Spin-polarized Weyl cones and giant anomalous Nernst effect in ferromagnetic Heusler films

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Weyl semimetals are characterized by the presence of massless band dispersion in momentum space. When a Weyl semimetal meets magnetism, large anomalous transport properties emerge as a consequence of its topological nature. Here, using in situ spin- and angle-resolved photoelectron spectroscopy combined with ab initio calculations, we visualize the spin-polarized Weyl cone and flat-band surface states of ferromagnetic Co2MnGa films with full remanent magnetization. We demonstrate that the anomalous Hall and Nernst conductivities systematically grow when the magnetization-induced massive Weyl cone at a Lifshitz quantum critical point approaches the Fermi energy, until a high anomalous Nernst thermopower of -6.2 μVK−1 is realized at room temperature. Given this topological quantum state and full remanent magnetization, Co2MnGa films are promising for realizing high efficiency heat flux and magnetic field sensing devices operable at room temperature and zero-field.
When electric and thermal currents flow through a ferromagnet, an electric field emerges orthogonally to the current path. The two effects are, respectively, called the anomalous Hall (AHE) and Nernst (ANE) effects and are exploited as operating mechanisms in various novel applications such as energy harvesting\(^1,2\), magnetic sensor\(^3\), and heat flux sensing\(^4\). The associated transverse voltage of the electric field is empirically proportional to its spontaneous magnetization. In contrast to the general belief, recent discoveries of both large AHE and ANE, which do not scale with magnetization, have elicited great surprise\(^5–10\). In particular, the observed AHE thermopower of single crystalline bulk Co\(_2\)MnGa at room temperature, ~6.0 μV K\(^{-1}\) is an order of magnitude larger than that of other ferromagnets with similar magnetizations\(^11,12\). These transverse properties are postulated to arise from a Berry curvature emerging within band structures near the Fermi energy\(^ (E_F)\)\(^11,12\).

Topologically non-trivial Weyl semimetals possessing spin-split massless fermions characterized by zero-gap and linear band dispersions are promising candidates featuring a large Berry curvature\(^13–15\). Weyl fermions in solids can be realized in materials that break inversion symmetry or time-reversal symmetry. With the breaking of such symmetries, Weyl nodes appear as pairs in momentum space and act as magnetic monopoles with positive and negative chiralities\(^16\). To date, Weyl nodes have been verified in experiments in non-centric-symmetric (e.g., TaAs-family) and magnetic materials (e.g., Mn\(_3\)Sn) through angle-resolved photoelectron spectroscopy (ARPES) and magneto-transport measurements\(^17–26\).

Recently, a Co\(_2\)MnGa Heusler alloy has also been theoretically predicted to be a ferromagnetic Weyl semimetal with a high Curie temperature and has been experimentally demonstrated in the bulk form to exhibit large anomalous transport properties under an external magnetic field\(^7,9,27\). The nature of this highly symmetric crystal (Fig. 1a) creates mirror-symmetry-protected Weyl nodal lines in the band structure as encountered by theory and experiments\(^28,29\). However, the nodal lines lead to vanishing Berry curvature when integrated over the whole Brillouin zone\(^30,31\) and cannot explain the observed phenomena. One way to obtain a large Berry curvature is to gap out their nodal lines using remanent magnetization or an external magnetic field (specifically, to break the mirror symmetry). Yet, the experimental evidence for broken mirror symmetry was not provided by the recent ARPES measurement on bulk Co\(_2\)MnGa crystal because the remanent magnetization was negligible as applying external magnetic fields is not permitted in this measurement. For practical applications in which zero-field operation and gigantic outputs are a requirement, it is thus indispensable to truly understand the band structure responsible for the anomalous transport properties in films with full remanent magnetization.

Here, we experimentally and theoretically investigated the topological band structure and anomalous transport properties of ferromagnetic Co\(_2\)MnGa thin films. Growth of high-quality thin films possessing full remanent magnetization and in situ spin-resolved ARPES (SARPES) measurements permit access to their non-trivial band structures modified by the broken mirror symmetry. We observed spin-polarized Weyl cones located mostly at a Lifshitz quantum critical point and a flat band of surface states. Furthermore, when the energy associated with the massive Weyl cone approaches \(E_F\) , the anomalous Hall and Nernst conductivities systematically increase as the electron number rises. In particular, the AHE reaches thermopower of ~6.2 μV K\(^{-1}\) at room temperature, which is the highest amongst magnetic films to the best of our knowledge.

### Results and discussion

**AHE and ANE properties of epitaxial Co\(_2\)MnGa films.** To examine the influence of the relative location of the Weyl cone-associated energy with respect to \(E_F\) on the transverse transport properties, we grew epitaxial Co\(_2\)MnGa films with different compositions and investigated their AHE and ANE properties. Highly \(L_2\)-ordered structure was confirmed in all Co\(_2\)MnGa films by the quantitative analysis of X-ray diffraction patterns with taking the off-stoichiometry in each film into account (Supplementary Fig. 1 and the associated text). Figure 1b, c show the dependence on the perpendicular external magnetic field \(\mu_0H_z\) of the anomalous Hall resistivity \(\rho_{xx}^A\) and the normalized transverse thermoelectric voltage \(E_T^A\) for Co\(_2\)MnGa films with different compositions labeled H8, H7, H5, H1, and E2 (see Table 1), leading to a different number of valence electrons (\(N_v\)) ranging from 25.6 (H8) to 28.5 (E2). These curves clearly show that for all these films the respective magnitude of the AHE and the ANE changes significantly depending on the composition ratio of Co\(_2\)MnGa regardless of its atomic ordering. It should be mentioned that here we apply the \(V_T\) and \(H_z\) for evaluating the thermopower of the AHE strictly, causing no ANE signal at \(\mu_0H_z = 0\) as the spontaneous magnetization does not appear to the z-direction due to the strong demagnetization field. Thus, we also measured ANE signal by applying the \(V_T\) and sweeping the magnetic field in the plane and observed clear ANE voltage at zero-field due to the perfect spontaneous in-plane magnetization as shown in Fig. 1d, which is advantageous to thermoelectric applications such as heat flux sensor\(^4\).

Resistivity \(\rho_{xx}^A\) and thermopower \(S_{xy}^A\) (Fig. 1f, i) were estimated by finding the intercept of the linear-fitted curve for the saturation region in Fig. 1b, c, respectively. From Fig. 1e, f, \(\rho_{xx}\) monotonically decreases with increasing \(N_v\), whereas \(\rho_{xx}^A\) has a maximum value of 22.5 μΩ cm at around \(N_v = 27.3–27.4\). \(\sigma_{xy}^A\) evaluated from \(\alpha_{xy}^A = \rho_{yx}^A/(\rho_{xx}^2 + \rho_{yx}^2)\) exhibits a nearly monotonous increase from 2 S cm\(^{-1}\) at \(N_v = 25.6\) to 485 S cm\(^{-1}\) at 28.5 (Fig. 1g).

Figure 1h displays the \(N_v\) dependence of the Seebeck coefficient \(S_{xx}\). In the small \(N_v\) region, \(S_{xx}\) is positive and gradually decreases with \(N_v\), changing sign at \(N_v = 26.7\). A very tiny ANE is observed in the small \(N_v\) region (Fig. 1i); for instance, \(0.3 \mu V K^{-1}\) at \(N_v = 25.6\). Interestingly, \(S_{xy}^A\) increases steeply with increasing \(N_v\) with the largest \(S_{xy}^A\) achieved being 6.2 μV K\(^{-1}\) at \(N_v = 27.3\), which is the highest in the ferromagnetic thin films\(^32,33\) and slightly smaller than the highest value in bulk Co\(_2\)MnGa ~ 8.0 μV K\(^{-1}\). \(S_{xy}^A\) is obtained from the linear response equation

\[
S_{xy}^A = \rho_{xx}\alpha_{xy}^A - \rho_{yx}\alpha_{xx}^A. \tag{1}
\]

Here, \(\alpha_{xx}\) and \(\alpha_{xy}\) are the longitudinal and transverse thermoelectric conductivities, respectively. This equation indicates that there are two different phenomenological contributions to ANE. To simplify our explanation, we denote the associated terms as \(S_1 = \rho_{xx}\alpha_{xy}^A\) and \(S_2 = -\rho_{yx}\alpha_{xx}^A\). As mentioned in refs.\(^35,36\), \(S_1\) is regarded as the contribution of AHE to ANE induced by a Seebeck-driven longitudinal current. Similarly, \(S_2\) stems from the direct conversion from a temperature gradient to a transverse current via \(\alpha_{xy}^A\). \(S_2\) can be converted to \(-S_{xx}^A\rho_{yx}/\rho_{xx}\) enabling a direct estimate from experimental data plotted in Fig. 1i. One clearly views the contribution of \(S_1\) to \(S_{xy}^A\) to be very limited. Therefore, \(S_1(S_1 = S_{xy}^A - S_{xx}^A)\) dominates the observed \(S_{xy}^A\) over the whole range of \(N_v\). Transverse thermoelectric conductivity \(\alpha_{xy}^A\) estimated from \(S_1\) and \(\rho_{xx}\) increases enormously with \(N_v\) in a similar way to \(\alpha_{xy}^A\) and has a maximal value of 3.3 A m\(^{-1}\)K\(^{-1}\) at \(N_v = 28.5\) (Fig. 1j). Figure 1k shows the relationship between \(\alpha_{xy}^A\) and \(\sigma_{xy}^A\) at 300 K for Co\(_2\)MnGa films compared to other magnets.
The perpendicular temperature gradient electron number represents standard deviation. Ref. 34).

Examined this ratio in our present samples as shown in Fig. 1k. While both $\alpha$ magnets have a universal relationship $\partial H_{\perp}$ and $\rho_{xx}$ normalized by given temperature gradient $\nabla T$, sweeping the in-plane magnetic field $H_y$ for the sample with $N_v = 28.5$. Dependence on total valence electron number $N_v$ of $\rho_{xx}$, $\rho_{xy}$, $\sigma_{xx}$, $\sigma_{xy}$, $\sigma_{yx}$, and $\sigma_{yy}$ and $\alpha_{xy}$. Green dashed lines in $\mathbf{e}-\mathbf{j}$ indicate $N_v$ for the stoichiometric composition. All error bars represent standard deviation. $\mathbf{k}$ Relationship between $\alpha_{xy}$ vs. $\sigma_{xy}$ in our Co$_2$MnGa films (red circles) and different magnets (gray squares: taken from ref. 34).

Table 1 Atomic compositions and valence electron numbers of Co$_2$MnGa films.

| Sample name | Co (at.%) | Mn (at.%) | Ga (at.%) | $N_v$ |
|-------------|-----------|-----------|-----------|-------|
| E2          | 53.0      | 23.8      | 23.2      | 28.5  |
| E1          | 52.6      | 22.3      | 25.1      | 28.2  |
| Stoichiometry | 50.0    | 25.0      | 25.0      | 28.0  |
| H1          | 47.4      | 25.1      | 27.5      | 27.4  |
| H2          | 47.6      | 24.6      | 27.8      | 27.4  |
| H3         | 45.3      | 27.6      | 27.1      | 27.3  |
| H4          | 44.9      | 27.0      | 28.1      | 27.1  |
| H5          | 45.6      | 24.9      | 29.5      | 26.9  |
| H7          | 41.4      | 27.9      | 30.7      | 26.4  |
| H8          | 35.4      | 31.8      | 32.8      | 25.6  |

Results of the composition analysis using XRF and estimated valence electron number ($N_v$) for all 10 Co$_2$MnGa films prepared. The stoichiometric composition ($N_v = 28.0$) is also shown as a reference.

A previous study by Xu et al.34 clarified that many topological magnets have a universal relationship $\alpha_{xy}/\sigma_{xy} \sim k_B/e$. Thus, we examined this ratio in our present samples as shown in Fig. 1k. While both $\alpha_{xy}$ and $\sigma_{xy}$ are enhanced more than one order of magnitude by increasing $N_v$ from 25.6 to 28.5, we confirmed that the $\alpha_{xy}/\sigma_{xy}$ ratios of our Co$_2$MnGa films also follow this universal behavior. It signifies that the main origin of AHE and ANE in all Co$_2$MnGa films comes from the intrinsic topological nature34.

We also found that $\rho_{xx}$ decreases with increasing $N_v$, whereas $S_{xy}$ increases in our Co$_2$MnGa films (Fig. 1e, i). This relation between $\rho_{xx}$ and $S_{xy}$ is opposite to that reported in Co$_3$Sn$_2$S$_2$, where $S_{xy}$ is enhanced by increasing $\rho_{xx}$. It is worth mentioning that this discrepancy arises from a difference in origin of enlargement of $S_{xy}$. Namely, Ding et al. prepared Co$_3$Sn$_2$S$_2$ single crystals having different impurity concentrations and found that the impurity scatterings in Co$_3$Sn$_2$S$_2$ enlarge $\rho_{xx}$ but preserve $\alpha_{xy}$ resulting in the enlargement of $S_{xy}$ through $S_1$ term. On the other hand, this study tunes the position of $E_F$ by adjusting the composition of Co$_2$MnGa film, leading to a drastic enlargement of $\alpha_{xy}$ with $N_v$ which is large enough to overcome the reduction of $\rho_{xx}$ thus $S_{xy}$ is enhanced through $S_1$ term as well.

Theoretical calculations. To understand the origin of the strong $N_v$ dependence of AHE and ANE, we have performed ab initio calculations. Figure 2a shows the band structure of Co$_2$MnGa along the X–K line at $k_z = 2\pi/a$ and along the K–Γ–W line at $k_z = 0$ plane in the Brillouin zone (Fig. 2h). The red and blue dashed lines represent the majority- and minority-spin bands, respectively, in the absence of the spin–orbit interaction (SOI). A large minority-spin hole pocket is found around Γ, whereas majority-spin bands dominate near $E_F$ around X, K, and W and form crossing bands, labeled A through E. Previous studies have shown that such majority-spin band structures have three types of Weyl nodal loops in the Brillouin zone reflecting mirror symmetries with respect to.

the $k_z = 0$ planes ($i = x, y, z$). For example, the nodal points of bands C and D in Fig. 2a are connected by the nodal loop shown in Fig. 2h.

When the SOI and the magnetization along the [100] direction are taken into account, only the mirror plane $k_z = 0$ remains; the other planes disappear. This is because the mirror plane perpendicular to the magnetization conserves the direction of spins whereas that parallel to the magnetization does not. Once the SOI is present, the energy gaps open at all points of the Weyl cones A–E, since the mirror symmetry is broken with respect to the $k_z = 0$ and the $k_z = 2\pi/a$ planes (Fig. 2a, gray curves). Specifically, several Weyl nodal loops collapse and become massive (gapped) Weyl cones, and only those protected by $k_z = 0$ mirror symmetry survive (Fig. 2i and Supplementary Fig. 7). Here, we emphasize that the gapped Weyl cones A and C are tilted, most being at a Lifshitz quantum critical point between type-I and type-II Weyl fermions.

From the calculated anomalous Hall conductivity $\sigma_{xy}$ (Fig. 2b), we see that $\sigma_{xy}$ has large values of $\sim 10^3$ S cm$^{-1}$ and exhibit a peak near $E_F$, consistent with previous results. In Fig. 2c, we show the calculated transverse thermoelectric conductivity $\alpha_{xy}^\Lambda$. Around $E = E_F$, $\alpha_{xy}^\Lambda$ increases with increasing $E - E_F$ (i.e., by electron doping) and takes a maximum at $E - E_F = 0.07$ eV, near to where $\sigma_{xy}$ sharply drops (Fig. 2b). This is reasonable as $\alpha_{xy}^\Lambda$ is approximately proportional to $-d\sigma_{xy}^\Lambda/dE$ (see “Methods” section, Eq. (4), and the Sommerfeld expansion).

To discuss the correlation between the large $\sigma_{xy}^\Lambda$ around $E = E_F$ (Fig. 2b) and the band structures (Fig. 2a), we plotted the $(k_x, k_y)$ dependences of the Berry curvature $\Omega^\Lambda(k)$ (Fig. 2d–g), the nodal loops at the $k_z = 0$ and $2\pi/a$ planes are marked as highlighted areas in Fig. 2i. At $E - E_F = 0.05$ and 0.03 eV (Fig. 2d and e), the Berry curvature has large values on the X–K line but has small values on the K–Γ–W line, because the gap of Weyl cone A mainly contributes to the Berry curvature at these energies (Fig. 2a). In contrast, at the lower energy of $E - E_F = -0.08$ eV (Fig. 2g), large values of the Berry curvature are obtained close to the W point on the Γ–W line, which is determined by the gap of Weyl cone D (Fig. 2a). From these results, we conclude that both gaps open on two different nodal loops in the $k_z = 0$ and...
The calculated Fermi surface of the stoichiometric Co$_2$MnGa ($N_v = 28.0$) obtained at 80 eV with $p$-polarized light. The calculated Fermi surface of the stoichiometric Co$_2$MnGa ($N_v = 28.0$) with 70 meV chemical potential shifted is overlaid. Band structures of an electron-doped Co$_2$MnGa film. We performed ARPES experiments for the E2 ($N_v = 28.5$) sample as it exhibits the highest $\sigma_{\text{xy}}$ and $\alpha_{\text{xy}}$, to determine the $E_F$ location and the band structure with the mirror-symmetry breaking that yields a large Berry curvature as well as anomalous transport properties. Figure 3a shows the observed Fermi surface recorded at 80 eV photon energy after magnetization along [100] (Supplementary Movie 1 for a detailed continuous change in constant energy maps). Around the $\Gamma$ point, a circular-shaped contour is evident. At each X point of the first Brillouin zone, we recognize a point-like structure. The calculated constant energy contour of the stoichiometric Co$_2$MnGa ($N_v = 28.0$) with the SOI along [100] was also plotted (Fig. 3a). Except for the intensities in between $\Gamma$ and K, the features observed in the experiments are not observed in the experimentally hole-doped samples. This discrepancy may be caused by an extrinsic mechanism or the formation of anti-site defects arising from off-stoichiometric compositions, which is not taken into account in the calculations.
well reproduced by the calculation when the chemical potential shifts by +70 meV (Supplementary Fig. 5 and the associated text). Figure 3b shows the ARPES images and the band dispersions calculated at several momentum cuts (Fig. 3a, white dashed lines). At cut 1 (Γ–K line), we confirmed the large hole-pocket crossing $E_F$ around Γ. One also finds distinct features that get closer to the K points with increasing $E - E_F$ and finally cross $E_F$, indicated by a red inverted triangle. These features are consistent with the calculated minority-spin hole band at Γ point and one branch of the tilted majority-spin Weyl cone C (Fig. 2a). In going from cut 1 to cut 3, the slope of the Weyl cone evolves to be sharper for both experiment and calculation. Here we also emphasize that an almost non-dispersive band is observed just below $E_F$ around the Γ point represented by a gray inverted triangle at cut 1. This flat band corresponds to the Fermi surface between the Γ and K points (Fig. 3a) and is not reproduced by the calculations. At the cut 4 (X–X line), we can confirm the hole bands with energy maximum of $E - E_F \sim -100$ and $-350$ meV around $k_\parallel = 0$ and ±0.8 Å$^{-1}$, respectively, in both experiment and calculation. We also realize that the bottom of the electron bands located near $E_F$ at the X points create prominent point-like structures on the Fermi surface (Fig. 3a).

Figure 3c, d shows the wide range ARPES images along the Γ–K–X line (cut 1) taken at 80 eV energy for incident photons with p- and s-polarization, respectively. With s-polarized light, a sharp electron-pocket is markedly enhanced around the X points, whereas the photoemission intensities of the tilted Weyl cone C and the flat band observed by p-polarization have mostly diminished. In Fig. 3e, f, we present the ARPES image and its second derivative with the calculated band structure. Here, to eliminate the effect of the light polarization-dependent matrix-element, these images acquired with p- and s-polarized light are mixed. The experimental result is well reproduced by the calculations with $E_F$ shifted upward by 70 meV (i.e., electron doping). This chemical potential shift is consistent with a higher $N_s$ of 28.5 for this sample than the stoichiometric one ($N_s = 28.0$). Small discrepancies are noted between the observed and calculated band dispersions (Fig. 3f), for instance, the location of the bottom of the band of the sharp electron-pocket around the X points. The differences may arise through correlation or $k_z$ broadening effects.41,42

Figure 3g shows the magnified ARPES image in the frame shown in Fig. 3e. With suppression through the matrix-element effect, the band structure around the X point at the $k_z = 2\pi/a$ plane in the second Brillouin zone is clearly visualized. In a comparison with the calculation (Fig. 3g, lower panel), we realized that the observed band structure around the X point resembles the tilted and gapped Weyl cone A (Fig. 2a). Because the upper part of the Weyl cone cannot be seen, $E_F$ is probably located in the gap of the massive Weyl cone A.

Here, we turn our attention to the flat band observed around the Γ point. To clarify the origin of the flat band, we show the photon-energy-dependent energy distribution curves (EDCs) at $k_{\perp} = -0.5$ Å$^{-1}$ taken after magnetization (Fig. 3h). The prominent peaks caused by the flat band do not show a clear photon-energy ($k_{\perp}$) dependence. Details of the photon energy dependence are shown in Supplementary Fig. 6 and the associated text. We therefore conclude that the observed flat band just below $E_F$ belongs to a surface state.

To gain deeper insight into the Weyl fermion and the peculiar surface state in the Co$_2$MnGa film, we performed spin-resolved measurements. Since the light spot size (~1 mm) is much larger than the magnetic domain, we carried out SARPES measurements before and after magnetizing the sample. Figure 4a and b shows the spin-resolved EDCs and spin-polarizations at $\theta_{\parallel} = -4^\circ$ ($k_{\perp} \sim -0.3$ Å$^{-1}$) taken before and after magnetizations, respectively. Although the spin-polarization is negligible over the whole energy region before magnetization due to the formation of magnetic domains, it is enhanced enormously after magnetization. In particular, the large negative spin-polarization (~40%) originating from the flat surface state has been observed at $E_F$. Figure 4c shows the calculated band structures (left) and the experimentally observed spin-polarization map along the Γ–K–X line overlaid with the calculated band structures (right). Here the positive (negative) spin-polarizations are marked in red (blue). Also, the spin-resolved band structures in the majority (left) and minority (right) spin channels (Fig. 4d) feature a large hole band around the Γ point having a minority-spin component. There are bands having a strong majority-spin component around the K point near $E_F$. From calculations, the Weyl cone C is characterized by the majority-spin component and tilting (see Fig. 2a). Furthermore, because Weyl cones A and C are mostly at Lifshitz quantum critical points, they have a large density of states at $E_F$ when the Weyl node approaches $E_F^-$.

These features are confirmed by our ARPES and SARPES measurements, and therefore we conclude that the observed spin-polarized feature with positive spin-polarization near the K point can be ascribed to one more branch of the tilted spin-polarized Weyl cone C induced by broken mirror symmetry.

In addition, we find that the flat surface state has a minority-spin component (Fig. 4d, right), the sign of which is opposite to that of the Weyl cone (Fig. 4d, left). Figure 4e shows the spin-resolved EDCs taken from $\theta_{\parallel} = 0^\circ$ to $20^\circ$, which corresponds to the $k$-line from Γ to X. The clear minority-spin peaks persist over a wide momentum region marked with inverted triangles. There are two main possibilities for the origin of this peculiar surface state. One is the topologically non-trivial Fermi-arc surface state. The other is a trivial surface resonance state, which was predicted for half-metallic Co-based Heusler alloys. Having considered the location of the Weyl node before magnetization, it seems that the minority-spin surface state connects the Weyl cones at positive and negative momenta although further study is needed to elucidate the origin of the surface state.

### Band structures of a hole-doped Co$_2$MnGa film

In order to compare the band structures of electron-doped and hole-doped samples, we also performed SARPES experiments for the sample H3$^+$ ($N_s = 27.3$). Figure 5a, b show the observed Fermi surface and wide range ARPES image along Γ–K–X line recorded at 50 eV photon energy with $p$-polarized light. At X point, the electron-pocket crossing $E_F$ can be seen while the large hole-pocket is located at Γ point. These features are in good agreement with the electron-doped sample (Fig. 3). In Fig. 5c, d, we present the magnified ARPES image along the Γ–K–X direction and its second derivative along the momentum axis. Around $-0.60$ Å$^{-1}$ near $E_F$, one can see a tilted band, in which the node is slightly located above $E_F$ (see gray arrow in Fig. 5d). As we can see in Fig. 5f, this tilted band has a strong majority-spin component. These experimental results agree with the results of the calculation, shown in Fig. 5e with the position of $E_F$ shifted downward by 220 meV. Therefore, we conclude that the tilted cone close to K point belongs to the Weyl cone E (see Fig. 2a).

Finally, we discuss the role of the Fermi energy tuning in optimizing the anomalous transport properties. From ARPES measurements from two samples, we determined the relative $E_F$ shifts from the stoichiometric condition ($N_s = 28.0$), specifically, +70 meV for the sample E2 ($N_s = 28.5$) and -220 meV for the sample H3$^+$ ($N_s = 27.3$). The latter has lower $\alpha_{xy}$ and $\alpha_{xy}$ than the former. These results reasonably explain the observed and
Fig. 4 Spin-polarized Weyl cone and flat band surface state of Co$_2$MnGa film. a, b Spin-resolved EDCs and spin-polarizations at $\theta_\parallel = -4^\circ$ ($k_\parallel = 0.3 \text{ Å}^{-1}$) taken before and after magnetization at 80 eV with $p$-polarized light. All error bars represent standard deviation. The insets show the schematics of multi-magnetic domains and a single-magnetic domain. c, d Calculated band dispersion with $E_F$ shifted upward by 70 meV (left) and spin-polarization map along the $\Gamma$-$K$-$X$ line (right). d Spin-resolved ARPES images of the majority (left) and minority (right) spin states. e Spin-resolved EDCs taken from $\theta_\parallel = 0^\circ$ to $20^\circ$ ($\Gamma$-$K$-$X$). The background signal of the secondary electrons was subtracted. Inverted triangles indicate the peak position of the minority spin-polarized flat band.

Fig. 5 Observed spin-polarized band structures of a hole-doped Co$_2$MnGa film. a Fermi surface of the sample H3$^*$ ($N_v = 27.3$) recorded at 50 eV with $p$-polarized light. b Wide ARPES image along the $\Gamma$-$K$-$X$ line indicated by the white dashed line in a, c, d Magnified ARPES image in the frame in b and its second derivative. e Calculated band dispersion with $E_F$ shifted downward by 220 meV. f Spin-polarization map along the $\Gamma$-$K$-$X$ line.
calculated large anomalous transport properties presented in Fig. 1 based on our calculations given in Fig. 2. In detail, because $E_k$ of sample E2 is closely located at the gapped region of the Weyl cones A and C through slight electron doping, it satisfies a criterion whereby a large Berry curvature in both $k_x=0$ and $k_y= 2\pi/a$ planes is generated and thereby results in a gigantic ANE because the $a_{\eta\rho}^{\alpha\beta}$ is large. Therefore, we have clearly confirmed that enhancing the anomalous transport properties of topological ferromagnets involves two key features: (1) the creation of a massive (gapped) Weyl cone from the nodal loop by mirror-symmetry breaking and (2) the tuning of the Fermi energy.

**Conclusion**

In summary, we have experimentally and theoretically investigated a one-to-one correspondence between the electronic structure and the anomalous transport properties in the film form of Co$_2$MnGa topological ferromagnets. By in situ SARPES, we provided a direct visualization of the spin-polarized and massive Weyl cones and the peculiar surface state under mirror-symmetry breaking. When $E_k$ approaches the gap of the massive Weyl cones by the electron doping, we have recorded the highest anomalous Nernst temperature, $T_{\text{AN}}$ = 0.96. Therefore, a single magnetic domain was overall obtained for the Brillouin zone integration ensuring good convergence for $a_{\eta\rho}^{\alpha\beta}$.

From Boltzmann transport theory, we calculated the transverse thermoelectric conductivity $a_{\eta\rho}^{\alpha\beta}$ for a temperature $T$ by substituting the obtained $a_{\eta\rho}^{\alpha\beta}$ into the following expression:

$$a_{\eta\rho}^{\alpha\beta} = \frac{1}{\pi T} \int \frac{d E}{\rho} \left( \frac{d f}{d E} \right) (E - \mu) a_{\eta\rho}^{\alpha\beta}(E),$$

where $f = 1/(\exp((E - \mu)/k_B T) + 1)$ denotes the Fermi distribution function with $\mu$ the chemical potential. Here, $\mu = 0$ corresponds to the Fermi level.

**Spin-resolved and angle-resolved photoelectron spectroscopy**

ARPES and SARPES measurements were performed at the Elettra-EBL (BL-9B) at the Hiroshima Synchrotron Radiation Center. The base pressure of the SARPES chamber was $5 \times 10^{-9}$ Pa. The photoelectrons were acquired using a hemispherical electron analyser (R4000, Scienta-Omicron). The spin-polarization factor was measured using a very low-energy electron diffraction-type spin detector. The experimental geometry is shown in Supplementary Fig. 4. The energy and angular resolutions for ARPES (SARPES) were set to 45 meV (55 meV) and ±0.3° (±1.5°), respectively. The effective Sherman function was 0.28 for the SARPES measurements.

During all SARPES measurements, the temperature was maintained below 40 K. Before each ARPES and SARPES measurement, the sample was annealed at 550 °C for 30 min at the preparation chamber (base pressure $4 \times 10^{-10}$ Pa). The quality and cleanliness of the annealed sample was checked by low-energy electron diffraction (Supplementary Fig. 3 and the associated text). A magnetic field as large as $-0.1 T$ was applied to the samples along the [100] for sample E2 ([110] for sample H3) easy-axis using a permanent magnet in the preparation chamber at room temperature. A 0.1 T magnetic field was sufficiently high to saturate the magnetoization (Supplementary Fig. 2 and the associated text). The ratio between the remanent and saturation magnetizations along the [100] easy-axis of the sample E2 is 0.96. Therefore, a single magnetic domain was overall obtained for SARPES measurements.

**Data availability**

The data presented in this paper are available from the authors on reasonable request.

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