS substrate, and then transferred onto a α-MoO$_3$ electrode. The stack was then vacuum annealed at 350 °C for 120 min. Afterwards, metal contacts (Ti/Au: 5/50 nm) were formed by EBL, electron-beam evaporation and lift-off processes. The device was finally passivated by a 5-nm-thick HfO$_2$ layer deposited by atomic layer deposition (ALD).

Fig. 3 The origin of the ultrahigh detectivity. a Four MoS$_2$ phototransistors with difference source (cathode) and drain (anode) electrodes marked T1 (Ti/Au, T2 (α-MoO$_3$-x, Ti/Au), T3 (Ti/Au, α-MoO$_3$-x), and T4 (α-MoO$_3$-x, α-MoO$_3$-x). b $I_{DS}$ − $V_{GS}$ measured in the dark (black line) and the light with a wavelength of 405 nm and a power density of 0.1 mW/cm$^2$ (colored line) for $V_{DS}=1$ V. The optoelectronic responses from T1 to T4 gradually increase, showing that $I_{DS}/I_{Dark}$ increases from <10 to more than 10$^4$ at $V_{GS}=-80$ V. c Scanning photocurrent map of the α-MoO$_3$-x/MoS$_2$/α-MoO$_3$-x phototransistor illuminated by a 633 nm laser with a spot size of ~2 μm using a nano-positioning stage with a 1 μm scanning resolution, for $V_{GS}=-60$ V and $V_{DS}=-1$ V, the color bars represents quantity of photocurrent.

Preparation of α-MoO$_3$ flakes. Bulk α-MoO$_3$ crystals were grown by chemical vapor deposition in air environment. Commercial MoO$_3$ powder (Alfa Aesar, 99.95%, metals basis) was placed in a quartz boat that was put in the center of a horizontal tube furnace (Lindeberg Blue M, TFS5035KC-1). The furnace was heated to 750 °C at a rate of 25 °C/min and this temperature was maintained for 60 min until the MoO$_3$ powder was completely volatilized. When the furnace cooled to room temperature, the bulk α-MoO$_3$ was synthesized on both ends of the quartz tube. The bulk α-MoO$_3$ crystals were exfoliated using Scotch® tape and multilayer α-MoO$_3$ flakes were placed on the surface of a 280-nm-thick SiO$_2$ layer grown on a heavily p-doped silicon (p$^+$) wafer.

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**Fig. 4 Double-heterojunction photo-induced barrier-lowering mechanism.**

**a** Absorbance spectrum of the pure and annealed \(\alpha\)-MoO\(_3\)-x flakes. \(E_b\) is the bandgap. The red line is an auxiliary line for extracting \(E_b\). **b** Ultraviolet photoelectron spectroscopy (UPS) measurement of \(\alpha\)-MoO\(_3\)-x flakes. A He-I UV light source (\(h\nu = 21.2\) eV) was used to obtain the UPS spectra. The binding energy is referred to the Fermi level. The work function (\(\Phi_b\)) was obtained from the cutoff region, which is 5.32 eV. The difference between the Fermi level and the valence band maximum was calculated to be 3.05 eV from the valence region. The red lines are auxiliary lines. **c** Energy band diagram at the light-off state. \(E_C\) is the conduction band minimum, \(E_F\) is the Fermi level, \(E_G\) is the defect band and \(E_V\) is the valence band maximum. The red circle represents electrons. The red arrow represents the electron inject from source electrode to channel and green arrow represents the electron inject from channel to drain electrode. **d** Slopes extracted from Supplementary Fig. 18 as a function of \(V_{GS}\). \(\phi_B\) is the Schottky barrier about 0.55 eV, derived from the \(\gamma\)-intercept, \(S_0\). **e** Energy band diagram at the light-on state to illustrate the photo-induced barrier-lowering mechanism. The blue symbol (1) represents the photo-generation of electron-hole pairs, the red symbol (2) the holes and electrons separating process to reduce barrier and increase electrons injection, and the green symbol (3) the injection electrons reducing the barrier at drain side. The \(h\nu\) represents incident photon. **f** Slopes extracted from Supplementary Fig. 18 as a function of \(V_{GS}\). \(\phi_B\) is about 0.042 eV, derived from the \(\gamma\)-intercept, \(S_0\). **g** Energy band diagram of device T1. When there is incident light, the photo response mainly comes from the MoS\(_2\) material itself. \(E_{FM}\) is the Fermi level of Ti. **h** Energy band diagram of device T2. When there is incident light, there is a slightly better photo response mainly due to barrier-lowering at Drain \(\alpha\)-MoO\(_3\)-x. **i** Energy band diagram of device T3. When there is incident light, a large photo gain was achieved because Source barrier-lowering enhanced electron injection. \(E_{FM}\) is the Fermi level of Ti.

**Characterization.** The materials and devices were characterized using an optical microscope (Nikon ECLIPSE LV100ND), an AFM (Bruker Dimension Icon), a TEM (Thermo Scientific, Titan Cube Themis G2, acceleration voltage of 80 kV), an X-ray photoelectron spectroscopy (XPS) analyzer (Thermo VG Scientific ESCALAB250), a micro-Raman analyzer (Jobin Yvon HR8000 using 532 nm laser excitation with a laser spot size of about 2 \(\mu\)m), an ultraviolet photoelectron spectroscopy (UPS) analyzer (Thermo ESCALAB 250Xi with a monochromatic Al K\(\alpha\) X-ray source) and a UV-Vis-NIR spectroscope (Varian Cary 5000). The electrical and optoelectronic performances were measured using a semiconductor analyzer (Agilent B1500A), a probe station (Cascade M150) and a laser diode controller (Thorlabs ITC4001, with laser excitations of 405, 516, and 638 nm) in a dark room at room temperature. The optoelectronic mapping was carried out using two semiconductor analyzers (Keithley 2400) and a micro-Raman spectroscopy. To characterize the response speed of this device, a 532 nm incident laser (MDL-III-785L) modulated at various frequencies using an optical chopper was used to illuminate the device. A current amplifier (Model SR570) was used to provide a bias voltage for the device, and an oscilloscope (Tektronix MDO3102) was used to pick up the signal. The noise was measured by a noise measurement system (PDANC300L and Fs Pro, 100 kHz bandwidth), the sketch of the noise measurement system is shown in Supplementary Fig. 22.

**Density functional theory (DFT) calculations.** DFT calculations were performed to study the electronic structure of the \(\alpha\)-MoO\(_3\)/MoS\(_2\) heterojunctions using the Vienna ab-initio simulation package\(^{44,45}\). The detailed computational settings as well as the constructions of the \(\alpha\)-MoO\(_3\)/MoS\(_2\) heterojunction are very similar to those used in ref.\(^{40}\). In order to obtain the accurate electronic structures, especially the bandgap values of semiconducting \(\alpha\)-MoO\(_3\)-x and MoS\(_2\), the hybrid Heyd-Scuseria-Ernzerhof (HSE) exchange-correlation functional\(^{45,46}\) was used. A consistent
screening parameter of $\mu = 0.2 \text{ Å}^{-1}$ was used for the semilocal exchange as well as for the screened nonlocal exchange as suggested for the HSE06 functional.

**Data availability**

The data that support the findings of this study are available at https://zenodo.org/record/4835973#.YLDXJ43is2w.

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