Observation of spin-current striction in a magnet

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The interplay among magnetization and deformation of solids has long been an important issue in magnetism, the elucidation of which has made great progress in material physics. Controlling volume and shapes of matter is now indispensable to realizing various actuators for precision machinery and nanotechnology. Here, we show that the volume of a solid can be manipulated by injecting a spin current: a spin current volume effect (SVE). By using a magnet Tb0.3Dy0.7Fe2 exhibiting strong spin-lattice coupling, we demonstrate that the sample volume changes in response to a spin current injected by spin Hall effects. Theoretical calculation reflecting spin-current induced modulation of magnetization fluctuation well reproduces the experimental results. The SVE expands the scope of spintronics into making mechanical drivers.
The magneto-volume effect (MVE), one of the magnetostriction effects, has been a central issue in the physics of magnetism in itinerant electron systems for a long time. One notable example is an invar alloy Fe$_{86.4}$Ni$_{13.6}$, where the magneto-volume change compensates for thermal expansion; the volume change is attributed to spin fluctuation in the alloy (see Fig. 1a). Since the discovery of the effect, extensive studies on MVE have made remarkable progress in the physics of spin fluctuation and electronic correlation in ferromagnetic metals.

Recently, a powerful tool for controlling spin fluctuation emerged in the field of spintronics: a spin current$^{7-13}$, a flow of spin angular momentum in a solid. By injecting a spin current into ferromagnets, magnetization fluctuation can be modulated via the angular momentum transfer between magnetization and a spin current$^{13,14}$, as shown in Fig. 1b, when the injected spin current carries spins along the field direction (the $z$-direction), the spin current turns the magnetization $\mathbf{M}$ toward the $z$-direction via the spin-transfer torque$^{13}$, and the magnetization fluctuation is suppressed. By combining the effect with MVE, a fascinating thickness modulation of the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film by the spin current injection, a spin-current induced magnetostriction effect, which offers a way for magneto-mechanical control of mechanical actuators based on spintronics.

Results

Sample characterization and measurement setup. Figure 1d shows a schematic illustration of the sample system used in the present study. To inject a spin current into a Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film, we used the spin Hall effect (SHE) in a paramagnetic metal Pt. When a charge current, $j_s$, is applied to a Pt film, it is converted into a spin current, $j_\sigma$, via the SHE, as shown in Fig. 1c. By putting a Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film onto a Pt film on a Si substrate by an electroplating method$^{21}$ (see Methods for details), the spin current with the spin polarization $\sigma \propto j_\sigma \times \mathbf{n}$ is injected into the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film, where $\mathbf{n}$ is a normal vector to the interfacial plane. The magnetostriction coefficient of the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film fabricated in the present study was found to be $\sim 550 \times 10^{-6}$ around 1400 Oe$^{21}$ (see Supplementary Note 5 for details).

The thickness change of the film is measured by means of laser Doppler vibrometry (LDV). In the measurement, as shown in Fig. 1d, an a.c. spin current is injected into the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film by applying an a.c. electric current $j_s$ to the Pt film, where the spin-transfer torque $\propto j_\sigma$ can increase and decrease the $\mathbf{M}$ fluctuation alternatively. The $\mathbf{M}$ fluctuation decrease (increase) causes the volume expansion (shrinkage) of the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film. Due to the in-plane constraints of the film fabricated on the Si substrate, the volume change should accompany a thickness change of the film, as shown in Fig. 1c. The LDV detects the out-of-plane displacement of the film surface in response to the a.c. spin current injection in terms of the Doppler shift of light reflected at the surface of the film. To extract the displacement synchronized with the input a.c. spin current, we performed Fourier transform and obtained its frequency spectra (see Methods for details). All the measurements were performed at room temperature.

Observation of spin current volume effect. Figure 2a shows the obtained frequency $f$ spectrum of the vibrational amplitude $A$ and

Fig. 1 Concept of spin current volume effects (SVEs). a A schematic illustration of the magneto-volume effect (MVE). A ferromagnet expands (shrinks) via the spin-lattice coupling when spin fluctuation in the magnet decreases (increases) due to the magnetic field application or temperature modulation. The left (right) panel shows the ferromagnet at higher (lower) temperature. b A schematic illustration of SVE. The volume of a ferromagnet can be tuned by spin current injection. The left (right) panel shows the ferromagnet before (after) the spin current injection. c A schematic illustration of SHE induced by the spin Hall effect (SHE) in a Pt/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ bilayer system. $\mathbf{H}$, $\mathbf{M}$, $j_s$, and $\sigma$ denote the magnetic field, magnetization of the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film, a charge current, a spin current, and the spin polarization vector of $j_\sigma$, respectively. When $j_s$ flows in the $+x$ direction in the Pt film, $j_\sigma$ with $\sigma$ is injected into the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film, and $\mathbf{M}$ fluctuation in the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film decreases, causing the volume expansion via the spin-lattice coupling. The volume expansion should accompany a thickness change of the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film due to the in-plane constraints of the film on a Si substrate. d A measurement setup in the present study. An a.c. spin current is injected into the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film via the SHE by applying $j_s$ to the Pt film, and the mechanical vibrational spectrum for the sample surface is obtained by laser Doppler vibrometry.

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Fig. 2 Observation of spin-current induced mechanical vibration in Tb$_{0.3}$Dy$_{0.7}$Fe$_2$. a Frequency $f$ spectra of the mechanical vibration amplitude $A$ (upper panel) and the vibration phase $\phi$ (lower panel) for the Pt/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ sample at the a.c. frequency $f_{AC} = 10$ kHz and the a.c. current amplitude $j_c = 50$ mA, measured by applying the magnetic field $H = 1115$ Oe. $A_{peak}$ and $\phi_{peak}$ are $A$ and $\phi$ at $f = f_{AC}$, respectively. b Spectra of $d = A_{peak} \cos \phi_{peak}$. $d_{peak}$ increases with the increase of $H$, which aligns $M$ along with the field direction. Furthermore, as shown in Fig. 3a, b, d, e, the W/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ sample exhibits a clear sign reversal of the displacement (green plots and curves) before the possible oxidation of the W film and the Cu/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ sample shows suppression of the displacement (gray plots and curves), being consistent with the characteristics of the spin current injection via the SHE. The results imply that the observed mechanical vibration originates from the interaction between $M$ and spin currents.

Comparison between experiments and theoretical model for spin current volume effect. Now we discuss the origin of the observed mechanical displacement due to the spin current injection. The injected spin current interacts with $m$, partial magnetization responsible for the volume effect, and exerts the spin-transfer torque$^{15}$ $\tau_{sst} \propto m \times (m \times \sigma)$ on $m$. The frequency of the current 10 kHz is much less than that of the magnetization dynamics $\sim$GHz, and the effective damping and fluctuation of $m$ are modulated by $\tau_{sst}$ via the anti-damping spin torque (Slonczewski spin torque$^{15}$) mechanism; $\tau_{sst}$ suppresses (enhances) the $m$ thermal fluctuation and increases (decreases) the thermally averaged $\sigma$ intensity when $\sigma$ is antiparallel (parallel) to $m$. The $m$ intensity increase (decrease) induces the expansion (shrinkage) of the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film via the spin-lattice coupling (see Fig. 4b), resulting in the out-of-plane mechanical displacement. In contrast, when $\sigma$ is perpendicular to $m$, the $m$ fluctuation remains unchanged due to the cancellation of $\tau_{sst}$, and the volume change does not occur. We note that the effect of the anti-damping torque is maximized when $m \parallel \sigma$ because it is exerted on the $m$ fluctuation component$^7$. Based on the above scenario, we constructed a theoretical model for the SME. The magnetization dynamics under thermal fluctuation is calculated from the stochastic LLG equation$^{25}$ $\frac{d\mathbf{m}}{dt} = -\gamma m \times [H + \mathbf{h}(t)] + \frac{\alpha}{m} \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} + \tau_{sst}$, where $\gamma$, $\alpha$, and $m$ are the gyromagnetic ratio, the magnetic damping coefficient, and the saturation magnetization, respectively. The thermal fluctuation of $m$ is taken into account with the random magnetic field $\mathbf{h}(t)$. By combining the above equation, the fluctuation-dissipation theorem, and phenomenological magnetoelectric theory$^{26}$, we derived the mechanical displacement $d_{SME}$ due to the SME in the linear response to $j_c$ (see Supplementary...
\[
d_{\text{SVE}} = \frac{a k_B T}{am_H H^2 V} \left( m_S - \frac{k_B T}{HV} \right) \sin \theta
\]

where \( k_B \), \( T \), \( V \), \( a \), and \( \theta \) are the Boltzmann constant, temperature, the magnetic coherence volume of the Tb\(_{0.3}\)Dy\(_{0.7}\)Fe\(_2\) film, a known constant parameter, and the relative angle between \( H \) and \( j_c \) (see Fig. 4a), respectively. Here, the result gives us the \( \theta \) dependence of the SVE: \( d_{\text{SVE}} \) is proportional to \( \sin \theta \). When the external field is much weaker than the magnetization saturation field, \( d_{\text{SVE}} \propto \sin \theta \), where \( H \) in Eq. (1) is replaced with the internal magnetic field in each magnetic domain and \( \theta \) represents the relative angle between local magnetization in each domain and \( j_c \).

The \( \sin \theta \) averaged over the magnetic domains increases with the external magnetic field application, consistent with the observed \( H \) dependence of \( d_{\text{peak}} \). (see also Supplementary Note 8).

Figure 4c shows the \( \theta \) dependence of the measured \( d_{\text{peak}} \). We found that \( d_{\text{peak}} \) exhibits a clear \( \sin \theta \) dependence for both the Pt/
Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ (blue plots) and W/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ (green plots) samples. The result is consistent with the theoretically obtained $d_{\text{SVE}} \propto \sin \theta$ and rules out the spin-current induced shear magnetostriction $\propto \cos \theta$, which originates from the magnetization rotation due to $\tau_{\text{eff}}$ (see Supplementary Note 8 for details). The agreement between the experimental results and the theoretical calculation supports our interpretation that the observed mechanical vibration is attributed to the volume change due to the SVE.

Discussion

Here, we discuss the influence of other effects on the observed mechanical displacements in the (Pt, W, and Cu)/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ samples. The first one is Lorentz force due to the a.c. current under the magnetic fields. By carrying out control experiments using (Pt, W, and Cu)/Si samples without the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ layer, we found that the mechanical peak signal disappears in the absence of the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ layer (see Supplementary Note 1). The result implies that the Lorentz force is irrelevant to the observed mechanical effect. We also examined the Oersted field effect due to the a.c. current flowing in the paramagnetic metals which might induce magnetostriction of the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film, but we found that this cannot be responsible for the observed paramagnetic metal dependence (sign reversal between Pt/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ and W/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$), although the small mechanical signal in the Cu/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ sample might be attributed to such Oersted field effects or a small finite SHE in the Cu film$^{27-29}$.

In summary, we found spin current volume effects (SVEs), volume modulation by spin current injection, in Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ films. The SVE observed here enables the direct mechanical actuation of a magnetostrictive thin film by using a spin current, which can be applied to making mechanical actuators driven by spin currents free from electricity. The high controllability of the SVE in terms of magnetic fields will present great advantages in designing spintronics-based mechanical devices.

Methods

Sample preparation. We used an electroplating method$^{34}$ to grow the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film on the paramagnetic metals (see Supplementary Note 5 for details). The polycrystalline Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film with the thickness of $\sim$100 nm was fabricated on the Pt film with the thickness of 140 nm (the W and Cu films with the thickness of 100 nm), which was sputtered as a seed electrode for electroplating on a Si substrate with the size of 20 mm $\times$ 20 mm. The obtained samples were cut into 2 mm wide and 10 mm long pieces. The resistance of the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film is in the order of 0.1 M$\Omega$ while the resistance of the paramagnetic films is less than 10 $\Omega$. Therefore, when an electric current flows in the (Pt, W, and Cu)/Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ samples, the portion of the electric current in the paramagnetic metal films is much greater than that in the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film. The spin current is injected into the Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ film via the SHE in the paramagnetic films and it modulates magnetization fluctuation (a type of the reverse processes of the dynamic spin pumping$^{12,13}$). In electroplating methods, it is not possible to fabricate a single layer of Tb$_{0.3}$Dy$_{0.7}$Fe$_2$ without the seed electrode films, such as Pt.

Mechanical vibration measurement setup. The samples were fixed with varnish on a stage located between the magnetic poles of an electromagnet. An a.c. charge current was applied to the samples to induce the SVE. The mechanical vibration of the sample surface was measured by means of LDV, where a laser light with the wavelength $\lambda = 532$ nm was split into a reference beam and an incident beam. The reflected light from the sample surface was analyzed with an LDV system (MSA-100-3D, Polytec, Inc.) to obtain the displacement and velocity of the surface along the laser-beam direction as a function of time. The data were Fourier transformed into $f$ spectra of $A$ and $f$. All the measurements were performed at room temperature and in a high vacuum of $\sim$10$^{-4}$ Pa.

Data availability

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

Code availability

The codes used in theoretical calculations are available from the corresponding author upon reasonable request.

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References

1. Chikazumi, S. *Physics of Ferromagnetism* (Oxford Science 17 Publications, 2009).
2. Shiga, M. Magnetovolume effects in ferromagnetic transition metals. *J. Phys. Soc. Jpn.* 50, 2573–2580 (1981).
3. Nakamura, Y. Magnetovolume effects in Laves phase intermetallic compounds. *J. Magn. Magn. Mater.* 31, 829–834 (1981).
4. Guillaume, C. E. Recherches sur les aciers au nickel. Dilatations aux temperatures eleves; resistance electrique. *CR Acad. Sci.* 125, 235–238 (1897).
5. Moriya, T. & Usami, K. Magneto-volume effect and invar phenomena in ferromagnetic metals. *Solid State Commun.* 34, 95–99 (1980).
6. Wassermann, E. F. The invar problem. J. Magn. Magn. Mater. 100, 346–362 (1991).

7. Maekawa, S., Valenzuela, S. O., Saitoh, E. & Kimura, T. Spin Current 2nd edn (Oxford Univ. Press, 2017).

8. Žutić, I., Fabian, J. & Das Sarma, S. Spintronics: fundamentals and applications. Rev. Mod. Phys. 76, 323–410 (2004).

9. Wolf, S. et al. Spintronics: a spin-based electronics vision for the future. Science 294, 1488–1495 (2001).

10. Azevedo, A., Vilela Leao, L. H., Rodriguez-Suarez, R. L., Oliveira, A. B. & Rezende, S. M. Dc effect in ferromagnetic resonance: evidence of the spin-pumping effect? J. Appl. Phys. 97, 10C715 (2005).

11. Saitoh, E., Ueda, M., Miyajima, H. & Tatara, G. Conversion of spin current into charge current at room temperature: inverse spin-Hall effect. Appl. Phys. Lett. 88, 182509 (2006).

12. Kajiwara, Y. et al. Transmission of electrical signals by spin-wave interconversion in a magnetic insulator. Nature 464, 262–266 (2010).

13. Ando, K. et al. Electric manipulation of spin relaxation using the spin Hall effect. Phys. Rev. Lett. 101, 056601 (2008).

14. Daimon, S., Uchida, K., Iguchi, R., Hioki, T. & Saitoh, E. Thermographic measurements of the spin Peltier effect in metal/yttrium-iron-garnet junction systems. Phys. Rev. B 96, 024424 (2017).

15. Słonczewski, J. Current-driven excitation of magnetic multilayers. J. Magn. Magn. Mater. 159, L1–L7 (1996).

16. Wohlfarth E. P. Ferromagnetic Materials (North-Holland Publ. Co., 1980).

17. Engdahl, G. & Mayergozy, I. D. Handbook of Giant Magnetostrictive Materials (Academic Press, 2000).

18. Duenas, T. A. & Carman, G. P. Large magnetostrictive response of Terfenol-D resin composites. J. Appl. Phys. 87, 4696–4701 (2000).

19. Mnuyk, Y. The true cause of magnetostriction. Am. J. Condens. Matter Phys. 4, 57–62 (2014).

20. Valenzuela, S. O. & Tinkham, M. Direct electronic measurement of the spin Hall effect. Nature 442, 176–179 (2006).

21. Shim, H. et al. Magnetostrictive performance of electrodeposited Tb,Dy1–xFex thin film with microcantilever structure. Micromachines 11, 523 (2020).

22. Arisawa, H. et al. Magnetomechanical sensing based on delta-E effect in Y3Fe5O12 micro bridge. Appl. Phys. Lett. 114, 122402 (2019).

23. Hoffmann, A. Spin Hall effects in metals. IEEE Trans. Magn. 49, 5172–5193 (2013).

24. Pai, C. F. et al. Spin transfer torque devices utilizing the giant spin Hall effect of tungsten. Appl. Phys. Lett. 101, 122404 (2012).

25. Xiao, J., Bauer, G. E. W., Uchida, K., Saitoh, E. & Maekawa, S. Theory of magnon-driven spin Seebeck effect. Phys. Rev. B 81, 214418 (2010).

26. Ishibashi, Y. & Iwata, M. A theory of morphotropic phase boundary in solid-solution systems of perovskite-type oxide ferroelectrics. Jpn. J. Appl. Phys. 38, 800–804 (1999).

27. Uchida, K. et al. Thermal spin pumping and magnon-phonon-mediated spin-Seebeck effect. J. Appl. Phys. 113, 103903 (2012).

28. An, H., Kageyama, Y., Kanno, Y., Inuiishi, N. & Ando, K. Spin-torque generator engineered by natural oxidation of Cu. Nat. Commun. 7, 13069 (2016).

29. Okano, G., Matsuo, M., Ohnuma, Y., Maekawa, S. & Nozaki, Y. Nonreciprocal spin current generation in surface-oxidized copper films. Phys. Rev. Lett. 122, 217701 (2019).

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Author contributions
H.A. and H.S. contributed equally to this work. E.S. supervised the study. H.S. and T.O. prepared samples. H.A. carried out the experiments and analyzed the data with help from S.D., T.K., and Y.O. H.A. formulated the theoretical model with help from S.T. H.A. and E.S. prepared the manuscript. All the authors discussed the results and commented on the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
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