Robust ferromagnetism carried by antiferromagnetic domain walls

Hishiro T. Hirose1, Jun-ichi Yamaura2 & Zenji Hiroi1

Ferroic materials, such as ferromagnetic or ferroelectric materials, have been utilized as recording media for memory devices. A recent trend for downsizing, however, requires an alternative, because ferroic orders tend to become unstable for miniaturization. The domain wall nanoelectronics is a new developing direction for next-generation devices, in which atomic domain walls, rather than conventional, large domains themselves, are the active elements. Here we show that atomically thin magnetic domain walls generated in the antiferromagnetic insulator Cd2Os2O7 carry unusual ferromagnetic moments perpendicular to the wall as well as electron conductivity: the ferromagnetic moments are easily polarized even by a tiny field of 1 mT at high temperature, while, once cooled down, they are surprisingly robust even in an inverse magnetic field of 7 T. Thus, the magnetic domain walls could serve as a new-type of microscopic, switchable and electrically readable magnetic medium which is potentially important for future applications in the domain wall nanoelectronics.

Domain wall nanoelectronics puts the spotlight on a new paradigm of ferroic devices1. For example, the magnetic racetrack memory uses mobile domain walls in a ferromagnetic nanowire to store information2, and conducting domain walls in the ferroelectric insulator BiFeO3 are proposed to be used for a local strain sensor and a memory device3,4. Thus far, the target elements of the domain wall nanoelectronics have been limited to domain walls in ferroic orders. However, those in antiferroic orders such as antiferromagnetic order are also attractive because of the superior stability: domain walls in antiferroic orders can be stable even in the nanometer scale and robust against external fields in the absence of macroscopic polarizations. Theoretically predicted for magnetic domain walls (MDWs) in antiferromagnetic orders is the presence of uncompensated magnetic moments at the interface5, which has been actually observed in the specific case of the antiferromagnetic iron monolayer on the tungsten (001) substrate by means of spin-polarized scanning tunneling microscopy6. Such a MDW carrying a net magnetic moment may be useful as a magnetic recording medium. Thus, expanding the target to antiferroic orders would provide us with a chance to find a new route to microscopic devices with novel functionality in the domain wall nanoelectronics.

Recently, the MDWs in the all-in/all-out (AIAO) type antiferromagnetic order found in the two pyrochlore oxides Cd2Os2O7 and LnIr2O7 (Ln = Y and lanthanoids)7,8 draw attention as they show interesting physical properties. In these compounds, 5d electrons are conducting at high temperatures, while are completely localized at low temperatures to induce AIAO type magnetic orders; the metal-insulator (MI) transitions and magnetic orderings occur almost simultaneously at ~227 K in the osmate9,10 and at 34–110 K in the iridates11,12. The crystal structure of Cd2Os2O7 is shown in Fig. 1a, which contains a pyrochlore lattice made of corner-sharing tetrahedra of Os atoms. In the AIAO order, all the four Os magnetic moments of every tetrahedron point in or out to its center and cancel out in total. These two spin structures, “all-in” and “all-out”, alternate from one tetrahedron to its neighbors, as shown in Fig. 1b. There are two kinds of magnetic domains that can coexist13: the AIAO and all-out/all-in (AOAI) orders related by the time reversal symmetry with each other. The coexistence of the two domains has actually been visualized in Cd2Os2O7 by the circular polarized resonant X-ray diffraction imaging technique14. On the other hand, microwave impedance microscopy successfully visualized the MDWs of NdIr2O7, which indicates that the MDWs remain conducting even when the domains themselves become insulating15,16. Similar conducting MDWs have also been suggested in Cd2Os2O717. Interestingly, weak ferromagnetism is observed below TN in both compounds10,11,18; the origin remains unclear and we speculate it related to the MDWs.

Results
In order to investigate the properties of the AIAO order and its MDWs in Cd2Os2O7, we have carried out precise magnetization M and resistivity ρ measurements under a various magnetic field H on bulk single crystals. The

1Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba 277-8581, Japan. 2Material Research Center for Element Strategy, Tokyo Institute of Technology, Yokohama, Kanagawa, 226-8503, Japan. Correspondence and requests for materials should be addressed to H.T.H. (email: hishirose@gmail.com) or Z.H. (email: hiroi@issp.u-tokyo.ac.jp)
successively upon cooling under the field (FC). This feature is typical for an antiferromagnetic order accompanied
forced to align along the applied
of osmium,
230 K. The temperature dependence of the remanent robust magnetization
at 180 K, while it gradually opens a hysteresis loop and simultaneously moves downward with increasing temper-
resistivity.

Figure 1. All-in/all-out (AIAO) order and temperature dependences of magnetic susceptibility and
resistivity. (a) Crystal structure of Cd$_2$Os$_2$O$_7$. Cadmium, osmium and oxygen atoms in the cubic unit cell of
10.1618(8) Å in edge are shown by cyan, black and red spheres, respectively. Four Os atoms, each of which is
octahedrally coordinated by six oxygen atoms, form a regular tetrahedron which shares vertices with the
surrounding four tetrahedra, resulting in the three-dimensional network of the pyrochlore lattice. (b) AIAO
magnetic order on the pyrochlore lattice made of osmium atoms. The arrows represent some osmium spins on
the vertices of tetrahedra; the tetrahedra with the all-in and all-out configurations are colored in yellow-green
and magenta, respectively. (c) Temperature dependences of $M/H$ measured on a single crystal of Cd$_2$Os$_2$O$_7$. After
subtracting $H_{\text{FC}}$ which is applied along the [111] direction while the crystal is cooled across
net; a symmetrical hysteresis loop with a complete sign change in the reversed field. Upon further heating, the
hysteresis loop gradually shrinks, but still survives at 227 K, just 1 K below
we call this robust magnetization
rob(0) at 180 K is shown in Fig. 3a. Even in subtle
$M_{\text{rob}}$ from the raw data at 180 K, there remains a nearly flat
independent of applied
$H_{\text{FC}}$ dependence of
$\rho(T)$ shows an expanded view of the low temperature region in the linear scale.

magnetic susceptibility $M/H$ exhibits a Curie-Weiss-like temperature dependence at high temperatures followed
by a distinct anomaly at $T_N = 228$ K (Fig. 1c), below which $\rho$ rapidly increases (Fig. 1d). Below $T_N$, there is a
difference between the two $M/H$ curves measured upon heating under 2 T after zero-field cooling (ZFC) and
successively upon cooling under the field (FC). This feature is typical for an antiferromagnetic order accompanied
by weak ferromagnetism$^{30}$; ferromagnetic moments of domains freeze in random direction in ZFC, while they are
forced to align along the applied $H$ upon cooling across $T_N$ in FC, so that the latter gives a larger $M$.

Figure 2a shows magnetization curves at two typical temperatures above (330 K) and below $T_N$ (180 K). In
each curve, there are small non-linear components near the origin in addition to a large linear component
$M_{\text{lin}}$ from a paramagnetic or an antiferromagnetic state. Appeared after the subtraction of $M_{\text{rob}}$, is a magnetization
curve that is characteristic to a soft ferromagnet at 330 K, while an almost identical curve parallely shifted upward
at 180 K (Fig. 2b). The ferromagnetic component $M_{\text{rob}}$ at 330 K is present above $T_N$, and is almost temperature
independent even across $T_N$, which means that it must be irrelevant to the AIAO order (Supplementary Section 1). After
subtracting $M_{\text{rob}}$ and $M_{\text{lin}}$, from the raw data at 180 K, there remains a nearly flat $M_{\text{in}}$ independent of applied $H$;
we call this robust magnetization $M_{\text{rob}}$. Note that the magnitude of $M_{\text{rob}}$, is less than 0.1% of the magnetic moment
of osmium, $\mu_{\text{Os}} = 1–1.5 \mu_B$ derived from $^{17}$O NMR experiments (Yamauchi, I. & Takigawa, M. in preparation).

The temperature evolution of $M_{\text{rob}}$ near $T_N$ is shown in Fig. 2c. The $M_{\text{rob}}$ is almost $H$ independent at 205 K as
at 180 K, while it gradually opens a hysteresis loop and simultaneously moves downward with increasing temper-
above 210 K. At 225 K, the $M_{\text{rob}}$ eventually shows a typical behavior expected for a conventional ferromag-
ett; a symmetrical hysteresis loop with a complete sign change in the reversed field. Upon further heating, the
hysteresis loop gradually shrinks, but still survives at 227 K, just 1 K below $T_N$. Then, it completely disappears at
230 K. The temperature dependence of the remanent robust magnetization $M_{\text{rob}}(0)$ shown in Fig. 2d, which was
measured in zero field after cooling to 2 K in $\pm 7$ T, is almost constant at low temperatures, gradually decreases in
approaching $T_N$, and vanishes above $T_N$. Therefore, it is obvious that the $M_{\text{rob}}$ is a weak ferromagnetic moment
“parasitic” to the AIAO order.

Although the $M_{\text{rob}}$ is insensitive to $H$ at low temperatures, it is highly sensitive to the cooling magnetic field
$H_{\text{FC}}$ which is applied along the [111] direction while the crystal is cooled across $T_N$. The $H_{\text{FC}}$ dependence of
$M_{\text{rob}}(0)$ at 180 K is shown in Fig. 3a. Even in subtle $\mu_B H_{\text{FC}}$ as low as $\pm 1$ mT, the $M_{\text{rob}}$ changes its sign and takes a
uncompensated moments appear at the monolayer MDWs and behave as uncorrelated quasi-free moments. A ferromagnet with a large anisotropy can generate MDWs of monolayer thickness at the anti-phase boundary. This is actually the case for $\text{Cd}_2\text{Os}_2\text{O}_7$. However, it is not trivial whether these uncompensated moments behave cooperatively to show ferromagnetic behavior. For example, in $\text{Na}_2\text{Ba}_2[\text{Fe}_3(\text{C}_2\text{O}_4)_6][\text{Al}(\text{C}_2\text{O}_4)_2]_2$ ($A = \text{Sn, Zr}$), which exhibits an anisotropic antiferromagnetic order analogous to the AIO order on a distorted kagome lattice, uncompensated moments appear at the monolayer MDWs and behave as uncorrelated quasi-free moments. A specific nature of the AIO order must be important as mentioned in the next paragraph.

Since $\text{Cd}_2\text{Os}_2\text{O}_7$ has a cubic symmetry, the [001], [110] and [111] planes may give stable interfaces. First we focus on the [001] MDW. In terms of the classical spin model, when AIO and AOAI domains meet at an (001) plane, an interface layer consisting of tetrahedra having the 2-in/2-out spin configuration is always formed, as illustrated in Fig. 3c (Supplementary Section 3 and Supplementary Fig. 1). Note that each 2-in/2-out tetrahedron possesses a net moment perpendicular to the plane, and all of them align in the same direction at one MDW.

Then the key question is whether the MDW magnetism can explain the observed feature of $M_{\text{rob}}$. In general, the MDWs in an antiferromagnet without magnetic anisotropy is similar to that of a ferromagnet, in which a gradual rotation of magnetic moments occurs. These MDWs can carry uncompensated moments but they must be easily flipped by external fields. In contrast, an antiferromagnet with a large anisotropy can generate MDWs of monolayer thickness at the anti-phase boundary. This is actually the case for $\text{Cd}_2\text{Os}_2\text{O}_7$. However, it is not trivial whether these uncompensated moments behave cooperatively to show ferromagnetic behavior. 

Figure 2. Magnetic field and temperature dependences of magnetization of $\text{Cd}_2\text{Os}_2\text{O}_7$. (a) Magnetization curves at 180 and 330 K. First, crystal A was cooled from 350 K to the temperature in a magnetic field of $\mu_0H = +7\text{T}$ along the [111] direction, and then the magnetization was measured with decreasing field to $-7\text{T}$ and with increasing field to $+7\text{T}$. The black straight line on the 330 K curve indicates a linear component $M_{\text{lin}}$ derived from a linear fitting at 6–7 T. (b) Magnetic field dependences of the non-linear component, $M - M_{\text{lin}}$. The ferromagnetic component observed at 330 K is almost temperature independent, which is denoted as $M_{\text{rob}}$. $M_{\text{rob}}$ at 180 K is a residual ferromagnetic component emerged after further subtracting $M_{\text{lin}}$, which is robust with almost no change in the magnetic field sweep between $\pm 7\text{T}$. (c) Temperature evolution of $M_{\text{rob}}$ between 205–230 K. The magnetization curves were measured sequentially from low to high temperatures after cooling to 205 K in $\mu_0H = +7\text{T}$. (d) Temperature dependences of remanent robust magnetizations $M_{\text{rob(0)}}$ on crystals A and B, which were measured in zero field upon heating after cooling to 2 K under $+7\text{T}$. 

value corresponding to $\sim 1/3$ of its saturation along $H_{\text{FC}}$. In sharp contrast, the $M_{\text{rob}}$ never changes at 180 K even in the large reverse $H$ of $\pm 7\text{T}$ (Fig. 3b). Furthermore, the magnitude of $M_{\text{rob}}$ is determined only by the $H_{\text{FC}}$ and takes nearly the same values in a thermal cycle as shown in the inset of Fig. 3a, demonstrating a good reproducibility.

Discussion

Now we would like to discuss the origin of $M_{\text{rob}}$. It is well known that, in antiferromagnets such as $\alpha$-Fe$_2$O$_3$, spin canting due to the Dzyaloshinskii-Moriya (DM) interaction induces weak ferromagnetism. However, such spin canting should not occur in the AIO order, because the DM interactions geometrically cancel out in every tetrahedron. On the other hand, it is suggested that the weak ferromagnetism of $\text{Cd}_2\text{Os}_2\text{O}_7$ is not a bulk property because its magnitude shows a significant sample dependence. In fact, our second crystal B has a larger $M_{\text{rob}}$ than the first crystal A, as compared in Fig. 2d. Thus, we think that $M_{\text{rob}}$ originates from MDWs; the sample dependence must be due to a difference in the density of crystalline defects that pin down MDWs. The magnitude of $M_{\text{rob}}$ is reasonably explained by the observed density of MDWs (Supplementary Section 2).

Then the key question is whether the MDW magnetism can explain the observed feature of $M_{\text{rob}}$. Now we would like to discuss the origin of $M_{\text{rob}}$. It is well known that, in antiferromagnets such as $\alpha$-Fe$_2$O$_3$, spin canting due to the Dzyaloshinskii-Moriya (DM) interaction induces weak ferromagnetism. However, such spin canting should not occur in the AIO order, because the DM interactions geometrically cancel out in every tetrahedron. On the other hand, it is suggested that the weak ferromagnetism of $\text{Cd}_2\text{Os}_2\text{O}_7$ is not a bulk property because its magnitude shows a significant sample dependence. In fact, our second crystal B has a larger $M_{\text{rob}}$ than the first crystal A, as compared in Fig. 2d. Thus, we think that $M_{\text{rob}}$ originates from MDWs; the sample dependence must be due to a difference in the density of crystalline defects that pin down MDWs. The magnitude of $M_{\text{rob}}$ is reasonably explained by the observed density of MDWs (Supplementary Section 2).
An interplay between the ferromagnetism and electron conductivity at the MDWs is observed in the magnetoresistance shown in Fig. 4. There is an unusual odd-symmetric contribution superimposed on a conventional positive magnetoresistance in each curve. This odd-symmetric contribution is obviously different from the Hall resistivity because its sign is reversed with the sign of $H_{\text{FC}}$. It is plausible that the robust ferromagnetism of the [001] MDWs affects conducting electrons in the vicinity of the MDWs. In such MDWs with both robust ferromagnetic moments and conducting electrons, one would expect an anomalous Hall effect or a spin-polarized electric current.
Finally, we would like to comment briefly on the relation between Cd$_2$Os$_2$O$_7$ and Ln$_2$Ir$_2$O$_7$, both of which exhibit similar MI transitions accompanied by the AIAO magnetic order and also possess similar MDWs. The basic electronic structures of the two compounds are quite different because of the different electron filling; 5$d^3$ and 5$d^5$ for Os$^{5+}$ and Ir$^{4+}$ ions, respectively$^{26,27}$. The origin of the conducting MDWs in Nd$_2$Ir$_2$O$_7$ is suggested to be the topological interface state arising from the Weyl points of opposite chiralities in the Weyl semimetal$^{27–29}$. Possibly, a similar Weyl semimetallic state exist in Cd$_2$Os$_2$O$_7$.$^{17}$ Otherwise, there is an alternative reason that is common to the two compounds.

To summarize, we have discovered the unique ferromagnetism in the MDWs of the AIAO order in Cd$_2$Os$_2$O$_7$. It is robust at low temperatures but can be easily flipped by a weak $H_{FC}$ upon cooling across $T_N$. The origin is ascribed to uncompensated magnetic moments in 2-in/2-out tetrahedron layers at the {001} MDW. Moreover, the electrical conductivity coexists in the MDWs, which is affected by the polarization of the robust ferromagnetism. These unique magnetic and electric properties of the MDWs in the AIAO order are not only interesting in materials science, but also important in the domain wall nanoelectronics. It would be possible to produce, for example, such a novel microscopic magnetic memory device as proposed in Supplementary Section 6 and Supplementary Fig. 4.

Methods

Sample preparation. Single crystals of Cd$_2$Os$_2$O$_7$ were grown by the chemical transport technique described in ref. 10. First, a polycrystalline sample was prepared from CdO and elemental osmium in ratio of 1.05:1 and 1.1:1 for batches A and B, respectively; the excess CdO was required to compensate a loss of Cd during the reaction. A mixture was sealed in an evacuated quartz tube with oxygen supplier Ag$_2$O, heated up to 1073 K and kept for 2 days. The obtained polycrystalline pellet was put in an evacuated quartz tube and placed in a temperature gradient of 1040–1200 K for 10 days. Several single crystals of the octahedral shape up to 1 mm$^3$ volume were obtained at the middle of the tube together with OsO$_2$ crystals at the lower-temperature side. One of key tricks for better crystal growth is to clean the tube carefully before the reaction. Two crystals were selected from batches A and B and used in the measurements: crystals A and B from batches A and B weigh 1.970 and 0.994 mg, respectively.

Magnetization measurements. The magnetizations of crystals A and B were measured in the temperature range of 2–350 K and in the field range between ±7 T in a SQUID magnetometer (MPMS3, Quantum Design). The vibrating sample magnetometer (VSM) mode allowed rapid measurements with a high accuracy of $10^{-9}$ emu and made it possible to obtain reliable data on one tiny single crystal.

In order to detect small ferromagnetic magnetizations from MDWs, which are superimposed on a much larger linear response from the bulk, it is crucial to know the exact magnitude of magnetic field near zero field at the sample position in the superconducting magnet of MPMS3. In general, there is always an inevitable remanent field of ~20 Oe left inside a superconducting magnet even if one sets “apparent” field $H_{FC}$ zero because of a trapped magnetic flux. This remanent field makes it difficult to obtain a true $M-H$ curve, as it changes the direction upon changing $H_{FC}$ across zero; a minus (plus) remanent field is left when $H_{FC}$ is reduced to zero from plus (minus) fields.

We have carefully estimated the remanent field as a function of $H_{FC}$ by measuring a reference paramagnetic sample of elemental palladium and corrected the actual applied magnetic field on a sample.

Most magnetization measurements were carried out on crystal A after cooling from above $T_N$ to the measurement temperatures under a magnetic field of ±7 T along the [111] direction, if not particularly mentioned. We have also examined several crystals and obtained essentially the same results except for the magnitude of the weak ferromagnetic moments; the variation is probably relevant to the different density or distribution of MDWs pinned by crystalline defects.
Transport measurements. Resistivity was measured on crystal B at temperatures between 2 and 300 K in magnetic fields up to \( \pm 9 \) T in a Physical Property Measurement System (Quantum Design). A standard four-probe method was employed with electrical current running along the [110] direction perpendicular to a magnetic field applied along the [111] direction.

Illustration. Figures for crystal structure and spin arrangements were rendered using VESTA\(^30\).

References
1. Catalan, G., Seidel, J., Ramesh, R. & Scott, J. F. Domain wall nanoelectronics. *Rev. Mod. Phys.* 84, 119–156 (2012).
2. Parkin, S. S. P., Hayashi, M. & Thomas, I. Magnetic Domain-Wall Racetrack Memory. *Science* 320, 190–194 (2008).
3. Seidel, J. et al. Conduction at domain walls in oxide multiferroics. *Nat. Mater.* 8, 229–234 (2009).
4. Béa, H. & Paruch, P. Multiferroics: A way forward along domain walls. *Nat. Mater.* 8, 168–169 (2009).
5. Papanicolaou, N. Antiferromagnetic domain walls. *Phys. Rev. B* 51, 15062–15073 (1995).
6. Bode, M. et al. Atomic spin structure of antiferromagnetic domain walls. *Nat. Phys.* 5, 477–481 (2009).
7. Yamaura, J. et al. Tetrahedral Magnetic Order and the Metal-Insulator Transition in the Pyrochlore Lattice of C\(_2\)O\(_4\)O\(_7\). *Phys. Rev. Lett.* 108, 247205 (2012).
8. Tomiyasu, K. et al. Emergence of Magnetic Long-range Order in Frustrated Pyrochlore Nd\(_2\)Ir\(_2\)O\(_7\) with Metal–Insulator Transition. *Phys. Soc. Jpn.* 81, 034709 (2012).
9. Sleigh, A., Gillson, J., Weiher, J. & Bindloss, W. Semiconductor-metal transition in novel C\(_2\)O\(_4\)O\(_7\). *Solid State Commun.* 14, 357–359 (1974).
10. Hiroi, Z., Yamaura, J., Hirose, T., Nagashima, I. & Omoto, Y. Lifshitz metal–insulator transition induced by the all-in/all-out magnetic order in the pyrochlore oxide C\(_2\)O\(_4\)O\(_7\). *AIP Mater.* 3, 041501 (2015).
11. Matsuhira, K., Wakeshima, M., Hinatsu, Y. & Takagi, S. Metal–Insulator Transitions in Pyrochlore Oxides Ln\(_2\)Ir\(_2\)O\(_7\). *J. Phys. Soc. Jpn.* 80, 094701 (2011).
12. Saga, Y. et al. Determination of long-range all-in-all-out ordering of Ir\(^{4+}\) moments in a pyrochlore iridate Eu\(_2\)Ir\(_2\)O\(_7\) by resonant x-ray diffraction. *Phys. Rev. B* 87, 100403 (2013).
13. Arima, T. Time-Reduction Symmetry Breaking and Consequent Physical Responses Induced by All-In–All-Out Type Magnetic Order on the Pyrochlore Lattice. *J. Phys. Soc. Jpn.* 82, 013705 (2013).
14. Tardif, S. et al. All-In–All-Out Magnetic Domains: X-Ray Diffraction Imaging and Magnetic Field Control. *Phys. Rev. Lett.* 114, 147205 (2015).
15. Ueda, K. et al. Anomalous domain-wall conductance in pyrochlore-type Nd\(_2\)Ir\(_2\)O\(_7\) on the verge of the metal-insulator transition. *Phys. Rev. B* 89, 075127 (2014).
16. Ma, E. Y. et al. Mobile metallic domain walls in an all-in-all-out magnetic insulator. *Science* 350, 538–541 (2015).
17. Néel, L. & Pauthenier, É. Étude thermomagnétique d’un monocrystall de Fe\(_2\)O\(_3\). *Compt. Rend. 234*, 2172–2174 (1952).
18. Dzyaloshinsky, I. A thermodynamic theory of “weak” ferromagnetism of antiferromagnetics. *J. Phys. Chem. Solids* 4, 241–255 (1958).
19. Moriya, T. Anisotropic Superexchange Interaction and Weak Ferromagnetism. *Phys. Rev. 120*, 91–98 (1960).
20. Li, Y. –Y. Domain Walls in Antiferromagnets and the Weak Ferromagnetism of \( \alpha \)–Fe\(_2\)O\(_3\). *Phys. Rev. 101*, 1450–1454 (1956).
21. Mitsumata, C. & Sakuma, A. Generalized Model of Antiferromagnetic Domain Wall. *IEEE T. Magn.* 47, 3501–3504 (2011).
22. Bogdanov, N. A., Maurice, R., Rousochatzakis, I., van den Brink, J. & Hozoi, L. Magnetic State of Pyrochlore C\(_2\)O\(_4\)O\(_7\) Emerging from Strong Competition of Ligand Distortions and Longer-Range Crystalline Anisotropy. *Phys. Rev. Lett.* 110, 127206 (2013).
23. Lhotel, E. et al. Domain-Wall Spin Dynamics in Kagome Antiferromagnets. *Phys. Rev. Lett.* 107, 257205 (2011).
24. Padilla, W. J., Mandrus, D. & Basov, D. N. Searching for the Slater transition in the pyrochlore C\(_2\)O\(_4\)O\(_7\) with infrared spectroscopy. *Phys. Rev. B* 66, 035120 (2002).
25. Sohn, C. H. et al. Optical Spectroscopic Studies of the Metal–Insulator Transition Driven by All-In–All-Out Magnetic Ordering in 5d Pyrochlore C\(_2\)O\(_4\)O\(_7\). *Phys. Rev. Lett.* 115, 266402 (2015).
26. Harima, H. Electronic bandstructures on 5d-transition metal pyrochlore: C\(_3\)d\(_2\)O\(_4\)O\(_7\). *J. Phys. Chem. Solids* 63, 1035–1038 (2002).
27. Wan, X., Turner, A. M., Vishwanath, A. & Savrasov, S. Y. Topological semimetal and Fermi-arc surface states in the electronic structure of pyrochlore iridates. *Phys. Rev. B* 83, 205101 (2011).
28. Yamaji, Y. & Imada, M. Metallic Interface Emerging at Magnetic Domain Wall of Antiferromagnetic Insulator: Fate of Extinct Weyl Electrons. *Phys. Rev. X* 4, 021035 (2014).
29. Yamaji, Y. & Imada, M. Modulated helical metals at magnetic domain walls of pyrochlore iridium oxides. *Phys. Rev. B* 93, 195146 (2016).
30. Momma, K. & Izumi, F. VESTA 3 for three-dimensional visualization of crystal, volumetric and morphology data. *J. Appl. Crystallogr* 44, 1272–1276 (2011).

Acknowledgements
We are grateful to Y. Yamaji and T. Arima for fruitful discussions. H.T.H. was supported by the Japan Society for the Promotion of Science through Program for Leading Graduate Schools (MERIT) and KAKENHI (No. 14J08469).

Author Contributions
The crystals were grown and characterized by H.T.H. with an assistance from J.Y. The most of the measurements and analyses of the results were performed by H.T.H. All the authors discussed the results. The manuscript was written by H.T.H. and Z.H., with contributions from J.Y.

Additional Information
Supplementary information accompanies this paper at http://www.nature.com/srep

Competing financial interests: The authors declare no competing financial interests.

How to cite this article: Hirose, H. T. et al. Robust ferromagnetism carried by antiferromagnetic domain walls. *Sci. Rep.* 7, 42440; doi: 10.1038/srep42440 (2017).

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
This work is licensed under a Creative Commons Attribution 4.0 International License. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in the credit line; if the material is not included under the Creative Commons license, users will need to obtain permission from the license holder to reproduce the material. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/

© The Author(s) 2017