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Exploring the link between domain wall resistance and current-induced domain wall motion

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Exploring the link between domain wall resistance and current-induced domain wall motion

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Abstract

A new and promising idea for a memory device is the magnetic racetrack memory, which is proposed by Stuart Parkin of IBM. The key concept in this device is that a spin polarized current can be used to move magnetic domain walls (DWs) through a ferromagnetic nanowire due to spin transfer torques. However, the effect of non-adiabatic spin transport on this current-induced domain wall motion is still unclear. Interestingly, a direct link between this non-adiabatic transport and intrinsic domain wall resistance is predicted and therefore investigated in this thesis.

Firstly, we show that we have full control over the nucleation, pinning and injection of DWs in structured Pt/Co/Pt strips by using Focused Ion Beam (FIB) irradiation to play with the local anisotropy. This way, we have obtained a handle to tune the width of DWs in Pt/Co/Pt. Furthermore, we have for the first time shown that a He$^+$ FIB has some notable advantages over conventional Ga$^+$ FIB.

Secondly, the effect of intrinsic DW resistivity is studied. It is shown that the resistivity is increased for the appearance of single DWs in the nanostrip and it originates from mistracking of the electron spins with the local magnetization. It is observed that the effect is more pronounced for narrow DWs, which is used to confirm that the Levy-Zhang model explains intrinsic DW resistivity. This model is succesfully implemented to determine the spin polarization of Pt/Co/Pt and shows that non-adiabatic spin transport is indeed present for our class of materials.

Finally, we have also investigated the dependence of the non-adiabatic spin transfer torque (STT), whose strength is characterized by $\beta$, on the DW width. This way we are able to study the direct relation between DW resistivity and $\beta$. However, the measurement method that was used is not accurate enough to investigate the DW width dependence of $\beta$. A comparison of the magnitude of DW resistivity and $\beta$ is still made and the results were at least in the same order of magnitude. Furthermore, in agreement with other experiments on Pt/Co-like structures we found high values for $\beta$, that are compatible with the measured DW resistance, suggesting that linear momentum transfer due to scattering of electrons dominates the effect of the non-adiabatic STT.
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Chapter 1

Introduction

Over the past decades, advances in physics have drastically changed the world, beginning with the development of the first electronic computer in 1946. Since then, tremendous progress has been made in many different scientific fields. One of these is the field of digital information storage, where the areal density of stored data has nowadays already reached several hundreds of Tbit/in$^2$. There is an ever-growing hunger for more data storage, pushing the scientific community to come up with new ideas for even better memory devices.

A relatively new and exciting field of research that aims for the development of such devices is the field of spintronics. Here, it is exploited that an electron is characterized by two quantities. The first is the well known electron charge, which is already known since the discovery of the electron in 1897 by Thompson. An electron however carries also a second quantity of interest, found in 1925 by Uhlenbeck and Goudsmit, which is dubbed spin. Semiclassically, this spin can be seen as a rotation of the electron around its own axis. This rotation can either be clockwise, which is called spin-down or anti-clockwise, labeled as spin-up. Because the electron also carries a charge, this rotation is essentially a charge current and can be assigned with a dipole magnetic moment and the electron spin is responsible for magnetism in many solid state systems. In spintronics, the fields of electronics and magnetism are combined, which allows for the development of a whole new range of applications and devices. Probably the most fascinating discovery in this field is that of Giant Magnetoresistance (GMR) in 1988 by Fert and Gruenberg[1, 2]. This effect states that the resistance of two ferromagnetic layers, separated by a nonmagnetic layer, depends on their magnetic geometry. This has also lead to the discovery of the very similar Tunneling Magnetoresistance effect (TMR) and since then, most commercial Hard Disk Drives are based on TMR.

This thesis is also positioned in the field of spintronics. In this introductory chapter, we first discuss the well-known GMR effect in section 1.1, which is used to
explain the relevant properties of spintronic devices. This discovery was however already several decades ago and new breakthroughs have to be developed within the spintronics community to develop better storage devices. One of the most promising concepts is that of the Magnetic Racetrack Memory (MRM), which is based on the so-called spin transfer torque. This concept is introduced in section 1.2. Although in theory the MRM is very promising, there are many scientific challenges that have to be overcome before it can be used in commercial application. In section 1.3 we therefore discuss the most important challenges that nowadays exist in this field. In the final, section 1.4 we show the main goals of this project in the context of these challenges.

1.1 Spintronic devices

The most basic requirement for spintronic devices is the existence of a spin polarized current. This idea is already introduced by Mott in 1936 [3] and essentially means that there is an imbalance between spin up and spin down electrons that contribute to the current. This can be described by a spin polarization, which is in its most general description given by [4]

\[ P = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}, \] (1.1)

where \( n_\uparrow(\downarrow) \) is the electron density for spin-up(down) electrons.

The easiest way to obtain a spin polarization is by sending a current through a ferromagnetic material, as will be explained from the simplified band structures for the 4s- and 3d-bands as depicted in figure 1.1(a). It can be seen that the 4s-band is symmetric for both spin states, whereas the 3d-band shows an asymmetric behaviour for spin-up and spin-down electrons. A current through this material is carried by the 4s-electrons at the Fermi level, which have a much lower effective mass and are therefore itinerant electrons. The 3d-electrons are more localized and therefore responsible for magnetism. Due to s-d exchange interactions, explained for the first time by Berger [5], itinerant 4s-electrons can scatter into 3d-states. As seen from figure 1.1(a), there are more 3d-states at the Fermi level for minority electrons. Assuming that spin is conserved during scattering, this effect is therefore more pronounced for 4s-electrons with minority spin, who experience a larger resistance. This effectively leads to a spin polarization.

Mott furthermore stated that a spin polarized current can be described by two independent spin current channels, so that conductance is determined by the total resistance of the two parallel spin current channels. This idea of a spin dependent resistance is explored in the GMR effect, for which Grünberg and Fert were awarded with the Nobel prize in 2007. As shown in figure 1.1(b), the idea is that a
1.1 Spintronic devices

Figure 1.1: (a) Sketch of the density of states (DOS) near the Fermi level for 4s- and 3d- band electrons in a Stoner material. Due to exchange splitting, there is an offset between the spin up and spin down band, leading to an imbalance in the spin polarization of the localized 3d-electrons at the Fermi level. (b) Schematic overview of GMR, where a magnetic layer is sandwiched between two ferromagnets. Due to a spin-dependent resistivity in the ferromagnetic layers, the total resistance depends on the relative orientation of magnetization of the layer. A low resistance is measure for a parallel configuration (top) and the anti-parallel configuration gives a much higher resistance.

non-magnetic conductor is sandwiched between two ferromagnetic layers. A current that is injected in the magnetic layer becomes spin polarized, meaning that the resistance for spin-up and spin-down electrons is different. The key concept in GMR is the length scale for which this spin polarization is conserved when the current enters the non-magnetic spacer layer. If this so-called spin-diffusion length is larger than the thickness of the spacer layer $d$, the spin polarized current enters the second ferromagnet, where the resistance is again different for both spin currents, depending on the magnetization of the ferromagnet. The total resistance of the stack is determined by the relative orientation of magnetization, which can be seen from the configuration of low and high resistances in the sketched resistance networks for the spin up and spin down current channels.

An important consideration from the GMR effect is that it is apparently possible to influence an electric current with the magnetization. It is therefore expected that the opposite is also possible. Again, the length scales are of key importance and with the lithography techniques of nowadays, it is possible to fabricate magnetic structures with submicron lateral size and layer thicknesses down to the atomic scale. It is in this region, where it is shown that it is possible to influence the magnetization by a current. This is especially the case for the transition regions between areas where the magnetization direction is different, which we call
domain walls (DWs). In a DW, the spin polarization of the current changes due to gradients in the local magnetization, meaning that the spin of an electron follows the direction of the local magnetization. Through conservation of spin angular momentum, this results in a torque on the DW, that is actually able to move it through a nanowire. This effect is labelled spin transfer torque (STT)[5] and in the next section we discuss the prospect of a new memory device, proposed by Stuart Parkin at IBM, that is based this STT[6].

1.2 Magnetic Racetrack Memory

The Magnetic Racetrack Memory (MRM) makes use of the same principle for data storage as a standard hard disk drive (HDD). A ferromagnetic material is divided into many different magnetic domains that act as the bits of our electronic devices. Whether a bit represent a digital ’0’, or ’1’, is determined by the local magnetization direction, which can either be up or down. The main difference between the MRM and usual HDD is the method by which the bits are transported to the read/write positions. In a conventional HDD, this is done by mechanical movement of the bit towards this position, i.e. rotating the magnetic disc at very large speeds. This is probably one of the biggest shortcomings of a HDD, since the mechanical movement of the disc is a very inefficient process.

Figure 1.2: The magnetic racetrack memory concept that is proposed by Parkin. The bottom images show a horizontal racetrack, which is mostly used for research purposes. The red and blue domains are coherently moved past a reading and writing position by the application of several current pulses. The top images show that in principle every configuration is possible. From [7].
In the conceptual MRM, as visualized in figure 1.2, it is not the ferromagnetic material that is moved, but the DWs, that separate the magnetic domains, move across the ferromagnet due to an applied current. This is best seen in the horizontal MRM in figure 1.2. Here the magnetic domains in a nanowire are indicated with a red/blue color scale and a current pulse pushes the magnetic bits through the nanowire because of the STT. Key to this interaction is that applying a current to the wire pushes all the DWs in the same direction so that the entire bit pattern can be transported. For this reason, motion by field is not possible, because at the end all the spins tend to align with the direction of the magnetic field, and the stored information is lost. Applying a current to the nanowire in figure 1.2 allows for the transportation of information to the read/write positions. Here, conventional methods, mostly a magnetic tunnel junction, are used to read out or write the magnetic bits. The absence of any mechanical parts already allows for a great enhancement of the speed of electronic applications.

In figure 1.2 it can also be seen that the nanowires that contain the bits could be formed in a three-dimensional shape. This is another advantage of the MRM over conventional HDD. Data storage is no longer limited to the surface of a magnetic disc and in principle every shape can be used. Although the fabrication of such configurations is not yet possible, the prospect of using the third dimension for data storage is another large advantage over other memory devices. However, at this moment research is devoted to the development and understanding of current-induced DW motion in nanowires that lie parallel to the plane.

### 1.3 Current issues

As explained in the previous section, conceptually the MRM is a very promising concept, although there are still a lot of problems in its realization. Therefore, a lot of research is going on in the topic of DW motion. These problems can be of technical nature, such as the choice of materials that provide the highest DW velocities, or very fundamental because for example the STT is not yet fully understood. In this section we therefore point out some of the recent developments and current issues in the field that are related to the experiments in this thesis.

#### 1.3.1 Out-of-plane magnetized materials

A first point of interest is the class of materials that are used in DW devices for research and application purposes. Before we discuss this topic, we first take a better look at a DW. It is defined as the area between two domains with opposite magnetization, as shown in figure 1.3(a). In general a magnetic material has an easy axis of magnetization, which is in figure 1.3(a) aligned with the long direction.
of the strip. Inside the DW the magnetization rotates from left to right. The interplay between different energy contributions determines the width of the DW.

Until now, most research has focused on the use of soft magnetic materials, such as Permalloy. The main advantage of this material is that the magnetic anisotropy, that determines the direction of the easy axis of magnetization, is solely determined by the shape of the structure. For a nanowire this means that the magnetization is in-plane, such as in the example of figure 1.3. This shape effect is however not very strong, which leads to very complicated magnetization profiles in DWs in these materials. This leads to typical DW structures such as a vortex and a transverse DW, which are shown in figure 1.3(b). Both the vortex and the transverse wall show very complicated magnetization profiles. Different DW configurations move differently under field and current, which makes the interpretation of experiments very complex [8, 9]. Moreover, DWs can also deform due to the interaction with the current, which leads to a decreased efficiency of the STT [10].

![Figure 1.3](image)

**Figure 1.3:** (a) A very simple illustration of a DW, that is the region between two magnetic domains of different local magnetization. In (b) a sketch of an Pt/Co/Pt stack is shown. This material has an easy axis of magnetization perpendicular to the stack. In (c) the alignment of the spins in a transverse and vortex wall, that are common for soft magnetic materials, is shown to be very complicated. From [11].

Recently, the field is therefore moving towards materials with a strong perpendicular anisotropy. An example of such a material is Pt/Co/Pt, that is also used in this thesis. In this material a very thin layer of Co (typically few Å) is grown in between two Pt layers as shown in figure 1.3(b). In this material, interface effects at the Pt/Co interfaces determine the magnetic anisotropy and hence the easy axis of magnetization, so that the Co layer is out-of-plane magnetized. This effect is much stronger and it is therefore energetically favourable to have narrow DWs so that as many spins as possible are aligned with the easy axis. The magnetization profiles in the DW are furthermore much simpler. There are several possible interface effects that can cause the Pt/Co/Pt stack to be perpendicularly magnetized:

- The strong spin orbit coupling of Pt leads to a symmetry breaking of the
electronic orbitals perpendicular to the interface. Due to this symmetry breaking, hybridization between the two materials at the interface induces a magnetic moment perpendicular to it.

- The lattice mismatch between the Pt and Co layers induces a strain which result in an additional magnetoelastic anisotropy. This is caused by a change in the distance between the atoms, resulting in different interaction energies.

One of the main advantages of narrow and simple DWs is that the former problem of a low and unpredictable STT efficiency can be overcome by using perpendicularly magnetized materials. This has been realized for example in an experiment on Pt/Co/AlO$_x$, which is only slightly different from our model system, where DW velocities of up to 400 m/s have been reported [12].

There are of course also some disadvantages for the use of perpendicularly magnetized materials. The main problem is that DWs can become pinned at material defects and this effect is more pronounced in perpendicularly magnetized materials. This is the case because narrow DWs are very sensitive to local variations in the energy landscape. A second problem is that the Curie temperature of Pt/Co/Pt is only around 500 K. When applying current to this material, current induced heating (or Joule heating), might raise the temperature close or beyond the Curie temperature and the wire might become demagnetized.

1.3.2 Controlled injection of DWs

There is however another disadvantage of the use of perpendicularly magnetized materials, which is that the anisotropy of the material is no longer sensitive to the shape of the structure. For Permalloy often a variation in shape is used to locally change the magnetic properties such as the coercive field (the field where the magnetization switches) or the easy axis of magnetization. This can be used to create DWs by making a simple variation in shape, such as a bend in the wire [13, 8] or a large nucleation pad [14]. An example of a zig-zag wire that can be used to create DWs is shown in figure 1.4(b). Applying the field perpendicular to the bends in the wire, results in DWs in the bend, as shown in the top image. It can also be seen that the type of DW is different for each bend in the wire, which can be a clear disadvantage of Permalloy.

For perpendicularly magnetized materials, the easy axis of magnetization is determined by the interface effects and such a geometrical approach is therefore not very effective. However, it is surprising that large nucleation pads are still used, based on the assumption that a larger area leads to an increased chance of the existence of a local defect where a DW can originate when a small field is applied [16, 17, 18]. It is however obvious that this method is not very reproducible.
Very recently it was demonstrated in our group that the use of a Ga$^+$ Focused Ion Beam (FIB) to modify the magnetic properties of Pt/Co/Pt very locally is a much more reproducible method and leads to the controlled injection of DWs [19]. It is generally accepted that FIB irradiation changes the magnetic properties of Pt/Co/Pt due to roughening of the interfaces as shown in figure 1.4(a) [20, 21]. However, it was never reported before that the position and the field that is needed to inject DWs into a nanowire can be controlled by using a FIB with variable Ga$^+$ dose. This shows that more reproducible DW devices with perpendicular magnetization can be fabricated using a Ga$^+$ FIB, which overcomes many of the problems of perpendicularly magnetized materials.

### 1.3.3 Origin of the spin transfer torque

In the previous sections we discussed some technical problems that are related to the fabrication of a MRM device. Probably the most debated topic, which is obviously very crucial for the development of a commercial MRM, is the exact origin and role that the current-induced STT plays in this device. It is now commonly accepted that there are actually two contributions from the current to DW motion [22, 23]. The first arises from conservation of angular momentum of the current through the DW and this term, which is dubbed the adiabatic STT, is quite well understood. However, there is also a contribution from non-adiabatic transport, that is phenomenologically introduced to explain many of the experiments on current-induced DW motion [24, 14]. It is the origin and the size of this non-adiabatic STT that is under a lot of discussion.

Without going into details, the relevance of non-adiabatic STT contribution,
1.3 Current issues

whose strength is denoted by $\beta$, is immediately visible figure 1.5. Here, the DW velocity is shown as a function of the current density $u$ for different $\beta$. In the situation where $\beta = 0$ it can be seen that there is a critical current density that is required to move the DW. Even in the case of a non-zero $\beta$ it is predicted that already very large current densities are required. One of the biggest challenges that has to be overcome to develop a commercial MRM, is to bring down the required current density by increasing the efficiency of the STT.

Apart from this search to increase the efficiency of the STT, also the origin of $\beta$ is still unclear. It is however commonly accepted that mistracking of the spin of conduction electrons with the local magnetization leads to a non-adiabatic STT. This situation is shown in figure 1.6. From this picture it is expected that the non-adiabatic STT is more important for narrow DWs, where mistracking is more pronounced. This is another motivation for the use of Pt/Co/Pt. The exact mechanism that leads to the non-adiabatic STT is however not clear and this has resulted in many different theoretical models [26, 27, 28].

There are also many conflicts in the experimentally observed results. Very different results have been observed for the strength of $\beta$ [29, 10, 18], in a wide variety of material classes. The most remarkable results are however related to the direction of current-induced DW motion. Both positive [16, 18, 29] and negative [30, 31] DW velocities have been reported, with respect to the direction of the electron flow and this strange inconsistency has not been explained in the theoretical models.

One experimental result, that has recently been demonstrated by Lavrijsen in our group [25], might lead to the solution of this problem. In his experiment it was found that the direction of current-induced motion was reversed for an inverted
1.3.4 DW resistivity

In this thesis, experiments have been performed with the ultimate goal of being able to understand the physical origin of the non-adiabatic STT. For this we use an approach that has not often been chosen before, namely by studying intrinsic DW resistivity. Our motivation for this choice stems from the simple mistracking model for the non-adiabatic STT in figure 1.6. If we go back to the beginning of this introduction, we know from GMR in figure 1.1(b) that the resistance of an electron in a ferromagnetic material depends on the alignment of the electron spin and the local magnetization. If mistracking is therefore present this probably leads to additional scattering and thus resistivity. In this sense, DW resistivity is therefore very much related to the non-adiabatic STT.

Elaborating a little more on the comparison with the conventional GMR effect, we can actually consider a DW as the limit of a GMR stack where the thickness \( d \) of the non-magnetic spacer layer reaches zero. If the resulting DW is so narrow that mistracking of the electrons with the magnetization occurs, again a GMR-like signal is expected, which we call intrinsic DW resistivity. This problem is therefore again a problem of length scales. In this thesis we are able to reach this
lengthscale by making use of the very narrow DWs in perpendicularly magnetized Pt/Co/Pt.

This similarity between DW resistivity and the non-adiabatic STT has also been suggested few times in literature and experiments [26, 32, 29]. However, only a limited amount of experiments exist that investigate intrinsic DW resistivity [33, 34, 35, 36], because the effect is very small and easily masked by other magnetization dependent resistance effects. A systematical investigation of the similarities between DW resistivity and the non-adiabatic STT has therefore never been reported. The main goal of this thesis is therefore to investigate this relation. We make use of the predictions of the DW width dependence of both $\beta$ and the DW resistivity to discriminate between the many models that exist.

1.4 This thesis

For this thesis we have worked on the current issues for the development of a commercial MRM, that have been identified in this chapter. We experimentally investigate structured Pt/Co/Pt systems, which have all the advantages that are described in section 1.3.1. For the injection of DWs we use FIB irradiation, which is a tool that will be optimized first. In particular, we focus however on the measurement of intrinsic DW resistivity in these perpendicularly magnetized materials. At the end of the thesis we compare these results with measurements of the non-adiabatic STT to investigate the direct fundamental link. An outline of the thesis is given below.

In chapter 2 we give a review of the theoretical descriptions that have been derived to understand the physics of DWs. We discuss several models that are useful to understand magnetism and especially current- and field-induced DW motion. Furthermore, a large part of this section is used to describe the theory of the non-adiabatic STT and DW resistivity and their similarities in more detail. Finally also the physics related to the pinning of DWs is explained.

Chapter 3 presents an overview of the different measurement set-ups that are used for the experiments. In particular we mention here the use of a Kerr microscope for magnetic imaging, that is modified for simultaneous electrical measurements.

In chapter 4 we first investigate one of the basic parameters for Pt/Co/Pt, the interface anisotropy, as a function of irradiation dose by using Stoner Wohlfart theory. Important to note is that the width of a DW depends on the local anisotropy and the systematic analysis in this chapter therefore gives us a handle to tune the DW width. Also, a study on the influence of the Co layer thickness is included.

Chapter 5 studies the pinning of DWs at anisotropy barriers that are created with the FIB. We will show that both the height and the width of the energy barrier
that DWs experience at an engineered anisotropy boundary can independently be change. Based on these results, we come up with some recommendations for the use of Ga\textsuperscript{+} FIB in DW devices. Furthermore, we have also reported on the first time use of a focused He\textsuperscript{+} beam for the fabrication of DW devices, and we show that this has several advantages over conventional Ga\textsuperscript{+} FIB.

In chapter 6 we demonstrate that we are able to measure intrinsic DW resistivity. By using our knowledge of Ga\textsuperscript{+} FIB and our unique setup, we show that the appearance of individual DWs leads to a change in resistance. Furthermore, we experimentally investigate the influence of the DW width on DW resistivity and show that this has a large impact. This result will be compared with the different theoretical models that exist.

In chapter 7, the non-adiabatic STT is measured by thermally activated depinning from an energy barrier. Again we investigate the influence of the DW width and use this to discriminate between the many theoretical models. Finally, the relation with DW resistivity is addressed and it is shown that the combination of both methods might lead to interesting new information on the direction of current-induced DW motion.

Finally in chapter 8 the most important conclusions from this thesis are summarized and a short outlook on following up experiments is presented.
Chapter 2

Theory of Domain Walls

In this chapter we provide the theory that is required for the understanding and discussion of the experiments in the report. The experiments in this thesis start with a study to influence and fully control one of the most basic parameters in our perpendicularly magnetized materials, the uniaxial anisotropy. To this end the behaviour of ferromagnetic material in an applied field is first described within the Stoner Wohlfart model in section 2.1. The motion of a DW in a nanowire is explained in section 2.2, by providing a detailed description of the magnetization dynamics, starting with the famous Landau-Lifshitz-Gilbert (LLG) equation. Using this theory the field- and current-induced motion of a DW is discussed, with a strong focus on the highly debated non-adiabatic contribution to the current-DW interaction.

The ultimate goal of this project is to determine the intrinsic electrical resistivity of DWs and to compare this with the current-induced non-adiabatic spin transfer torque in the LLG equation. Many different theoretical models that describe a possible origin of DW resistivity exist and a short overview is given in section 2.3. The model that seems to be the most relevant according to the few experiments that have been performed [4] is proposed by Levy and Zhang [37] and based on an increased scattering due to mistracking of the electron spin with the local magnetization. This model is therefore discussed in more detail. At the end of this section the similarities between the scattering mechanisms that possibly cause DW resistivity and non-adiabatic spin transfer are pointed out and a theory that actually links them together is presented. To be able to investigate this relation, a measurement of the strength of the non-adiabatic transfer torque is required. In section 2.4.2 we first discuss a simple model for the pinning of DWs at an energy barrier, which is used to understand the experiments in chapter 5. After this, a theory for temperature- and current-assisted depinning over an energy barrier is presented. This theory is exploited in an experiment in chapter 7 to compare the non-adiabatic spin transfer torque to DW resistivity measurements.
2.1 Stoner-Wohlfart Theory

To explain the important parameters of magnetism in this report, we start with one of the most straightforward situations in magnetism, that of a homogeneously magnetized thin film of ferromagnetic material in an external field. This situation can be described with the Stoner-Wohlfarth (SW) model, that has been widely used since its introduction in 1948[38]. In the model the energy of a magnetic system in an uniform external field is described, assuming a coherent rotation of the spins in the material. The magnetization can be modelled as a single macrospin vector. Because of this assumption a non-uniform object such as a DW can not exist in this model. Furthermore, the SW theory only involves energy minimalization and is therefore a static approach to magnetism. Current induced effects are also not included and will be introduced later in section 2.2.

Our system consists of a thin ferromagnetic layer of volume $V$ and thickness $t$, where the width $W \ll t$ and the length $L \ll t$. Such structures are typical for the deposition methods used in this report (section 3.1). Furthermore, the length $L > W$ so that we can speak of a magnetic strip. The system is placed in a uniform magnetic field $\mathbf{H}$, which makes an angle $\alpha$ with the normal of the magnetic film, the $z$-axis. The magnetic macrospin is given by $\mathbf{M}$ and its direction is described by the angle $\theta$ with the $z$-axis. The total magnetic moment is constant and given by the saturation magnetization $M_s = |\mathbf{M}|$. A schematic picture of this geometry is shown in figure 2.1. In the following we provide the different energy contributions that arise in this situation. The SW model is based on energy minimalization of these terms.

The first important contribution to the energy density $\mu_{\text{tot}}$ is due to the demagnetization field $\mathbf{H}_d$. This field is the result of the spins that are organized in such a way to minimize stray fields in the material. The field is related to $\mathbf{M}$ by the
demagnetization tensor $\mathbf{N}$ that is written as

$$\mathbf{H_d} = -\mathbf{N}\mathbf{M} = -\begin{pmatrix} N_x & 0 & 0 \\ 0 & N_y & 0 \\ 0 & 0 & N_z \end{pmatrix} \mathbf{M},$$

(2.1)

which is only dependent on the geometry of the magnetic layer. For certain known objects, for example ellipsoids, the demagnetization factors $N_x$, $N_y$ and $N_z$ are exactly known. For a rectangular thin strip with $L > W$ the demagnetization factors are known [39] and in general are given as $N_z \gg N_y > N_x$. The demagnetization field can qualitatively be understood by considering that magnetic poles exist at the edges of the sample and the demagnetization tends to pull the poles as far from each other as possible. The field depends on the direction of the magnetization and for a perpendicularly magnetized layer this means that a strong negative demagnetization field in the perpendicular direction exists. Because of the geometrical dependence of the demagnetization field term, it is often referred to as shape anisotropy. The energy density contribution from the demagnetization field is written in equation 2.2. From minimizing this term only, it can be shown that thin layers of soft magnetic materials (where other anisotropy contribution are small and the shape anisotropy is dominant) have an in-plane magnetization. An example of such a material is the widely used Permalloy [10, 40, 41, 13].

$$\mu_{d} = -\frac{\mu_0}{2} \mathbf{H_d} \cdot \mathbf{M}. \quad (2.2)$$

In chapter 1 it is already explained that for our class of materials (thin Pt/Co/Pt films), the magnetization is perpendicular to the plane due to interface effects and a second anisotropy term is thus present. This extra contribution is given by the uniaxial anisotropy. For Pt/Co/Pt this effect arises from spin-orbit coupling at the interfaces that tends to align the spins in the z-direction. This effect is much stronger than the shape anisotropy and its strength is given by the first and second order anisotropy constants $K_1$ and $K_2$ [42], which are material parameters. Since the easy axis is pointing in the z-direction, the energy density contribution of the material anisotropy is given by equation 2.3. In general $K_2$ is very small so that the contribution of the second order anisotropy term can be neglected.

$$\mu_m = K_1 \sin^2 (\theta) + K_2 \sin^4 (\theta). \quad (2.3)$$

In the Stoner Wohlfarth model the demagnetization energy and all first order anisotropy terms are collected in a single effective anisotropy $K_{\text{eff}}$. For an infinite thin layer, where the demagnetization factors $N_x = N_y = 0$ and $N_z = 1$, the effective anisotropy is $K_{\text{eff}} = K_1 - \frac{\mu_0 M_s^2}{2}$, where the second term originates from equation 2.2. With this the effective energy density $\mu_{\text{eff}}$ is given as
\[
\mu_{\text{eff}} = K_{\text{eff}} \sin^2(\theta). \tag{2.4}
\]

From the definition of \(\sin^2(\theta)\) it is seen that the uniaxial anisotropy dominates for \(K_{\text{eff}} > 0\) where the magnetization is thus perpendicular. An in-plane magnetization due to shape anisotropy is found when \(K_{\text{eff}} < 0\).

The final term that contributes to the energy density of our system comes from the interaction of the external field \(H\) with the magnetization of the ferromagnetic layer. This so-called Zeeman term states that it is energetically favourable for the spins to align with \(H\). The Zeeman energy contribution is therefore minimal when \(M\) is in the same direction as \(H\). Theoretically this term is written as

\[
\mu_h = -\mu_0 M \cdot H = -\mu_0 M_s H \cos(\alpha - \theta). \tag{2.5}
\]

Combining all the contributions to the energy density and neglecting \(K_2\) gives the result for the total energy density \(\mu_{\text{tot}}\), which is found to be

\[
\mu_{\text{tot}} = K_{\text{eff}} \sin^2(\theta) - \mu_0 M_s H \cos(\alpha - \theta). \tag{2.6}
\]

The total internal energy can be calculated by integrating over the volume \(V\). For a given applied field \(H\), the SW model therefore predicts the angle \(\theta\) of the magnetization \(M\), by minimizing the energy for the given material parameters \(K_{\text{eff}}\) and \(M_s\). This result is exploited in chapter 4 by measuring \(\theta\) as a function of \(H\) for various \(\alpha\) to determine \(K_{\text{eff}}\). This way \(K_{\text{eff}}\) can be determined which shows that the Stoner-Wohlfarth model is a very simple but powerful technique to describe static magnetization processes.

### 2.2 Domain wall dynamics

In this section we will describe the dynamic motion of DWs in a magnetic nanostrip under both current and field. To do this, we first have to let go the macrospin model and assume that the magnetization of the nanowire is built up from a collection of many single spins. The spins tend to align their magnetization (now given by \(M\)) with the neighbouring spins via the exchange interaction, that is proportional to the exchange stiffness constant \(A\). This leads to an extra contribution in the energy density from equation 2.6.

\[
\mu_{\text{exc}} = -\frac{A}{|M|^2} (\nabla M)^2 \tag{2.7}
\]
2.2 Domain wall dynamics

Integrating $\mu_{\text{tot}}$ over the volume $V$ leads, in absence of an external field, to the internal energy $U$ that is written as

$$U = \int_V \left[ \frac{A}{|M|^2} (\nabla M)^2 + K_{\text{eff}} \sin^2(\theta) \right] dV. \tag{2.8}$$

Here, $M$ can depend on the position. From equation 2.8 it can be seen that the perpendicular anisotropy $K_{\text{eff}}$ is again very important. Let us consider a DW in a perpendicularly magnetized nanowire, for example one of the DWs that are sketched in figure 2.2. Inside the DW the magnetization has to rotate from up (down) to down (up). The exchange energy contribution now tends to minimize its energy by widening the DW to have only minor differences between neighbouring spins. The anisotropy however has the lowest energy contribution for a sudden change in magnetization, because the magnetization is then always aligned with the easy axis. The width of the DW is therefore determined by the interplay of the exchange energy and the effective anisotropy. Manipulating the effective anisotropy gives us a handle to change the width of the DW. This idea is optimized in chapter 4 and 5 and exploited in chapter 6 and 7 to investigate the DW width dependence of intrinsic DW resistivity and the non-adiabatic STT.

![Spin configuration in a Bloch and Néel wall.](image)

Figure 2.2: Spin configuration in a Bloch and Néel wall.

Considering a simple 1D model, where $M$ is constant in magnitude ($M_s$) throughout the whole material and can only vary in the x-direction, a profile of the spin structure inside the DW can be obtained. It is shown that the spins in such a DW follow the well known Bloch profile that is given by [43]

$$\theta(x) = 2 \arctan \left[ \exp \left( \frac{-x}{\Delta} \right) \right], \tag{2.9}$$

where $\theta$ is the angle with the z-axis, $x$ is the position in the wire and $\Delta$ is the DW width. The latter is determined by minimizing the energy integral from equation 2.8. Several methods can be used to find an expression for the DW width, for example by using a simple 1D model [44] or a simplified Heisenberg exchange Hamiltonian [4]. The result in general is however that the DW width is determined by the interplay between $A$ and $K_1$ and is given by
\[
\Delta = \pi \sqrt{\frac{A}{K_{\text{eff}}}}.
\] (2.10)

Depending on the exact model that is used in the derivation, the prefactor of \( \pi \) enters in equation 2.10. For the 1D DW model this is not the case, but for the linear approximation of DW resistance measurements, where we expect that scattering of electrons across the whole DW is important, it is probably better to include the \( \pi \). Equation 2.10 is very important in the remainder of this report, because it relates \( K_{\text{eff}} \) to \( \Delta \).

As mentioned before, the uniaxial anisotropy in out-of-plane magnetized strips is in general much larger than in for example permalloy and dominates the shape anisotropy. In these materials, the DWs are therefore very narrow and have simple spin structures. Figure 2.2 shows two of the most basic DW structures, a Bloch and a Néel wall. In both walls the magnetization rotates from up to down according to the profile in equation 2.9. The difference is that spins in a Bloch wall rotate in the plane of the DW and the magnetization in a Néel wall rotates in the direction of the nanowire.

Whether a Bloch or a Néel wall is present in a material is determined by the demagnetization factors \( N_{x,\text{DW}} \) and \( N_{y,\text{DW}} \) inside the DW. Since the magnetization is not uniform, these depend on the local spin configuration and are hard to calculate. They can however be estimated by assuming an effective DW volume from which it can exactly be calculated whether a Bloch or Néel wall is the favourable spin configuration in the DW [11]. It is shown that a Bloch wall minimizes the energy for \( N_{x,\text{DW}} > N_{y,\text{DW}} \) and a Néel wall is favourable for \( N_{y,\text{DW}} > N_{x,\text{DW}} \). For the typical dimensions that we use in this thesis, a Bloch wall is definitely favourable. Decreasing the width of the nanowire has however shown that a transition from a Bloch to a Néel wall can indeed be observed [45].

### 2.2.1 Field induced DW motion

To account for the magnetization dynamics of a moving DW, we introduce here the Landau-Lifshitz-Gilbert (LLG) equation, that describes the evolution of the magnetization in time under applied field and current [22]. Only considering field terms at first, the LLG equation is written as

\[
\frac{\partial \mathbf{m}(t)}{\partial t} = -\gamma \mu_0 \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}(t)}{\partial t},
\] (2.11)
In this equation \( m = M / M_s \) is the magnetization direction and \( H_{\text{eff}} \) is an effective field, that includes contributions from the external field and from the anisotropy, demagnetization, exchange interactions in equation 2.8. To convert these energy density contribution to a magnetic field contribution, it is used that

\[
H = -\frac{1}{\mu_0} \frac{\partial \mu}{\partial M},
\]

where \( \mu \) is the energy density. Furthermore in equation 2.11, \( \gamma \approx 1.76 \cdot 10^{11} \text{ rad/sT} \) is the gyromagnetic ratio and \( \alpha \) is the dimensionless Gilbert damping constant.

The physical origin and direction of both field torque terms in equation 2.11 is shown in figure 2.3. The first term describes the precessional motion of the magnetization around \( H_{\text{eff}} \). The second torque is the damping torque that makes the spins relax towards the field due to dissipative (scattering) processes. The combination of both torques results in a spiral motion of the magnetization around \( H_{\text{eff}} \).

![Figure 2.3: Schematic picture of the geometry of the field torques in the LLG equation. In (a) the precessional torque is shown and in (b) the damping torque that is proportional to the Gilbert damping constant is depicted. From [46].](image)

For a complex but realistic structure such as a DW, both \( H_{\text{eff}} \) and \( m \) are non-uniform and the LLG equation is therefore hard to solve. Many approximations are available to overcome these problems, such as the 1D model of a DW in equation 2.9. Micromagnetic simulations are another strong method to model and understand the dynamics of DWs. In this report we are only interested in some of the general results that arise from the LLG equation. More extensive investigations, including simulations, of the LLG equation can for example be found in [11, 7].

Figure 2.4 shows the general result for the DW velocity as a function of applied field, which is obtained from micromagnetic simulations [44]. Two regimes can be observed, below and above the so-called Walker breakdown \( H_w \). Below \( H_w \) the velocity increases strongly with the applied field and the spins in the DW are canted towards the direction of motion because of the applied field. At the point where the applied field is large enough to overcome the transverse anisotropy, the tilt angle becomes so large that the DW is no longer stable and starts to precess. The field at which this happens is the Walker breakdown field [47] and this changes the solution drastically. The Walker breakdown field is written as
Figure 2.4: DW velocity as a function of applied field. Before the Walker breakdown the velocity of the DW linearly depends on the applied field. For $H > H_w$ the DW starts to precess which strongly reduces its velocity. For high fields the DW velocity is again linear in field, although now the slope is much smaller. From [47].

\[ H_w = 2\pi\alpha M_s |N_y - N_x|, \]  

(2.12)

where $N_{y,DW}$ and $N_{x,DW}$ are the demagnetization factors of the wall. Above $H_w$ the precession of the tilt angle of the DW has a large negative impact on the DW velocity. At higher fields the DW velocity increases again linearly with field, which is called the linear precession regime.

### 2.2.2 Current induced DW motion

In the previous section we have discussed the DW velocity as a function of the applied field. In chapter 1 it is already mentioned that the direction of this velocity is opposite for different DW polarities, because all the spins tend to align with the field. Since this destroys the bit pattern in possible memory applications, the field-induced DW velocity is not so interesting for commercial applications. We therefore discuss the effect of a current on the motion of a DW. It is shown that this induces several additional torques on the magnetization due to spin transfer torques (STT) [5].

It is generally accepted that the inclusion of current-induced STT leads to two extra terms in the LLG equation of 2.11. These are an adiabatic and a non-adiabatic contribution [22, 27]. Although we will elaborate later on the fact that the origin of the non-adiabatic term is still highly debated, it can be phenomenologically introduced and the extended LLG equation reads
\[ \frac{\partial \mathbf{m}(t)}{\partial t} = -\gamma \mu_0 \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}(t)}{\partial t} - (\mathbf{u} \cdot \nabla) \mathbf{m} + \beta \mathbf{m} \times [(\mathbf{u} \cdot \nabla) \mathbf{m}] \] \quad \text{(2.13)}

Here, \( \mathbf{u} \) is the effective velocity in the direction of the electron flow, that takes the role of the current and the dimensionless parameter \( \beta \) accounts for the strength of the non-adiabatic spin transfer torque. The magnitude of \( \mathbf{u} \) follows directly from conservation of angular momentum for the adiabatic torque and is given by \[ u = \frac{g \mu_B P J}{2eM_s} \] \quad \text{(2.14)}

with \( g \) the Landé factor of approximately 2, \( \mu_B \) the Bohr magneton, \( J \) the current density, \( P \) the spin polarization of the current and \( e \) the elementary electron charge.

\[ \begin{array}{c|c|c|c|c|c} u / v_W & 0 & 0.5 & 1 & 1.5 & 2 \\ \hline \beta = 0 & 0.10 & 0.04 & 0.02 & 0.01 & 0 \\ \end{array} \]

**Figure 2.5:** Effect of a current-induced DW motion for different \( \beta \), while \( \alpha = 0 \). Important is to note that for \( \beta = 0 \) a threshold current is needed to have any current induced effect on the DW velocity. From [22]

Before we comment on the origin of the non-adiabatic STT, we use the LLG equation to show the importance of this term. Again we will not solve equation 2.13 by ourselves, but only look at the resulting DW velocity as a function of current. The result is adapted from [22] and shown in figure 2.5 for different \( \beta \), while \( \alpha = 0.2 \). The importance of \( \beta \) is immediately seen when assuming that \( \beta = 0 \) so that only
the adiabatic spin transfer torque induces DW motion. In this situation, the current density has to exceed an intrinsic threshold value to have any effect on the DW. For \( \beta > 0 \) there is always DW motion and thus the current densities that are required for a DW motion device can be decreased by orders of magnitude.

A sketch of the origin of both spin transfer torques is shown in figure 2.6 and we start with the description of the adiabatic STT. The basics of the adiabatic spin transfer torque lie in the fact that a current flowing in the direction of magnetization through a ferromagnet is spin-polarized. As explained in section 1.1, this is caused by an imbalance in the amount of 3d-electrons with majority and minority spin at the Fermi level. This induces a spin-dependent resistivity of the itinerant electrons in the 4s-band, due to s-d interactions [5] with the 4d-band, which effectively results in a spin-polarized current. In the case that current flows through a DW, where the magnetization locally changes direction, this means that the spin of the conduction electron follows the magnetization adiabatically, as shown in the left of figure 2.6. Due to spin angular momentum conservation a reaction torque on the DW is also present, which makes the DW effectively move in the direction of the electron flow. The interaction between the itinerant s-electrons and the localized d-electrons is called the s-d exchange force [5].

The adiabatic spin transfer torque was however not sufficient to explain many of the experimental results [24, 48, 49], and therefore an additional STT contribution was introduced phenomenologically in [22]. This term is known as the non-adiabatic contribution and has a field-like character, meaning that it induces a direct force on a DW [26]. The strength of this force is depicted by the dimensionless parameter \( \beta \).

Although there is still no consensus on the exact physical origin of the non-adiabatic STT, one of the often used explanations is that the conduction electrons are not able to follow the local magnetization in the DW. The exchange of spin angular momentum is not conservative in this case and the current induces a force.
on the DW. Intuitively this force is stronger for narrow DWs, when the mistracking is more pronounced, which is one of the motivations for using perpendicularly magnetized materials in this thesis. The non-adiabatic process is visualised in the right side of figure 2.6.

**Theoretical models of the non-adiabatic spin transfer torque**

At the moment the exact mechanism behind the non-adiabatic spin transfer torque is still unclear and many sophisticated theories are present that attempt to describe the origin and the strength (which is depicted by $\beta$) in a phenomenological way [22, 50, 27, 26, 32, 28, 51]. We therefore give a brief overview of some of these theories that seem to be the most relevant. For a full mathematical description of these models we refer to the articles, because we are mostly interested in the physical origin and the resulting behaviour that can be compared with experiments. Since smart use of a Focused Ion Beam in chapter 4 allows us to tune the DW width in our Pt/Co/Pt devices, we are mainly interested in the DW width dependence. The DW width ($\Delta$) dependence of DW resistivity will first be investigated (chapter 6) and then compared with measurements of $\beta$ (chapter 7). This investigation of the DW width dependence, which has not been reported before, possibly gives us a new way to discriminate between the many available models.

In the theory of Zhang and Li that is based on the LLG equation, the mistracking of the electron spin with the local magnetization profile in a DW leads to a non-equilibrium spin accumulation across the DW [27, 50]. The spins then relax via spin-flip scattering, which induces both an additional adiabatic and a non-adiabatic torque on the DW. It is shown that the non-adiabatic torque leads to current-induced DW velocities that can dominate adiabatic effects and is essentially the explanation that is visualized in figure 2.6. In the model of Zhang and Li, $\beta$ is a material parameter that depends on the spin-flip lifetime $\tau_s$ and a lifetime $\tau_{ex}$ that is related to the strength of the exchange coupling $J_{ex}$ between the itinerant (conduction) and local (magnetization) electrons. In general it is shown that $\beta \approx \alpha$, with $\alpha$ the Gilbert damping constant. In this model, $\beta$ does not depend on the width of the DW, given as $\Delta$.

A different approach to consider the non-adiabatic STT in the LLG equation is taken by Tatara and Kohno, who find the same torques as Zhang and Li but also propose that electrons are reflected at the DW because of a sudden change in magnetization [26]. This term only becomes important in the limit that $\Delta < \lambda_F$, with $\lambda_F$ the Fermi wavelength of ~ 1Å. Due to linear momentum transfer a force is exerted on the DW, which is proportional to the charge current and the resistivity $\rho_{DW}$ of a DW. In this model $\beta = \beta^{sr} + \beta^{na}$, where $\beta^{sr}$ is the contribution due to spin relaxation and is essentially the result that is calculated by Zhang and Li. Furthermore, $\beta^{na}$ is the contribution due to linear momentum transfer.
Interestingly, the latter depends on $\Delta^2$. Because of the direct link between $\beta$ and the DW resistivity, this model will be explained in more detail in the next section.

Finally, we want to mention an even more unexpected result that is found in [28]. Here the non-adiabatic STT is calculated from transport theories and found to be strongly spatially inhomogenous. For wide walls $\beta$ does therefore not depend on the width of the wall, but for a narrow walls an oscillatory dependence of $\beta$ on the DW width is therefore found. For very narrow walls it is even predicted that $\beta$ can become negative $\beta$. Such behaviour has never been observed experimentally, but the theory shows that there is still a lot of uncertainty in the mechanism that contribute to the non-adiabatic STT.

Apart from the inconsistency in the mechanism that is dominant in the theoretical models, strong deviations are also observed between the experimental results. Here, it is found that the size of $\beta$ varies by orders of magnitude [18, 29]. In all of the description of the non-adiabatic spin transfer torque in the above discussion, it is assumed that DW motion is induced in the direction of electron flow. Even more striking is therefore that recently several experiments have shown current induced DW motion in the non-conventional direction [25, 30, 16], meaning that either $\beta$, or the spin polarization should be negative. More experiments are definitely required to understand the nature of these results.

### 2.3 DW resistance

In this section we will theoretically investigate the effect of DWs on the resistivity of a nanowire. The section is divided into two parts. In the first part a brief review of the different scattering mechanisms that are proposed to cause DW resistivity is given. It turns out that the model of Levy and Zhang, which implies spin mistracking in the DW as the most important contribution, is probably the most relevant for our class of perpendicularly magnetized materials with narrow DWs. This model is treated more carefully and especially the dependence on the DW width $\Delta$ is discussed. The second part of this section is devoted to the relation between $\beta$ and DW resistivity. Since DW resistivity arises from the scattering of electrons into different spin states, high enough current densities also induce a significant reaction force on the magnetization in a DW. Following this argument we have already argued in section 1.3.4 that intuitively $\beta$ and DW resistivity are closely linked. A more mathematical expression is also derived, based on the model for linear momentum transfer of Tatara and Kohno, that is described in the previous section [26].
2.3.1 Intrinsic DW resistivity

The problem of understanding DW resistivity is simply stated but very difficult to solve. Many different theoretical models have been proposed that differ strongly in size and sign of the effect. One of the reasons for this is that there is still a lack of experiments on this topic, mainly because it is hard to separate intrinsic DW resistivity, which is the interesting parameter that theorists seek for, from the many other magnetization dependent resistivity contributions. These can all be summarized in the following expression for the electric field that is generated by a current density [35],

\[
E = \rho(B)J + \rho_{\text{AMR}} \left( \frac{M}{|M|} \cdot J \right)^2 / |J| + \rho_{\text{OHE}} [B \times J] + \rho_{\text{EHE}} [M \times J] + \rho_{\text{diff}} J. \tag{2.15}
\]

In this equation the first term is the \( B \)-dependence of the ordinary resistivity and the second term is the contribution of the anisotropic magnetoresistance. This term gives a resistivity increase for a magnetization in the direction of the current and is therefore the dominant term in many vortex and Néel walls. The third and fourth term are the ordinary and extraordinary Hall effects (see section 3.4.2). The final term is for additional scattering due to spin diffusion terms and includes all effects that are related to spin accumulation, spin-dependent scattering and spin diffusion. Intrinsic DW resistivity is therefore determined by this term.

It is noted that the available models are mostly developed from a phenomenological point of view. In the remainder of this section we shortly mention some of the available models and their most important conclusions for intrinsic DW resistivity are shown to be very different. For a more extensive and excellent overview of all the modeled approaches to DW resistance, the reader is referred to [4].

![Figure 2.7: Simplified picture of Viret model to explain DW resistance by mis-tracking of the electrons with the magnetization profile in a DW. It can be seen from the parallel resistor network for majority and minority spin channels that the total resistance increases, mainly because the low-resistance channels is increased.](image)
The idea of intrinsic DW resistance of a spin polarized current was used by Viret et al. [35] to explain small deviations from AMR behaviour in the magnetoresistance of Ni and Co thin films. They supposed that in the wall the local magnetization cants away from the spin direction of the conduction electrons, which is explained in figure 2.7. First, we see in the situation without DWs that current is given by two independent spin current channels for electrons with majority and minority spin. If we however introduce a DW in the magnetization of the wire, we see that mistracking of the spin of the electron $e$ with the magnetization $m$ occurs. This means that the majority carriers will have a small degree of minority character and vice-versa. The effect of this on the resistance is depicted in the parallel resistance network for both spin currents. The total resistance can be calculated from which it is understood that the resistance of the low (high)-current channel increases (decreases) and this increases the total resistance of the wire. In other words, the DW resistance is caused by mixing of the otherwise independent spin current channels that effectively induces a change in the resistance across the DW. In a classical model, where the scattering varies linearly with the cosine of the angle between the spin and the magnetization, a modified free path was used to calculate the DW resistance, which was found to be independent of the overall scattering rate and proportional to $\sim \frac{2P}{(1-P)^4} \frac{1}{\Delta^2}$ with $\Delta$ the DW width and $P$ the polarization.

The model of Viret is essentially the same as that of Levy and Zhang, that is also based on spin relaxation due to mistracking [37]. This time only the problem was treated in a full quantummechanical way, based on the well known Hamiltonian from GMR. Mistracking of the electron spin with the local magnetization is the cause of the DW resistivity in the model. Since the idea of mistracking closely resembles the available theories for $\beta$, the Levy-Zhang (LZ) theory is discussed in more detail in section 2.3. Moreover, this theory agrees with the few experiments that have been performed so far [4].

A very different approach to determine the DW resistivity is proposed by Tatara and Fukuyama [52, 53], where they focus on the contributions of quantum transport in magnetic wires. They claim that in the absence of DWs, i.e. when the wire is uniformly magnetized, the conduction electrons are weakly localized in the ferromagnetic wire. The introduction of DWs leads to a symmetry breaking that removes this localization of electrons. The intrinsic resistivity due to DWs therefore has negative sign in this context.

The final theory that we mention is that of Van Gorkom et al. [54], who calculated the effect of DW resistance semiclassically by taking into account the electronic structure of the DW. From this, it is shown that the effect of DW resistance can be both negative or positive, depending on the ratio of the relaxation times for spin up and spin down channels. They therefore conclude that the above models can all originate from the same intrinsic effect.
2.3 DW resistance

2.3.2 Levy-Zhang DW resistivity model

To determine the resistivity in the framework of the LZ theory, we follow the description as given in [37], starting with the Hamiltonian that is often used to describe the GMR effect in magnetic multilayers and can be written as

\[
H_0 = -\frac{\hbar^2 \nabla^2}{2m} + V(r) + J \sigma \cdot M(r). \tag{2.16}
\]

Here \(V(r)\) is the non-magnetic scattering potential, \(J\) denotes the exchange splitting, \(\sigma\) is the carrier spin vector and \(M(r)\) is a unit vector that gives the direction of the magnetization at position \(r\). The eigenstates of this Hamiltonian are the spin-dependent band structures of the ferromagnetic material. When this material is uniformly magnetized in the direction of the spin vector \(\sigma\), we can identify two independent spin current channels as shown in figure 2.8(a).

If there are no DWs in the wire, it is shown by Levy and Zhang that, independent of the magnetization direction, always possible to retain a Hamiltonian in the form of equation 2.16. This is done by rotating along any axis to parallelize \(\sigma\) with the magnetization direction \(M\). In figure 2.8(b) it is shown that this can simply be done by a rotation of the magnetization over the angle \(\theta\). The quantummechanical equivalence of this picture is a rotation that is given by \(R_\theta \equiv \exp (-i \frac{\theta}{2} \hat{n} \cdot \sigma)\), where \(\hat{n}\) is the axis about which the magnetization rotates. The rotated Hamiltonian in spin space is then written as

\[
H_\theta = R_\theta^{-1} H_0 R_\theta = -\frac{\hbar^2 \nabla^2}{2m} + V + J \sigma_z, \tag{2.17}
\]

from which it is shown that \(H_0\) is invariant under rotation.

Now introducing a DW in the initially uniformly magnetized wire, introduces a spatial dependent magnetization as shown in figure 2.8(c). To align the spin vector \(\sigma\) with the magnetization at every position, we therefore need to perform a rotation \(\theta(x)\) that depends on the position in the wire \(x\). Since the position \(x\) and the momentum term in \(H_0\) are noncommuting variables, diagonalization according to equation 2.17 is no longer possible and the Hamiltonian does no longer have pure eigenstates. This is the quantum mechanical equivalent of the mixing of spin-current channels that was already explained by Viret in figure 2.7 and increases the overall resistance of the wire. It is emphasized once more that the additional resistance due to DWs is the result of mixing of the spin-current channels due to mistracking and a DW is not a source of scattering by itself.

Levy and Zhang have shown that the perturbed term in the Hamiltonian in case of a DW is then given as
Figure 2.8: Schematic overview of the LZ model for DW resistivity, which is the quantum mechanical representation of that of Viret in figure 2.7. In (a) electron spin is parallel to the magnetization, leading to independent spin-current channels for majority and minority electrons. (b) For a uniform magnetization a rotation of $\theta$ is always possible to retain this situation. (c) Introducing a DW requires a position dependent rotation $\theta(x)$, that does not commute with the kinetic energy term in the Hamiltonian $H_0$ of the electron and results in mixing of the channels. This increases the resistivity. In (d) the effect of a smaller DW width on $\theta$ and the DW resistance is depicted.

\[
R_\theta^{-1} \frac{\hbar^2 \nabla^2}{2m} R_\theta = \frac{\hbar^2 \nabla^2}{2m} + V_{\text{pert}}, \quad \text{where} \quad (2.18)
\]

\[
V_{\text{pert}} = \frac{\hbar^2}{m} (\sigma \cdot \hat{n}) (\nabla \theta) \cdot p - \frac{i\hbar^2}{4m} (\sigma \cdot \hat{n}) \nabla^2 \theta + \frac{\hbar^2}{8} |\nabla \theta|^2. \quad (2.19)
\]

It can be seen that equation 2.19 depends on $\nabla \theta$ and $\nabla^2 \theta$. As shown in figure 2.8, the gradient of the local magnetization, given by $\nabla \theta$, is larger for narrow DWs. From this it can already be seen that the effect of DW resistivity depends on the width of the DWs, because narrow DWs induce more mistracking between the electron and magnetization spins.
Using a very simplified DW profile where \( \theta(x) = \pi x / \Delta \) for \( 0 < x < \Delta \), with \( \Delta \) the DW width and \( x \) the position in the DW, an estimate can be made of the effect of resistivity with perturbation theory. After some calculations two important expressions are found for the DW resistivity for a current in-wall (CIW) and for a current perpendicular (CPW) to the plane of the wall. This result is written as

\[
\frac{\rho_{\text{CIW}}}{\rho_0} = \left( \frac{\xi^2}{5} \right) \left( \frac{\rho_\uparrow / \rho_\downarrow}{2 + \rho_\downarrow / \rho_\uparrow} \right) \quad \text{and} \quad (2.20)
\]

\[
\frac{\rho_{\text{CPW}}}{\rho_0} = \left( \frac{\xi^2}{5} \right) \left( \frac{\rho_\uparrow / \rho_\downarrow}{2 + \rho_\downarrow / \rho_\uparrow} \right) \left( 3 + \frac{10 \sqrt{\rho_\uparrow / \rho_\downarrow}}{\rho_\uparrow / \rho_\downarrow + 1} \right). \quad (2.21)
\]

It can be seen that the effect of DW resistivity is fully determined by the spin polarization of the current \( \rho_\uparrow / \rho_\downarrow \) and a prefactor \( \xi^2 \). This factor is given by the following relation

\[
\xi = \pi \hbar^2 k_f / 4m \Delta J, \quad (2.22)
\]

with \( k_f = 1 / \lambda_f \) the fermi wavevector, \( J \) the exchange splitting and \( \Delta \) the DW width.

From the result of these quantum mechanical calculations, some important features of the DW resistivity in this model can be derived. First of all, it is explained that the DW resistance in the LZ model is based on scattering due to mistracking of the conduction electron spin with the local magnetization in a DW. This results in an increase of the local resistivity, which is proportional to the saturated resistivity \( \rho_0 \). DW resistivity is therefore not a source of resistance but only mixes the spin current channels. The size of the effect is therefore fully determined by the spin polarization \( \rho_\uparrow / \rho_\downarrow \). Furthermore it is shown that the \( \rho_{\text{CPW}} / \rho_0 \propto 1 / \Delta^2 \). This result is used to investigate the LZ model as the source of intrinsic DW resistance in chapter 6. In the remainder of this thesis we define \( \rho_{\text{DW}} \equiv \rho_{\text{CPW}} \), since we are only interested in this type of DW resistivity.

### 2.3.3 Relation between DW resistivity and the non-adiabatic spin transfer torque

In the previous section we have derived the LZ theory for DW resistivity. This theory is based on increased scattering in a DW due to mistracking which leads to mixing of the spin current channels. Intuitively this idea of mistracking is very much alike the explanation of the non-adiabatic spin transfer torque as from figure 2.6. It is for this obvious reason that we focus in thesis on the investigation...
of both $\beta$ and $\rho_{DW}/\rho_0$. In the final part of this section we therefore describe the model of Tatara and Kohno [26, 32] more carefully, since they find a direct link between both quantities of interest. This link is investigated experimentally in chapter 7.

In the theory of Tatara and Kohno a distinction is made between the transfer of linear and angular momentum from electrons to the DW and $\beta = \beta^{sr} + \beta^{na}$. The latter corresponds to a force of $\hbar(k_f - k_i)$, where $k_f$ and $k_i$ are the final and initial momenta of an electron that scattered from the DW. The loss of momentum of the electron is conserved and therefore transferred to the DW and dependents on the overall scattering rate or the resistivity in the DW. Furthermore, the first term described that angular momentum is transferred when the spin is flipped to the magnetization at the opposite side of the wall, which leads to an additional damping term ($\alpha^{sm}$) and a non-adiabatic spin transfer torque $\beta^{sr}$. The mechanism of $\beta^{sr}$ is analogous to the spin relaxation theory of Zhang and Li [27] (section 2.2). Tatara and Kohno then claim that $\beta^{na}$ is dominant in the case of $\Delta < \lambda_f$, where $\lambda_f$ is the Fermi wavelenght which is typically in the order of 1 Å. This limit can normally not be reached, although some experiments report on spin momentum transfer as a possible mechanism to explain their results [29].

To extract an expression for the force ($F_{el}$) and torque $\tau_{el}$ on the DW, Tatara and Kohno used the well-known 1D DW model and a Lagrangian and the most important result is that is that they were able to describe the equations of motion of a DW. We will not discuss the full derivation here [32], but only focus on the result for the non-adiabatic STT. This term in shown to be

$$\beta \equiv \beta^{na} + \beta^{sr} = \frac{e^2 n \rho_{DW} \Delta^2}{P \hbar \pi} + \beta^{sr}, \quad (2.23)$$

where $n$ is the electron density. It is estimated that $\beta^{sr} \approx \alpha$ in this model. Most interesting is however that in the limit of $\Delta < \lambda_f$, linear momentum transfer is the dominant mechanism so that $\beta = \beta^{na}$ is directly related to $\rho_{DW}$. This depicts the idea that additional scattering in the DW gives rise to the force on the wall. In [26] and [32] Tatara and Kohno of course often refer to their own model for negative DW resistivity in [52], but there is no constriction on the exact scattering model that is responsible for $\rho_{DW}$. Other DW resistance models for $\rho_{DW}$ are therefore also valid to use in equation 2.23.

This is the result that is also used in [29] to make a first quantitative comparison of $\beta$ and $\rho_{DW}$. To explain their measurements, Boulle et al. claimed that the adiabatic spin transfer torque and spin relaxation mechanism ($\beta^{sr}$) were not sufficiently large. Their contribution of the current to the DW displacement therefore indicated that $\beta^{na}$ is the dominant mechanism. Interesting to observe is however that Tatara and Kohno suggested that the effect of momentum transfer is only dominant for extremely narrow DWs (in the order of $k_f \sim 1$ Å). This is rather
counterintuitive, since $\beta^{na}$ also depends on $\Delta^2$ and therefore decreases for more narrow walls. This is a strong difference between the contribution of $\beta^{na}$ and $\beta^{sr}$, where no dependence on $\Delta$ is expected. However, an additional $\Delta$ dependence might enter via $\rho_{DW}$. An experimental investigation of these prediction will be given in chapter 7.

2.4 DW pinning and depinning at an energy barrier

In section 2.2 we have given a theoretical description of DW motion in magnetic nanostrips. In practice however, local pinning sites play an import role in the magnetization dynamics, leading to typically slow DW motion velocities in the so-called creep regime\[55, 56\]. In this chapter we describe two situations that are related to the pinning of DWs. In section 2.4.1 we give the description for pinning of a DW at an anisotropy boundary, based on the 1D DW model. In chapter 5 we make use of a Focused Ion Beam (FIB) to engineer these local pinning sites to be able to controllably inject DWs into our devices. In section 2.4.2 we use a more general model of thermally assisted depinning processes over an energy barrier. It is shown that both current and field can be included in an effective energy barrier and the characteristic time scales of depinning can be used to measure the non-adiabatic spin transfer torque $\beta$. In chapter 7 we use this theory to investigate $\beta$ as a function of DW width at engineered pinning sites.

2.4.1 1D model of DW pinning

In this section we investigate the pinning of a DW at an anistropy step in the simple 1-dimensional DW model, that is introduced before\[11\]. It is assumed that the DW has a simple Bloch structure, from which the out-of-plane angle along the wire axis is given by equation 2.24, where $\Delta$ is the DW width and $q$ is its position at the $x$-axis,

$$\theta(x) = \pm 2 \arctan \left( \exp \left( \frac{x - q}{\Delta} \right) \right). \quad (2.24)$$

The DW resides in a nanostrip with a perpendicular anisotropy that changes at $x = 0$. This transition is linear over a characteristic length $\delta$. We assume that the anisotropy is given by $K_{eff,0}$ for $x > \delta/2$ and $K_{eff} < K_{eff,0}$ for $x < \delta/2$. This situation is sketched in figure 2.9(a). Furthermore the energy of the DW is related to the local anisotropy and given by

$$E_{DW} = 4\sqrt{AK_{eff}}. \quad (2.25)$$
The DW therefore experiences an energy barrier between the high and the low anisotropy region, where $K_{\text{eff}} < K_{\text{eff},0}$. This situation is sketched in figure 2.9b.

\[ H_{\text{pin}} = \frac{K_{\text{eff},0} - K_{\text{eff}}}{\mu_0 M_s} \times \frac{2\Delta}{\delta} \tanh \left( \frac{\delta}{2\Delta} \right). \] (2.26)

First we consider the situation that $K_{\text{eff}} > 0$ so that the strip is perpendicularly magnetized at both sides of the anisotropy step [11]. From the sketch of the energy landscape it can be seen that the DW initially resides in the low anisotropy region. The energy barrier can be overcome by applying an external field $H$. The field induces an extra Zeeman energy and effectively cants the energy landscape. At a certain field this contribution is large enough to overcome the energy barrier, as shown in figure 2.9(c).

An expression for the depinning field $H_{\text{pin}}$ can be obtained by considering the derivative of the energy with respect to the position of the DW. If this quantity is negative in the whole nanostrip, the tilt of the energy landscape is large enough to depin the DW and a value for $H_{\text{pin}}$ can be obtained. From this it can be calculated that $H_{\text{pin}}$ is

First we consider the limit of an infinitely steep anisotropy step, where $\delta = 0$. In this case $H_{\text{pin}} = \frac{K_{\text{eff},0} - K_{\text{eff}}}{\mu_0 M_s}$ and scales directly with $K_{\text{eff},0} - K_{\text{eff}}$. This means that the pinning strength scales directly with the anisotropy difference. Considering the opposite limit, where $\delta >> \Delta$ shows that $H_{\text{pin}} = 0$. This means that a more gradual increase of the anisotropy leads to a weaker pinning, as is expected from the observation that tilting the energy landscape leads to depinning of the DW.
2.4 DW pinning and depinning at an energy barrier

If $K_{\text{eff}} < 0$, the left side of the nanowire is in-plane magnetized. In the following part of this section, we will perform a similar analysis as above to obtain an expression for the depinning field in this limit. Here, it is assumed that the in-plane anisotropy is so large that the spins are completely in-plane, irrespective of the applied field. In this situation a semi-Bloch profile can be assumed, where the angle of magnetization in the DW rotates from out-of-plane to in-plane. This profile is given by

$$\theta(x) = \pm \arctan \left[ \exp \left( \frac{x - q}{\Delta} \right) \right]. \quad (2.27)$$

Again we can obtain an expression for $H_{\text{pin}}$, which is in this limit given by

$$H_{\text{pin}} = \frac{K_{\text{eff},0}}{\mu_0 M_s}. \quad (2.28)$$

Interesting to observe is that the pinning field of the DW no longer depends on the anisotropy difference $K_{\text{eff},0} - K_{\text{eff}}$, but is only determined by $K_{\text{eff},0}$.

To conclude we have shown that a simple 1D model is capable to qualitatively describe the pinning field $H_{\text{pin}}$ of a DW at an anisotropy barrier. This result will be used in chapter 5, where a Ga$^+$ FIB is used to control the energy landscape at the nm scale, thereby tuning the pinning of DWs in a controllable fashion.

2.4.2 Temperature and current-assisted depinning

In section 2.3, it is argued that there might be a relation between the intrinsic resistivity of a DW and the non-adiabatic STT. To investigate this relation we obviously need a method to determine the strength of this spin transfer torque, given by $\beta$. In this section we therefore present a model that describes the depinning of a DW from an energy barrier, driven by thermal activation, proposed by Kim and Burrowes [57]. They claim that the effect of current on the transition rate of this process is linear and an expression is found which links this effect to $\beta$. This effect can be used to determine $\beta$ experimentally.

In the model a simple 1-dimensional Bloch wall is assumed in an energy potential, given by $U(x)$, that also contains the Zeeman energy of an applied field, as sketched in figure 2.10. This depinning potential has several characteristic features; the minimum of the energy is at $x_a$ and the maximum at $x_b$, so that the width of this barrier $\delta = x_b - x_a$ and the height of the barrier at zero current is $\epsilon_{b,0}$. Furthermore, the shape of the energy potential is given by $\omega_a$ and $\omega_b$ that represent the curvature (second derivative) of the potential at $x_a$ and $x_b$ respectively.
Kim and Burrowes implement this simple model in the LLG equation (equation 2.13) with an addition stochastic force term to include thermal fluctuations, and from this they calculate a typical transition rate $1/\tau$. This transition rate obeys an Arrhenius law for thermal activation over a single barrier which is given by

$$\frac{1}{\tau} = \frac{1}{\tau_0} \exp \left[ -\frac{\epsilon_b}{k_b T} \right]. \quad (2.29)$$

Here, $k_b$ is the Boltzmann constant, $T$ is the temperature and $1/\tau_0$ is the attempt frequency, where $\tau_0 = \tau_0 (\omega_a, \omega_b)$ only depends on the form of the energy barrier.

Furthermore it is shown that the effect of a current $I$ can be included by assuming an effective energy barrier $\epsilon_b (I)$ for which equation 2.29 is still valid. An expression for the energy barrier is also found and written as

$$\epsilon_b (I) = \epsilon_{b,0} - \beta P \frac{h}{e} \frac{\delta}{\Delta} I, \quad (2.30)$$

where $P$ is the spin polarization, $h$ is Planck's constant, $e$ is the electron charge and $\Delta$ is the width of the DW. Higher order terms in $I$ are also present but since low currents are used in experiments, the dominant contribution is the linear term in equation 2.30.

This result is used in several experiments to determine the non-adiabaticity parameter $\beta$, by applying a field just below the depinning field, and measure the time
distribution of depinning under varying DC current \cite{18,8}. Using equation 2.29 and 2.30 it can be measured how the energy barrier varies with applied current and $\beta$ can be extracted. An advantage of this method is that only small amplitude current densities are required, due to the exponential character of the transition time. This is an interesting conclusion, since Joule heating can often mask the effect of spin transfer torque \cite{58}, which can be avoided with this method.

Field dependence of the energy barrier

A disadvantage of the method proposed by Kim and Burrowes, is that equation 2.30 depends on the width of the energy barrier $\delta$. In \cite{18} the crude estimate had to be made that $\delta \approx \Delta$, because DW pinning only occurs for energy barriers that are of the same length scale as the DW width. A better approximation can however be made by using the expression that is often used to describe thermally activated domain wall propagation, that is defined as

$$
\frac{\partial \epsilon_b}{\partial H} = -2M_sV = -2\mu_0M_s\delta A.
$$

(2.31)

Here, $V$ is the activation volume that is switched in a depinning event, which for our system is given by the cross-sectional area of the Co layer $A$ and the width of the pinning potential $\delta$. Interestingly, this expression is directly comparable with equation 2.30, by using the current-field equivalence that follows from a comparison of the non-adiabatic spin transfer torque and field terms in the LLG equation \cite{53} and is given by

$$
\left| \frac{\partial H}{\partial J} \right| = \frac{\beta P h \pi}{2eM_s\Delta}.
$$

(2.32)

In \cite{18} it is argued that this current-field equivalence in equation 2.32 is only valid if the energy barrier varies linearly with an applied magnetic field. It is therefore not useful for the description of thermal activation under general experimental conditions. We agree that $\frac{\partial \epsilon_b}{\partial H}$ in equation 2.32 is not constant because $\delta$ depends on the field $H$, but is still valid for every value of $H$. We can therefore use the field current equivalence in equation 2.32 if only small ranges of $H$ and $I$ are taken into account. Because the characteristic time $\tau$ depends exponentially on both $H$ and $I$, this is often the case in experiments since otherwise the waiting times become very long.

\footnote{In \cite{8} the depinning times of a DW hopping between two pining sites is investigated. Essentially the physics are the same and are described by two Arrhenius laws for hopping from left to right or from right to left. In \cite{8} it is used that $\delta$ is then the distance between both pinning sites. This is however wrong, since it is only the distance from the minimum of the energy potential to its maximum, which can be much smaller.}
To summarize the consequences of this, we state that the field-dependence of the energy barrier, that can be determined from the transition time according to equation 2.29, is a better way to extract an estimate of $\delta$ by using equation 2.31 for small field ranges. This can be used in combination with the current dependence (equation 2.30) of the barrier to extract a more accurate value for the non-adiabatic spin transfer torque $\beta$. 
Chapter 3

Experimental tools

In this chapter an overview is presented of the experimental tools that are used for fabrication and measurement of DW devices. In section 3.1 we start by discussing the fabrication process of patterned magnetic nanostructures, using EBL, sputtering and lift-off. Section 3.2 then gives a short review of results that are previously obtained in our group on the use of a FIB for DW injection. This knowledge is further optimized in chapter 4 and 5 to be able to make efficient use of the FIB. Many of the experiments in this report are performed with a recently acquired Kerr microscope and the properties of this set up are discussed in section 3.3. At the end of this section, some important modifications that are introduced to allow the set-up to perform DW resistance measurements are presented. Finally in section 3.4 a laser MOKE and a magnetotransport set-up are introduced. A more elaborate description of the full experimental toolbox that is used is found in [25].

3.1 Fabrication of magnetic nanostructures

In this project the magnetic properties of perpendicularly magnetized Pt/Co/Pt are investigated. These materials are deposited by DC magnetron sputtering, as explained in section 3.1.1. Patterning of the samples is performed by an EBL and lift off procedure (section 3.1.2) and gold contacts are used for electrical measurements, as explained in section 3.1.3.

3.1.1 DC magnetron sputtering

The magnetic films in this project are deposited using DC magnetron sputtering in the CARUSO ultra-high vacuum (UHV) sputter facility [59]. In this facility, six
deposition targets are placed above a rotatable sample stage. This way, complex metallic structures can easily be deposited. The base pressure inside the system is typically $3 \cdot 10^{-8}$ mbar.

A target material is placed in a pure argon atmosphere of $10^{-2} - 10^{-3}$ mbar. The target acts as a cathode so when a large voltage is applied, the Ar gas ionizes and high energy argon ions collide with the target, where they knock out single atoms of the material. The atoms whirl down where they condense on a substrate forming thin films via layer by layer growth. Obtained deposition speeds are in the order of Å/s. A mechanical shutter is used to control the layer thickness. Among its simplicity and ability to grow complex multilayer structures with relative ease, the control of layer thicknesses down to the sub-nanometer regime is definitely one of the greatest benefits of DC magnetron sputtering.

### 3.1.2 Electron beam lithography

In all of the experiments that are performed in this report, micron-sized structured Pt/Co/Pt samples are used. DC magnetron sputtering is therefore implemented in a standard electron beam lithography (EBL) and lift-off procedure. A schematic drawing of this fabrication recipe is shown in figure 3.1(a). A description of the different fabrication steps is given below.

- At first a Si/SiO$_2$ substrate is cleaned thoroughly in acetone and isopropanol and subsequently spin-coated with two layers of PMMA. PMMA is a positive resist and it is spin-coated at 5000 rotations per minute for 50 seconds. The bottom layer consists of polymers of $\sim 495k$ repetitions and is approximately 200 nm thick. The top PMMA layer is 60 nm thick and is much harder due to the increased length of the polymers of up to $\sim 950k$ repetitions. The solvent of the resist (Anisole) is removed in a 2 minute baking process at a hot plate of 150°C.

- The sample is placed in a FEI Nova 600i Nanolab dual beam system, consisting of a Scanning Electron Microscope (SEM) and a Focused Ion Beam (FIB). In this case a connected RAITH-Elphy-Quantum system is used to define the desired structure by writing the pattern with the electron beam. The high energy electrons (30 keV) that hit the sample locally break the chains of PMMA and make it softer.

- In the development step the sample is immersed in a solution of methyl isobuthyl ketone (MIBK). The exposed areas dissolve into the solution due to the reduced strength of the polymer chains. An undercut appears because the bottom PMMA layer is softer. After 45 seconds the sample is immersed in isopropanol to stop the development process.
• After the development, the sample is loaded into the CARUSO system and sputter-coated with a Pt/Co/Pt layer. Lift-off in acetone removes all the remaining PMMA resist and the Pt/Co/Pt on top of it and the desired pattern is transferred to the substrate.

The EBL lift-off procedure has the advantage that it is relatively fast compared to subtractive processes that involve ion beam milling and are able to deposit much smaller nanowires. The limiting step for the minimum size of the deposited nanostructures with our procedure, is that the edges are rather rough due to shadowing by the undercut. For the structures in this investigation, which are often \( > 1 \mu m \) in lateral size, this is not really problematic and EBL and lift-off is therefore advantageous to other available techniques.

![Figure 3.1:](image)

**Figure 3.1:** In (a) a schematic overview of the process for the fabrication of patterned structures with EBL, sputtering and lift off is presented. A microscope image of a predefined substrate for electrical measurements is shown in (b).

### 3.1.3 Electrical contacting

In many of the experiments electrical contacting of the Pt/Co/Pt layers is required. Essentially this is acquired by depositing Pt/Co/Pt on a substrate with predefined Ti(10nm)/Au(100nm) leads (defined by UV-lithography). As seen in figure 3.1(b), these electrical leads connect a small \( 100 \times 100 \mu m^2 \) area to large contact pads. These are finally connected to a chip carrier by wire bonding. A second EBL step via the procedure in figure 3.1(a) is used to deposit 20nm thick Pt layers between the magnetic structure and the end of the Ti/Au gold leads to have low-ohmic contact. The only difference with the previous EBL step is that the PMMA resist is baked for 1 minute at 100°, to prevent annealing or degradation of the already deposited magnetic structures.

A surprising discovery was found for the influence of the SiO\(_2\) capping layer of the substrate on the results. Initially, a 100nm SiO\(_2\) layer was used to have good
thermal contact with the underlying Si to prevent current induced heating as much as possible. For measurements inside a dark cryostat, no problems occurred, but measurements with the Kerr microscope (section 3.3) revealed photovoltaic effects. Without any current source, turning on a light source resulted in an induced voltage up to 10 mT. This was caused by the Au wire bonds that went straight through the 100 nm thick SiO$_2$ layer and formed a Schottky barrier with Si. This Au/Si interface is a well-known solar cell [60]. For DW resistance measurements in chapter 6 this is definitely not desired. Electrical samples that are used inside the Kerr microscope are therefore deposited on substrates with a capping layer of 2 μm of SiO$_2$.

### 3.2 Focused Ion Beam irradiation for DW injection

The FEI Nova dual beam system that is used for EBL in the previous section, also contains a focused ion beam (FIB) of Ga$^+$. In this system, a liquid metal ion source of Ga$^+$ is used to create a beam with energies up to 30 keV which is focused into a tiny spot (3.5 nm according to the specifications). The FIB is an ideal tool to locally mill away some material, for example to make cross-sectional scans. Interestingly, in previous work in our group, it is shown that the FIB can also be used in a totally different way, namely to change the magnetic properties of perpendicularly magnetized materials by using very low Ga$^+$ doses. This way, the anisotropy can locally be reduced which leads to the controlled nucleation and pinning of DWs in devices [11][19]. In chapter 4 and 5 we further investigate the properties of FIB irradiated Pt/Co/Pt strips and optimize the use of this tool for fabrication of DW devices. In this section we therefore extensively discuss the previously obtained results for FIB irradiation of Pt/Co/Pt.

It is generally accepted that low dose Ga$^+$ irradiation can be used to significantly alter the magnetic properties of Pt/Co/Pt, while removal of material by sputtering does not yet occur [21][61]. In particular, the perpendicular interface anisotropy of the material can locally be reduced. These regions have a lower coercive field which can be used to create DWs in Pt/Co/Pt devices [20][62]. Two mechanisms actually contribute to the lowering of the anisotropy for FIB irradiated Pt/Co/Pt [15]. First of all the tensile stress in the Co layer due to a lattice mismatch with Pt is released under FIB irradiation. Therefore the magnetoelastic anisotropy contribution is also reduced.

A second effect, that is even more pronounced for the ultrathin Co layers that we use, is the increase of interface roughness by FIB irradiation. The process is caused by intermixing of Co atoms with the Pt layers, as sketched in figure 3.2 [15]. The intermixing is mainly caused by diffusion of Co atoms. The Co atoms move more easily in the downward direction and therefore a difference between the two Pt/Co interfaces arises. Co atoms travel approximately one interatomic distance in the
direction opposite to the ions and the roughness of the upper Pt/Co interface is therefore increased. For the bottom interface, the Co atoms diffuse further into the Pt layer and alloying occurs. Both mechanisms lead to a reduction of the uniaxial anisotropy that is introduced in section 2.1.

Although the effect of FIB irradiation is very well understood, interesting results are just recently obtained in our group for the dependence on the irradiation dose of the injection of a DW from an irradiated area of Pt/Co/Pt into the rest of the device. A brief overview of the experiment is shown in figure 3.3[19]. In the experiments part of a Pt/Co/Pt cross is irradiated with low Ga$^+$ dose as seen in the top of figure 3.3(a). The images reveal the magnetic contrast of the wire and show that indeed the coercive field of the irradiated region is lowered and the magnetization reversal starts in this region when an external field is applied. For higher field, the DW propagates further into the wire. The external field at which this happens is defined as $H_{in}$ and is investigated as a function of Ga$^+$ dose.

The result of this is shown in the bottom of figure 3.3(b), where $H_{in}$ is plotted versus the Ga$^+$ dose. The result is fully understood by using the 1D DW model for pinning at an anisotropy barrier that is discussed in section 2.4.1 and the result is shown in figure 3.3(b). Three different regimes (A),(B) and (C) can be identified and explained as follows:

- In the first regime (A) the injection field $H_{in}$ decreases linearly, as shown by the closed symbols in figure 3.3(b). Here the coercive field $H_c$ of the irradiated part of the wire reduces due to Ga$^+$ irradiation. $H_c = \frac{2K_{eff}}{\mu_0M_s}$ is given by the anisotropy field of this part of the wire. This field is larger than the pinning field of the DW, which is therefore immediately injected into the non-irradiated wire. This means that $H_{in}=H_c$.

- For higher Ga$^+$ doses in regime (B), $H_{in}$ increases because the DW gets pinned at the anisotropy boundary. Here, $H_c$ becomes smaller than the pinning field $H_{pin}$, that scales with the anisotropy difference, and $H_{in}$ increases
The results of experiments on DW injection from a Ga\(^+\) irradiated part of Pt/Co/Pt. The Kerr images show that the coercive field of the irradiated Pt/Co/Pt is lowered and the magnetization reversal starts in this region. The DW is pinned at the boundary and for higher fields propagates into the Hall cross. The bottom graph shows that pinning of the DW increases the injection field. (b) Result of the micromagnetic simulations that confirm the experimentally found behaviour. The different symbols represent the simulations and the dashed, solid and dotted lines represent the result of calculations in a simple 1D model.

![Figure 3.3](image_url)

Figure 3.3: (a) The results of experiments on DW injection from a Ga\(^+\) irradiated part of Pt/Co/Pt. The Kerr images show that the coercive field of the irradiated Pt/Co/Pt is lowered and the magnetization reversal starts in this region. The DW is pinned at the boundary and for higher fields propagates into the Hall cross. The bottom graph shows that pinning of the DW increases the injection field. (b) Result of the micromagnetic simulations that confirm the experimentally found behaviour. The different symbols represent the simulations and the dashed, solid and dotted lines represent the result of calculations in a simple 1D model.

as a function of Ga\(^+\) dose. This limit is depicted in figure 3.3(b) by the open circles for \(\delta = 0\). In this regime \(H_{in}=H_{pin}\).

- In the final regime (C) for very high Ga\(^+\) doses it is observed that the irradiated area becomes in-plane magnetized so that \(K_{eff} < 0\). In section 2.4.1 it is shown that the pinning field of a DW at an anisotropy barrier between an in-plane and out-of-plane magnetized is given by \(H_{pin} = \frac{K_{eff}}{\mu_0 M_s}\) and only determined by the anisotropy of the non-irradiated layer. This result is plotted as the dotted lines in figure 3.3(b) and it is shown that the total result resembles the measurements quite well. The quantitative values however do not agree, since the effect of temperature is not included in this simple model.

To conclude this section, we have shown that interesting results are recently obtained on the injection field of DWs at an engineered anisotropy barrier. It shows that the injection field for DWs is actually a combination of two effects, the decreasing anisotropy of the irradiated part of the structure and the increasing pinning field that scales with the anisotropy. This result shows that a Ga\(^+\) FIB is a very promising tool for the DW devices. In this thesis we further optimize the use of a FIB in chapter 4 and 5 and show that we can basically tune the full energy
landscape in our Pt/Co/Pt strips at the nm scale. This is used to controllably nucleate and inject DWs in several device structures.

3.3 Magneto-optical Kerr microscopy

For the investigation of DW physics, several characterization techniques are used. By far the most used setup in this thesis was an Evico magnetics wide-field magneto-optical Kerr microscope, that was recently acquired in our group [63]. The microscope is able to directly image the magnetic domain structure of rather large areas, depending on the microscope objective. The resolution of the technique is only limited by the diffraction of visible light. This makes Kerr microscopy a very useful and versatile technique for the investigation of DW physics.

![Figure 3.4](image)

**Figure 3.4:** In (a) a simple illustration of the magneto-optical interaction of the longitudinal Kerr effect is shown. The linearly polarized electric field of the incoming beam is slightly rotated due to a Lorentz force that is given by equation 3.1. The rotation can be detected by using a second polarizer [64]. The top, middle and bottom images in (b) respectively show the geometries for the polar, longitudinal and transversal MOKE. The incident and reflected beams are indicated by (i) and (r).

The ability of the Kerr microscope to probe the magnetization depends on the Magneto-Optical Kerr Effect (MOKE) [64]. MOKE is a rotational effect, meaning that the polarization of a light beam is slightly rotated on reflection from a non-transparent sample. Phenomenologically this can be interpreted as a Lorentz force on the electrons that are set in vibrational motion by the light wave. This gives rise to a Lorentz motion that is given by
\[ v_L \propto m \times E, \]  

(3.1)

where \( m \) is the local magnetization and \( E \) is the electric field of the plane light wave. Figure 3.4(a) shows that projection of this Lorentz movement on the plane perpendicular to the propagation direction of the reflected light, leads to a so-called Kerr amplitude \( K \) and hence a rotation of the polarization of the reflected light beam. Using a second polarizer (called the analyzer) at a near 90° angle, this results in an intensity difference that can be detected. Switching the magnetization changes the direction of the Lorentz movement and therefore results in a contrast difference that is detected in the microscope. Three different MOKE geometries are shown in figure 3.4(b), depending on the magnetization of the sample that is measured, because from equation 3.1 it can be seen that the effect is maximized for \( E \perp m \). Figure figure 3.4(b) shows from top to bottom, Polar MOKE, Longitudinal MOKE and Transverse MOKE. Since we investigate samples with perpendicular magnetization, polar MOKE is used in our experiments.

The Kerr microscope and a schematic image of the ray diagram through the most important components is shown in figure 3.5. The microscope is equipped with a high intensity Xe arc that is placed directly behind the aperture diaphragm. Positioning this diaphragm determines the angle of incidence of the light rays and thereby the MOKE geometry. The different possibilities are shown in the inset of figure 3.5(b). For polar MOKE, a centered opening is used so that the light rays hit the sample vertically. The light rays then pass through a polarizer and are focused on the sample by the objective lens. After reflection the Kerr rotation is converted into an intensity difference by the analyzer. The compensator is used to compensate for the ellipticity of the reflected light beam, but is not needed for polar MOKE. Finally a CCD camera is used to observe the resulting light at a maximum frame rate of \( \sim 40 \) Hz. Real-time digital image processing is used to improve the magnetic contrast.

Initially our Kerr microscope was equipped with a one- and a two-dimensional in-plane magnet. However, for the investigation of perpendicular DW devices mostly a perpendicular field is required. Therefore an air coil that produces magnetic fields up to \( \sim 100 \) mT was developed. A significant drawback of this setup is the rather large Faraday effect that is induced by the perpendicular magnet. The Faraday effect is a similar rotation of the plane polarization of light as in the Kerr effect, but is induced by transmission through an optically transparent specimen in an applied field. Since the stray fields of our air coil are directly dispersed into our objective lens, large Faraday effects are present for increasing field strength. Although the Faraday effect itself is linear with field, in combination with the other optical components, it can lead to remarkable non-linear intensity variations as shown in Appendix A.
3.3 Magneto-optical Kerr microscopy

Figure 3.5: An image of the Kerr microscope (a) and a schematic illustration of the most important optical components and the light path for the incidence and reflected light beam (b). The inset in (b) shows different configurations for the aperture diaphragm that correspond to the depicted Kerr geometries.

3.3.1 DW resistance measurements with Kerr microscopy

One of the main goals of this project is the measurement of a change in resistance when DWs appear in a Pt/Co/Pt wire. Difficulties in separating DW resistance from other magnetoresistance effects have strongly plagued this field for many years and a lot of analysis is required to eliminate these effects to accurately measure DW resistance effects [35]. Combining the capability of Kerr microscopy to directly observe magnetization reversal processes, and thus the appearance of DWs, with electrical measurements is therefore a strong method to investigate DW resistance, which we will show in chapter 6.

For this reason, a sample holder that is equipped with a chip socket is developed and fabricated to fit exactly in the air coil of the Kerr microscope. The sample holder is connected to a BNC distribution board to easily connect different equipment. To be able to measure resistance changes very accurately, a Wheatstone bridge configuration of Pt/Co/Pt is deposited on the sample and contacted to the chip carrier. A Kerr microscope image of such an on-sample Wheatstone bridge is shown in figure 3.6. In this configuration, a change in resistance due to the appearance of DWs leads to a voltage of

\[ V_{A-B} = V_0 \frac{R_1R_4 - R_2R_3}{(R_1 + R_2)(R_3 + R_4)}. \]  

(3.2)

The equipment that is used to measure the small resistances is a combination of a Keithley 6221DC-AC current source and an analog lock-in Amplifier. The
Figure 3.6: In (a) an image of the newly developed sample holder for the combination of electrical measurements with wide-field Kerr microscopy is shown. The Wheatstone bridge configuration on one of the samples is shown in (b). The magnetic contrast of the magnetic domains, created by FIB irradiation, is clearly visible.

Keithley is a very stable current source, preventing voltage spikes that can destroy the sample. The lock-in amplifier is used to increase the signal to noise ratio. Much attention is also devoted for grounding of the whole set up, since even small electrical discharges can evaporate a carefully fabricated sample. For this reason, all the contacts in the BNC distribution board can be connected in parallel to ground by a 10 kΩ resistor. Finally, a LabView program is developed and implemented into the existing software for the Kerr microscope. Measurements of the resistance as a function of applied external field are fully automatized, while Kerr images can simultaneously be obtained for each measurement point. This allows for the direct comparison of the electrical signal and visible magnetization behaviour.

3.4 Other characterization techniques

Apart from the wide-field Kerr microscope, other setups are also used to study DW physics. The most important among these are a laser MOKE setup and a magneto transport measurement setup and are discussed in this section.

3.4.1 Laser MOKE setup

The laser MOKE setup is based on a Tsunami (Spectra Physics) Ti:Sapphire laser that generates pulses of approximately 70 fs with a repetition rate of 80 MHz at a wavelength of 790µm. The laser beam is linearly polarized and modulated with
a photo elastic modulator at a frequency of 50 kHz. The intensity of the reflected beam is measured with a lock-in technique to increase the signal to noise ratio. Due to the laser spot of only \( \sim 20 \mu m \) in diameter the laser MOKE setup can be used for probe the magnetization very locally. The setup is equipped with a rotatable electro magnet that can produce fields up to \( \sim 500 \text{mT} \), depending on the distance between the poles of the electromagnet.

### 3.4.2 Magneto transport measurement setup

For electrical measurements a magneto transport setup is used. The setup consists of a variable temperature flow cryostat that is mounted between the poles of an electromagnet. The electromagnet is 360° rotatable and controlled by two Delta electronic power supplies allowing fields up to 800 mT. During the measurements, the field is directly probed by a Lakeshore 420 Hall probe. Via a BNC distribution board, the sample can be connected to multiple measurement devices. In our case, mostly four Stanford Research 830 lock-in amplifiers are used to simultaneously measure the voltage over different contact pairs. The internal oscillator of one of the lock-in amplifiers is used to apply a current. All the equipment is digitally controlled via a GPIB connection.

An excellent method to electrically probe the magnetization of perpendicularly magnetized materials is to make use of the so-called Extraordinary Hall Effect (EHE). In these materials EHE is very strong effect and therefore easy to measure. The EHE is only one of the many different Hall effects that exist and is comparable to the Ordinary Hall Effect (OHE), where the perpendicular magnetization takes the role of the perpendicular applied field. A schematic overview of both the OHE and the EHE in a Hall cross configuration is shown in figure 3.7.

In general a Hall effect is defined as a potential difference perpendicular to the direction of current, often induced by a magnetic field. In the case of the OHE, this potential difference arises due to the Lorentz force \( (\sim B \times I) \) that acts on the moving charge carriers. This force pushes the electrons in a direction perpendicular to the current and a potential difference is created at the edges of the wire.

The exact origin of the EHE is subject to a lot of debate [65], but it is generally accepted that in this case the perpendicular magnetization is the driving force. However, this is not due to its contribution to the total field, but it has a different origin. In the EHE the direction of the transverse movement of the electrons depends on their spin. An imbalance between up and down spins at the Fermi level (effectively a spin polarization) thus leads to a potential difference between the transverse contacts. In measurements on the Hall resistivity both effects contribute to the measured 4-point resistivity that is given by
Figure 3.7: Schematic view of the Ordinary (left) and Extraordinary (right) Hall Effect in a double Hall cross. An external perpendicular field $H_z$ and the perpendicular magnetization $M_z$ respectively, induce transversal motion of the charge carriers. This results in a potential difference over the leads of Hall cross.

$$\rho_{Hall} = R_{OHE}H_z + R_{EHE}M_z,$$

where $R_{OHE}$ and $R_{EHE}$ are constants that characterize the strength of the respective effects. It can immediately be seen that the OHE is linear in field and is therefore easily subtracted from the measurements. Moreover, for our class of materials EHE is generally much larger than OHE. These measurements are therefore very suitable for the investigation of magnetic behaviour.
Chapter 4

Manipulating the anisotropy of Pt/Co/Pt

In the study on the use of current induced domain wall motion in commercial electronic memory devices, it is vital to have direct control of DW motion in nanostructures. In a previous work it is shown that the use of a FIB of Ga\(^+\) ions leads to controlled nucleation and injection of DWs in magnetic nanowires. The experimentally found behaviour of DW injection into Pt/Co/Pt layers\[19\] was verified by micromagnetic simulations and the 1D-model of section 2.4.1, in which the anisotropy was lowered for the Ga\(^+\) irradiated parts of the wire (also see section 3.2).

Whereas the influence of a decrease in anisotropy to the nucleation and pinning of a DW is fully understood, the exact relation between the perpendicular anisotropy of Pt/Co/Pt, depicted by the effective anisotropy constant \(K_{\text{eff}}\) that is introduced in section 2.1, and the amount of Ga\(^+\) ions is still unclear. In general it is widely accepted that FIB irradiation reduces the perpendicular anisotropy of Pt/Co/Pt\[21, 61, 66, 67, 68\], but most of these investigations base there conclusions on indirect measurements through the coercive field. Only a single experiment is available for a systematic measurement of the anisotropy as a function of He\(^+\) dose\[15\], but to our knowledge, a quantitative measurement of the anisotropy as a function of Ga\(^+\) dose is lacking. A systematic investigation of the perpendicular anisotropy for Ga\(^+\) irradiated Pt/Co/Pt is therefore insightful for the discussion of further measurements where Ga\(^+\) irradiation is used for the fabrication of DW devices. This chapter details such an investigation.

From previous work in for example \[69, 56, 70\], it is known that decreasing the thickness of the Co layer in Pt/Co/Pt generally increases the anisotropy. Intuitively one might thus expect that higher doses of Ga\(^+\) can be applied before the Pt/Co/Pt strip becomes in-plane magnetized. This is an interesting property for
both research and technological applications, since it increases the upper amount of Ga\(^{+}\) irradiation that can safely be applied. The effect of changing the Co thickness is also investigated throughout this chapter.

A common method to quantitatively measure the anisotropy of magnetic samples makes use of Stoner Wohlfart theory [38]. The theoretical description of the model is given in section 2.1. Experimentally the method can be employed by applying an external field under an angle with the easy axis of magnetization. The magnetization is pulled away from its favourable direction, towards the field direction. The ease by which this can be done is an indication for the strength of the anisotropy. A quantitative value for the effective anisotropy \(K_{\text{eff}}\) can be obtained by fitting the results with the theoretical model [71].

The anisotropy of the Pt/Co/Pt samples is determined in two different experimental methods, one optical and one electrical. Although the results of the electrical measurements turned out to be more accurate, both methods are described and a comparison is made at the end of the chapter. Section 4.1 first deals with the experimental setup and the results of the electrical measurements. The optical measurements are discussed in section 4.2. The final results and a comparison of both measurement methods are given in section 4.3.

4.1 Electrical anisotropy measurements

For the determination of the perpendicular anisotropy \(K_{\text{eff}}\), we make use of the Stoner Wohlfart (SW) model that is discussed in section 2.1. In our convention the easy axis of magnetization of the Pt/Co/Pt stack is aligned with the \(z\)-direction. The relevant input parameters for the SW model are therefore the magnetization \(M_{z}/M_{s}\), the external field \(H\) and the angle \(\alpha\) between the applied field and the \(z\)-axis. For the electrical measurements \(\alpha\) can directly be read out from an accurate scale and is therefore known. The perpendicular magnetization \(M_{z}\) as a function of \(H\) and \(\alpha\) is determined by the EHE (see section 3.4.2).

4.1.1 Experimental considerations

Samples containing four Hall crosses of \(5\mu m\) wide Pt\(_{4\text{nm}}\)/Co\(_{x\text{nm}}\)/Pt\(_{2\text{nm}}\) are deposited on a 100 nm thick SiO substrate. From now on we will omit the addition of nm and label the samples as Pt\(_{4}/Co_{x}Pt_{2}\). The thickness of the Co layer is varied between 4, 5 and 6 Å. The samples were fabricated using a standard EBL, DC magnetron sputtering and lift off recipe (see section 3.1). On top of the branches of the Hall crosses, 20 nm thick layers of Pt are deposited in a second EBL step for electrical contact. A microscope image of the resulting sample is shown in figure 4.1.
4.1 Electrical anisotropy measurements

Figure 4.1: Pt/Co/Pt sample with four Hall crosses for EHE measurements. A current is sent through the 5μm Pt/Co/Pt strip and for each cross the Hall voltage perpendicular to the current is measured by a lock-in amplifier. The dark red areas show where the sample has been irradiated with Ga⁺ ions.

After the deposition of the Pt contacts, the Hall crosses are irradiated with different Ga doses. The beam ions have an energy of 30 keV at a beam current of several pA. The dose is varied from a minimum of $0.07 \cdot 10^{13}$ ions/cm² to $1.3 \cdot 10^{13}$ ions/cm². According to literature this dose range affects the Pt/Co interfaces, but does not significantly remove material [21, 61]. The used doses are at the minimum of the range that can be reached with our dual-beam system due to a limited minimum dwell time of 0.4μs. For low doses the dwell time is fixed at its minimum and the step size is increased to a maximum of 30 nm. For higher doses, the step size is fixed at 10 nm and the dwell time is adjusted. The irradiated region for each Hall cross is $18 \times 34 \mu m^2$ so that the probed Pt/Co/Pt area is fully irradiated.

Four lock-in amplifiers are used to measure the EHE as a function of applied field for four different Ga doses at the same time. One of the lock-in amplifiers is also used to send an AC current with a current density of $\approx 3.0 \cdot 10^9$ A/m² and a frequency of 5 kHz through the strip. The measured lock-in voltage consists of the EHE plus a small contribution of the ordinary Hall effect (OHE). Since we know from section 3.4.2 that the EHE is constant for an external field that is fully perpendicular, i.e. $\alpha = 0^\circ$, we can use this to subtract the OHE from all other measurements.

Figure 4.2 shows a typical measurement of $M_z/M_s$ as a function of the applied field $H$ for various $\alpha$. The traces are fitted with a global fitting routine based on energy minimalization of the SW model. Input parameters within the model are the applied field $H$, the angle $\alpha$, the perpendicular magnetization $M_z$ and the saturation magnetization $M_s$. Apart from the latter, which is estimated to be $1.4 \times 10^6$ A/m from SQUID measurements [70], all the values are extracted from the experiment. The model then gives a value of the perpendicular anisotropy $K_{eff}$. The second order crystalline anistropy constant $K_2$ is found to be of low importance and therefore not taken into account in the final fit.

In the depicted data it can be seen in figure 4.2 that for nearly in-plane fields ($\alpha >$
**Figure 4.2:** Example of a measurement of the perpendicular magnetization of a Pt$_4$/Co$_{0.4}$/Pt$_6$ sample, irradiated with 0.07 · $10^{13}$ ions/cm$^2$, as a function of $H$ for different $\alpha$. The open circles are the normalized EHE values, which are a direct measurement for $M_z/M_s$. The red curves are the result of a global fit for $\alpha$ between 30 and 70°. Higher $\alpha$ are not incorporated because of non-coherent magnetization processes. The inset shows the geometry of the experiment.
4.1 Electrical anisotropy measurements

80°), there is a strong deviation between the fits and the experimental data. This effect is known to happen due to a non-coherent reversal of the magnetization [72, 71] The structure no longer behaves as a single magnetic domain and the SW model is not valid for such a structure. More detailed information on this non-coherent magnetization reversal and some simulations to verify the results are given in [70]. To dismiss the influence of the effect on the final result, only measurements up to an angle of 70° are incorporated in the fit.

Furthermore, for low values of $H$ the Pt/Co/Pt sample seems to be less than 100% remanent. This effect is similar for all $\alpha$ and is, irrespective of the Ga$^+$ irradiation dose of the sample, in the order of approximately 1% of $M_s$. The physical origin of the loss of remanence is not clear, so it might as well be an artifact of the measurement. The effect has a small impact on the quantitative value of $K_{\text{eff}}$ but because it was visible in all measurements, it does not influence the trends that are described in section 4.1.2.

4.1.2 Anisotropy of Ga-irradiated Pt/Co/Pt

![Figure 4.3](image)

**Figure 4.3:** The anisotropy constant $K_{\text{eff}}$ as a function of the Ga irradiation dose for Pt/Co/Pt structures with a different Co thickness. The dashes lines are only drawn as a guide to the eye. The solid line is obtained by an exponentially decaying fit through the measurement on Pt$_4$/Co$_{0.5}$/Pt$_2$ samples. The result is used as a reference for $K_{\text{eff}}$ of irradiated samples in chapter 6 and 7.
Figure 4.3 visualizes the effect of Ga\(^+\) irradiation on the anisotropy of Pt/Co/Pt structures. The measured values for \(K_{\text{eff}}\) are comparable to earlier measurements in our group\[70\] and the error bars are estimations, based on the quality of the fits. First of all we describe the general trend of \(K_{\text{eff}}\) as a function of Ga\(^+\) dose. For low irradiation doses, we see an approximately linear decrease for increasing dose, which flattens at high doses. Even higher irradiation doses than the ones shown are also measured, but the perpendicular magnetization at zero field was significantly reduced, resulting in a lower remanence. For these samples, SW could no longer be applied to obtain \(K_{\text{eff}}\), since SW assumes an out-of-plane magnetization at zero field. Eventually the magnetization of the sample becomes completely in-plane so that \(K_{\text{eff}} < 0\). The flattening at high doses might already be affected by a loss of remanence, although it was not observed from the quality of the fits. More likely is therefore that the effect of Ga\(^+\) on the Pt/Co interfaces can be described with an exponential decaying function. This means that the process becomes less effective for higher doses. It is therefore more difficult to reduce the anisotropy if the layer already has a large roughness.

Comparing the influence of the Co layer thickness \(t_{\text{Co}}\) at zero irradiation, it is observed that the anisotropy increases if the Co thickness is reduced from 6 to 5 Å. This increase of the anistropy for thin Co layers is expected because\[73\]

\[
K_{\text{eff}} = K_V + 2K_s/t_{\text{Co}}. \tag{4.1}
\]

Here, \(K_s\) is the interface anisotropy, for Pt/Co/Pt dominated by the uniaxial anistropy discussed in section 2.1 and \(K_V\) is the volume anisotropy that contains the shape anisotropy and is therefore negative. However, in contradiction to equation 4.1, the anisotropy of the 4 Å Co layer does not differ significantly from the 5 Å sample. This means that growth-related phenomena are starting to play a role for the sputtered Co layer of 4 Å thick. The Pt/Co interfaces are more ill-defined, resulting in a lower interface anisotropy contribution. Such an observation is reported many times before\[69, 56, 70\] and is also reflected in the lower coercivities that are measured in chapter 5, indicating a more disordered layer with many nucleation sites.

An interesting observation is that the slope of the decrease of \(K_{\text{eff}}\) a low Ga\(^+\) dose is constant for all Co thicknesses. This is slightly counterintuitive, because if Ga\(^+\) irradiation reduces the uniaxial anisotropy \(K_s\) by the same amount for every Co thickness, a \(1/t\) dependence of the slope would be expected. The effect of Ga\(^+\) irradiation therefore seems to be dependent on the thickness of the ultrathin Co layer in Pt/Co/Pt. The observation that the slope of \(K_{\text{eff}}\) is constant, irrespective of the starting anisotropy of the unirradiated stack is very promising from an experimental point of view. This means that the range of Ga\(^+\) doses that can be applied can be expanded by changing the Co thickness. This way we can increase our tunable anisotropy range by more than a factor of 2.
4.2 Optical anisotropy measurements

For high irradiation doses it can be observed in figure 4.3 that the effect on the 4 Å sample is less pronounced than for the 5 Å sample. This again points to the conclusion that the effect of Ga\(^{+}\) irradiation becomes smaller when the Pt/Co interfaces have a certain roughness. Because the interface of the 4 Å sample are more ill-defined, this situation occurs at a lower irradiation dose.

As a final remark of this section, it is mentioned that the solid line is a fit of the Pt\(_4\)/Co\(_{0.5}\)/Pt data with an exponential decaying function. An exponential decay function is used to account for the flattening off at high doses. The result of this fit is in good agreement with the experiment and used in the chapter 6 and 7 as a reference for \(K_{\text{eff}}\) at variable Ga\(^{+}\) doses.

4.2 Optical anisotropy measurements

Measurements of \(K_{\text{eff}}\) are also performed in a laser MOKE setup (section 3.4.1). In this case, the Kerr rotation of a reflected polarized laser beam is used as a measurement for \(M_z/M_s\). A very important advantage of the optical method is the absence of any contacts on top of the structure. This makes a direct comparison of the results with further experiments possible.

4.2.1 Experimental layout

For this investigation, 50 \(\times\) 50\(\mu\)m\(^2\) squares of Pt\(_4\)/Co\(_x\)/Pt\(_2\) are deposited on a 100 nm thick SiO substrate and subsequently irradiated with a Ga\(^{+}\) dose up to \(1.3 \cdot 10^{18}\) ions/cm\(^2\). The structures are deposited within a grid of gold lines and reflectivity scans are used to localize the appropriate structures. The Pt/Co/Pt samples are placed between the poles of an electromagnet. Although the poles were positioned as close to each other as possible, the applied fields could not exceed 420 mT. Another disadvantage of the setup is that only \(\alpha\) between 80° and 90° were attainable and the readout was not very accurate (\(\pm 2°\)). Especially for large \(\alpha\), the accuracy of the field angle is very important. Electrical measurements have furthermore shown that at high \(\alpha\) non-coherent reversal of the magnetization has a large impact on the outcome of the measurements.

The measurement of \(M_z/M_s\) as a function of external field \(H\) is performed by modulating the intensity of the laser beam at 5 kHz and measuring the intensity of the reflecting beam with a lock-in amplifier at that frequency. Apart from the change in intensity due to Kerr rotation, this signal also contains a contribution from the Faraday effect. Analogous to the OHE effect in the electrical measurements, this effect varies linearly with an applied field. The Faraday effect is compensated for by measuring the non-magnetic substrate and subtracting its linear contribution from all other measurements. The Faraday effect is also much larger than the
Figure 4.4: The experimental data of $M_z/M_s$ of an unirradiated Pt/Co$_{0.5}$/Pt layer as a function of applied field is shown for different $\alpha$. The red lines depict the result of a fit with the Stoner Wohlfart model. Due to high $\alpha$ and low fields the appearance of buckling behaviour cannot be excluded. The inset shows the same measurement for a non-irradiated Pt/Co$_{0.4}$/Pt sample. It can be seen that there is more noise due to the smaller total magnetic moment. The problematic exclusion of the relatively large faraday effect caused the large deviation between the measurement and the Stoner Wohlfart fit.
4.2 Optical anisotropy measurements

OHE. A typical measurement of the normalized Kerr rotation as a function of external field $H$ at various $\alpha$ is depicted in figure 4.4.

In a comparison between figure 4.4 and figure 4.2 it can be seen that the field $H$ in the optical set-up is too small to align the magnetization fully with the applied field. Furthermore, non-coherent magnetization reversal is probably present in all of the measurements, but thich can not be properly accounted for, since only large $\alpha$’s are being measured. These two effects and the large Faraday background effect that had to be subtracted make a reliable estimation of $K_{\text{eff}}$ definitely not straightforward. However, if we look at quality of the fits of of an unirradiated Pt/Co$_{0.5}$/Pt structure in the figure, we see that it quite accurately describes the three different angles.

4.2.2 Optical vs electrical measurements

From the traces in figure 4.4, $K_{\text{eff}}$ is determined for each irradiation dose and the result is shown in figure 4.5. The error bars are based on the quality of the fits and the fact that subtraction of the Faraday effect is rather uncertain. We first concentrate at the the 5 and 6Å samples. Despite the complications in the measurements that are discussed before, a similar behaviour as measured with EHE is observed. The values of $K_{\text{eff}}$ are only slightly higher and for low doses a linear decrease of $K_{\text{eff}}$ is observed. The slope of the decrease in $K_{\text{eff}}$ is again constant and irrespective of the Co thickness. For high doses a flattening of the decrease can be seen. For even higher doses the structures were again in-plane magnetized and these measurements are therefore not included in the figure because SW theory cannot predict a value of $K_{\text{eff}}$ for non-remanent structures.

So far both measurements techniques show similar results, but a remarkable behaviour is observed for the Pt/Co$_{0.4}$/Pt structure. Although the sample remains out of plane magnetized for a larger range of Ga irradiation doses, the anisotropy of the unirradiated sample seems to be lower than the anisotropy of Pt/Co$_{0.5}$/Pt. This might again be related to problems with the growth of these ultrathin Co layers, but the result is still in disagreement with the electrical measurements that we have performed before. Looking at an example of a SW fit of the measurement of $M_Z/M_S$ of a Pt/Co$_{0.4}$/Pt sample, given in the inset of figure 4.4, shows a large deviation from the actual data. Due to a small total magnetic moment of the Pt/Co/Pt the optical signal was in the same order as the Faraday background effect. Subtraction of the latter was therefore very problematic and has presumably affected the outcome of the SW fit. This is also reflected in the large error bars and fluctuations in the trace in figure 4.5. It is therefore very hard to draw any conclusions from this measurement.
Figure 4.5: The result of the anisotropy constant $K_{\text{eff}}$, subtracted from the fits in figure 4.4, as a function of Ga$^+$ dose is shown. For Pt/Co$_{0.6}$/Pt and Pt/Co$_{0.5}$/Pt the observed values and the qualitative behaviour are similar to the electrical measurements. However, for Pt/Co$_{0.4}$/Pt a different trend is observed, probably related to the large uncertainty in the deviation of the background Faraday rotation.

4.3 Conclusions and Outlook

In this chapter the anisotropy of Ga$^+$ irradiated Pt/Co/Pt samples has been studied. A very clear decrease of the anisotropy for increasing doses of Ga has been observed, which confirms the outcome of many earlier experiments that attributed their conclusions to the change in anisotropy [20, 62, 19, 74]. Theoretically the effect is caused by intermixing of the Pt/Co interfaces, as described in section 3.2.

The anisotropy is determined by using SW theory to fit the behaviour of the perpendicular magnetization for an applied magnetic field under an angle. The measurements of perpendicular magnetization are performed in two totally different experiments. One is an electrical measurement that makes use of the EHE, the other experiment involves a laser MOKE setup that measures the Kerr rotation of the reflected laser beam.

Comparing the two measurement techniques shows that both have their advantages. The optical measurement required no electrical contacting of the sample so that the Pt/Co/Pt layers are not influenced by the contacts. This makes a direct comparison with the DW injection experiments in chapter 5 on structures that are deposited on the same samples possible. However, in the setup only a limited variation of $\alpha$ and $H$ was attainable which is clearly disadvantageous.
In the electrical experiment large $H$ could be applied at every desired $\alpha$. Non-coherent magnetization reversal effects could therefore be observed and properly accounted for. Besides the deposited contacts on top of the Pt/Co/Pt samples, only a small ordinary Hall effect that could easily be compensated for was present. The most important disadvantage of the optical method is the presence of a rather large Faraday background effect. Especially for the Pt/Co$_{0.4}$/Pt sample, which has a small total magnetic moment, this influenced the reliability of the measured anisotropies. It is therefore concluded that electrical determination of the anisotropy of Ga$^+$ irradiated Pt/Co/Pt is more accurate. Figure 4.3 will therefore be used as a reference for $K_{\text{eff}}$ in the rest of the report.

In figure 4.3 it is observed that the anisotropy decreases linearly at low Ga$^+$ doses. For higher doses the decrease flattens off, indicating that the first Ga$^+$ ions have the largest impact on the Pt/Co interfaces. For very high doses, the sample becomes in-plane magnetized and at this point, the Stoner Wohlfart model is no longer valid. These measurements are therefore not included in the figure.

Interestingly it is shown that decreasing the Co thickness from 6 to 5 Å increases the starting anisotropy, while the slope of the decrease in $K_{\text{eff}}$ remains constant. Although this effect is slightly counterintuitive, it is very promising for the fabrication of DW devices, because the sample remains out-of-plane magnetized for a large irradiation dose range. This allows for precise tuning of the local magnetic properties of Pt/Co/Pt, as we will show in chapter 5. A similar increase was expected for a Co layer of 4 Å, but was not observed due to growth related problems resulting in an ill-defined layer.

Another very useful result of this systematic investigation is that figure 4.3 allows us to deduce a quantitative value of $K_{\text{eff}}$ for Ga$^+$ irradiated Pt/Co/Pt structures. From chapter 2.2 it is known that this is related to the DW width by

$$\Delta = \pi \sqrt{\frac{A}{K_{\text{eff}}}},$$

where $A$ is the exchange constant. Theoretical models predict that the DW width is of high importance for both the $\beta$ parameter and DW resistance[22, 26, 27, 37, 52]. Both of these effects will be further investigated in this thesis and the results in this chapter have given us the possibility to tune the DW width by using different Ga$^+$ doses. This will be of vital importance for the experiments in the rest of this report.

To conclude this chapter, it is seen that the anisotropy of unirradiated Pt/Co/Pt samples increases for thin Co layers, while the reduction of anisotropy with Ga$^+$ dose remains constant. From an experimental perspective this is a very useful result and we can increase our control of the anisotropy by using thin Co layers. In section 5 we will further investigate the consequences of this on the nucleation,
pinning and injection of DWs in Pt/Co/Pt layers. Furthermore, we have linked the Ga\(^+\) dose to a quantitative value of \(K_{\text{eff}}\). This is a very important result since it allows us to tune the width of DWs in Pt/Co/Pt, which will be used in chapter 6 and chapter 7 to investigate the fundamental properties of the non-adiabatic STT.
Chapter 5

Controlling Domain Walls in Pt/Co/Pt strips

Being able to initially create DWs in a reproducible way is an essential ingredient for the study on DW physics, as explained in chapter 1. For in-plane DW devices of for example permalloy, often a variation in shape, such as a bend in the wire or a large pad at the end of the wire, is used to locally reduce the shape anisotropy [13, 14]. Such an extrinsic defect can lead to nucleation or pinning of a DW. For PMA materials the situation is somewhat more difficult, since the shape anisotropy is dominated by the huge uniaxial anisotropy. It is therefore very remarkable that a geometric approach of a large nucleation pad is still often used in these materials [16, 29, 75]. The statistical chance to have an intrinsic defect where DW nucleation can take place is higher in the pad due to the larger area. A clear disadvantage of this method is that it is not very reproducible, since DW nucleation might also occur at other places.

In line with the previous chapter, it is recently shown that irradiation by Ga$^+$ ions with a FIB locally reduces the anisotropy [19]. A FIB can therefore be used as a much more elegant method to precisely control the nucleation and injection of DWs in magnetic devices. Detailed information is found in section 3.2, where it turns out that both the nucleation of a DW and its pinning at an anisotropy barrier are of importance. In the present chapter the effects of local irradiation of Pt/Co/Pt layers by a FIB are investigated experimentally.

In section 5.2 first a more systematic analysis of the experimental results in [19] is performed. The influence of Ga$^+$ irradiation on Pt/Co/Pt is described in terms of the injection field into the wire and the effect of a change in the size of the nanowire is investigated. Furthermore, the effect of reducing the Co thickness is shown to be in agreement with results in the previous chapter. Due to the higher anisotropy of thin Co layers, higher irradiation doses can be applied which
results in stronger pinning of DWs. These materials are thus more suitable for experiments on the DW resistivity.

Interesting results are also obtained on the use of a He$^+$ FIB to control the anisotropy. Many studies with unfocused He$^+$ beams have reported similar effects on the magnetic properties as for irradiation with Ga$^+$ ions\cite{76, 77, 78}. Focused Helium Ion Microscopy systems have become commercially available only very recently and this is to our knowledge the first time that a focused He$^+$ beam is used to alter the magnetic properties of Pt/Co/Pt. In section 5.3 the results of these new experiments are discussed and it is shown that the use of a He$^+$ FIB has some notable advantages over a conventional Ga$^+$ FIB. The results are fully explained in terms of the 1D-DW model that is introduced in section 2.4.1.

## 5.1 Experimental details

The investigated structures for DW injection are rectangular Pt$_4$/Co$_x$/Pt$_2$ strips of $15 \times 2 \, \mu m^2$, $10 \times 1 \, \mu m^2$, $5 \times 0.5 \, \mu m^2$ and $2.5 \times 0.25 \, \mu m^2$. The Co thickness is varied between 4, 5 and 6 Å. The structures are grown on a substrate of 100 nm SiO$_2$ by DC magnetron sputtering and the desired pattern is defined by EBL and lift-off in acetone. For each measurement, several structures are deposited within a $100 \times 100 \, \mu m^2$ grid of gold lines. An example of the topview of a patterned Pt/Co/Pt sample is shown in figure 5.1. The Pt/Co/Pt rectangles of different sized are clearly visible.

![Figure 5.1: Kerr microscopy image of the rectangular nanostructures that are used for the investigation of DW injection by Ga$^+$ and He$^+$ FIB irradiation.](image)

After the fabrication of the Pt/Co/Pt layers, the left half of the strips is irradiated
by either Ga\textsuperscript{+} or He\textsuperscript{+} ions at a variable dose.\textsuperscript{1} These regions are indicated by the red color in figure 5.1. As outlined in chapter 4, this reduces the local anisotropy. A DW therefore nucleates in this area and subsequently moves into the remainder of the wire. For higher doses, the DW gets pinned at the anisotropy barrier between the two segments of the strip.

Polar Kerr microscopy is used to study the effect of FIB irradiation on nucleation and pinning of DWs in Pt/Co/Pt. A change in intensity of the reflected polar light indicates switching of the magnetization, which can be used to study DW nucleation, pinning and injection in both segments of the nanowire. A more systematic analysis is based on the injection field $H_{\text{in}}$, which is defined as the external field at which the DW penetrates into the non-irradiated part of the structure. As explained in section 3.2, $H_{\text{in}}$ is determined by the maximum of the coercive field $H_c$ of the irradiated part of the wire and the pinning field $H_{\text{pin}}$ at the anisotropy barrier. In the measurements the magnetic field is swept from negative to positive and a sudden change in intensity of the Kerr signal occurs in the non-irradiated area when the DW is injected. Decent statistics are obtained by averaging $H_{\text{in}}$ over 12 or 9 structures (see figure 5.1). The error bars in all figures where $H_{\text{in}}$ is plotted against the irradiation dose represent the statistical variation (structure to structure) of $H_{\text{in}}$.

5.2 DW nucleation and injection

5.2.1 Dependence on the structure size

To understand the nature of DW nucleation, pinning and injection in a partly irradiated nanowire, first the effect of Ga\textsuperscript{+} irradiation on Pt\textsubscript{4}/Co\textsubscript{0.6}/Pt\textsubscript{0.2} structures of various sizes is studied. Figure 5.2 shows exemplary Kerr images of switching of the magnetization in several 10 $\times$ 1 $\mu$m\textsuperscript{2} strips. The Kerr images for four different irradiation doses are shown. In the following we first use these images to describe the three regimes for $H_{\text{in}}$ as a function of Ga\textsuperscript{+} dose that were identified in a previous study and explained in section 3.2\textsuperscript{[19]}. The interpretation of their measurements, that were based on the EHE, is in this section visualized and fully confirmed.

In figure 5.2(a) and 5.2(b) the result for an irradiation dose of 0.34 $\times$ 10\textsuperscript{13} ions/cm\textsuperscript{2} is shown. This situation resembles regime (A) in figure 5.3, where $H_{\text{in}}$ is determined by the nucleation field $H_c$ of the irradiated area. In figure 5.2(a) it is seen that at a certain field strength, the bright structures already switched their magnetization, while the dark have not. At a slightly higher field in figure 5.2(a) two more strips have reversed their magnetization. This indicates that a DW has

\textsuperscript{1}He\textsuperscript{+} FIB irradiation was performed at TNO Science and Industry in Delft, the Netherlands with the help of E. van Veldhoven and D.J. Maas
Figure 5.2: Polar Kerr microscopy snapshots of the nucleation and injection process of DWs in 10 $\times$ 1 $\mu$m$^2$ Pt$_4$/Co$_{0.6}$/Pt$_2$ structures for various doses of Ga$^+$ irradiation. The magnetic contrast in (a)-(g) is enhanced by subtraction of a background image, which is obtained at zero field after saturation at high negative fields. In (h) the subtracted background is obtained at a high field.

Figure 5.2(c) and 5.2(d) are obtained at a higher dose of 0.41 $\times$ 10$^{13}$ ions/cm$^2$, where a transition from regime (A) to regime (B) takes place. It can be seen that some of the DWs that nucleate in the left area immediately move into the remainder of the wire. Other DWs are pinned at the boundary and require a higher field to be injected. For these DWs, $H_{\text{pin}} > H_c$ and $H_{\text{in}}$ therefore starts to increase due to pinning.
5.2 DW nucleation and injection

At a slightly higher dose of $0.44 \times 10^{13} \text{ions/cm}^2$ in figure 5.2(c) a strong change in the nucleation of the DW is observed. Instead of the instantaneous switching that was observed before, the magnetization of the irradiated area now switches in many small domains. By increasing the applied field as seen in figure 5.2(f), a uniform domain with a single DW will again appear that can be injected into the non-irradiated Pt/Co/Pt. Although the experiment proves that it is possible to create stable DWs at this dose, it can be seen that the wire reverses its magnetization in many small domains, which is not desirable for applications. The fully switched structures in figure 5.2(f) also show a very slight decrease of the brightness of the irradiated part. This effect is almost not visible by eye, but becomes very clear when the average intensity is measured. The effect of a reduced brightness in the irradiated wire is even better visible in figure 5.2(g), which is obtained at a very high dose. It is not caused by a lower saturation magnetization, but it is the result of the method that we use to enhance the magnetic contrast. For this, we saturate the structures at a large negative field and then obtain a background image at zero field. The background image is subtracted from the all other images to be only sensitive to intensity changes that result from the magnetic signal. Due to the relatively high Ga\textsuperscript{+} dose the easy axis of magnetization has become in-plane and the structures are no longer remanent. Obtaining a background image at zero field is therefore not very useful for these in-plane magnetized structures. In figure 5.2(h) the background is obtained at high fields and it clearly shows that the structure has a remanence of less than 100\%, indicating a transition to regime (C). Referring to the quantitative measurement of the perpendicular anisotropy $K_{\text{eff}}$ for Ga\textsuperscript{+} irradiated strips in section 4.1.2, this means that the Stoner Wohlfart model was no longer valid. Figure 4.3 shows that this is indeed expected to happen for a dose of $\sim 0.4 \times 10^{13} \text{ions/cm}^2$.

In figure 5.3, a measurement of $H_{\text{in}}$ as a function of Ga\textsuperscript{+} dose is depicted for structures of different sizes. The three regimes as observed in the Kerr images are clearly visible. In regime (A), $H_{\text{in}} = H_c$ and rapidly decreases to a minimum, where $H_{\text{pin}} = H_c$. This is caused by lowering of the local anisotropy while the DW is not pinned at the anisotropy boundary and thus immediately injected into the non-irradiated part. The injection field then increases in regime (B) due to increasing $H_{\text{pin}}$ at the anisotropy boundary, which scales linearly with the difference in anisotropy between the two parts of the wire. Eventually in regime (C), $H_{\text{in}}$ saturates to a value where the perpendicular magnetization of the irradiated part is no longer 100\% remanent. Here the DW resides at the interface between the in-plane and out-of-plane area. The data is similar to the previous results in [19], but with much more detail.

From figure 5.3 a comparison can be made between the different sizes. For the wires of $15 \times 2 \mu\text{m}^2$, $10 \times 1 \mu\text{m}^2$ and $5 \times 0.5 \mu\text{m}^2$ the behaviour is very alike. The $2.5 \times 0.25 \mu\text{m}^2$ structures however behave somewhat different. Although there is a clear consistency in trend, it can be seen that these structures have a significantly lower injection field in the first regime. Since all structures are grown and measured at the same conditions on the same sample, this effect must be related to the
Figure 5.3: DW injection field as a function of Ga\textsuperscript{+} dose. The data is obtained from hysteresis loops that are made by Kerr microscopy. All injection fields are averaged over multiple structures. The lines are drawn as a guide to the eye.

decrease in size. Most likely, due to the limitations of the used lithography method, the roughness of the strips is significant as compared to its width. This resulted in a poor-defined strip. The coercive field of the irradiated area is determined by random nucleation of small domains at the edges of the structure and therefore very sensitive to the roughness. The coercive field is therefore significantly reduced and also the anisotropy might be affected.

5.2.2 Increasing the pinning strength

In the previous section it is shown that DWs can be nucleated and injected into a Pt\textsubscript{4}/Co\textsubscript{0.6}/Pt\textsubscript{2} strip by locally decreasing the anisotropy with a FIB. As calculated in the 1D DW model, the pinning strength of the anisotropy barrier ($H_{\text{pin}}$) varies linearly with the anisotropy difference between the non-irradiated, $K_{\text{eff},0}$, and the irradiated, $K_{\text{eff}}$, area (section 2.4.1). Furthermore it is observed that pinning of the DW only occurs in regime (B), so that a minimum Ga\textsuperscript{+} dose is required have $H_c < H_{\text{pin}}$. 
In the case of the investigated Pt$_4$/Co$_{0.6}$/Pt$_2$ wires in figure 5.2 pinning was observed for some individual wires. However, for none of the applied Ga$^+$ doses a situation was found were all the DWs were simultaneously pinned, without becoming in-plane magnetize. This means that the range of fields where DWs are pinned is smaller than the structure to structure variation of the coercive fields. This is not desirable for the fabrication of DW devices, because for many samples the DW will not be pinned and the fabrication process is not very reproducible. In this section we therefore aim to improve the field range for which DWs are pinned by reducing the Co thickness. Chapter 4 revealed that thin layers of Co exhibit a higher initial $K_{\text{eff}}$ and higher Ga$^+$ doses can therefore be applied before the magnetization becomes in-plane. Because the strength of $H_{\text{pin}}$ scales with the anisotropy difference, this leads to stronger pinning.

Figure 5.4 shows a comparison of $H_{\text{in}}$ as a function of Ga$^+$ dose for different Co thicknesses in Pt$_4$/Co$_{x}$/Pt$_2$ structures of 10 $\times$ 1$\mu$m$^2$. First of all it is seen that the Pt$_4$/Co$_{0.4}$/Pt$_2$ structures have an overall lower injection field. This is probably related to the quality of the growth of such ultrathin films and is agreement with the observations in figure 4.1.2. Interestingly the Pt$_4$/Co$_{0.5}$/Pt$_2$ and Pt$_4$/Co$_{0.6}$/Pt$_2$ strips show very similar behaviour in the pinning regime (B). The minimum of the curve, where $H_{\text{pin}} = H_c$, is found at a dose of 0.44 $\times$ 10$^{13}$ ions/cm$^2$ for both the Pt/Co$_{0.5}$/Pt and Pt/Co$_{0.6}$/Pt strips. This is the expected behaviour since in this regime $H_{\text{pin}} = (K_{\text{eff},0} - K_{\text{eff}})/\mu_0M_s$. According to figure 4.3 this quantity is rather insensitive to the layer thickness. For the Pt/Co$_{0.4}$/Pt structures $H_c$ is slightly lower due to growth-related problems so the minimum of the curve is shifted to the left and found at 0.31 $\times$ 10$^{13}$ ions/cm$^2$. Furthermore, $[K_{\text{eff},0} - K_{\text{eff}}]$ also determines the slope of the increase in the pinning regime, which is also shown to be roughly the same for all three structures, in agreement with the anisotropy measurements from before.

From figure 4.3 it is observed that $K_{\text{eff},0}$ is higher for thin Co layers, so that much larger Ga$^+$ doses can be applied before the perpendicular anisotropy is quenched and the magnetization becomes in-plane. This way, the pinning strength of the anisotropy barrier also becomes much stronger. Decreasing the Co thickness is therefore expected to lead to more controllable DW pinning. Before the increased control on DW pinning is proven with some exemplary Kerr microscopy images, we shortly focus on regime (C) where the irradiated region has an in-plane magnetization. In this regime, $H_{\text{in}}$ is theoretically (in the case of an infinitely small anisotropy barrier) given by $K_{\text{eff},0}/\mu_0M_s$. For Pt/Co$_{0.5}$/Pt and Pt/Co$_{0.6}$/Pt samples it can be seen that at large doses $H_{\text{in}}$ is approximately 10% higher for the 0.5 nm Co layer. Comparing this to difference in $K_{\text{eff},0}$ with the observation in figure 4.3 shows that this at least qualitatively confirms the theoretical model. A comparison with Pt/Co$_{0.4}$/Pt is difficult due to its lower $H_c$, which masks the behaviour of DW pinning at high dose.

To compare the suitability of the Pt/Co$_x$/Pt structures for experiments on DW physics, we define an optimal dose for each structures. This is based on two
requirements that are important in DW devices. First of all, we want to maximize $|K_{\text{eff},0} - K_{\text{eff}}|$, so that the pinning strength is as large as possible. This means that is advantageous to use the highest dose that is possible. This is however limited by the second criterion which states that the strip must remain fully perpendicular magnetized to have simple Bloch DWs. The optimal dose is thus defined as the highest dose for which the structure is 100% remanent. For Pt/Co$_{0.6}$/Pt this dose is found to be $0.41 \times 10^{13}$ ions/cm$^2$, for Pt/Co$_{0.5}$/Pt it is $0.56 \times 10^{13}$ ions/cm$^2$ and for Pt/Co$_{0.4}$/Pt it is $0.81 \times 10^{13}$ ions/cm$^2$. The increasing trend closely resembles the fact that thin Co layers intrinsically have a higher anisotropy.

The exemplary Kerr images at the optimal doses, illustrated in figure 5.5, lead to a conclusion concerning DW pinning in the wires. For a Co layer of 0.6 nm thick, it is already observed that a stable situation where all DWs are pinned could not be obtained due to statistical deviations. This is shown in figure 5.5(a). The result for 0.5 nm Co is already more promising as seen in figure 5.5(b). Applying a field of 7.2 mT at the optimal dose results in a situation where all the DWs are pinned. This situation was retained for a field range of 0.8 mT. For structures with only 0.4 nm of Co between the Pt layers, the stable field range is even larger. From figure 5.5(c) it is observed that all DWs are pinned for 4.7 mT.
5.3 Tuning the anisotropy barrier

From the previous results we can conclude that decreasing the thickness of the Co layer in Pt/Co/Pt is a very useful method to increase the control on the pinning of DWs. As already expected from the anisotropy measurements in chapter 3.2, much larger Ga\(^+\) doses can be applied to samples with a thin Co layer, without destroying the perpendicular magnetization. This way, larger anisotropy barriers and hence stronger pinning can be obtained. For further experiments on for example DW resistivity, it is therefore better to make use of thin Co layers.

5.3 Tuning the anisotropy barrier

5.3.1 Controlled DW injection by Helium focused ion beam\(^2\)

A possible new and promising method to increase the control on the nucleation and injection of DWs in perpendicular magnetized Pt/Co/Pt is to make use of a He\(^+\) FIB. Helium Ion Microscopes (HIM) have become commercially available only

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\(^2\)A condensed version of the use of a He\(^+\) FIB for the injection of DWs in PMA materials as described in this section, is found in [79].
very recently and have the advantage that imaging and nanostructuring should be possible with sub-nm resolution. Based on earlier studies on the influence of irradiation by unfocused He$^+$ ion beams on magnetic properties, it is expected that irradiation with He ions also reduces the local anisotropy, although much higher doses are required\cite{15, 76, 80}. Furthermore, according to the specifications, the beam spot of the Ga$^+$ FIB is 3.5 nm while the He$^+$ beam spot is as small as 0.75 nm. Although the damage radius of both FIBs is probably much larger than these specifications, the smaller beam spot of a He$^+$ FIB might enhance the control of magnetic behaviour in the wires. In this section we report on the first time use of a He$^+$ FIB for the control of DWs and compare its properties to the more conventional Ga$^+$ FIB.

Figure 5.6 shows the effect of He$^+$ FIB irradiation on $H_{in}$ for structures of 10 $\times$ 1 $\mu$m$^2$. For an accurate direct comparison with Ga$^+$ FIB, the measurements are obtained on Pt$_4$/Co$_{0.6}$/Pt$_2$ structures on the same sample as used in section 5.2. Again the previously described behaviour for irradiation with a Ga$^+$ FIB is observed, meaning that a He$^+$ FIB can be a good alternative for controlling the nucleation and injection of DWs. For a reliable comparison between both methods, the decrease in $H_{in}$ for He$^+$ FIB irradiation in regime (A) is fitted with a linear expression and scaled with the same region for Ga$^+$ irradiation. In regime (A), the decrease of $H_{in}$ originates directly from the decrease in anisotropy and has the same physical origin for both methods. From the result of this scaling in figure 5.6 it is immediately seen that the He$^+$ dose that is required for the same reduction in anisotropy, is $\sim$ 700 times larger than the Ga$^+$ dose. He$^+$ ions apparently do less damage and hence controlling the dose of He$^+$ FIB irradiation is much more precise. A significant drawback of the use of He$^+$ ions for the control of anisotropy is that the exposure time is also increased.

Another interesting observation from figure 5.6 is the transition regime (B) where DW pinning at the anisotropy boundary dominates the injection field. It can be seen that for He$^+$ irradiation the pinning occurs at lower doses (and also at higher injection fields), indicating that pinning at the anisotropy boundary in the case of He$^+$ irradiation is stronger. This is in agreement with the results from the 1D DW model that is discussed in section 2.4.1. It is shown that a more gradual increase of the anisotropy boundary between the irradiated and the non-irradiated area results in a weaker pinning of the DW. The inclusion of a finite width of the anisotropy barrier results in an extra term in the relation for the pinning field, as given by

$$
\mu_0 H_{pin} = \frac{K_{eff,0} - K_{eff}}{2M_s} \cdot \frac{2\Delta}{\delta} \tanh \frac{\delta}{2\Delta}.
$$

(5.1)

Here, $\delta$ resembles the width of the anisotropy barrier and $\Delta$ is the DW width. Since the beam spot of the He ions is significantly smaller than for Ga$^+$, it is expected that the anisotropy boundary is much sharper. According to equation 5.1 this indeed increases the pinning strength. To confirm the conclusion, measurements
are also performed for Ga\(^+\) irradiation where the FIB is intentionally blurred to FWHM of approximately \(~\sim 200\) nm. The anisotropy gradient length \(\delta\) is therefore much larger and the plot in figure 5.6 confirms that the pinning strength decreases very strongly. A final remark is made on the slopes in regime (B) for different \(\delta\). At zero irradiation, it is expected that these cross the y-axis at the same offset value, that depicts the intrinsic pinning in the Pt/Co/Pt layer. A linear fit on the measured slopes in figure 5.6 was however very inaccurate because the increase in \(H_{\text{pin}}\) is only linear for a small dose range. Apart from the qualitative agreement of \(H_{\text{pin}}\) with \(\delta\), no other useful quantitative information could be obtained.

Finally, figure 5.7 shows several Kerr microscopy images of the nucleation and injection of DWs in the pinning regime for structures that are partly irradiated with He\(^+\) ions. Figures 5.7(a) and figure 5.7(b) are obtained at a dose of \(300 \times 10^{13}\) ions/cm\(^2\). It turned out that this was the optimal dose as defined before. It can be seen that all the DWs are pinned at the anisotropy boundary, while the structures are still remanent. This result is obtained without any fine tuning.

**Figure 5.6:** Comparison of the DW injection field for He\(^+\) and Ga\(^+\) FIB irradiation on a 10 \(\times\) 1 \(\mu\)m\(^2\) Pt/Co/Pt structure. For a good comparison the graphs are scaled in such a way that the rapid decrease of \(H_{\text{in}}\) due to lowering of the anisotropy overlaps for both methods. The dotted line is the result of irradiation with an intentionally blurred Ga\(^+\) beam, resulting in a very wide and therefore weak anisotropy boundary.
Chapter 5: Controlling Domain Walls in Pt/Co/Pt strips

(a) $300 \times 10^{13}$ ions/cm$^2$, 7.3 mT
(b) $300 \times 10^{13}$ ions/cm$^2$, 9.1 mT
(c) $400 \times 10^{13}$ ions/cm$^2$, 5.0 mT
(d) $400 \times 10^{13}$ ions/cm$^2$, 10.7 mT

Figure 5.7: Polar Kerr microscopy images of the nucleation and injection of DWs in $10 \times 1 \mu m^2$ Pt$_4$/Co$_{0.6}$/Pt$_2$ structures for different doses of He$^+$ irradiation. In (a) and (b) it can be seen that a dose of $300 \times 10^{13}$ ions/cm$^2$ results in a situation where all the DWs are nucleated and pinned. This is caused by the stronger pinning at the sharp anisotropy boundary. Figures (c) and (d) show that a higher dose again leads to a loss of remanence.

with smaller dose steps. In section 5.2 it was shown that this result could not be obtained for similar Ga$^+$ irradiated structures. When looking at higher doses in figure 5.7(c) and figure 5.7(d) again a transition to in-plane magnetization and a resulting loss of remanence is observed. It is expected even better results can be obtained for thinner Co layers. For the engineering of DW devices, the increased pinning strength and the higher dose control makes He$^+$ FIB a very attractive candidate for the controlled pinning of DWs in Pt/Co/Pt.

In conclusion, we have reported on the use of a He$^+$ FIB for the injection of DWs in Pt/Co/Pt. It is observed that this results basically in the same behaviour that was explained before using a more standard Ga$^+$ FIB. However, the dose of He$^+$ ions that is needed for the same effects is approximately 700 times larger, resulting in a more precise control of the local anisotropy. It is also observed that the beam spot of a He$^+$ FIB is much finer, which makes the anisotropy barrier smaller. The pinning of a DW at the boundary is therefore much more pronounced. Finally, Kerr microscopy images have revealed that irradiation with He$^+$ ions has a better homogeneity.

5.3.2 Using an out-of-focus Gallium beam

To conclude the discussion on the use of a He$^+$ FIB for controlled injection of DWs in Pt/Co/Pt we illustrate the effect of a changing width of the anisotropy barrier more carefully. In figure 5.6 a blurred Ga$^+$ beam is already used to confirm the role of the barrier width $\delta$ in the pinning process. However, it can be seen that
5.3 Tuning the anisotropy barrier

A beam blurred to a Full Width Half Maximum (FWHM) of \(\sim 200\) nm results in such a wide barrier that DWs almost never pin at the barrier. In this section the beam spot is blurred more gradually. Due to damaging of the sample that was previously used, this measurement is performed on a different Pt\(_{4}/\)Co\(_{0.5}/\)Pt\(_{2}\) sample.

Figure 5.8 illustrates the behaviour of the injection field \(H_{in}\) for various Ga\(^+\) doses. The Ga\(^+\) beam is changed from an optimal focused beam to a beam that is blurred to a FWHM of \(\sim 80\) nm. This results in a decrease of the barrier width \(\delta\), which according to equation 5.1 results in a decrease of the pinning strength. Indeed, it can be seen that the pinning strength in regime (B) is reduced more and more for increasing beam blur and the minimum where \(H_{in} = H_{pin}\) is shifted to the right. A very interesting result for the fabrication of DW devices is that this measurement shows that in some cases it is beneficial to work with a defocused Ga\(^+\) beam. If a small injection field \(H_{in}\) is required, for example to study DW velocity at low applied fields, a defocused beam gives the best results.

Finally, it is again expected that the slopes of \(H_{pin}\) converge to the same point at the y-axis. This behaviour has been fitted for several data sets to obtain a quantitative value for \(\delta\) for values of the beam blur. It was however again not possible to find an accurate results from which \(\delta\) could be obtained.

![Figure 5.8: A measurement that shows the DW injection field for Ga\(^+\) FIB irradiation on \(10 \times 1\) \(\mu\)m\(^2\) Pt\(_{4}/\)Co\(_{0.5}/\)Pt\(_{2}\) structures. The Ga\(^+\) beams are defocused to alter the width of the anisotropy barrier \(\delta\). As expected, the pinning strength is reduced for increasing \(\delta\).](image-url)
5.4 Conclusions and recommendations

In this chapter the use of a FIB to nucleate and inject DWs in a Pt/Co/Pt wire is systematically studied under variation of structure size and thickness of the Co layer. Also a He$^+$ FIB is used for the first time to alter magnetic properties of Pt/Co/Pt. The experiments have revealed a lot of insight in the nature of the DW nucleation, pinning and injection of DWs in these materials. Playing with the anisotropy with our FIB, we can independently tune the width and the height of energy barriers in our Pt/Co/Pt and essentially we can design every desired energy landscape. This gives us full control over the injection and pinning of DWs in these systems and will be extensively used in the next chapters. We conclude this chapter by several recommendations that can be given for the use of a FIB for the fabrication of DW devices.$^3$

- In the first section it is shown that irradiation with a focused Ga$^+$ beam can lead to the nucleation, pinning and injection of DWs in Pt/Co/Pt. The previous interpretation of three regimes in [19] is confirmed by Kerr microscopy images. For low doses a DW is nucleated in the irradiated part of the structure and immediately injected into the remainder of the wires. For higher doses the anisotropy difference at the boundary between the irradiated and the non-irradiated Pt/Co/Pt leads to pinning of the DW. In the final regime of high Ga$^+$ dose the irradiated part is in-plane magnetized. DWs still originate at the anisotropy boundary, but for a study on DW physics this is an unfavourable situation. Tuning the irradiation dose in the second regime therefore leads to the initialization of pinned DWs which is used in the remainder of this report. This result is independent of the size of the structures.

- In section 5.2.2 the results from the anisotropy measurements in chapter 4 are used to increase the pinning strength at the anisotropy boundary. It is confirmed that higher doses can be applied without loosing remanence, when the thickness of the Co layer in Pt/Co/Pt is decreased. This leads to larger anisotropy differences and therefore stronger pinning. For these materials it is more easy to tune the irradiation dose in such a way that statistical fluctuations have no influence on the DW pinning. They are therefore advantageous for usage in DW studies. The optimal Ga$^+$ dose has been determined for Pt/Co/Pt wires with 0.4, 0.5 and 0.6 nm of Co.

- It is for the first time demonstrated that irradiation with a He$^+$ FIB leads to similar results and has some advantages over conventional Ga$^+$ FIB. In section 5.3 it is shown that much higher doses of He$^+$ are required for similar effects which leads to a better control. Furthermore, pinning of the DWs is much more pronounced in He$^+$ irradiated samples. This is linked to a finer

\[3\text{An overview of the results from chapter 4 and 5 is submitted at Journal of Physics: Condensed Matter}\]
beam spot and therefore steeper gradient at the anisotropy barrier. A He$^+$ FIB is therefore a promising new fabrication tool for DW devices, especially when more precise control of the energy landscape is required.

- Defocused Ga$^+$ beams are used in section 5.3.2 to confirm the influence of the gradient of the anisotropy boundary. It is shown that defocusing the beam indeed leads to a decrease of the pinning at the anisotropy boundary by a changed length of the pinning barrier. Interestingly, it is therefore better to use a defocused beam if the injection of DWs at low fields in a Pt/Co/Pt wire is required.
Chapter 6

Intrinsic DW Resistivity in Perpendicularly Magnetized Materials

Intrinsic DW resistivity is an interesting fundamental property of DWs. In section 2.3, we argued that the additional scattering of electrons that causes DW resistivity is closely linked to the highly debated non-adiabatic spin transfer torque. Several theoretical works have confirmed this dependency [26, 32]. Despite the huge potential of this seemingly easy to measure quantity, only few measurements of intrinsic DW resistivity have been performed [33, 34, 35, 36]. A large variety of theoretical models exist, that propose different scattering mechanisms as the origin of DW resistivity are present. Positive, negative and contributions of either sign have all been predicted [37, 54, 52, 81].

One of the main problems in measuring DW resistivity is that the effect is expected to be only in the order of $\sim 1\%$ of the normal resistivity. Furthermore, the effect only occurs across the DW, which is very narrow in the case of perpendicular magnetized materials. This makes it very hard to separate intrinsic DW resistivity from other magnetization-dependent contributions such as the anisotropic magnetoresistance (AMR) and the extraordinary Hall effect (EHE) [35]. It is important to remember that many studies are present that investigate the resistivity change due to DWs, where the increased resistivity is caused by other contributions [82]. This is especially the case for DW resistivities in bulk systems or in systems where complex vortex or Néel walls are favourable. In this case the DW resistivity mostly originates from AMR, which is not so relevant for fundamental DW physics and is a much stronger effect [45].

In this chapter we use a Kerr microscope that is equipped with a special sample holder to perform electrical measurements. This way, we can directly observe the
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appearance of DWs in our Pt/Co/Pt structures, while simultaneously measuring the electrical resistivity of the wire. A strong advantage of using Pt/Co/Pt is that it has a large perpendicular anisotropy, resulting in simple Bloch DWs. For these DWs the local magnetization is never aligned with the direction of the current so there is no contribution from AMR [33]. Using FIB irradiation, we can furthermore reproducibly control the position and nucleation fields of DWs. This allows us to exclude other masking effects with relative ease.

In section 6.2, we first prove that accurate DW resistivity measurements are possible by measuring the stepwise increase and decrease of the resistance of a Pt/Co/Pt wire for the introduction and disappearance of single DWs. The obtained values for DW resistivity are positive and comparable to other experimental results. For a reliable comparison with theoretical models (and with the non-adiabatic spin transfer torque later on), the effect of the current distribution in the Pt/Co/Pt wire is discussed.

In section 6.3 we present for the first time an investigation of the dependence of DW resistivity on the DW width. Using our knowledge of pinning of DWs at an anisotropy boundary from chapter 5, it is known that a range of Ga$^+$ doses can be used to create pinned DWs in Pt/Co/Pt. This way, DWs can be created in regions with different anisotropy, effectively tuning the DW width. The measurements are intensively discussed and it is proven that a clear dependence of the DW resistivity on the DW width exists. This result is compared with the Levy-Zhang theory and is shown to agree well with the prediction of an increasing positive DW resistivity for narrow DWs [37].

### 6.1 Experimental considerations

For the experiments on DW resistivity in this chapter, the set-up of section 3.3.1 is used. The electrical resistance and the magnetic behaviour of the samples can be studied under influence of magnetic fields up to $\sim 100$ mT. The samples consist of four Pt$_{4}$/Co$_{0.5}$/Pt$_{2}$ strips of 30 $\times$ 1.5 $\mu$m$^2$ that are deposited in a Wheatstone bridge configuration, which is shown in figure 6.1(a). The thickness of Co is chosen as 0.5 nm to have an large perpendicular anisotropy, as shown in chapter 4. It is explained that a larger range of irradiation doses can be applied, where $H_{\text{pin}} > H_c$ so that the DW gets pinned. A Co layer of 0.4 nm increase the range even more, but it is shown that growth-related problems start to play a role for this thickness. A second disadvantage of an even thinner Co layer is that a larger proportion of the current flows through the non-magnetic Pt. These electrons do not contribute to the DW resistance, which makes the measured change in resistance much smaller. Ga$^+$ FIB is used to lower the coercive field of several regions of a single strip to be able to inject DWs.

Before each measurement, we want to accurately know the resistance of each
Pt/Co/Pt strip in the Wheatstone bridge. For this reason, the resistance over all neighbouring contacts is measured, for example between $V_0$ and $V_A$ in the geometry of figure 6.1(a). Due to the parallel resistor network, effectively we measure in this case that

$$\frac{1}{R_{\text{measured}}} = \frac{1}{R_1} + \frac{1}{R_2 + R_3 + R_4}. \quad (6.1)$$

Doing this for all wires, a coupled set of four equations in the form of equation 6.1 is found from which the resistance of each Pt/Co/Pt wire is calculated. The resistance of the wires was always around 1.3 kΩ.

For the actual DW resistance measurement an AC current (typically 100 μA peak amplitude) is applied from $V_0$, while $V_{A-B}$ is measured using an analog lock-in amplifier at a relatively long integration time (300 ms up to 1 s) to increase the signal to noise ratio. The voltage offset $V_{A-B}$ is determined by the four wire resistances and is given by

$$V_{A-B} = V_0 \frac{R_1 R_4 - R_2 R_3}{(R_1 + R_2)(R_3 + R_4)}. \quad (6.2)$$

This voltage is monitored as a function of applied field while the magnetization behaviour is simultaneously studied with the Kerr microscope. A change in $V_{A-B}$ when domains (and thus DW’s) appear in the Kerr microscope images is observed.
Chapter 6: Intrinsic DW Resistivity in Perpendicularly Magnetized Materials

and used to recalculate the resistance of the wire that includes the DWs, which is \( R_2 \) in the geometry of figure 6.1(a). It is found that a change of \( \Delta R \) in \( R_2 \) is in the order of several m\( \Omega \) when all of 20 DWs are present. Due to low or high doses of Ga\(^+\) irradiation it can occur that not all the DWs are present at the same time and this is corrected for manually. With this technique, that has never been used before, we are able to study the magnetization reversal in real time, while simultaneously measuring the resistance. A direct link between the resistance and the appearance of DWs is easily made, which overcomes many problem related to other effects that can mask intrinsic DW resistivity. For example OHE and EHE can be identified since they only induce a voltage perpendicular to the direction of the current. By using Pt/Co/Pt, where the DWs have simple Bloch spin structures, AMR can also be excluded because the magnetization in the DW is never aligned with the current. With this method we are therefore even able to measure the resistance of single DWs, which will be shown later on.

A typical measured magnetoresistance curve is shown in figure 6.1(b). At a certain applied field the irradiated regions (with lower coercive field) reverse their magnetization and DWs are introduced in the wire. This raises the resistance of the wire. At a higher field the DWs depin and the resistance decreases to the value of a saturated wire. For a full field sweep this leads to two resistance peaks as shown in figure 6.1(b). Apart from this effect also a weakly varying linear background signal seems to be present. This is not always visible and therefore probably related to some other magnetization dependent effect under the contact areas (see equation 2.15).

6.2 Resistance of single DWs in Pt/Co/Pt

To study the effect of DW resistivity more carefully, figure 6.2 concentrates on only one of the two the resistance peaks in a Pt/Co/Pt wire. In this wire ten regions of 1\( \mu \)m are irradiated with a dose of 0.56 Ga\(^+\) ions/cm\(^2\). This induces a maximum of 20 DWs in the strip. The initial resistance of the saturated strip is 1.33 k\( \Omega \). In figure 6.2(a) the change in resistance \( \Delta R \) is given as a function of the applied field \( H \). A first important result is that the resistance of Pt/Co/Pt increases for the appearance of DWs. The sign of \( \Delta R \) is not directly obtained from the lock-in signal, since the phase is adjusted to always measure positive values. However, by measuring the resistance of all 4 leads in the Wheatstone bridge, the sign of \( V_{A-B} \) can be derived. This result is also verified for a few wires by directly measuring the sign of \( V_{A-B} \) with an accurate Keithly sourcemeter.

The coercive fields of the irradiated domains show statistical variations and therefore not all DWs appear simultaneously in the wire. This leads to a stepwise increase of \( \Delta R \) in figure 6.2(a). The solid red lines indicate ranges where the amount of DWs in the wire has just increased and the corresponding images are
6.2 Resistance of single DWs in Pt/Co/Pt

Figure 6.2: A measurement for the change in resistance $\Delta R$ due to the appearance of DWs in a single Pt/Co/Pt wire. In (a) the stepwise increase of the resistance is visualized by solid red (dashed blue) lines for upcoming (leaving) DWs. The corresponding Kerr microscope images are shown in (c). In (b) $\Delta R$ is plotted for the number of DWs switching. From the linear fit (red line) it is found that the change in resistance is $0.40 \pm 0.01 \text{mΩ}/\text{DW}$.

shown in figure 6.2(c). The dashed blue lines show field ranges where the number of DWs has just decreased. The linear dependence of $\Delta R$ on the amount of DWs clearly proves that the effect is due to the appearance of DWs in Pt/Co/Pt. For example, in the step from (c) to (d) it can be seen that 6 more DWs appear in the wire. This leads to a resistance increase of $\sim 2 \text{mΩ}$. Figure 6.2(b) contains all this information and shows the stepsize of $\Delta R$ versus the number of DWs that have (dis)appeared. The line is a linear fit that, within error margins, goes through zero and shows that all DWs have a similar effect on the resistance. From the fit it is obtained that the DW resistance is $0.40 \pm 0.01 \text{mΩ}/\text{DW}$.

As mentioned before, other effects might mask DW resistivity effects. For example if we look at the transition from (d) to (e) we see a large increase in the resistance for only 1 extra DW. However, in the Kerr images we also see that the
magnetization of the Pt/Co/Pt under the top contact is reversed. This leads to an additional contribution to the resistance, probably due to EHE or AMR, since equation 2.15 shows that these effects depend on the local magnetization. The final step (h)-(i) shows a similar large decrease due to the magnetization reversal under the bottom Pt contact. The difference between the resistance of the up and down saturated states is attributed to this effect. The Kerr microscope images are used to discriminate between this effect and intrinsic DW resistivity to properly take them into account. The ease by which this can be done due to the combination of resistance measurements and magnetization imaging is a unique feature of our set-up.

6.2.1 Current density in Pt/Co/Pt

In the discussion so far we have only considered the change in resistance $\Delta R$ of the Pt/Co/Pt stack. In the geometry of figure 6.1(a) this resistance is $R_2$, but from now on we label it as $R_{\text{Pt/Co/Pt}}$, to emphasize that it is the resistance of the whole stack. For comparison with other experiments, theoretical predictions and the efficiency of the non-adiabatic spin transfer torque in chapter 7, it is important to consider only the magnetic layer, which in our case is Co. The reason for this is two-fold. First of all, a spin polarization of the current is required to have any effect of additional scattering due to the non-uniform magnetization in a DW. In principle spin polarization is only present in the ferromagnetic Co, but a small spin polarization might still be present for a short distance in the Pt layer\cite{4}. Furthermore, a DW is mainly present in the Co layer and only extends slightly into the Pt layers due to exchange coupling of the spins. Since both effects are small in the Pt layers, we propose that it is definitely more accurate to state that DW resistivity arises only from the Co layer. The relevant parameter that we are looking for is therefore $\rho_{\text{DW}}/\rho_0$, where $\rho_0$ is the resistivity of the Co layer without DWs and $\rho_{\text{DW}}$ is the intrinsic DW resistivity.

Figure 6.3 shows the geometry of a current flowing through a Pt/Co/Pt layer. For simplicity the resistance of both Pt layers is given as $2R_{\text{pt}}$, so that the total resistance of the Pt layers is $R_{\text{pt}}$. First we describe the situation without any DWs. From the measurement we have obtained the resistance of the total Pt/Co/Pt stack, which is $R_{\text{Pt/Co/Pt}}$. We are however only interested in the magnetic Co layer. The Pt/Co/Pt stack is therefore divided into three parallel resistances, one for each layer. The resistance of the Co layer is denoted as $R_{\text{Co}}$ and the total resistance of the two Pt layers is $R_{\text{Pt}}$. When a current $I$ flows through the stack it is for now assumed that the proportion of current through the Co layer is $p$, so that $I_{\text{Co}} = pI$. The rest of the current is divided over both Pt layers. In the next section we will derive an accurate value for $p$ from a Fuchs-Sondheimer model. The following expressions are then used to determine the resistance of the Co and Pt layers:
6.2 Resistance of single DWs in Pt/Co/Pt

Figure 6.3: Geometry of the current distribution between the Pt and Co layers with (left) and without DWs (right). Due to the requirement of a spin polarized current and presence of a DW, DW resistance only exists in the magnetic Co layer. The effect of a measured DW resistivity therefore originates only from the electrons that flow through this layer. This makes the proportion of the total current $p$ that travels through Co an important parameter to consider.

$$R_{Co} = \left( \frac{1-p}{p} + 1 \right) \cdot R_{Pt/Co/Pt} \quad \text{and}$$

$$R_{Pt} = \left( \frac{p}{1-p} + 1 \right) \cdot R_{Pt/Co/Pt} \quad (6.3)$$

Now that the resistance of each individual layer is known, the situation in figure 6.3 with DWs is considered. From the measurement a resistance change of the Pt/Co/Pt layer of $\Delta R$ is obtained. Very important is to understand that this $\Delta R$ is caused by a $\Delta R_{DW}$ due to the DWs that only exists on the Co layer. This immediately shows the importance of the current proportion $p$, since the measured $\Delta R$ is only caused by the few electrons that flow through the magnetic Co layer. With this we can derive an expression from which $\Delta R_{DW}$ in the Co layer can be determined:

$$\Delta R_{DW} = \frac{\Delta R (R_{Pt} + R_{Co})}{R_{Pt/Co/Pt}R_{Pt} - R_{Co}\Delta R} R_{Co} \quad (6.5)$$

Finally we use $\Delta R_{DW}$ and $R_{Co}$ and the geometry of our strip to determine the resistivity of our Co magnetic layer without any DWs ($\rho_0$) and the intrinsic DW resistivity $\rho_{DW}$ via

$$\rho_0 = R_{Co}A/L \quad \text{and}$$

$$\rho_{DW} = \Delta R_{DW}A / (N \cdot \Delta). \quad (6.6)$$
Here $L = 30 \mu m$ is the length of the wire, $A = 0.75 \times 10^{-3} \mu m^2$ is the cross-section of the Co layer, $N$ is the number of DWs and $\Delta$ is the width of one DW. The product of $N \cdot \Delta$ accounts for the fact that only part of the length of the wire is covered by DWs. The DW width can be calculated from $K_{\text{eff}}$ using equation 2.4. For the irradiation dose that is used it is found that $\Delta = 36 \text{nm}$.

To summarize and emphasize the important quantities in this derivation, it is again repeated that the quantities that we measure are $\Delta R$ and $R_{\text{Pt/Co/Pt}}$ and we are interested in $\rho_{\text{DW}} / \rho_0$. For this we have to make an estimation of the current through the Co layer $p$ and of the DW width $\Delta$. The latter is derived via $\Delta = \pi \sqrt{\frac{A}{K_{\text{eff}}}}$ using our measurements of $K_{\text{eff}}$ as a function of $\text{Ga}^+$ dose in chapter 4. In section 6.2.2 we will derive a value for $p$ by using a Fuchs-Sondheimer model.

### 6.2.2 Fuchs-Sondheimer model

In many experimental reports $p$ is determined by considering the Pt/Co/Pt stack as a simple parallel resistor network and assuming bulk values of the resistivities (where $\rho_{\text{Pt}} \approx \rho_{\text{Co}}$ [58]). It can then be estimated that in our case approximately 8% of the current flows through the Co layer. In a recent report, however, the current distribution through a Pt/Co/Pt stack was calculated in a Fuchs-Sondheimer (FS) model and it is shown that the picture of a parallel resistor network is not complete and the current density in the Co layer is much smaller than expected [58]. Especially the spin dependent interface scattering plays an important role in isolating the Co layer from the rest of the stack. Input parameters in the FS model are the spin dependent interface transmission coefficients and the mean free paths of both the Pt and the Co layers. With these parameters the current distribution for spin up and spin down electrons is calculated throughout the Pt/Co/Pt stack. More detailed information on the used parameters is found in Appendix B and the result of the calculations is shown in figure 6.4. We will use this result to extract a parameter for the total current that flows through the Co layer, which is given by $p$.

Figure 6.4 shows the current density as a function of the height $z$ in a Pt$_4$/Co$_{0.5}$/Pt$_2$ structure. It can clearly be seen that there is a large difference between the current flowing through the top and bottom Pt layers and through the Co layer in between. Furthermore, there is a considerable difference between spin up and spin down electrons in the Co. Due to the influence of this, there is also a small spin polarization in the Pt layer visible, but this is neglected in the analysis. Integrating the current density of both spin polarities in the Co layer and dividing it by the integral over the total stack gives the proportion of the total current that flows through the magnetic Co. With this method it is found that $p=3.1\%$, much smaller than the prediction of 8% that follows from a simple parallel resistor network for Pt$_4$/Co$_{0.5}$/Pt$_2$. As we have seen in the previous calculations, the
6.2 Resistance of single DWs in Pt/Co/Pt

Figure 6.4: The current density as a function of the z-position in a Pt\(_4/\)Co\(_{0.5}/\)Pt\(_2\) stack. The blue (red) line shows the current distribution for spin up (down) electrons in the stack. From this model, interesting parameters such as the spin polarization and the amount of current in the Co layer can be obtained. More details of the calculation are found in [58].

effective DW resistivity (and other effects that depend on the amount of current) is therefore underestimated in many cases.

With the obtained result on the current density, we can now estimate the important quantity \(\rho_{DW}/\rho_0\). Averaging over 8 measurements on two different samples that are irradiated with a dose of 0.56 Ga\(^+\) ions/cm\(^2\), gives a DW resistance \(\Delta R=6.9\pm0.9\) m\(\Omega\) for 20 DWs. Furthermore, with the help of equation 6.3 and equation 6.6 it is found from the measurements that \(\rho_0=107\) \(\mu\)\(\Omega\) cm. Using equation 6.3, 6.4, 6.5 and 6.7 it is calculated that \(\rho_{DW}/\rho_0=0.7\pm0.1\%\). This result is in agreement with the DW resistivity that is found in a similar stack in [33]. They found that \(\rho_{DW}/\rho_0=0.1\%\) in a Pt\(_{3.5}/\)Co\(_{0.6}/\)Pt\(_{1.6}\) stack, for an estimated \(p\) of 15\%. Using the FS model we find that \(p \approx 4\%\), meaning that they underestimated \(\rho_{DW}/\rho_0\) by approximately a factor of 4. From this it can be concluded that their result is quite similar to ours. This also stipulates once more that the amount of current in the Co layer is of major importance. Comparison with other experiments is less relevant since totally different materials are being used, but at least the measured values are in the same order of magnitude [35, 34, 36]. So far it can therefore be concluded that our results are in agreement with earlier experiments.
6.3 DW width dependence

In the previous section it is seen that the observed contribution of DWs to the resistivity is positive, in agreement with the Levy-Zhang (LZ) theory. Most other intrinsic DW resistivity measurements that have been performed up to now can also be interpreted in terms of this model and it is therefore the most supported available theory [4]. In the LZ model, the additional resistivity arises from the increased scattering due to mistracking of the conduction electrons with the magnetization profile in a DW. Recapping the most important result from section 2.3, the following relation is given for the DW resistivity:

\[
\rho_{DW}/\rho_0 = \left(\frac{\xi^2}{5}\right) \left(\rho_\uparrow/\rho_\downarrow - 2 + \rho_\downarrow/\rho_\uparrow\right) \left(3 + \frac{10\sqrt{\rho_\uparrow/\rho_\downarrow}}{\rho_\uparrow/\rho_\downarrow + 1}\right),
\]

(6.8)

where

\[
\xi = \pi \hbar^2 k_F/4mJ.
\]

(6.9)

This equation shows that the increased resistance is only dependent on the spin polarization of the current \(\rho_\uparrow/\rho_\downarrow\) and a prefactor \(\xi^2\), that depends on the Fermi wavevector \(k_F\), Planck's constant \(\hbar\), the electron mass \(m\) and the exchange splitting \(J\). Interestingly, equation 6.9 shows that \(\xi\) also depends on the width of the DW.

We furthermore know that we can create DWs at an anisotropy barrier by partly irradiating a Pt/Co/Pt wire. An important feature in this process is that the energy of the DW is given by

\[
E_{DW} = 4\sqrt{AK_{eff}}.
\]

(6.10)

At zero applied field the DW therefore always resides at the irradiated side of the barrier, where the anisotropy is the lowest. This situation is depicted in the inset of figure 6.5. We also know from chapter 4 and chapter 5 that DWs can be pinned for different irradiation doses and the effective anisotropy \(K_{eff}\). Finally, it is known that the width of the DW depends on \(K_{eff}\) as

\[
\Delta = \pi \sqrt{A/K_{eff}}.
\]

(6.11)

Combining equation 6.8-6.11 the dependence of \(\rho_{DW}/\rho_0\) on \(K_{eff}\) is found to be
6.3 DW width dependence

\[
\frac{\rho_{DW}}{\rho_0} = \left( \left( \frac{\hbar k_f}{4mJ\sqrt{A}} \right)^2 \right) \left( \frac{\rho_\uparrow}{\rho_\downarrow} - 2 + \frac{\rho_\downarrow}{\rho_\uparrow} \right) \left( 3 + \frac{10\sqrt{\rho_\uparrow/\rho_\downarrow}}{\rho_\uparrow/\rho_\downarrow + 1} \right) \cdot K_{\text{eff}}. \tag{6.12}
\]

It can be seen from this expression that the change in resistance \( \frac{\rho_{DW}}{\rho_0} \) is, according to LZ, linear in \( K_{\text{eff}} \). Since the DW resides in the irradiated region we can therefore tune the DW resistivity by using different Ga\(^+\) doses to pin the DW. This effectively tunes the width of the DW and gives us a unique possibility to investigate the validity of the LZ theory by exploring the predicted DW width dependence. Other parameters in equation 6.12 that might influence the results are discussed in section 6.3.2.

Figure 6.5: Effect of using different Ga\(^+\) doses to inject DWs on the measured change in resistance of the whole Pt/Co/Pt layer. The inset of the graph shows that the DW resides in the irradiated part of the wire. The open and closed circles represent two different batches of samples. The error bars for low doses are larger due to a decreased DW pinning probability.

Figure 6.5 shows the result of such an experiment. The resistance change \( \Delta R \) of 20 DWs in a Pt/Co/Pt wire is measured in the same way as in section 6.2, but with variable Ga\(^+\) dose. To increase the range of possible Ga\(^+\) irradiation doses, a smart trick is introduced. For very low irradiation doses it is discussed in section 3.2 that the coercive field \( H_c \) of the irradiated part of the strip is larger than the pinning field \( H_{\text{pin}} \) and therefore DWs are immediately injected into the non-irradiated part of the strip. However, we have shown in chapter 5 that we can tune \( H_c \) and \( H_{\text{pin}} \) independently, by irradiating a gradient instead of a sharp step. To decrease the nucleation field in the irradiated region, a high irradiation
dose is applied in the centre of the domain to stimulate nucleation of a DW in this region. This can be seen in figure 6.6. A gradient decrease of the dose is used, allowing the DW to move towards the boundary between the irradiated and the non-irradiated region, where it gets pinned. This way, the DW resistivity can be measured of DWs in higher $K_{\text{eff}}$ regions, where DWs are very narrow, although the energy barrier is very small. \(^1\)

![Figure 6.6: Irradiation scheme that is used for the injection of pinned DWs in high anisotropy regions. A nucleation site is engineered in the centre of a 1µm wide domain by irradiation with a large dose. The anisotropy is than gradually increased towards the edge of the domain to inject the nucleated DW in the intermediate anisotropy region, where it gets pinned at the steep anisotropy barrier.](image)

Each point in figure 6.5 is averaged over a few measurements on 1 or 2 different samples. Due to electrical discharges, the lifetime of the samples was not very long and therefore not all the points are averaged over the same amount of experiments. The error bars are estimations based on the variation between the samples. For the low Ga\(^+\) dose only a few DWs were pinned simultaneously because the strength of the energy barrier scales with the difference in anisotropy. The error bar for this point is therefore also larger. Furthermore, $R_{\text{Pt/Co/Pt}}$ was measured for each sample, but no clear correlations was found because of large sample to sample deviations. Despite these complications, a clear decrease of $\Delta R$ of the Pt/Co/Pt wire is measured for increasing irradiation dose, or decreasing $K_{\text{eff}}$. This agrees with the expected trend from equation 6.12. It is noted that the open and closed circles belong to different batches of samples. Slight changes in the layer thickness or in the effect of the FIB on the Pt/Co/Pt stack might have shifted the result for the open circles upwards.

A final remark is made on the effect of AMR, that arises when the magnetization in the DW aligns with the direction of the current. This situation should occur if the DWs do not follow the Bloch profile from equation 2.9. Direct observation of

\(^1\)At the end of the project the minimum beam current of the Ga\(^+\) FIB increased due to long-time milling of the beam aperture. Precise control of the anisotropy landscape became more difficult and only the dose of 0.44 Ga\(^+\) ions/cm\(^2\) was added to the figure. Otherwise, more measurement points would have become available. Tests have shown that it is possible to pin DWs at a dose of 0.3 Ga\(^+\) ions/cm\(^2\).
6.3 DW width dependence

the DW type is not possible, but it is expected that the contribution to $\Delta R_{\text{AMR}}$ is linear in $\Delta$ and becomes smaller for more narrow DWs\cite{23}. This is exactly the opposite from what we found and therefore a proof that we have clear Bloch DWs in our devices.

6.3.1 Comparison with LZ theory

For a quantitative comparison of our results with the LZ model, we would like to investigate the DW resistivity $\rho_{\text{DW}}/\rho_0$ of the magnetic Co layer in our Pt$_4$/Co$_{0.5}$/Pt$_2$ stack for increasing $K_{\text{eff}}$. This result is shown in figure 6.7. The values for $\rho_{\text{DW}}/\rho_0$ are obtained from $\Delta R$ in figure 6.5, using the geometry of the current density from figure 6.3 and using that $p = 3.1\%$. For the determination $K_{\text{eff}}$ for different irradiation doses, the fit in figure 4.3 in chapter 4 is used. From $K_{\text{eff}}$ we also calculated the DW width $\Delta$ via equation 6.11. The inset of figure 6.7 shows the same data, but now as a function of the DW width.

![Figure 6.7: The effect of DW resistivity as a function of anisotropy. As shown in the inset, the DW resistivity increases for narrow DWs. The open and closed circles in the measurements again represent two batches of samples. The red line is a linear fit through the data and also plotted in the inset figure. This is the expected behaviour according to the LZ model and a $\rho_l/\rho_t$ of 8.0 is calculated, which is in agreement with both theoretical and experimental work\cite{37}\cite{33}.
](image-url)
Chapter 6: Intrinsic DW Resistivity in Perpendicularly Magnetized Materials

It was earlier shown in equation 6.12 that the LZ model for DW resistivity predicts a linear increase of the DW resistivity as a function of $K_{\text{eff}}$. Figure 6.7 shows at least a clear monotonic increasing behaviour, which is in line with this prediction. The red line is obtained from a linear fit of the data through the origin and is very accurate, apart from the highest value, which was from a different sample batch. According to the LZ theory the slope of the fit should be given by

$$\frac{\partial \rho_{\text{DW}}/\rho_0}{\partial K_{\text{eff}}} = \left( \frac{\hbar^2 k_f}{4mJ\sqrt{A}} \right)^2 / 5 (\rho_\uparrow/\rho_\downarrow - 2 + \rho_\downarrow/\rho_\uparrow) \left( 3 + \frac{10\sqrt{\rho_\uparrow/\rho_\downarrow}}{\rho_\uparrow/\rho_\downarrow + 1} \right).$$  \hspace{1cm} (6.13)

Using the input parameters from table 6.1, it is estimated from the fit that $\rho_\uparrow/\rho_\downarrow \approx 8$. This is in agreement with the estimation in [37] that $\rho_\uparrow/\rho_\downarrow \approx 5 - 20$ for room-temperature Co. The red line in the inset of figure 6.7 shows the result of the same fit for the effect of the physically more relevant DW thickness. It can be seen that DW resistivity is more pronounced for thin DWs.

Table 6.1: Used values for the determination of $\rho_\uparrow/\rho_\downarrow$ from the measurements, which are adapted from [37].

<table>
<thead>
<tr>
<th>Fermi wavelength ($k_f$)</th>
<th>Exchange constant ($A$)</th>
<th>Exchange splitting ($J$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Å$^{-1}$</td>
<td>16 · 10$^{-12}$ J/m</td>
<td>0.5 eV</td>
</tr>
</tbody>
</table>

A further comparison with experimental work in [33], can now also be made. In section 6.2 it was shown that similar results were found for the DW resistivity in their Pt$_{3.5}$/Co$_{0.6}$/Pt$_{1.6}$ structure, although they overestimated the current density in the Co layer. Calculated DW resistivities from their results were therefore an order of magnitude below predictions by LZ theory. However, by separating DW resistivity contributions for current perpendicular and current parallel to the DW for DWs under an angle, they were able to use LZ theory to obtain a value for $\rho_\uparrow/\rho_\downarrow$ of approximately 5.5. Taking into account the uncertainty of the parameters in table 6.1 that we used for our determination of $\rho_\uparrow/\rho_\downarrow$ in the Co layer, these are also in reasonable agreement.

From this measurement we can conclude that the agreement of our measured DW resistivity $\rho_{\text{DW}}/\rho_0$ in the Co layer as a function of DW width with the model of LZ is striking. A simple linear fit through the origin represents the data very well and a reasonable value for $\rho_\uparrow/\rho_\downarrow$ could be obtained. Our results therefore lend a strong support to the prediction that DW resistivity is caused by mixing of the spin current channels due to scattering of itinerant electrons that are misaligned with the local magnetization in the DW. This mistracking is more pronounced in thin DWs and therefore the DW resistivity also increases. Before we elaborate more on the consequences of our observations, some remarks will be made on the experiment, concerning other parameters in equation 6.12 that might change due to Ga$^+$ irradiation.
6.3.2 Discussion

A clear disadvantage of using a FIB for the injection of DWs, is that the Pt/Co/Pt structure is altered. In chapter 4 we have shown that the moderate Ga$^+$ irradiation doses that we use, locally lower the anisotropy due to intermixing of the Pt/Co interfaces. It might therefore be expected that other interface dependent effects are also modified to some extent and it is not straightforward to exclude their contribution to the result in figure 6.7. In this section some estimations are made to be able to comment on the contribution due to other effects than a change in the DW width.

Two properties that might also cause the observed trend in figure 6.5 are the change in current density and the spin polarization in the Co layer. Intuitively, one might expect that both values are lowered for higher irradiation doses, where intermixing of the Pt/Co interfaces is more pronounced. In case of a decreasing spin polarization, the DW resistivity becomes smaller, as immediately seen from equation 6.8 for decreasing $\rho_\uparrow/\rho_\downarrow$. Lowering of the amount of current through the Co layer $p$ also reduces the measured DW resistivity, since more electrons travel through the Pt layer where DW resistivity is not possible. This can be seen from figure 6.3.

To investigate these effects in the following discussion, we ask ourselves three important questions that need to be solved:

1. How much do we need to change the interface effects in the FS model to find significant changes in the DW resistivity and what does this mean for the current density and spin polarization in the Co layer?

2. How do these changes affect the total resistance of the Pt/Co/Pt wire?

3. Are these resistance variations observed for our moderate Ga$^+$ doses?

The first two effects are investigated by implementing the parameters from the FS model, that has been introduced already in section 6.2.1 in the result of the LZ model for DW resistivity. The third question is answered by an in-situ measurement in the Dual-Beam set-up (section 3.2), where the resistance of a Pt/Co/Pt wire is measured during Ga$^+$ irradiation.

**Modified Fuchs-Sondheimer model**

We start our analysis with the description of the FS model, where we have implemented the LZ equation for DW resistivity. To answer the first question that is raised above, we are interested in the proportion of current that flows through
Chapter 6: Intrinsic DW Resistivity in Perpendicularly Magnetized Materials

the Co layer $p$ and the spin polarization which is given by $\frac{\rho_\uparrow}{\rho_\downarrow}$. These parameters are adjusted by changing the Pt/Co interfaces and the effect of these changes on the DW resistance $\Delta R$ is investigated. Since $\Delta R$ is the quantity that is actually measured in the experiment we can make a direct comparison between the model and the experiments. In section 6.3 we have observed that for 20 DWs $\Delta R$ varies roughly from 3-13 mΩ. The modified FS model that we use to investigate whether we can get a similar trend in DW resistivity, by changing $p$ and $\frac{\rho_\uparrow}{\rho_\downarrow}$, works as follows:

- In the model we investigate a Pt$_4$/Co$_{0.5}$/Pt$_{2}$ structure of 30 μm long and 1.5 μm wide. These dimensions are exactly similar to the wires that are used in the experiments. To describe the transport of electrons in the Pt and Co layers we need to define the mean free path. For this we use a similar approach as in [58], where it is used that the product of the resistivity and the mean free path ($\rho l$) is a well-known material constant. From the experiments $\rho_{Pt}$ and $\rho_{0}$ are known and this is used to find the mean free paths in the Pt and Co layers respectively. For Co we furthermore have to define a bulk value for $(\frac{\rho_\uparrow}{\rho_\downarrow})_{\text{bulk}}$, from which the spin dependent mean free paths are calculated.

- The interface effects in the model are implemented via the interface transmission coefficients $T_\downarrow(\uparrow)$, that describe the chance $T$ that an spin down(up) electron at the Pt/Co interface is transmitted without any change in its velocity. If not, the electron is randomly scattered. The spin asymmetry coefficient $N = \frac{1-T_\downarrow}{1-T_\uparrow}$ gives the difference between both transmission coefficient and is the single parameter in the FS model that will be varied. In [58] it is found that $N=1.15$ for a similar Pt/Co/Pt stack that is lightly irradiated. The minimum value of $N$ is 1, where the interface scattering is no longer spin dependent. We to vary $N$ over a large range between 1.0 and 1.4. The maximum is $N$ is picked to find a significant change of $\Delta R$ in the model.

- Now that we have defined all the input parameters, we use the FS model to calculate the spin polarization $\frac{\rho_\uparrow}{\rho_\downarrow}$ in the magnetic Co layer, the total current (in arbitrary units) and the amount of current through the Co layer $p$ (in %). For comparison with the experiments the total resistance is set as $R_{Pt/Co/Pt} \approx 1.3k\Omega$. 


For every value of $N$, $\frac{\rho^T}{\rho^L}$ is used to calculate $\rho_{DW}/\rho_0$ with the LZ expression for DW resistance. For this we assume a DW width of 36 nm which is not changed (adapted from section 6.2). Any effect can therefore only result from changes in polarization and current distribution.

Finally $R_{Pt/Co/Pt}$, $\frac{\rho_{DW}}{\rho_0}$ and $p$ are known. With these the resistance change due to 20 DWs in the Pt/Co/Pt layer is calculated for variable spin asymmetry coefficients $N$. This value is directly comparable with the measurement in figure 6.5. The result of the simulations is shown in figure 6.8.

Figure 6.8: Calculated results for the effect of a changing spin asymmetry coefficient $N$ on the resistance of a Pt/Co/Pt wire in a combined FS and LZ model. A decrease in $N$ reduces the amount of current through the Co layer and the spin polarization in this layer. The black line shows that this can lead to an observed decrease in DW resistance. At the same time this effect is accompanied by an increase of the total resistance of the Pt/Co/Pt stack, as shown by the red curve.

With the model that we have just described we will now start to answer the first question that has been raised. Observing figure 6.8 shows that lowering of $N$ indeed results in a similar decrease of the DW resistance of a Pt/Co/Pt layer as observed in the measurements. This trend is caused by a variation of the percentage of the total current through Co ($p$) from 3% to 2.2% and a change in the spin polarization $\frac{\rho^T}{\rho^L}$ from 7 to 4.7. For the full range of the spin asymmetry coefficient $N$, it can be seen that the DW resistance varies roughly from 8 to 4 mΩ. The calculated values for $\Delta R$ are in the same range as the 7 mΩ that was measured for a DW width of 36 nm. In the measurements we however observed a change in $\Delta R$ from 13 to 3 mΩ. The variation of $\Delta R$ for $N$ between 1 and 1.4 is much smaller and is therefore considered as a lower estimate of the change in interface effects that is required to explain the results.
Now that we have verified that at least a transition of $N$ from 1.4 to 1.0 is required to find a reasonable effect on the DW resistivity, we have to answer question 2 to see whether this is a realistic effect. We will therefore use the same modified FS model and look at the effect on the total resistance of the Pt/Co/Pt stack, which is also shown in figure 6.8. Interesting to see is that the decrease in $\Delta R$ is accompanied by a rather strong increase in the resistance of the Pt/Co/Pt stack and an increase in $R_{Pt/Co/Pt}$ of approximately 27$\Omega$ is calculated. This is an increase of 2.0%, which should definitely be measurable. It is noted that for comparison with the experiment that we perform in the next section, $R_{Pt/Co/Pt}$ is calculated for a wire that is irradiated over its full area. Furthermore, we have now only considered the effect of Ga$^+$ irradiation on the interfaces and neglected other effects. These are expected to contribute to the resistance as well, so an increase of 27$\Omega$ might even be considered as a lower estimate.

Referring to the questions that were brought up before, we have now identified that a resistance change of at least 2.0% should be visible if changes in the current distribution and spin polarization due to Ga$^+$ irradiation cause strong changes in the DW resistivity as a function of Ga$^+$ dose. In the following we therefore perform an interesting experiment to investigate this effect to be able to conclude on the third question.

In-situ resistance measurement of Ga$^+$ irradiated Pt/Co/Pt

To answer the final question, we need to determine the resistance of Pt/Co/Pt as a function of Ga$^+$ dose. Since the resistance of each individual Pt/Co/Pt wire varies slightly and no clear correlation between the total resistance and the Ga$^+$ irradiation is found, it is important to measure the influence of FIB irradiation on a single wire. For this reason, in-situ resistance measurements are performed in our dual beam set-up. A SEM image of the setup is shown in figure 6.9(a). Two Kleindiek manipulators are used to make electrical contact with a 1$\mu$m wide Pt/Co/Pt wire in one of the Wheatstone bridges that are used for DW resistance measurements. To prevent shorting via the other leads of the wheatstone bridge, a gap is milled in one of the other wires. This can still be seen in the top left of the image. The wire has a resistance of 1.5k$\Omega$, which is slightly higher than the wires we discussed before because the wire is smaller. The contact resistance of the Kleindiek manipulators, measured on the thick gold contact leads, is around 20-30$\Omega$ and therefore almost negligible.

The wire is then irradiated with steps of $0.062 \cdot 10^{13}$ Ga$^+$ ions/cm$^2$ and after each step the resistance of the wire is obtained by measuring the current as a function of voltage. The wire resistance for the cumulative irradiation dose is shown in figure 6.9(b). The strange effect around $0.4 \cdot 10^{13}$ Ga$^+$ ions/cm$^2$ is probably caused by charging of the wire due to irradiation with the positive ions. Due to charging the waiting time before taking an I-V curve is important, as can be seen in the
6.3 DW width dependence

Figure 6.9: (a) SEM image of the experimental set-up for in-situ measurements of the effect of Ga$^+$ irradiation of a Pt/Co/Pt wire. Two Kleindiek manipulators are used for electrical contact with a 1.5 $\mu$m wide Pt/Co/Pt in a Wheatstone bridge. High dose milling is used to prevent shorting through the other leads. (b) Resistance as a function of Ga$^+$ dose. After each step of $0.062 \times 10^{13}$ Ga$^+$ ions/cm$^2$, an I-V curve is obtained to determine the resistance. The inset in (b) shows that charging of the wire is present by directly monitoring the resistance during the irradiation process.

inset where the resistance is real-time monitored at constant voltage. Important to see in figure 6.9(b) is that the increase in resistance for the irradiation dose range used in the DW resistance experiments (between 0.4 and $0.85 \times 10^{13}$ Ga$^+$ ions/cm$^2$) is only 0.67% (10$\Omega$).

We can compare this value of 0.67% with the result of the modified FS model, which predicts a change in resistance of at least 2% if the observed trend in DW resistivity as a function of Ga$^+$ irradiation is affected a lot by changes in the current distribution and spin polarization. However, we see that the measured value is a factor of 3 smaller than the lower estimate from the FS model. This means that the dominant mechanism behind the observations on DW resistivity in figure 6.7 is the DW width dependence as predicted by the LZ model.

A final remark that strengthens the conclusions from before is based on the trend in figure 6.7, instead of the size of the effect of DW resistivity. It is shown that the trend exactly follows the expected linear behaviour. Especially the observation that a linear fit with no constraints went straight through the origin is very striking. The exact effect of Ga$^+$ irradiation on $p$ and $\frac{\Delta}{p_0}$ is of course unknown, but it would be very surprising if it would lead to such a nice behaviour. The qualitative result $\rho_{DW}/\rho_0$ with $K_{eff}$ already leads to the suggestion that the dependence on $\Delta$ is indeed the cause of the change in DW resistivity.
Other effects

In the former discussion on the reliability of the trend in DW resistance for increasing Ga\textsuperscript{+} dose, only the spin polarization and the current density are treated. Considering equation 6.12 it can be seen that the exchange splitting $J$ (and the related exchange constant $A \propto \sqrt{J}$) are parameters that might change under FIB irradiation. However, if anything, both values are expected to be lowered and the resulting effect would be in the opposite direction as observed.

Other effects such as spin-orbit coupling are also present and expected to change (since it determines the perpendicular anisotropy). Increased spin-orbit coupling due to alloying of the Pt and Co layers might lead to spin mixing of the up and down channels, effectively destroying the polarization. This effect is similar to the role of a decreasing spin asymmetry coefficient $N$ and also leads to changes in spin polarization, current distribution and finally a change in the resistance of the Pt/Co/Pt stack. Similar arguments can therefore be used to rule out this effect.

6.4 Conclusions

In this chapter it is shown that the use of a Kerr microscope to directly image magnetization processes in combination with high accuracy resistance measurements is a very powerful technique to investigate intrinsic DW resistivity. The comparison of measured resistance changes with simultaneously obtained Kerr images has enabled us to separate intrinsic DW resistivity from other masking effect with relative ease. Furthermore, we have used our knowledge on local Ga\textsuperscript{+} irradiation from the previous chapters to inject DWs in Pt/Co/Pt wires in a controlled way, making the measurements even more reproducible. This way it is possible to discriminate between many DW resistivity models that are available.

Using this newly developed setup, we have succeeded in the first section to measure the intrinsic contribution to the resistance of individual DWs. It is observed that the resistance of a single Pt/Co/Pt wire that has a resistance of approximately 1 kΩ, increased stepwise for the appearance of DWs. The increase of resistance is $\sim 0.4$ mΩ/DW and in comparable to earlier experiments. It is shown that an accurate prediction of the current distribution in the Pt/Co/Pt stack is of vital importance to calculate the local change in resistivity in the magnetic Co layer. For this reason a Fuchs-Sondheimer model is adapted.

In section 6.3 the dependence of DW resistivity on the width of the DWs is investigated for the first time, by using the Ga\textsuperscript{+} dose as a handle to tune the DW width. The DW resistivity is determined as a function of the DW width and proven to be in qualitative and quantitative agreement with the model of Levy and Zhang [37]. As predicted in their model, the DW resistivity is positive and increases for narrow
6.4 Conclusions

DWs. By fitting the expected linear behaviour of DW resistivity with the effective anisotropy, a spin polarization \( \rho_\uparrow/\rho_\downarrow \) of 8 is found. This value is in agreement with both theoretical and experimental observations [37, 33]. In an extensive discussion we then argued that the observed effects are indeed related to the change in DW width and not due to other local changes in the Pt/Co/Pt wire. This argument was based on the absence of a strong increases in the total resistance, that was predicted otherwise from the combination of the FS model and the LZ theory.

From the result in this chapter, several interesting conclusions can be drawn. As explained in chapter 2.3, DW resistivity in the LZ model originates from increased scattering of conduction electrons due to mistracking of their spin with the local magnetization in a DW. This mixes the otherwise independent spin current channels and thereby leads to an increased resistance. Our proof for the model of LZ therefore also strongly suggests that non-adiabatic spin transport takes indeed place in narrow DWs, such as in perpendicular magnetized Pt/Co/Pt. This might be of importance for discriminating between the many theories that describe the strength of the non-adiabatic contribution to current-induced DW motion. The existence of spin mistracking in these materials is therefore very promising for the development of low current density DW motion devices.

A final important result from our measurements of DW resistivity for different DW widths, is that it is shown that the DW width and hence the effect of DW resistivity can be tuned by a smart use of our Ga\(^+\) FIB. In the following section we will again use this powerful tool to investigate the relation between the non-adiabatic spin transfer torque and DW resistivity more carefully.
Chapter 7

The non-adiabatic STT in relation to DW resistivity

One of the most debated subjects in research on current-induced DW motion is the role of the non-adiabatic STT. This torque is phenomenologically introduced in the LLG equation (section 2.2) [22], as a contribution that is characterized by the dimensionless parameter $\beta$, because taking only adiabatic spin transfer torques into account could not explain many of the experimental results [24, 49, 48]. Since then the existence and the physical origin of this $\beta$-term are heavily debated. The presence of a large $\beta$ is of high importance since it requires much smaller current densities to move a DW. This prospect is very promising for the development of commercial DW devices.

Very remarkable results are recently obtained for the direction of current-induced DW motion [30]. Although from simple spin conservation arguments it is expected that the DW always moves in the direction of the electron flow, recent reports have shown conflicting results [18, 16, 31, 30]. Furthermore, experiments in our group have indicated that the direction of current-induced DW motion is tunable by changing the thicknesses of the Pt layers in a Pt/Co/Pt stack [25]. This indicates that either $\beta$ or the spin polarization $P$ changes sign for only slight modifications in the Pt/Co/Pt stack, which is at least remarkable. Much more research is therefore required to gain some insight into the origin of current-induced DW motion and especially the non-adiabatic STT.

As shown already in chapter 2, many models relate the non-adiabatic STT to mistracking of the conduction electron spin with the local magnetization in a DW. This situation has many similarities with the origin of intrinsic DW resistivity and the relation between $\beta$ and $\rho_{DW}$ has therefore been suggested in both theoretical and experimental reports [52, 26, 29]. Now that we have established a way to tune the DW resistivity by changing the DW width in chapter 6, we have a method to
investigate this relationship, which will be done in this chapter.

Furthermore, also the dependence of $\beta$ on the DW width will be investigated. Transport theories predict that $\beta$ is more pronounced for thin DWs\cite{83, 26} and different theories predict different dependences on the DW width\cite{27, 26}. A recent theoretical report even suggests an oscillatory relationship between $\beta$ and the DW width, for thin DWs\cite{28}. In this theory a sign change of $\beta$, depending on the DW width, is predicted. This would be a novel way to explain the confusion about the sign of $\beta$.

There are several methods to obtain $\beta$ experimentally. One can for example investigate current-induced DW motion, where the change in field-driven DW velocity is measured under influence of an assisting current\cite{30}. In another technique, one measures the effect of current on the escape of a DW over an energy barrier\cite{8}. In this report we take the second approach and we have adapted the method that is used in\cite{18}. Here we investigate the effect of an applied current on the depinning time from a single energy barrier created by a Ga$^+$ irradiation step. A clear advantage of this method is that the used current densities are low and that the same set of samples as for the DW resistivity measurements can be used. This make a direct comparison very convincing.

In the first section of this chapter we discuss the experiment in more detail and show the typical result for a single measurement of $\beta$. In section 7.2, the DW width dependence of $\beta$ is investigated and the results are compared to the DW resistivity measurements of chapter 6 and other theoretical models. In the final outlook section it is shown that the combination of DW resistivity and $\beta$ measurements with this method is very useful for further investigation of the influence of the thickness of the Pt layers on $\beta$.

7.1 Thermally activated depinning experiments

To determine the strength of the non-adiabatic STT $\beta$, we study the effect of an applied current on thermally activated depinning of a DW from a single energy barrier\cite{18}. As shown in section 2.4.2, this stochastic process is described with an Arrhenius law, where the probability of escape over the barrier is characterized by a transition time $\tau$. It is shown that the effect of current is linear on the energy barrier with a proportionality constant that depends on $\beta$\cite{57}. To obtain a quantitative value for $\beta$ we therefore need to measure the distribution of depinning times of a DW from an energy barrier. The underlying physics is explained in section 2.4.2.

For an accurate comparison with DW resistivity the same set of samples as in chapter 6 is used for the depinning experiments. The measurements are performed in the Kerr microscope set-up for electrical measurements. The relevant part of
one of the used samples is again shown in figure 7.1 and the measurement process is as follows. First a large negative (or positive) magnetic field is applied to saturate the magnetization of the Pt$_4$/Co$_{0.5}$/Pt$_2$ wire in one direction. A smaller positive (negative) magnetic field is then applied to nucleate a pinned DW at the anisotropy boundary. The field is increased to just below the depinning field and from this moment a timer is started, which is defined as $t = 0$. From this time, the intensity of the Kerr image of the area just behind the DW (the blue square in figure 7.1) is monitored as a function of time. After a certain duration, thermal activation causes the wall to depin from the pinning site and propagate into the remainder of the wire. This is observed by an abrupt intensity change and is denoted as the depinning time $t_d$. Note that $t_d$ is the depinning time of one single depinning event and only a distribution of many events gives a measurement for the transition time $\tau$. A typical measurement of $t_d$ is shown in figure 7.1. The DW under investigation is intentionally chosen at the end of the nanowire, because otherwise it is impossible to discriminate between the depinning events of the two adjacent DWs. The accuracy of $t_d$ is limited by the frame rate of the microscope, which is approximately 30 Hz. The process is fully automated by a LabView script and repeated 200 times to obtain decent statistics of the distribution of $t_d$. The procedure is repeated for various current densities up to $1.5 \cdot 10^{10}$ A/m$^2$. This is one order of magnitude smaller than current densities that are used in current-induced DW motion experiments in our group [25] and probably far below the Walker breakdown. Therefore, the adiabatic STT is supposed to have no significant effect and Joule heating will also be much smaller. In our convention a positive current is applied in the same direction as the depinning of the DW, as indicated by the arrow in figure 7.1.

**Figure 7.1:** Overview of the experimental set-up for thermally activated depinning. The microscope image shows a Pt/Co/Pt nanostrip where depinning of the bottom DW is investigated for applied current and field. The Kerr microscope monitors the intensity of the blue square and observes the depinning as a decrease of the intensity. The time at which this happens is defined as $t_d$. 
Figure 7.2 shows the normalized distribution of $t_d$ for different combinations of field and current. The measurements are obtained from a Pt$_4$/Co$_{0.5}$/Pt$_2$ strip that is irradiated with 0.62 Ga$^+$ ions/cm$^2$ to be able to inject DWs. From the difference between figure 7.2(a) and 7.2(b), which are obtained for two different field strengths $H$, we see that the average $t_d$ becomes smaller and the spread in the distribution is increased for larger $H$. Due to the Zeeman energy of the applied field, the potential landscape is tilted and the effective energy barrier is lowered. This increases the probability of depinning. A similar effect is observed for an applied positive current in figure 7.2(d). The opposite behaviour is found for a negative applied current in figure 7.2(c). Here the spread in the distribution of $t_d$ becomes wider and the average value is larger. The asymmetry for positive and negative currents suggests that the effect of Joule heating plays only a minor role, since it would lead to an increase of the depinning probability for both current polarities due to the increased temperature. This also agrees with the observation that no significant resistance change of the wire is measured after the experiments. It is furthermore noted that the changes in depinning times are rather large, in the order of tens of seconds. This is much larger than any possible time delays due to artifacts in the set-up.

![Figure 7.2](image-url)
To obtain the characteristic Arrhenius time $\tau$ we consider the cumulative distribution $F(t)$, which is the probability that a DW has depinned at after a time $t$. $F(t)$ has been calculated from the results in figure 7.2 and shown in figure 7.3. Here, the open symbols show the measurements for variable applied currents at an external field of 7.3 mT. It can again be seen that the effect of an applied current density of up to $1.5 \cdot 10^{10} \text{A/m}^2$ in the Pt/Co/Pt leads to a significant change of the cumulative depinning distribution. These results are fitted by a cumulative distribution function that is given by

$$F(t) = 1 - \exp\left(-\frac{t - t_0}{\tau}\right).$$

(7.1)

In equation 7.1, $\tau$ is the Arrhenius time constant and $t_0$ is an incorporated delay time of the set-up, which becomes more important for fast depinning processes and is found to be approximately 0.1 s. The resulting fits are shown by the solid lines in figure 7.3 and are in good agreement with the experimental data. From this, the Arrhenius time $\tau$ is obtained, typically with an error of less than 0.01 s that is based on the quality of the fit. The quality of the fits is furthermore an indication that we indeed measure depinning from a single defect, that can be described by an Arrhenius law. Multi-step processes would result in different probability distributions [84].

![Figure 7.3: The cumulative probability function $F(t)$ for many applied currents at a field of 7.3 mT. The effect of current on the result is clearly visible.](image)
7.1.1 Results

To extract a value for the non-adiabaticity parameter $\beta$ from the depinning experiments, we consider the linear variation of $\ln(\tau)$ under applied current. According to the Arrhenius law as described in section 2.4.2, this is directly related to the current-dependent energy barrier in the form $\epsilon_b = \epsilon_{b,0} - \sigma I$. It is shown that the proportionality constant $\sigma$ is given by

$$\sigma = \beta P \frac{\hbar}{e} \frac{\delta}{\Delta},$$  \hspace{1cm} (7.2)

where $P$ is the spin polarization, $\delta$ is the energy barrier width, $\Delta$ is the DW width and $\hbar$ and $e$ are Planck's constant and the electron charge, respectively. There are several important issues in the determination of $\beta$. First of all, in chapter 6 it is argued that it is important to realize that for current-DW interactions only the small proportion of the current that flows through the magnetic Co layer ($I_{Co}$) is important. From a FS model it is calculated that this proportion $p$ is equal to 3.1% of the total current in the Pt/Co/Pt stack, which is directly used to calculate $I_{Co}$. For the determination of $\beta$ from equation 7.2 we therefore have to consider the linear variation of $\ln(\tau)$ for $I_{Co}$.

Furthermore, in equation 7.2 it can be seen that the width of the energy barrier $\delta$ is an unknown constant. In [18] it is estimated that $\delta \approx \Delta$, because pinning of a DW is important if the $\delta$ is on its own length scale. In section 2.4.2 we however presented a different way to measure $\delta$, making use of the field-current equivalence. It is shown that for small field ranges the field dependence of the energy barrier can be used to extract a more accurate estimation of $\delta$. Furthermore, in chapter 6 we have shown that the measurement of $K_{eff}$ from chapter 4 can be used to determine $\Delta$ for the used Ga+ doses. With these methods we are able to measure both $\delta$ and $\Delta$, which is probably better than making the crude estimation that $\delta = \Delta$. However, for simplicity we use in this section that $\delta = \Delta$ to explain the first results. In section 7.2 we will also measure the field-dependence of the energy barrier from which we deduce $\delta$.

In figure 7.4(a) the Arrhenius transition time $\tau$ is shown on a log scale as a function of $I_{Co}$ for two different $H$. This is the result that is obtained from the measurement in figure 7.3. The solid line represents a linear fit and shows the clear linear reduction in the barrier height. It is seen that a positive current reduces the depinning times. This means that the depinning is assisted in the direction opposite to the electron flow, indicating a negative $\beta$ if the spin polarization is positive. However, recently also a negative spin polarization is predicted from first principles calculations on Pt/Co alloys[85]. Although the result is counterintuitive and not yet understood, it is in agreement with other experiments on Pt_{4}/Co_{0.5}/Pt_{2} stacks in our group[25]. A further outlook on the investigation of the sign of $\beta$ will be given in section 7.4.
From the asymmetry of the result in figure 7.4(a) around $I_{Co} = 0$, we conclude that Joule heating is not present in the measurement. The effect of Joule heating would be similar for positive and negative applied currents and is therefore symmetric around 0. Important to note is that the same symmetry is obtained if we reverse the applied field in figure 7.4(b). In this case the polarity of the DW is also reversed, so that the magnetization in the DW rotates from up to down instead from down to up. At the same time, the direction of the applied current is not changed. The fact that the same symmetry for $\beta$ is found rules out any Oersted fields that originate from a current through the Pt/Co/Pt strips as a possible explanation for our results.

\[ \tau (s) \]
\[ \text{ICo (} \mu \text{A)} \]
\[ H= 7.3 \text{ mT} \]
\[ H= 7.8 \text{ mT} \]
\[ H= -6.5 \text{ mT} \]
\[ H= -6.6 \text{ mT} \]

(a) Positive DW polarity  
(b) Negative DW polarity

**Figure 7.4:** The result of the characteristic time $\tau$ as a function of the current that flows through the magnetic Co layer $I_{Co}$. In (a) the result is shown for a DW from up to down and in (b) the spins in the DW rotate from down to up. Both measurements show a decrease of the pinning times against the direction of the electron flow, ruling out the Oersted fields and indicating that either $\beta$ or $P$ is negative. The clear linear behaviour rules out the effect of Joule heating.

From the slope of the linear fits in figure 7.4 a value for $\beta$ can be obtained via equation 7.2. Making the simple approximation that $\delta = \Delta$ and assuming that $P = 0.46$ for Co (from [29]), it is found for the results of figure 7.4 that $\beta = 4.8 \pm 0.5$. It can however be seen in figure 7.4(a) that the decrease of ln($\tau$) with $I_{Co}$ is quite different for 7.3 and 7.8 mT. This indicates that $\delta$ is not constant in this field range and the approximation that $\delta = \Delta$ does not hold. For a smaller field range such as in figure 7.4(b) this effect was not visible.

This shows that for the investigation of the influence of the DW width on $\beta$, where many different samples are measured, a determination of $\delta$ via the field dependence of $\tau$ is definitely required. This is important because the measured values for $\beta$ otherwise depends on the field at which it is measured.
7.2 DW width dependence of the non-adiabatic STT

To perform a measurement of the dependence of $\beta$ on the DW width we use the same set of samples as used for the investigation of the DW width dependence of intrinsic DW resistivity in section 6. Here, variable Ga$^+$ doses are used to be able to inject DWs, which essentially tunes $\Delta$ as shown in chapter 4. For all samples the same procedure as described in the previous section is used to obtain a value for $\beta$.

As stated before, figure 7.4(a) shows that the slope of $\ln(\tau)$ as a function of $I_{Co}$ depends on the applied field $H$. This is probably attributed to a change in the width of the energy barrier $\delta$. Since we use different samples to investigate $\beta$ as a function of $\Delta$, it is even more important to be able to make an accurate estimation of $\delta$. We therefore use the field dependence of the energy barrier, as explained in section 2.4.2. In this theory it is shown that for small magnetic field ranges, $\delta$ can be extracted from the measurement via

$$\frac{\partial \epsilon_{b,0}}{\partial H} = -2\mu_0 M_s \delta A,$$

where $\epsilon_{b,0}$ is again related to $\ln(\tau)$ via the Arrhenius law.

![Figure 7.5: Example for the dependence of the energy barrier on the applied field. It can be seen that the trend is not linear because the width of the energy barrier $\delta$ depends on the applied field $H$. The measurement is obtained at zero current.](image)
A typical measurement of the field dependence of $\ln(\tau)$ is given in figure 7.5. The result is obtained without an additional current and it is seen that the relation between $\tau$ and $H$ is not linear. However, as argued in section 2.4.2, the field-current equivalence is valid at every single value (or small range) of $H$. For each field $H$ we can therefore determine the slope of $\ln(\tau)$ as a function of $H$ and use equation 7.3 to determine the width of the energy barrier $\delta$. One problem that is seen from figure 7.5, is that for large $H$ the depinning time $\tau$ becomes very small and the error in the measurement is more significant. This increases the uncertainty of this method.

To determine $\beta$, the result is fitted with a simple exponential function from which the decrease of $\ln(\tau)$ for increasing field is determined. By using equation 7.3 it is found that $\delta=18$ nm for a field of 7.3 mT and $\delta=10$ nm for a field of 7.8 nm. For all the different samples that we have measured, it was found that $8$ nm $< \delta < 22$ nm.

In chapter 4, we have measured that for the used Ga$^+$ doses $35$ nm $< \Delta < 70$ nm. The assumption that $\delta = \Delta$ is therefore not very well satisfied, and definitely not useful to investigate a more subtle trend, such as the $\Delta$-dependence of $\beta$.

Figure 7.6 shows the final result for $\beta$ as a function of the DW width $\Delta$. Every closed symbol is obtained from a single sample, by measuring $\beta$ for two different applied fields. The open symbol data point is obtained from the measurement with a reversed DW polarity (see figure 7.4(b)), ruling out the Oersted fields from our measurement. It can be seen that the open symbols overlap with the corresponding measurement that is performed on the same sample. We calculated $\beta$ in two ways, first by estimating that $\delta = \Delta$ and then by using the field dependence of the energy barrier. The first method is shown by the red triangles. The black circles are found by determining $\delta$ experimentally. These values are higher because it is found that $\delta < \Delta$. We will discuss the result in figure 7.6 in relation to available theories and experiments in the next section.

7.3 Discussion

Let us now discuss the results in figure 7.6 in more detail. First of all we see that there is a significant difference between both methods used to determine $\delta$. This is because the measured $\delta < \Delta$, which leads to a larger $\beta$. Furthermore, measuring $\delta$ experimentally does not seem to decrease the spread in the measured $\beta$ and no specific trend is visible (which we will come back to later). This can of course have a physical reason such as the possibility that random growth artifacts determine the strength of the non-adiabatic STT. A significant problem in measuring $\delta$ using the field dependence of the energy barrier, is however the assumption in the derivation of equation 7.3 that the depinning takes place in an activation volume $V$. This volume is based on the 1D-model in section 2.4.1 and therefore given by $V = \delta A$, where $A$ is the cross-sectional area of the Co layer. This activation
volume is sketched in figure 7.7(a). The real Pt/Co/Pt system is however far from one-dimensional and it is therefore not necessary that the activation volume is given by $\delta A$. In figure 7.7(b) it is shown that $V$ might as well be much smaller, depending on the local microscopic structure of the wire. This probably gives a large uncertainty in the measurements. This problem is also the case for the assumption that $\delta = \Delta$.

As already mentioned, no clear dependency of $\beta$ on $\Delta$ is observed in figure 7.6. One reason is that the sample-to-sample variations are large, while multiple measurements on a single sample were very reproducible. Looking for example at the two measurements for $\Delta = 41$ nm, a large difference between the observed $\beta$ is found, even when the change in $\delta$ is accounted for. The most likely explanation is that the DW width is also not constant. For the DW resistivity measurements we are confident that the DW resides in the low anisotropy region and the DW width is constant. Here, we however measure the transition of a DW from the low to the high anisotropy region and it is very likely that $\Delta$ is not constant when magnetic fields and currents are applied. Measuring the $\Delta$-dependence of $\beta$ by thermally activated DW depinning is therefore very difficult.
7.3 Discussion

Figure 7.7: The activation volume \( V \) for depinning of a DW can be different in the case of a 1-dimensional (a) or 2-dimensional (b) DW. The assumption that \( V = \delta A \) is therefore not always valid.

Despite these complications, it can be claimed that all the \( \beta \) are found in the same range and a strong and clear increase or decrease for \( \beta \) is not visible, let alone an oscillatory behaviour of \( \beta \) as predicted in [28]. We therefore calculated the average value of \( \beta \) for both approximations of \( \delta \) and the result is shown as the red and black dashed lines in figure 7.6. For the assumption that \( \delta = \Delta \) a value of \( \beta = 2.6 \pm 1.3 \) is found. With the other method is is found that \( \beta = 9.5 \pm 3.7 \). It is noted that we also used the value of \( \Delta \) to calculate \( \beta \), otherwise a slight linear decrease would have been visible in the data.

A final remark on figure 7.6 is related to the discussion of the influence of \( \text{Ga}^+ \) on the DW resistivity in section 6.3.2. Here, we argued in an extensive analysis that \( \text{Ga}^+ \) irradiation did not affect the spin polarization or the current distribution in such a way that it could explain the observed changes in the DW resistivity. It was therefore concluded that this was indeed caused by a changing DW width due to \( \text{Ga}^+ \) irradiation. The result in figure 7.6 confirms this conclusion, because large changes in the spin polarization or the current distribution would induce a similar decrease for \( \beta \) as measured for the DW resistivity. This effect is definitely not visible, which confirms that our conclusions in chapter 6 are valid.

7.3.1 DW resistance in relation to the non-adiabatic STT

We will now compare our values for \( \beta \) with other experimental results and theoretical models that exist. However, before we continue it is interesting to note that due to our result of chapter 6 that DW resistivity is described by the LZ model, both the contribution to the non-adiabatic STT from spin relaxation (\( \beta_{sr} \)) and from linear momentum transfer (\( \beta_{na} \)) predict that \( \beta \) is constant. As explained in section 2.2, Zhang and Li already claimed that \( \beta_{sr} = \alpha \), with \( \alpha \) the Gilbert damping constant, irrelevant of \( \Delta \). For \( \beta_{na} \) it was found in the model of Tatara and Kohno [26, 32] that

\[
\beta_{na} = \frac{e^2 n \rho_{DW} \Delta^2}{P \hbar \pi},
\]  
(7.4)
where \( n = 5.25 \cdot 10^{28} \text{m}^{-3} \) is the electron density for Co. We have shown in chapter 6 that the DW resistivity \( \rho_{DW} \sim 1/\Delta^2 \) in agreement with the LZ model. This means that \( \Delta \) cancels from equation 7.4 so that \( \beta_{na} \) is roughly constant and independent of the DW width. It is thus not possible to distinguish \( \beta_{sr} \) and \( \beta_{na} \) from each other, based on the \( \Delta \)-dependence. This possibility has already been mentioned by Thomas and Parkin [23], but it was never verified experimentally.

First, we compare our results with the spin relaxation theory for \( \beta_{sr} \). Since we have already excluded Oersted fields, Joule heating and adiabatic spin transfer torques (very low current densities), from our measurements the only remaining explanation is the presence of a non-adiabatic STT. For the spin-relaxation torque, it is estimated that \( \beta_{sr} \sim \alpha \), where \( \alpha \) is the Gilbert damping parameter. In our class of materials \( \alpha \approx 0.1 \), which is much smaller than the measured \( \beta \). The only remaining explanation is therefore linear momentum transfer, given by \( \beta_{na} \).

Interestingly, the strength of this torque depends on the resistivity that is measured in chapter 6. We therefore use the measured data for \( \rho_{DW} \) and use equation 7.4 to calculate \( \beta \) in figure 7.6. The result is shown as the blue data points in figure 7.6 and the blue line is a linear fit through the data. By using this method, it is found that \( \beta \sim 1.5 \), which is at least in the same order of magnitude. This suggests that the spin momentum transfer is the dominant mechanism for \( \beta \) in our Pt/Co/Pt. An important note is that spin momentum transfer from the model of Tatara and Kohno is predicted to be small for DWs with \( \Delta > \lambda_f \), where \( \lambda_f = 1 \text{Å} \) is the fermi wavelength [26].

Finally, we compare our results with other experimentally observed values for \( \beta \). One issue is that these reports do not take it into account that only the current through the magnetic layer contributes to the current-DW interaction. For these materials we therefore make a simple estimation, based on the layer thicknesses, of the current that flows through the magnetic layer and we calculate an adapted \( \beta \) value that can be compared with our results. An overview of experimental results for \( \beta \) is shown in table 7.1. In table 7.1, the first three lines are our results for the different methods that we have used.

An interesting result in table 7.1 is the measurement by Boulle [29], where \( \beta \) is measured for a very similar Pt\(_2\)/[Co\(_{0.6}\)Pt\(_{1.4}\)]\(_2\)/Co\(_{0.6}\)Pt\(_2\) multilayer, that has been deposited in the sputter facility at our group. It is shown that their result is in agreement with the values that we find. In [29] they also claim that linear momentum transfer seems to be the dominant mechanism for current-induced DW motion.

Furthermore, the results are also in agreement with the adapted \( \beta \) that are found in experiments on Pt/Co/AlO\(_x\) [86] and Pt\(_{2.8}\)/[Co\(_{0.5}\)Pt\(_{1.0}\)]\(_2\) [16]. Finally it is noted that for other materials, in general smaller \( \beta \) are found, for example \( \beta = 0.01 \) for permalloy [8], \( \beta = 0.06 \) for FePt and \( \beta = 0.022 \) for CoNi [18].
7.4 Outlook: Direction of current induced DW motion

Table 7.1: Overview of the experimentally found values for $\beta$. An adapted value for $\beta$ is calculated by taking into account that only part of the current contributes to the non-adiabatic STT.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\beta$</th>
<th>adapted $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt$<em>{4}$/Co$</em>{0.5}$/Pt$_{2}$, from $\delta \sim H$</td>
<td>-</td>
<td>9.5</td>
</tr>
<tr>
<td>Pt$<em>{4}$/Co$</em>{0.5}$/Pt$_{2}$, from $\delta = \Delta$</td>
<td>-</td>
<td>2.6</td>
</tr>
<tr>
<td>Pt$<em>{4}$/Co$</em>{0.5}$/Pt$<em>{2}$, from $\rho</em>{\text{DW}}$</td>
<td>-</td>
<td>1.5</td>
</tr>
<tr>
<td>Pt$<em>{2}$/[Co$</em>{0.6}$Pt$<em>{1.4}$]$</em>{2}$/Co$<em>{0.6}$Pt$</em>{2}$ [29]</td>
<td>0.35</td>
<td>1.7</td>
</tr>
<tr>
<td>Pt$<em>{3}$/Co$</em>{0.6}$/AlO$_{2}$ [86]</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Pt$<em>{2.8}$/[Co$</em>{0.5}$Pt$<em>{1.0}$]$</em>{2}$ [16]</td>
<td>1</td>
<td>5.8</td>
</tr>
<tr>
<td>Permalloy [8]</td>
<td>0.01</td>
<td>-</td>
</tr>
<tr>
<td>FePt [18]</td>
<td>0.06</td>
<td>-</td>
</tr>
<tr>
<td>[Co$<em>{0.15}$/Ni$</em>{0.6}$]$<em>{4}$/Co$</em>{0.3}$/Pd$_{0.7}$ [18]</td>
<td>0.022</td>
<td>0.1</td>
</tr>
</tbody>
</table>

To conclude, we have shown that $\beta$ seems to be independent of the DW width, although there is a lot of variation between different samples, probably related to the measurement technique. Despite these complications, our result is in agreement with other experiments that have observed large $\beta$ for Pt/Co based structures. These values suggest that the spin momentum transfer mechanism, which predicts realistic values according to the DW resistivity measurements from chapter 6, is probably the most relevant mechanism. This way also $\beta$ and DW resistivity are linked together and at least the correct order of magnitude is observed.

7.4 Outlook: Direction of current induced DW motion

In the final outlook section of this chapter we present a single measurement that is related to the discussion on the direction of current-induced DW motion. Results where the DW velocity is in the direction of the electron flow [16, 12, 18] or in the opposite direction [31, 30] have both been reported. Only very recently, it is shown in our group by Reinoud Lavrijsen [25] that the direction of motion can be tuned by changing the layer thicknesses in a Pt/Co/Pt stack. His experimental findings can, in its simplest form, be summarized as in figure 7.8. For a Pt$_{4}$/Co/Pt$_{2}$ stack it is found that the DW motion is in the direction of the current, or opposite to the electron flow. This is line with our results in figure 7.4. For a reversed stack of Pt$_{2}$/Co/Pt$_{4}$, the direction of DW motion switches its sign and is in the direction of the electron flow. This is the conventional result from simple momentum conservation considerations. Finally, it was found that for Pt$_{3}$/Co/Pt$_{3}$ the effect of current-induced DW motion was almost not visible.

In this section we will point out that our method of thermally assisted depinning to investigate the non-adiabatic spin transfer torque confirms the results in fig-
Figure 7.8: Summary of the results in [25] on the direction of current-induced DW motion for different Pt/Co/Pt stack. Here, $J$ gives the direction of the current and $v_{DW}$ is the direction of the DW motion due to current.

Figure 7.9 shows the measurement of a Pt$_2$/Co$_{0.5}$/Pt$_4$ stack that has been irradiated with $0.56 \text{Ga}^+ \text{ions/cm}^2$ to create domains. We have used exactly the same measurement technique as in the previous sections. In comparison with figure 7.4 it can be seen that the direction of the effect is indeed reversed. This sign change in the direction of current-induced DW motion can be caused by two effects, either the spin polarization $P$ changes from positive to negative or $\beta$ switches its sign.

An interesting experiment that we performed was therefore to measure both intrinsic DW resistivity and $\beta$ on a Pt$_2$/Co$_{0.5}$/Pt$_4$ sample. It was found that $\rho_{DW}/\rho_0 \approx 0.7$, similar to the Pt$_4$/Co$_{0.5}$/Pt$_2$ strips that were investigated in chapter 6. The uncertainty in this value is however large because the effect of Ga$^+$ irradiation is different for the changed stack and the DW width is therefore unknown. We are in this section only interested in the sign of $\rho_{DW}$, which is found to be positive. This is in agreement with the theory of Levy Zhang that finds the same resistance contribution for positive and negative spin polarization and a negative DW resistivity was therefore not expected. From this comparison no other conclusions are therefore possible.

The combination of DW resistivity measurements and thermally assisted depinning is however more interesting if the intermediate case of a Pt$_3$/Co$_{0.5}$/Pt$_3$ stack is considered. From figure 7.8 it is expected that the effect of current vanishes. If we are able to reproduce this result with thermally activated depinning, a measurement of the DW resistance is very worthwhile. We will now consider two situations that might occur:
7.4 Outlook: Direction of current induced DW motion

Figure 7.9: The transition time $\tau$ as a function of the current that flows through the magnetic Co layer $I_{Co}$ for a Pt$_{2}$/Co$_{0.5}$/Pt$_{4}$. A decrease of the depinning time in the direction of the electron flow is observed, which is opposite to the result in figure 7.4, where a Pt$_{4}$/Co$_{0.5}$/Pt$_{2}$ is measured.

1. We are able to also measure DW resistivity on the same sample, that is comparable in size to previous measurement in chapter 6. With this result, we can immediately state that $P \neq 0$, because a spin polarization is definitely required to have DW resistivity. In this case it can therefore be concluded that there is a sign change of $\beta$ at the Pt$_{3}$/Co$_{0.5}$/Pt$_{3}$ stack and here $\beta \approx 0$. This is a very powerful method, especially because a direct measurement of $P$ is not possible in Pt/Co/Pt. This idea is therefore proposed as a followup experiment, that might give more information on the origin of $\beta$.

2. If, however, the DW resistivity also vanishes, the situation is more difficult. It might be possible that $P = 0$, but other mechanisms that affect both the non-adiabatic STT and the DW resistivity can not be excluded directly. In this case it is therefore probably be insightful to use the $\Delta$-dependence of the DW resistivity to obtain $\rho_{T}/\rho_{L}$. This can be done for multiple stack geometries to study $\rho_{T}/\rho_{L}$ as a function of $\beta$. This will probably lead to a better understanding of the role of the spin polarization in these materials.

To conclude, we have pointed out in this section that recently remarkable results are obtained on the direction of current-induced DW motion for different Pt/Co/Pt stacks. In a first experiment we have shown that our measurements on Pt$_{4}$/Co$_{0.5}$/Pt$_{2}$ and Pt$_{2}$/Co$_{0.5}$/Pt$_{4}$ are in agreement with other experiments in our group. More information can be obtained by combining DW resistivity and
measurements. We therefore propose to measure also the Pt₃/Co₀.₅/Pt₃ stack, which can possibly exclude a sign change of the spin polarization as a possible explanation.
Chapter 8

Conclusions and outlook

The main goal of the experiments in this thesis is to investigate the link between DW resistivity and the non-adiabatic STT. For this reason, we first investigated the possibilities of FIB irradiation for the fabrication of perpendicularly magnetized Pt/Co/Pt samples. With the outcome of this analysis, we were able to investigate the DW width dependence of both the DW resistivity and the non-adiabatic STT. In the first part of this chapter we summarize the results of the experiments. Subsequently, we present an outlook on further research that might provide us with new insights in the physics of current-induced DW walls, allowing us to eventually be able to develop a commercially Magnetic Racetrack Memory (MRM) as introduced in section 1.2.

8.1 Conclusions

In chapter 4 and 5 we have shown that a FIB is a very powerful tool to locally modify the anisotropy of Pt/Co/Pt nanostrips. The results can be summarized in the following:

- We have for the first time systematically shown that FIB irradiation decreases the anisotropy of Pt/Co/Pt using the SW-model. Quantitative values have been obtained for the perpendicular anisotropy from which the DW width can be calculated. FIB can therefore be used to tune the DW width.

- FIB was proven to be a useful tool for the injection and pinning of DWs at engineered anisotropy boundaries. Varying the irradiation dose can be used to tune the height of the energy barrier that DWs experience. This way the pinning strength of the barrier can be tuned.
• It is verified that Pt/Co/Pt has intrinsically a higher anisotropy when thin Co layers are used. This provides us with another tool to tune the pinning strength, because larger anisotropy differences can be engineered in these materials.

• The width of the energy barrier can be tuned independently from its height by using defocused beams. It is shown widening the width of the barrier also decreases the pinning strength. Interestingly, for DW injection at low fields it is therefore advisory to make use of a defocused ion beam.

• Finally, we have reported for the first time on the use of a He$^+$ FIB to control the anisotropy of Pt/Co/Pt and we have shown that it has the notable advantages of better dose control and improved DW pinning over conventional Ga$^+$ FIB.

With these results, we are able to tune the full energy landscape that DWs experience in Pt/Co/Pt strips. This gives us full control on the injection, motion and pinning of DWs. Furthermore, the FIB can be used to vary the DW width in our devices.

In chapter 6 we investigated the intrinsic DW resistivity as a function of the DW width. For this we used a Kerr microscope set-up, where we could directly observe the magnetic reversal of a Pt/Co/Pt strip in real-time, while simultaneously the resistance of the wire was measured. A small increase in the resistivity could be measured, even for the appearance of single DWs. A $1/\Delta^2$ dependence of the DW resistivity $\rho_{DW}/\rho_0$ on the DW width $\Delta$ was observed. This allowed us to discriminate for the first time between the different models for DW resistivity and the results are shown to be in full agreement with the theory of Levy and Zhang. This result shows that spin mistracking due to non-adiabatic transport is the microscopic mechanism that is responsible for DW resistivity in our Pt/Co/Pt strips. The LZ model is furthermore successfully used to fit the experimental data and a reasonable value for the spin polarization $\rho_\uparrow/\rho_\downarrow = 8$ is found. Apart from the explanation of the origin of DW resistivity, which is already very interesting on its own, our results strongly suggest that non-adiabatic transport indeed exists for our narrow DWs. This is a promising prospect for the efficiency of current-induced DW motion.

To be able to directly compare the non-adiabatic STT, depicted by $\beta$, with the DW resistivity, we studied thermally activated depinning from engineered anisotropy barriers on the exact same set of samples. From the dependence of a characteristic depinning time on an applied current, it is shown that $\beta = 2.6\pm1.3$ or $\beta = 9.5\pm3.7$, depending on the way we estimate the width of the energy barrier $\delta$. Unfortunately the spread in $\beta$ for different samples is very large and the uncertainty in the used method to measure $\beta$ seems to be too large to be able to show a clear dependence of $\beta$ on the DW width. Furthermore, because of our results in chapter 6 for DW resistivity, $\beta$ is predicted to be constant and independent of the DW width for
both the mechanism of spin relaxation and for spin mistracking. The magnitude of $\beta$ is in agreement with other experiments on Pt/Co-like materials and in the same order of magnitude as could be calculated from the expected link to DW resistivity. This suggests that linear momentum transfer of scattered electrons is the dominant mechanism for the non-adiabatic STT and the non-adiabatic STT torque is linked to the DW resistivity. However, this dependency could not be verified directly from the dependence on the DW width and more research is therefore required to be conclusive on this point.

8.2 Outlook

In the final section of this thesis we present some recommendations for further research on especially DW resistivity and the non-adiabatic STT. As for the use of FIB irradiation to control DWs in Pt/Co/Pt, we have already shown that tuning of the energy landscape is fully accomplished. Using this knowledge, all kind of devices can be reproducibly fabricated to perform new and exciting DW experiments. In this case it might however be advantageous to switch fully to He$^+$ FIB irradiation, since this increases the dose control and resolution and more narrow energy barriers can be engineered. In this thesis only a first experiment on Pt$_4$/Co$_{0.6}$/Pt$_2$ is performed, which already showed promising results. These results can be improved in the same way as for Ga$^+$ irradiation by decreasing the Co thickness, which probably leads to even better control of the properties of DWs in Pt/Co/Pt.

A second interesting experiment is to systematically investigate the width of the energy barrier $\delta$ more carefully. In chapter 4 we have shown that by using a defocused beam the width of the energy barrier is increased, leading to weaker pinning of the DW. Furthermore, in chapter 7 we have used a method to determine $\delta$ from the field-dependence of the characteristic time for thermally assisted dependence. A combination of these techniques can be used to verify that the barrier indeed changes and might possibly give more information on the reliability of the method that is used in chapter 7 to determine $\delta$.

More interesting experiments are possible concerning the DW resistivity and non-adiabatic STT measurements. One very promising example has already been mentioned in the outlook of chapter 7, where the combination of DW resistivity and $\beta$ measurements is expected to be able to separate whether the polarization or the non-adiabatic STT induces the sign switch that is observed in the direction of current-induced DW motion. As explained, simple measurement on a Pt$_3$/Co$_{0.5}$/Pt$_3$ might already prove which of the two parameters is responsible for this effect.

Furthermore, we have argued in chapter 7 that the large uncertainty in our method to determine $\beta$ as a function of $\Delta$ is probably related to the fact that we describe
a process where the DW follows a transition from the low to the high anisotropy region. An alternative method where such a transition is not present, might therefore be able to give better results on the $\Delta$-dependence of $\beta$. One idea is to investigate $\beta$ by determining field-assisted current-induced DW velocity, similar to the measurements in [25]. To tune the DW width, in this case the whole wire can be irradiated so that the anisotropy is lowered but constant in the whole wire. A disadvantage of this measurement is however that much larger current densities are required and Joule heating makes the measurement very hard to perform.

A final idea to continue the work in this thesis is to study DW resistivity and $\beta$ in Pt/Co/AlO$_x$ samples. Recently, very high current-induced DW velocities have been observed in these kind of materials [12] and Pt/Co/AlO$_x$ seems to be a very suitable material for implementation in a MRM. It is therefore interesting to investigate how the DW resistance and $\beta$ in these materials are related to the results for Pt/Co/Pt. Also, from the DW width dependence of the DW resistivity, the spin polarization can again be determined to see if there are considerable differences as compared to the value we obtained in chapter 6.
Bibliography


Appendix A

Jones Formalism

The Faraday effect is a rotation of the polarization of light that is induced by transmission through a transparent specimen. The effect is similar to the Kerr rotation that is used as a measurement for the magnetization in the Kerr microscope, as described in section 3.3. It is therefore important to separate the Faraday effect from the Kerr effect in the measurements. In principle this is not very difficult since the Faraday effect is linear with the applied magnetic field $H$. However, in the Kerr microscope it can lead to remarkable behaviour of the intensity. An example is shown in figure A.1, where the hysteresis loop of a perpendicularly magnetized Pt/Co/Pt structure is shown. Interestingly, during the field sweep, both sides of the hysteresis loop cross in intensity.

These strange effects due to the linear Faraday rotation can be explained by considering the optical elements of the Kerr microscope within the Jones formalism. Here, the polarization of light is given by a Jones vector, which contains the two electric field components of the light that travels in the $z$-direction. The normalized Jones vector is then given as

$$
\begin{pmatrix}
E_x \\
E_y
\end{pmatrix}.
$$

(A.1)

With this definition linear polarized is given as $(1, 0)$ and right $(+)$ or left $(-)$ circularly polarized light is defined as $\left(\frac{1}{\sqrt{2}}(1, \pm i)\right)$. The intensity of the light is given as $|E|^2$.

In terms of the Jones vector, it is easy to introduce several active and passive optical components, that can be described as a matrix transformation of the Jones vector. For the simple case of a polarizer, the transformation matrix is given by
Figure A.1: Example of the strange magnetic behaviour of an hysteresis loop of perpendicularly magnetized Pt/Co/Pt. It can be seen that the lines cross near zero field.

\[ M_p = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}. \] (A.2)

Furthermore, we define the general rotation matrix. This can be used to model the Faraday effect by \( \theta \propto H \) and it can be used twice on another optical matrix transformation for incoming light at an angle \( \theta \). The rotation matrix is given as

\[ M_r(\theta) = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix}. \] (A.3)

The final Jones matrix that we define is reflection from a magnetic sample. This matrix contains the Kerr rotation, denoted as MO1 and the ellipticity that is given as MO2. Furthermore, p- and s-wave reflection are given by the reflection constants \( R_1 \) and \( R_2 \). The transition matrix is given as

\[ M_{\text{sample}} = \begin{pmatrix} 1 & \text{MO1 + iMO2} \\ -\text{MO1 + iMO2} & \text{R1 + iR2} \end{pmatrix}. \] (A.4)

Using this formalism we are able to explain the remarkable features of figure A.1, by considering all the optical components of our system. These are, following the ray path of the light beam, a polarizer, the objective lens where a Faraday rotation
occurs, the reflection from the magnetic sample, another Faraday effect from the objective lens and finally an analyzer (essentially a polarizer that is 90° rotated to observe only the magnetic contrast). It is now assumed that the rotation due to the Faraday effect is linear with the applied field $H$. Furthermore, for the reflection of the sample it is assumed that $R_1$ and $R_2$ are approximately 1 and the Kerr rotation $MO_1 = \pm 0.0001$, and the sign describes the direction of the rotation for either up or down magnetization. The ellipticity constant $MO_2 = 0.0000001$ is almost negligible. With these values the following expression for the resulting electric field can be used to qualitatively explain figure A.1:

$$E_f = M_r(\theta)[M_r(90^\circ + \alpha) M_p M_r(-90^\circ - \alpha)] M_r(-H) M_{sample} M_r(H) M_p E_i$$

(A.5)

We now introduce the parameter $\alpha$ that gives the additional angle between the analyzer and the polarizer. Looking at the simulations in figure A.2, it can be seen that for $\alpha = 0$, so that the analyzer and polarizer are 90° rotated, the intensity as a function of field has a quadratic character. Furthermore, the red and blue lines show the effect for an up and down magnetization and it can be seen that they indeed cross near zero field. This result is in qualitative agreement with the measurement in figure A.1.

Figure A.2: The intensity of the reflected light beam as a function of field for various $\alpha$. It is shown that for $\alpha = 0$ the Faraday effect becomes quadratic with respect to field.

\(^1\)Calculations have been performed in Maple, but due to an expired license that has not been renewed by the university, only these kind of images were available.
By rotating the analyzer with respect to the polarizer over a small additional angle $\alpha$, it is shown that the quadratic terms become smaller and the intensity as a function of $H$ due to the faraday effect becomes linear again. However, for increasing $\alpha$ the signal to noise ratio of the Kerr effect also become smaller. It is therefore advisory to rotate $\alpha$ only slightly to get rid of the quadratic Faraday effect. Experimentally it is found that $\alpha \approx 10^\circ$ is optimal.
Appendix B

Fuchs-Sondheimer model

In this Appendix we shortly describe the Fuchs-Sondheimer model that has been used in chapter 6 to determine the amount of current \( p \) that flows through the Co layer in a Pt/Co/Pt stack. In this model, the current density in the Pt/Co/Pt stack is calculated as a function of the vertical position in the stack. The model is based on the semi-classical Fuchs-Sondheimer theory [87], that describes the mean free path of electrons in a model. In our case, the model uses the mean free path from bulk material and then considers the enhanced interface contributions to electron scattering to determine the increased electron scattering in the Pt and Co layers. Because the Co layer is magnetic, the interface transmission is also spin-dependent, so that the model can be used to find the spin polarized and the total current in the Co layer. In this section we will explain the input parameters of the model. For a more detailed description of the model, the reader is referred to [58].

The most basic parameter in the model is the mean free paths of electrons in both Pt and Co. Furthermore, for Co these are spin-dependent. In [58] these are determined by using that \( \rho l \) is a material parameter that is well-known from the literature. Here \( \rho \) is the resistivity of one of the layers and \( l \) is the mean free path. For the Pt layers \( l \) can directly be calculated if \( \rho_{pt} \) is measured. For the Co layer these values are spin dependent and another input parameter is required. This is the bulk spin asymmetry parameter \( \alpha = \rho_\downarrow / \rho_\uparrow \) that is a measure for the spin polarization in bulk Co. This value can be used to measure \( \rho_{Co\uparrow} \), \( \rho_{Co\downarrow} \), \( l_{Co\uparrow} \) and \( l_{Co\downarrow} \) from the overall cobalt resistivity \( \rho_{Co} \) and mean free path \( l_{Co} \):

\[
\rho_{Co\uparrow} = \rho_{Co} \frac{1 + \alpha}{\alpha}, \quad (B.1)
\]

\[
\rho_{Co\downarrow} = \rho_{Co} (1 + \alpha), \quad (B.2)
\]
Apart from the mean free paths of the electrons in the different layers, we need to describe the effect of the interfaces. For the Pt/Co interface, the effect is determined by the spin-dependent interface transmission coefficients $T_{\uparrow}$ and $T_{\downarrow}$. These coefficients give the probability $T$ that an electron at the interface is transmitted without any change in its velocity. Otherwise, the electron is randomly scattered, loosing all its memory. In [58], $T_{\uparrow}$ and $T_{\downarrow}$ are determined from the sheet conductance of a lightly He$^+$ irradiated Pt/Co/Pt stack and it is shown that $T_{\uparrow} = 0.22$ and $T_{\downarrow} = 0.1$. The fact that both transmission coefficients are low shows that the Co layer is more or less isolated from the Pt layers. The amount of current through the Co layer is therefore much smaller than expected from a simple parallel resistor network approximation. Finally it is noted that $T_{\uparrow}$ and $T_{\downarrow}$ can be combined in a single parameter $N$, that is the spin asymmetry coefficient. $N$ is given by

$$N = \frac{1 - T_{\downarrow}}{1 - T_{\uparrow}}$$

and in [58] it is found that $N = 1.15$.

These are the most important input parameters in the Fuchs-Sondheimer. Other parameters that can be included are the surface specularity parameters $p$ and $q$ that describe reflection at the top and bottom interfaces with the Pt layers. These are however negligible for Pt/Co/Pt structures, because the Pt/Co interfaces are much more important. In the model it is chosen that $p = q = 0.42$. Apart from these, the only remaining parameters are the thicknesses of each layer, that determine how important the interfaces are. With these parameters the Fuchs-Sondheimer model calculates the adjusted mean free paths as a function of the vertical position in the Pt/Co/Pt stack and from this the current distribution is determined for both spin current channels.