Magnetic proximity and nonreciprocal current switching in a monolayer WTe$_2$ helical edge

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The integration of diverse electronic phenomena, such as magnetism and nontrivial topology, into a single system is normally studied either by seeking materials that contain both ingredients, or by layered growth of contrasting materials$^{5-9}$. The ability to simply stack very different two-dimensional van der Waals materials in intimate contact permits a different approach$^{10,11}$. Here we use this approach to couple the helical edges states in a two-dimensional topological insulator, monolayer WTe$_2$ (refs. 12-16), to a two-dimensional layered antiferromagnet, CrI$_3$ (ref. 17). We find that the edge conductance is sensitive to the magnetization state of the CrI$_3$, and the coupling can be understood in terms of an exchange field from the nearest and next-nearest CrI$_3$ layers that produces a gap in the helical edge. We also find that the nonlinear edge conductance depends on the magnetization state of the CrI$_3$ layer relative to the current direction. At low temperatures this produces an extraordinarily large nonreciprocal current that is switched by changing the antiferromagnetic state of the CrI$_3$.

The introduction of magnetic order into topological band structure gives rise to new phenomena such as the quantum anomalous Hall effect$^{18,19}$ and nonreciprocal magnetoelectric effects$^{20,21}$. In the case of a two-dimensional topological insulator (2DTI), topology guarantees the existence of helical edge modes in which the spin is locked to momentum, causing current at the edge to be fully spin-polarized (the quantum spin Hall effect)$^{20}$. Combining 2DTIs with magnets should therefore directly yield magnetoelectric coupling$^{20,21}$. For example, a magnetic proximity effect may modify the spin polarization and hence the current, or the flow of current in the edge may produce a torque on the magnetization$^{22,23}$. Since backscattering in the edge modes is suppressed by time-reversal symmetry, the edge conductance should be affected by magnetic order, which will mix the two opposite-spin branches and so modify backscattering. The expected gapping of the helical edge modes by proximity with a ferromagnet is an important way to control them that, combined with induced superconductivity$^{24,25}$, plays a role in schemes to produce Majorana modes$^{26}$.

Stacking van der Waals materials offers a simple, flexible and low-disorder approach to combining magnets with other materials$^{10,11}$. In this work we measure transport through a 2DTI, monolayer WTe$_2$ (refs. 13-15), stacked under the layered magnetic insulator CrI$_3$ (refs. 17,27-29). We find that the magnetism of the CrI$_3$ suppresses the edge conduction in the WTe$_2$ in a manner consistent with the opening of a gap by an exchange field. The linear edge conductance is sensitive to the magnetization state of the CrI$_3$, and changes suddenly when the magnetization of the nearest or next-nearest CrI$_3$ layer flips. In addition, the nonlinear current-voltage characteristic has an even component that changes sign when the magnetization of the adjacent CrI$_3$ layer reverses. This is related to the ‘unidirectional magnetoresponse’ seen in magnetically doped three-dimensional topological insulator (3DTI) structures where it has been explained by spin-flip scattering of electrons by magnons$^{30-32}$. However, in the helical edge at low temperatures the effect exists at zero external field and can be extremely large, creating a difference in (nonreciprocal) current of the order of 100% between the two opposite antiferromagnetic ground states of the CrI$_3$.

The structure and magnetic configuration of CrI$_3$ at zero magnetic field is indicated in Fig. 1a. Each layer is internally ferromagnetic, with the moments aligned out of the plane below a critical temperature of $T_c \approx 45$ K. In thin exfoliated CrI$_3$ flakes, adjacent layers are antiferromagnetically coupled and thus have opposite magnetization. The structure of monolayer WTe$_2$ is sketched in Fig. 1b. Although semimetallic at room temperature or when doped, below ~100 K and at low gate voltages the two-dimensional bulk shows insulating behaviour while the edge remains conducting. Both theory$^{33}$ and experiments$^{13-16}$ indicate that the edge states are helical (signified by the green and pink bordering lines representing the two spins channels); that is, this is a quantum spin Hall system. For example, the edge conductance is strongly suppressed by an in-plane magnetic field. Each of our devices contains a monolayer flake of WTe$_2$, which is either partly or completely covered by a few-layer flake of CrI$_3$, as sketched in Fig. 1c. The thicknesses of monolayer WTe$_2$ and few-layer CrI$_3$ were determined from optical contrast$^{13,17}$ (Supplementary Information). The WTe$_2$ overlies prepatterned platinum contacts, all encapsulated between two hexagonal boron nitride (hBN) dielectric layers, with a graphite bottom gate to which a gate voltage $V_g$ is applied (see Methods and Supplementary Information).

Figure 1d shows the $V_g$ dependence of the linear-response conductance $G$ measured between two adjacent contacts in device C1, which has trilayer CrI$_3$ covering most of the WTe$_2$ (see the inset optical image). $G$ exhibits a minimum near $V_g=0$. The value at the minimum, plotted versus $T$ in Fig. 1e (black points), decreases monotonically on cooling. Above about 50 K the behaviour is similar to that of a typical bare monolayer WTe$_2$ device M1 (red points), in which the bulk conductivity steadily decreases on cooling. However, at lower temperatures in the bare device the conductance levels off due to temperature-independent edge conduction, whereas in C1 it continues to drop to the lowest temperature of 5.6 K. Similar behaviour was seen in four devices whenever CrI$_3$ covered at least part of the edge in the current path (Supplementary Information). The blue dashed line is an Arrhenius fit of the form $G \propto \exp(-E_a/k_B T)$.
to the data in this regime, where $k_B$ is Boltzmann’s constant, yielding an activation energy $E_a = 2.5 \pm 0.3$ meV. This activated suppression of the edge conduction is similar to the behaviour seen in an applied magnetic field, where the activation energy is found to be approximately proportional to the field. However, a theory of this suppression that takes into account the combined effects of wavefunctions at the edge, disorder, magnetism and electron–electron interactions is not yet available. We therefore focus here on the effects of changing the magnetization state of the CrI$_3$, which we do using a perpendicular applied field $B$.

Figure 2a shows the linear conductance of device C1 as $B$ is swept upwards (orange) and downwards (green) at a series of temperatures, measured at a gate voltage ($V_g = -0.5$ V) where edge conduction dominates. Factoring out the noise in the measurements, the upwards traces are the same as the downwards traces reflected in $B = 0$, as should be the case by time-reversal considerations. At temperatures above ~45 K, $G$ decreases smoothly with increasing $B$ as does the edge conduction in bare WTe$_2$. Below 45 K a jump appears in the vicinity of $1.2 \times 10^{-12}$ cm$^{-2}$ V$^{-1}$ s$^{-1}$. Inset, optical image of device C1; the trilayer CrI$_3$ and monolayer WTe$_2$ flakes are outlined by purple and pink dashed lines, respectively. Scale bar, 5 µm. e, Temperature dependence of the minimum conductance for device C1 (black) and for bare (no CrI$_3$) monolayer WTe$_2$ device M1 (red). The insets indicate the relevance of bulk and edge currents in each case.

The sizes and signs of the conductance jumps are consistent with a simple model in which the WTe$_2$ conduction electrons experience a perpendicular exchange magnetic field, $B_{ex}$, that adds to the external field so that the conductance becomes $G_{ex}(B + B_{ex})$, where $G_{ex}(B)$ is conductance without the CrI$_3$. We assume $B_{ex}$ takes values $\pm B_f$ for $\uparrow\uparrow$ and $\downarrow\downarrow$, and $\pm B_{ex}$ for $\uparrow\downarrow$ and $\downarrow\uparrow$, respectively. The variation of $B + B_{ex}$ with $B$ is sketched in Fig. 2c. In this model the higher-field jump is between $G_{ex}(B + B_{ex})$ and $G_{ex}(B - B_{ex})$. Since $G_{ex}(B)$ is roughly linear with similar slope on either side of this jump, as indicated by the dashed lines drawn on the 25 K data in Fig. 2a, we can use the separation of these lines to estimate $B_f - B_{ex} = \approx 1$ T. The lower-field jump, which should be between $G_{ex}(B + B_{ex})$ and $G_{ex}(B - B_{ex})$, cannot be analysed so simply, but making use of the Onsager symmetry $G_{ex}(B) = G_{ex}(-B)$ we can infer that $B_{ex}$ is much larger than the coercive field, putting it at several Tesla (Supplementary Information). If we consider (without theoretical rigour) that the activation energy $E_a$ for the edge is a Zeeman energy associated with $B_{ex}$ that is, $E_a \approx g\mu_B B_{ex}$ and use a $g$-factor of $g = 4$ estimated from the magnetoresistance (Supplementary Information), we obtain $B_{ex}$ of ~10 T, where $\mu_B$ is the Bohr magneton. This is similar in magnitude to the exchange field of 13 T found in WSe$_2$/CrI$_3$ heterostructures$^{10}$ and of >14 T in graphene/EuS$^{11}$.

We next investigate the nonlinear conductance, which yields additional information since it is not constrained by the Onsager symmetry imposed by near-equilibrium conditions. We begin by working at higher temperatures where the linear conductance $G$ is measurable. We apply an a.c. bias of r.m.s. amplitude $V_f$ at frequency $f$ and measure the resulting a.c. current components at $f$ and $2f$, with $V_f$ chosen such that $I_{2f} \ll I_f$. If we write $I = GV_f + aV_f^2 + \ldots$ then $I_f = GV_f$ and $I_{2f} = aV_f^2/2$ is proportional to the coefficient $a$ that parameterizes the conductance asymmetry between positive and negative bias directions, as indicated in Fig. 3a. Measurements of $I_f$ versus $B$ for device C1, shown in Fig. 3b, match the a.c. linear conductance measurements in Fig. 2a as expected, exhibiting four jumps. Measurements of $I_{2f}$ at several temperatures, plotted in Fig. 3c, show large jumps corresponding to the $\uparrow\uparrow \rightarrow \downarrow\downarrow$
Conductance jumps and magnetic state changes in an applied magnetic field. a, Linear conductance (measured using 1 mV a.c. bias) versus out-of-plane magnetic field $B$ at $V_f = -0.5$ V for device C1 at the indicated temperatures. The dashed lines indicate the effective shift of the characteristic that occurs at one of the jumps (see text). The traces are vertically offset for clarity; the conductance at $B = 0$ can be read off in Fig. 1e. b, Upper, conductance, and lower, RMCD signal as a function of $B$ (10 mV a.c. bias, $V_f = -1 V$, $T = 11.8$ K). Inset, spatial map of RMCD signal at $B = 0$ after reducing $B$ from $+2.5$ T. Scale bar, 2 μm. The boundaries of the Pt contacts and trilayer CrI$_3$ are indicated by dark yellow and purple dashed lines, respectively. Beneath are schematics of the corresponding magnetic states of the trilayer CrI$_3$ (blue and red for down and up polarizations) atop monolayer WTe$_2$ (pink). c, Schematic variation of the sum of the real and exchange magnetic fields used to interpret the behaviour of $G$ in b.

transitions, detectable up to 40 K, but no discernible features at the $\parallel \parallel \parallel - \parallel \parallel$ or $\uparrow \uparrow \uparrow - \parallel \parallel$ transitions in which the magnetization of the lowest layer does not flip (Supplementary Information). We conclude that the asymmetry parameter $\alpha$ is sensitive to the magnetization, $\mathbf{m}$, of the nearest layer of CrI$_3$ but not to that of the next-nearest layer.

In these nonlinear measurements the larger bias used could potentially drive some current through the WTe$_2$ bulk, whose activation gap is ~50 meV (ref. 14), so we performed an experiment to test whether this bulk current is relevant. Figure 3d shows $I_g$ versus $B$ for a large a.c. bias ($V_f = 100$ mV) applied to a device C3, which has the contact pattern indicated in the sketches (see Supplementary Information for device and other details). In two-terminal measurements between the outer contact pair (left), $I_g$ shows large jumps. However, when the intervening contact is grounded (right) the jumps almost disappear even though the linear conductance remains substantial. This implies that when current is prevented from flowing along the edge there is no sensitivity to the state of the CrI$_3$. We deduce that in both nonlinear and linear regimes the sensitivity to the magnetic state of the CrI$_3$ is dominated by the sample edges.

Finally, we turn to the nonlinear behaviour at lower temperatures, where the linear conductance freezes out. Figure 4 shows two-terminal $I$–$V$ traces at 1.6 K for bilayer CrI$_3$ device C2 at $B = 0$. The magnetization transitions in bilayer CrI$_3$ follow a different pattern from those in trilayer (Fig. 2b) and occur at different magnetic fields. The bilayer is antiferromagnetic (|$\uparrow$| or |$\downarrow$|) at low $B$ and flips to a fully polarized state (|$\uparrow\uparrow$| or |$\downarrow\downarrow$|) for $B \geq 0.9$ T. Here, no current is detected below a threshold bias of ~70 mV in either direction. Above this bias the current depends strongly on $B$ and exhibits hysteresis between two stable states at low fields (upper inset). Correspondingly, either of the two different $I$–$V$ traces shown (blue and red) can be obtained. RMCD measurements (shown at the bottom of the upper inset) connect them unambiguously with the |$\uparrow\downarrow$| or |$\downarrow\uparrow$| states. An RMCD map taken at $B = 0$ (lower inset) shows a uniform magnetic state over most of the WTe$_2$. Note that a finite RMCD signal in the antiferromagnetic state, as seen here, is normal for CrI$_3$ bilayers$^{29,30}$ and implies uncompensated magnetization between the two layers, probably in this case related to contact with the WTe$_2$ (for more temperatures, see Supplementary Information).

Inspection of Fig. 4 shows that in the |$\uparrow\uparrow$| state (blue) the current at positive bias is roughly double that at negative bias; that is, it is strongly nonreciprocal. This difference is hard to understand in terms of an exchange field, because reversing the exchange field in going from |$\uparrow\uparrow$| to |$\downarrow\downarrow$| does not affect the linear conductance at all at zero field by Onsager symmetry. In the |$\downarrow\downarrow$| state (red) the opposite is true, indicating that the dominant part of the nonreciprocal current is connected to the orientation of the magnetization of the lowest CrI$_3$ layer, $\mathbf{m}$, relative to the current direction. This is consistent with the corresponding property of $\mathbf{p}$ discussed above. A similar nonreciprocal resistance change on magnetization reversal, referred to as unidirectional magnetoresistance, was reported in magnetic/nonmagnetic 3DTI thin-film heterostructures$^{54}$. However, in that case, the effect was much smaller and vanished at zero applied field. This is because the spin polarization of the current-carrying states in the 3DTI is in-plane, perpendicular to the magnetization of the Cr dopants at zero field. For the magnetization to distinguish opposite in-plane spin polarizations it must be rotated to have an in-plane component using an in-plane applied magnetic field. In our case, the nonreciprocal effect is orders of magnitude larger (of the order of 100%) and is present at a zero applied field. This is allowed because the spin of the 2DTI edge state is not in-plane, and so states with opposite current have an out-of-plane spin polarization component that couples to the magnetization, even at a zero field.

Fig. 2 | Conductance jumps and magnetic state changes in an applied magnetic field. a, Linear conductance (measured using 1 mV a.c. bias) versus out-of-plane magnetic field $B$ at $V_f = -0.5$ V for device C1 at the indicated temperatures. The dashed lines indicate the effective shift of the characteristic that occurs at one of the jumps (see text). The traces are vertically offset for clarity; the conductance at $B = 0$ can be read off in Fig. 1e. b, Upper, conductance, and lower, RMCD signal as a function of $B$ (10 mV a.c. bias, $V_f = -1 V$, $T = 11.8$ K). Inset, spatial map of RMCD signal at $B = 0$ after reducing $B$ from $+2.5$ T. Scale bar, 2 μm. The boundaries of the Pt contacts and trilayer CrI$_3$ are indicated by dark yellow and purple dashed lines, respectively. Beneath are schematics of the corresponding magnetic states of the trilayer CrI$_3$ (blue and red for down and up polarizations) atop monolayer WTe$_2$ (pink).
As a mechanism for this giant nonreciprocal current, we can exclude a current-induced spin-orbit torque effect because no current flows in the insulating CrI\textsubscript{3}. Another possibility is the anomalous Nernst effect\textsuperscript{5}, where a temperature gradient $\nabla T$ is created perpendicular to the edge by ohmic heating and induces a voltage along the edge proportional to $m^\prime \nabla T$. Such a transverse temperature gradient seems unlikely to develop because the ohmic heat should be generated within the edge state itself or in the contacts. Another possible mechanism is analogous to the one put forward in ref. \textsuperscript{5}. Backscattering that opposes current flowing, say, to the right in the helical edge requires spin flips from ‘up’ to ‘down’ (note that the actual spin alignment axis is presently unknown), and vice versa for current flowing in the opposite direction. The spin flip may be assisted by excitation of magnons within the nearest CrI\textsubscript{3} layer. These magnons carry spin opposite to the ferromagnetic polarization of that layer; therefore, one polarization allows more scattering of a right-flowing current, and the opposite allows more scattering of a left-flowing current. In this system, the effect can be very large because no small-angle scattering is possible in the 1D helical edge, and also because there is little or no conduction in parallel through the bulk.

In summary, we have observed and studied coupling of the magnetism in insulating layered CrI\textsubscript{3} to the edge states of a quantum spin Hall insulator (monolayer WTe\textsubscript{2}). The results are consistent with the edge states being helical (spin locked to momentum) such that time-reversal symmetry breaking due to the magnetization suppresses their conductance. The effect on the linear edge conductance can be interpreted in terms of an exchange field of order 10 T from the nearest CrI\textsubscript{3} layer and a much smaller one, of order $(B_1 - B_2)/2 = 0.5$ T, from the next-nearest CrI\textsubscript{3} layer. The nonlinear.

**Fig. 3 | Nonlinear current measurements.** a. Sketch indicating the relationship of the first- and second-harmonic current components to the asymmetry in the $I$–$V$, which is parameterized by quadratic coefficient $\alpha$. b. $I_1$ versus $B$ for device C1 at $V_g = -0.5$ V and $T = 12$ K with a.c. voltage bias $V_f = 15$ mV. c. $I_2$ versus $B$ measured under the same conditions (lowest traces) and at several other current values as labelled. The traces are vertically offset for clarity and the dashed horizontal lines show the zero level for each temperature. The schematics are repeated from Fig. 2c. d. Second-harmonic current versus $B$ for device C3 at $V_g = 0.1$ V, $T = 27$ K and $V_f = 100$ mV, compared between the two different measurement configurations as indicated. Bulk and edge currents are signified by blue and red arrows, respectively.

**Fig. 4 | Large nonreciprocal current controlled by the antiferromagnetic state.** $I$–$V$ traces at zero magnetic field at 1.6 K and $V_g = 0$ V for device C2, which has bilayer CrI\textsubscript{3}. The schematics indicate the magnetization state of the CrI\textsubscript{3} and the current flow direction in the monolayer WTe\textsubscript{2}. Upper inset, current at 100 mV d.c. bias (corresponding to the points marked with symbols in the $I$–$V$ traces) and RMCD signal versus magnetic field. Lower inset, spatial map of RMCD signal at 0 T after reducing from $+2.5$ T. The current is measured between the upper two contacts. The boundaries of bilayer CrI\textsubscript{3}, Pt contacts and WTe\textsubscript{2} are outlined with purple, dark yellow and black dashed lines, respectively.
conductance shows a large directional asymmetry that depends on the magnetization of only the nearest CrI₃ layer, and is thus highly sensitive to the AF ground state.

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References
1. Chang, C.-Z. et al. Experimental observation of the quantum anomalous Hall effect in a magnetic topological insulator. Science 340, 167–170 (2013).
2. Katmis, F. et al. A high-temperature ferromagnetic topological insulating phase by proximity coupling. Nature 533, 513–516 (2016).
3. Wei, P. et al. Exchange-coupling-induced symmetry breaking in topological insulators. Phys. Rev. Lett. 110, 186807 (2013).
4. Avci, C. O. et al. Unidirectional spin Hall magnetoresistance in ferromagnet/normal metal bilayers. Nat. Phys. 11, 570–575 (2015).
5. Yasuda, K. et al. Large unidirectional magnetoresistance in a magnetic topological insulator. Phys. Rev. Lett. 117, 127202 (2016).
6. Fan, Y. et al. Unidirectional magneto-resistance in modulation-doped magnetic topological insulators. Nano Lett. 19, 692–698 (2019).
7. Lv, Y. et al. Unidirectional spin-Hall and Rashba–Edelstein magneto-resistance in topological insulator-ferromagnet layer heterostructures. Nat. Commun. 9, 111 (2018).
8. Deng, Y. et al. Quantum anomalous Hall effect in intrinsic magnetic topological insulator MnBi₂Te₄. Science https://doi.org/10.1126/science.aax8156 (2020).
9. Chang, L. et al. Robust axion insulator and Chern insulator phases in a two-dimensional antiferromagnetic topological insulator. Nat. Mater. https://doi.org/10.1038/s41563-019-0573-3 (2020).
10. Zhong, D. et al. Van der Waals engineering of ferromagnetic semiconductor heterostructures for spin and valleytronics. Sci. Adv. 3, e1603113 (2017).
11. Wei, P. et al. Strong interfacial exchange field in the graphene/EuS heterostructure. Nat. Mater. 15, 711–716 (2016).
12. Qian, X. et al. Quantum spin Hall effect in two-dimensional transition metal dichalcogenides. Science 346, 1344–1347 (2014).
13. Fei, Z. et al. Edge conduction in monolayer WTe₂. Nat. Phys. 13, 677–682 (2017).
14. Tang, S. et al. Quantum spin Hall state in monolayer 1T’-WTe₂. Nat. Phys. 13, 683–687 (2017).
15. Wu, S. et al. Observation of the quantum spin Hall effect up to 100 kelvin in a monolayer crystal. Science 359, 76–79 (2018).
16. Shi, Y. et al. Imaging quantum spin Hall edges in monolayer WTe₂. Sci. Adv. 5, eaat8799 (2019).
17. Huang, B. et al. Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit. Nature 546, 270–273 (2017).
18. Tokura, Y. et al. Nonreciprocal responses from non-centrosymmetric quantum materials. Nat. Commun. 9, 3740 (2018).
19. König, M. et al. Quantum spin Hall insulator state in HgTe quantum wells. Science 318, 766–770 (2007).
20. Liu, C.-X. et al. Quantum anomalous Hall effect in Hg₋ₓMnₓTe quantum wells. Phys. Rev. Lett. 101, 146802 (2008).
21. Gong, C. & Zhang, X. Two-dimensional magnetic crystals and emergent heterostructure devices. Science 363, eaav4450 (2019).
22. Liu, L. et al. Spin-torque switching with the giant spin Hall effect of Tantalum. Science 336, 555–558 (2012).
23. MacNeill, D. et al. Control of spin-orbit torques through crystal symmetry in WTe/ferromagnet bilayers. Nat. Phys. 13, 300–305 (2017).
24. Sajadi, E. et al. Gate-induced superconductivity in a monolayer topological insulator. Science 362, 922–925 (2018).
25. Fatemi, V. et al. Electrically tunable low-density superconductivity in a monolayer topological insulator. Science 362, 926–929 (2018).
26. Fu, L. & Kane, C. L. Josephson current and noise at a superconductor/quantum-spin-Hall-insulator/superconductor junction. Phys. Rev. B 79, 161408 (2009).
27. Song, T. et al. Giant tunneling magnetoresistance in spin-filter van der Waals heterostructures. Science 360, 1214–1218 (2018).
28. Klein, D. R. et al. Probing magnetism in 2D van der Waals crystalline insulators via electron tunneling. Science 360, 1218–1222 (2018).
29. Huang, B. et al. Electrical control of 2D magnetism in bilayer CrI₃. Nat. Nanotechnol. 13, 544–548 (2018).
30. Jiang, S. et al. Controlling magnetism in 2D CrI₃ by electrostatic doping. Nat. Nanotechnol. 13, 549–553 (2018).

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Methods

Device fabrication. First, graphite and hBN crystals were mechanically exfoliated onto thermally grown SiO$_2$ on a highly doped Si substrate. The thickness of hBN flakes as top and bottom dielectrics are listed in Supplementary Table 1. By using a polymer-based dry transfer technique, the few-layer graphite is covered by an hBN flake (bottom hBN). After dissolving the polymer, the hBN/graphite is annealed at 400 °C for 2 h. Next, Pt metal contacts (~7 nm) were deposited on the hBN by standard e-beam lithography and metallized in an e-beam evaporator. Then, another step of e-beam lithography and metallization was used to define bond pads (Au/V) connecting to the metal contacts and the graphite gate. CrI$_3$ and WTe$_2$ crystals were exfoliated in a glove box (O$_2$ and H$_2$O concentrations <0.5 ppm). CrI$_3$ flakes from bilayer to four-layer and monolayer WTe$_2$ flakes were optically identified. A CrI$_3$ flake was picked up under another hBN flake (top hBN), followed by a pick-up of the monolayer WTe$_2$ flake. The stack was then put down on the Pt contacts in the glove box. Finally, the polymer was quickly dissolved in chloroform (~1 min).

Electrical measurements. Electrical measurements were carried out in an Oxford He-4 VTI cryostat with temperature down to 1.6 K and magnetic field up to 14 T. A 1 mV a.c. excitation at 101 Hz was applied for linear responses. For second-harmonic responses, a 15–100 mV a.c excitation at 101 Hz was applied, while at the same time we also connected a 30 μF capacitor in series with the device.

Reflective magnetic circular dichroism measurements. Reflective magnetic circular dichroism measurements were performed in a closed-cycle cryostat (attoDRY 2100) with a base temperature of 1.6 K and an out-of-plane magnetic field up to 9 T. A 632.8 nm helium–neon laser was used to probe the device at normal incidence with a fixed power of 100 nW. The standard lock-in measurement technique used to measure the RMCD signal closely followed the previous magneto-optical Kerr effect and RMCD measurements of the magnetic order in atomically thin CrI$_3$ (ref. 27).

Data availability
The data that support the findings of this study are available from the corresponding author on reasonable request.

References
31. Zomer, P., Guimaraes, M. H. D., Brant, J. C., TOMBROS, N. & van Wees, B. J. Fast pick up technique for high quality heterostructures of bilayer graphene and hexagonal boron nitride. Appl. Phys. Lett. 105, 013101 (2014).

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Author contributions
D.H.C. and X.X. conceived the experiment. W.Z., Z.F., H.K.C., T.P. and B.S. fabricated the devices. W.Z. and Z.F. performed transport measurements. T.S. performed magnetic circular dichroism measurements. P.M. and J.-H.C. grew the WTe$_2$ crystals. M.A.M. grew CrI$_3$ crystals. D.H.C., W.Z., X.X. and Z.F. wrote the paper with comments from all authors.

Competing interests
The authors declare no competing interests.

Additional information
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