Towards coherent spin precession in pure-spin current

Hiroshi Idzuchi1,2, Yasuhiro Fukuma2,3 & YoshiChika Otani1,2

1Institute for Solid State Physics, University of Tokyo, Kashiwa 277-8581, Japan, 2Advanced Science Institute, RIKEN, 2-1, Wako 351-0198, Japan, 3Frontier Research Academy for Young Researchers, Kyushu Institute of Technology, Iizuka 820-8502, Japan.

Non-local spin injection in lateral spin valves generates a pure spin current which is a diffusive flow of spins (i.e. spin angular momentums) with no net charge flow. The diffusive spins lose phase coherency in precession while undergoing frequent collisions and these events lead to a broad distribution of the dwell time in a transport channel between the injector and the detector. Here we show the lateral spin-valves with dual injectors enable us to detect a genuine in-plane precession signal from the Hanle effect, demonstrating the phase coherency in the in-plane precession is improved with an increase of the channel length. The coherency in the spin precession shows a universal behavior as a function of the normalized separation between the injector and the detector in material-independent fashion for metals and semiconductors including graphene.

Results
Enhanced spin accumulation in lateral spin valves with dual injectors. A conventional LSV consists of a pair of injector and detector ferromagnetic wires which are bridged by a nonmagnetic wire. The spins are injected by applying a bias voltage across the ferromagnetic/nonmagnetic interface and accumulate in its vicinity. Their density decays exponentially with a factor of \( \exp(-d/\lambda_s) \) where \( d \) is the distance from the injector and \( \lambda_s \) is the spin diffusion length. Unlike the above LSV, our structure shown in Fig. 1a consists of three Fe80Ni20 (Permalloy) wires bridged by a Ag wire. The current \( I \) is applied between FM1 and FM2 for the spin injection into the Ag wire, and the spin accumulation is detected in voltage \( V \) by using FM3. To avoid the spin absorption by FM wires, we use the Permalloy/MgO/Ag junction in the present study22,23. For comparison between conventional and our schemes, we diffusion is a transport process driven by gradients in the concentration of particles in random motion with undergoing collisions such as molecules in water, disorder in crystals, and electrons and holes in a semiconductor1. Recent advance in nano-scale fabrication technology has opened up a possibility for studying such a diffusive transport of accumulated spins in a nonmagnet by means of nonlocal spin injection2-5. The mean free path for consecutive spin flip events is called “spin diffusion length”, and is much longer than that of electrons' collision2. Therefore, the diffusive transport of spins, i.e., the pure spin current, provides not only a variety of scientific interests but also an additional data transfer functionality for future spintronic device applications3,4.

Hanle effect measurement is one of the most effective methods to characterize dynamic properties of the pure spin current9,10. When the magnetic field is applied perpendicular to the spin orientation, a collective spin precession is induced by its torque. In ballistic spin transport, spins can coherently rotate at a frequency proportional to the applied magnetic field. This allows us to control the direction of the spins in the channel and to manipulate the output signal of lateral spin valves (LSVs) by adjusting an effective external parameter such as the Rashba field tunable via a gate voltage11. This scheme realizes an active spin device such as the spin-transistor12. However, in a diffusive pure spin current in nonmagnets, the distributed transit times for individual spins cause the dephasing in the spin precession, and decreases drastically the spin accumulation in the Hanle effect measurement13-22. In this study, we employ dual spin injectors for LSVs to study coherency in the collective precession of the diffusive spins, which enhance the spin accumulation in the channel and also suppress the out of plane contribution to the Hanle effect signals due to the magnetization process of the ferromagnetic electrodes. Thereby we can detect a genuine in-plane precession signal in a 10 \( \mu \)m-long Ag wire which is much longer than its spin diffusion length. The coherent characteristics are investigated by the spin precession signal, revealing that the dwell time distribution narrows as the spins diffuse longer distance in the channel between the injector and the detector of LSVs.

Hanle effect measurement is one of the most effective methods to characterize dynamic properties of the pure spin current9,10. When the magnetic field is applied perpendicular to the spin orientation, a collective spin precession is induced by its torque. In ballistic spin transport, spins can coherently rotate at a frequency proportional to the applied magnetic field. This allows us to control the direction of the spins in the channel and to manipulate the output signal of lateral spin valves (LSVs) by adjusting an effective external parameter such as the Rashba field tunable via a gate voltage11. This scheme realizes an active spin device such as the spin-transistor12. However, in a diffusive pure spin current in nonmagnets, the distributed transit times for individual spins cause the dephasing in the spin precession, and decreases drastically the spin accumulation in the Hanle effect measurement13-22. In this study, we employ dual spin injectors for LSVs to study coherency in the collective precession of the diffusive spins, which enhance the spin accumulation in the channel and also suppress the out of plane contribution to the Hanle effect signals due to the magnetization process of the ferromagnetic electrodes. Thereby we can detect a genuine in-plane precession signal in a 10 \( \mu \)m-long Ag wire which is much longer than its spin diffusion length. The coherent characteristics are investigated by the spin precession signal, revealing that the dwell time distribution narrows as the spins diffuse longer distance in the channel between the injector and the detector of LSVs.
The Permalloy wires are 140 nm in width and 20 nm in thickness. The Ag wire is 120 nm in width and 100 nm in thickness.

The center-to-center separation between FM1 and FM2 is 350 nm. (b) Schematic diagram of LSV with single injector and the spatial variation of spin accumulation $\delta \mu$ for Ag. Arrows in Ag and FM respectively represent the non-equilibrium magnetization of Ag and the magnetization of FM. The spin current $I_S = I_1 - I_2$ flows in both directions along the Ag wire. The magnitude of $I_S$ is proportional to the spatial gradient of $\delta \mu_{Ag}$ (c). (d) Schematic diagram of LSV with dual injectors with parallel or anti-parallel configuration and the spatial variation of spin accumulation $\delta \mu$ for Ag. The red and blue lines respectively show $\delta \mu_{Ag}$ induced by spin injectors of FM1 and FM2. In parallel configuration, the flow direction of spin current from FM2 $I_{S2}$ is opposite to that of FM1 $I_{S1}$. In anti-parallel configuration, the flow direction of $I_{S1}$ is the same as that of $I_{S2}$.

The analytical expression of $\Delta R_S$ for DLSV, for the case where the interface resistance is enough higher than the spin resistance of the nonmagnetic wire $R_N$, is approximated by using a solution of one-dimensional spin diffusion equation (see Supplementary Information for details). 

$$\Delta R_S = zP_1^2R_N e^{-L/\lambda_N},$$ (1)

where $z = 1 + \exp(-2d_{12}/\lambda_N) + 2\exp(-d_{12}/\lambda_N)$ is the enhancement factor, $P_1$ is interfacial polarization, $\lambda_N$ is the spin diffusion length of the nonmagnet and $d_{12}$ is the separation between FM1 and FM2. The $\Delta R_S$ for DLSV is remarkably enhanced by a factor of $z$ compared to that of SLSV, corresponding to the reduced equation (1) of $\Delta R_S$ for SLSV$^{26}$ with $d_{12} \gg \lambda_N$. The first and second terms in $z$ represent the spin current injected from FM2 and the third term does the spin current injected from FM1. The obtained experimental results in Fig. 2c were fitted to equation (1) with adjusting parameters $P_1$ and $\lambda_N$, yielding $P_1 = 0.36$, $\lambda_N = 1500$ nm and $z = 3.2$. Note that the obtained values of $P_1$ and $\lambda_N$ are consistent with our previous data for SLSV with Permalloy/MgO/Ag junctions$^{26}$ and $z$ is decreased due to the spin relaxation in the channel between the two injectors.

Experimental observation of genuine spin precession signal. The Hanle effect measurements were performed on LSVs by applying perpendicular magnetic fields. Figure 3a shows the modulated non-local spin signal for SLSV and DLSV. A parabolic background signal is observed for the SLSV, the origin of which is the magnetization process of FMs. When the applied magnetic field is increased above the demagnetizing field of the FM wires, the magnetizations for the injector and the detector are tilted up along
the field direction, pushing the background signal up towards the value of parallel configuration for FMs. To describe the both contributions of spin precession and magnetization process, we decompose them into that of spin precession in x-y plane and that of the z component reflecting the magnetization process. The non-local spin signal $V/I$ in the presence of $B_z$ is thus given by the sum of the above two contributions:

$$V = R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}) + R_{S}^{\text{single}}(0, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}),$$

with $R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z})$ represents the nonlocal resistance at the precessional frequency $\omega_{s}$, and $R_{S}^{\text{single}}(0, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z})$ does that without spin precession (see Supplementary Information for details).

For SLVs, we obtain $P_{1} = 0.37$ and $\lambda_{\text{av}} = 1420 \text{ nm}$ by fitting equation (2) to the experimental data as shown in Fig. 3a, which are consistent with those obtained alternatively from the $L$ dependence of $\Delta R_{S}$ in the previous section. For DLVs, the z component of the injectors is canceled out because of the opposite direction of the applied current to the junctions as depicted in Fig. 3b. This allows us to detect the genuine precession signal in Fig. 3a.

### Towards coherent spin precession.

In the diffusive pure-spin transport, the collective spin precession decoheres due to broadening of the dwell time distribution in the channel between the injector and the detector$^{30}$. The amplitude of the spin valve signal at $B_{z} = 0$ decreases after the $\pi$ rotation at $B_{x} = 0.16 \text{ T}$, as can be seen in Fig. 3a. In order to better quantify the coherence in the collective spin precession, we define the figure of merit as the ratio $\Delta R_{S}^{x}/\Delta R_{S}^{y}$, where $\Delta R_{S}^{x}$ and $\Delta R_{S}^{y}$ are respectively the amplitude of the spin valve signal right after the $\pi$ rotation and that in zero field right before the rotation begins. The $\Delta R_{S}^{x}/\Delta R_{S}^{y}$ increases with increasing $L$, and the experimental trend is well reproduced by equation (2) as shown in Fig. 3c. To understand the observed trend in more detail, we employ the one-dimensional diffusion model which gives the $y$-component reflecting the magnetization process.

$$<S_{y}> \propto \frac{1}{\sqrt{4\pi D_{N}^{y}}} \exp \left(-\frac{L^{2}}{4D_{N}^{y}} t \right),$$

where $D_{N}^{y}$ is utilized to suppress the distributed transit time of the spins and the channel length becomes longer, of which evolution is depicted in Fig. 3c. To understand the observed trend in more detail, we employ the one-dimensional diffusion model which gives the $y$-component reflecting the magnetization process. The non-local spin signal $V/I$ in the presence of $B_{z}$ is thus given by the sum of the above two contributions:

$$V = R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}) + R_{S}^{\text{single}}(0, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}),$$

with

$$R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}) = \frac{1}{2} P_{1} R_{0} \Re[\epsilon_{s}(\lambda_{av}/\lambda_{S}) \exp(-L/\lambda_{av})],$$

where $\omega_{s} = \alpha^{\text{FM1}}/\alpha^{\text{FM2}}(1 + \exp(-2d_{1}/\lambda_{S})) - 2\epsilon^{\text{FM1}}/\epsilon^{\text{FM2}} \exp(-d_{1}/\lambda_{S})$. The non-local spin signal $V/I$ in the presence of $B_{z}$ is thus given by the sum of the above two contributions:

$$V = R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}) + R_{S}^{\text{single}}(0, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}),$$

with

$$R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}) = \frac{1}{2} P_{1} R_{0} \Re[\epsilon_{s}(\lambda_{av}/\lambda_{S}) \exp(-L/\lambda_{av})],$$

where $\omega_{s} = \alpha^{\text{FM1}}/\alpha^{\text{FM2}}(1 + \exp(-2d_{1}/\lambda_{S})) - 2\epsilon^{\text{FM1}}/\epsilon^{\text{FM2}} \exp(-d_{1}/\lambda_{S})$. The non-local spin signal $V/I$ in the presence of $B_{z}$ is thus given by the sum of the above two contributions:

$$V = R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}) + R_{S}^{\text{single}}(0, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}),$$

with

$$R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}) = \frac{1}{2} P_{1} R_{0} \Re[\epsilon_{s}(\lambda_{av}/\lambda_{S}) \exp(-L/\lambda_{av})],$$

where $\omega_{s} = \alpha^{\text{FM1}}/\alpha^{\text{FM2}}(1 + \exp(-2d_{1}/\lambda_{S})) - 2\epsilon^{\text{FM1}}/\epsilon^{\text{FM2}} \exp(-d_{1}/\lambda_{S})$. The non-local spin signal $V/I$ in the presence of $B_{z}$ is thus given by the sum of the above two contributions:

$$V = R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}) + R_{S}^{\text{single}}(0, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}),$$

with

$$R_{S}^{\text{dual}}(\omega_{s}, e^{\text{FM1}}e_{z}, e^{\text{FM2}}e_{z}, \epsilon^{\text{FM3}}e_{z}) = \frac{1}{2} P_{1} R_{0} \Re[\epsilon_{s}(\lambda_{av}/\lambda_{S}) \exp(-L/\lambda_{av})].$$

## Discussion

To better understand the coherence in collective spin precession for the pure-spin current, $t = t_{\pi}T$ is substituted into the distribution function at $B_{z} = 0$. We then obtain $<S_{y}> \propto \frac{1}{\sqrt{T}} \exp \left(-L(2\lambda_{S})^{2}/T - T \right)$, where $T$ is dimensionless time. This implies that the distribution of the dwell time, i.e., coherence, is characterized only by $L/\lambda_{S}$ and more importantly it does not depend on the kind of materials as long as their transport is diffusive. To check this idea the $L/\lambda_{S}$ dependence of $\Delta R_{S}^{x}/\Delta R_{S}^{y}$ are summarized by using the data so far reported for metals, semiconductors and graphene in Fig. 4. Interestingly the relation between the coherence and the normalized $L/\lambda_{S}$ dependence of $\Delta R_{S}^{x}/\Delta R_{S}^{y}$ are summarized by using the data so far reported for metals, semiconductors and graphene in Fig. 4. Interestingly the relation between the coherence and the normalized $L/\lambda_{S}$ dependence of $\Delta R_{S}^{x}/\Delta R_{S}^{y}$ are summarized by using the data so far reported for metals, semiconductors and graphene in Fig. 4. Interestingly the relation between the coherence and the normalized $L/\lambda_{S}$ dependence of $\Delta R_{S}^{x}/\Delta R_{S}^{y}$ are summarized by using the data so far reported for metals, semiconductors and graphene in Fig. 4.
magnetizations of injectors and non-equilibrium magnetization field for single and dual injector LSVs with effective length are well reproduced by \( \text{equation (2)} \). We shall note here that the parameters as used in (a). Data are corrected by taking account of the influence of magnetization process. (d)–(f), Density of coherent parameter of the spin precession during the diffusive transport in the channel. Therefore, the high spin injection efficiency of the Permalloy/MgO/Ag junction and the confinement effect in the DLSV structure could offer advantages for realizing giant spin accumulation as well as coherent spin precession along a 10 \( \mu \text{m} \)-long Ag wire which is much longer than the spin diffusion length.

For spintronic devices using such a long-diffusion spin current, fast spin transport may be critical. The high coherence of the spin precession over \( \Delta R_S^0/\Delta R_S^0 = 0.4 \) is reported for Al and graphene as can be seen in Fig. 4, however, the diffusion constant of the pure spin current is 0.003 \( \text{m}^2/\text{s} \) and 0.01 \( \text{m}^2/\text{s} \), respectively, which is much slower than that of Ag (0.047 \( \text{m}^2/\text{s} \)). Therefore, the experimental results in this study could be useful in developing a new class of spintronic devices and the material-independent perspective for the spin precession will be beneficial for us to design pure-spin-current-based memory and logic devices by using a variety of metallic and semi-conductive materials including graphene.

**Methods**

Lateral spin valves with Permalloy/MgO/Ag junctions are prepared on a Si/SiO\(_2\) substrate by means of shadow evaporation using a suspended resist mask which is patterned by e-beam lithography. All the layers are e-beam deposited in an ultra-high vacuum condition of about 10\(^{-8}\) Pa. First, 20-nm-thick Permalloy layer is obliquely deposited at a tilting angle of 45\(^\circ\) from substrate normal. Second, the interface MgO layer is deposited normal to the Si substrate. Finally, 3-nm-thick capping MgO layer is deposited to prevent surface contamination of the devices. After the liftoff process, the devices are annealed at 400 \( ^\circ\)C for 40 min in an \( \text{N}_2 \) (97%) + \( \text{H}_2 \) (3%) atmosphere\(^{28}\).

The non-local measurements are carried out by a dc current source and nanovoltmeter. The bias current in the range between 200 and 400 \( \mu \text{A} \) is applied to the injector. The magnetic field is applied parallel to the Permalloy wires for the spin valve measurements. The switching field of Permalloy wires is controlled not only by changing the width but also by attaching a large domain wall reservoir at the edge. For the Hanle effect measurements, the magnetic field is applied perpendicular to the Si.
1. Jost, W. *Diffusion in solids, liquids, gases* (Academic Press, 1960).
2. Johnson, M. & Silsbee, R. H. Interfacial charge-spin coupling: injection and detection of spin magnetization in metals. *Phys. Rev. Lett.* 55, 1790–1793 (1985).
3. Johnson, M. & Silsbee, R. H. Thermodynamic analysis of interfacial transport and of the thermomagnetoelectric system. *Phys. Rev. B* 35, 4959–4972 (1987).
4. Van Son, P. C., van Kempen, H. & Wyder, P. Boundary resistance of ferromagnetic-nonferromagnetic metal interface. *Phys. Rev. Lett.* 58, 2271–2273 (1987).
5. Jedema, F. J., Filip, A. T. & van Wees, B. J. Electrical spin injection and accumulation at room temperature in an all-metal mesoscopic spin valve. *Nature* 410, 345–348 (2001).
6. Baas, J. & Pratt Jr, W. P. Spin-diffusion lengths in metals and alloys, and spin-flipping at metal/metal interfaces: an experimentalist’s critical review. *J. Phys.: Condens. Matter.* 19, 183201 (2007).
7. Žutić, I., Fabian, J., & Sarma, S. D. Spintronics: fundamentals and applications. *Rev. Mod. Phys.* 76, 323–410 (2004).
8. Chappert, C., Fert, A. & Van Dau, F. N. The emergence of spin electronics in data storage. *Nature Mater.* 6, 813–823 (2007).
9. Johnson, M. & Silsbee, R. H. Coupling of electronic charge and spin at a ferromagnetic-paramagnetic metal interface. *Phys. Rev. B* 37, 5312–5325 (1988).
10. Jedema, F. J., Heersche, H. B., Filip, A. T., Baselmans, J. J. A. & van Wees, B. J. Electrical detection of spin precession in a metallic mesoscopic spin valve. *Nature* 416, 713–716 (2002).
11. Bychkov, Y. A. & Rashba, E. I. ‘Oscillatory effects and the magnetic susceptibility of carriers in inversion layers.’ *J. Phys. C: Solid State Phys.* 17, 6039 (1984).
12. Datta, S. & Das, B. Electronic analog of the electro-optic modulator. *Appl. Phys. Lett.* 56, 665–667 (1990).
13. Valenzuela, S. O. & Tinkham, M. Direct electronic measurement of the spin Hall effect. *Nature* 442, 176–179 (2006).
14. Van Staai, A., Wudhorst, J., Vogel, A., Merkt, U. & Meier, G. Spin precession in lateral all-metal spin valves: Experimental observation and theoretical description. *Phys. Rev. B* 77, 214416 (2008).
15. Lou, X. et al. Electrical detection of spin transport in lateral ferromagnet-semiconductor devices. *Nature Phys.* 3, 197–202 (2007).
16. Vant Erve, O. M. J. et al. Information Processing With Pure Spin Currents in Silicon: Spin Injection, Extraction, Manipulation, and Detection. *IEEE Trans. Electron Devices* 56, 2343–2347 (2009).
17. Sasaki, T. et al. Temperature dependence of spin diffusion length in silicon by Hanle-type spin precession. *Appl. Phys. Lett.* 96, 122101 (2010).
18. Tombros, N., Józsa, C., Popinciuc, M., Jonkman, H. T. & Van Wees, B. J. Electronic spin transport and spin precession in single graphene layers at room temperature. *Nature* 448, 571–574 (2007).
19. Popinciuc, M. et al. Electronic spin transport in graphene field-effect transistors. *Phys. Rev. B* 80, 214427 (2009).
20. Maassen, T., Dejene, F. K., Guimarães, M. H., Józsa, C. & Van Wees, B. J. Comparison between charge and spin transport in few-layer graphene. *Phys. Rev. B* 83, 115410 (2011).
21. Han, W. et al. Tunneling spin injection into single layer graphene. *Phys. Rev. Lett.* 105, 167202 (2010).
22. Fukuma, Y. et al. Giant enhancement of spin accumulation and long-distance spin precession in metallic lateral spin valves. *Nature Mater.* 10, 527–531 (2011).
23. Fukuma, Y., Wang, L., Iizuki, H. & Otani, Y. Enhanced spin accumulation obtained by inserting low-resistance MgO interface in metallic lateral spin valves. *Appl. Phys. Lett.* 97, 012507 (2010).
24. Elliott, R. J. Theory of the effect of spin-orbit coupling on magnetic resonance in some semiconductors. *Phys. Rev.* 96, 266–279 (1954).
25. Yafet, Y. g Factors and Spin-Lattice Relaxation of Conduction Electrons: Solid State Physics. pp. 1–98 (Academic, New York, 1963).
26. Takahashi, S. & Maekawa, S. Spin injection and detection in magnetic nanostructures. *Phys. Rev. B* 67, 052409 (2003).
27. Huang, B., Monsma, D. J. & Appelbaum, I. Coherent spin transport through a 350 micron thick silicon wafer. *Phys. Rev. Lett.* 99, 177209 (2007).
28. Wang, L. et al. Effect of annealing on interfacial spin polarization and resistance in Permalloy/MgO/Ag lateral spin valves. *Appl. Phys. Express.* 4, 093004 (2011).

**Acknowledgements**

This work is partly supported by Grant-in-Aid for Scientific Research (A) (No. 23244071) and Young Science Aid (A) (No. 23681032) from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

**Author contributions**

H. I. and Y. F. designed the experiments, fabricated devices and performed analysis. Y. O. supervised the project. All authors discussed the results and commented on the manuscript.

**Additional information**

Supplementary information accompanies this paper at http://www.nature.com/scientificreports/

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

License: This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivative Works 3.0 Unported License. To view a copy of this license, visit http://creativecommons.org/licenses/by-nc-nd/3.0/

**How to cite this article:** Iizuki, H., Fukuma, Y. & Otani, Y. Towards coherent spin precession in pure-spin current. *Sci. Rep.* 2, 628; DOI:10.1038/srep00628 (2012).