Giant magnetoresistance in multilayers grown on grooved substrates

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Giant Magnetoresistence in multilayers grown on grooved substrates.

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Report of a graduate research project, carried out in the group Experimental and Theoretical Physics of the Philips Research Laboratories in Eindhoven. This work is part of a collaboration between the group Co-operative Phenomena of the section Solid State Physics at the Eindhoven University of Technology and Philips Research.

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Summary

In this report, we present a new method to measure the magnetoresistance in the Current Perpendicular to the Plane (CPP) geometry. The interest of the CPP geometry lies in the predicted and experimentally observed high magnetoresistance values. Magnetic field sensors based on magnetoresistance effects are already in use in read-heads for various information storage media (DCC, Hard-disks).

The new method we present is based on growing the multilayer on a grooved InP substrate. This gives rise to a natural CPP-like configuration. The technique is demonstrated with a study on Co/Cu multilayers with Co thicknesses varying from 1.5 nm to 50.0 nm, and Cu thicknesses from 4.0 nm to 50.0 nm. Both the CPP and the Current-in-plane CIP magnetoresistance were measured from liquid helium temperature up to room temperature. A maximum magnetoresistance effect of 37% is found for a 32x[1.5 nm Co + 6.0 nm Cu] multilayer at 4.2 K. Our results are comparable with those obtained by other groups using different techniques.

We analyse our data, using a two-channel magnetoresistance model. We are able to determine the temperature dependence of the resistances involved, as well as the temperature dependence of the spin-dependent scattering parameters.
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1. Introduction

1.1 General introduction

It is known for about a century that the resistance in a conductor changes when a magnetic field is applied. This phenomenon is called magnetoresistance (MR). It is not difficult to understand this 'classical' or 'normal' magnetoresistance effect. It arises from the fact that the path of an electron in a conductor changes when a magnetic field is applied due to the Lorentz force. As a result of this, the fraction of the mean free path length in the direction of the net current decreases, and the resistance increases. This effect occurs in every conducting material, magnetic as well as nonmagnetic, and it also occurs in bulk materials as well as in thin films.

Around 1950 there was renewed interest in the so-called anomalous or anisotropic magnetoresistance (AMR) effect, which was discovered a century before by William Thomson, Lord Kelvin. This effect occurs in ferromagnetic materials and has its origin in the existence of an angle between the magnetisation and the current direction. Electrons which are moving parallel to the magnetisation of the material are scattered more than electrons moving perpendicular to the magnetisation. The resistance in the former case is thus higher than in the latter case. The magnitude of this effect ranges from 5% in some bulk materials to 1% in thin films. This magnitude is defined as the maximum difference in resistance between the limiting cases (zero field resistance value minus high field resistance value, compared to the high field value). More details can be found in [1].

An important technological application of materials which exhibit this effect is their use in reading heads in magnetic recording equipment. Since the discovery of magnetic recording, the reading method was usually based on the induction principle. A great disadvantage of this method is its indirect nature: the induction current caused by a change in the magnetic field is detected, rather than the field itself. To obtain higher information densities a direct detection method was needed, and a magnetoresistive sensor which uses the AMR effect provides such a direct method. It also enables the use of digital information storage. This type of sensor is now often used in hard disk technology, and is also used in the read head of the DCC player.

Because of its rather small effect, the AMR sensor also has its limitations in information density. In order to further increase the performance of magnetic reading equipment, a larger effect had to be found. This happened in 1988, when a magnetoresistance effect was found in multilayers consisting of ferromagnetic layers separated by nonmagnetic layers. The effect can be as high as 220% [2] in Fe/Cr multilayers, so this type of magnetoresistance effect was called giant magnetoresistance (GMR) effect.

Later an even bigger effect was detected in some MnO based bulk materials, at low temperatures and at high fields. This was called the colossal magnetoresistance effect. However, no important application for this last effect seems imminent in the near future.
For GMR sensors, however, some applications are expected in the near future. Because of the higher effect, lower currents can be applied to detect the same signal. Consequently an improvement in accuracy, storage density or power need can be achieved. Several research labs in the world, both industrial and at universities, are now looking for a way to make this type of sensor suitable for use in electronic devices [3,4,5]. These labs include the Philips Research Laboratories and the Eindhoven University of Technology. The present work is part of this research.

1.2 The giant magnetoresistance effect

To get an idea about what causes the GMR effect in a multilayer, it is useful to look at Figure 1-1. In this picture bulk scattering, as well as interface scattering is taken into account.

![Figure 1-1: Schematic view of the two different scattering situations. The thick arrows indicate the magnetisation direction, the thin arrows the spin direction. FM means ferromagnetic layer, NM means nonmagnetic layer.](image)

In this figure the multilayer is represented by two layers of ferromagnetic (FM) material separated by a layer of nonmagnetic (NM) material. It has been shown [6] that there is a coupling between the two ferromagnetic layers across the nonmagnetic layer. This coupling occurs for thin NM layers, up to about 4 nm. The coupling can be ferromagnetic (F) as well as antiferromagnetic (AF).

Electrons, having either spin up or spin down, have a different scattering chance in some situations. The difference occurs for spin parallel or antiparallel to the magnetisation in the ferromagnetic material, because of the difference in band structure for the spin up and spin down situation in these materials. This is discussed more in detail in paragraph 2.1. In a simplified view, it is possible to
understand the mechanism of GMR in the way described below. A more rigorous discussion will be given in the theory chapter.

If the FM layers in the multilayer are aligned antiferromagneticly, a spin up electron encounters as many layers with the magnetisation parallel to its spin as with the magnetisation antiparallel to its spin. The same holds for the spin down electrons, so both types of electrons contribute equally to the resistance.

In the case of ferromagnetic alignment of the FM layers, one of the electron types is scattered often in all FM layers, while the other electron type is scattered less frequently. Which electron type scatters most is dependent on the exact band structure of the material used. For the electron type which scatters least, the resistance of the material is lower than in the AF coupling case, and because the total resistance is heavily dependent on the lowest resistance (the shunting effect), the total resistance is lower in the F case than in the AF case. One of the electron types appears to form a short-circuit in the F case. This can be made clear by a schematic view of the resistances, as is shown in Figure 1-2.

![Figure 1-2: Equivalent resistor model of the two coupling situations. Thick arrows again indicate the magnetisation direction, thin arrows the spin direction. Big blocks indicate a big resistance. Clearly the shunting in the ferromagnetic situation can be observed.](image)

If the ferromagnetic layers in a multilayer are AF coupled, the application of a magnetic field forces the magnetisation in one direction. If the applied field becomes larger than the saturation field, the F situation is formed, in which the resistance is lower. The magnetic field thus changes the resistance, so there is a magnetoresistance effect. This also applies to uncoupled layers, where the magnetisation switches from random to parallel if a magnetic field is applied.
1.3 Short historical background

During the early part of the 1980s it became possible to grow very thin layers of a number of materials, smooth enough to 'build' a multilayer with [7]. This was due to the rapid developments in thin film growing technologies like Molecular Beam Epitaxy (MBE). A new direction in the research became the studying of the transport effects in multilayers with alternating magnetic and non-magnetic layers. In 1986 the group of Peter Grünberg found antiferromagnetic coupling [6,8] between two ferromagnetic layers for certain interlayer thicknesses. Some years later it was calculated [9,10,11] and found experimentally [12,13] that this coupling oscillates as a function of the spacer layer. This was ascribed to the RKKY (Ruderman, Kittel, Kasuya, Yosida) interaction.

The first significant change in resistance in a magnetic field was reported by the group of Albert Fert for an Fe/Cr multilayer [14]. They reported a magnetoresistance effect of about 100% at low temperatures. They also explained the effect by spin-dependent scattering, as was explained in paragraph 1.2. Another early measurement of this effect was reported by the Grünberg group [15], who measured the effect in Fe/Cr/Fe trilayers. This effect, soon called giant magnetoresistance effect, was reproduced in multilayers of different materials in the years that followed. All these layers are MBE-grown, which reduces the practical applications because of the slow growing rate and the complicated system. More experiments on the Fe/Cr system were performed [2,16,17,18]. Record GMR values, as high as 220%, were reported. The disadvantage of this system is the high field that is necessary for saturation of the MR (more than one Tesla), which limits its practical uses. From the practical point of view softer magnetic materials, such as permalloy (Ni_{20}Fe_{80}), are more interesting. This has been examined as well [19,20]. This material is used in the AMR read heads mentioned in paragraph 1.1.

In 1990 the magnetoresistance effect was also observed in high-vacuum sputtered multilayers [12]. This opened the way for more extensive research and applications, because of the strongly reduced sample preparation time. In the same time, a lot of work has been done on the Co/Cu system [19,21,22,23,24], which is quite well known by now. This is one of the reasons why this system was used to experiment with a new measurement set-up, discussed in the present work. A new way of growing multilayers is by means of electrodeposition. This technique is even easier and cheaper then sputtering, because no vacuum facilities are necessary. However, the quality of the layers grown by this method is not always satisfactory [25,26,27,28].

1.4 GMR in the CPP-configuration

All the samples mentioned in the previous paragraph were measured in the configuration with the current in plane (CIP) of the layers, as shown in Figure 1-3. It is difficult to model this configuration theoretically, mainly because of the complex dependence of the conduction process on the individual layer thicknesses. Therefore it is difficult to predict the GMR in this situation. In the configuration with the current
perpendicular to the plane of the multilayer (CPP), also shown in Figure 1-3, this problem does not appear, because all interfaces have to be passed by an electron to get from one end of the multilayer to the other.

![Figure 1-3: Schematic view of the Current In Plane and Current Perpendicular to Plane configuration.](image)

Therefore this configuration is easier to model. For the CPP configuration the predicted effect is also larger, at least in the systems we look at in this work, because no shunting and channelling effects are present [29]. In the CPP configuration all available scatterers come into play, whereas in the CIP configuration they can be bypassed. Unfortunately measuring the CPP configuration is much more difficult than for the CIP configuration, because of the small resistances involved in metallic multilayers. A multilayer can be made quite wide to increase the resistance in the CIP case, but not thick to enhance the resistance in the CPP case. Several solutions to this problem were found in order to measure in the CPP configuration, as shown schematically in Figure 1-4.

The first solution was presented by the Michigan State University group (Schroeder, Pratt Jr., Bass) [30,31,32,33,34], who used superconducting contacting leads and a very sensitive SQUID to measure the very small resistances. The disadvantage of this method is that it can only be used at very low temperatures because of the critical temperature of the superconductor involved. This hinders any practical application of this method. For a number of different multilayers (Co/Cu, Co/Ag, NiFe/Cu and others) a study was performed to determine the spin-dependent scattering parameters of these materials. See Figure 1-4 a).

Another possible solution was introduced by the group of Martin Gijs at Philips Research in Eindhoven [35,36,37,38,39]. They succeeded in increasing the resistance by decreasing the cross-section of the multilayer by means of microlithography (see Figure 1-4 b). They made 'pillars' of multilayer with cross-sections between 10 and 200 μm² and resistances between 10 mOhm and 1 Ohm, which could be measured with a conventional four-probe technique. Because of the difficulties involved in the microlithography process, no systematical studies could be carried out. Typical results for Co/Cu and Fe/Cr are 98% and 110% at 4K.
respectively. This method was also used by Gary Prinz and co-workers, who experimented with Co/Cu/NiFeCo/Cu multilayers [40].

Figure 1-4: Several methods to measure the CPP-MR. a) The superconducting wire technique [30], b) the microstructured pillar technique [35], c) the electrodeposited nanowire technique [42], d) the metal-base transistor method [41], e) the grooved substrate method [46], and f) the CAP method [47].
In their recent paper [41] Monsma et al. introduced still a new method to measure the CPP-GMR, using a Co/Cu multilayer as a base region for an n-silicon metal-base transistor structure (see Figure 1-4 d). They report a 215% change in the collector current, which is due to magnetically tuneable electron transport through the metal base.

Another relatively new approach is trying to enlarge the thickness of the multilayer, while keeping the horizontal dimensions low. Two such methods have been used so far. The first is the growing of multilayer in holes in a membrane [42,43,44], with a typical diameter of 40 nm and a typical length of 6 µm. The multilayer is grown by electrodeposition (see Figure 1-4 c). Because of the constraints of this technique, rather thick layers have to be used, and the quality of the layers is not very good. Therefore the measured effect is not higher than about 20% at low temperatures.

The other construction invented to achieve the increase of the thickness is the connection of separate pillars on a microstructured substrate, as shown in Figure 1-4 e). This was proposed by Shinjo [45], who made CIP multilayer wires, and by the group of Martin Gis [46]. Shinjo recently published experiments on a different geometry on a microstructured substrate [47], the so-called current with an angle to plane (CAP) geometry (Figure 1-4 f)). This geometry is an intermediate case between pure CIP and pure CPP. The subject of this thesis is the study of Co/Cu multilayers deposited at an angle on grooved substrates. In chapter 2 the theory of the magnetoresistance is explained, as far as it is relevant for the understanding of our results. In chapter 3 the fabrication of the samples is described, as well as the apparatus used to perform the various measurements. In chapter 4 the results of the measurements are given, and a discussion is presented. Finally, in chapter 5 some conclusions are drawn.
2. Theory

2.1 Origin of the GMR effect

In paragraph 1.2 was stated that the giant magnetoresistance effect is caused by spin-dependent scattering of electrons, when going through layers of ferromagnetic material and through ferromagnet/normal metal interfaces. The cause of the spin-dependence of the scattering lies in the band structure of ferromagnetic materials. In a simple picture, the 4s electrons are responsible for the conduction of the crystal, while the 3d electrons determine the magnetic properties. The intrinsic magnetic moment of ferromagnetic materials lies in the partial filling of the 3d band in those materials. When a single atom is considered, without interaction with its environment, electron states are discrete states. When this atom is placed in a solid crystal, electron orbitals overlap. The energy states of these electrons spreads into bands, due to the Pauli principle. This principle prohibits two electrons to occupy the same state. Because there are only two s states in each energy level, and ten d states, the 4s band becomes much more stretched in the vertical direction then the 3d band, as is shown in Figure 2-1.

For the magnetic 3d transition metals (Co, Fe, Ni) the forces in the atoms combine in such way that the two bands for spin up and spin down electrons are no longer symmetric. This means that at the Fermi surface a different number of states is available for spin up and spin down electrons. Because the 3d bands are the main scattering centres for the 4s electrons, the 4s spin up and spin down electrons have different scattering probabilities, depending on the available states in the d-bands.

![Figure 2-1: Simplified representation of the band-structure of a) Cu, b) a nonmagnetic transition metal (Cr), and c) the magnetic transition metals Co, Fe or Ni.](image-url)
The spin-dependent scattering at interfaces can be explained in a similar way. However, it is not the difference between the two spin directions in the bulk of the ferromagnetic material that matters most in this case, but the differences between those two levels and the levels in the neighbouring nonmagnetic material. If there is a large difference between the levels, there is a big scattering chance for that spin direction, and if there is a small difference, there is a small scattering chance (the matching principle).

2.2 Oscillatory coupling between multilayers

The other condition necessary for the GMR effect, mentioned in paragraph 1.2, is the possibility to change the magnetisation of the layers from antiparallel to parallel. Actually an antiparallel situation is not strictly necessary, it is sufficient that the system is not ferromagnetically coupled, so in an uncoupled system GMR can be measured as well. An uncoupled system, will have a randomly oriented domain structure.

Discussing the exact mechanism behind the exchange coupling is beyond the scope of this work. A good discussion can be found in [48]. It is worth to mention the oscillatory nature of this coupling. The coupling strength between two ferromagnetic layers proved to be oscillating as a function of the spacer layer. The coupling energy can be written as:

$$E_\text{i} = -J_1 \frac{M_1 \cdot M_2}{|M_1||M_2|} - J_2 \left( \frac{M_1 \cdot M_2}{|M_1||M_2|} \right)^2$$

Here $E_\text{i}$ is the interlayer coupling areal energy density, and $\Delta \varphi$ is the angle between both magnetisations $M_1$ and $M_2$ on both sides of the interlayer. When the coupling strength is plotted as a function of the interlayer thickness, it looks like Figure 2-2. Because of the form of the plot, with several intersections of the zero coupling axis, it is clear that the coupling can be ferromagnetic as well as antiferromagnetic, corresponding with positive respectively negative coupling strength values.
Theory

2.3 The two-channel model

To describe the magnetoresistance of a multilayer, one can use the so-called two-channel model. In this model, it is assumed that there are two independent spin channels carrying current. The assumption of independence is only valid in the low-temperature limit, when the spin flip scattering length $l_{sf}$ is much larger than the bilayer thickness $t_F + t_N$. A schematic view of the equivalent circuit of this model is given in Figure 2-3.

![Schematic view of the equivalent circuit for the two-channel model](image)

Figure 2-3: Schematic view of the equivalent circuit for the two-channel model, with $r = AR_{FN}$. 

---

Figure 2-2: Calculated values from the interlayer coupling as function of the interlayer thickness. From Bruno and Chappert [11].
Theory

One of the advantages of this model is that simple expressions can be obtained when keeping some of the parameters \((t_F, t_N, \text{ or } \alpha_1)\) constant. The model was also used by Schroeder et al. [49] in their analysis of the spin-dependent scattering parameters at 4.2 K. In the following formulas we use the notation of Valet and Fert [50], where + and - refer to absolute spin directions.

The two spin channels yield resistance values \(R^+\) and \(R^-\), which have to be added in parallel to calculate the total resistance:

\[
R_{\text{tot}} = \frac{R^+ R^-}{R^+ + R^-}
\] (2-2)

We can calculate these resistances as follows, whereby in our notation \(\uparrow\) refers to the situation where spin and magnetisation are in the same direction, and \(\downarrow\) refers to the situation where spin and magnetisation are in the opposite direction. \(\rho_F^+\) and \(\rho_F^-\) are the spin-dependent resistivities of the ferromagnetic metal, \(R_{\text{FIN}}^+\) and \(R_{\text{FIN}}^-\) are the spin-dependent interface resistances. They are defined by

\[
\rho_F^+ = \frac{2\rho_F}{1 + \beta}, \quad \rho_F^- = \frac{2\rho_F}{1 - \beta}, \quad R_{\text{FIN}}^+ = \frac{2R_{\text{FIN}}}{1 + \gamma}, \quad R_{\text{FIN}}^- = \frac{2R_{\text{FIN}}}{1 - \gamma}
\] (2-3)

where \(\rho_F\) and \(R_{\text{FIN}}\) are the experimentally measurable resistivity of the ferromagnetic material, and the interface resistance, respectively. \(\beta\) and \(\gamma\) are parameters which are a measure of the spin-dependence, like \(\alpha_F\) and \(\alpha_{\text{FIN}}\) which are defined as

\[
\alpha_F = \frac{\rho_F^+}{\rho_F} = \frac{1 + \beta}{1 - \beta}, \quad \alpha_{\text{FIN}} = \frac{R_{\text{FIN}}^-}{R_{\text{FIN}}^+} = \frac{1 + \gamma}{1 - \gamma}
\] (2-4)

We assume that the normal metal resistivity \(\rho_N\) and the contact resistance with the sample leads \(R_{\text{LM}}\) are spin-independent. In the case that the neighbouring layers are antiferromagnetically coupled, both spin channels have the same \(\uparrow\) and \(\downarrow\) resistance contribution. Both spin channels are thus equivalent, and the total resistance in the AF case is given by

\[
AR_{\text{AF}} = 2AR_{\text{LM}} + M[\rho_F^+ t_F + \rho_N t_N + 2AR_{\text{FIN}}^+]
\] (2-5)

where \(A\) is the cross-section of the sample, and where \(\rho_F^*\) and \(AR_{\text{FIN}}^*\) are defined by:

\[
\rho_F^* = \frac{\rho_F}{1 - \beta^2}, \quad AR_{\text{FIN}}^* = \frac{AR_{\text{FIN}}}{1 - \gamma^2}
\] (2-6)
Useful relations can be obtained from equation (2-5) in two special cases: \( t_n \) is constant and \( t_F \) is constant. Due to our geometry, in our experiments the total multilayer thickness \( t_{101} \) always has to be constant as well. With

\[
t_F = -t_N + \frac{t_{101}}{M} \quad (t_N \text{ is constant}), \quad \text{and} \quad t_N = -t_F + \frac{t_{101}}{M} \quad (t_F \text{ is constant})
\]

(2-7)

the equation can be written as

\[
AR_{101} = 2 AR_{LM} + \rho_N t_{101} + M [(\rho_N - \rho_F) t_N + 2 AR^{*}_{F/N}] \quad \text{if} \quad t_N \text{ is constant},
\]

\[
AR_{101} = 2 AR_{LM} + \rho_F t_{101} + M [(\rho_F - \rho_N) t_F + 2 AR^{*}_{F/N}] \quad \text{if} \quad t_F \text{ is constant}
\]

(2-8)

In the ferromagnetic coupled case, the situation is more complicated. Here one of the channels only encounters \( \uparrow \) contributions to the magnetoresistance, and the other one only \( \downarrow \) contributions. Because \( \uparrow \) and \( \downarrow \) contributions are no longer equal, \( R^\uparrow \) and \( R^\downarrow \) are not equal. One finds that

\[
AR^\uparrow_{FM} = M [\rho_F t_F + 2 \rho_N t_N + AR^\uparrow_{F/N}] + 4 AR_{LM}
\]

\[
AR^\downarrow_{FM} = M [\rho_F t_F + 2 \rho_N t_N + AR^\downarrow_{F/N}] + 4 AR_{LM}
\]

(2-9)

\[
AR_{FM} = AR_{AF} - \frac{M^2 [\beta \rho_F t_F + 2 \gamma AR^{*}_{F/N}]^2}{AR_{AF}}
\]

(2-10)

This last equation can be rewritten as

\[
\sqrt{(AR_{AF} - AR_{FM}) AR_{AF}} = M [\beta \rho_F t_F + 2 \gamma AR^{*}_{F/N}]
\]

(2-11)

If one plots the square root on the left of equation (2-11) against the number of bilayers \( M \), one expects to find a line through the origin of the plot, with slope \( \beta \rho_F t_F + 2 \gamma AR^{*}_{F/N} \). From such plots one can obtain the parameters \( \beta, \gamma, \rho_F, \rho_N \), and \( R_{FM} \) in these expressions as a function of \( T \). Once again consider the special cases

* \( t_F = \text{constant} \): equation (2-11) remains valid.
* \( t_{101} = \text{constant} \): equation (2-11) can be rewritten my making use of
The new expression (2-16) can be seen as a line with slope $-\beta p_F t_N + 2\gamma AR_{FM}$ and a non-zero intercept $\beta p_F t_{tot}$.

$$\sqrt{(AR_{AF} - AR_{PM}) AR_{AF}} = \beta p_F t_{tot} + M[-\beta p_F t_N + 2\gamma AR_{FM}]$$  \hspace{1cm} (2-13)

### 2.4 The Boltzmann model

A microscopic approach to calculate the magnetoresistance in the multilayer is the Boltzmann model. It starts with the Boltzmann transport equation to calculate the transport through the multilayer. The model can be applied to both the CIP and CPP case. As will be shown, the two-channel model given in the previous paragraph is a limiting case of the CPP Boltzmann model. Because already some comprehensive derivations of this model exist [50], and the derivation is of no great importance to this work, only the most important results are given.

The general idea of the Boltzmann transport equation is the balance between acceleration and relaxation of electrons.

$$\frac{df_\sigma}{dt} = \left( \frac{df_\sigma}{dt} \right)_{\text{col}}$$  \hspace{1cm} (2-14)

where $f_\sigma$ is the distribution function, $\text{E}$ denotes the contribution of the electric field, and 'col' denotes the collision contribution.

In the CIP case, we consider a small perturbation $g_\sigma$ of the Fermi-Dirac distribution $f^0$. This term $g_\sigma$ describes the Fermi surface shift.

$$f_\sigma = f^0 + g_\sigma, \quad f^0 >> g_\sigma$$  \hspace{1cm} (2-15)

This leads to a solution of the form

$$g_{p\pm\sigma}(z,v) = \frac{eEz\sigma}{m^*v_f} \frac{\partial f^0}{\partial v_x} \left[ 1 + A_{p\pm\sigma} e^{z v^2 / k_0^2} \right]$$  \hspace{1cm} (2-16)
In this equation \( p \) denotes the layer, \( A_{p\alpha} \) is an integration constant determined by the boundary conditions, and \( \lambda_{e} \) is the electron mean free path in layer \( p \). \( E \) is the local electric field, \( e \) is the electron charge, \( m^* \) is the effective electron mass, and \( v_{f} \) is the Fermi velocity. Applying the appropriate the boundary conditions, the following expression for the total current \( J \) is found:

\[
J = \sigma E = \sum_{p=1}^{N} \sum_{\alpha} \int_{z_{p}}^{z_{p+1}} d\bar{z} d^3\nu (\varepsilon v_x) g_{p\alpha} (z, \bar{\nu})
\]  

(2-17)

With this formula, the magnetoresistance can be calculated. For both ferromagnetic and antiferromagnetic arrangements the resistivities \( \sigma \) have to be calculated.

In the CPP case, in addition to the Fermi surface shift term \( g_{\alpha} \), another small perturbation term is introduced. A spin and position dependent chemical potential \( \mu_{\alpha} (z) \) takes into account spin accumulation.

\[
F_{\alpha} = f^0 + \frac{\partial f^0}{\partial \nu} \left\{ \left[ \mu^0 - \mu_{\alpha} (z) \right] + g_{\alpha} \right\}
\]  

(2-18)

Because of the cylindrical symmetry of the CPP case around the z-axis (normal to the multilayer), it is possible to develop \( g_{\alpha} \) into Legendre polynomials:

\[
g_{\alpha} = \sum_{n=1}^{\infty} g_{\alpha}^{(n)} P_n (\cos \theta)
\]  

(2-19)

From the solution of this problem, it follows that in the limit that the electronic mean free path is much shorter than the spin-flip diffusion length, the macroscopic transport equations are given by

\[
\frac{e}{\sigma_{\alpha}} \frac{\partial J_{\alpha}}{\partial \nu} = \frac{\bar{\mu}_{\alpha} - \bar{\mu}_{-\alpha}}{i^2}
\]  

(2-20)

\[
J_{\alpha} = \frac{\sigma_{\alpha}}{e} \frac{\partial \bar{\mu}_{\alpha}}{\partial \nu}
\]  

(2-21)

Evaluating those two equations for the cases of parallel and antiparallel resistances \( r^0 \) and \( r^{AP} \) we can write

\[
r^{(P,AP)} = r_0 + 2r_{si}^{(P,AP)}
\]  

(2-22)

with \( r_0 = (1 - \beta^2) \rho_r r_F + \rho^*_n r_n + 2r^*_v \) and \( r_{si}^{(P,AP)} \) a spin-coupled interface resistance given by
In these formulas bulk as well as interfacial spin-dependent scattering is taken into account. A bulk spin-asymmetry coefficient $\beta$ is introduced, as well as an interfacial spin-asymmetry coefficient $\gamma$. The definitions of these parameters are already given in (2-4). In the limit where the total thickness $t$ is much smaller than the spin-flip diffusion length $l_s$, the two-channel model expressions presented in paragraph 2.3 follow directly.

$$r_{sl}^{(P)} = \frac{(\beta - \gamma)^2}{\rho_{Nsf}^*} \coth \left[ \frac{t_N}{2l_{sf}} \right] + \frac{\gamma^2}{\rho_{Fsf}^*} \coth \left[ \frac{t_F}{2l_{sf}} \right] + \frac{\beta^2}{r_b^*} \coth \left[ \frac{t_F}{2l_{sf}} \right]$$

$$r_{sl}^{(AP)} = \frac{(\beta - \gamma)^2}{\rho_{Nsf}^*} \coth \left[ \frac{t_N}{2l_{sf}} \right] + \frac{\gamma^2}{\rho_{Fsf}^*} \coth \left[ \frac{t_F}{2l_{sf}} \right] + \frac{\beta^2}{r_b^*} \coth \left[ \frac{t_F}{2l_{sf}} \right]$$

In these formulas bulk as well as interfacial spin-dependent scattering is taken into account. A bulk spin-asymmetry coefficient $\beta$ is introduced, as well as an interfacial spin-asymmetry coefficient $\gamma$. The definitions of these parameters are already given in (2-4). In the limit where the total thickness $t$ is much smaller than the spin-flip diffusion length $l_s$, the two-channel model expressions presented in paragraph 2.3 follow directly.

### 2.5 Temperature dependence of the GMR effect

One of the assumptions made in the models of the previous paragraphs is the absence of spin-mixing. This is valid when the temperature is very low. However, the model has to be adjusted to include electron-magnon scattering at high temperatures. It is therefore necessary to consider a spin-mixing term in the equations. This was already done by Fert and Campbell [51] to describe the temperature dependence of the resistance in ferromagnetic alloys. However, because of the resemblances between alloy systems and multilayers, this model can also be used for the CPP-MR data.

In this model the total resistivity as function of temperature is given by

$$\rho(T) = \frac{\rho_{\uparrow}(T)\rho_{\downarrow}(T) + \rho_{\uparrow\downarrow}(T)(\rho_{\uparrow}(T) + \rho_{\downarrow}(T))}{\rho_{\uparrow}(T) + \rho_{\downarrow}(T) + 4\rho_{\uparrow\downarrow}(T)}$$

(2-25)
In this formula \( \rho_\sigma(T) \) is the resistivity for each spin \( \sigma \) and \( \rho_{\uparrow\downarrow}(T) \) is the spin-mixing resistivity. In Figure 2-4 the resistor schemes for the F and AF coupled cases are given. In the F case, two limiting cases can be seen. When \( \rho_{\uparrow\downarrow}(T) \) is infinite, the two channels are totally mixed and their resistivities are equal. When \( \rho_{\uparrow\downarrow}(T) \) is negligible, the two-channel model of paragraph 2.3 reappears. In the antiferromagnetic case both spin channels are always completely mixed.

\[
\rho(T) - \rho_0 = \left(1 + \frac{(\alpha - \mu)^2}{(1 + \alpha)^2 \mu} \right) \rho_\uparrow(T) + \frac{(\alpha - 1)^2}{(\alpha + 1)^2} \rho_{\uparrow\downarrow}(T) \tag{2-26}
\]

The definitions \( \rho_\uparrow' = \rho_{\uparrow'} + \rho_{\downarrow'} \) and \( \rho_\downarrow' = \rho_{\uparrow'} + \rho_{\downarrow'} \) are used in this formula.
2.6 The as-grown state

As was first shown by Schroeder et al. [52], the resistance of a sample directly after growing $R(H_0)$, before the presence of any magnetic field, can be considerably different from the resistance after having applied a magnetic field $R(H_{m})$ (see Figure 2-5). It appears that the magnetic state of the sample undergoes an irreversible change when brought into a magnetic field. It is not clear up till now what is the speciality of the as-grown state, or why it occurs. It is also not clear if this state can be reproduced in one way or another. However, because of the fact that this as-grown resistance is generally higher than the resistance after the first measurement, it also enhances the GMR effect. Therefore this state is of interest for research. The suggestion made by Schroeder et al. is that the as-grown state corresponds with a truly antiferromagnetically coupled state. This originates from the theoretical prediction that the AF state has the highest possible resistance (no shunting at all). Unfortunately, not all experimental data seem to support that claim. They themselves present NiFe/Cu data with an as-grown resistance lower than the resistance after measurement, so the statement is certainly not in all cases true. Still more research has to be done to solve this problem.

![Figure 2-5: The 'virgin' state, with resistance $R(H_0)$, compared to the reversible resistance cycles, with resistance $R(H_{m})$.](image-url)
3. Experimental Set-up

3.1 Fabrication of the samples

The new approach to the CPP-MR measurements discussed in this work lies not in the type of multilayer we used. In fact, Co/Cu multilayers are well studied over the last few years. This is exactly the reason why the Co/Cu system is used: we compare our results with the new set-up with the known results to evaluate our novel experimental geometry.

The most important feature in our new set-up is the use of a grooved substrate (Figure 3-1) instead of the flat substrate used in all experiments up to now. This grooved substrate enables us to measure in a CPP-like configuration without having the difficulty of complicated lithography to create pillars.

![Diagram of grooved substrate and multilayer deposition](image)

*Figure 3-1: Schematic view of a) the grooved substrate, and b) the multilayer on the grooved substrate, with the transport direction in the CPP case.*

The production of the grooved substrates is a standard process developed at Philips Research, developed for optical gratings. The procedure to make these substrates is shown in Figure 3-2. First, a semi-insulating InP substrate is covered with a 100 nm photoresist layer (HPR 204). Using a single-frequency holographically interfering Ar-laser beam (Spectra Physics 2045E), the resist is exposed to a line pattern with a period of 201.4 nm. The photoresist is developed leaving a periodical line pattern on the substrate. Subsequently the InP is anisotropically wet-etched with an aqueous etchant: 60 H$_2$O : 30 HBr (47%): 0.1 Br$_2$. A characteristic of this etching process is the strong difference in etching rate between the different crystallographic directions in the substrate. The resulting plane is a (111) plane [53,54]. The grooved substrate thus made is shown in Figure 3-1.
Figure 3-2: Schematic view of the substrate fabrication process. a) An InP substrate, covered with a layer of photoresist, is exposed to a line pattern. b) The resist is developed. c) The substrate is wet-etched, leaving (111) planes. d) The remainder of the resist is removed, leaving the grooved substrate as used in our experiments.

The deposition of the layers was done in a multichamber MBE system (VG Semicon V80M). The principle of an MBE system is to thermally evaporate material from a source and deposit it onto a substrate. All depositions are carried out at room temperature and at a pressure of less than $10^{-9}$ mbar. Two types of sources are used in the deposition of our samples:

* Knudsen cell: In a Knudsen cell the material is evaporated in a crucible by electrical heating. The crucible has a stretched out form, so a homogeneous beam of focused particles is directed towards the substrate, which is necessary to get a controlled growth. The Cu is deposited with a Knudsen cell, and the Cr is deposited with a homebuild source resembling a Knudsen cell.

* e-gun: With an e-gun highly energetic electrons are focused onto a target, of which atoms will evaporate by means of physical bombardment. A well focused, homogeneous beam can be created by using the right shutters. Both Co and Fe are deposited by an e-gun.

The layers are deposited under an angle to the substrate normal. This results in pillarlike growth in the (111) direction. Despite the fact that the growth direction is hard to check by x-ray diffraction because of the non-flat substrate surface, we found that different textures do not greatly influence the result [46]. First, a thin (3 nm) Cr or Fe layer is deposited to enhance the adhesion on the substrate. The idea is to grow the pillars longer than the separate step width, so the separate pillars become linked to each other. To improve the connection between the pillars, before and after
Experimental setup

The deposition of the multilayer a Cu-layer is deposited, which is in almost all measured samples 20 nm thick. The result is shown in the picture of Figure 3-3 a). The layers are not as smooth as in the ideal schematic view of Figure 3-1, they are rather more rounded. Figure 3-3 b) is a schematic view of our interpretation of this picture. It proved to be impossible to grow multilayers which are not ferromagnetically coupled when the Cu spacer layer becomes thinner than 5 nm. An explanation can possibly be found in the increasing number of magnetic pinholes at the edges of the pillars, where according to the pictures the layers are thinner than the deposition rate suggests. The total layer thickness, this is the thickness of the multilayer combined with the thicknesses of the top and bottom layers, has to be a constant to ensure a good contact between the separate pillars. This constant thickness is 260 nm, which is larger than can be expected from the ideal situation, because of the rounding of the multilayer. In Figure 3-1 this is shown schematically for the ideal situation, without rounding, and in Figure 3-3 the rounded case is shown. The fact that a larger total thickness is needed can also be described to the rounding of the multilayers, because of the smaller thickness at the edge, where the contact has to take place.

Figure 3-3: SEM-picture of the multilayer, and our interpretation of this picture. The problems we expect are indicated.
3.2 Magnetisation measurements

The magnetisation of the samples was measured using a vibrating sample magnetometer (VSM). A schematic picture of this apparatus is given in Figure 3-4. The VSM measures the magnetic moment of the sample as a function of the applied field. The principle of the VSM is to vibrate a magnetic sample with a frequency of about 80 Hz in a homogeneous applied field, in our case stepwise varying from -800 to 800 kA/m.

![Figure 3-4: Schematic picture of the VSM set-up.](image)

The vibration of a magnetic sample induces an inductive current in the pick-up coils wound around the sample. This current is proportional to the total magnetic moment of the sample. The sample to be measured can be rather large, up to 1 cm by 1 cm. For measuring the magnetisation loops along different magnetic axes, the sample can be turned in different alignments with the field. The VSM sensitivity is $10^8$ Am$^2$, and the maximum range is 35 mAm$^2$.

3.3 Magnetoresistance measurements

All transport measurements were done in a four-probe measuring geometry. This excludes the possible effects of lead resistivities on the measured results, because the voltage and current leads are independent. A schematic view of this geometry is given in Figure 3-5. The two outer contacts serve as current leads, whereas the voltage is measured between the two inner contacts. The resistance is found by
dividing the voltage difference by the current. In order to ensure a homogeneous current flow between the voltage leads, the current leads are placed approximately one square away from the current leads. This means that the width of the sample is also the distance between the two contacts.

![Schematic picture of the four-probe measuring geometry.](image)

**Figure 3-5**: Schematic picture of the four-probe measuring geometry.

Electrical resistance measurements, without the presence of a magnetic field, were performed with a standard four-probe measurement device, as shown in Figure 3-6 a). With this apparatus the sheet-resistance of the samples was measured. Also with this set-up every sample was checked before further measurements.

Another such device has recently been equipped with a water-cooled magnet, with a maximum field of 400 kA/m. This set-up, shown in Figure 3-6 b), has been used to do room-temperature magnetoresistance measurements on the samples, to check if an appreciable magnetoresistance value could be found.

![Standard four-probe measuring device, b) with and a) without magnetic field.](image)

**Figure 3-6**: Standard four-probe measuring device, b) with and a) without magnetic field.
The ether magnetoresistance measurements, which were used for the results in chapter 4, were performed with the set-up shown in Figure 3-7. The main device in the set-up is an AC resistance bridge. The used bridge was a Linear Research LR-400, which has resistance scales from 20 mΩ to 200 kΩ and uses a four-probe technique. The typical measurement current used during the our experiments was 1 mA, and the operation frequency is 17 Hz. The accuracy of this apparatus is about 0.1%, with a four-digit readout. The readout can be improved by subtracting an offset to measure a small effect: five digits then can be found. Our measurements were all done in the four-digit mode, because the effect was generally large enough. The measurements where performed from the 200 mΩ to the 20 Ω range, dependent on the shape (number of squares) of the sample. The resistance per square of the samples was of the order of 0.5-1 Ω. The measurement range and the measurement current have to be pre-set manually, while the readout is done automatically by a computer.

![Schematic view of the magnetoresistance set-up.](image)

The magnetic field was applied through two water-cooled copper coils, through which a current flows, generated by an independent power supply. The maximum field thus generated is 2 T, but most of our experiments were performed with a maximum field of 1 T, because that is sufficient to saturate the Co/Cu multilayers. The magnetic field can be controlled by applying a steering voltage to the power supply. This voltage is applied by a HP function generator. In all our experiments a triangular signal was applied, with frequencies ranging from 0.001 Hz in high field to 0.0002 Hz near zero field. The resulting single sweep time lies between 15 and 30 minutes. During this time more than thousand measurements were performed, resulting in a well-defined magneto-resistance curve. The function generator can be controlled by the computer. The magnetic field is measured by a Hall sensor close to the cryostat. The output of the sensor is converted to a computer-interpretable signal by a digital voltage meter.
Experimental setup

The temperature of the sample can be regulated. This is necessary to perform temperature-dependent measurements. This regulation is accomplished by a combination of a He\textsubscript{4} continuous flow cryostat and a PID (proportional, integrate, differentiate) controller. With the flow cryostat, a temperature of 4.2 K can be reached in the wall of the sample space. The sample is then cooled to the same temperature with the aid of a contact gas (in this case, also helium). The PID controller is attached to a wire in the cryostat, which can be electrically heated, and to a temperature sensor in the cryostat. The temperature sensor needs a vessel of liquid nitrogen as a reference temperature. Thus the temperature is controlled by heating the helium to the preferred temperature. Both flow rate and preferred temperature have to be set manually. We varied the temperature between 4.2 K and about 300 K. Because the temperature sensor of the PID controller is not placed exactly at the place of the sample, a independent temperature sensor is attached to sample holder at the same height as the sensor, in order to accurately measure the temperature. The read-out of this sensor also is done by computer.

Three different pumps are used in the set-up. The first is needed to pump the helium through the flow cryostat. This pump is working when the sample is cooled. The second is used to keep the space between the walls of the cryostat as vacuum as possible. This pump is working continuously. The third pump is needed to extract the air from the sample space, to allow filling with the contact gas, helium. This pump is only used when the sample space has been opened, for example to change the sample.

The samples which came from the MBE system had usually a size of about 4 by 12 mm. For all samples a substrate was used with the grooves parallel to the short edge. For some samples simultaneously a substrate with the grooves parallel to the long edge was used, to make CIP measurements easier. Two contacting techniques were used to attach the leads to the sample.

- Contacting with silverpaint. In this case four copper leads are attached to the sample with silverpaint. The advantage of this method is the fact that no great pressure has to be applied to the (very fragile) substrate. It also can be done at the site of the measurement, no further apparatus is needed. The disadvantages are the fact that the leads have to be torn of the sample when samples are changed, and the relative big contact surface needed, which limits the size of the samples used.

- Bonding with aluminium. Four aluminium leads are acoustically drilled into the sample, and are attached to a chip-holder. The advantages of this method are the durability of the contact, and the fact that the contact points are very small, so much smaller sample pieces can be used.

With the painting technique the whole sample has to be contacted, or at least a mayor fraction of it, because otherwise the leads are placed too close to each other for a nice homogeneous current profile. With the bonding technique the sample can be cut into several smaller pieces without difficulty. This enables more measurements on the same sample. The sample holder to which the samples are attached, can be rotated around the vertical axis to enable the positioning of the sample in the magnetic field, along a magnetic hard or soft axis.
4. Results

4.1 Magnetisation experiments

To determine the magnetic properties of our samples, the room temperature magnetisation was measured with VSM equipment. A typical result is shown in Figure 4-1. To get such a symmetric graph, we had to subtract the magnetisation of substrate and holder. The effect of these contributions was determined by measuring the magnetisation of a substrate without multilayer. The magnetisation was measured with the applied field along the direction of the steps ($H \parallel$ groove) as well as with the applied field perpendicular to the groove ($H \perp$ groove). Obviously, the direction parallel to the grooves is the easy axis of magnetisation. This can be deduced from the geometrical shape of individual ferromagnetic layers. The fact that there is a substantial remanent magnetisation, and the relatively low saturation field indicate that the layers are uncoupled, rather than antiferromagnetically coupled. This is what one expects for copper interlayers of such thickness. In the perpendicular situation the field is applied parallel to the substrate, and not in the plane of the film. Therefore a demagnetisation factor is present, and this explains the high saturation field (larger than the scale of Figure 4-1) in the perpendicular case.

![Figure 4-1: Room temperature magnetisation curves for a 20 nm Cu + 32 x [1.5 nm Co + 6.0 nm Cu] + 20 nm Cu sample.](image-url)
Similar curves are measured for as-grown samples with various Cu thicknesses. The result for the field-direction parallel to the grooves, along the easy axis, is given in Figure 4-2. These graphs are not corrected for holder and substrate magnetisation. The first point to note is the difference between the 'virgin' curves (given in Figure 4-2 a) and c)), and the following hysteresis loops in a) and c), after having exposed the sample to a magnetic field. This effect, which only can be found in the as-grown samples during their first measurement, will be discussed in more detail later. From b) it can be seen that this effect disappears once a field has been applied to the sample, as was the case with this sample. Unfortunately no as-grown samples with equal Co-layer were available, so two different Co-layers (1.5 nm and 5.0 nm) were used. We describe the decrease in coercive field with the decrease of the Co-layer thickness, which is contrary to the expected increase in a smaller volume, to increasing anisotropy in the layers.

As can be seen clearly in Figure 4-2, the samples with the thin Cu spacer layers show predominantly ferromagnetic coupling.

Figure 4-2: Four magnetisation curves for the field direction $H \parallel$ groove. The multilayers are a) $27 \times [4.0 \text{Cu} + 5.0 \text{Co}]$, b) $26 \times [5.0 \text{Cu} + 5.0 \text{Co}]$, c) $35 \times [6.0 \text{Cu} + 1.5 \text{Co}]$, and d) $5 \times [50.0 \text{Cu} + 1.5 \text{Co}]$. 
This adds to our belief that pinholes are present at the edges of the multilayers with these Cu thicknesses. The magnetisation curves of the samples with the thicker Cu layers show rather uncoupled behaviour.

4.2 CPP- magnetoresistance

Because of the structure of our samples, supposedly consisting of multiple columns in series forming one very thick multilayer, it is not straightforward to determine which part of the current goes parallel to the layers (CIP) and which part straight through the layers (CPP). Looking at Figure 3-1, in the ideal case about 25% of the total layer per step overlaps with the next layer. Only in one of the layers the current will go through the interfaces between separate layers, so the total number of interfaces crossed is 25% less then the total number of interfaces. In the realistic, rounded case this is of course not exactly true, but it is difficult to estimate the correction needed in that case.

As can be seen also in Figure 3-1, when crossing from one column to another, the current has to go parallel to the planes for a while. Also, the individual pillars have to be crossed diagonal to reach the next pillar. In both cases it is clear that a CIP component is involved in the CPP case. More detailed current distribution calculations with the finite-element method show that in the ideal geometry about 85% of the transport is due CPP, and 15% CIP.

A typical resistance measurement, as measured by the experimental set-up of Figure 3-7, is given in Figure 4-3.

![Figure 4-3: Magnetoresistance measurement.](image-url)
This measurement was done on a 20 nm Cu + 32 x [1.5 nm Co + 6.0 nm Cu] + 20 nm Cu multilayer. The resistance curves at 4.2 K and room temperature are given in this figure. The highest resistance doesn't appear at zero field, but with an offset. This offset is caused by the hysteresis effect that can be seen also in the magnetisation curves of Figure 4-1. Hysteresis is usual for uncoupled samples, antiferromagnetically coupled samples do not show hysteresis. The broadening of the peaks at low temperature can be explained by the decrease of the importance of kT compared to $E_{\text{Anisotropy}}$, which makes it harder for the domains to turn. To evaluate only the giant magnetoresistance effect, the slope of the curve in the saturated area, which is not a GMR effect, is subtracted before the actual calculation. With each sample, the resistance curve mentioned above was measured for approximately eight temperature values between 4.2 K and room temperature. In this way the temperature dependence of the magnetoresistance was determined. For the sample described above, this results in Figure 4-4. As can be seen, the CPP-MR decreases from about 37% at 4.2 K to about 17% at room temperature. The results for this sample were the highest obtained in our experiments. For this sample, the decrease is fairly gradual as a function of temperature.

![Graph](image)

**Figure 4-4: Temperature dependence of the magnetoresistance.**

To gain information about the dependence of the MR on the Co and Cu layer thicknesses, two series of samples have been grown. One has a constant Co layer thickness of 1.5 nm and a Cu layer thickness varying between 4.0 nm and 50.0 nm, the other has a constant Cu layer thickness of 10.0 nm and a Co layer thickness varying between 1.5 nm and 50.0 nm.
The result for the varying Cu layer is given in Figure 4-5. In this figure the MR value at 4.2 K is displayed. The low values for the MR at small Cu layer thicknesses (< 6 nm) probably result from pinholes and/or ferromagnetic coupling, as explained in paragraph 3-1. This interpretation is supported by the magnetisation measurements of Figure 4-2. After the maximum at $t_{Cu} = 6.0$ nm, the MR value decreases again. This can be explained by the smaller number of interfaces and bulk material at increasing copper thickness. There also can be some spin-mixing in the larger Cu layers. Remember that the total thickness of the multilayer is kept constant.

![MR as function of Cu layer thickness](image)

**Figure 4-5: MR as function of Cu layer thickness.**

**Figure 4-6:** MR versus temperature plots for the varying samples, a) with constant Co layer thickness and b) with constant Cu layer thickness. The different layer thicknesses in the legend are given in angstroms.
The temperature dependence for the various samples is given in Figure 4-6. In plot a) the points with Cu layer thickness < 6.0 nm have been left out. From both graphs it is clear that the MR decreases as the thickness of one of the layer increases. The MR decreases as well as a function of temperature for all layer thicknesses. An important feature is that for both thick Co and Cu layers still an appreciable MR is found.

If we plot in pictures like Figure 4-5 the number of bilayers M in stead of the layer thicknesses, we get graphs like those in Figure 4-7. In this graphs use is made of a normalised resistance. With the four-probe method the resistivity per square at zero field and room temperature was measured, and this resistivity was compared to the resistivity at zero field and room temperature in our measurements. The factor that results is the number of squares measured in our measurements. This number is used to convert all our data to one-square data, which makes them comparable.

The pillar cross-section A is 3.42 x 10^{-14} m^2, which follows from a simple geometrical calculation based on the structure of Figure 3-1.

![Graph A](image1)

![Graph B](image2)
In this figure the plots are shown for the T = 4.2 K measurements. The same plots are made for all other temperatures mentioned above. The graphs in Figure 4-7 are put in the right form to be compared with equations (2-8), (2-11) and (2-13). When a line is drawn through the points, this gives numerical values for the slopes and intercepts predicted by theory. The lines were a best fit to the eye. This results in a system of seven equations with five unknown variables. There is a solution for these kind of problems, but generally not all requirements can be satisfied. It is therefore necessary to look for a solution that fits all equations reasonably well. We have chosen a solution that starts with the values which seem to be the least uncertain. A similar approach was used by Schroeder et al. [49].

One of the big problems, and presumably the largest source of errors, is the fact that it is necessary to compare samples which have been grown under different conditions and measured in different conditions. Almost eight months lie between preparation of the first sample and measurement of the last. It is very difficult to quantify these errors by means of error bars.
Figure 4-8: Resistivities of a) Co and b) Cu and c) interface resistance of Co/Cu interface as a function of temperature, as calculated from equations (2-8), (2-11) and (2-13). The values found by the MSU group are indicated.
In Figure 4-8 the obtained values of $\rho_{m}$, $\rho_{n}$, and $2AR_{fin}$ as a function of temperature are given. The values for the resistivities where obtained by inserting the intercepts from plots like Figure 4-7 a) and b) for all temperatures in (2-8). The values thus obtained are inserted in the slope determined from the same equations. This results in two values for the interface contribution, from which the average is taken and given in Figure 4-8 c). The resulting figure shows that the strongest temperature dependence is found in the resistivity of the copper. All three resistance contributions increase with rising temperature. The decrease in MR ratio with higher temperatures seems thus to rise from increasing bulk resistivity. The spin dependence is, as shall be shown in Figure 4-9, only weakly temperature dependent so that the change in magnetoresistance $dR$ does not alter very much. It may be noted that for our layer thicknesses the bulk Co and interface resistances are of the same order of magnitude. There is no apparent dominance of the interface resistance in our case.

Figure 4-9: Spin-asymmetry parameters a) $\beta$ for bulk material and b) $\gamma$ for interfaces as a function of temperature. The value found by the MSU group at 4.2 K is also indicated.
In Figure 4-9 the spin-asymmetry parameters $\beta$ and $\gamma$, as defined in (2-4) are given as a function of the temperature. The value for $\beta$ is found by inserting the earlier calculated value for $\rho_{\text{Co}}$ in the intercept part of (2-13). The value for $\gamma$ is calculated by solving $\gamma^* 2AR^*_{\text{Co/Cu}}$ from the two slope equations from (2-11) and (2-13), and then inserting the value for $2AR^*_{\text{Co/Cu}}$ given earlier. It appears that both parameters are only weakly temperature dependent, with a small decrease with increasing temperature. This can be an intrinsic effect, but it could also be caused by increasing spin-mixing at higher temperatures. However, Gijs et al. showed for Co/Cu multilayers in pillars, using the model described in paragraph 2.5, that the spin-mixing term is negligible up to 300 K.

In Figure 4-10 the spin-asymmetry parameters $\alpha_s$ and $\alpha_{\text{FM}}$, which are also widely used, are given. They are directly related to $\beta$ and $\gamma$ by (2-4). One can see that the interface scattering is more spin-dependent than the bulk scattering, but the bulk scattering also appears to be spin-dependent.

It is assumed that for thin films like the ones we used the spin-flip diffusion length is much longer then the individual layer thicknesses. According to the predictions of Valet and Fert [50], it should be possible to determine from plots like the ones in Figure 4-7 if this assumption is true. In case this limit is not valid, an exponential drop is expected near the origin of the graph, so for a small number of bilayers. Unfortunately the uncertainty in our data is too big to draw conclusions on this subject. Both predicted curves can be fitted through the data within the assumed margins of error. To reach a decisive conclusion on this subject, more measurement points are needed. At the moment we have found no contradiction with the relation $t_{\text{Cu}} t_{\text{Co}} << l_r$. 

**Figure 4-10:** Two other spin-asymmetry parameters as function of temperature.
4.3 CIP-magnetoresistance

Not only the CPP magnetoresistance was measured, but also the CIP magnetoresistance was determined during the experiments. One of the reasons for this is the fact that this has been measured a lot for the Co/Cu system. It thus can be easily compared to other results, to check the quality of our samples. This was done with a piece of the CPP sample in most of the cases. For some layer thicknesses however, a special CIP-like sample was grown in the same time as the corresponding CPP sample. In the CIP case the grooves were parallel to the long side of the sample, while in the CPP case they were parallel to the short side. There proved to be little difference between the CIP sample and a CIP piece of the simultaneously grown CPP sample. Values obtained with these two methods thus can be compared to each other.

![Graph](image-url)

**Figure 4-11:** Example of a) a CIP-MR measurement, and b) the temperature dependence of the CIP-MR of the same sample.
In Figure 4-11 an example of a CJP measurement is given. The sample used was a part of the CPP sample of Figure 4-3. In comparison one can see a similar-shaped curve, with a smaller MR effect, as was expected. The temperature dependence of the same sample is also given in Figure 4-11, where it is compared to the already given CPP values. This was done for all available samples, and the results of this are shown in Figure 4-12. As in the CPP case, the CJP magnetoresistance decreases with the increase of the layer thickness.

\[
\begin{align*}
&\text{Cu} = 10.0 \text{ nm} \\
&\text{Co} = 1.5 \text{ nm}
\end{align*}
\]

Figure 4-12: Temperature dependence of the CJP magnetoresistance for the various layer thicknesses measured. The different layer thicknesses in the legend are given in angstroms.
4.4 As-grown state measurements

For some of the samples we have also measured the 'virgin-state' magnetoresistance. These are indicated as $H_0$ values, and the measurements after saturation are indicated as $H_m$ when the two values are compared. One of the resulting graphs, as well as a magnetisation measurement of another sample, is given in Figure 4-13. It is clear that for this sample the resistance of the as-grown state is higher than the resistance after the appliance of a field. However, because of the fact that the as-grown effect is destroyed by only small applied fields, the
measurements didn't succeed for all samples. There also appears to be a problem with the bonded samples. The effect in those samples was destroyed during the preparation for the experiments, presumably by a small magnetic field in the heater used to attach the samples to the chip-holders. Because of these problems, only a few reliable as-grown magnetoresistance values could be measured. Unfortunately, these values proved not enough for a serious calculation of parameters. It is therefore necessary to measure these values for a new series of samples, when the problems mentioned above are sorted out. It is clear, however, from the few data that have been gathered, that the as-grown effect is bigger than the saturation magnetoresistance. Therefore this state is of great interest for the calculation and interpretation of the temperature dependence of the spin-dependent parameters.

4.5 Comparison with other experiments

It is necessary for the interpretation of our results to examine the quality of our multilayers. Unfortunately, most usual control techniques, such as RHEED, LEED or X-ray diffraction, can not be used because of our grooved substrates. It is therefore necessary to compare our results with those of others. Lenczowski et al. [22] reported CIP-MR measurements for up to 5 nm Cu spacer layer at room temperature (see Figure 4-14). They found values of around 10%, compared to our 3% for comparable layer thicknesses. However, they used 100 bilayers compared to our 32 bilayers, and their layers were grown in the (100) direction. A explanation for the difference can be the bigger shunting effect in our case, because of the 20 nm top and bottom contacting layers we use.

![Figure 4-14: CIP-MR values against copper layer thickness at room temperature. From Lenczowski et al. [22].](image)
CPP magnetoresistance measurements for Co/Cu multilayers were performed by the MSU group at liquid helium temperatures [49]. Their results are shown in Figure 4-15.

\[ \text{Fe(5nm)[Co(1.5nm)/Cu(t)] Cu(5nm)} \]

Their higher MR values for comparable samples can be understood by the fact that in our samples there is a CIP contribution to our CPP measurements. They also quantified the spin-dependent scattering parameters, but of course only at 4.2 K. The values they found were already given with our results in Figure 4-8 and Figure 4-9. Their values are reasonably comparable to ours. The difference between the values can be attributed to the difference between the \( H_0 \) values they used for calculations and our \( H_m \) values. There is also some uncertainty in the number of layers actually involved in the transport in our case, due to the large total thickness \( t_{\text{total}} \). This influences the bilayer number \( M \) in the formulas. Another point is again the CIP contribution in our CPP geometry, and the uncertainty because of the low number of points in our analysis. Finally, these can of course be differences between their sputtered samples and our MBE grown samples. It is therefore too early to draw strong conclusions from the differences in obtained values. More experiments are necessary to get more insight in the contributions of the various spin-dependent scattering mechanisms in the multilayer.

*Figure 4-15: CPP-MR values against Cu layer thickness for Co/Cu at 4.2 K. From Schroeder et al.[49].*
5. Conclusions

The first conclusion that can be drawn from our experiments is that the method we proposed to measure the CPP-MR is working. Our results are the first in their kind. The method can be used to measure the temperature dependence of the CPP-MR effect. A value of 37 % was found for a 32x[1.5 nm Co + 6.0 nm Cu] multilayer at liquid helium temperature. At room temperature an CPP-MR value of 17 % was found in the same sample. Using a two-channel model, we can also calculate the temperature dependence of the resistivities involved and of the spin-dependent scattering parameters. However, because of the uncertainties involved in the measurement method, there is also an uncertainty in the obtained values. The uncertainty can be decreased by performing more measurements.

Unfortunately, this brings up another drawback of the current method. The growing rate that can be achieved in the available MBE system, about one sample a week, is not enough to grow large series of samples within a reasonable time. Therefore, another method to grow multilayers onto the grooved substrates has to be found. One candidate for this is thermal evaporation. Also a measurement method has to be found to measure these samples at a faster rate than is now possible (two full days to measure both CPP-MR and CIP-MR temperature dependence, including $H_0$ values, of one sample). It will perhaps be possible to do some measurements with the four-probe measurement device with the electromagnet. This device is only capable of room-temperature measurements, but room-temperature measurements may be enough to find out more about the uncertainties mentioned above.

It is still not possible to grow multilayers with a copper-layer smaller than 5.0 nm which are not ferromagnetically coupled. We describe this by pinholes forming at the edges of the rounded multilayer, where the layer thicknesses are much smaller than their nominal values. The rounding of the multilayers is presumably caused by a shadow effect during the growth of the layers.

Concluding, we can say that the growing of multilayers on grooved substrates is working. A CPP-MR effect is measured. However, for a full understanding of the effect and for further use of this method, more experiments are needed.
Appendix

Short summary of the samples measured, and the most important results and characteristics.

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