Chapter 8

Observation of spin injection in an all-metal mesoscopic spin valves

The electrical injection of spin polarized electrons can be achieved in principle by driving a current from a ferromagnetic metal, where current is known to be significantly spin polarized, into the semiconductor or normal metal via ohmic conduction. For detection a second ferromagnet can be used as drain. Here we report the electrical injection and detection of spin currents and spin accumulation at room temperature in an all-metal lateral mesoscopic spin valve. The ferromagnets were making good ohmic contact either to a Cu cross. In the all-metal case we observe a clear spin accumulation signal. Due to spurious magnetoresitive contribution of the ferromagnetic electrodes, this could only be detected in a non-local geometry. Our results are in quantitative agreement with the theoretical predictions based on a diffusive model.

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8.1 introduction

An exciting new direction in the field of spin based electronics or 'spintronics', is the possibility to generate, control and apply spin polarized currents [1-3]. Spin currents and the associated phenomenon of spin accumulation can be created by driving a current from a ferromagnetic electrode into a non-magnetic metal or semiconductor. This was first demonstrated in a spin injection experiment by Johnson and Silsbee on a single crystal aluminium bar at 27K [4]. recent experiments have shown successful optical generation and detection of spin injection in semiconductors at low temperatures, using circularly polarized light and magnetic semiconductors [5-7]. However, the realization of fully electrical spin injection as well as detection at room temperature has remained outstanding. Here we report the electrical injection and detection of spin currents and spin accumulation at room temperature in an all-metal lateral mesoscopic spin valve.

Spin accumulation plays an important role in spin polarized phenomena as giant magnetoresistance (GMR), domain wall magnetoresistance and spin current induced magnetization switching experiments [8-11]. This makes it desirable to study the effect isolated from other spin related phenomena, such as spin dependent interface scattering, anisotropic magnetoresistance(AMR) and Hall effects. Large spin accumulation effects have been claimed by Johnson using a ferromagnet - normal metal - ferromagnet geometry [12-13]. However the interpretation of the data has raised problems since the magnitude of the observed effect require a polarization in the normal metal very close to 100% [14-17]. Another problem is that the magnetoresistance of the ferromagnetic contacts, such as AMR and Hall effects, can mask or even mimic the spin accumulation signal.

We have fabricated mesoscopic lateral spin valves to completely isolate the spin accumulation signal, using a multiterminal geometry. In our experiment we use NiFe electrodes to drive a spin polarized current into copper (Cu) strip, see fig 1. We observe clear spin signals at T=4.2K, as well as room temperature. From our analysis we deduce a spin flip length in the Cu wire of about 1µm at 4.2K, which is reduced to around 350nm at room temperature.

8.2 device fabrication

Two batches of samples were made in a two step lift-off process, using e-beam lithography for patterning. The frist batch (i) had a fixed Py electrode spacing (i),
whereas in the second batch (II) L is varied from 250 to 2\( \mu m \). To avoid magnetic fringe fields from the ferromagnetic electrodes, the 40nm thick Py electrodes were sputtered first on a thermally oxidized substrate. Different geometric ratios of Py1 and Py2 are used to obtain different coercive fields [19]. These allow to control the relative magnetization configuration (parallel/anti-parallel) of the Py1 and Py2, by sweeping an applied magnetic field, directed parallel to their easy magnetic axis. The sizes of the Py1 and Py2 in the batch I were 2.0x0.8\( \mu m^2 \) and 14x0.5\( \mu m^2 \) respectively, as shown in fig 1a. An additional set of Py1 and Py2, with sizes of 2.0x0.5\( \mu m^2 \) and 14x0.1\( \mu m^2 \), was used in batch 2. This set showed an improved magnetic behavior and had 3 times larger coercive fields.

In the second fabrication step, 50nm thick crossed Cu strips were deposited by e-gun evaporation in \( 1.010^{-8} \) mbar. Prior to the Cu deposition, the oxide of the Py electrodes was removed by ion milling, to ensure transparent contacts. The conductivities of the Py and Cu films were determined to be \( \sigma_{py} = 6.6 \cdot 10^7 \Omega m^{-1} \) and \( \sigma_{cu} = 3.5 \cdot 10^7 \Omega m^{-1} \) at RT. The RRR ratio was 2 for both metals.

### 8.3 non-local spin valve measurements and analysis

The measurements were performed by standard ac-lock-in techniques, using current magnitudes of 100\( \mu A \) to 1mA. First we note that in the conventional spin valve geometry (sending a current from contacts 1 to 7, and measuring the voltage between contacts 4 and 9), the signal was completely dominated by the AMR and Hall effects of the Py contacts, having a typical magnitude of 10m\( \Omega \). Although we have used the AMR signal to confirm the switching of the Py electrodes, its presence has made any observation of a spin signal in the conventional geometry impossible.

However, in the non-local spin valve geometry, see fig 8.1b, the spurious effects can be eliminated. This technique is similar to the potentiometric method of Johnson. However in our case we have completely separated the current and voltage circuits. Current now enters from contact 1 (Py1) and is extracted at contact 5 (Cu), whereas the voltage is measured between contact 6 (V\(_{Cu}\)) and contact 9 (V\(_{Py}\)). Changing the relative magnetization configuration from parallel to anti-parallel will yield a signal only if the densities (electrochemical potentials) of the spin-up and the spin-down electrons in the center of the Cu cross are unequal. In a parallel configuration it will measure a lower value. Changing from parallel to anti-parallel configuration will therefore decrease the voltage V\(_{Py2}\) measured by
Py2, resulting in an increase in the voltage difference \((V_{Cu} - V_{Py})\) measured, and hence an increase in the resistance.

Figures 2a and b show typical data taken at 4.2K and room temperature for a sample from batch 2, with 250nm Py electrode spacing. While sweeping the mag-
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FIGURE 8.2. The spin valve effect at $T=4.2\text{K}$ (a) and room temperature (b) in the non-local geometry for a sample with 250nm Py electrode spacing. An increase in the resistance is observed, when the magnetization configuration is changed from parallel to anti-parallel configuration. The solid (dashed) lines correspond to negative (positive) sweep direction. c, d The ‘memory’ effect. For clarity c and d are offset downwards. We note that the vertical scale of a is different from that of b, c and d. The sizes of Py1 and Py2 electrodes are $2.0 \times 0.5\mu m^2$ and $14 \times 0.1\mu m^2$. 
netic field from negative to positive field, we observed an increase in the resistance when the magnetization of the Py1 flips at 9mT, resulting in an anti-parallel magnetization configuration. When the magnetization of Py2 flips at 47mT (4.2K) and 38mT (RT), the magnetization are parallel again, but now point in the opposite directions. The magnitude of the background resistance, around $30 \, \text{m} \Omega$ at 4.2K and $120 \, \text{m} \Omega$ depends on the geometrical shape of the Cu cross and is typically a fraction of the Cu square resistance.

Figure 8.2 c and d shows the 'memory effect'. Coming from high positive magnetic fields, the sweep direction of $\mathbf{B}$ is reversed after Py1 has switched, but Py2 has not. At the moment of reversing of the sweep direction, the magnetic configuration of Py1 and Py2 is anti-parallel, and accordingly a higher resistance is measured. When the magnetic field is swept to its original high positive value, the resistance remains at its increased value until Py2 switched back at a positive field of $8 \, \text{mT}$. At zero $\mathbf{B}$ field the resistance can have two different values, depending on the magnetic history of the Py electrodes. Samples with larger Py electrode spacing show identical switching behavior, but the magnitude of the spin signal $\Delta R$ is reduced, as we will discuss below.

![Figure 8.3](image_url)

**Figure 8.3.** Dependence of the magnitude of the spin signal $\Delta R$ on the Py electrode distance $L$. The solid squares represent data taken at T=4.2K; the solid circles represent data taken at room temperature. The solid line represent the best fits based on equation (8.1)
We have calculated the theoretically expected magnitude and the Py electrode distance dependence of the spin valve signal $\delta R$ for the non-local geometry fig. 8.1b in the diffusive transport regime and for transparent interfaces, following the lines of the standard Valet Fert model for GMR [20,21], adapted for our multi-terminal geometry. We obtain [22]:

$$\Delta R = \frac{\alpha_F^2 \lambda_N}{(M+1)(M \sinh(l/2\lambda_N) + \cosh(l/2\lambda_N))}$$

(8.1)

with

$$M = \frac{1}{1 - \alpha_F \lambda_F \sigma_N}$$

(8.2)

where $\alpha_F = (\sigma_1 - \sigma_1)/(\sigma_1 + \sigma_1)$ is the bulk current polarization of the Py electrodes, $\sigma_1(\sigma_1)$ are the spin up (down) conductivities in the metal, $\sigma_N(\sigma_F)$ is the total conductivity of the normal metal (ferromagnet), $\lambda_N(\lambda_F)$ is the spin flip length in the normal metal (ferromagnet), $L$ is the distance between the two Py electrodes, and $A$ is the cross-sectional area of the normal metal wire. Equation 8.1 implies that for $\lambda_N \ll L$, the magnitude of the spin signal $\Delta R$ will decay exponentially as a function of $L$. In the opposite limit $\lambda_F \ll L \ll \lambda_N$, the spin signal has a $1/L$ dependence. We note that the spin signal $\Delta R$ is determined by the bulk conductances of the ferromagnet and of the normal metal over a distance of the spin flip lengths. The origin of the spin signal is therefore different from the spin dependent transport in tunnel junctions experiments, where the density of states at the interface is crucial, whereas for transparent contacts, which is the case in our devices, the interface properties are expected to be less important [16,22].

We have measured the reduction of the magnitude of spin signal $\Delta R$ as function of the Py electrode spacing $L$, as shown in fig. 8.3. By fitting the data to eq. 8.1 we have obtained $\lambda_N$ in the Cu wire. From the best fits we find that $\lambda_N = 1 \pm 0.2 \mu m$ at $T = 4.2 K$ and $\lambda_N = 350 \pm 50 nm$ at room temperature. The obtained values are compatible with those reported in the literature [24]: $\lambda_N \approx 450 nm$ for Cu in GMR measurements at 4.2K. However, we cannot 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 the surface scattering, causing the conductivity of the Cu to be much smaller than in GMR multilayers. We also note that in fig. 8.3 no good fit can be obtained for the data where $L = 250 nm$. As the Py spacing is approaching the width $W$ of the Cu wire, the presence of the side arms (fig 8.1.a) will give rise to a local enhancement of the conductance of the Cu cross and hence
can result in an increase in the spin signal. Therefore in this limit we can expect deviations from our one-dimensional model.

We can calculate the spin flip times \( \tau_{sf} \) in the Cu wire, using a Fermi velocity \( v_F = 1.57 \times 10^6 \text{m/s} \) \( \text{(ref. 25)} \). At 4.2K we find \( \tau_{sf} = 42 \text{ps} \), while at room temperature \( \tau_{sf} = 11 \text{ps} \). We will not discuss the physics of the spin flip scattering processes er. However, comparing the spin-flip time with the elastic scattering time \( \tau_e = 2.9 \times 10^{-14} \text{s} \) at 4.2K, 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 8.3 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, because in the relevant limit \( (M \gg 1) \) which applies to our experiment \( (12 < M < 36) \), the spin signal is proportional to the product \( \alpha_F^2 \lambda_F^2 \). From the fits we find that \( \alpha_F \lambda_F = 1.2 \text{nm} \) at 4.2K and \( \alpha_F \lambda_F = 0.5 \text{nm} \) at room temperature. Taking from refs. 17 and 18 a spin flip length in the Py of \( \lambda_F = 5.5 \text{nm} \) (at 4.2K) a bulk current polarization of 22\% in the Py electrodes is found: \( \alpha_F = 0.22 \). These values are in the same range as the results obtained from the analysis of the GMR effect \[10,11,18,?,24\].

With the obtained parameters we can calculate the maximum current polarization \( P = I_\uparrow - I_\downarrow / I_\uparrow + I_\downarrow \) in the Cu wire. For the samples with the smallest Py electrode spacing we obtain \( P \approx 2\% \text{at 4.2K} \). When we scale the observed signals to the device cross sections, we find that the scaled spin-valve signals of refs. 13 and 14 are typically four orders of magnitude larger than ours. This contract corresponds with the need to invoke a spin polarization of the current in the normal metal of about 100\% to explain the results of refs. 13 and 14 in terms of spin accumulation. In our opinion this must imply that the observed effects of refs. 13 and 14 cannot be related to spin accumulation.

We have thus demonstrated spin injection and accumulation in a mesoscopic spin valve. We find an surprisingly long spin flip length in Cu of around 1\( \mu \text{m} \) at 4.2K and about 350nm at room temperature. 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 \( (\lambda_F/\sigma_F) \). In principle, larger signals can therefore be obtained by a proper choice of materials and geometries.

Finally, we note that our system permits the study of spin transport phenomena, such as controlled spin precession in solid states devices and the control of the spin
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polarized currents at room temperature by additional ferromagnetic contacts [4,26].
References

[1] The work described here was performed in close collaboration with F.J. Jedema.
[23] Note that M includes the bulk conductances over a spin flip length.
Orlando (1976)
