Spin Hall voltages from a.c. and d.c. spin currents

Dahai Wei¹, Martin Obstbaum¹,*, Mirko Ribow¹,², Christian H. Back¹ & Georg Woltersdorf¹,²

In spin electronics, the spin degree of freedom is used to transmit and store information. To this end the ability to create pure spin currents—that is, without net charge transfer—is essential. When the magnetization vector in a ferromagnet–normal metal junction is excited, the spin pumping effect leads to the injection of pure spin currents into the normal metal. The polarization of this spin current is time-dependent and contains a very small d.c. component. Here we show that the large a.c. component of the spin currents can be detected efficiently using the inverse spin Hall effect. The observed a.c.-inverse spin Hall voltages are one order of magnitude larger than the conventional d.c.-inverse spin Hall voltages measured on the same device. Our results demonstrate that ferromagnet–normal metal junctions are efficient sources of pure spin currents in the gigahertz frequency range.

¹ Institut für Experimentelle und Angewandte Physik, Universität Regensburg, Universitätsstraße 31, 93053 Regensburg, Germany. ² Institut für Physik, Martin-Luther-Universität Halle, von-Danneckelmann-Platz 3, 06120 Halle, Germany. * These authors contributed equally to this work. Correspondence and requests for materials should be addressed to G.W. (email: georg.woltersdorf@physik.uni-halle.de).
or spin electronic technology, the ability to create pure spin currents—that is, without net charge transfer—is essential. Spin pumping is the most popular approach to generate pure spin currents in metals\(^1\)–\(^3\), semiconductors\(^4\)–\(^7\), graphene\(^8\) and even organic materials\(^9\). When the magnetization vector in a ferromagnet (FM)–normal metal (NM) junction is excited at ferromagnetic resonance (FMR), spin pumping leads to the injection of pure spin currents in the NM. The polarization of this spin current is time-dependent\(^1\) and contains a very small d.c. component\(^10\), as illustrated in Fig. 1. Spin torque corresponding to this spin current is time-dependent\(^1\) and contains a very small d.c. component\(^10\), as illustrated in Fig. 1. Spin torque corresponding to the a.c. component has been observed by light scattering\(^11\). Recently, also d.c. voltage signals in ferromagnetic insulator/ferromagnetic conductor bilayers have been interpreted as spin rectification in the ferromagnetic conductor material\(^12\). These experiments provide strong evidence for the presence of a large a.c. component of the spin current generated by spin pumping. The d.c. component of the injected spin current has been intensely studied in recent years and given rise to controversial discussions concerning the magnitude of the spin Hall angle, which is a material-dependent measure of the efficiency of spin-to-charge current conversion\(^13\)–\(^16\). However, in contrast to the rather well-understood d.c. component\(^4\)–\(^5\),\(^17\) the two orders of magnitude larger a.c. component has escaped experimental detection so far\(^18\).

The time dependence of the polarization of a spin current injected by spin pumping is related to the dynamics of the magnetization vector \(\mathbf{m}\) and given by \(\sigma \sim \mathbf{m} \times \mathbf{dm}/dt\) (ref. 1) as illustrated in Fig. 1. The absorption of a spin current in a nonmagnetic metal with a finite spin Hall effect leads to an electric field \(\mathbf{E}\) and is referred to as the inverse spin Hall effect (ISHE). The voltage \(U_{\text{ISHE}}\) transverse to the spin current \(\mathbf{J}_S\) and spin polarization \(\sigma\) is:

\[
U_{\text{ISHE}} \sim \mathbf{E} \sim \mathbf{J}_S \times \sigma. \tag{1}
\]

Therefore, the d.c. and a.c.-ISHE voltage components may be measured as shown in Fig. 1.

In the following, we demonstrate experimentally the presence of a large a.c. component in the ISHE voltage signal in NM/FM bilayers, where the a.c. spin current is generated by spin pumping at FMR. The magnitude of the a.c.-ISHE signal is measured as a function of frequency, angle and power. In addition, the d.c.- and a.c.-ISHE signals are measured in the same device in order to compare their relative amplitudes. The spectral shape, angular dependence, power scaling behaviour and absolute magnitude of the signals are in line with spin pumping and ISHE effects. Our results demonstrate that FM–NM junctions are very efficient sources of pure spin currents in the GHz frequency range and we believe that our result will stimulate the development of a.c. spintronics\(^18\)–\(^19\).

### Results

#### Experimental setup

The experimental configuration is shown in Fig. 2a, the NM–FM bilayer stripes are either integrated on top of the signal line or in the gap between the signal and ground lines of a grounded coplanar waveguide (CPW). In these two configurations, the magnetization in the FM is excited by an in-plane and out-of-plane microwave magnetic field \(\mathbf{h}_{\parallel}\) respectively. The difficulty to detect the a.c.-ISHE signal lies in the ability to measure sub-mV GHz signals and isolate them from a large background signal caused by the excitation of FMR at the same frequency. As sketched in Fig. 2a, the microwave signal is transmitted from terminal 1 to terminal 2, where FMR can be measured inductively. In order to measure a.c.-ISHE signals, the NM–FM stripe is connected to a 50-Ω waveguide (terminal 3). In addition, the sample structure was designed as a transmission line (as microstrip for in-plane excitation and as CPW for out-of-plane excitation) such that the a.c.-ISHE voltage signal can propagate along the NM–FM stripe. The microwave signal isolation from terminal 1 to terminal 3 is only about 10 dB and is frequency-dependent (as shown in Supplementary Fig. 1) leading to a large crosstalk a.c. signal amplitude on terminal 3. This signal is 2 orders of magnitude larger than the expected a.c.-ISHE signal. In order to suppress the background signal, an additional reference signal is added in a power combiner where amplitude and phase can be adjusted to almost fully compensate the crosstalk signal. The expected ISHE signal has a magnitude in the mV range allowing for detection by a power meter (detection scheme 1) or by a rectifying diode and a lock-in amplifier (detection scheme 2). For lock-in detection the static magnetic field is modulated with an amplitude of 0.5 mT. The lock-in signal is converted into the a.c. voltage amplitude at terminal 3 using field integration and the power to voltage conversion characteristics of the Schottky detector.

#### Dynamic properties

First the dynamic properties of the bilayer devices are studied by frequency-dependent FMR measurements. For these measurements, in-plane excitation is used and the magnetic field is applied along the x axis (\(\phi_H = 90°\)). The results are summarized in Fig. 2b where a typical FMR spectrum obtained at a microwave frequency of 8 GHz is shown as the upper left inset. The resonance field \(H_r\) and line width \(\Delta H\) are extracted from the spectra as a function of frequency. The frequency dependence of \(H_r\) can be well reproduced by a Kittel fit with effective magnetization \(\mu_0M_{\text{eff}} = 0.9\, \text{T}\). \(\Delta H\) is strictly proportional to the microwave frequency, and the Gilbert damping constant determined from the slope of \(\Delta H(f)\) is \(\alpha = 0.016\), which is enhanced compared with \(\alpha = 0.008\) obtained for a reference Ni$_{80}$Fe$_{20}$ layer, because of spin pumping\(^1\). Typical signals of the a.c.-ISHE \(U_{\text{ISHE}}\) measured at \(\phi_H = 90°\) on a Pt/Ni$_{80}$Fe$_{20}$ stripe at 8 GHz using in-plane excitation are shown in Fig. 2c. The top spectrum (red line) is the amplitude of the a.c. voltage along the Ni$_{80}$Fe$_{20}$/Pt stripe measured directly with a microwave power meter (detection scheme 1), as outlined in Fig. 2a. At the resonance field, a step-like feature with an amplitude of 1 mV is observed. This signal is attributed to the a.c.-ISHE. The bottom spectrum (blue line) is the a.c.-ISHE signal measured by field modulation and lock-in amplification.
The sum of the superposition of two a.c. signals. A numerical simulation of the line shape of these spectra can be well explained by an antisymmetric signal depending on the microwave frequency. This spectrum was converted into the detection scheme 2. The shapes of the resonance in ISHE at 6 GHz. The measured a.c.-ISHE signals are symmetric under magnetic field reversal as expected from the symmetry of the susceptibility (cf. Fig. 3a Supplementary Fig. 3, and Supplementary Note 1).

Angular dependence. The angular dependence of $U_{\text{ISHE}}^{\text{ac}}$ measured at 6 GHz is shown in Fig. 3c,d. For this experiment, out-of-plane excitation is used and a rotatable magnetic field $H$ is applied in the $x$-$y$ plane; thus, the magnetic excitation and the spin pumping process do not depend on the in-plane field angle $\phi_H$. The spectra for $\phi_H$ between 90° and $90^°$ (from top to bottom) are shown in Fig. 3c. The spectrum at $\phi_H = 90^°$ ($H$ applied along the stripe) shows a symmetric line shape, and its intensity decreases monotonically to zero when $\phi_H$ is $90^°$ ($H$ perpendicular to the stripe); for even smaller angles the signal reverses. The amplitude of $U_{\text{ISHE}}^{\text{ac}}$ as a function of $\phi_H$ is shown in Fig. 3d and can be well fitted to a sine function, as expected from Equation 1. At $\phi_H = 0^°$, since the a.c. spin current polarization $\sigma$ is rotating in the $x$-$z$ plane, the a.c.-ISHE voltage is generated along the $y$ direction, leading to a vanishing voltage along the $x$ direction (along the stripe). For the in-plane excitation, the measured a.c.-ISHE signals are symmetric under magnetic field reversal as expected from the symmetry of the susceptibility (cf. Fig. 3a Supplementary Fig. 3, and Supplementary Note 1).

Signal amplitude. In the following, we compare the amplitudes of the d.c.- and a.c.-ISHE signals. For the d.c.-ISHE measurements the voltage is measured by connecting a nanovoltmeter to terminal 3 of the sample. In Fig. 4a, the top (red) and bottom
This behaviour is perfectly reproduced in our experiment as shown in Fig. 3a: the microwave power \( P \) for the d.c.-ISHE is approximately three times larger at the sample. One expects \( U_{\text{dc}-\text{ISHE}} \) to scale linearly with the microwave power \( P \), while for a.c.-ISHE a scaling behaviour with \( P^{1/2} \) is expected (cf. Equation 2). This behaviour is perfectly reproduced in our experiment as shown in Fig. 3b. Furthermore, the expected ratio of the amplitudes of the a.c.- and d.c.-ISHE voltages is given by (see Supplementary Note 1)

\[
\frac{U_{\text{ac}-\text{ISHE}}}{U_{\text{dc}-\text{ISHE}}} = \frac{M_S}{\sqrt{\gamma_{zz} h_z}}.
\]

This ratio can be easily calculated for parameters that apply to the measurements shown in Fig. 3a: \( f = 6 \text{ GHz} \), \( H_z = 45 \text{ mT} \), using \( \mu_0 M_S = 0.9 \text{ T} \), \( \gamma_{zz} = 61.5 \) and \( \mu_0 h_z = 0.3 \text{ mT} \). Results in \( U_{\text{ac}-\text{ISHE}}/U_{\text{dc}-\text{ISHE}} = 50 \). Experimentally, we only observe \( U_{\text{ac}-\text{ISHE}}/U_{\text{dc}-\text{ISHE}} = 12 \); however, one needs to consider the poor transmission of the rf signal into the 50-\( \Omega \) terminal. In the case of out-of-plane excitation, the bilayer stripe in the gap of the CPW can be considered as a waveguide with a characteristic impedance of 250\( \Omega \). The resistance mismatch between this waveguide and the 50-\( \Omega \) terminal leads to a transmission of only 33% of the signal as can be calculated from the voltage standing wave ratio \( T = 1 - \frac{x_0}{x_c + x_t} \) (see Supplementary Note 2). This implies that the ratio of the amplitudes of the a.c.- and d.c.-ISHE voltages is 12 in fact three times larger at the sample.
Experimentally, we find an amplitude of 0.5 mV in excellent standing wave ratio. Therefore, the expected amplitude is 0.7 mV.

Cu/Ni$_{80}$Fe$_{20}$ and Al/Ni$_{80}$Fe$_{20}$ measured at 8 GHz. (configuration. The a.c.-ISHE voltage is same device measured at 6 GHz in the out-of-plane excitation Z

Figure 4 | Comparison of the a.c.- and d.c.-ISHE amplitude and material dependence. (a) Comparison of the a.c.- and d.c.-ISHE voltages for the same device measured at 6 GHz in the out-of-plane excitation configuration. The a.c.-ISHE voltage is ~10 times larger than the d.c. one. (b,c) Comparison of the a.c.-ISHE signals for Pt/Ni$_{80}$Fe$_{20}$, Au/Ni$_{80}$Fe$_{20}$, Cu/Ni$_{80}$Fe$_{20}$ and Al/Ni$_{80}$Fe$_{20}$ measured at 8 GHz. (b) Shows data for samples with in-plane excitation while (c) shows the corresponding measurements with out-of-plane excitation. All NM and FM layers have a thickness of 10 nm. Only for NM = Cu the NM layer is 20 nm.

Using published values for the spin Hall angle $\lambda_{SH} = 0.12$ (refs 22,23) and $\lambda_{sd} = 1.4$ nm$^{22,24}$, the ISHE voltages at resonance (6 GHz) can be calculated as $U_{\text{ISHE}}^{ac} = 0.4$ mV and $U_{\text{ISHE}}^{dc} = 10$ $\mu$V, respectively. Note that for the sake of simplicity no backflow correction as suggested in Jiao and Bauer$^{18}$ is considered here. The observed $U_{\text{ISHE}}^{ac}/U_{\text{ISHE}}^{dc}$ ratio and the absolute amplitude (cf. Fig. 4a) is in agreement with theory$^{18}$ and previous d.c.-ISHE experiments. A similar analysis can be performed with the signal amplitudes shown in Fig. 3a. For example, for FMR at 10 GHz one obtains the following parameters: $\chi_{yy}^{res} = 56.5$ (because of the in-plane excitation $\chi_{yy}^{res}$ has to be used instead of $\chi_{xx}^{res}$) and $\mu_0H_z = 0.27$ mT. From this and Equation 2, a peak-to-peak amplitude of 4.2 mV is expected. In addition, the waveguide properties of the Ni$_{80}$Fe$_{20}$/Pt stack on top of the gold waveguide need to be considered. As discussed in Supplementary Note 2, this configuration is equivalent to a microstrip with a characteristic impedance $Z_0 = 480 \Omega$. One expects a transmission of only 18% into $Z_1 = 50 \Omega$ using the voltage standing wave ratio. Therefore, the expected amplitude is 0.7 mV. Experimentally, we find an amplitude of 0.5 mV in excellent agreement with theory (see Fig. 3a).

Discussion

The measured a.c. signals may also be generated by parasitic mechanisms instead of ISHE. These are (i) inductive coupling of the magnetization with the conducting wire loop used for signal detection and (ii) anisotropic magnetoresistance (AMR). The magnitude of both of these effects will be addressed in the following.

The exclusion of an inductive signal component in the presumed ISHE signal cannot be based on angular or rf-power dependency since the amount of out-of-plane magnetic flux generated by the in-plane component of the magnetization has the same angular and power dependence as the ISHE signal$^{25}$, as illustrated in Supplementary Fig. 4. For this reason, we use a series of different conducting materials with different spin Hall angles to quantify the importance of inductive coupling in our experiments. In Fig. 4b,c we show the a.c. voltage signals generated at 8 GHz by Pt/Ni$_{80}$Fe$_{20}$, Au/Ni$_{80}$Fe$_{20}$, Cu/Ni$_{80}$Fe$_{20}$ and Al/Ni$_{80}$Fe$_{20}$ bilayers with identical thicknesses (only the NM = Cu layer has a thickness of 20 nm). The experiments are performed for both in-plane and out-of-plane configurations (cf. Fig. 2b).

The scale bar for the out-of-plane data in Fig. 4c was chosen such that the signal amplitude for the Pt/Ni$_{80}$Fe$_{20}$ measurement is equal to the in-plane case. From the fact that the signal for Au/Ni$_{80}$Fe$_{20}$ (90 $\mu$V) is about 10% of the Pt/Ni$_{80}$Fe$_{20}$ signal (648 $\mu$V) it becomes clear that the inductive contribution must be less than 10% for the Pt/Ni$_{80}$Fe$_{20}$. Further details we refer to Supplementary Note 3 and Supplementary Fig. 4. For Al and Cu, it is well accepted that the spin Hall effect is very small because of the weak spin–orbit interaction$^{26,27}$. Therefore, our conclusion is further corroborated by additional experiments on Cu/Ni$_{80}$Fe$_{20}$ and Al/Ni$_{80}$Fe$_{20}$ bilayers as shown in Fig. 4b,c where in agreement with smaller spin Hall angles in these materials a similarly low signal magnitude was found. It is also obvious that the signal amplitudes for these different samples are very reproducible even when a different excitation or coupling geometry is used as demonstrated by comparing Fig. 4b,c. Furthermore, if the NM layer thickness is doubled, the inductive signal amplitude is also doubled (cf. Supplementary Fig. 5). Samples NM = 10 nm Cu and NM = 10 nm Pt have almost identical resistances of 1.6 and 1.7 k$\Omega$, respectively. Therefore, comparing the magnitude of the a.c. voltage generated in these two samples provides the most accurate estimate of the inductive contribution. From Fig. 4c and Supplementary Fig. 5 we have $U_{\text{ISHE}}^{ac}/U_{\text{ISHE}}^{dc} = 6\mu V/108\mu V$ and one can conclude that the inductive coupling contribution is only 5% in the Pt/NiFe bilayers.

A possible AMR contribution can be determined by examining the angular dependence of the signal measured for Al/Ni$_{80}$Fe$_{20}$ (where no measurable a.c.-ISHE signal is expected). In the vicinity of $\phi_M = 90^\circ$ the precessing magnetization leads to a small $2\omega$ variation of the wire resistance because of AMR. This time-dependent resistance mixes with the inductively or capacitively coupled microwave current in the metallic bilayer stack oscillating at $\omega$. The corresponding a.c. voltage is given by $U_{\text{AMR}} = I(\omega)^*R(2\omega)$ with mixing products oscillating at $\omega$ and $3\omega$. Using a band pass filter with a pass band centred at $\omega$, only the $3\omega$ contribution can be suppressed. For the given excitation amplitude, wire resistance and AMR amplitude, the a.c.-AMR voltage at $\omega$ can be estimated to have a magnitude of less than 1 $\mu$V for the Al/NiFe sample. As derived in equation 4 of Mecking et al.$^{28}$ the dominating $2\omega$ component of the resistance follows a $\cos(2\phi_M)$ dependence and vanishes at $\phi_M = 45^\circ$. We experimentally verify the insignificance of the AMR contribution by comparing signals at $\phi_M = 90^\circ$ and $\phi_M = 45^\circ$. From Supplementary Fig. 6 one sees that the signal amplitude follows the $\cos(\phi_M)$ dependence that is consistent with inductive coupling.
The capping layer material dependence, the angular dependence, power dependence, line shape and magnitude of the signal are in line with the theory of a.c.-ISHE and strongly indicate that the a.c. signals measured for Pt/Ni$_{80}$Fe$_{20}$ bilayers are indeed a consequence of the spin currents generated by spin pumping and detected by the ISHE.

In summary, we demonstrated the presence of large a.c.-ISHE signals because of spin pumping at FMR with a.c.-ISHE signals reaching amplitudes of up to 1.5 mV. The direct comparison of the a.c.- and d.c.-ISHE voltage on the same device for out-of-plane excitation shows that $|V_{\text{ISHE}}|$ is $\sim 12$ times larger than $|V_{\text{ISHE}}|$ despite the fact that our experiment can only detect 33% of the a.c.-ISHE signal. The large a.c.-ISHE voltages indicate the presence of large rf spin currents in agreement with the theory of spin pumping. Such spin currents and their detection via ISHE may prove very useful for the development of future a.c. spintronic devices.

**Methods**

**Sample fabrication.** The bilayer stripes are prepared by electron beam lithography, magnetron sputter deposition and lift-off techniques on semi-insulating GaAs substrates. Subsequently, the CPW and the electronic contacts are fabricated by optical and electron beam lithography using gold metallization. All FM and NM layers in this manuscript have a thickness of 10 nm. Only the NM = Cu layer used for in-plane excitation in Fig. 4b has a thickness of 20 nm. A thick alumina layer (50 nm Al$_2$O$_3$) deposited by atomic layer deposition is used to insulate the NM–FM bilayer stripes and the contact electrodes from the CPW. In all experiments the stripes are 5 μm wide and 400 μm long.

**Electrical sample properties.** The electrical resistance of the NM–FM bilayer stripes is $1.6, 0.7, 0.7$ and 2.9 kΩ for Pt/Ni$_{80}$Fe$_{20}$, Au/Ni$_{80}$Fe$_{20}$, Cu/Ni$_{80}$Fe$_{20}$ and Al/Ni$_{80}$Fe$_{20}$ respectively. Note that the Cu/Ni$_{80}$Fe$_{20}$ bilayer is 20-nm thick. A 10-nm-thick Ni$_{80}$Fe$_{20}$ single layer has a resistance of 4.2 kΩ. All measurements are performed at room temperature. The input microwave power was nominally constant and fixed at 320 mW (25 dBm) for all experiments except for the measurements shown in Figure 3b.

**References**

1. Tserkovnyak, Y., Brataas, A. & Bauer, G. E. Enhanced gilbert damping in thin ferromagnetic films. Phys. Rev. Lett. 88, 117601 (2002).
2. Urban, R., Woltersdorf, G. & Heinrich, B. Gilbert damping in single and multilayer ultrathin films: role of interfaces in nonlocal spin dynamics. Phys. Rev. B 64, 024420 (2001).
3. Murakami, S., Ando, Y. & Miyazaki, T. Ferromagnetic resonance linewidth for NM/Ni$_{80}$Fe$_{20}$/NM films (NM = Cu, Ta, Pd and Pt). J. Magn. Magn. Mater. 226, 1640–1642 (2001).
4. Mosendz, O. et al. Quantifying spin hall angles from spin pumping: experiments and theory. Phys. Rev. Lett. 104, 046601 (2010).
5. Azzevedo, A. Videsco, J., Rodriguez-Suarez, R., Santos, A. L. & Rezende, S. Spin pumping and anisotropic magnetoresistance voltages in magnetic bilayers: theory and experiment. Phys. Rev. B 83, 144402 (2011).
6. Ando, K. et al. Electrically tunable spin injector free from the impedance mismatch problem. Nat. Mater. 10, 655–659 (2011).
7. Chen, L., Matsukura, F. & Ohno, H. Direct-current voltages in (Ga, Mn) As structures induced by ferromagnetic resonance. Nat. Commun. 4, 2055 (2013).
8. Tang, Z. et al. Dynamically generated pure spin current in single-layer graphene. Phys. Rev. B 87, 140401 (2013).
9. Ando, K., Watanabe, S., Moosen, S., Saitoh, E. & Siringhaus, H. Solution-processed organic spin-charge converter. Nat. Mater. 12, 622–627 (2013).
10. Brataas, A., Zarand, G., Tserkovnyak, Y. & Bauer, G. E. Magnetoelectronic spin echo. Phys. Rev. Lett. 91, 166601 (2003).
11. Woltersdorf, G., Mosendz, O., Heinrich, B. & Back, C. H. Magnetization dynamics due to pure spin currents in magnetic double layers. Phys. Rev. Lett. 99, 246603 (2007).
12. Marcham, M. K. et al. Phase-resolved X-ray ferromagnetic resonance measurements of spin pumping in spin valve structures. Phys. Rev. B 87, 180403 (2013).
13. Fohr, F. et al. Optical detection of spin transport in nonmetallic magnets. Phys. Rev. Lett. 106, 226601 (2011).
14. Hyde, P. et al. Electrical Detection of Direct and Alternating Spin Current Injected from a Ferromagnetic Insulator into a Ferromagnetic Metal. Preprint at http://arxiv.org/abs/1310.4840 (2013).
15. Morota, M. et al. Indication of intrinsic spin hall effect in 4d and 5d transition metals. Phys. Rev. B 83, 174405 (2011).
16. Liu, L. et al. Spin-torque switching with the giant spin hall effect of tantalum. Science 336, 555–558 (2012).
17. 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, 182509–182509 (2006).
18. Jiao, H. & Bauer, G. E. Spin backflow and ac voltage generation by spin pumping and the inverse spin hall effect. Phys. Rev. Lett. 110, 217602 (2013).
19. Kochan, D., Gmitra, M. & Fabian, J. Theory of the ac spin-valve effect. Phys. Rev. Lett. 107, 176604 (2011).
20. Wirthmann, A. et al. Direct phase probing and mapping via spintronic micelson interferometry. Phys. Rev. Lett. 105, 017202 (2010).
21. Costache, M., Sladkov, M., Watts, S., Van der Wal, C. & Van Wees, B. Electrical detection of spin pumping due to the precessing magnetization of a single ferromagnet. Phys. Rev. Lett. 97, 216603 (2006).
22. Obubsbaum, M. et al. Inverse spin hall effect in Ni81Fe19-normal-metal bilayers. Phys. Rev. B 89, 060407 (2014).
23. Liu, L., Mortiyama, T., Ralph, D. & Buhrman, R. Spin-torque ferromagnetic resonance induced by the spin hall effect. Phys. Rev. Lett. 106, 036601 (2011).
24. Liu, L., Buhrman, R. & Ralph, D. Review and analysis of measurements of the spin hall effect in platinum. Preprint at http://arxiv.org/abs/1111.3702 (2011).
25. Weiler, M., Nembach, H. T., Shaw, J. M. & Silva, T. J. Comment on detection of microwave spin pumping using the inverse spin hall effect. Preprint at http://arxiv.org/abs/1401.6407 (2014).
26. Valenzuela, S. O. & Tinkham, M. Direct electronic measurement of the spin hall effect. Nature 442, 176–179 (2006).
27. Niihi, Y. et al. Extrinsic spin hall effect induced by iridium impurities in copper. Phys. Rev. Lett. 105, 126601 (2011).
28. Mecking, N., Gui, Y. & Hu, C.-M. Microwave photovoltage and photoresistance effects in ferromagnetic microstrips. Phys. Rev. B 76, 224430 (2007).
29. Hahn, C. et al. Detection of microwave spin pumping using the inverse spin hall effect. Phys. Rev. Lett. 111, 217204 (2013).
30. Weiler, M., Shaw, J. M., Nembach, H. T. & Silva, T. J. Phase-sensitive detection of spin pumping via the ac inverse spin hall effect. Preprint at http://arxiv.org/abs/1401.6469 (2014).

**Acknowledgements**

We would like to acknowledge financial support from the German Research foundation (DFG) through programs SFB 689 and SPP 1538 and from the European Research Council (ERC) through starting grant no. 280048 ECOMAGICS. D.W. would like to acknowledge a stipend from the Alexander von Humboldt foundation (AvH). Spirited discussions with Dr. T. Silva and Dr. M. Weiler are gratefully acknowledged. These interactions helped us greatly to improve the reference measurements. During this work, we became aware of a parallel efforts of detecting a.c.-ISHE using parametric pumping (Hahn et al.) and phase-sensitive detection (Weiler et al.)

**Author contributions**

G.W. and C.H.B. designed and supervised the experiments. D.W., M.O. and G.W. prepared the experimental setup. D.W. and M.O. performed the experiments. The samples were prepared by M.O. and M.R. D.W. and M.O. carried out the data analysis. D.W., M.O., C.H.B. and G.W. wrote the paper. All authors analysed the data, discussed the results and commented on the manuscript.

**Additional information**

**Supplementary Information** accompanies this paper at http://www.nature.com/naturecommunications

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

**Reprints and permission** information is available online at http://npg.nature.com/reprintsandpermissions/

**How to cite this article:** Wei, D. et al. Spin Hall voltages from a.c. and d.c. spin currents. Nat. Commun. 5:3768 doi: 10.1038/ncomms4768 (2014).

This work is licensed under a Creative Commons Attribution 3.0 Unported 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/3.0/