Spin injection and spin accumulation in permalloy-copper mesoscopic spin valves.

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We study the electrical injection and detection of spin currents in a lateral spin valve device, using permalloy (Py) as ferromagnetic injecting and detecting electrodes and copper (Cu) as non-magnetic metal. Our multi-terminal geometry allows us to experimentally distinguish different magneto resistance signals, being 1) the spin valve effect, 2) the anomalous magneto resistance (AMR) effect and 3) Hall effects. We find that the AMR contribution of the Py contacts can be much bigger than the amplitude of the spin valve effect, making it impossible to observe the spin valve effect in a 'conventional' measurement geometry. However, these 'contact' magneto resistance signals can be used to monitor the magnetization reversal process, making it possible to determine the magnetic switching fields of the Py contacts of the spin valve device. In a 'non local' spin valve measurement we are able to completely isolate the spin valve signal and observe clear spin accumulation signals at $T = 4.2$ K as well as at room temperature. We obtain spin diffusion lengths in copper of 1 micrometer and 350 nm at $T = 4.2$ K and room temperature respectively.

I. INTRODUCTION

Spintronics is a rapidly emerging field in which one tries to study or make explicit use of the spin degree of freedom of the electron. So far, the most well known examples of spintronics are the tunneling magneto resistance (TMR) of magnetic tunnel junctions, and the giant magneto resistance (GMR) of multilayers. A new direction is emerging, where one actually wants to inject spin currents, transfer and manipulate the spin information, and detect the resulting spin polarization. Because of spin-orbit interaction, the electron spin can be flipped and consequently a spin polarized current will have a finite lifetime. For this reason it is necessary to study spin transport in systems, where the 'time of flight' of the electrons between the injector and detector is shorter than the spin flip time. In diffusive metallic systems, this corresponds to typical length scales of a micrometer. We use a lateral mesoscopic spin valve, to access and probe this small length scale. It consists of a ferromagnetic injector electrode and detector electrode, separated over a distance $L$ by a normal metal region, see Fig. 2.

In this paper a review of the basic model for spin transport in the diffusive transport regime will be given and applied to our multi-terminal device geometry. Secondly, a description and measurements of the magnetic switching behavior of the Py electrodes used in the spin valve device will be presented. Finally measurements of the spin valve effect in a 'conventional' and 'non-local' geometry will be shown and analyzed using the model for spin transport in the diffusive regime.

II. THEORY OF SPIN INJECTION AND ACCUMULATION

We focus on the diffusive transport regime, which applies when the mean free path $l_s$ is shorter than the device dimensions. The description of electrical transport in a ferromagnet in terms of a two-current (spin-up and spin-down) model dates back to Fert and Campbell. Van Son et al. have extended the model to describe transport through ferromagnet-normal metal interfaces. A firm theoretical underpinning, based on a Boltzmann transport equation has been given by Valet and Fert. They have applied the model to describe the effects of spin accumulation and spin dependent scattering on the giant magneto resistance (GMR) effect in magnetic multilayers. This "standard" model allows for a detailed quantitative analysis of the experimental results.

An alternative model, based on thermodynamic considerations, has been put forward and applied by Johnson. In principle both models describe the same physics, and should therefore be equivalent. However, the Johnson model has a drawback in that it does not allow a direct calculation of the spin polarization of the current ($\eta$ in refs.8 and 9), whereas in the standard model all measurable quantities can be directly related to the parameters of the experimental system.

The transport in a ferromagnet is described by spin dependent conductivities:

$$\sigma_{\uparrow} = N_{\uparrow} e^2 D_{\uparrow}, \text{ with } D_{\uparrow} = \frac{1}{3} v_{F\uparrow} l_{\uparrow} \quad (1)$$

$$\sigma_{\downarrow} = N_{\downarrow} e^2 D_{\downarrow}, \text{ with } D_{\downarrow} = \frac{1}{3} v_{F\downarrow} l_{\downarrow} \quad (2)$$

where $N_{\uparrow,\downarrow}$ denotes the spin dependent density of states (DOS) at the Fermi energy, and $D_{\uparrow,\downarrow}$ the spin dependent diffusion constants, expressed in the spin dependent Fermi velocities $v_{F\uparrow,\downarrow}$, and electron mean free paths $l_{\uparrow,\downarrow}$. Note that the spin dependent conductivities is determined by both density of states and diffusion constants. This should be contrasted with magnetic $F/I/F$ or $F/I/N$ tunnel junctions, where the spin polarization of the tunneling electrons is determined by the spin-dependent DOS. Also in a typical ferromagnet several bands (which generally have different spin dependent
density of states) contribute to the transport. However, provided that the elastic scattering time and the interband scattering times are shorter than the spin flip times (which is usually the case) the transport can still be described in terms of well defined spin up and spin down conductivities.

Because the spin up and spin down conductivities are different, the current in the bulk ferromagnet will be distributed accordingly over the two spin channels:

\[ j_\uparrow = \left( \frac{\sigma_\uparrow}{e} \right) \frac{\partial \mu_\uparrow}{\partial x}, \]

\[ j_\downarrow = \left( \frac{\sigma_\downarrow}{e} \right) \frac{\partial \mu_\downarrow}{\partial x}, \]

where \( j_\uparrow \) and \( j_\downarrow \) are the spin up and spin down current densities and \( e \) is the absolute value of the electronic charge. According to eqs. 3 and 4, the current flowing in a bulk ferromagnet is spin polarized, with a polarization given by:

\[ \alpha_F = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}. \]

The next step is the introduction of spin flip processes, described by a spin flip time \( \tau_{sf} \) for the average time to flip an up-spin to a down-spin, and \( \tau_{ retard} \) for the reverse process. The detailed balance principle imposes that the spin-up and spin-down conductivities are related by the elastic scattering time and the spin-flip time:

\[ \frac{\sigma_{\uparrow}}{\sigma_{\downarrow}} = \frac{\tau_{\uparrow}}{\tau_{\downarrow}}. \]

According to eqs. 5 the current flowing in the bulk ferromagnet is spin polarized, with a polarization given by:

\[ \alpha_F = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}}. \]

The effect of the spin-flip processes can now be described by the following equation (assuming diffusion in one dimension only):

\[ D \frac{\partial^2 (\mu_\uparrow - \mu_\downarrow)}{\partial x^2} = \frac{(\mu_\uparrow - \mu_\downarrow)}{\tau_{sf}}, \]

where \( D = D_\uparrow D_\downarrow (N_\uparrow + N_\downarrow)/(N_\uparrow D_\uparrow + N_\downarrow D_\downarrow) \) is the spin averaged diffusion constant, and the spin-relaxation time \( \tau_{sf} \) is given by: 1/\( \tau_{sf} \) = 1/\( \tau_{\uparrow} \) + 1/\( \tau_{\downarrow} \). Using the requirement of current conservation, the general solution of eq. 6 for a uniform ferromagnet or non-magnetic wire is now given by:

\[ \mu_\uparrow = A + Bx + \frac{C}{\sigma_\uparrow} \exp(-x/\lambda_{sf}) + \frac{D}{\sigma_\uparrow} \exp(x/\lambda_{sf}), \]

\[ \mu_\downarrow = A + Bx - \frac{C}{\sigma_\downarrow} \exp(-x/\lambda_{sf}) - \frac{D}{\sigma_\downarrow} \exp(x/\lambda_{sf}), \]

where we have introduced the spin flip diffusion length \( \lambda_{sf} = \sqrt{D \tau_{sf}} \). The coefficients A, B, C, and D are determined by the boundary conditions imposed at the junctions where the wires is coupled to other wires. In the absence of spin flip scattering at the interfaces the boundary conditions are: 1) continuity of \( \mu_\uparrow \), \( \mu_\downarrow \) at the interface, and 2) conservation of spin-up and spin-down currents \( j_\uparrow \), \( j_\downarrow \) across the interface.

### III. SPIN ACCUMULATION IN MULTI-TERMINAL SPIN VALVE STRUCTURES

We will now apply the "standard" model of spin injection to a multi-terminal geometry, which reflects our device geometry used in the experiment, see Fig. 1.

![Multi-terminal Spin Valve Structure](image)

**FIG. 1.** (a) Schematic representation of the multi-terminal spin valve device. Regions I and VI denote the injecting (F1) and detecting (F2) ferromagnetic contacts, whereas regions II to V denote the four arms of a normal metal cross (N) placed in between the two ferromagnets. A spin polarized current is injected from region I into region II and extracted at region IV. (b) Diagram of the electrochemical potential solutions (eqs. 7 and 8) in each of the six regions of the multi-terminal spin valve. The nodes represent the origins of the coordinate axis in the 6 regions, the arrows indicate the (chosen) direction of the positive x-coordinate. Regions II and III have a finite length of half the separation distance between the Py electrodes: L/2. The other regions are semi-infinite.

In our 1-dimensional geometry we can identify 6 different regions for which eqs. 7 and 8 have to be solved according to their boundary conditions at the interface. The geometry is schematically shown in Fig. 1b, where the 6 different regions are marked with roman letters I to VI. According to eq. 8 the equations for the spin up electrochemical potentials in these regions, assuming parallel magnetization of the ferromagnetic regions, read:
\[ \mu_\uparrow = A - \frac{e}{\sigma_F} x + \frac{2C}{\sigma_F(1 + \alpha_F)} \exp(-x/\lambda_F) \]  \hspace{1cm} (I) \\
\[ \mu_\downarrow = \frac{-e}{\sigma_N} x + \frac{2E}{\sigma_N} \exp(-x/\lambda_N) + \frac{2F}{\sigma_N} \exp(x/\lambda_N) \]  \hspace{1cm} (II) \\
\[ \mu_\downarrow = \frac{2H}{\sigma_N} \exp(-x/\lambda_N) + \frac{2K}{\sigma_N} \exp(x/\lambda_N) \]  \hspace{1cm} (III) \\
\[ \mu_\downarrow = \frac{je}{\sigma_N} + \frac{2G}{\sigma_N} \exp(-x/\lambda_N) \]  \hspace{1cm} (IV) \\
\[ \mu_\downarrow = \frac{2G}{\sigma_N} \exp(-x/\lambda_N) \]  \hspace{1cm} (V) \\
\[ \mu_\downarrow = B + \frac{2D}{\sigma_F(1 + \alpha_F)} \exp(-x/\lambda_F) \]  \hspace{1cm} (VI)

where we have written \( \sigma_\uparrow = \sigma_F(1 + \alpha_F)/2 \) and \( A, B, C, D, E, F, G, H \) and \( K \) are 9 unknown constants. The equations for the spin down electrochemical potential in the six regions of fig. 3 can be found by putting a minus sign in front of the constants \( C, D, E, F, H, K, G \) and \( \alpha_F \) in eqs. I to VI. Constant \( B \) is the most valuable to extract from this set of equations, for it gives the difference between the voltage measured with a normal metal probe at the center of the normal metal cross in fig. 3, and a ferromagnetic voltage probe. Solving the eqs. I to VI by taking the continuity of the spin up and spin down electrochemical potentials and the conservation of spin up and spin down currents at the 3 nodes of Fig. 3b, one obtains:

\[ B = -\frac{je}{2(M + 1)} \frac{\alpha_F^2 \lambda_N}{\sigma_N} e^{-L/2\lambda_N} \]  \hspace{1cm} (9)

where \( M = (\sigma_F \lambda_N/\sigma_N \lambda_F)(1 - \alpha_F^2) \).

In the situation where the ferromagnets have an antiparallel magnetization alignment, the constant \( B \) of eq. 4 gets a minus sign in front. Upon changing from parallel to anti-parallel magnetization configuration (a spin valve measurement) a difference of \( \Delta \mu = 2B \) will be detected in electrochemical potential between a normal metal and ferromagnetic voltage probe. This leads to the definition of the so-called spin coupled or spin dependent resistance of \( \Delta R = \frac{2B}{\sigma_F \lambda_N} \):

\[ \Delta R = \frac{\alpha_F^2 \lambda_N}{(M + 1)[\sigma_F \lambda_N] e^{-L/2\lambda_N}} \]  \hspace{1cm} (10)

Equation 10 shows that for \( \lambda_N << L \), the magnitude of the spin signal \( \Delta R \) will decay exponentially as a function of \( L \). In the opposite limit, \( \lambda_F << L << \lambda_N \), the spin signal \( \Delta R \) has a 1/L dependence:

\[ \Delta R = \frac{2\alpha_F^2 \lambda_N^2}{M(M + 1)(\sigma_F \lambda_N)AL} \]  \hspace{1cm} (11)

Actually, for eq. 10 to hold a more precise constraint has to be full filled, requiring the relation \( ML/2\lambda_N >> 1 \) to be satisfied. However, the important point to notice is that eq. 10 clearly shows that even in the situation when there are no spin flip processes in the normal metal (\( \lambda_N = \infty \)), the spin signal \( \Delta R \) is reduced with increasing \( L \). The reason is that the spin dependent resistance of the injecting and detecting ferromagnets remains constant for the two spin channels, whereas the spin independent resistance of the normal metal increases linearly with \( L \).

Finally, the current polarization at the interface of the current injecting contact, defined as \( P = \frac{I_{\uparrow} - I_{\downarrow}}{I_{\uparrow} + I_{\downarrow}} \), can be calculated. For parallel magnetized ferromagnetic electrodes the polarization \( P \) yields:

\[ P = \frac{\alpha_F}{M + 1} \]  \hspace{1cm} (12)

In the limit that \( L = \infty \) we obtain the polarization of the current at a single F/N interface:

\[ P = \frac{\alpha_F}{M + 1} \]  \hspace{1cm} (13)

IV. SAMPLE FABRICATION

We use permalloy \( Ni_{80}Fe_{20} \) (Py) electrodes to drive a spin polarized current into copper (Cu) crossed strips, see fig. 2.

FIG. 2. Scanning electron microscope (SEM) picture of the lateral mesoscopic spin valve device. The two horizontal strips are the ferromagnetic electrodes Py1 and Py2. A copper cross is placed in between the Py electrodes, which vertical arms lay on top of the Py electrodes. A total of 10 contacts (not all visible) are connected to the device.

The devices are fabricated in two steps on a thermally oxidized Si wafer by means of conventional e-beam lithography with PMMA resist. To avoid magnetic fringe fields
from the ferromagnetic electrodes, the 40 nm thick Py electrodes were sputter deposited first on a thermally oxidized silicon substrate, using a 2 nm tantalum (Ta) adhesion layer and applying a small B-field of 3 mT along the long axis of the Py electrodes. In the second fabrication step, 50 nm thick crossed Cu strips were deposited by e-gun evaporation in a 10\textsuperscript{-8} mbar vacuum. Prior to the Cu deposition, around 5 nm of Py material was removed of the Py electrodes by ion milling, thereby removing the oxide to ensure transparent contacts. The conductivities of the Py and Cu films were determined to be $\sigma_{Py} = 6.6 \times 10^5 \Omega^{-1} m^{-1}$ and $\sigma_{Cu} = 3.5 \times 10^7 \Omega^{-1} m^{-1}$ at RT. At 4.2 K both conductivities increased by a factor 2.

V. MAGNETIC SWITCHING OF THE PY ELECTRODES

The resistance of a single ferromagnetic strip is a few percent smaller when the magnetization direction is perpendicular to the current direction as compared to a parallel alignment. This effect is known as the anomalous magneto resistance(AMR) effect\[5]. The AMR effect can therefore be used to monitor the magnetization reversal processes in mesoscopic wires\[6]. Different models can be considered for describing the magnetization reversal processes in mesoscopic wires\[5,6].

A. Magnetization reversal models

The simplest description is provided by the Stoner and Wohlfarth model (SW)\[8]. It assumes a single ferromagnetic domain and coherent magnetization rotation. Neglecting the magneto-crystalline anisotropy, the total energy for an ellipsoid of revolution is written as a sum of magnetostatic and shape anisotropy energies:

$$E = \frac{\mu_0 M_s^2}{2} (D_z - D_x) \cos^2(\phi - \theta) - \mu_0 H M_s \cos \phi,$$  

(14)

where $M_s$ is the saturation magnetization, $D_z$ and $D_x$ are the demagnetization factors, and $\phi$ and $\theta$ are the angles between the magnetization direction and the applied field, and, respectively, the external field and the easy axis. The first term on the right of eq. (14) represents the shape anisotropy energy of the ellipsoid, which is equal to the magnetostatic self-energy of the particle. For an elongated ellipsoid along the z-axis, the demagnetization factors would be $D_z = 0.5$ and $D_x = 0$. The angle between the magnetization and the applied field for a given field can be determined analytically by minimizing the total energy. The switching or coercive field as a function of the direction of the applied field reads:

$$H_c(\theta) = H_0^w (\sin^{2/3} \theta + \cos^{2/3} \theta)^{-3/2},$$  

(15)

where $H_0^w = M_s (D_z - D_x)$ is the saturation field in perpendicular ($\theta = 90^\circ$) direction, which corresponds to the demagnetization field along the (short) x-axis of the ellipsoid of revolution. We thus obtain an upper value estimate of the switching field for a permalloy ellipsoid of: $\mu_0 H_0^w = 5400 \text{mT}$, using $M_s = 860 \text{kA/m}$.

However for fields applied parallel to the easy axis (small $\theta$) of a mesoscopic wire, it was found that the switching field is one order of magnitude smaller than the SW-model predicts\[7,8]. To explain these low switching fields two other switching mechanisms have been proposed: a magnetization curling process and a domain-wall nucleation process.

The curling model assumes that the magnetization direction rotates in a plane perpendicular to the anisotropy axis of the wire, effectively reducing the longitudinal component of the magnetization and hence the magnitude of the switching field\[7,8]. For rectangular shaped strips, the upper and lower bound of the magnitude of the switching field have been calculated for a B-field applied parallel to the easy axis ($\theta = 0^\circ$) of the strip. For aspect ratios $d/h < 4$, where $2d$ is width and $2h$ is the height of the strip, these upper and lower bounds are the same. The magnitude of switching field for a magnetic field applied parallel to the easy axis ($\theta = 0^\circ$), as calculated by Aharoni, can then be written as:

$$H_c^{curl}(0^\circ) = \frac{\pi}{2} M_s \frac{d^2}{d^2},$$  

(16)

where $d_s = \sqrt{A/M_s}$ is the exchange length, $A$ being the exchange constant and $M_s$ is the saturation magnetization. For permalloy we find that $d_s \approx 12 \text{nm}$, using $A = 1 \times 10^{-11} \text{J/m}$ and $M_s = 860 \text{kA/m}$. For a 100 nm wide rectangular Py electrode and a field applied parallel to the long (easy) axis, we would thus obtain a switching field of $H_c^{curl}(0^\circ) = 91 \text{mT}$.

The other mechanism assumes that the switching of the magnetization is mediated by the nucleation of a domain-wall\[9]. A domain-wall is nucleated (annihilated) when the cost of exchange energy associated with the domain wall is lower (higher) than the gain in magnetostatic energy upon increasing the external field. Once it is nucleated it sweeps through the material, thereby lowering the total magneto static energy. This mechanism has been confirmed experimentally by Lorentz micrography by Otani\[10]. Recent MFM studies of 1 $\mu$m wide iron and permalloy wires seem to indicate that in these wires a multi-domain structure is formed during the reversal process\[9]. However an analytical expression of the magnitude of the nucleation field cannot easily be given, as one has to numerically solve the time dependent Landau-Lifschitz equations for each value of the applied magnetic field.
B. The AMR behavior of rectangular Py electrodes

The AMR behavior of the 150, 500 and 800 nm wide rectangular Py electrodes used in the spin valve samples, as shown in fig. 2 was measured four terminal by using contacts 1 and 4 as current contacts and 2 and 3 as voltage contacts. In fig. 3 the magneto resistance behavior at \( T = 4.2 \text{K} \) of the 2.0 \( \times 0.8 \mu m^2 \) (bottom curves) and 2.0 \( \times 0.5 \mu m^2 \) (top curves) sized Py electrodes is shown, where the magnetic field is applied parallel to the long axis of the Py electrode (\( \theta = 0^\circ \)).

Coming from a negative B-field the 2.0 \( \times 0.8\mu m^2 \) electrode already has a change in the resistance before the magnetic field reaches zero. After this first drop in the resistance at \(-3 \mu T\), a broad step like transition range is observed up to \(+15 \mu T\), which indicates that the Py strip breaks up in a multiple domain structure. The amplitude of the AMR signal is about 3.3\% of the total resistance, which is a commonly reported value in literature. The 2.0 \( \times 0.5\mu m^2 \) Py electrode shows a more ’ideal’ switching behavior, showing only a resistance change after the magnetic field has crossed zero and showing a much narrower transition range from 7 to 14 mT. However, the amplitude of the resistance dip has changed to 0.7\%. Taking the minimum of the resistance dip as the switching field we find a value of 10 mT, which is much below the SW switching field of \( \mu_0H_{sw} = 540 \mu T \). Applying eq. 1 to calculate the curling switching field is not allowed, as the ratio \( d/h \) of this electrode is bigger than 4 (\( d/h = 13 \)).

C. Magneto resistance behavior of the Py/Cu contacts

A possible formation of a domain structure in the Py electrodes is important for a spin valve measurement, since the spin flip length of Py is very short (\( \lambda \approx 5 \) nm, see fig. 3) as compared to the domain size. In case of domain formation the magnetization direction of the injecting and detecting electrodes would be determined by the local domain(s) present at the Py/Cu contact area which could a have different magnetic switching behavior as the entire Py electrode.

Figure 3 shows the ”contact” magneto resistance behavior at \( T = 4.2K \), 2mT of three rectangular Py electrodes with dimensions: 2.0 \( \times 0.8 \mu m^2 \), 2.0 \( \times 0.5 \mu m^2 \), 14.0 \( \times 0.15 \mu m^2 \).

For the narrowest strip with a width of 150 nm (see fig. 2) we do not observe any magneto resistance signal in parallel field, which is an indication that this electrode behaves as a single domain or reverses its magnetization by means of a fast domain wall sweep.
behavior as the magneto resistance plots of the entire strips shown in fig. 3, except that there seems to be more asymmetry. For the 500 nm wide electrode a 'positive' peak is shown in the positive sweep direction and a 'negative' peak in the negative sweep direction. This indicates that the magnetization reversal process is different for a positive and negative magnetic field sweep, resulting in different domain structures at the Py/Cu contact. However, it is important to note that amplitude of the 'contact' magneto resistance can be as high as 7nΩ for the 800 nm wide Py electrode. This magnitude is large as compared to the amplitude of the spin valve effect, as we will show in the next section.

For the 150 nm wide Py electrode( bottom curve) a "contact" magneto resistance behavior is observed, which appearance resembles much of a Hall signal, showing a difference in resistance at large negative and positive magnetic fields. A Hall voltage perpendicular to the substrate surface (z-direction) can be expected, as Py electrode is etched prior to the Cu deposition, causing the Cu wire to be a little bit 'sunk' into the Py electrode. Changing one voltage probe from contact 7 to contact 9 (at the other side of the Py/Cu contact area, see fig. 2) produces the same signal. Also the signal amplitude of 0.3 mΩ lies in the range of a Hall signal, which would have a maximum of 1 mΩ, using a Cu Hall resistance of 1 mΩ/T for a 50 nm thick film and a maximal obtainable magnetic field change upon magnetization reversal of about 1 T. When we take the position of the Hall step as the switching field at 42 mT, we find a good agreement with the curling switching field \( H_{\text{curl}}^c(0^\circ) = 40 \text{ mT} \) for a width \( 2d = 150 \text{ nm} \).

VI. THE SPIN VALVE EFFECT

Two different measurement geometries are used to measure the spin valve effect in our device structure, the so called 'conventional' geometry and 'non-local' geometry. In the conventional measurement geometry the current is sent from contact 1 to 7 and the signal \( R = V/I \) is measured between contacts 4 and 9, see fig. 2. In the non-local measurement geometry the current is sent from contact 1 to 5 and the signal \( R = V/I \) is measured between contacts 6 and 9, see also fig. 2a. This technique is similar to the "potentiometric" method of Johnson used in ref. 8. The difference between the two measurement geometries is that the conventional geometry suffers from a relatively large background resistance as compared to the spin valve resistance. The bad news is that this background resistance includes also small parts of the Py electrodes underneath the vertical Cu wires of the cross and the Py/Cu interface itself, which give rise to the "contact" magneto resistance as was described in the previous section. Experimental measurements show that the spin valve signal can be completely dominated by the "contact" magneto resistance of the Py electrodes.

A. Spin valve measurements

The measurements were performed by standard ac-lock-in-techniques, using current magnitudes of 100 µA. The spin valve signals of two different samples (of the same batch) with a separation distance of \( L = 250 \text{ nm} \) are shown in fig. 4 and 5. The first sample, see fig. 4, had a current injector Py electrode of size \( 2 \times 0.8 \mu m^2 \), whereas the detector electrode had a size of \( 12 \times 0.5 \mu m^2 \).

The second sample, see fig. 5, had narrower Py electrodes of \( 2 \times 0.5 \mu m^2 \) and \( 14 \times 0.15 \mu m^2 \). This difference in width of the Py electrodes can be observed in the increased switching fields of the second sample.

![Fig. 5. The spin valve effect using a conventional measurement geometry (top curve) at \( T = 4.2 \text{ K} \) and non-local measurement geometry (bottom curve), with a Py electrode spacing \( L = 250 \text{ nm} \). The sizes of the Py electrodes are \( 2 \times 0.8 \mu m^2 \) (Py1) and \( 14 \mu m \times 0.5 \mu m^2 \) (Py2). The B-field is applied parallel to the long (easy) axis of the Py electrodes. The solid(dotted) curve corresponds with a negative (positive) sweep direction of the B-field.](image-url)
fore conclude that the 'contact' magneto resistance of the 800 and 500 nm wide Py electrodes are completely dominating the magneto resistance signal in a conventional measurement geometry, making it impossible to detect a spin valve signal.

For the sample with Py electrodes of sizes $2 \times 0.5 \mu m^2 \ \text{and} \ 14 \times 0.15 \mu m^2$ a spin valve signal can be observed in the conventional geometry. This is shown in the top curve of fig. 6. A small magneto resistance dip around 10 mT can be observed in this sample upon switching from parallel to the anti-parallel magnetization configuration. The position of this peak in the magnetic field sweep and the amplitude of $2 \Omega$ correspond to the 'contact' magneto resistance behavior of the $2 \times 0.5 \mu m^2$ Py electrode, see fig. 6. However, after the magnetization of this Py electrode has switched, we observe a resistance 'plateau' up to a magnetic field of 45 mT, where the second 150 nm wide Py electrode switches. The magnitude of the spin valley effect measured in the conventional geometry is about 4 $\Omega$. This is more than 2 times bigger than the magnitude of the spin signal of 1.6 $\Omega$ (at $T = 4.2$ K), measured in a 'non-local' geometry, as shown in the bottom curve of fig. 6 (see also ref. 3). Calculations show (see eq. 3) that the magnitude of the spin valley signal measured in a conventional geometry should be twice the magnitude of the spin valley signal measured in the non local geometry. At this moment we do not clearly understand why the measured ratio of the two spin signals is slightly larger than 2 (factor of 2.5).

**B. Dependence on Py electrode spacing**

A reduction of the magnitude of spin signal $\Delta R$ is observed with increased electrode spacing $L$, as shown in fig. 6. By fitting the data to eq. 10 we have obtained $\lambda_N$ in the Cu wire. From the best fits we find a value of 1 $\mu m$ at $T = 4.2$ K, and 350 nm at RT. These values are compatible with those reported in literature, where 450 nm is obtained for Cu in GMR measurements at 4.2 K. However one should be careful to make a straightforward comparison between the GMR results and ours. In the thin films we use, the elastic mean free path of the electrons is limited by surface scattering, causing the conductivity of the Cu to be smaller than in GMR layers.

We can calculate the spin flip time $\tau_N$ in the Cu wire, using a Fermi velocity $1.59 \cdot 10^6 \ \text{m/s}$. At $T = 4.2$ K we find $\tau_N = 42 \ \text{ps}$, while at RT $\tau_N = 11 \ \text{ps}$. Comparing the spin flip time to the elastic scattering time $\tau_e = 2.9 \cdot 10^{-14} \ \text{s}$ at $T = 4.2$ K, we find that on average the spin is flipped after about $10^3$ elastic scattering events in the Cu wire.

In principle the fits of fig. 6 also yield the spin polarization $\alpha_F$ and the spin flip length $\lambda_F$ of the Py electrodes. However, the values of $\alpha_F$ and $\lambda_F$ cannot be determined separately, as in the relevant limit ($M >> 1$) which applies to our experiment (12 $<< M << 26$), the spin signal $\Delta R$ is proportional to the product $\alpha_F \lambda_F$. From the fits we find that $\alpha_F \lambda_F = 1.2$ nm at 4.2 K and $\alpha_F \lambda_F = 0.5$ nm at RT. Taking, from literature, a spin flip length in the Py electrode of $\lambda_F = 5$ nm (at 4.2 K), a bulk current polarization of 22 % in the Py electrodes at $T = 4.2$ K is obtained: $\alpha_F = 0.22$. These values are
in the same range as the results obtained from the analysis of the GMR effect. However, the current polarization $P$ at the interface of the current injecting Py electrode is much lower. Using eq. 12, a polarization $P$ for the samples with the smallest Py electrode spacing of $L = 250$ nm at $T = 4.2$ K is found to be only 2%. $P = 0.02$. The reason for this reduction is caused by the unfavorable ratio of the 'small' spin dependent resistance ($\lambda_F^s/\sigma_F$) and the 'large' spin independent resistance ($L/\sigma_N$), which applies even in the absence of spin flip scattering events in the normal (Cu) metal.

### VII. CONCLUSIONS

We have demonstrated spin injection and accumulation in a mesoscopic spin valve. We have shown that in conventional measurement geometry the magneto resistance effects of the injecting and detecting contacts can be much larger than the spin valve effect. These contact effects can be used to monitor the magnetization reversal process of the spin injecting and detecting contacts. In a non-local measurement geometry we can completely isolate the spin valve effect, as was reported earlier in ref. [8]. Using this geometry we find a spin flip length in Cu of around 1 $\mu$m at $T = 4.2$ K and 350 nm at RT. For the smallest Py electrode spacing, the magnitude of the spin signal and the current polarization $P$ in the Cu wire are limited by the unfavorable ratio of the spin independent resistance of the Cu strips ($L/\sigma_N$) and the spin dependent resistance of the Py ferromagnet ($\lambda_F^s/\sigma_F$).

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