Chapter 3

Thermally driven spin injection

Creating, manipulating and detecting spin polarized carriers are the key elements of spin based electronics[1, 2]. Most practical devices[3–5] use a perpendicular geometry in which the spin currents, describing the transport of spin angular momentum, are accompanied by charge currents. In recent years, new sources of pure spin currents, i.e., without charge currents, have been demonstrated[6–9] and applied[10–12]. In this paper, we demonstrate a conceptually new source of pure spin current driven by the flow of heat across a ferromagnetic/non-magnetic metal (FM/NM) interface. This spin current is generated because the Seebeck coefficient, which describes the generation of a voltage as a result of a temperature gradient, is spin dependent in a ferromagnet[13, 14]. For a detailed study of this new source of spins, it is measured in a non-local lateral geometry. We developed a 3D model that describes the heat, charge and spin transport in this geometry which allows us to quantify this process[15]. We obtain a spin dependent Seebeck coefficient for Permalloy of -3.8 μV/K demonstrating that thermally driven spin injection is a feasible alternative for electrical spin injection in, for example, spin transfer torque experiments[16].

3.1 Introduction

The interplay of spin dependent conductivity and thermoelectricity was already known for half a century where it was used to describe the conventional Seebeck effect of ferromagnetic metals[17]. The discovery of the GMR effect[3] sparked the interest of the community in spin dependent conductivity and novel spin electronics which is going on until today[4, 5, 8, 18]. Due to experimental difficulties in controlling heat flows it was only until very recent that thermoelectric spintronics was investigated[19, 20] leading to the new field of spin caloritronics[13]. A relevant example is given by Uchida et al. [9] who interpreted their results in terms of the generation of a bulk spin accumulation due to an applied temperature gradient in a ferromagnet film. In contrast, the effect we describe in this paper arises from a heat current flowing through a
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Figure 3.1: Conceptual diagram. A charge current $J_C$ is sent through ferromagnet 1 (FM$_1$) causing Joule heating due to the large resistivity of FM$_1$. The NM contacts (yellow) are highly thermally conductive, thereby providing heat sinks. The heat current Q through the center FM$_1$/NM interface injects a spin current into the NM depending on the magnetization direction M$_1$. The generated spins diffuse towards the FM$_2$/NM interface where they generate a potential $\Delta \mu = P \mu_s$ depending on the magnetization direction M$_2$. As a consequence of Joule heating, the signal expected to arise from thermal spin injection scales with $\nabla T \propto I^2$. This potential is measured using the indicated voltage scheme by selectively switching the magnetization directions M$_1$ and M$_2$ by a magnetic field H.

The concept of how we generate a heat current over a FM/NM junction and subsequently measure the spin accumulation is shown in figure 3.1. The scheme is essentially a lateral non local spin valve structure[6] with the electrical injection replaced by thermal spin injection. We use this non local scheme to separate spin injection from possible spurious effects[6, 11, 12] and because the observed thermally generated non-spin related voltage, which we refer to as the baseline resistance, allows to extract the temperature distribution in the device by comparing this to modeling[15].

3.2 Theory

We first formulate an appropriate diffusive transport theory for thermally driven spin injection. The Seebeck coefficient describes that an applied temperature gradient across a conductor generates an electric field[21]. In a ferromagnet, the transport processes for the majority and minority spin are different leading to a spin dependent conductivity $\sigma_{\uparrow,\downarrow}$ and Seebeck coefficient $S_{\uparrow,\downarrow}$[14, 17]. The first is used to describe magnetoelectronics[22] in FM/NM systems where the latter one is usually disregarded. In order to consider what happens when heat is sent through the system, we write the spin dependent currents in both the bulk ferromagnetic and normal metal
3.3. Measurement Technique

The signal due to thermally driven spin injection in the geometry of figure 1 scales with Joule heating: \( \nabla T \propto I^2 \). Therefore, we use a lock-in technique to determine the relevant parameters \( R_1(\mu V/\text{mA}) \) and \( R_2(\mu V/\text{mA}^2) \) from the observed voltage[15]:

\[
V = R_1 I + R_2 I^2 + ...
\]  

(3.3)

The baseline 'resistance', defined in terms of a parallel and antiparallel contribution as \( (R_P^P + R_{AP}^P)/2 = R_1^P \), allows to extract the magnitude of Joule and Peltier heating effects and possible conventional Ohmic potential drops[15]. Here \( R_1^P \) is determined by the Ohmic potential drop and Peltier heating/cooling measured by the FM2-NM
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Figure 3.2: Thermal spin injection by the spin dependent Seebeck coefficient across a FM/NM interface. Schematic figure showing the resulting spin dependent chemical potentials $\mu_{\uparrow}, \mu_{\downarrow}$ 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 $\nabla T$. 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 creates a spin imbalance $\mu_{\uparrow} - \mu_{\downarrow}$ at the boundary which relaxes in the FM and NM on the length scale of their respective spin relaxation lengths $\lambda_i$. A thermoelectric interface potential $\Delta \mu = P \mu_s$ also builds up. On the left side no spin current is allowed to leave leading to a spin accumulation of opposite sign.

thermocouple while the baseline resistance $R^b_2$ is determined by Joule heating measured by the same thermocouple. The spin dependent contribution $R^P_1 - R^{AP}_1 = R^s_1$ to $R_1$ is due to a conventional spin valve signal while this contribution to $R_2$ comes from thermal spin injection.

A dedicated device was fabricated to study this effect and is shown in figure 3.3. The heating of FM$_1$ has been kept very localized to an area of 150 x 150 nm$^2$ by using thick gold contacts. Moreover, the contacts are placed asymmetrically to minimize the possible current flowing in and out of the FM$_1$/NM interface. An additional contact 5 is present to be able to send a current directly through the FM$_1$/NM interface. By comparing the obtained signal $R^s_1$ to a model (see methods), we can extract the spin injection/detection efficiency[15], which has been made as high as possible by keeping the size of the FM/NM contacts small. All measurements are performed at room temperature.

3.4 Results

Figure 3.4 shows our principal results on thermal spin injection. Four distinct P-AP and AP-P switches are observed up to 70 nV in magnitude scaling with $I^2$ on a large background originating from the Py$_2$/Cu thermocouple.

The interpretation of the obtained signals requires a detailed knowledge of the
Figure 3.3: Coloured SEM picture of the fabricated device. The device consists of two 15 nm thick Permalloy (Ni$_{80}$Fe$_{20}$) ferromagnets FM$_1$ and FM$_2$ of 1 $\mu$m x 300 nm and 150 x 40 nm$^2$ separated from each other by 100 nm. They are connected by a 60 nm thick copper funnel with small effective FM/NM contact areas of 40 x 40 nm$^2$ and 30 x 40 nm$^2$. 5/175 nm thick Ti/Au contacts 1 and 2 are placed asymmetrically on FM$_1$ to Joule heat it while contacts 3 and 4 are used to measure Joule heating and thermal spin injection. An additional contact 5 is present to measure a regular non-local spin valve signal.

heat, charge and spin currents in the device. For this purpose a 3D thermoelectric spin model was constructed which extends the spin-dependent current model[24] to include thermoelectricity as well as thermal spin injection by the spin dependent Seebeck coefficient.

The calculated average contribution $R^b_2$ is 2.4 $\mu$V/mA$^2$ lower then the observed 7.69 $\mu$V/mA$^2$. The difference between the observed and modelled value was seen before in non-local spin valve samples[15]. It can be explained by a reduction in the Permalloy thickness due to its oxidation, which effectively increases the Joule heating. In the following, we scale the overall Joule heating in our model to fit our measured result $R^b_2$. We then find that we were able to heat FM$_1$ to a maximum of $\approx$ 40K at which $\nabla T_{FM}$ at the FM$_1$/NM interface is $\approx$ 50 K/µm. At this moment the current density is $\approx$ 8×10$^{11}$ A/m$^2$, close to the point where the device will fail due to electromigration.

Electrical spin injection was also measured by sending the current directly through the Py$_1$/Cu interface, and the result is shown in figure 3.5c. From the measured resistance $R_{NLSV}(\Omega)$, we see that a relatively large 9 mΩ spin valve signal is present on top of a 1.05 mΩ background, being only slightly different to the 7.8 mΩ and 640 mΩ calculated signals with the metallic spin parameters $\lambda_{Cu} = 350$ nm, $\lambda_{Py} = 5$ nm and $P_{Py} = 0.25$ obtained from previously fabricated samples[6, 15]. Here $P_{Py}$ is positive as shown before[27].

The observed thermal spin injection signal $R^t_2 = -15.6$ nV/mA$^2$ is determined from figure 3.4b. We obtain a spin-dependent Seebeck coefficient for Permalloy of $-3.8$ $\mu$V/K, a fraction of the conventional Seebeck coefficient $S_F = -20$ $\mu$V/K[9]. This
Figure 3.4: **Thermal spin injection measurements.** a, Measurement scheme of the experiment. b, Second harmonic measurement result $R_s^2 I^2$ (nV) of the observed thermal spin signal as a function of $I^2$. The error bars represent the standard deviation in the average height of the four P-AP and AP-P switches. c, Measured second harmonic signal at a rms current of 1.5 mA showing the four distinct switches resulting from the magnetization alignment of FM$_1$ and FM$_2$ illustrating thermal spin injection.

gives a polarization of the Seebeck coefficient of $P_s = S_s/S_F = 0.19$ not too different from the spin polarization of the conductivity. At the maximum currents used, we extract a net spin accumulation of $\approx 1 \mu$eV at the FM$_1$/NM interface. The magnitude of the spin dependent Seebeck coefficient is in good agreement with theoretical predictions[14, 16]. The previously deduced spin Seebeck coefficient $S_s = -2 \, \text{nV/K}$ and spin dependent Seebeck coefficient in this paper are similar by definition, but describe physical processes (Suplementary Information A). The discrepancy between both values arises from the modeling, which is different. We also do not exclude that the relevant physics itself in their experiment could be different, as alternative explanations have been reported[28].

In addition to the thermal spin injection signal, a small regular spin valve signal $R_{s1}^b = -20 \mu\Omega$ is also present and is shown in figure 3.5a. The baseline resistance $R_{s1}^b$ of 90 $\mu\Omega$ is in line with the calculated 95 $\mu\Omega$. This is caused by Peltier heating and cooling of the two current injecting contacts[15].

The negative regular spin valve signal $R_{s1}^b$ can be understood as follows. Due to the
3.4. Results

Figure 3.5: **Rectification effects and electrical spin injection.** **a**, first harmonic measurement $R_1$ for the measurement setup of figure 3.4. **b**, Calculated temperature distribution at a height of 10 nm with a current of 2 mA sent through FM$_1$. It illustrates the localized Joule heating, Peltier cooling and heating of the two Au/Py current injecting contacts and subsequent thermal conduction towards the three connected metallic contacts. **c**, Measured electrical spin injection scheme and resulting spin valve. **d**, Calculated spin accumulation at a height of 10 nm. A small part of the current path is short circuited by the Cu connection so that 4% still flows in and out of the Py$_1$/Cu contact because of its large conductivity. This creates a large positive and negative spin accumulation. Due to the asymmetry in spin injection and the asymmetrical placement at FM$_2$ a small fraction of 3% is still predicted to give a small regular spin valve signal $R_S^1$.

high conductivity of the copper, a fraction of the current flows into and out of Cu/Py$_1$ interface electrically injecting spins. A small net spin accumulation at the detector interface remains caused by the asymmetric placement of FM$_2$. It is illustrated by the calculation of the spin accumulation at the Py$_1$/Cu interface shown in figure 3.5d which shows the high geometrical dependence of this effect. The observed $R_S^1$ is somewhat smaller than the calculated -45 $\mu$Ω. We believe that the small 40 x 40 nm$^2$ size of the copper contact makes sure copper grain size, lithographic precision and ballistic effects start dominating the magnitude of this effect.

A previous device showed a thermal spin injection signal -5nV/mA$^2$ at a FM-FM distance of 400 nm, only visible at the highest current (Supplementary information
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B). A similar calculation gives $S_{Py}^\epsilon = -5 \mu V/K$ in agreement with the analysis for the sample presented. This measurement also rules out any influence of nonlinear behaviour of the process seen in the $R_1^1I$ signal on the $R_1^2I^2$ signal (Supplementary Information C).

3.5 Outlook

Now that the parameters governing equation 3.9 are known we may compare this to the electrical spin injection results for the transparent Cu/Py interface. We can calculate that for thermal spin injection $\mu_S / \nabla T \approx 2 \times 10^{-14}$ eV m/K versus $\mu_S / J \approx 3 \cdot 10^{-16}$ eV m$^2$/A for electrical spin injection through a transparent Cu/Py contact.

Due to the lateral non-local geometry and Joule heating method used in this paper, we are limited to a maximum temperature gradient of $\approx 50$ K/\mu m. However, in a typical perpendicular geometry switching by spin transfer torque this does not have to be the case. In order to switch the magnetization by electrical spin transfer torque one needs a typical charge current density of $\approx 5 \cdot 10^{11}$ A/m$^2$. The same stack should be able to switch by applying a temperature difference of only a few tens of degrees as earlier theoretical and experimental studies have indicated. This simple example shows that despite the weak signals observed in this paper, thermal spin injection can be a viable alternative, or even work alongside, electrical spin injection.

3.6 Methods

3.6.1 Fabrication

The sample in this paper was fabricated by a 1 step optical and 5 step electron beam lithography process. In each step, metals are deposited using e-beam deposition. For the e-beam lithography process a PMMA 950K resist is used of 70-400 nm thickness depending on the thickness of the deposited material and resilience to Ar ion milling. The first e-beam lithography process produces 5/30 nm thick and 100 nm wide Ti/Au markers which using an automatic alignment procedure can be aligned to in the next e-beam deposition steps with high precision. In the next four steps, the 15 nm Py, 5/30 nm Ti/Au, 5/180 nm Ti/Au and 65 nm Cu layers are deposited. For the last three steps, Ar ion milling was used prior to deposition to remove any polymer residue and the Py oxide to obtain our highly ohmic contacts.

3.6.2 Measurements

The measurements were performed using a AC current source of a frequency < 1kHz far below the characteristic thermolectric time scale of such sized systems of $\approx 1$-100 ns. The obtained signal is sent to 3 Lock-in systems measuring the $1^{st}$, $2^{nd}$ and $3^{rd}$ harmonic response simultaneously. Care was taken in deriving $R_1$, $R_2$ by scanning
the current from 500 µA to 1.5 mA rms to make sure that higher harmonics, as well as cross talk, were negligible.

3.6.3 Modeling

We constructed a 3D model of the fabricated sample using the finite element program Comsol Multiphysics. The physics is defined in terms of a thermoelectric spin model where the spin up, down and heat currents are given by:

\[
\begin{pmatrix}
\vec{J}_\uparrow \\
\vec{J}_\downarrow \\
\vec{Q}
\end{pmatrix} = -\begin{pmatrix}
\sigma_\uparrow & 0 & \sigma_\uparrow S_\uparrow \\
0 & \sigma_\downarrow & \sigma_\downarrow S_\downarrow \\
\sigma_\uparrow \Pi_\uparrow & \sigma_\downarrow \Pi_\downarrow & k
\end{pmatrix} \begin{pmatrix}
\vec{\nabla} \mu_\uparrow / e \\
\vec{\nabla} \mu_\downarrow / e \\
\vec{\nabla} T
\end{pmatrix}
\] (3.4)

where \(\Pi_{\uparrow,\downarrow}\) are the spin dependent Peltier coefficients given by \(S_\uparrow, S_\downarrow\cdot T_0\). Here \(T_0 = 300\)K which is the reference temperature of the device. We take these currents to be continuous across boundaries. At the end of all contacts we set the temperature to be \(T_0\). At contact 1 in figure 3.3 we set \(J_{\uparrow,\downarrow} = J/2\) to inject a charge current which is being sent through the system by setting \(\mu_{\uparrow,\downarrow} = 0\) at contact 2 or 5. At all other interfaces the currents are set to 0. We include Valet-Fert spin relaxation by assuming \(\nabla J_{\uparrow,\downarrow} = \pm (1-P^2)S_\uparrow \nabla T/2\) in the bulk. Joule heating is included by assuming \(\nabla Q = \zeta \left( \frac{J^2_\uparrow}{\sigma_\uparrow} + \frac{J^2_\downarrow}{\sigma_\downarrow} \right)\) where a scaling factor \(\zeta = 3.2\) is used to make the model correspond to the measured \(R^b_2\). The system was meshed most accurately at the FM/NM interfaces where the mesh size was 1 nm in order to accurately calculate thermal spin injection. The dependencies \(R^{(s)}_1\) up till \(R^{(s)}_4\) were determined by calculating the results at \(\pm 1\) & 2 mA for the parallel and antiparallel configuration. The measured resistivities \(\sigma_{Au} = 2.2 \cdot 10^7\) S/m, \(\sigma_{Cu} = 4.26 \cdot 10^7\) S/m and \(\sigma_{Py} = 4.32 \cdot 10^6\) S/m were taken as inputs for the model. In this model, the substrate was also taken into account[15]. The Seebeck coefficients \(S_{Au} = 1.7\) µV/K, \(S_{Cu} = 1.6\) µV/K, \(S_{Py} = -20\) µV/K and thermal conductances \(k_{Au} = 300\) W/m/K, \(k_{Cu} = 300\) W/m/K, \(k_{Py} = 30\) W/m/K, \(k_{substrate} = 1\) W/m/K were taken from various sources in literature[9, 30].

3.7 Supplementary information A

Here we calculate what happens when heat is sent through the FM/NM system in figure 3.1. We begin by writing the spin dependent currents:

\[
J_{\uparrow,\downarrow} = -\sigma_{\uparrow,\downarrow}\left(\frac{1}{e} \nabla \mu_{\uparrow,\downarrow} + S_{\uparrow,\downarrow} \nabla T\right)\] (3.5)

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 \(J_s = J_\uparrow - J_\downarrow = -\sigma_F (1 - P^2) S_{\uparrow} \nabla T/2\) 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...
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\[ P = (\sigma_\uparrow - \sigma_\downarrow) / (\sigma_\uparrow + \sigma_\downarrow) \]

of the FM and \( \sigma_F \) is the conductivity of the ferromagnet. Charge and spin current conservation[24, 25] leads to the thermoelectric spin diffusion equation:

\[
\nabla^2 \mu_s = \frac{\mu_s}{\lambda^2} - e \left( \frac{dS_s}{dT} \right)^2 + S_s \nabla^2 T
\]

(3.6)

where \( \mu_s \) 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 3.1 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 \( \nabla T \) is constant in both regions individually, and for first order effects we may assume \( S_s \) is constant, the source terms in equation 3.6 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:

\[
\mu_{\uparrow,\downarrow}(x) = A + Bx \pm C / \sigma_{\uparrow,\downarrow} e^{-\lambda_i / \sigma_i} \pm D / \sigma_{\uparrow,\downarrow} e^{\lambda_i / \sigma_i}
\]

(3.7)

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:

\[
B = e \frac{\sigma_\uparrow S_\uparrow + \sigma_\downarrow S_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \nabla T_{FM} \equiv e S_{FM} \nabla T_{FM}
\]

(3.8)

where we use the definition of the conventional Seebeck coefficient of a ferromagnet \( S_{FM}[17] \). The spin accumulation at the interface is:

\[
\frac{\mu_s}{\nabla T_{FM}} = -e \lambda_F S_s R_{mis}
\]

(3.9)

where \( R_{mis} = R_N / (R_N + R_F / (1 - P^2)) \) is a conductivity mismatch[26] factor in which \( R_i = \lambda_i / \sigma_i \) are the spin resistances determined by the relaxation lengths \( \lambda_i \) and the conductivities \( \sigma_i \).

For the explanation of the results of Uchida et al.[9] a similar derivation was made[23]. However, they introduce an extra source term for spin accumulation to equation 3.6 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 \( S_S \equiv \frac{1}{e} \left( \frac{\partial \mu^b_{\uparrow}}{\partial T} \right)_{n_\uparrow} - \left( \frac{\partial \mu^b_{\downarrow}}{\partial T} \right)_{n_\downarrow} \) by virtue of the definition of the Seebeck coefficients (eq. 3.5).

### 3.8 Supplementary information B

In this section we report on the measurements of a previous sample. A SEM picture is shown in figure 3.6 (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 3.6 (b). In this case a 13.8 m\( \Omega \) background \( R_{b1}^1 \) is observed on top of a non local spin valve signal \( R_{s1}^1 \) of 3 m\( \Omega \). The background is originating from Peltier heating/cooling of the FM/NM interfaces[15]. Both signals are close to the calculated 14.1 m\( \Omega \) and 4.1 m\( \Omega \).
When the current is sent from contact 1 to 2, we obtain the results shown in figure 3.6 (c,d). A regular spin valve signal $R_s^1$ of 10 $\mu\Omega$ is observed on top of a small -15 $\mu\Omega$ background $R_b^1$. This is somewhat different then the calculated -100 $\mu\Omega$ background and -4 $\mu\Omega$ 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 3.6 (d). The background $R_b^2$ 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 $\approx -7$ nV/mA$^2$ signal a spin dependent Seebeck coefficient for Permalloy of $\approx -5$ $\mu$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.

3.9 Supplementary information C

Here we exclude any influence of possible nonlinear behaviour of the physical effect represented by the $R_s^1I$ signal on our measured thermally driven spin injection signal $R_s^2I^2$.

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 $R_s^1I$ signal can give a contribution to the $R_s^2I^2$ signal. However, from the modeling we know that at the typical current of 1 mA we used, the effective Joule heating is $\approx 10$ times larger. The $R_s^3I^3$ signal, then representing the Joule heating induced change, should therefore be $\approx 10$ times larger than the $R_s^2I^2$ signal. However, $R_s^3I^3$ was simultaneously measured and found absent. This excludes any thermally related contributions to our measured $R_s^2I^2$ signal.

Our contacts are highly ohmic, causing the $R_s^1I$ 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 $R_s^1I$ signal can still have an influence on our thermally driven spin injection signal $R_s^2I^2$ without being present in the $R_s^3I^3$ signal.

By checking the magnitude of such effects in previous samples[15] 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 $R_s^1I \approx 20$ nV, while $R_s^2I^2 \approx -15.6$ nV. We see from previous measurements[15] that at these currents the change in electrical spin injection visible in the $R_s^3I^3$ signal is less then 5%. Any signal in the $R_s^2I^2$ 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 $R_s^1I$ 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.

References

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