Gate-tuneable and chirality-dependent charge-to-spin conversion in tellurium nanowires

Francesco Calavalle1,7, Manuel Suárez-Rodríguez ⊗1,7, Beatriz Martín-García1, Annika Johansson2,3, Diogo C. Vaz1, Haozhe Yang ⊗1, Igor V. Maznichenko2, Sergey Ostanin2, Aurelio Mateo-Alonso4,5, Andrey Chuvilin ⊗1,4, Ingrid Mertig2, Marco Gobbi ⊗1,4,6, Felix Casanova ⊗1,4 and Luis E. Hueso ⊗1,4

Chiral materials are an ideal playground for exploring the relation between symmetry, relativistic effects and electronic transport. For instance, chiral organic molecules have been intensively studied to electrically generate spin-polarized currents in the last decade, but their poor electronic conductivity limits their potential for applications. Conversely, chiral inorganic materials such as tellurium have excellent electrical conductivity, but their potential for enabling the electrical control of spin polarization in devices remains unclear. Here, we demonstrate the all-electrical generation, manipulation and detection of spin polarization in chiral single-crystalline tellurium nanowires. By recording a large (up to 7%) and chirality-dependent unidirectional magnetoresistance, we show that the orientation of the electrically generated spin polarization is determined by the nanowire handedness and uniquely follows the current direction, while its magnitude can be manipulated by an electrostatic gate. Our results pave the way for the development of magnet-free chirality-based spintronic devices.

Chiral materials are the ultimate expression of broken symmetry, lacking inversion and mirror symmetry. Indeed, the relation between structural chirality and spin effects has been investigated for organic molecules25–28, which act as efficient spin filters in spite of their low electrical conductivity. This phenomenon, which is often named chiral-induced spin selectivity, remains poorly explored in chiral inorganic crystals29–32. Tellurium (Te), a material that possesses strong spin–orbit coupling and broken inversion symmetry, such as strained semiconductors33, Rashba systems34–36 and the surface of topological insulators37–39. In these systems, the spins of the electrons are locked in the direction perpendicular to their momenta, so that the flow of a charge current results in a perpendicularly oriented homogeneous spin polarization. Further lowering the crystal symmetry allows the creation of spin polarizations in unconventional directions36–38 and enables new fundamental effects39,40 and configurations for devices41–44.

Chiral materials are the ultimate expression of broken symmetry, lacking inversion and mirror symmetry. Indeed, the relation between structural chirality and spin effects has been investigated for organic molecules25–28, which act as efficient spin filters in spite of their low electrical conductivity. This phenomenon, which is often named chiral-induced spin selectivity, remains poorly explored in chiral inorganic crystals29–32. Tellurium (Te), a material that possesses strong spin–orbit coupling and broken inversion symmetry, such as strained semiconductors33, Rashba systems34–36 and the surface of topological insulators37–39. In these systems, the spins of the electrons are locked in the direction perpendicular to their momenta, so that the flow of a charge current results in a perpendicularly oriented homogeneous spin polarization. Further lowering the crystal symmetry allows the creation of spin polarizations in unconventional directions36–38 and enables new fundamental effects39,40 and configurations for devices41–44.

Here, we report a chirality-dependent and gate-tuneable Edelstein effect in naturally hole-doped single-crystalline Te NWs. A net spin polarization is detected by recording a unidirectional magnetoresistance (UMR)41–44 dependent on the relative orientation of the electrical current and the external applied magnetic field. Our results show that, unlike Rashba systems and topological insulators, the charge current flow in Te leads to a spin polarization oriented along the current path and pointing in opposite directions for left- or right-handed NWs. The measured UMR is explained on the basis of a chirality-dependent Edelstein effect arising from the radial spin texture at the H point of the valence band of Te, which dominates the transport in our hole-doped Te NWs. Using a conventional UMR figure of merit45, we show that this effect in Te is the largest yet observed, to the best of our knowledge. More importantly, the electrostatic gating of the Te NWs allows us to tune its Edelstein effect, leading to an electrical tuning of the UMR amplitude by a factor of six. The all-electrical generation, control and detection of spin polarization in chiral Te NWs opens the path to exploit chirality in the design of solid-state spintronic devices.

A hydrothermal process in the presence of a reducing agent was employed to grow single-crystalline Te NWs that were tens-of-micrometres long and a few hundred nanometres wide (Methods section and Fig. 1a). Scanning transmission electron microscopy (STEM) was employed to confirm that the Te NWs were single crystals displaying one of the two enantiomorphic chiral space groups, P3_1_21 or P3_21 (refs. 33,46). Figure 1b displays a three-dimensional sketch of the right- and left-handed Te chains arranged in their characteristic helical structure that twists around the chiral c axis. van der Waals forces keep together adjacent atomic chains, which possess the same helicity, providing a defined chirality to the Te crystal structure. Figure 1c shows a STEM image of...
a NW cross-section perpendicular to the c axis. Individual chains appear as triangles stemming from the projection of superimposed Te atoms. This atomic arrangement (Fig. 1b) indicates that the long axis of the Te NWs is oriented along the chain direction (c axis). While the image in Fig. 1c shows the high quality of the NW (also Supplementary Section 1), it cannot be used to identify its chirality. However, it is possible to unambiguously distinguish between right- and left-handed crystals through a comparison between the atomic arrangement in different crystalline planes33,34. In Fig. 1d, we observe that the STEM images of two NWs with opposite handedness match with the models for the space groups P3121 and P3221.

The lack of mirror and inversion symmetries, deriving from the chiral nature of Te, in combination with a high spin–orbit coupling, result in a complex band structure characterized by non-degenerate spin bands at highly symmetric k points (more details on the band structure are in Supplementary Section 2). The relevant region for electrical transport is located around the H point, where a bandgap of 0.335 eV separates the conduction and valence bands, and where the two upper branches of the valence band are separated by 0.126 eV (ref. 38). Figure 1e shows a zoomed-in view of the valence bands around this point, calculated from an effective model (Methods)38. The iso-energy contours corresponding to a cut of the valence band at energy $\varepsilon = -0.1$ eV below the band edge is characterized by a radial spin texture with spins pointing inward/outward in right-/left-handed crystals, as shown in Fig. 1f. Recent spectroscopic observations confirmed the link between the handedness of Te and the direction of the radial spin texture45,46. This is analogous to the spin-momentum locking observed in bulk Rashba systems11,12, but with a chirality-dependent radial spin texture instead of the conventional helical configuration1.

For the electrical characterization, we transferred Te NWs onto Si/SiO2 substrates using a Langmuir–Schaefer approach. Individual
NWs were subsequently selected and contacted using Pt contacts defined by standard lithography methods (Methods). Figure 2a shows the optical image of a contacted Te NW, with a sketch of the four-probe configuration used for the transport experiments. We redefine a Cartesian coordinate system to describe the directions of currents and magnetic fields applied, where z is in the same direction as the c crystallographic axis and x(y) is orthogonal to z and directed in/out of the device plane (Supplementary Section 3 for more details). Figure 2b–d shows the magnetotransport characteristics of a typical Te NW. For these measurements, we plot the average resistance $R_{\text{av}} = (R(+I) + R(−I))/2$, where $R(+I)$ and $R(−I)$ are the resistances measured with a d.c. positive and negative current ($I_z$), respectively (Methods). This way, we obtain the equivalent of the first harmonic response in a.c. transport measurements, excluding current-dependent contributions to the resistance. The temperature ($T$) dependence of the four-probe resistance shows a monotonic decrease of $R$ with decreasing $T$ (Fig. 2b). From the transfer characteristics, we observed that the Te NWs are hole doped, with a field effect mobility that ranges from $\sim 500$ cm$^2$/V$-s$ at $300$ K to $\sim 2.500$ cm$^2$/V$-s$ at $10$ K (Supplementary Section 4).

Fig. 2 | Magneto-electrical characterization of a Te NW. a, Optical image of a typical Te NW contacted with Pt contacts (the scale bar corresponds to $10$ μm), illustrating the scheme of the four-probe measurement configuration. The angle $\alpha$ defining the orientation between the magnetic field $B$ and the NW is also drawn. V, voltage. b, Temperature dependence of the four-probe resistance $R_{\text{av}} = (R(+I) + R(−I))/2$ at zero magnetic field. c, Te magnetoresistance $\Delta R = (R(0) - R(B))/R(0)$ measured along $\alpha = 0°$ and transversely to $\alpha = 90°$ the chiral axis at different temperatures (2, 10, 50 and 100 K). d, Angular dependence of $R_{\text{av}}$ at different magnetic fields and $T = 10$ K. The dashed line indicates the resistance at zero field. Small shifts in angle are caused by misalignments introduced when mounting the sample on the chip carrier. Inset, the variation of the angular-dependent magnetoresistance amplitude $\delta R = |R(90°) - R(0°)|$ with the field applied.

In all our transport experiments, we focused our attention on the regime at $B = 0$ T where, for every field, the resistance measured at $\alpha = 90°$ (0° and 180°) is higher (lower) than the resistance measured at $B = 0$ T, which is shown as a dashed line. The appearance of the maxima and minima is a direct consequence of the magnetoresistance curves shown in Fig. 2c, which transit from positive at 90° to negative at 0°. Additionally, we notice that, at 10 K and for $B > 3$ T, the dependence of the resistance on the field is almost linear for both the transverse and the longitudinal magnetoresistance, but with an opposite slope (Fig. 2c). Consequently, the difference between the maximum and the minimum values in the angular dependence $\delta R(\alpha) = |R(90°) - R(0°)|$ increases linearly with the applied field (inset in Fig. 2d).

We now focus on the detection of the chirality-dependent current-induced spin polarization in the Te NWs. Figure 3a,b displays a sketch of the radial spin texture of Te for left- and right-handed crystals. An electric field applied along the z direction generates a current density $j_z$, and causes a redistribution of states along the k direction, which is depicted as a $\Delta k$ shift of the Fermi contour. Due to the radial spin texture of Te, $\Delta k$ induces a homogeneous spin density that is parallel or antiparallel to $j_z$, depending on the chirality of the NWs. Unlike Rashba systems, the electrical current in Te is expected to acquire a net spin polarization oriented along $j_z$, which is a peculiar manifestation of the Te symmetries (Supplementary Section 6). This current-induced spin polarization can be detected in magnetotransport measurements since it introduces a dependence of the resistance on the mutual orientation of current and magnetic field. This effect, also known as UMR or non-reciprocal charge transport, allows one to map the spin texture of a material.

Using the configurations of the current and magnetic field illustrated in Fig. 3c, we analysed the angle-dependent magnetoresistance of the NWs, measured for opposite current directions along z ($±I_z$). By changing the current direction and varying the angle $\alpha$ between the NWs at a fixed magnetic field, we reverse the mutual orientation of $I_z$ and $B$. A parallel alignment between field and current is obtained at 0° for $+I_z$ and at 180° for $−I_z$ (Fig. 3c).

Figure 3d,e shows the resistance measured for $+I_z$ and $−I_z$ as a function of the angle $\alpha$ between the NW and a magnetic field ($B = 9$ T) for the two NWs with opposite chirality (cross-sections of these same two devices are shown in Fig. 1d). For both the right- and left-handed NWs, we find a strong dependence of the resistance on the relative alignment between $I_z$ and $B$, which is the hallmark of UMR. This dependence demonstrates the presence of a net spin.
polarization in the Te NWs. In particular, the left-handed NW shows a substantially higher (lower) resistance when the current is parallel (antiparallel) to the external magnetic field (Fig. 3d). This non-reciprocal effect can also be observed as a shift in the magnetoresistance traces measured for opposite current directions (Supplementary Section 5 and Supplementary Fig. 5). Conversely, the right-handed NW displays lower (higher) resistance for $I_{\parallel}$ parallel (antiparallel) to $B$ (Fig. 3e), indicating that the UMR of Te is mirrored in NWs with opposite chirality. Hence, the current-induced spin polarization is reversed for opposite NW handedness.

To analyse these data, we calculate the half difference $|A^{\text{diff}}| = |R(0^\circ) - R(180^\circ)|$ as a function of magnetic field and current, showing in both cases a linear behaviour.
180°), corresponding to the asymmetries in Fig. 3d,e. This indicates that, in agreement with the Edelstein mechanism (Fig. 3a,b), the spin polarization is oriented along the direction of the current, parallel to the chiral axis z. The deviation of $R^{\text{diff}}(\alpha)$ from the spin dependence typically observed for UMR signals can be explained by analysing the presence of additional UMR components not related to the chirality and the dependence of UMR on the peculiar magnetoresistance recorded in our Te NWs (Supplementary Section 5).

Moreover, the trend of the magnetoresponse (measured in right- and left-handed NWs) is peculiar since it is directly related to the chirality of the NWs. In this regard, the orientation of spin polarization is determined by the Te handedness, in a similar way to how the spin polarization in a ferromagnetic metal is determined by its magnetization. By matching the transport measurements with the STEM analysis in Fig. 1, we can distinguish the NW handedness through their magnetotransport behaviour.

Figure 3fg shows the variation of $R^{\text{diff}}(\alpha)$ measured at $B = 9$ T and different current values $I$. A larger magnetoresponse is measured at higher currents, with the signal amplitude $|A^{\text{diff}}| = |R(0^\circ) - R(180^\circ)|$ increasing linearly with current $I$ (insets). This dependence can be understood considering that the spin density generated by the Edelstein effect increases linearly with the displacement $\Delta k$, induced by the current. According to the model in Fig. 3a,b, a higher current induces a larger spin density, resulting in more spins coupling to the magnetic field.

Figure 3hi shows $R^{\text{diff}}(\alpha)$ measured for fixed current and different magnetic fields. Even in this case, we observe a linear increase of $|A^{\text{diff}}|$ with $B$, which indicates that the UMR recorded in our Te NWs possesses a bilinear response to current and magnetic field. This bilinearity, which has been observed in spin-momentum-locked states in Rashba systems and in topological insulators, originates from the B-dependent relaxation processes at scalar and spin–orbit defects, respectively.

Besides the fundamental connection between the chirality of Te and its magnetotransport, we highlight that the UMR amplitude in our NWs is substantial. For the NW shown in Fig. 3dfh, the maximum $|A^{\text{diff}}|$ measured at 9 T and 5 μA amounts to 800 Ω, which corresponds to a 7% variation with respect to the current-averaged resistance measured at the same field and at the same angle, $R(0^\circ, 9\text{T}) = 10.8\text{kΩ}$. To the best of our knowledge, in previous reports of UMR, the relative variation in resistance was always <1% (refs. 1,4,14,43,44). To further compare our results with previous works, we use the figure of merit $\eta$ defined as $\eta = \frac{R_{\text{diff}}(R_{\text{B}})}{R_{\text{B}}}$. We show how the shifts in energy of the Fermi level ($\epsilon_F$) and the appearance of shoulders close to the peaks at $\alpha = 0^\circ$ and $\alpha = 180^\circ$) correspond to a 7% variation with respect to the current-averaged $R(0^\circ)$, whereas the solid band is not fully occupied. The blue/red colour displays the opposite spin projection

Finally, we focus on the control of the UMR by the gate voltage ($V_G$). We show how the shifts in energy of the Fermi level ($\epsilon_F$) of the Te NWs lead to tuning the Edelstein effect. In Fig. 4a, we show the magnetoresponse evolution under changes of carrier density, driven by $V_G$. To account for the variation of resistance with the gate (Supplementary Section 7), we normalize $R^{\text{diff}}(\alpha)$ measured at different $V_G$ with respect to the value $R^{\text{diff}}(90^\circ)$. For negative $V_G$, that is, lowering the Fermi level and increasing the hole concentration, the magnetoresponse trend is relatively flat except for the two prominent features at $\alpha = 0^\circ$ and $\alpha = 180^\circ$, indicating that the electrical current induces a substantial spin polarization only in the z direction. Increasing $V_G$, that is, decreasing the hole concentration and bringing the Fermi level closer to the bandgap, we observe an increase in the amplitude of the UMR (up to a factor of six; Fig. 4b) and the appearance of shoulders close to the peaks at $\alpha = 0^\circ$ and $\alpha = 180^\circ$. Similar shoulders were observed for $V_G = 0$ V in some NWs, including those shown in Fig. 3f–i. Their relative intensity was found to change from sample to sample (Supplementary Section 8), probably due to the slightly different doping in different NWs.

The increase of the magnetoresponse at positive $V_G$ can be correlated with the Te band structure. Looking at the band structure at different energies, a change of the Fermi contour in k-space is expected to cause a variation of the Edelstein effect efficiency.
and, consequently, a variation of the magnetoresistance. In Fig. 4b,c, we compare the gate dependence of the normalized amplitude $|A_{\text{norm}}| = (R_{\alpha\beta}(0°) - R_{\alpha\beta}(180°))/R_{\alpha\beta}(90°)$ with the calculated spins per unit cell ($S_{\alpha}$), generated by the Edelstein effect at different $V_{\text{g}}$ and a constant charge current density of 10$^{-3}$ A m$^{-2}$ (Methods).

To compare experiments and calculations, we measured the carrier density of a Te NW through ordinary Hall measurements to estimate the position of $e_F$ in the band structure shown in Fig. 1c. The extracted hole density was $p = 7.4 \times 10^{17}$ cm$^{-3}$ at $V_{\text{g}} = 0$ V, and it could be varied in the range 7–8 $\times$ 10$^{17}$ cm$^{-3}$ using the back-gate voltage ranging from −30 V to 10 V (Supplementary Section 9). Interestingly, the rather small modulation in $p$ induces important changes in the recorded signals, highlighting that it is possible to finely tune the Edelstein effect in Te by acting on its band structure through standard electrostatic gating.

Our calculations on the charge carrier density reveal that the extracted $p$ corresponds to an $e_F$ approximately 20 meV below the band edge, which can be tuned in a 5 meV energy window by gating. Figure 4c shows that $S_{\alpha}$, which is associated with the efficiency of the Edelstein effect creating the spin polarization, increases when $e_F$ is moved towards the valence band edge, in good agreement with the increase of $|A_{\text{norm}}|$ with $V_{\text{g}}$ displayed in Fig. 4b. Moreover, we highlight that the calculated $e_F$ position implies a single band occupancy, since the band that lies closest in energy is populated at energies 130 meV below the valence band edge (Supplementary Section 9). This situation is ideal to maximize the Edelstein effect and thus the UMR, since the occupation of the lower band, with opposite radial spin texture, would partially compensate the induced spin density (Supplementary Sections 10 and 11 for more details on the calculations and for the full $S_{\alpha}$ versus $e_F$).

In conclusion, we demonstrated all-electrical generation, manipulation and detection of chirality-dependent spin polarization in single-crystalline Te NWs. The spin polarization from chiral origin gives rise to a UMR that is one to several orders of magnitude larger than those reported in other non-chiral systems. The UMR is also tunable with electrical gating, providing us with an extra knob for controlling the spin polarization. These effects are induced by an Edelstein effect emerging from the Te radial spin texture. Unlike conventional Rashba systems and similar to the chiral-induced spin selectivity observed in organic molecules, the induced spin polarization is oriented along the current direction. We think that our description of this phenomenon on the basis of the Edelstein effect might be extended to other chiral systems characterized by translational symmetry. Our results put on a firm ground the fundamental interplay between structural chirality and electron spin in inorganic chiral Te NWs, enabling the design of unconventional all-electrical devices in which the spin polarization is not determined by the direction of a magnetization, but by the handedness of the crystal.

Online content
Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41563-022-01211-7.

Received: 18 September 2021; Accepted: 24 January 2022; Published online: 7 March 2022

References
1. Sinova, J., Valenzuela, S. O., Wunderlich, J., Back, C. H. & Jungwirth, T. Spin Hall effects. Rev. Mod. Phys. 87, 1213–1260 (2015).
2. Edelstein, V. M. Spin polarization of conduction electrons induced by electric current in two-dimensional asymmetric electron systems. Solid State Commun. 73, 233–235 (1990).
3. Soumyanarayanan, A., Reyren, N., Fert, A. & Panagopoulos, C. Emergent phenomena induced by spin–orbit coupling at surfaces and interfaces. Nature 539, 509–517 (2016).
4. Manpatrani, S. et al. Scalable energy-efficient magnetoelectric spin–orbit logic. Nature 565, 35–42 (2019).
5. Pham, V. T. et al. Spin–orbit magnetic state readout in scaled ferromagnetic/ heavy metal nanostructures. Nat. Electron. 3, 309–315 (2020).
6. Manchon, A. et al. Current-induced spin-orbit torques in ferromagnetic and antiferromagnetic systems. Rev. Mod. Phys. 91, 035004 (2019).
7. Grimaldi, E. et al. Single-shot dynamics of spin–orbit torque and spin transfer torque switching in three-terminal magnetic tunnel junctions. Nat. Nanotechnol. 15, 111–117 (2020).
8. Threshold. H. T. C. Spin-galvanic effect. Nature 417, 153–156 (2002).
9. Kato, Y. K., Myers, R. C., Gossard, A. C. & Awschalom, D. D. Current-induced spin polarization in strained semiconductors. Phys. Rev. Lett. 93, 8–11 (2004).
10. Sánchez, J. C. R. et al. Spin-to-charge conversion using Rashba coupling at the interface between non-magnetic materials. Nat. Commun. 4, 2944 (2013).
11. Li, Y. et al. Nonreciprocal charge transport up to room temperature in bulk Rashba semiconductor α-GeTe. Nat. Commun. 12, 540 (2021).
12. Ishizaka, K. et al. Giant Rashba-type spin splitting in bulk BiTeI. Nat. Mater. 10, 521–526 (2011).
13. Rojas-Sánchez, J.-C. et al. Spin to charge conversion at room temperature by spin pumping into a new type of topological insulator: α-Sn films. Phys. Rev. Lett. 116, 096602 (2016).
14. Kondou, K. et al. Fermi-level-dependent charge-to-spin current conversion by Dirac surface states of topological insulators. Nat. Phys. 12, 1027–1031 (2016).
15. Culcer, D. & Winkler, R. Generation of spin currents and spin densities in systems with reduced symmetry. Phys. Rev. Lett. 99, 226601 (2007).
16. Seemann, M., Kolderitzsch, D., Wimmer, S. & Ebert, H. Symmetry-imposed shape of linear response tensors. Phys. Rev. B 92, 155138 (2015).
17. Ma, Q. et al. Observation of the nonlinear Hall effect under time-reversal-symmetric conditions. Nature 565, 337–342 (2019).
18. Kang, K., Li, T., Sohn, E., Shan, J. & Mak, K. F. Nonlinear anomalous Hall effect in few-layer WTe$_2$. Nat. Mater. 18, 324–328 (2019).
19. MacNeill, D. et al. Control of spin–orbit torques through crystal symmetry in WTe$_2$/ferromagnet bilayers. Nat. Phys. 13, 300–305 (2017).
20. Safeer, C. K. et al. Large multidirectional spin-to-charge conversion in low-symmetry semimetal MoTe$_2$ at room temperature. Nano Lett. 19, 8758–8766 (2019).
21. Stiehl, G. M. et al. Layer-dependent spin-orbit torques generated by the centrosymmetric transition metal dichalcogenide β–MoTe$_2$. Phys. Rev. B 100, 184402 (2019).
22. Shi, S. et al. All-electric magnetization switching and Dzyaloshinskii–Moriya interaction in WTe$_2$/ferromagnet heterostructures. Nat. Nanotechnol. 14, 945–949 (2019).
23. Zhao, B. et al. Unconventional charge–spin conversion in Weyl-semimetal WTe$_2$. Adv. Mater. 32, 2000818 (2020).
24. Liu, Y. & Shao, Q. Two-dimensional materials for energy-efficient spin–orbit torques devices. ACS Nano 14, 9389–9407 (2020).
25. Ray, K., Ananthavel, S. P., Waldeck, D. H. & Naaman, R. Asymmetric scattering of polarized electrons by organized organic films of chiral molecules. Science 283, 814–816 (1999).
26. Liu, Y., Xiao, J., Koo, J. & Yan, B. Chirality-driven topological electronic structure of DNA-like materials. Nat. Mater. 20, 638–644 (2021).
27. Yang, S.-H., Naaman, R., Paltiel, Y. & Parkin, S. S. P. Chiral spintronics. Nat. Rev. Phys. 3, 328–343 (2021).
28. Suda, M. et al. Light-driven molecular switch for reconﬁgurable spin ﬁlters. Nat. Commun. 10, 2455 (2019).
29. Rikken, G. L. J. A., Fölling, J. & Wyder, P. Electrical magnetochirality anisotropy. Phys. Rev. Lett. 87, 236602 (2001).
30. Yoda, T., Yokoyama, T. & Murakami, S. Current-induced orbital and spin magnetizations in crystals with helical structure. Sci. Rep. 5, 12024 (2015).
31. Inui, A. et al. Chirality-induced spin-polarized state of a chiral crystal CrNb$_5$.S$_x$. Phys. Rev. Lett. 124, 166602 (2020).
32. Shiozawa, K. et al. Chirality-induced spin polarization over macroscopic distances in chiral disilicide crystals. Phys. Rev. Lett. 127, 126602 (2021).
33. Dong, Z. & Ma, Y. Atomic-level handedness determination of chiral crystals using aberration-corrected scanning transmission electron microscopy. Nat. Commun. 11, 1588 (2020).
34. Ben-moshe, A. et al. The chain of chirality transfer in tellurium nanocrystals. Science 373, 729–733 (2021).
35. Mayers, B. & Xia, Y. One-dimensional nanostructures of trigonal tellurium with various morphologies can be synthesized using a solution-phase approach. J. Mater. Chem. 12, 1875–1881 (2002).
36. Wang, Y. et al. Field-effect transistors made from solution-grown two-dimensional tellurene. *Nat. Electron.*, 1, 228–236 (2018).
37. Vorob’ev, L. E. et al. Optical activity in tellurium induced by a current. *Sov. J. Exp. Theor. Phys. Lett.*, 29, 441–445 (1979).
38. Shalygin, V. A., Sofronov, A. N., Vorob’ev, L. E. & Farbshtein, I. I. Current-induced spin polarization of holes in tellurium. *Phys. Solid State* 54, 2362–2373 (2012).
39. Furukawa, T., Shimokawa, Y., Kobayashi, K. & Itou, T. Observation of current-induced bulk magnetization in elemental tellurium. *Nat. Commun.*, 8, 954 (2017).
40. Furukawa, T., Watanabe, Y., Ogasawara, N., Kobayashi, K. & Itou, T. Current-induced magnetization caused by crystal chirality in nonmagnetic elemental tellurium. *Phys. Rev. Res.*, 3, 023111 (2021).
41. Vaz, D. C. et al. Determining the Rashba parameter from the bilinear magnetoresistance response in a two-dimensional electron gas. *Phys. Rev. Mater.*, 4, 071001 (2020).
42. Dyrdał, A., Barnaś, J. & Fert, A. Spin-momentum-locking inhomogeneities as a source of bilinear magnetoresistance in topological insulators. *Phys. Rev. Lett.*, 124, 046802 (2020).
43. He, P. et al. Bilinear magnetoelectric resistance as a probe of three-dimensional spin texture in topological surface states. *Nat. Phys.*, 14, 495–499 (2018).
44. Guillet, T. et al. Observation of large unidirectional Rashba magnetoresistance in Ge(111). *Phys. Rev. Lett.*, 124, 027201 (2020).
45. Sakano, M. et al. Radial spin texture in elemental tellurium with chiral crystal structure. *Phys. Rev. Lett.*, 124, 136404 (2020).
46. Gatti, G. et al. Radial spin texture of the Weyl fermions in chiral tellurium. *Phys. Rev. Lett.*, 125, 216402 (2020).
47. Zhang, N. et al. Magnetotransport signatures of Weyl physics and discrete scale invariance in the elemental semiconductor tellurium. *Proc. Natl Acad. Sci. USA* 117, 11337–11343 (2020).
48. Epstein, A. S., Fritzsche, H. & Lark-Horovitz, K. Electrical properties of tellurium at the melting point and in the liquid state. *Phys. Rev.* 107, 412–419 (1957).
49. He, P. et al. Observation of out-of-plane spin texture in a SrTiO3(111) two-dimensional electron gas. *Phys. Rev. Lett.*, 120, 256802 (2018).
50. Vaz, D. C. et al. Mapping spin–charge conversion to the band structure in a topological oxide two-dimensional electron gas. *Nat. Mater.*, 18, 1187–1193 (2019).

*Publisher’s note* Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2022
Methods

Chemical synthesis of Te NWs. The synthesis consists of a high-temperature reduction of a tellurium oxide in the presence of hydrazine (N\textsubscript{2}H\textsubscript{4}) in a basic aqueous medium\textsuperscript{34,35}. We followed the hydrothermal growth recipes proposed in the literature\textsuperscript{36,51,52}. Briefly, we mixed Na\textsubscript{2}TeO\textsubscript{3} (104 mg) and polyvinylpyrrolidone (average molecular weight, 360,000; 547.9 mg) in 33 ml of MilliQ water by magnetic stirring to achieve a clear solution at room temperature. Then, NH\textsubscript{4}OH solution (3.65 ml, 25% by weight in water) and hydrazine hydrate (1.94 ml, 80% w/w) were added while stirring. The mixture was transferred to an autoclave that was sealed and heated at 180 °C for 23 h. We washed the resulting material by successive centrifuge-assisted precipitation (5,000 r.p.m., 5 min) and redispersion with MilliQ water (ten steps of 4 ml water each). At this stage, we are still not able to produce selectively one or the other enantiomer, and the distribution of left- and right-handed NWs is random.

Sample preparation. Te NWs were dispersed in a dimethylformamide/CHCl\textsubscript{3} mixture (1:3:1 v/v) to be used for the drop-casting of solution droplets at the deionized-water/air interface in a homemade Langmuir trough. After the evaporation of the solvent, Te NWs floating on the water surface were picked up (Langmuir–Schaefer technique) with Si/SiO\textsubscript{2} substrates (Si doped n+, 5×5 mm, 300 nm thermal oxide). Isolated NWs with opportune dimensions were selected with an optical microscope, without knowing a priori the handness of the NWs. The contacts were defined through electron-beam lithography performed on a poly(methylmethacrylate)-A4/poly(methylmethacrylate)-A2 double layer, and then Pt was deposited by sputtering. Seven NW-based devices (D1–D7) were fabricated and used for magnetotransport measurements at low temperature. Results obtained from D1 are shown in Fig. 1d (left-handed), Results from D2 and D3 in Fig. 3d,e,f. Results obtained from D2 are shown in Fig. 4a,b. Results obtained from D3 are shown in Fig. 1b,d (right-handed), Fig. 2a and Fig. 3c,g,i. Devices D4–D7 are included in the Supplementary Information.

Transmission electron microscopy imaging. Two devices showing opposite magnetoresponses were sectioned by focused ion beam microscopy for STEM charactirization. Two lamellae were prepared from every device: one perpendicular to the wire in the contact area (to validate the quality of electrical contact) and one along the wire for measuring the chirality (Supplementary Section 1). A Helios 600 DualBeam (ThermoFisher) was used for lamella preparation and scanning electron microscopy imaging: a TitanG2 60–300 operated at 300kV without STEM corrector was used for STEM imaging. For chirality determination, samples were imaged in either of the zones symmetric to [010] and then tilted ±30°, resulting in mirrored images. The handedness was determined by comparison to atomic models of known chirality. The absence of the mirror plane between the sample and digital image has been ruled out by imaging an alphanumeric grid. The STEM analysis was performed after the samples were already measured electrically.

Magnetotransport measurements. The devices were wire-bonded to a sample holder and installed in a physical property measurement system (Quantum Design) for transport measurements with a temperature range of 2–400 K and maximum magnetic field of 9 T. We performed measurements of d.c. longitudinal and transversal resistance using a Keithley 6221 current source and a Keithley 2128 nanovoltmeter. Asymmetric (I+>0 and I−<0) and symmetric (I+<I−) delta modes (16 to 32 counts) were employed to improve the signal-to-noise ratio (with current ranging from 50 nA to 10 μA). The average of the signals obtained from the asymmetric delta mode measurements was equivalent to the signals obtained from the symmetric delta mode measurements as well as the spin density \(S\) corresponds to the chirality \(\chi\) (Ref. 21) as well as the radial spin texture\textsuperscript{37} to model the valence bands around the H point. Therefore, we use an effective model Hamiltonian that reproduces the effective band structure introduced in ref. 31 as well as the radial spin texture\textsuperscript{37} to model the valence bands around the H point:

\[
H(k) = -\Delta - A k_x^2 - B (k_x^2 + k_y^2 + k_z^2) + \chi \begin{pmatrix} \Delta & k_x & k_y & k_z \end{pmatrix} \begin{pmatrix} k_x & k_y & k_z \end{pmatrix} + j_k \hat{\sigma}
\]  

(1)

Here, \(H\) is the Hamiltonian and \(k\) is the crystal momentum, \(j_k\) is along the H–K direction and the Pauli spin vector \(\hat{\sigma}\) represents the spin degree of freedom.

We use the parameters proposed in ref. 31, \(\Delta = 63\) meV, \(A = 3.64 \times 10^{-10}\) eV m\(^2\), \(B = 3.26 \times 10^{-18}\) eV m\(^2\), \(\beta = 2.4 \times 10^{-10}\) eV m. The \(\chi\) corresponds to the chirality with \(j = 1\) being left-handed and \(j = -1\) being right-handed. The corresponding effective band structure is shown in Fig. 1c, and the spin texture is shown in Fig. 1f.

We calculate the charge current density \(j\) as well as the spin density \(S\) response to an external electric field \(E\),

\[
j = -\frac{e}{V} \int k \hat{f}_k \hat{f}_k
\]

(2)

\[
S = \sum_k (\hat{f}_k \hat{f}_k)
\]

(3)

Here, \(e\) is the absolute value of the elementary charge, \(V\) is the sample volume, \(\hat{f}_k\) is the group velocity with \(\hbar\) the reduced Planck constant, \(\chi\) is the spin expectation value, \(\epsilon\) is the energy dispersion and \(j_k\) is the distribution function. The evolution of \(j_k\) under the influence of an external electric field \(E\) as well as scattering is described by the Boltzmann equation:

\[
\frac{\partial \hat{f}_k}{\partial t} = \frac{\partial \hat{f}_k}{\partial t}_{\text{scatt}} - \frac{\partial \hat{f}_k}{\partial t}_{\text{relax}}
\]

(4)

where we have assumed the system to be spatially and statistically homogeneous; \(t\) is time and \(\partial \hat{f}_k/\partial t_{\text{relax}}\) is the scattering term, which we approximate by the relaxation time approximation:

\[
\frac{\partial \hat{f}_k}{\partial t}_{\text{relax}} = -\frac{1}{\tau_k} \hat{f}_k
\]

(5)

Here \(\delta E = f_k - f_0^c\) is the non-equilibrium part of the distribution function, \(f_0^c\) is the Fermi–Dirac distribution function and \(\tau_k\) is the momentum relaxation time. The Boltzmann equation (4) is solved by

\[
j_k = f_k^0 + \frac{\partial \hat{f}_k}{\partial \epsilon} \frac{\epsilon}{k} \hat{v}_k \cdot E
\]

(6)

Thus, the electric field \(E\) leads to a reoscillation of states, depending on their group velocity and momentum relaxation time. In a simplified picture, this can be understood as a ‘shift’ of the Fermi contour in k-space. Inserting equation (6) into equations (2) and (3) yields

\[
j = -\frac{e^2}{V} \sum_k \frac{\partial \hat{f}_k}{\partial \epsilon} \chi_k \cdot (\hat{v}_k \cdot E) = : \sigma E
\]

(7)

\[
S = \frac{e}{V} \sum_k \frac{\partial \hat{f}_k}{\partial \epsilon} \chi_k \cdot (\hat{v}_k \cdot E) = : \kappa E
\]

(8)

In our calculations, we assume \(T=0\) and a constant relaxation time \(\tau_k\). Hence, only states at the Fermi level contribute to the transport. Using equations (7) and (8), we calculate the charge current as well as the current-induced spin density in bulk Te, which is shown as a function of the Fermi level in Fig. 4c. To calculate the induced spin density, we use \(\chi_j = e j /\sigma j\), where \(j\) and \(\sigma\) are the current density and the charge conductivity, respectively, and the Edelstein susceptibility \(\chi\) is the tensor that connects the induced spin density \(S\) to the applied electric field, \(S=\kappa E\) (Supplementary Section 10 for more details).

Data availability
Source data are provided with this paper. Any further data are available from the corresponding authors upon reasonable request.

Code availability
The computational codes used in this study to obtain the transport properties are available from the corresponding authors upon reasonable request. The band structure ab initio calculations were performed using VASP (https://www.vasp.at/).

The results are provided with this paper.

References
51. Qiu, G. et al. Quantum Hall effect of Weyl fermions in n-type semiconducting tellurium. Nat. Nanotechnol. 15, 585–591 (2020).
52. Roy, M., Sen, S., Gupta, S. K. & Tyagi, A. K. Comment on high-quality luminescent tellurium nanowires of several nanometers in diameter and high aspect ratio synthesized by a poly (vinyl pyrrolidone)-assisted hydrothermal process. Langmuir 23, 10873 (2007).

Acknowledgements
This work is supported by the Spanish Ministerio de Ciencia e Innovación (MICINN) under projects RTI2018-094861-B-100 and PID2019-101853GA-100 and under the
Maria de Maeztu Units of Excellence Programme (MDM-2016-0618); by the European Union Horizon 2020 under the Marie Skłodowska-Curie Actions (7066025-QuESTech and 892983-SPECTER); and by Intel Corporation under ‘FEINMAN’ and ‘VALLEYTRONICS’ Intel Science Technology Centers. B.M.-G. acknowledges support from the Gipuzkoa Council (Spain) in the frame of the Gipuzkoa Fellows Program. M.S.-R. acknowledges support from La Caixa Foundation (no. 100010434) with code LCF/BQ/DR21/11880030. M.G. acknowledges support from La Caixa Foundation (no. 100010434) for a Junior Leader fellowship (grant no. LCF/BQ/PI19/11690017). A.J. acknowledges support from CRC/TRR 227 of Deutsche Forschungsgemeinschaft.

**Author contributions**

F. Calavalle, M.G., F. Casanova and L.E.H. conceived the study. F. Calavalle and M.S.-R. fabricated the samples and performed the magnetotransport measurements with the help of D.C.V. and H.Y.; B.M.-G. synthesized the Te NWs with the support of A.M.-A., and A.C. performed the STEM analysis. A.J. conducted the theoretical calculations with the support of I.M.; I.V.M. and S.O. performed the ab initio calculations. F. Calavalle and M.G. wrote the manuscript with input from all authors. All authors contributed to the discussion of the results and their interpretation.

**Competing interests**

The authors declare no competing interests.

**Additional information**

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41563-022-01211-7.

Correspondence and requests for materials should be addressed to Marco Gobbi, Felix Casanova or Luis E. Hueso.

Peer review information Nature Materials thanks Evgeny Tsymbal, See Hun Yang and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.