Piezomagnetic switching of the anomalous Hall effect in an antiferromagnet at room temperature

M. Ikhlas1,2,3,11, S. Dasgupta2,4,11, F. Theuss5, T. Higo1,2,3, Shunichiro Kittaka6, B. J. Ramshaw5, O. Tchernyshyov7, C. W. Hicks8,9 and S. Nakatsuji1,2,3,7,10

Piezomagnetism couples strain linearly to magnetic order, implying that it can produce and control magnetization. Unlike magnetostriiction, which couples magnetization quadratically to strain, it enables bidirectional control of a net magnetic moment. If this effect becomes large at room temperature, it may be technologically relevant, similar to its electric analogue, piezoelectricity. However, current studies of the piezomagnetic effect have been primarily restricted to antiferromagnetic insulators at cryogenic temperatures. Here we report the observation of large piezomagnetism in the antiferromagnetic Weyl semi-metal Mn3Sn at room temperature. This material is known for its nearly magnetization-free anomalous Hall effect. We find that a small uniaxial strain on the order of 0.1% can control both the sign and size of the anomalous Hall effect. Our experiment and theory show that the piezomagnetism can control the anomalous Hall effect, which will be useful for spintronics applications.

Mn3Sn has a hexagonal D019 structure (in space group P6/mmm) comprising [0001]-axis stacked kagome lattice layers of Mn atoms with a Sn site at the centre of a Star of David. We use a right-handed coordinate system with axes x, y and z to represent the [2110], [0110] and [0001] directions of the crystal structure. Below its ordering temperature of $T_N \approx 430\, \text{K}$, the Mn moments form the $120^\circ$ 'antichiral' magnetic order shown in Fig. 1a (ref. 25). The magnetic moments $\mathbf{m}_i$ on sublattices $i = 1, 2$ and $3$ with magnitude $m_i \approx 3\mu_B$ are oriented in the $x-y$ plane and cancel each other nearly perfectly, adding up to a spontaneous net moment $\mathbf{M}_s = \sum_{i=1}^3 \mathbf{m}_i$ with a magnitude of $10^{-4}\mathbf{m}$, that is proportional to the strength of the local anisotropy (Supplementary Information). Neglecting this small net dipolar magnetic moment, the magnetic unit cell can be viewed as a magnetic octupole. The octupolar order parameter, under local $D_{3h}$ point group operations, reduces to the following vector order parameter in the $x-y$ plane:

$$
\mathbf{K} = K(\cos \Phi_x, \sin \Phi_x).
$$

In the ground state, $\mathbf{K}$ is parallel to the direction of the Mn moment that points along the local easy axis $\hat{n}$ (Fig. 1a). For example, in the ground-state configuration illustrated in Fig. 1a, $\mathbf{K}$ points in the $+x$ direction. We illustrate local magnetic states of Mn3Sn as points on a clock in Fig. 1b. When the moments are collectively rotated by an angle $+\phi$, $\mathbf{K}$ rotates by $-\phi$. The odd-numbered states (I, III, etc.) are ground states, while the even-numbered states are at energy maxima. In the absence of perturbations, the magnetization obeys $\mathbf{M}||\mathbf{K}$ in all states. However, we shall see that, in the presence of both strain and external magnetic field, their directions diverge strongly.

The time reversal, $T$, symmetry-breaking octupolar order generates Weyl nodes near $E_p$ (refs. 27–28), leading to the magnetization-free,
large transverse responses: the AHE, the anomalous Nernst effect and magneto-optical effects. On the other hand, the small residual dipolar moment $M_d$ provides a negligible perturbation to the electronic structure. This broken $T$ symmetry also allows finite piezomagnetic coupling. From its magnetic point group symmetry, the piezomagnetic tensor $\Lambda$ of the antichiral phase expresses a proportionality between the components of the in-plane magnetization and the strain (Supplementary Information). Microscopically, under uniaxial stress, the bond lengths, and hence the in-plane nearest-neighbour exchange interactions, become unequal. The rotation of the sublattice moments in response generates a net dipole moment. Since the initial spontaneous magnetization of a domain is tiny, a small strain can invert its direction (Fig. 1c). Consequently, under a constant magnetic field in the $x$–$y$ plane, the piezomagnetic effect can mediate 180° domain reversal. The free-energy diagram (Fig. 1d) shows how this 180° domain reversal occurs. At zero and negative (compressive) $x$ axis strain, a positive field along $\hat{x}$ stabilizes state III ($\Phi_S = 0$), since it has the lowest energy. On the other hand, a uniaxial tension with an associated energy greater than the local anisotropy $\delta$ will favour state IX ($\Phi_S = \pi$) as the lowest energy state for $H \parallel \hat{x}$. This causes a sign change of the AHE under the combination of field and strain.

We first demonstrate the piezomagnetism in Mn$_3$Sn. We measure the uniaxial stress dependence of the magnetization of three single crystals grown by the Bridgman method, labelled M1, M2 and M3, using a Cu-Be piston–cylinder cell (Methods). The samples have compositions of Mn$_{3+\delta}$Sn$_{1-x}$ ($x = 0.01–0.02$) and exhibit a first-order transition to an incommensurate state on cooling below...
The piezomagnetic effect in the topological antiferromagnet Mn₃Sn under in-plane uniaxial compression. 

**Fig. 2** | The sample configurations for the magnetization measurements under uniaxial stress, with coloured spheres representing the strained state and faded spheres for the unstrained state. 

**a**. The sample configurations for the magnetic field $\mu H$ at $T = 300$ K under a uniaxial stress of $\sigma$ along the $x$ axis for sample M1 (left) and along the $y$ axis for sample M3 (right). The dashed line is a linear fit to the data in the region where the hysteresis loop closes ($\mu H > 0.5$ T). 

**b**. The longitudinal magnetization $M$ versus the magnetic field $\mu H$ at $T = 300$ K under a uniaxial stress of $\sigma$ along the $x$ axis ($y$ axis). $T_{c1}$ indicates the incommensurate transition temperature for each sample. 

**c**. The uniaxial stress $\sigma$ dependence of the spontaneous magnetization $M_s$ and the magnetic susceptibility $\chi$ for sample M1, M2 and M3 at $T = 300$ K. Blue (red) data points correspond to data taken with field along $x$ axis and stress applied along the $y$ axis $(x$ axis). The upper axis shows the corresponding uniaxial strain $\epsilon$ inferred from the experimental Young's modulus $E_y = 121$ GPa. Solid blue and red lines are linear fits to the data of sample M1 and M3, respectively. $\sigma_r \approx 120$ MPa is the critical uniaxial stress for which the stress-induced magnetization compensates the ambient-pressure spontaneous magnetization $M_0$ ($\sigma = 0$). Negative (positive) stress denotes compression (tension).

$T_{c1} \approx 270–280$ K at ambient pressure, which is accompanied by a sharp decrease in the magnetization and a full suppression of the AHE [12,31,34]. The uniaxial stress $\sigma$ can be converted to the strain $\epsilon$ using the elastic constants determined by resonant ultrasound spectroscopy (Methods).

Figure 2b shows the room-temperature longitudinal magnetization $M$ versus the magnetic field $\mu H$ for samples M1 and M3 under compressive stresses of $\sigma_{xx}$ and $\sigma_{yy}$, respectively. At zero stress, M1 (M3) exhibits a spontaneous magnetization of $M_s$ ($\sigma = 0$) ≈ 3.6 μB f.u. -1 per formula unit (f.u.) (3.5 μB f.u. -1), which can be flipped by a small coercive field of $\mu H_c \approx 0.03–0.06$ T, indicating a weak in-plane anisotropy. Furthermore, $M$ increases linearly with the field, with a slope of $\chi = \partial M/\partial H \approx 12.5$ μB f.u. -1 T -1 for M3. Significantly, for M1, a threefold increase in $M_s$ to approximately 11 μB f.u. -1 is obtained by a compression of $\sigma_{xx} = -270$ MPa, before the sample fractures for $\sigma_{yy} < -300$ MPa. A similar response to compression is observed in M3, although fracture occurs at a lower compression of $\sigma_{yy} < -270$ MPa. Below the fracture point, $M_s$ returns to nearly its unstressed value when the pressure is released, indicating that the stress is predominantly elastic (Supplementary Information). Except for the increase in $M_s$, no change is seen in the shape of the hysteresis curve or the susceptibility $\chi$. This confirms that, below the fracture point, the sample quality did not degrade and that $M$ represents the magnetization of a single magnetic domain. The temperature scan measurements (Fig. 2c) show that the stress-induced enhancement of $M_s$ only occurs in the antichiral phase ($T > T_{c1}$).

We also obtain similar results for sample M2 (Extended Data Fig. 1).
As crucial evidence for piezomagnetism, the σ dependence of \( M_s \) is found to be linear for all samples and nearly isotropic in the \( x-y \) plane (Fig. 2d). We fitted the data of M1 with

\[
M_s = M_s(\sigma = 0) + A_{11} \sigma_{xx},
\]

where \( A_{11} \) is the relevant piezomagnetic coefficient for the experimental configuration of sample M1 in Fig. 2a,b. We obtain \( |A_{11}| \approx 0.029 \pm 0.001 \text{ mT} / \text{K} \cdot \text{MPa}^{-1} \) (0.055 Gauss MPa\(^{-1}\)) at room temperature. For the configuration of M3, we obtain \( |A'| \approx 0.025 \pm 0.001 \text{ mT} / \text{K} \cdot \text{MPa}^{-1} \) (0.048 Gauss MPa\(^{-1}\)). These piezomagnetic coefficients are larger than the values reported for the prototypical piezomagnet CoF\(_2\) (Table 1) but smaller than the value of \( A_{11} = 0.226 \text{Gauss MPa}^{-1} \) at \( T = 2.5 \text{K} \) reported for UO\(_2\) (ref. 1). Notably, this value for Mn\(_3\)Sn is comparable to the value exhibited at \( T = 187 \text{K} \) by a thin-film form of Mn\(_3\)NiN (Supplementary Information)\(^6\), a compound that belongs to the family of Mn-based antiperovskites, some of which are predicted to exhibit a large piezomagnetic effect at room temperature. Importantly, the susceptibility \( \chi \) is stress independent. Moreover, in the tensile region \( (\sigma > 0) \), which our apparatus cannot access, the stress-induced magnetization is expected to compensate the zero-stress magnetization at a critical stress of \( \sigma_c \approx 120 \text{MPa} (\sigma_c \approx 0.1%) \) (Fig. 2d). As shown below, the energy scale of \( \sigma \) is directly connected to the strength of the local anisotropy \( \delta \) and determines the sign-switching point of the AHE.

Next, we show that the piezomagnetism in Mn\(_3\)Sn leads to a striking effect in electrical transport, that is, strain control of the AHE sign. Generally, the dominant intrinsic contribution to the AHE in magnetic conductors is associated with a fictitious field experienced by conduction electrons in momentum space\(^26,28\). This field can be quantified by the Hall vector \( \mathbf{G} \) representing the net Berry curvature of the occupied electronic states in the Brillouin zone\(^27,28\). The Hall vector directly determines the anomalous part of the Hall conductivity tensor:

\[
\sigma_{H} = \frac{e^2}{2\pi^2} h c_{a'b'} G_{a'b'}. \tag{3}
\]

The pseudovectors \( \mathbf{G} \) and \( \mathbf{M} \) have the same symmetry properties, are linearly related and are often collinear. In Mn\(_3\)Sn, however, it is \( \mathbf{K} \), not \( \mathbf{M} \), that induces the intrinsic Hall conductivity in the antichiral phase at \( T_{H} < T < T_{K} \) (refs. 16,63). Thus, \( \mathbf{K} \) and \( \mathbf{G} \) should be identified as parallel to each other and confined to the \( x-y \) plane (Fig. 1b)\(^{28}\), and hereafter we use \( \mathbf{K} \) to label both.

To study the AHE under a continuous change of strain, we employ a high-precision piezoelectric-based strain device\(^9\) and Mn\(_3\)Sn single crystals, labelled H1 and H2, with similar high quality as the magnetization samples. In the following, the strain values have been corrected for the effect of epoxy deformation, and the zero-strain points are verified by a separate set of measurements on a third sample, H3 (Methods and Supplementary Information). We begin by describing the effect of \( x \) axis uniaxial strain, \( \varepsilon_{xx} \), on the Hall resistivity \( \rho_{xy} \) at \( T = 300 \text{K} \) using sample H1 (Fig. 3a). Figure 3d shows the field dependence of \( \rho_{xy} \) at various strains. At zero strain \( (\varepsilon_{xx} = 0%) \), the Hall resistivity exhibits a sharp hysteresis curve with a spontaneous Hall component of \( \rho_{xy}(H = 0) = -3.85 \mu \Omega \cdot \text{cm} \) and a coercivity of approximately 0.04 T. Under tension parallel to the \( x \) axis of \( \varepsilon_{xx} = 0.194% \), the overall shape of the sharp hysteresis curve is maintained. Namely, the spontaneous Hall component retains the negative sign at positive fields but is slightly enhanced by 10% from its unstrained value to \( \rho_{xy}(H = 0) = -4.2 \mu \Omega \cdot \text{cm} \). For \( \varepsilon_{xx} < 0\), significant changes to the field response of the Hall resistivity are observed. The remnant Hall resistivity, \( \rho_{xy}(H = 0) \), gradually decreases under compression and is completely suppressed for \( \varepsilon_{xx} \leq -0.2\% \). Furthermore, for \( \varepsilon_{xx} < -0.06\% \), \( \rho_{xy}(H) \) develops a component that is linear in \( \mu H \). At negative strain of \( \varepsilon_{xx} = -0.21\% \), \( \rho_{xy} \) increases linearly with a slope of \( \mu H \approx 1 \mu \Omega \cdot \text{cm} \text{T}^{-1} \) until it reaches a positive saturation value of \( \rho_{xy} = +4.4 \mu \Omega \cdot \text{cm} \) at \( \mu H = +3.8 \text{T} \).

Apart from the AHE sign change, under strongly negative strain, the shape of the hysteresis curve acquires the qualitative form of a ferromagnet magnetized along its hard axis. This implies that a hard axis (easy axis) is induced perpendicular to the negative (positive) strain direction, analogous to the inverse magnetostriuctive effect in ferromagnets\(^4\), which is exactly what happens according to our theoretical analysis. Similar changes are observed in \( \rho_{xy} \) when strain is applied along the \( y \) axis in sample H2 (Fig. 3b,c). From a practical standpoint, this tunability of the magnetic anisotropy with strain on the order of 0.1% could be leveraged to engineer thin films with perpendicular magnetic anisotropy, which is desirable for memory device applications\(^8\). In the antichiral state, a \( z \) axis strain \( \varepsilon_{zz} \) can couple to the in-plane magnetization \( (M_x, M_y) \), through changes in the strength of the local in-plane anisotropy \( \delta \). This affects the magnitude of \( \mathbf{K} \) but leaves its direction unchanged as the six-fold symmetry of the kagome plane is left intact (Supplementary Information). Experimentally, we find that \( \varepsilon_{zz} \) has a negligible effect on \( \rho_{xy} \) (Supplementary Fig. 8), and hence we ignore \( \varepsilon_{zz} \) for Mn\(_3\)Sn.

To examine the sign change of AHE in detail, we perform Hall resistivity measurements with a continuous change of strain under a fixed magnetic field of \( \mu H = 6 \text{T} \) perpendicular to the electric current and strain. Figure 3f shows the strain dependence of the Hall resistivity for the three representative samples normalized by their zero-strain values, \( \rho_{xy}/\rho_{xy|\varepsilon=0} \) at \( T = 300 \text{K} \). Tensioning the sample enhances \( \rho_{xy}/\rho_{xy|\varepsilon=0} \) slightly, for example from +1 to +1.18 at \( \varepsilon = 0.2\% \) in sample H2. The most noticeable feature appears in the compression measurements. For all the samples, \( \rho_{xy}/\rho_{xy|\varepsilon=0} \) decreases at negative strain and changes sign at the switching strain \( \varepsilon_{\text{switch}} \approx -0.075 \pm 0.02\% \). This approximately the same magnitude as the critical stress \( \sigma_c \) inferred from the magnetization measurements, suggesting that \( \sigma_{\text{switch}} \approx \sigma_c \). For \( \varepsilon < -0.2\% \), \( \rho_{xy}/\rho_{xy|\varepsilon=0} \) asymptotically approaches a value around −1. Additionally, \( \rho_{xy}/\rho_{xy|\varepsilon=0} \) reversibly changes its sign under strain cycles, indicating that the samples remained elastic up to strain of \( -0.3\% \) (approximately 360 MPa), in contrast to the magnetization samples, which fracture for \( -\sigma > 270-300 \text{MPa} \). This is consistent with previous studies showing that stress can be applied more homogeneously through epoxy than anvil-based cells\(^8\), which may mitigate premature sample failure. Similar to the stress-induced enhancement of the magnetization, the strain-induced sign reversal of AHE only occurs at \( T > T_K \) (Fig. 3g), indicating that both phenomena are intrinsic to the antichiral phase.

The piezomagnetism and the reversal of AHE can be captured in a Landau theory for the order parameter \( \mathbf{K} \) (Supplementary Information). Deep in the ordered phase, the Hall vector has a well-defined magnitude \( K \) and can be parametrized by its azimuthal angle \( \Phi_K \) in equation (1). Its couplings to an in-plane

| Table 1 | Experimental piezomagnetic (PM) coefficients of selected bulk materials |
|---------------------------------|------------------|--------------|------------------|
| Compound | \( T \) (K) | \( \rho \) (Gauss MPa\(^{-1}\)) | Ref. |
| Mn\(_3\)Sn | 300 | 0.055 | This work |
| CoF\(_2\) | 20 | 0.021 | 50 |
| MnF\(_2\) | 60 | 0.00087 | 15 |
| \( \alpha-FeO\(_3\) \) | \( \approx 80 \) | 0.024 | 51,52 |
| DyFeO\(_3\) | 6 | 0.075 | 53 |
| YFeO\(_3\) | 6 | 0.010 | 54 |
| UO\(_2\) | 2.5 | 0.226 | 8 |

NATURE PHYSICS | VOL 18 | SEPTEMBER 2022 | 1086-1093 | www.nature.com/naturephysics 1089
Fig. 3 | The AHE of the Weyl antiferromagnet Mn₃Sn and its sign reversal under in-plane uniaxial strain.  

**a, b.** The Hall measurement configuration for sample H1 (a) and H2 (b).  
**c.** A sample mounted on the strain cell.  
**d, e.** Results of measurements in the configurations illustrated in a (d) and b (e).  
**f.** The in-plane uniaxial strain ε dependence of the Hall resistivity normalized by its zero-strain value, ρ_{H}/ρ_{H,0}, for three representative samples with different strain, magnetic field (H) and current (I) directions, taken at μ₀H = 6 T and T = 300 K. Sample H3 is measured using a special sample mounting method (Methods). Closed squares represent data measured as ε is swept from its highest tensile value (ε > 0) to its highest compressive value (ε < 0), while open squares represent the data taken in the opposite scan direction. The upper axis shows the uniaxial stress value σ corresponding to the applied strain, obtained using a Young’s modulus of E11 = 121 GPa. The error bar of Δε = ±0.02% is associated with the uncertainty in the strain transmission value (Methods). ε_{switch} ≈ 0.075% is the point where the AHE changes sign.  
**g.** The temperature dependence of the Hall resistivity ρ_{zx} of sample H1 for various applied strains, taken at μ₀H = 6 T parallel to the y axis. The blue (red) curve corresponds to data taken when cooling down (warming up) between 250 and 300 K. Arrows indicate the location of the first-order incommensurate transition temperature T_{H}. Negative (positive) strain denotes compression (tension).
Fig. 4 | Distinct strain controls of the Hall vector $K$ under a magnetic field in the ferrohalic, parahallic and diahallic regimes. a,b,c. Theoretical curves for the $x$ component of the Hall vector $K_x(H)$ (blue) and magnetization $M(H)$ (red) for a fixed shear strain $\epsilon$ applied perpendicular to the field $H$ along $-x$ ($\Phi_1 = \pi/2; \Phi_2 = 0$) (a), parahallic ($-\delta<\epsilon<0$) (b) and diahallic regimes ($\epsilon<-\delta$) (c). Panel c shows the experimental result (open blue squares) of the Hall resistivity at $T=300$ K for sample H2 at $\epsilon$ (open blue squares) of the Hall resistivity at $T=300$ K for sample H2 at $\epsilon$ (open blue squares) normalized by its zero-strain value at $T=300$ K. The figure also shows the experimental data for sample H2 at $T=300$ K and $\mu_B H = 6$ T. All the curves are calculated with $J=1$, $\delta = 0.005$, $S = 3/2$ and $\gamma = 2\mu_B h$. Schematic configurations of domains III and IX are shown with the parameter $3\delta$ and $-3\delta$, respectively. Red and blue spheres and arrows represent the Mn atoms and spin configurations. Faded arrows represent the ideal 120° configuration, and the rotation of the sublattice moments from the ideal configuration is exaggerated by a factor of 25.

The first term here is the Zeeman coupling $-HM$ to the weak ferromagnetic moment $M_0 = 3K$ (ref. 41), the second term represents the uniaxial anisotropy induced by strain and the last term describes the piezomagnetism. For brevity, the material constants and $K$ in equation (4) are set to unity by an appropriate choice of units for the energy density, field and strain.

Owing to the piezomagnetic term, $M_0$ varies linearly with the in-plane uniaxial strain. For the configuration shown in Fig. 2a, the magnetization along $H$, per formula unit is (Supplementary Information)

$$M = \frac{\hbar S}{2J}(\delta - \epsilon) + \frac{\hbar^2 \gamma^2}{2J} \mu_B H,$$

where the first (last) term is the spontaneous $M_s$ (paramagnetic) component. For a tensile strain of $\epsilon = \delta$, the strain-induced magnetization compensates the zero-strain magnetization. Note that the susceptibility $\chi = \partial M/\partial H$ is independent of strain, as observed in experiment. Assuming a local moment of $S = 3/2$ and a gyromagnetic ratio of $\gamma = 2\mu_B / h$ (ref. 41), fitting of equation (5) to our results shown in Fig. 2 yields parameter values of $3\delta$ and $-3\delta$, respectively. Red and blue spheres and arrows represent the Mn atoms and spin configurations. Faded arrows represent the ideal 120° configuration, and the rotation of the sublattice moments from the ideal configuration is exaggerated by a factor of 25.

Fig. 4 | Distinct strain controls of the Hall vector $K$ under a magnetic field in the ferrohalic, parahallic and diahallic regimes. a,b,c. Theoretical curves for the $x$ component of the Hall vector $K_x(H)$ (blue) and magnetization $M(H)$ (red) for a fixed shear strain $\epsilon$ applied perpendicular to the field $H$ along $-x$ ($\Phi_1 = \pi/2; \Phi_2 = 0$) (a), parahallic ($-\delta<\epsilon<0$) (b) and diahallic regimes ($\epsilon<-\delta$) (c). Panel c shows the experimental result (open blue squares) of the Hall resistivity at $T=300$ K for sample H2 at $\epsilon$ (open blue squares) of the Hall resistivity at $T=300$ K for sample H2 at $\epsilon$ (open blue squares) normalized by its zero-strain value at $T=300$ K. The figure also shows the experimental data for sample H2 at $T=300$ K and $\mu_B H = 6$ T. All the curves are calculated with $J=1$, $\delta = 0.005$, $S = 3/2$ and $\gamma = 2\mu_B h$. Schematic configurations of domains III and IX are shown with the parameter $3\delta$ and $-3\delta$, respectively. Red and blue spheres and arrows represent the Mn atoms and spin configurations. Faded arrows represent the ideal 120° configuration, and the rotation of the sublattice moments from the ideal configuration is exaggerated by a factor of 25.

The first term here is the Zeeman coupling $-HM$ to the weak ferromagnetic moment $M_0 = 3K$ (ref. 41), the second term represents the uniaxial anisotropy induced by strain and the last term describes the piezomagnetism. For brevity, the material constants and $K$ in equation (4) are set to unity by an appropriate choice of units for the energy density, field and strain.

Owing to the piezomagnetic term, $M_0$ varies linearly with the in-plane uniaxial strain. For the configuration shown in Fig. 2a, the magnetization along $H$, per formula unit is (Supplementary Information)

$$M = \frac{\hbar S}{2J}(\delta - \epsilon) + \frac{\hbar^2 \gamma^2}{2J} \mu_B H,$$

where the first (last) term is the spontaneous $M_s$ (paramagnetic) component. For a tensile strain of $\epsilon = \delta$, the strain-induced magnetization compensates the zero-strain magnetization. Note that the susceptibility $\chi = \partial M/\partial H$ is independent of strain, as observed in experiment. Assuming a local moment of $S = 3/2$ and a gyromagnetic ratio of $\gamma = 2\mu_B / h$ (ref. 41), fitting of equation (5) to our results shown in Fig. 2 yields parameter values of $3\delta$ and $-3\delta$, respectively. Red and blue spheres and arrows represent the Mn atoms and spin configurations. Faded arrows represent the ideal 120° configuration, and the rotation of the sublattice moments from the ideal configuration is exaggerated by a factor of 25.
allowed interval \(-1 \leq K_s \leq 1\) below the saturation field \(H_s = 2K_s/d\). \(K_s\) increases linearly with \(H\) before saturating at \(K_s = \pm 1\) for \(|H| \geq H_s\). The slope \(dK_s/dH = (\delta + \epsilon)/4\delta\epsilon\) is positive (parahallic) for moderately negative strain in the range \(-\delta < \epsilon < 0\) (Fig. 4b) but negative (diahallic) for strongly negative strain in the range \(\epsilon < -\delta\) (Fig. 4c), before saturating at \(K_s = \text{sgn}(H)\) and \(K_s = -\text{sgn}(H)\), respectively.

It is instructive to examine the shear strain dependence of \(K\) in a fixed magnetic field. Three distinct regimes are also seen (Fig. 4d).

For \(\epsilon \geq 0\), we find \(K_s = \text{sgn}(H)\). As the strain decreases below an upper critical strength \(\epsilon_c = -\frac{10}{H^2} < 0\), \(K_s\) begins to decrease and crosses zero at \(\epsilon = -\delta\). If the field is weak, that is, \(H < \epsilon\), \(K_s\) descends toward an asymptotic value of \(-H/\delta\). For strong fields of \(H > 4\delta\), \(K_s\) reaches \(-1\) at the lower critical strain \(\epsilon_c = -\frac{10}{H^2}\) and saturates at \(K_s = -\text{sgn}(H)\). Intuitively, the critical strain \(\epsilon_c = -\delta\) is the point at which the direction of \(M_s\) of a domain inverts.

Our theory enables a quantitative estimate of the parameter values using the results of the Hall effect measurements (Fig. 4c,d). The strain dependence of the Hall resistivity observed at \(\mu_H = 6\, T\) features a complete reversal of \(\rho_s\) if the field is weak, that is, \(H < \epsilon\), \(K_s\) descends toward an asymptotic value of \(-H/\delta\). For strong fields of \(H > 4\delta\), \(K_s\) reaches \(-1\) at the lower critical strain \(\epsilon_c = -\frac{10}{H^2}\) and saturates at \(K_s = -\text{sgn}(H)\). This implies that the local anisotropy \(\delta\) is equivalent to a field of \(H = 0.67\, T\) (\(\approx 0.04\, mV\)), which renders a shear strain energy in the range of \(d\epsilon/d\delta = 0.3\)–0.6 mV GPa\(^{-1}\). These values are roughly consistent with those obtained in the magnetization measurements. While the theory can fully account for the AHE sign change, it does not explain why the magnitude of the AHE increases by \(\approx 10\%\) from its ambient-pressure value in the high-strain region, that is, \(|\epsilon| > 0.15\%\) (Fig. 3d–f). Such an effect is likely connected to the influence of strain on the band structure, the discussion of which lies beyond the scope of this study.

The theoretical analysis yields another important implication. Without strain, the magnetization is parallel to the Hall vector, \(M = Kx\), but this simple relation breaks down in the presence of applied strain due to the piezomagnetic effect. While \(K\) can be rotated \(180^\circ\) away from the direction of the field by applying a sufficiently strong strain, the Zeeman coupling \((-H \cdot M)\) ensures that the magnetization always has a component aligned with the magnetic field, even in the presence of strain. Indeed, as seen in Fig. 4a–c, the sign of the longitudinal magnetization is fixed, while \(K\) changes sign (Supplementary Information). With a variable strain and magnetic field, we can fully adjust the angle between \(M\) and \(K\), as shown in Supplementary equation (17) and illustrated in Supplementary Fig. 10.

Finally, our strain control of AHE engenders an additional means to control antiferromagnets, complementary to the use of a magnetic field or electrical current\(^{16,22,30}\). In thin films, a large strain can be applied by arranging a lattice mismatch with respect to the substrate or by using a piezoelectric material\(^{11,32}\). Previous studies of \(\text{D}_{09}, \text{Mn}\_X(X = \text{Sn}, \text{Ga})\) thin films grown on ferroelectric lead magnesium niobate–lead titanate substrate reported a large change in the AHE signal with the applied voltage\(^{14,4}\). However, unlike the sign change of the AHE was not observed, possibly due to insufficient strain transfer. Given the recent report on the gigantic THz optical enhancement\(^{16}\) as well as the perspective of AF spintronics\(^{17,19}\), the piezomagnetic effect may become useful in facilitating the ultrafast operation of antiferromagnets.
32. Li, X. et al. Anomalous Nernst and Righi–Leduc effects in Mn3Sn: Berry curvature and entropy flow. *Phys. Rev. Lett.* **119**, 056601 (2017).
33. Higo, T. et al. Large magneto-optical Kerr effect and imaging of magnetic octupole domains in an antiferromagnetic metal. *Nat. Photonics* **12**, 73–78 (2018).
34. Matsuda, T. et al. Room-temperature terahertz anomalous Hall effect in Weyl antiferromagnet Mn3Sn thin films. *Nat. Commun.* **11**, 909 (2020).
35. Krén, E., Paitz, J., Zimmer, G. & Zsoldos, É. Study of the magnetic phase transformation in the Mn3Sn phase. *Physica B+C* **80**, 226–230 (1975).
36. Song, Y. et al. Complicated magnetic structure and its strong correlation with the anomalous Hall effect in Mn3Sn. *Phys. Rev. B* **101**, 144422 (2020).
37. Nagaosa, N., Sinova, J., Onoda, S., MacDonald, A. H. & Ong, N. P. Anomalous Hall effect. *Rev. Mod. Phys.* **82**, 1539–1592 (2010).
38. Xiao, D., Chang, M. C. & Niu, Q. Berry phase effects on electronic properties. *Rev. Mod. Phys.* **82**, 1959–2007 (2010).
39. Hicks, C. W., Barber, M. E., Edkins, S. D., Brodsky, D. O. & Mackenzie, A. P. Piezoelectric-based apparatus for strain tuning. *Rev. Sci. Instrum.* **85**, 065003 (2014).
40. Dieny, B. & Chshiev, M. Perpendicular magnetic anisotropy at transition metal/oxide interfaces and applications. *Rev. Mod. Phys.* **89**, 025008 (2017).
41. Liu, J. & Balents, L. Anomalous Hall effect and topological defects in antiferromagnetic Weyl semimetals: Mn3Sn/Ge. *Phys. Rev. Lett.* **119**, 087202 (2017).
42. Cable, J., Wakabayashi, N. & Radhakrishna, P. A neutron study of the magnetic structure of Mn3Sn. *Solid State Commun.* **88**, 161–166 (1993).
43. Park, P. et al. Magnetic excitations in non-collinear antiferromagnetic Weyl semimetal Mn3Sn. *npj Quantum Mater.* **3**, 63 (2018).
44. Wang, X. et al. Integration of the noncollinear antiferromagnetic metal Mn3Sn onto ferroelectric oxides for electric-field control. *Acta Mater.* **181**, 537–543 (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

Sample synthesis and preparation. Single crystals of Mn₃Sn were synthesized by the solution Bridgman method with excess Sn (ref. 45). First, we pre-melted Mn (99.99%; Rare Metallics) and Sn (99.999%; Rare Metallics) at a molar ratio of 2:97:1 within a conical alumina crucible in an evacuated quartz ampoule at 1050°C. Then, we transferred the precursor ingot to a two-zone vertical Bridgman furnace with a central temperature of T=1100°C. Finally, the melt was passed through a temperature gradient of approximately 6°C/mm to a growth speed of 0.25 mm h⁻¹. The resulting ingot contained two well-segregated sections: a lower section consisting of Mn₃Sn single crystals and a top section consisting of Sn-rich eutectic. The orientation of the Mn₃Sn crystals was confirmed using backscattering Laue X-ray diffraction (Photonic Science Ltd.), and their phase purity was confirmed using powder X-ray diffraction analysis (Cu Kα, Rigaku SmartLab). We cut the crystals using spark erosion and polished them into bar-like shapes for transport, magnetization and resonant ultrasound spectroscopy measurements. Chemical analysis performed using inductively coupled plasma optical emission spectroscopy indicated that the samples used in this study had compositions of Mn₉₃Sn₆₇, with x in the range of 0.01–0.02.

Resonant ultrasound spectroscopy. We determined the elastic moduli of the Mn₃Sn samples using resonant ultrasound spectroscopy. A single crystal was polished to a rectangular prism with faces perpendicular to the x: [2110], y: [0110] and z: [0001] crystallographic directions. To perform resonant ultrasound spectroscopy, the sample was held in weak coupling contact between two piezoelectric transducers. The excitation frequency of one transducer was swept while the response on the second transducer was detected via standard lock-in techniques. This provided all the mechanical resonances of the sample over a chosen frequency range. In this case, we measured 68 resonances between 950 kHz and 4 MHz. From these resonance frequencies, we obtained the full elastic tensor by inverse solving the three-dimensional elastic wave equation.

There are four irreducible representations of strain in D₃h, the combined point group of Mn₃Sn/Ge. This results in five independent elastic moduli Cᵢⱼ: one for each strain and another couple the two A₁₈ strains together. In Voigt notation, this reduces the stress–strain relationship, \( \sigma = C \epsilon \), to

\[
\begin{pmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3 \\
\sigma_4 \\
\sigma_5 \\
\sigma_6 \\
\end{pmatrix}
= \begin{pmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\
C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66} \\
\end{pmatrix}
\begin{pmatrix}
\epsilon_1 \\
\epsilon_2 \\
\epsilon_3 \\
\epsilon_4 \\
\epsilon_5 \\
\epsilon_6 \\
\end{pmatrix}
\]

\( C_{ij} \) are the elastic constants, \( \epsilon \) is the strain and \( \sigma \) is the stress. In this case, \( C_{ij} \) and \( \epsilon \) are related to the stress and strain in the [0001], [11̅10], [0110] and [11̅20] directions.

Supplementary Table 1 presents the elastic moduli of Mn₃Sn at T=435 K and T=395 K as measured by resonant ultrasound spectroscopy. Additionally, we computed the Young's moduli and Poisson's ratios. These are most easily expressed in terms of the compliance tensor, given by the inverse of the elastic tensor \( C \) as \( S = C^{-1} \). We can derive the Young's modulus along the \([0001]\) axis from \( E_{xx} = S_{xx}^{-1} \), the Young's modulus along the [0110] axis from \( E_{yy} = S_{yy}^{-1} \), the in-plane Poisson's ratio from \( \nu_{xx} = -S_{yy}/S_{xx} \), and the out-of-plane Poisson's ratio from \( \nu_{zz} = -S_{zz}/S_{zz} \). In the table, the errors represent an uncertainty of 5% in the unit dimension, following ref. 45.

Magnetization measurements under uniaxial compression. We performed direct-current (DC) magnetization measurements under uniaxial stress using a piston–cylinder-type pressure cell made of Cu–Be alloy with a polycrystalline hexagonal cylindrical outer body. The samples were shaped into cuboids with a mass of approximately 10–20 mg, and their faces were put into direct contact with the piston. We estimated the uniaxial stress by dividing the force \( F \) applied to the piston using a precision load cell at \( T=300 \) K by the cross section \( A \) of the samples: \( \sigma = F/A \). The stress is maintained by a set of Be–Cu disk springs. Because of the differential thermal contraction between the cell body and the sample, the actual sample stress increases upon cooling from room temperature. We estimate this thermally induced stress in the Supplementary Information. We carried out the measurements using a commercial system (Quantum Design MPMS) in the temperature range of T=240–300 K and magnetic field up to ±2 Tesla parallel to the stress direction. To obtain the sample's magnetic moment, we first measured the magnetic field \( \mu_0 H \) in the range of ±6 Tesla perpendicular to the current \( I \) and strain \( x \). We measured the capacitance of the displacement sensor using a Keysight E4980AL LCR meter and drove the piezoelectric actuators using DC power supplies with proportional–integral–derivative control (Texitio PSW-10810H800). The strain was ramped at a rate of approximately 10⁻⁵ s⁻¹. The Hall resistivity \( \rho_{xy}(i,j=x,y,z;i≠j) \) was extracted by an antisymmetrization procedure as \( \rho_{xy}(H) = \rho_{xy}(H=0) - \rho_{xx}(H=0) / 2 \). To carry out strain sweep measurements (Fig. 3), we first applied a positive field \( H=+10 \) T before scanning the strain from the highest tensile point down to the lowest compression point (downsweep), and finally back to the highest tensile point (upsweep). Similar steps were taken when the applied field was negative \( H<0 \). After that, an antisymmetrization procedure was performed on the downsweep and upsweep curves separately.

Data availability

Source data are provided with this paper. All other data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Code availability

The codes that support the plots within this paper and other findings of this study are available on GitHub (https://github.com/SayakD-hub/Mn3Sn_Hall).

References

45. Caillat, T., Fleurial, J.-P. & Borschchevsky, A. Bridgman-solution crystal growth and characterization of the stannidite compounds Co₃Sb₂ and Rh₃B₆. J. Crystal Growth 166, 722–726 (1996).
46. Ghosh, S. et al. Thermodynamic evidence for a two-component superconducting order parameter in Sr₃RuO₄. Nat. Phys. 17, 199–204 (2021).
47. Ramshaw, B. et al. Avoided valence transition in a plutonium superconductor. Proc. Natl Acad. Sci. USA 112, 3285–3289 (2015).
48. Kittaka, S., Taniguchi, H., Yonezawa, S., Yaguchi, H. & Maeno, Y. Higher-Tc superconducting phase in Sr₃RuO₄ induced by uniaxial pressure. Phys. Rev. B 81, 180510 (2010).
49. Coak, M. J. et al. Squidlab—a user-friendly program for background subtraction and fitting of magnetization data. Rev. Sci. Instrum. 91, 023901 (2020).
50. Borovik-Romanov, A. Piezomagnetism in the antiferromagnetic fluorides of cobalt and manganese. Sov. Phys. JETP 11, 786–793 (1966).
51. Andratski, V. & Borovik-Romanov, A. Piezomagnetic effect in α-Fe₃O₄. JETP 24, 687–691 (1967).
52. Voskanyan, R., Levitin, R. & Shchurov, V. Magnetostriiction of a hematite monocrystal in fields up to 150 Koe. Sov. Phys. JETP 27, 423–426 (1968).
53. Zvezdin, A. et al. Linear magnetostriiction and the antiferromagnetic domain structure in dysprosium orthoferrite. J. Exp. Theor. Phys. 88, 1098–1102 (1985).
54. Kadomtseva, A., Agafonov, A., Milov, V. & Moskvin, A. Direct observation of a ferroelectricity change induced in orthoferrite crystals by an external magnetic field. JETP Lett. 33, 383–386 (1981).

Acknowledgements

The work at the Institute for Quantum Matter, an Energy Frontier Research Center, was funded by the DOE Office of Science, Basic Energy Sciences under award...
This work was partially supported by JST-Mirai Program (JPMJMI20A1), JST-CREST (JPMJCR18T3), JST-PRESTO (JPMJPR20L7), Japan Science and Technology Agency, Grants-in-Aids for Scientific Research on Innovative Areas (15H05882, 15H05883 and 15K21732) from the Ministry of Education, Culture, Sports, Science and Technology of Japan, and Grants-in-Aid for Scientific Research (19H00650). S.N. acknowledges support from the CIFAR as a Fellow of the CIFAR Quantum Materials Research Program. The use of the facilities of the Materials Design and Characterization Laboratory at the Institute for Solid State Physics, The University of Tokyo, as well as the Cryogenic Research Center, The University of Tokyo, is gratefully acknowledged. M.I. is supported by a JSPS Research Fellowship for Young Scientists (DC1). S.D. is supported by funding from the Max Planck-UBC-UTokyo Center for Quantum Materials, the Canada First Research Excellence Fund, Quantum Materials and Future Technologies Program, and the Japan Society for the Promotion of Science KAKENHI grant no. JP19H01808. C.W.H. acknowledges support from the Deutsche Forschungsgemeinschaft through SFB 1143 (project ID 247310070) and the Max Planck Society. The identification of any commercial product or tradename does not imply endorsement or recommendation by the National Institute of Standards and Technology.

**Author contributions**

S.N. and O.T. conceived the project. S.N., B.J.R. and C.W.H. planned and supervised the experiments. M.I. synthesized and prepared the samples. M.I. and T.H. performed the transport measurements under uniaxial strain and the magnetization measurements under uniaxial stress. M.I. performed the finite element simulations. F.T. and B.J.R. conducted the resonant ultrasound spectroscopy measurements. S.K. developed the piston–cylinder-type pressure cell. C.W.H. developed the uniaxial strain cell. S.D. and O.T. developed the Landau theory, and S.D. performed the numerical calculations. M.I., S.D., S.N. and O.T. wrote the manuscript with comments from F.T. and C.W.H. All authors read and commented on the manuscript.

**Competing interests**

The authors declare no competing interests.

**Additional information**

Extended data is available for this paper at https://doi.org/10.1038/s41567-022-01645-5.

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41567-022-01645-5.

Correspondence and requests for materials should be addressed to S. Nakatsuji.

Peer review information Nature Physics thanks Cheng Song 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.
Extended Data Fig. 1 | See next page for caption.
Extended Data Fig. 1 | (a) $M(H)$ curves of Sample M2 at $T = 300K$ for various $y$-axis stress. (b) $M(T)$ curves of Sample M2 under $\mu_0 H_y = 1T$ for various stress along $y$-axis, taken on cooling from 300 K. (c) $M(H)$ curves of Sample M2 at $T = 300K$ for various stress along $x$-axis. (d) $M(T)$ curves of Sample M2 under $\mu_0 H_x = 1T$ for various stress along $x$-axis, taken on cooling from 300 K. $T_s \approx 271 K$ is the incommensurate transition temperature for Sample M2. ((e, f)) $M(H)$ curves of Sample M1(M3) at $T = 300 K$ for various stress along $x(y)$-axis.