Spin battery operated by ferromagnetic resonance

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Precessing ferromagnets are predicted to inject a spin current into adjacent conductors via Ohmic contacts, irrespective of a conductance mismatch with, for example, doped semiconductors. This opens the way to create a pure spin source (“spin battery”) by the ferromagnetic resonance. We estimate the spin current and spin bias for different material combinations.

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The research field of magnetoelectronics or spinelectronics strives to utilize the spin degree of freedom for electronic applications. Devices made from metallic layered systems displaying the giant magnetoresistance have been proven useful for read-head sensors and magnetic random-access memories. Integration of such devices with semiconductor electronics is desirable but difficult because a large resistivity mismatch between magnetic and normal materials is detrimental to spin injection. Spin injection into bulk semiconductors has been reported only in optical pump and probe experiments and with high-resistance ferromagnetic injectors or Schottky/tunnel barriers. In these cases, the injected spin-polarized carriers are hot and currents are small, however. Desirable are semiconductor devices with an efficient all-electrical cold-electron spin injection and detection via Ohmic contacts at the Fermi energy, just as has been realized by Jedema et al. for metallic devices.

We introduce a concept for DC spin-current injection into arbitrary conductors through Ohmic contacts, which does not involve net charge currents. The spin source is a ferromagnetic reservoir at resonance with an rf field. Pure spin-current injection into low-density conductors should allow experimental studies of spintronic phenomena in mesoscopic, ballistic, and nanoscale systems, which up to now has been largely a playground of theoreticians like Datta and Das whose spin transistor concept has stimulated much of the present interest in spintronics.

The combination of a ferromagnet at the ferromagnetic resonance (FMR) in Ohmic contact with a conductor can be interpreted as a “spin battery”, with analogies and differences with charge batteries. For example, charge-current conservation dictates that a charge battery has two poles, plus and minus. A spin battery requires only one pole, since the spin current does not need to be conserved. Furthermore, the polarity is not a binary, but a three-dimensional vector. The important parameters of a charge battery are the maximum voltage in the absence of a load, as well as the maximum charge current, which can be drawn from it. In the following we present estimates for the analogous characteristics of the spin battery.

Central to our concept is a precessing ferromagnet, which acts as a source of spin angular momentum, when in contact with normal metals, see Fig. 1. This spin injection can be formulated in analogy with the adiabatic pumping of charge in mesoscopic systems. When the ferromagnet is thicker than the ferromagnetic coherence length (a few Ångströms in transition metals such as Co, Ni or Fe), the spin current emitted into the normal metal is determined by the mixing conductance between transverse modes $m$ and $n$ in the normal metal at the interface to the ferromagnet, where the latter is characterized by the magnetization direction $\mathbf{m}$. The mixing conductance governs the transport of spins that are noncollinear to the magnetization direction $\mathbf{m}$. The mixing conductance can be disregarded due to the randomization of spin up and spin down in the normal metal space and this is assumed in the following. The spin current emitted into the normal metal is then, simply

$$ I_{\text{source}} = \frac{\hbar}{4\pi} g_{\text{mix}} \mathbf{m} \times \frac{d\mathbf{m}}{dt}. \quad (1) $$

In our notation, the spin current is measured in units of mechanical torque. Eq. (1) is a time-dependent corre-
tion to the Landauer-Büttiker formula for noncollinear ferromagnetic–normal-metal (F-N) hybrid systems. A physical picture can be inferred from the following thought experiment. Suppose we have a F-N interface at equilibrium and switch the magnetization instantaneously. The mismatch of the spin-up and spin-down chemical potentials leads to large non-equilibrium spin currents on the length scale of the spin-diffusion length. A slower magnetization reversal naturally induces smaller spin currents. Eq. (1) represents the adiabatic limit of the spin currents pumped by a slow magnetization dynamics. When the spin current \( \langle \dot{\mathbf{m}} \rangle \) is channeled off sufficiently rapidly, the corresponding loss of angular momentum increases the (Gilbert) damping of the magnetization dynamics. Eq. (1) is the maximum spin current that can be drawn from the spin battery.

Next, we need the maximum spin bias obtained when the load vanishes. When the spin-flip relaxation rate is smaller than the spin-injection rate, a spin angular momentum \( \mathbf{s} \) (in units of \( \hbar \)) builds up in the normal metal. We can neglect spacial dependence within the ferromagnet when the film is sufficiently thin. Under these conditions, one finds that the component of the backflow current \( I_\text{back}^s \) from the normal metal to the ferromagnet, parallel to the instantaneous magnetization direction \( \mathbf{m} \) is cancelled by an opposite flow from the ferromagnet. The component of \( I_\text{back}^s \) perpendicular to \( \mathbf{m} \) is

\[
I_\text{back}^s = \frac{g_{\alpha H}}{2\pi N} [s - m(\mathbf{m} \cdot \mathbf{s})],
\]

where \( N \) is the one-spin density of states. We note that the mixing conductance in Eqs. (1) and (2) ought to be renormalized in highly transparent junctions.

The relation between spin excess \( s \) and total spin current \( I_s = I_\text{source}^s - I_\text{back}^s \) in a normal diffusive metal is governed by the spin-diffusion equation

\[
\frac{\partial s}{\partial t} = D \frac{\partial^2 s}{\partial x^2} - \frac{s}{\tau_s},
\]

where \( D \) is the diffusion coefficient, in three (two) dimensions \( D = v_F^2 \tau/6 \) \((D = v_F^2 \tau/4)\), and \( \tau_s \) are the elastic and spin-flip relaxation times, respectively. We solve the diffusion equation with boundary conditions at \( x = 0 \), where \((DA\hbar)\partial_s s = -I_s \), and at the end of the sample \( x = L \), where the spin current vanishes, \( \partial_x s = 0 \). \( A \) is the cross section of the system.

The precession of the magnetization vector of a ferromagnet under a resonant rf electromagnetic field applied perpendicularly to a DC magnetic field can be used to drive the spin battery. The magnitude of the spin current \( I_\text{source}^s \) and spin bias \( \Delta \mu \equiv 2 \langle \dot{\mathbf{m}} \rangle/N \) as a function of the applied field \( H_0 \) follows from the Landau-Lifshitz-Gilbert equation \( \dot{\mathbf{m}} = -\gamma^* s \mathbf{m} \times \mathbf{H}_0 + \alpha \mathbf{m} \times \dot{\mathbf{m}} \), where \( \gamma^* \) is the gyromagnetic ratio, \( \alpha \sim 0.01 - 0.001 \) the Gilbert damping factor, and magnetic anisotropies have been disregarded for simplicity. The spin bias also has AC components. However, its frequency \( \omega \) harmonics are strongly suppressed when \( l_s/(\omega \tau_s)^{1/2} \ll L < l_s \), which can be easily realized when \( \omega \tau_s > 1 \), e.g., \( \tau_s > \omega^{-1} \sim 10^{-11} \text{s}/H_0 \text{ [T]} \). \( l_s = \sqrt{\tau / D} \) is the spin-diffusion length in the normal metal. The dominant contribution to the spin bias is then constant in time and directed along \( \mathbf{H}_0 \). The magnitude of the time-averaged spin accumulation \( \Delta \mu = 2 \langle s(t) \rangle/N \) in the normal metal close to the F-N interface then reads:

\[
\Delta \mu = \hbar \omega_0 \frac{\sin^2 \theta}{\sin^2 \theta + \eta},
\]

where the precession cone angle between \( \mathbf{H}_0 \) and \( \mathbf{m} \) is \( \theta \), \( \eta = (\tau_2/\tau_1) \tan h(L/l_s)/(L/l_s) \) is a reduction factor, and we have introduced the spin-injection rate \( \tau_{1}^{-1} = g_{\alpha H_0}/(2\pi \hbar N AL) \). Large systems have a smaller injection rate since more states have to be filled.

The ratio of the injection and spin-flip relaxation times can be evaluated for a planar geometry. We consider a free-electron gas in contact with a metallic ferromagnet. The mixing conductance is \( g_{\alpha H} = \kappa Al_2^2/(4\pi) \) \((g_{\alpha H} = \kappa Al_2^2/\pi \) for spin injection into three-(two-)dimensional systems. First-principles band-structure calculations show that for combinations like Co/Cu or Fe/Cr \( \kappa \) remains close to unity. The ratio between the injection and spin-flip relaxation times in three (two) dimensions can be calculated to be \( \tau/\tau_s = \sqrt{8/3\kappa^{-1}} \sqrt{\tau/(L/l_s)} \), \( \kappa \) is the ratio of the elastic scattering rate and the spin-flip relaxation rate, which is usually much smaller than unity.

When the spin relaxation time is longer than the spin injection time and the precession cone angle is sufficiently large, \( \sin^2 \theta \gg \eta \), the spin bias saturates at its maximum value \( \Delta \mu_{\text{max}} = \hbar \omega_0 \). In this regime the spin accumulation does not depend on the material parameters. It should be feasible to realize the full spin bias when \( L < l_s \) since \( \eta \approx \sqrt{8/3\kappa^{-1}} \sqrt{\tau/(L/l_s)} \), e.g., when \( L/l_s = 0.1 \), \( \sqrt{8/3\kappa^{-1}} \sqrt{\tau} = 0.1 \) the precession cone angle should be larger than 6 degrees. For small precession cone angles \( \theta \approx H_0/(\alpha H_0) \), for e.g. \( H_0 = 1.0 \text{T}, \alpha = 10^{-3} \) this requires a \( H_0 = 0.1 \text{mT} \) field with a resulting spin bias of \( \Delta \mu = 0.1 \text{nAeV} \). For a smaller precession angle, e.g., \( \theta = 0.6 \) degrees the spin-bias is smaller, \( \Delta \mu = 1 \mu \text{V} \), but still clearly measurable. Epitaxially grown clean samples with even longer spin-diffusion lengths and smaller spin-flip to non-spin-flip relaxation ratios \( \epsilon \) will function as spin-batteries with smaller precession angles. The precession cone angle \( \theta \) in FMR is typically small, but \( \theta > 15 \) degrees can be achieved for a sufficiently intense rf field and a soft ferromagnet, e.g., permalloy. The maximum DC spin current source is \( |I_\text{source}^s| \approx \hbar \omega_0 \kappa Al_2^2 \sin^2 \theta/(4\pi) \), e.g. for a precession cone angle of \( \theta = 6 \) degrees the equivalent electrical spin current \( e/\hbar |I_\text{source}^s| \) is 0.1 nano Ampere per conducting channel \( Al_2^2/(4\pi) \). The total number of channels is a large number since the cross sections may be chosen very much larger than the Fermi wavelength thus ensuring that a large spin current may be drawn from the battery.

Ferromagnetic resonance dissipates energy proportional to the damping parameter \( \alpha \) of the magnetization.
The power loss $dE/dt = \alpha \hbar \omega_0^2 N_s \sin^2 \theta$ is proportional to the volume of the ferromagnet through the number of spins in the ferromagnet in units of $\hbar$, $N_s$. The power loss can be significant even for a thin film ferromagnet, e.g., for a 10 monolayer thick Fe film with $\alpha \sim 10^{-3}$, $\sin^2 \theta \sim 10^{-2}$, and $\omega_0 \sim 10^{11}$ s$^{-1}$, the power loss per unit area is $(1/A)dE/dt \sim 0.1$ W/cm$^2$. The temperature can be kept low by e.g. immersing the sample in superfluid helium. The heat transfer is then approximately 8 W/cm$^2$K for small temperature gradients and increases for larger temperature gradients which appears sufficient for the present purpose.

Schmidt et al. realized that efficient spin injection into semiconductors by Ohmic contacts is close to impossible with transition-metal ferromagnets since virtually all of the applied potential drops over the nonmagnetic part and is wasted for spin injection. The present mechanism does not rely on an applied bias and does not suffer from the conductance mismatch, because the smallness of the mixing conductance for a ferromagnet-semiconductor interface is compensated by the small spin current that is necessary to saturate the spin accumulation.

Possible undesirable spin precession and energy generation in the normal-metal parts of the system is of no concern for material combinations with different $g$-factors, as, e.g., Fe ($g = 2.1$) and GaAs ($g = -0.4$), or when the magnetic anisotropy modifies the resonance frequency with respect to electrons in the normal metal.

The optimal material combinations for a battery depend on the planned usage. From Eq. (0) it follows that the largest spin current can be achieved when the conductor is a normal metal, whereas any material combination appears suitable when the load is small, as long as the contact is Ohmic and the system is smaller than the spin-diffusion length.

Standard metals, like Al and Cu, are good candidate materials, since the spin-diffusion length is very long, $l_s \sim 1$ µm at low temperatures, and remains quite long at room temperature. [4] Indirect indications of spin accumulation in Cu can be deducted from the absence of any enhancement of the Gilbert damping in FMR when in contact with thin ferromagnetic films.

Semiconductors have the advantage of a larger ratio of the conductance mismatch, because the smallness of the spin-precession length in terms of the spin-orbit interaction can be included by adding

$$\Gamma^\text{nuc} = \frac{\hbar s_n}{T_n}$$

(5)

to the electron spin dynamics so that $\mathbf{I} \rightarrow \mathbf{I}_s^\text{source} - \mathbf{I}_s^\text{back} + \mathbf{I}_n^\text{nuc}$, where $\mathbf{I}_s^\text{nuc}$ is the nonequilibrium nuclear spin accumulation and $T_n$ is the electron-nuclear relaxation time. The nuclear spin dynamics is described by

$$\frac{ds_n}{dt} = -\frac{s_n}{T_n} + \frac{s}{T_e}$$

(6)

where $T' \leq T_n$ is the nuclear-spin relaxation time and $T_e$ is the nuclear-electron relaxation. In steady state, $s_n = (T' \tau_\text{back} / T_n)(T_n / T_e)$ remains unchanged. $T_{n/e} = 8(I + 1)\epsilon_F\hbar N / (9k_B T_{n/e})$ for small polarizations, where $\epsilon_F$ is the Fermi energy of the electron gas, $k_B T$ is the thermal energy, $n_N$ is the nuclear density and $n_e$ is the one-spin electron density. Using $N = (3/2)n_e/\epsilon_F$ ($N = n_e/\epsilon_F$ in two dimensions) and Eq. (3) the relative enhancement
of the DC nuclear spin polarization is

\[ s_n = n_N \frac{T_n^s}{T_n} \frac{2}{3} I(I + 1) \frac{\Delta \mu}{k_B T}. \]

(7)

for \( \Delta \mu \ll k_B T \). The nuclear-spin polarization increases with the spin bias and by lowering the temperature. The hyperpolarized nuclei, in turn, produce an effective nuclear field that polarizes the equilibrium properties of the electron gas \( s_0 \). In bulk GaAs, the magnetic field is \( B_n = 5.3 \) T when the nuclei are fully spin-polarized which should occur at sufficiently low temperatures.

Berger proposed to generate a DC voltage by the FMR, which bears similarities with our proposal. But Berger’s mechanism of spin injection, originating from the spin-flip scattering in the ferromagnet as induced by spin waves appears to be different from ours. We propose to achieve spin injection \( \eta \) through the modulation of the inter-face scattering matrix by the coherent precession of the magnetization, which allows, for example, quantitative calculations for various materials.

In conclusion, we present the new concept of a spin battery, which is a source of spin, just as a conventional battery is a source of charge, and estimate its performance for different material combinations.

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