Electromagnetic generation and detection of dc/ac spin current

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The term “spintronics” has appeared in scientific literature for almost a decade. [1] It is broadly defined to mean any electronic application where the spin degree of freedom of an electron is non-trivially utilized. [2] The word, however, suggests another narrower definition, i.e., electronics with the electron charge replaced by the electron spin. In this narrower definition, an electric current is replaced by a spin current, which means that the spin-up and -down electrons are moving in opposite directions. (The direction of a spin current is then that of the spin-up electrons. In a non-spin-polarized conductor such a spin current is not accompanied by a net charge current.) At the same time, an electromotive force (emf) is replaced by a spinomotive force (smf), which pushes spin-up and -down electrons in opposite directions with the same force magnitude. (The direction of an smf is then that of the forces acting on the spin-up electrons.) One may also define such terms as spinoresistance, and, for an ac spin current, spinocapacitance and spinoinductance, and even entertain such notions as spinotransformer, spinorectifier, spinotransistor, etc. Will this whole line of thoughts [3] be as practically useful as electronics? An important prerequisite for any yes answer is to have a convenient power source for spin current, i.e., a device to generate an smf. Recently, the idea of a “spin-cell” has been introduced, [4] which has to some extend achieved such a goal. However, in electronics, by far the most convenient way to provide an emf is through induction — i.e., via Faraday’s law, \( \nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t \). It has the additional advantage of allowing either a dc or an ac emf to be generated. One purpose of this letter is to show that there is indeed an inductive way to generate an smf, but not by Faraday’s law, but rather by its magnetic analog:

\[
\nabla \times \mathbf{H} = \partial \mathbf{D}/\partial t \left( + J_e \right),
\]

or the Ampère-Maxwell law (with the current term enclosed in brackets not important here). [5] Unfortunately, as we shall see, this process can only generate a very weak smf, although probably sufficient for some purposes. A second purpose of this letter is to show how the magnetic analog of the Biot-Savart law, or equivalently, that of Ampère’s law,

\[
\nabla \times \mathbf{E} = -\mathbf{J}_m,
\]

allows a simple electromagnetic detection of a (dc or ac) spin current, but the sensitivity is quite low, so only very large spin currents can be detected this way. Still, we think that this second idea can also have some usefulness, since observing this effect would be a solid confirmation of the existence of a spin current.

If electrons had only spin property but no charge property (like neutrons), the inductive way to generate an smf and the electromagnetic way to detect a spin current would be already contained in a paper published by the author a long time ago. [6] (That work was presented in the context of superfluid \(^3\)He-A1, so it can hardly reach the spintronics community. The magnitudes examined there were even smaller, due to the involvement of \(^3\)He nuclear magnetic moment, rather than the electronic magnetic moment involved here, and the very small superfluid fraction \(\rho_s/\rho\), because the A1 phase of superfluid \(^3\)He exists in a narrow temperature range near \(T_c\) only.) The fact that electrons also have charge property requires a modification of the idea presented there. More specifically, it is the necessity to solve the problem that an external electric field applied to a conductor is screened, and cannot reach most of the electrons in a conductor. This problem may be simply solved by fabricating a heterostructure, which is made of alternating layers of conductors and insulators, as is schematically illustrated in Fig. 1. The thicknesses of these layers do not have to be strictly uniform, and the interfaces need only be reasonably flat (just to reduce surface scattering). Each conducting layer needs only to be well connected and thinner than the screening length — hence it may be necessary to use conductors with low carrier concentrations so that the screening length can encompass several atomic layers. Each insulating layer also needs to be so thick as to prohibit tunneling between the neighboring conducting layers, but not too thick in order to allow many conducting layers to be packed into a convenient size. In this way screening can be essentially suppressed for electric field applied perpendicular to the layers. The total number of conducting layers must be such that their total thickness is macroscopic, so that the device can drive...
FIG. 1. A heterostructure made of alternating conducting (grey) and insulating (white) layers (perpendicular to the y axis) for generation and detection of spin current. The two end faces perpendicular to the x axis are coated with conducting material so that leads attached to them are connected to all conducting layers of the heterostructure.

a macroscopic spin current. Each conducting layer can be taken as a \( L_x \times L_z \) rectangular sheet, as shown in Fig. 1, where the edges of these sheets are parallel to the x and z axes. The \( x = \pm (1/2)L_x \) end faces of this heterostructure must still be coated with a thin layer of conducting material — the two \( L_y \times L_z \) rectangular conducting sheets at \( x = \pm (1/2)L_x \) in Fig. 1, so that one lead connected to one end face can send spin current into all conducting layers in the heterostructure, and another lead connected to the other end face can take spin current out of them. The leads then serve as the two terminals of this “spinovoltage generator”. [7]

To generate a dc smf \( \mathcal{E}_m \) across these two terminals, one must subject this heterostructure to a uniform constant time rate of change of electric field \( dE_y/dt \) in the y direction, i.e., perpendicular to the conducting sheets in the heterostructure. Let the spin-up(down) electron density in the conducting sheets be denoted as \( n_\uparrow \) (\( n_\downarrow \)) (defined with respect to the z axis). Then the spin-up electrons contribute a magnetization \( M_{\uparrow z} = -\mu_B n_\uparrow \) in the conducting sheets (in the z direction), and the spin-down electrons contribute a magnetization \( M_{\downarrow z} = \mu_B n_\downarrow \) in the conducting sheets, where \( \mu_B \) is the Bohr magneton.

Assuming that the electron densities are uniform in the conducting sheets, \( M_{\uparrow z} \) (\( M_{\downarrow z} \)) is equivalent to a surface magnetic-charge density \( \sigma_{\uparrow z} = M_{\uparrow z} \) (\( \sigma_{\downarrow z} = M_{\downarrow z} \)) at \( z = \pm L_z/2 \), and another surface magnetic-charge density \( -\sigma_{\uparrow z} = -M_{\uparrow z} \) (\( -\sigma_{\downarrow z} = -M_{\downarrow z} \)) at \( z = -L_z/2 \). If the system is unpolarized, these magnetic charge densities exactly cancel each other. But that does not prevent opposite magnetic charges from moving in opposite directions if they are subject to a magnetic field. This magnetic field is induced by the applied \( dE_y/dt \) according to the Ampère-Maxwell law (Eq. 1) and is

\[
H_{y \pm} = \pm \epsilon_0 (L_z/2) (dE_y/dt) \text{ at } z = \pm L_z/2 \]

where we have neglected the dielectric property of the conducting sheets. The forces acting on all magnetic charges at \( z = \pm L_z/2 \) due to spin-up (or down) electrons are then in the same direction, and have the magnitude

\[
F_{\mp y} = \pm \sigma_{n \mp}(L_x L_y) H_{y \pm} \text{ This leads to a volume force} \]

acting on all spin-up (down) electrons uniformly in \( -x \) \((+x)\) directions (if \( dE_y/dt > 0 \)), and is therefore an smf. We propose to artificially measure it in terms of the familiar unit, volt (V) which actually means to measure the potential energy gain per electron in eV. Then the smf induced in this device (in the x direction) is

\[
\mathcal{E}_m = -\epsilon_0 (\mu_B/e) L_x (dE_y/dt). \quad (3)
\]

One can also generate an ac smf this way, if one replaces the constant \( dE_y/dt \) by the time rate of change of an ac electric field in the y direction: \( E_y(t) = E_0 \cos \omega t \). Then one has

\[
\mathcal{E}_m(t) = \epsilon_0 (\mu_B/e) L_x E_0 \sin(\omega t). \quad (4)
\]

To estimate the magnitude of this ac smf, one needs to use \( \mu_B = 9.27410 \times 10^{-24} \text{J/T} \). This \( \mu_B \) must still be multiplied by the magnetic permeability of vacuum, \( \mu_0 \), before it should be used in Eq. 4, since a magnetic dipole moment \( \mu \) appears in such formulas as (energy) \( U = -\mu \cdot \mathbf{B} \) and (torque) \( \mathbf{N} = \mu \times \mathbf{B} \), which contains \( \mathbf{B} \) rather than \( \mathbf{H} \), so it does not yet have the unit of magnetic charge times length until it is multiplied by \( \mu_0 \), as a magnetic charge \( q_m \) should appear in the formula (force) \( \mathbf{F} = q_m \mathbf{H} \), with \( \mathbf{H} \) appearing rather than \( \mathbf{B} \). [8] Knowing that the effect is very weak, we insert in our estimate rather large but presumably still achievable values of \( L_x, E_0 \) and \( \omega \) viz., 10 cm, 10\(^6\) V/m, and 10\(^{12}\) Hz, just to see what is the largest possible magnitude we can obtain. We then obtain the magnitude of the induced ac smf to be about \( 6.44 \times 10^{-5} \text{ V} \). This is still very small, but probably already sufficient for some purposes. One could still connect many such devices in series in order to get a larger smf (by another factor of 10 or even 100). Thus one could conceivably generate a several-milli-volt smf through such an inductive process. Since the frequency used already corresponds to a wave length of about 2 mm, we need to limit \( L_x \) to be below about 1 mm, so that the electric field experienced by all electrons in the conducting sheets can be in phase. The length \( L_y \) has no limitations except that it should not be too big, so it can be, say, 10 cm. The heterostructure should then be in a microwave cavity designed so that the (standing) wave vector is in the z direction. (The wave vector should not be in the x direction since the so-generated smf is proportional to \( L_x \), so we need \( L_x \) to be as large as possible.) One could in principle also rotate the heterostruction in a constant electric field to get the electrons to see an ac field, but one can hardly rotate the device at \( \omega = 10^{12} \text{ Hz} \), so this alternative approach is impractical.

The design shown in Fig. 1, with slight modification, can also serve as a detector of a dc or ac spin current, but we shall see that the sensitivity is quite low, so only very large spin currents can be detected this way. One
the magnetude of the electric field generated along the
axis: 

$$E_y(0, 0, y) = \frac{\mu_B}{2\pi} \frac{\mu_B (n_\uparrow v_\uparrow - n_\downarrow v_\downarrow) t L_z/2}{(y - nd)^2 + L_z^2/4}, \quad (5)$$

where $t$ and $d$ (assumed $> t$) are the thicknesses of each conducting and insulating sheet, respectively, and $(v_\uparrow, v_\downarrow)$ denote the velocities of the spin-(up,down) electrons, respectively. We have also assumed that there are $2n_0 + 1$ conducting sheets symmetrically placed between $y = -nd$ and $y = +nd$. Since $d$ is still very small, we can approximate the above sum by an integral. It gives

$$E_y(0, 0, y) = \frac{\mu_B t (n_\uparrow v_\uparrow - n_\downarrow v_\downarrow)}{\pi d} \times \left[ \arctan \left( \frac{y + nd}{L_z/2} \right) - \arctan \left( \frac{y - nd}{L_z/2} \right) \right]. \quad (6)$$

For $e(n_\uparrow v_\uparrow - n_\downarrow v_\downarrow) = 10^7$ A/m$^2$, and $d = 10t$, we calculate the front factor to be $7.274 \times 10^{-5}$ V/m. This is a weak but observable electric field, but the very large spin current used in this calculation can hardly be generated by the induction method discussed above. However, in a strongly polarized or half metallic ferromagnetic metal, a very large polarized current can be generated with an ordinary $\text{emf}$. If such a current is sent through the present device, a detectible electric field should be generated as shown here, besides the magnetic field which must also occur because a spin-polarized current is still a charge current. Observing this electric field would then be a definitive way to confirm the existence of a spin-polarized current.

Integrating the above electric field along the whole $y$ axis, we find the total voltage drop along this axis to be:

$$\Delta V \equiv \int_{-\infty}^{\infty} E_y dy = \mu_B (n_\uparrow v_\uparrow - n_\downarrow v_\downarrow) (t/d) L_y. \quad (7)$$

For the same spin current and $t/d$ considered in the previous paragraph, and let $L_y = 10$ cm, we obtain $\Delta V = 7.274 \times 10^{-6}$ V, which is a detectible voltage difference, but it is certainly a very weak one. If the spin current is ac, then the induced electric field is also ac at the same frequency. One can then possibly use a resonance technique to detect this electric field with an improved sensitivity.

We conclude this work with some remarks: (1) The conducting sheets can not be made of singlet superconductors, since if the spin-up electrons and spin-down electrons form bound Cooper pairs then they can not flow in opposite directions. $p$-wave superconductors do not have this problem, and it has the advantage of contributing no internal spinoresistance, so it has the potential of generating larger spin current, but one needs to worry about suppressed order parameter in sheets much thinner than their coherence length. So low-carrier-density normal conductors with low resistance and low magnetic and spin-orbit scattering centers are still the best bet for making this device. (2) Spinoresistance can result from both scattering (which reduces electrons’ forward momentum) and spin conversion. So in most good conductors it should be of the same order of magnitude as its usual resistance unless the conductor has a lot of magnetic and/or spin-orbit scattering centers, in which case its spinoresistance should be larger than its usual resistance. (3) If the spin-up and -down currents can be separated in a short section of the spin circuit using half-metallic conductors, and the usual capacitors, inductors, transformers, rectifiers, or transistors, etc., are inserted in the two separate circuit branches, one would have created a spinocapacitor, a spinoinductor, a spinotransformer, a spinorectifier, or a spinotransistor, etc., but it doesn’t appear that they can allow spin circuits to maintain their advantages over the usual charge circuits. Thus more clever ideas are needed before spin circuits can compete with the usual charge circuits for usefulness.

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[1] S. A. Wolf and D. M. Treger, Proc. IEEE 91, 650 (2003).
[2] For recent reviews of this research area, see S. A. Wolf et

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al., Science 294, 1488 (2001); H. Akinaga and H. Ohno, Trans. Nanotech. 1, 19 (2002); and all articles in the special issue of Proc. IEEE cited in Ref. 1. See also, S. Das Sarma, Nature Materials 2, 292 (2003). L. P. Rokhinson et al., Microelec. Eng. 63, 147 (2002); J. De Boeck et al., Thin Solid Films 412, 3 (2002); J. Fabian and S. Das Sarma, Phys. Rev. B 66, 024436 (2002); P. Mavropoulos, O. Wunnicke, and P. H. Dederichs, Phys. Rev. B 66, 024416 (2002).

[3] We suggest calling this whole line of thoughts “orthospintronics”, and referring to all other spintronic ideas and applications as “paraspintronics”.

[4] Q.-F. Sun, H. Guo, and J. Wang, Phys. Rev. Lett. 90, 258301 (2003).

[5] If magnetic charge exists, this law allows the generation of a magnetomotive force to drive a magnetic charge current. (This term has been used in another sense which is really a misnomer [cf., for example, Sear, Zemansky, and Young, University Physics, part II, 5th ed., Addison-Wesley, 1976, pp. 604].) Here we show that the same law can also lead to an smf.

[6] C.-R. Hu, Phys. Rev. Lett. 82, 1493 (1982).

[7] This heterostructure may be also fabricated as a semiconductor multi-quantum-well structure. However, in order for the device to work at room temperatures, a very wide gap semiconductor must be used as the material between the quantum wells. The quantum wells must also be doped to serve as the conducting sheets. Their electron density can be controlled to ensure that the width of the quantum wells are less than the screening length.

[8] See, for example, J. D. Jackson, Classical Electrodynamics, 3rd Ed. (John Wiley and Sons, Inc., New York, 1999), Eqs. (5.1), (5.72), and (6.150). The units of $\mu$ and $q_m$ can be obtained through these equations.