Thermally driven spin injection from a ferromagnet into a non-magnetic metal

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SUPPLEMENTARY INFORMATION

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I. SUPPLEMENTARY INFORMATION A

Here we calculate what happens when heat is sent through the FM/NM system in figure 1. We begin by writing the spin dependent currents:

$$J_{\uparrow,\downarrow} = -\sigma_{\uparrow,\downarrow}(\frac{1}{e}\nabla\mu_{\uparrow,\downarrow} + S_{\uparrow,\downarrow}\nabla T) \quad (1)$$

here $\mu_{\uparrow,\downarrow}$ is the spin dependent chemical potential. When a heat current Q is sent through the bulk of a ferromagnet in the absence of a charge current, a spin current $J_s = J_\uparrow - J_\downarrow = -\sigma_F(1-P^2)S_s\nabla T/2$ flows, driven by the spin dependent Seebeck coefficient, which we define as $S_s \equiv S_\uparrow - S_\downarrow$. Here P is the conductivity polarization $P = (\sigma_\uparrow - \sigma_\downarrow)/(\sigma_\uparrow + \sigma_\downarrow)$ of the FM and σ_F is the conductivity of the ferromagnet. Charge and spin current conservation[1,2] leads to the thermoelectric spin diffusion equation:

$$\nabla^2\mu_s = \frac{\mu_s}{\lambda^2} - e(\frac{dS_s}{dT}(\nabla T)^2 + S_s\nabla^2 T) \quad (2)$$

where μ_s is the spin accumulation $\mu_\uparrow - \mu_\downarrow$. In addition to the Valet-Fert spin diffusion equation $\nabla^2\mu_s = \frac{\mu_s}{\lambda^2}$ two source terms are present. Both terms can in principle create (albeit small) bulk spin accumulations. We note that we ignored such terms in deriving the above spin current $J_s = -\sigma_F(1-P^2)S_s\nabla T/2$ flowing through the bulk ferromagnet such that we have $\mu_\uparrow = \mu_\downarrow$.

In figure 1 we sent a heat current Q through the FM/NM interface while we allow no charge or spin current to leave. The heat current $Q = -k\nabla T$ needs to be continuous throughout the system, leading to $\nabla T_{FM} = k_{NM}/k_{FM}\nabla T_{NM}$ at the interface. Since ∇T is constant in both regions individually, and for first order effects we may assume S_s is constant, the source terms in equation 2 are irrelevant. Therefore, we may use the standard Valet-Fert spin diffusion equation to solve the bulk spin accumulation leading to the general expression for the spin dependent potentials in the bulk:

$$\mu_{\uparrow,\downarrow}(x) = A + Bx \pm C/\sigma_{\uparrow,\downarrow}e^{-x/\lambda_i} \pm D/\sigma_{\uparrow,\downarrow}e^{x/\lambda_i} \quad (3)$$

with A-D the parameters to be solved in both regions. At the FM/NM interface we take the chemical potentials $\mu_{\uparrow,\downarrow}$ to be continuous as well as the spin dependent currents $J_{\uparrow,\downarrow}$. At the outer interfaces we set the spin dependent currents to zero. This leads to a set of equations which can be solved. We obtain:

$$B = e\frac{\sigma_\uparrow S_\uparrow + \sigma_\downarrow S_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}\nabla T_{FM} \equiv eS_{FM}\nabla T_{FM} \quad (4)$$

where we use the definition of the conventional Seebeck coefficient of a ferromagnet S_{FM}[3]. The spin accumulation at the interface is:

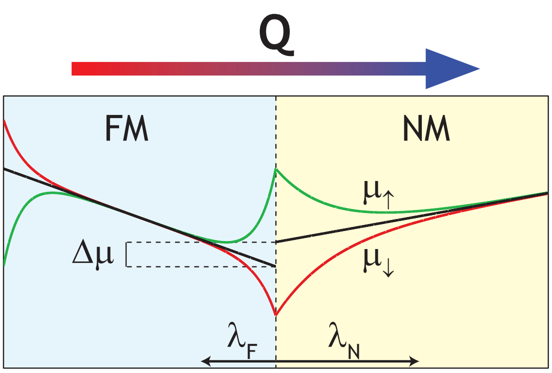

FIG. 1: **Thermal spin injection by the spin dependent Seebeck coefficient across a FM/NM interface.** Schematic figure showing the resulting spin dependent chemical potentials $\mu_{\uparrow,\downarrow}$ across a FM/NM interface when a heat current $Q = -k\nabla T$ crosses it. Heat current is taken to be continuous across the interface leading to a discontinuity in ∇T. No currents are allowed to leave the FM, nevertheless, a spin current proportional to the spin dependent Seebeck coefficient flows through the bulk FM which needs to become unpolarized in the bulk NM. This injects a spin imbalance $\mu_\uparrow - \mu_\downarrow$ at the boundary which relaxes in the FM and NM with the length scale of their respective spin relaxation lengths λ_i. A thermoelectric interface potential $\Delta\mu = P\mu_s$ also builds up[1,2]. On the left side no spin current is allowed to leave leading to an opposite spin accumulation.

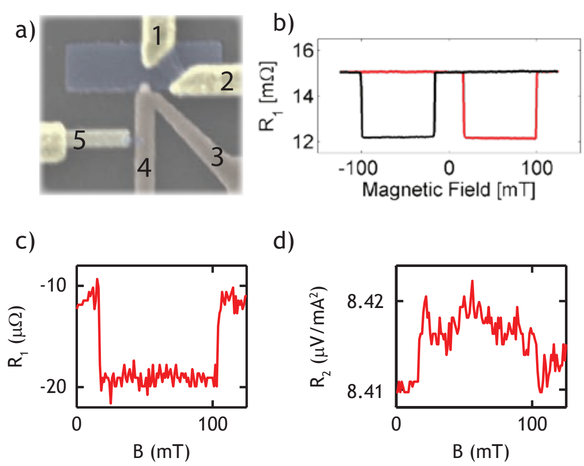

FIG. 2: **Previous device results**. a) Coloured SEM figure of the device. The sample consist of the same two ferromagnets which are now placed 400 nm apart. It is connected by a copper V shape instead of a funnel. b) Non local spin valve signal by sending current from contact 1 to 3 and measuring the potential from contact 5 to 4. c,d) Thermal spin injection result. The current is now sent from contact 1 to 2 while the potential was measured between contacts 5 and 4.

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$$\frac{\mu_s}{\nabla T_{FM}} = -e\lambda_F S_s R_{mis} \quad (5)$$

where $R_{mis} = R_N/(R_N + R_F/(1-P^2))$ is a conductivity mismatch[4] factor in which $R_i = \lambda_i/\sigma_i$ are the spin resistances determined by the relaxation lengths λ_i and the conductivities σ_i.

For the explanation of the results of Uchida et al.[5] a similar derivation was made[6]. However, they introduce an extra source term for spin accumulation to equation 2 which does not decay on the scale of the spin relaxation length. This allows in their analysis to have a spin accumulation in the bulk at interface distances further than the spin relaxation length.

As a consequence, their experiment is interpreted as a result of spin accumulation in the bulk which is probed by the inverse spin Hall effect at different locations.

In contrast, our effect cannot produce a bulk spin accumulation since we exclude the higher order effects mentioned before. It can only arise at the interface where it can inject spins into the NM region.

We note that our definition of the spin *dependent* Seebeck coefficient $S_S \equiv S_\uparrow - S_\downarrow$ is in principle the same as their definition of the spin Seebeck coefficient $S_S \equiv \frac{1}{e}\left(\left(\frac{\partial \mu_\uparrow^{ch}}{\partial T}\right)_{n_\uparrow} - \left(\frac{\partial \mu_\downarrow^{ch}}{\partial T}\right)_{n_\downarrow}\right)$ by virtue of the definition of the Seebeck coefficients (eq. 1).

II. SUPPLEMENTARY INFORMATION B

In this section we report on the measurements of a previous sample. A SEM picture is shown in figure 2 (a). A regular spin valve signal was measured by sending a current from contact 1 to 3 and measuring the potential between contact 5 and 4 of which the result is shown in figure 2 (b). In this case a 13.8 mΩ background R_1^b is observed on top of a non local spin valve signal R_1^s of 3 mΩ. The background is originating from Peltier heating/cooling of the FM/NM interfaces[7]. Both signals are close to the calculated 14.1 mΩ and 4.1 mΩ.

When the current is sent from contact 1 to 2, we obtain the results shown in figure 2 (c,d). A regular spin valve signal R_1^s of 10 μΩ is observed on top of a small -15 μΩ background R_1^b. This is somewhat different then the calculated -100 μΩ background and -4 μΩ spin valve signal. However, these effects are highly dependent on the exact geometry and are due to the small 30 x 30 nm^2 size of the contact. This makes sure grain size, lithographic precision and ballistic effects dominate.

Thermal spin injection was observed and is shown in figure 2 (d). The background R_2^b is again larger then the calculated 3.4 $\mu V/mA^2$. If we compensate for this in the modelling we obtain from the observed ≈ -7 nV/mA^2 signal a spin dependent Seebeck coefficient for Permalloy of ≈ -5 $\mu V/K$.

We conclude that also in this device we have good agreement between observed and calculated thermoelectric voltages when we apply a similar correction for the Joule heating. A very similar value for the spin Seebeck coefficient was found.

III. SUPPLEMENTARY INFORMATION C

Here we exclude any influence of possible nonlinear behaviour of the physical effect represented by the $R_1^s I$ signal on our measured thermally driven spin injection signal $R_2^s I^2$.

We start by reasoning what happens if the amount of current flowing through, or the spin injection efficiency of, the Py_1/Cu interface depends on the temperature. In that case, a Peltier heating/cooling induced change of the physical effect represented by the $R_1^s I$ signal can give a contribution to the $R_2^s I^2$ signal. However, from the modeling we know that at the typical current of 1 mA we used, the effective Joule heating is ≈10 times larger. The $R_3^s I^3$ signal, then representing the Joule heating induced change, should therefore be ≈10 times larger than the $R_2^s I^2$ signal. However, $R_3 I^3$ was simultaneously measured and found absent. This excludes any thermally related contributions to our measured $R_2^s I^2$ signal.

Our contacts are highly ohmic, causing the $R_1^s I$ signal in the first place. In the case of tunnel contacts, electrical spin injection can depend on the bias voltage applied. We can reason that if our contacts are slightly tunnelling, the effect represented by the $R_1^s I$ signal can still have an influence on our thermally driven spin injection signal $R_2^s I^2$ without being present in the $R_3 I^3$ signal.

By checking the magnitude of such effects in previous samples[7] which have been prepared in an identical way, we can also rule out such effects. We note that at a typical current of 1 mA $R_1^s I \approx 20$ nV, while $R_2^s I^2 \approx$ -15.6 nV. We see from previous measurements[7] that at these currents the change in electrical spin injection visible in the $R_2^s I^2$ signal is less then 5%. Any signal in the $R_2^s I^2$ should then be less then 1 nV. On top of that, it should also be of different sign then our observed thermally driven spin injection signal.

Finally, we note that the $R_1^s I$ signal for our device is of different sign then that observed in a previous device reported on in the previous section. However, the thermally driven spin injection signal is of identical sign, showing the fact that there are no spurious contributions.

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