Domain wall motion in Permalloy nanowires

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Abstract
Together with numerical computations, we have characterized the transport properties of devices with notched Permalloy nanowires. The driving mechanism of current-induced domain wall motion has been the subject of much debate. Permalloy is, with its easy axis along the nanowire, a good candidate to study the fundamental properties of a current-induced domain wall velocity, as its magnetic properties are well defined. A strong temperature dependence of the anisotropic magnetoresistance has been found, resulting in a decrease of the (de)pinning fields when the temperature increases. We believe that temperature is an important factor to take into account in studying the domain wall dynamics, and can even be helpful in identifying the relevant driving mechanism in current-induced domain wall motion. Although a start is made on the experimental realisation of domain wall velocity experiments in the PPMS (Physical Property Measurement System), much effort is still necessary in order to conduct actual velocity measurements.
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Chapter 1

Introduction

Conventionally, reading and writing of information in magnetic memory devices have been done by applying magnetic fields, that are able to sense or switch the magnetization locally. These applied fields are generated in electric circuits. The magnitude of the fields that are generated is proportional to the applied current going through the circuit. This proportionality becomes problematic when going to smaller scales, as the current densities may increase tremendously. The circumvention of these high current densities, therefore, plays a key role in the quest for smaller and more efficient memory devices.

In 1978 already, Luc Berger was able to show that instead of relying on Ampère’s law to generate a field which acts on the magnetization, a current itself is able to switch the magnetization locally in a magnetic wire. He showed that the speed of the domain wall, separating two homogeneous magnetic domains, was not proportional to the current itself, but to the current density, making it a more scalable mechanism and more attractive for today’s technology [1, 2]. Moreover, this meant that not only one, but also multiple magnetic domain walls could be moved along a single wire, by the same current [2, 3].

In recent years, the technology to built nanoscale devices has been developed further, making this type of research more accessible and interesting with respect to applications, such as the Racetrack memory proposed by Stuart Parkin in 2008 [4]. In Racetrack memory, multiple domains exist along a single wire creating a dense memory device in three dimensions. Electrical pulses are used to move the domains along the wire, in order to change or determine the magnetization locally.

Current research has been focused on the understanding of the physical mechanism behind the dynamics of the domain walls. After thirty years, the field has not reached a consensus yet on what mechanism is the dominating driving force behind the domain wall velocity. Especially, the damping of the dynamics is still under debate. Although a phenomenological description, in the form of the Landau-Lifshitz-Ginzburg equation exists, a general quantitative description is still lacking. Both experimental and theoretical research is under development in order to clarify the mechanism and to explore the dynamics even further.
1.1 Permalloy nanowires

In the field of current-induced domain wall motion, a lot of experimental and numerical research has been conducted on Permalloy nanowires (Ni$_{80}$Fe$_{20}$). As a soft magnet, Permalloy has a low coercive field, which means that it is highly sensitive to external fields and that the magnetization can be switched easily. This is illustrated by the narrow hysteresis loop, in figure 1.1a. Figure 1.1a also shows a large saturation magnetization of: $M_s = 7.15 \times 10^5$ Am$^{-1}$, pointing at a high permeability[5]. From figure 1.1b, it can be observed that the saturation magnetization only changes less than one order of magnitude in the range of 10 K to 300 K, so the saturation magnetization is often set to a constant value in the simulations.

![Magnetic Hysteresis](image1.png)  ![Temperature dependence of $M_s$](image2.png)

**Figure 1.1:** SQUID characterization of Permalloy sample 35 nm Permalloy thin film sputtered on 5x5 mm$^2$ SiO$_2$/Si wafer in UHV magnetron sputtering machine. Offset in figure 1.1a with respect to zero field is due to the remnant field of the magnet in the field sweep mode.

Moreover, the magnetostriction in Permalloy is almost zero, which means that the shape of the material does not change, or only very little, under an applied strain. The dimensions of the nanowire are, therefore, well-defined under varying field. When Permalloy is confined into the dimensions of a nanowire ($w = 300$ nm, thickness = 20-40 nm), the magnetostatic energy is so low, that the ground magnetic configuration is confined into a single magnetic domain, resulting in a well-defined ground state. A change from this ground state into a two-domain configuration, can be detected in anisotropic magnetoresistance measurements. This effect is relatively large, a few percent at room temperature, for Permalloy nanowires [6], making it a reliable method to detect domain walls.

Thus, because of these convenient and well-defined properties, Permalloy nanowires are suitable objects in manipulating magnetic domains.
1.2 Spin-polarized currents

When an electrical current flows through a ferromagnet, the conduction electrons have the property to align their spins with the magnetization of the local magnetic moments in the material. This interaction is caused by the intratomic exchange field [1]. The efficiency of this interaction is characterized by means of the spin polarization, which can be defined as:

\[ P = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} \] (1.1)

where \( N_{up} \) and \( N_{down} \) represent the number of up and down oriented spins respectively. For Permalloy, this efficiency is estimated between 0.4 and 0.7 [7].

1.3 Anisotropic Magnetoresistance

Magnetoresistance is the change of the resistance under an effective field. The anisotropic magnetoresistance effect (AMR), that can be utilized to detect the presence of domain walls, depends on the angle between the spin-polarized current and the direction of the local magnetization. It follows the phenomenological relation [8]:

\[ \rho \sim \rho_0 + \Delta \rho_{ani} \langle \cos^2 \phi \rangle \] (1.2)

\( \phi \) here is the angle between the direction of the spin-polarized current and the local magnetic moment. \( \rho_0 \) constitutes the field-independent part and \( \Delta \rho_{ani} \) measures the strength of the anisotropy in the resistivity. In 3d transition metals and alloys (which is the case of Permalloy), its origin lies in the spin-orbit coupling between the 4s conduction electrons and the 3d localized electrons in the ferromagnet. The 3d orbitals are affected by the local magnetization, thereby creating a larger effective cross section, leading to more spin-dependent scattering for parallel magnetization and current [9]. A local magnetization perpendicular to the current will thus result in a smaller effective cross section and therefore a drop in the resistance. In a domain wall, the magnetization is rotated from one domain to the other, associated with a component perpendicular to the spin-polarized current, which can be distinguished by a lower resistance.

![Figure 1.2: AMR effect as a function of \( \phi \)](image)
In a recent research from M. Hayashi [10], the AMR signal is used to determine domain wall velocities in field-driven domain wall motion. Analogue to this experiment, a current can be used to drive the motion. In figure 1.3, one of the advantages of current-induced over field-induced domain wall motion is illustrated: the ability to move multiple domains along the wire. As the length of the nanowire is generally on the order of a few micrometers, nanosecond resolution is necessary in order to allow time-resolved experiments. This can be achieved by sending pulses of nanosecond width, with a voltage pulse generator. The pulse generator can trigger an oscilloscope to probe the specific (time) region of interest. The oscilloscope probes the voltage with respect to the ground. In the experiment of M. Hayashi, the nanowires had a resistance of typically $\sim 400 \, \Omega$. When a domain wall is inserted in this region, this resistance decreases due to the AMR effect. The voltage drop that occurs along the wire, will be less than the one corresponding to the single-domain wire. Therefore, the pulse shape gains in amplitude. When the domain wall has travelled away from the probed region, the pulse shape returns to its original amplitude. In this way, the entering and the leaving time of the domain wall can be determined and when the length of the probed region is known, a velocity can be deduced. M. Hayashi was able to show that domain wall velocities can reach velocities of 150 m/s [10].

![Figure 1.3: Domain wall movement driven by field or current.](image)

In current-driven domain wall motion (J), the domain walls are driven in the direction of the electron flow (opposite to the direction of the current), hereby moving multiple domain walls along the wire. In field-driven domain wall motion, however, only a single domain wall can be moved. In case of multiple domains, the domain with opposite magnetization w.r.t. to the driving field, will be annihilated.

### 1.4 Approach

In this thesis, we will start by explaining the theory behind current-induced domain wall motion on the basis of the phenomenological description given by Landau-Lifshitz and Gilbert as well as two additional spin-torque terms. We will discuss the physical origin of the two spin-torque terms, and discuss the part of the theory that is still being investigated. Following the theory section, we will explain the numerical methods we used to solve the LLG equation in the presence of an applied field or a spin-polarized current, together with the corresponding results. In the sample fabrication and characterization chapter, we will explain the methods we used in order to produce nanoscale devices on which we did transport measurements, the results of which are shown in the next chapter. In this chapter, Joule heating measurements are discussed. The AMR signal is obtained as well as the temperature dependence of the resistance and of the AMR signal. Moreover, the AMR signal is used to pin a domain wall. We will discuss our progress on the experimental set-up for the current-induced domain wall motion, and give a proposal on what to improve in the set-up and sample design for future domain wall velocity experiments. In the final chapter, we will conclude our results.
Chapter 2

Theory

In this chapter, we will first discuss the static picture of domain formation, and the main responsible energy contributions in Permalloy. Secondly, we will discuss the dynamics of the magnetization in the presence of an effective field in terms of the phenomenological description introduced by Landau, Lifshitz and Gilbert. We will introduce the spin-torque terms, that are used to explain the influence of a spin-polarized current.

2.1 Energy contributions

The formation of magnetic domains arises due to a balance between different energy contributions. The main contributors to the total energy, $E_{tot}$, in Permalloy are the magnetostatic and the exchange energy, which favour contradicting magnetic configurations [11]:

$$E_{tot} \approx E_{Exch} + E_{MS} + ... + E_{Zeeman}$$ (2.1)

Namely, the exchange energy describes the short range interaction between neighbouring spins. For a ferromagnet, such as Permalloy, the total magnetic moment has a non zero value at zero field. This net magnetization arises due to the preference for parallel alignment of neighbouring spins, which is described by a positive exchange constant $A$:

$$E_{Exch} \propto - \sum_{i,j} A \vec{S}_i \cdot \vec{S}_j$$ (2.2)

$\vec{S}_i$ and $\vec{S}_j$ represent the neighbouring spins.

The strength of the exchange constant determines the length, $l_{ex}$, over which parallel alignment is relevant:

$$l_{ex} = \sqrt{\frac{A}{\mu_0 M_s^2}}$$ (2.3)

For Permalloy, with saturation magnetization $M_s = 8 \cdot 10^5$ A/m and exchange constant $A = 1.3 \cdot 10^{-11}$ J/m [12], the exchange length is 4 - 5 nm.
On a larger scale, however, a single domain structure produces a stray field, \( H_d \). This stray field is generated due to the divergence of the magnetization, \( \vec{M} \), and are illustrated by the arrows in figure 2.1. The corresponding energy originates from the classical dipole-dipole interactions. As can be seen from figure 2.1, the magnetostatic energy can be reduced by the formation of smaller magnetic domains, that reduce the total magnetic moment of the system \[13\]. The magnetostatic energy can be given by:

\[
E_{\text{magnetostatic}} = -\frac{1}{2} \int_{\text{sample}} \vec{H}_d \cdot \vec{M} dV
\] (2.4)

In Permalloy nanowires, that are investigated in this project, a minimization of the magnetostatic energy and the exchange energy induces a shape anisotropy for which the ground state magnetic configuration is a homogeneous one-domain configuration pointing along the wire axis.

In some crystalline materials, the magnetization prefers to align along a certain crystalline axis. The preference for such an easy axis is accounted for by adding a crystalline anisotropy term to \( E_{\text{tot}} \). However, as Permalloy has a polycrystalline structure, this term is often neglected for Permalloy.

Finally, in the presence of an external magnetic field, \( \vec{H}_{\text{ext}} \), also the Zeeman energy has to be included in \( E_{\text{tot}} \). The Zeeman energy is given by:

\[
E_{\text{Zeeman}} = \mu_0 \int \vec{H}_{\text{ext}} \cdot \vec{M} dV
\] (2.5)

A minimization of the Zeeman energy corresponds to an alignment of the magnetic moments with the direction of the external magnetic field.

**Figure 2.1: Domain configurations and resulting stray fields.** For a relatively large, or bulk, single domain structure the magnetostatic energy is relatively large. When domains start to form, the magnetostatic energy corresponding to the stray fields decrease. For the fourth configuration, the total magnetic moment is zero, and thus the magnetostatic energy is zero as well.
The total energy can be described as an effective field (using variational methods), acting on the local magnetization [14]:

$$\vec{H}_{\text{eff}} = -\frac{1}{\mu_0} \frac{\partial E_{\text{tot}}}{\partial \vec{M}}$$  (2.6)

### 2.2 Domain wall types

The way the magnetization is rotated from one domain to the other depends on the dimensions of the system. As the width of domain walls is much larger than the electron wavelength, a wall represents a continuous rotation of the local magnetization [1]. Conventionally, domain walls are divided into two types of walls: Néel walls and Bloch walls. In bulk materials, the domain walls usually are of the latter type. For Bloch walls, the magnetization rotates out of the plane of the domain wall. For thin films, Néel walls are more likely. In Néel walls, the magnetization rotates in the plane of the domain wall.

![Transverse and Vortex Domain Walls](image)

**Figure 2.2:** Difference between transverse and vortex domain walls. Figure adopted from Beach et al. [7]

In thin Permalloy nanowires, Néel-type domain walls are expected. Numerical simulations and experiments have shown, however, that additional configurations exist such as a transverse, Néel-type, wall and a vortex domain wall (see figure 2.2) [7].

![Width-thickness Relation](image)

**Figure 2.3:** Width-thickness relation dividing transverse and vortex domain walls. For a 35 nm thick and 300 nm wide nanowire, vortex walls are expected. Figure adopted from Beach et al. [7]
Whether a vortex or a transverse domain wall exists in the structure strongly depends on the dimensions of the system. For a nanowire, a quadratic relation exists between the width, \( w \), and the thickness, \( t \), of the system, dividing transverse walls from vortex walls (see figure 2.3) [15]:

\[
w \cdot t^2 \propto 60 l_{ex}
\] (2.7)

In figure 2.2, the result of two different simulations is shown. For even wider wires, structures such as double and triple vortex walls can arise [16].

### 2.3 Magnetization dynamics

In a ferromagnet, the magnetic configuration, and its dynamics can be phenomenologically described by the Landau-Lifshitz-Gilbert (LLG) differential equation. It describes the evolution of the magnetization \( \vec{M} \) in the presence of an effective field \( \vec{H}_{eff} \):

\[
\frac{\partial \vec{M}}{\partial t} = -\gamma \vec{M} \times \vec{H}_{eff} + \frac{\alpha}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial t}
\] (2.8)

\( \gamma \) here is the Landau-Lifshitz gyromagnetic ratio (\( \gamma = 2.211 \cdot 10^5 \text{ mA}^{-1}\text{s}^{-1} \) [17]). The damping constant \( \alpha \) is to be determined in experiments, but is often set to 0.5 in numerical simulations [17], and \( M_s \) is the saturation magnetization of the material.

![Figure 2.4: The effective field induces two different torques.](image)

The effective field induces a torque due to which the magnetization will start precessing at a frequency of \( \omega = \gamma |\vec{H}_{eff}| \). The effect of the torques on a single magnetic element is illustrated in figure 2.4. The first term describes the precession of the magnetization around the effective field. The second term describes the damping and results in the alignment of the magnetization with the effective field.
2.3.1 Field-driven domain wall motion

The LLG equation can be applied to a domain wall configuration. The effect of an applied field on a domain wall is shown in figure 2.5. In figure 2.5a, an analytic one-dimensional solution to equation 2.8 is plotted as a function the applied field \( H \) for a \( 500 \times 20 \text{ nm}^2 \) Permalloy nanowire and damping constant \( \alpha = 0.2 \). Figure 2.5b shows the experimentally measured domain wall velocity for a \( 490 \times 20 \text{ nm}^2 \) Permalloy nanowire. In figure 2.5c, the velocity deduced from micromagnetic simulations for a \( 200 \times 20 \text{ nm}^2 \) Permalloy nanowire is plotted. One specific resemblance in the shape of the curves is the discontinuity in the velocity at an applied magnetic field \( H_W \), called the Walker Breakdown field. It illustrates the breakdown of the ability of the wall to sustain a steady-state motion (static domain wall plane) to a precessing motion, in which the domain wall plane is precessing, due to an effective field. The corresponding velocity is the Walker Breakdown velocity, \( V_W \) [7].

![Figure 2.5: Field-driven domain wall velocity in Permalloy nanowire. Figure adopted from Beach et al. [7].](image)

What is most prominent, is that the Walker Breakdown fields differ significantly between the analytical solution and the experimental measurements and numerical simulations. This change is attributed to the change of the structure of the domain wall. Starting from a transverse wall, a vortex wall is nucleated above a certain field threshold that indirectly slows down the motion of the domain wall [7].

2.4 Spin-transfer torque

In order to account for the presence of a spin-polarized current, two extra terms are added to the existing LLG equation: an adiabatic term \(-u \frac{\partial \vec{M}}{\partial x}\) and a non-adiabatic term \(\beta \frac{u \vec{M}}{M_s} \times \frac{\partial \vec{M}}{\partial x}\). \(\beta\) is the spin-transfer torque (STT) non-adiabatic parameter [18]. \(u\) in these expressions has the dimension of velocity and can be expressed in terms of the current density \(J\):

\[
u = \frac{g \mu_B P}{2eM_s} J = 7 \times 10^{-11} \text{ m}^3\text{C}^{-1} \times PJ
\]
\(\text{g is here the Landé factor, } \mu_B \text{ the Bohr magneton, } e \text{ the electron charge and } P \text{ is the spin polarization [18].}

Together, with the original LLG equation, the phenomenological description of current-induced domain wall motion is:

\[
\frac{\partial \vec{M}}{\partial t} = \gamma \vec{H}_{\text{eff}} \times \vec{M} + \frac{\alpha}{M_s} \vec{M} \times \frac{\partial \vec{M}}{\partial t} - u \frac{\partial \vec{M}}{\partial x} + \beta u M_s \vec{M} \times \frac{\partial \vec{M}}{\partial x}
\]

(2.10)

2.4.1 Adiabatic spin-transfer

The influence of current on the domain wall motion can be intuitively explained in terms of the conservation of spin angular momentum. The conduction electrons in a spin-polarized material have the property to align their spins with the magnetization of their environment, due to the interaction with the intratomic (Hund) exchange field [1]. When such an electron traverses a domain wall, it will feel a change in magnetization, and therefore it realigns itself with the magnetization of the new domain. This means that the total angular momentum of the system has changed from its initial value. To compensate for this change, the size of the first domain must grow, which is equivalent to a motion of the domain wall in the direction of the electron flow.

![Figure 2.6: Spin-transfer torque. Schematic illustration of angular momentum conservation in the transfer of spin angular momentum to the domain wall, resulting in a movement of the domain wall.](image)

The mechanism behind this type of transfer is the s-d exchange interaction of the 4s spins of the conduction electrons (\(\vec{s}\)) with the 3d localized spins in the domain wall (\(\vec{S} \propto \vec{M}\)) [19]:

\[
H_{\text{ex}} = -J_{\text{ex}} \vec{s} \cdot \vec{S}
\]

(2.11)

Here \(J_{\text{ex}}\) is the exchange coupling strength. This interaction generates a torque that is responsible for the movement of the domain wall [2, 18]:

\[
\vec{T} = \frac{\partial \vec{M}}{\partial t} = \vec{M} \times \vec{s}
\]

(2.12)

The electron spin will start precessing around the local magnetization. The conduction electron spin can thus not only be expressed in terms of the polarization of the injected spin current \(\vec{p}\), but also in terms of the local magnetization \(\vec{M}\) [18]:

\[
\vec{T}_{\text{adiabatic}} = \vec{M} \times \vec{s} = \vec{M} \times (\vec{M} \times \vec{p}) = -u \frac{\partial \vec{M}}{\partial x}
\]

(2.13)
For this mechanism to be relevant, the lifetime \( \tau_{\text{life}} \) of the conduction electrons’ spins must be large enough, i.e. that it is larger than its precession period \( P_{\text{precession}} \) around the domain wall spin.

### 2.4.2 Non-adiabatic spin-transfer

For short lifetimes, the conduction electron’s spin will not be dependent on the local magnetization, and thus will be directly proportional to the spin polarization \( \tau_{\text{life}} < P_{\text{precession}} \). Consequently, the non-adiabatic torque can be described as [18]:

\[
\vec{T}_{\text{non-adiabatic}} = \vec{M} \times \vec{s} = \vec{M} \times \vec{p} = \frac{\beta u M_s}{M} \vec{M} \times \frac{\partial M}{\partial x} \quad (2.14)
\]

The interaction mechanism behind this phenomenological torque is still being debated. Originally, Berger ascribed it to the resulting force gradient from the s-d interaction, that is the origin of the adiabatic spin-transfer [2, 7]. In 2004, Tatara described it by means of linear momentum transfer [20] from fast electrons reflecting with the domain wall. The inhomogeneity of the domain wall results in scattering of the electrons by a force that is directly proportional to the reflection coefficient and the current density. In thin films, in which the transition inside the domain wall is relatively sharp, this mechanism should dominate over the adiabatic spin-transfer mechanism. In 2007, Stiles et al. argue that in equation 2.10, not the common Gilbert-type damping should be used, but that the original damping term from the LL equation is sufficient [21]. Their arguments, however, were soon after the publication, debated by Smith in 2008 [14]. By means of energy considerations, he argued that the Gilbert term, which is purely dissipative, is the correct damping mechanism, rather than the LL type counterpart in describing the spin-transfer torque.

Comparing the two spin-transfer torque terms (due to the current) with the original torques in the LLG (due to the magnetic field), the adiabatic spin-transfer torque is often referred to as the STT damping term, as it contributes (when \( u > 0 \)) or competes (when \( u < 0 \)) with the Gilbert damping term [18]. Similarly, the non-adiabatic spin-transfer term is often referred to as the field-like torque, where the current density \( J \) plays a similar role as the effective field \( \vec{H}_{\text{eff}} \).

### 2.4.3 Current-driven domain wall motion

Analytically, equation 2.10 has only been solved in one dimension [22]. In figure 2.7, the results of the velocities, for different values of \( \beta \) and \( \alpha = 0.02 \), are shown. Constant wall width is assumed. Some of the curves, show a similar discontinuity as is observed in figure 2.5 for field-driven domain wall motion. Similar to the field-driven case, the corresponding current density is called the Walker Breakdown threshold current density, separating steady-state motion from precessional motion. For \( \beta = \alpha = 0.2 \), no transition is observed [23]. Moreover, a threshold current density is observed only for \( \beta = 0 \).
One of the reasons, for which the non-adiabatic term has got so much attention, is because of this strong dependence of the velocity curves on the value of $\beta$. In figure 2.8, one of the first direct observations of current-induced domain wall motion is plotted [24]. In this research, a domain wall is introduced in the curvature of an L-shaped Permalloy nanowire and then moved by current pulses of $1 \mu$s width and a current density of $1.2 \times 10^{12}$ A/m$^2$. In figure 2.8a, it can be seen that DWs are moved opposite to the direction of the current. The authors observed unpredictable behaviour of the velocity as a function of current density, which they attributed to additional pinning sites along the nanowire. For this reason, they could only determine a reliable average DW velocity for five different current densities.
Micromagnetic simulations

In large systems with many variables, a calculation to predict or compare the outcomes of an experiment is often not available. When an analytic description is lacking, numerical methods can be helpful. If the energy contributions are known, the equations of motion of a system can, however, be reasonably computed in numerical simulations. Moreover, simulations can not only predict physical situations reliably, but computing how a system evolves can also be a very intuitive way to start understanding the important physical processes or parameters of a system.

In order to simulate the dynamics of the Permalloy system, we made use of the existing Object Oriented MicroMagnetic Framework (OOMMF, version 1.2b1) [17]. OOMMF uses finite difference methods in order to calculate the energetically favoured magnetic configuration of a single magnetic body. It takes into account energy contributions of the interactions with the bodies’ nearest neighbours, in terms of the effective field, as described by the LLG equation (see equation 2.10).

In order to solve the LLG equation, one can specify in the OOMMF software, different types of solving methods. We have chosen the standard Runge-Kutta implementation OOMMF offers: Ox_sRungeKuttaEvolve. The Runge-Kutta solution to a differential equation describes the \( i + 1 \) configuration of a single cell in terms of its previous configuration \( i \). The Runge-Kutta method is an initial value problem, so the 0th configuration always has to be known. For our simulations, we start by setting the initial configuration to be saturated along the wire (easy) axis. In later simulations, we will also show the possibility of using a two-domain state as initial magnetization.

The magnetic bodies are described as single cells with variable size in each dimension. The Permalloy system is then specified by setting the total width, depth and thickness. A shape can be added by using a two dimensional mask. An example of the used masks is given in figure 3.1. The total system is then divided into a number of cells that fill up the volume. The number of cells, naturally, defines the number of computations which are necessary to be run. Therefore, a large cell size is preferred. However, for the cell to be still considered as a single
Micromagnetic simulations

magnetic body, one should choose a cell size that is less (or on the order of) the exchange length, which is approximately 5 nm for Permalloy [7].

Figure 3.1: Simulation mask of a 10 \( \mu \text{m} \) long and 300 nm wide nanowire. The notch in the center of the wire has a depth of 80%. The size of the contact pad is 1 \( \mu \text{m} \times 1 \mu \text{m} \), which we reduced greatly, compared to actual devices, in order to reduce the simulation time.

We use a saturation magnetization of \( M_s = 800 \cdot 10^3 \text{Am}^{-1} \), similar to previous research on Permalloy nanowires [6]. The constant \( \alpha \) was set to 0.5, which is a bit high for a physical system but, in order to converge to a solution in a reasonable time, is necessary. As a criterion for the computation to converge, we set \( \frac{dm}{dt} \leq 0.1 \).

Finally, the presence of a current is taken into account by an extension to the Runge-Kutta evolver: spintevolve [25]. This method includes the spin-torque terms discussed in the previous chapter. Instead of the current density \( J \), we set directly the value \( u \) (in units of m/s) as defined in equation 2.9 and \( \beta \) is set to 0.04.

3.1 System characterization: field sweep

We start by characterizing the system by means of a magnetic field sweep, the results of which are summarized in figure 3.2. The initial magnetization is set to be saturated in the negative field (pointing to the left) direction. The magnetic field starts at -100 mT and is then reduced to zero field. Especially in the contact pad, but also at the right end of the wire, a change from the saturated state is already observed at 0 mT. Although the overall magnetization is still negative (blue), the magnetostatic energy is already starting to dominate in the contact pad, hereby trying to form domains.

Figure 3.2: Results of a field sweep for a 10 \( \mu \text{m} \)-long and 300 nm wide nanowire, with a 1 \( \mu \text{m} \times 1 \mu \text{m} \) contact pad. The field is swept from negative direction to positive and vice versa in steps of 2 mT. In both directions, domain walls are created at a pinning field magnitude of 16 mT.

The points for which the magnetostatic energy favours a positive magnetization are flipped first, as an increasing positive field (pointing to the right) is applied. For small positive field, a domain wall is therefore first created at the contact pad. By increasing the field even more, the region of positive magnetization is extended into the wire until it has reached the notch.
at +16 mT. From figure 3.2, we see that at this point, the increase of the positive region is inhibited by the shape of the notch. The notch apparently leads to a potential that pins the domain wall for a certain field range, as can be seen from figure 3.3. At some point, however, the field has reached a certain threshold for the domain wall to overcome this potential and finally the entire wire is magnetized positively (red).

The field sweep is repeated in the opposite direction and a symmetric behavior around 0 mT is observed, with a pinned domain wall at -16 mT, as can be seen from figure 3.2.

Sweeping from negative to positive field in this way, creates a head-to-head domain wall, whereas sweeping from positive to negative generates a tail-to-tail domain wall.

In figure 3.3, we plot the absolute value of the average magnetic moment along the wire axis (|⟨mx⟩|) around the notch, hereby only probing the region around the notch and neglecting the magnetization in the contact pad. We normalize this value by dividing it with the absolute value of the initial saturated magnetization m0 at B = -100 mT. It is observed that the motion of the domain wall through the notch corresponds to a deformation of the domain wall. This results in a non-constant value of |⟨mx⟩/m0| in the pinned regime.

Figure 3.3: Trace of the absolute value of the normalized average magnetization of the different cells around the notch. The two drops in the magnetization signify the presence of a two-domain state. As the domain wall changes its shape during its motion through the notch |⟨mx⟩/m0| is not constant in this field region.

### 3.1.1 Wire length dependence

In order to determine the dependence on the wire length, we conducted the same computation for 5 µm and 10 µm long nanowires, of equal width and notch depth, 300 nm and 80 % respectively. Here we define the pinning field as the first field for which the domain wall is pinned.
Micromagnetic simulations

by the notch. The depinning field, is the minimum field necessary to saturate the wire from a two-domain state to a single domain state. In table 3.1, the results are shown. What must be noted, is that a different field step size is used for the 10 \( \mu \text{m} \) long wire, resulting in a higher uncertainty on the value for the fields. A more reliable conclusion can be drawn by comparing the 5 and 20 \( \mu \text{m} \) long wires.

<table>
<thead>
<tr>
<th>wire length</th>
<th>pinning field</th>
<th>depinning field</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 ( \mu \text{m} )</td>
<td>15.5 ( \pm ) 0.5 mT</td>
<td>32.5 ( \pm ) 0.5 mT</td>
</tr>
<tr>
<td>10 ( \mu \text{m} )</td>
<td>16 ( \pm ) 2 mT</td>
<td>32 ( \pm ) 2 mT</td>
</tr>
<tr>
<td>20 ( \mu \text{m} )</td>
<td>16 ( \pm ) 0.5 mT</td>
<td>31 ( \pm ) 0.5 mT</td>
</tr>
</tbody>
</table>

Table 3.1: (De-)pinning fields for different wire lengths. The difference between the uncertainties is due to the fact that we used a bigger field step size for the 10 \( \mu \text{m} \) long wire.

Observed is that the pinning field for the 20 \( \mu \text{m} \) wire is only 0.5 mT smaller for the 5 \( \mu \text{m} \). What is more significant, is the difference between the two (pinning and depinning) fields, which is 7 mT for the 5 \( \mu \text{m} \) long wire in contrast to the 5 mT width for the 20 \( \mu \text{m} \) wire. We believe that this is due to a higher shape anisotropy for the longer wire.

![Figure 3.4: Pinning procedure of a domain wall at the notch in the center of the Permalloy nanowire.](image)

First the wire is saturated in the negative field direction and then the field is increased towards the pinning field of 16 mT. When the domain wall is pinned, we return to zero field and we observe clear vortex domain wall structure that remains pinned at the notch.

### 3.1.2 Domain wall pinning

In the previous simulations, it was observed that a domain wall can be pinned at the notch for a certain field range. Now that we have defined the pinning field of the wire to be 16 mT, we can conduct a second field sweep, for which we stop increasing the field after the domain wall has been pinned at 16 mT. After the domain wall has been pinned, we return to zero field. From figure 3.4, we see that the domain wall remains a stable configuration, even at zero field.
3.2 Current-induced domain wall motion

Current-induced domain wall motion is studied by varying the value of $u$ in a 300 nm Permalloy nanowire at zero magnetic field. In order to study this motion, we use the previously found (zero field) pinned domain wall configuration. The domain wall in figure 3.4 is a head-to-head vortex domain wall, for which the magnetization curls around a central point, which is expected for Permalloy nanowires with a width of 300 nm and a thickness of 35 nm [7].

![Numerical results of current-induced domain wall motion simulation.](image)

From the micromagnetic simulations, we determine the domain wall velocity by:

$$v = \frac{l_s - l_p}{t_s - t_p}$$  \hspace{1cm} (3.1)

Where $t_s$ is the time for which the current has saturated the wire fully and moved the domain across the entire wire. The corresponding length, $l_p$, is the total wire length: 10 µm. $t_p$ here is the pinning time, which is the time the domain still feels the pinning potential of the notch, which inhibits it from accelerating. We assume that 1 µm away from the notch, the pinning potential is no longer sufficient to inhibit the motion of the domain wall, therefore $l_p$ is set to 6 µm. We assume that within this region, the domain wall velocity is more or less constant. However, it must be noted, that the end of the wire also acts as an attractive pinning site, due to (a small amount) of transverse modes that are created due to the shape anisotropy. In future simulations, this can be avoided by taking a diamond-shaped end. In such a structure, the shape anisotropy will ensure that the domain wall is annihilated at the end of the wire [10].

We observe, that not only the velocity of the domain wall depends on the current as is shown in figure 3.6b, but that also the time the domain wall stays pinned at the notch strongly depends
on the current density, shown in figure 3.5. Current densities of $u \leq 140$ m/s were not sufficient to depin the domain wall from the notch. We have therefore only plotted the velocities and pinning times for $u \geq 160$ m/s.

Moreover, for high current densities $u \geq 300$, the shape of the domain walls were distorted due to the effect of the current, making it more difficult to estimate the position of the center of the domain wall. The domain wall size sometimes even reached a width of 1 µm. This can become a problem when storing dense information [18].

In the deduced domain wall velocity, a linear trend can be observed, similar to the one dimensional solution of the LLG shown in figure 2.7 [22]. The high current densities necessary to depin the domain wall, result in high domain wall velocities as soon as the domain wall is depinned from the notch. These high current densities correspond to the precessional propagation regime. The Walker threshold is not observed, as the corresponding current density is probably too low to depin the domain wall.

We attribute the small deviations from linearity to both the pinning potential of the notch, as well as that of the end of the wire.

![Figure 3.6: Results from current-induced domain wall velocity computations](image-url)
Sample fabrication and characterization

Analogue to the numerical computations, we have designed a Permalloy nanowire with a notch and a Permalloy contact pad (left contact pad in figure 4.1). In order to apply a current or a voltage, we have added a non-magnetic (gold) contact at the right end of the wire. We have added two more gold contacts, in order to monitor the resistance around the notch in a four-probe measurement.

![Four-probe measurement device](image1)

![Permalloy nanowire and the gold contact lines](image2)

Figure 4.1: Optical images of four probe measurement device. Left contact pad is the Permalloy contact pad, that enables the creation of the domain wall.

### 4.1 Fabrication methods

The Permalloy nanowires are fabricated using Electron Beam Lithography (EBL) and Ultra High Vacuum (UHV) sputtering techniques. We cap the Permalloy nanowires with gold, to prevent oxidation. Gold contacts are subsequently fabricated using EBL and resistance evaporation. A thin (3nm) chromium layer is used as a sticking layer for the gold film. As a substrate we use silicon wafers with 300 nm thermalized silicon oxide at its surface.
In table A.1 in appendix A, all steps and parameters used in the sample fabrication are summarized. A brief explanation of all techniques is explained below.

4.1.1 Electron Beam Lithography

The process of EBL with positive resist is summarized in figure 4.2. In EBL, one exposes an electron sensitive resist that covers the substrate. During the exposure, the beam scans over the substrate in a specifically designed pattern. After the exposure, one develops the resist. The exposure has altered the strength of the resist’s polymer bonds. For positive resist, these bonds are weakened during the exposure. In the development step, the resist is first removed at places where the bonds are weakest. By developing for a certain time, the exposed parts of the resist are removed while the unexposed parts remain as a mask. A thin film can be deposited on top of this mask, using for example sputtering (or evaporation). Finally, the mask can be removed in the lift-off phase.

![Figure 4.2: EBL summary](image)

4.1.2 Spin coating

Before the EBL exposure, we deposit an electron beam resist by means of spin coating. The process of spin coating is the deposition of an electron beam resist on top of a substrate, the substrate is then rotated at a high frequency in order to distribute the resist homogeneously across the substrate. The resists are usually baked after spin coating.

![Figure 4.3: Double-layered resist creating an undercut.](image)
resist is used. By choosing a more sensitive resist as a bottom layer, an undercut is created. For a big enough undercut, particles are no longer able to attach to the edges of the mask.

### 4.1.3 Sputtering

After producing a mask, a film is grown (typically of Permalloy or gold). For this, we have used two different sputtering techniques available in the lab. We initially started with the Leybold RF diode sputtering system. The system consists of two plates, of which the bottom side is grounded and acts as a sample holder at the same time. At the other side, at the position of the target material, an alternating potential is applied [26]. In the presence of a gas, in our case a gas of Argon atoms, the alternating voltage can result in a glow discharge, resulting in a plasma of energetic (positive) Argon ions. As the Argon atoms start to bombard the negatively charged target plate (cathode), momentum transfer causes particles to be removed from the target material. Finally, the atoms condense into a thin film at the position of the substrate holder.

### 4.1.4 Lift-off

After sputtering, the material was lift-off by leaving it in acetone for thirty minutes. The acetone dissolves the resist mask, leaving only the part of the material that had attached to the surface.

![Graph](image)

**Figure 4.4: Height profiles of Z407 and UHV magnetron**

As can be seen from figure 4.4, inspection of the structures with Atomic Force Microscopy show that the stack of two layers of resist is not sufficient to prevent ears from forming. In the RF
Z400 sputtering machine (Z407), the ratio between target size and target distance is so large, that the material is deposited on the sidewalls of the bottom layer of resist.

**Ultra high vacuum magnetron sputtering**

In order to decrease the target size and target distance ratio, we switched to a different sputtering technique. The Ultra High Vacuum (UHV) sputtering system uses a DC magnetron sputtering technique. The introduction of a magnet, in the correct configuration, enables a more efficient way of sputtering which allows to increase the distance between target and sample. The increase of the sample distance and the decrease of target size finally results in a more uniform way of material deposition. Although it still has not completely solved the ear problem, the height of the ears has been reduced drastically, as can be seen from figure 4.4.

### 4.1.5 Resistance evaporation

For the fabrication of the gold contact lines and pads, it was possible to circumvent the ear problem by using resistance evaporation as the deposition technique. It is based on the principle that, by sending current through a resistance, heat can be created locally. For a high enough current, the gold can be heated until its melting point. When the pressure is low enough, the evaporated atoms can now move toward the sample, where they form a thin film. By depositing the material in this way, the distance from target to sample is high enough so that it can be considered as a uniform material deposition method.

### 4.1.6 Gold lift-off

The lift-off with thin gold films can be difficult, as gold does not adhere easily to the SiO$_2$ substrates. In order to prevent the gold film to be removed completely in the lift-off phase, a thin sticking layer of chromium (3nm) is deposited first.

### 4.2 Characterization

In order to characterize the quality of the Permalloy nanowire and the contacts, we use different microscopy techniques, and conduct transport measurements in the Physical Property Measurement System (PPMS).

#### 4.2.1 Transport properties

The PPMS is a commercial instrument built by Quantum Design. In its cryogenic chamber, it can reach temperatures down to 2 K, and by means of a superconducting magnetic, reach field strengths up to 9 Tesla. We used external electronics, in order to measure the transport properties. For this, we used different measurement instruments: an SR830 DSP lock-in amplifier AC
for standard AC measurements at low frequency, as well as a Keithley 2400 current source and a Keithley 2182A nanovoltmeter for DC measurements.

**Lock-in amplifier measurements**

AC lock-in techniques are used to monitor the resistance as a function of temperature and field. For this, we used a lock-in that operated at a low frequency of $\sim 72$ Hz. A voltage of $V_{AC} = 1$ V was put across the nanowire in series with a load resistance of $R_L = 100 \, \text{k}\Omega$, resulting in an effective current of approximately $10 \, \mu\text{A}$. During the temperature and field sweeps, the voltage around the notch was monitored. The resulting sample resistance ($R_S$) is then given by:

$$R_S = R_L \cdot \frac{\langle V_m \rangle}{V_{AC} - \langle V_m \rangle} \quad (4.1)$$

$\langle V_m \rangle$ is the average voltage measured by the lock-in during one second (constant time of the lock-in).

![Figure 4.5: AC lock-in measurement circuit.](image)

The field, $B$, is applied along the wire axis.

We conduct resistance measurements as a function of temperature (RT) in order to use it as a calibration curve for Joule heating experiments. Moreover, this measurement helps to check if our Permalloy nanowires behave like a normal metal. In a normal metal, the resistance is determined by various scattering processes, which depend differently on temperature. An RT measurement can expose the dominating scattering processes. For a normal metal, RT curves follow the relation:

$$R = \alpha + \beta T^2 + \gamma T^5 \quad (4.2)$$

Where the residual resistance, $\alpha$, which is independent of temperature, is due to electron-impurity scattering and is important for low temperatures. $\beta$ describes the amount of electron-electron scattering, and $\gamma$ is the electron-phonon contribution to the resistance, which is important at higher temperatures.
Anisotropic magnetoresistance

Analogue to the simulations, we determine the pinning and depinning fields of the Permalloy nanowire by monitoring the resistance as a function of field. The field is always applied in plane and parallel to the wire.

DC Joule heating measurements

Before we are able to apply the high current densities necessary to depin the domain wall, it is determined at what current density Joule heating effects start to play a role. Applying high current densities may lead to an increase in temperature of the nanowire and even affect the magnetization of the nanowire as it reaches the Curie temperature. For this we have used a DC current source and a nanovoltmeter in order to probe the resistance around the notch. The measured voltage as a function of current (during an IV sweep) can be converted into the power generated as a function of current. Using the above obtained relation that converts resistance into a temperature, we can then determine the temperature increase, $\Delta T$.

4.2.2 Microscopy techniques

Several microscopy techniques are employed in determining the quality and the dimensions of the nanowires. Below, we briefly illustrate the operation principles of the Atomic Force Microscope and its applications in magnetic force microscopy.

Atomic Force Microscopy

Above, we have already shown a trace obtained from an atomic force microscopy (AFM) image, obtained with the Bruker AFM. AFM is a scanning probe microscopy technique, in which a probe is used to scan over the surface of a sample to measure the interactions between the last atom on the tip of the probe and the surface atoms of the sample. By means of a sensitive piezoelement, the xy - position of the tip above the surface can be determined with high accuracy.

In atomic force microscopy, the forces that are probed are the van der Waals forces between the atom on the tip and the surface atom. In a linear approximation, the resulting force on such a probe can be converted into a displacement, using Hooke’s law:

$$ F = -kx $$

(4.3)

here is $k$ the stiffness of the probe. The vertical deflection is determined from the reflection of a laser beam shining the reflective side of the probe. A photodetector determines the amount of deflection. Finally, by scanning across the surface plane, an image with height information can be obtained.
In AC mode, the cantilever is dynamically driven by a chosen setpoint amplitude and a frequency that is generally (close to) the cantilever’s resonance frequency, above the surface. When the height of the surface changes, a feedback loop is implemented to ensure that, to compensate for the damped amplitude, the cantilever returns to its original distance above the sample. The corresponding feedback voltage is a measure of the height difference.

For each line, a trace and retrace are obtained. How well the trace and retrace correspond to each other is a measure of the quality of the feedback loop parameters [27].

**Magnetic Force Microscopy**

The AFM is not only used to probe the van der Waals forces, but also the magnetic forces (MFM), which can be done by using a magnetically coated tip. For our MFM measurements, we used Bruker MESP-LM-V2 Antimony doped Silicon tips, with on both the front and the backside a CoCr coating, with a medium to low coercivity and a low magnetic moment.

The magnetic interaction of the stray fields, that arise at the boundary of two magnetic domains, and the tip result in a phase change between the driving frequency and the measured frequency, which is proportional to the strength of the magnetic field gradient.

In order to distinguish the magnetic forces from the van der Waals forces, a different distance-to-sample regime must be probed. The van der Waals force is known for its short range (< 25 nm), and its effect dies out quickly as a function of distance between tip and sample. The magnetic stray field that arises at the boundaries of two different magnetic regions, has a vertical field gradient, which can be probed even outside the van der Waals region. In MFM, this difference can be utilized by obtaining an image in the similar way as described above, where the trace is used to probe the topography profile, but in the retrace, the tip is lifted above the van der Waals regime. Therefore, van der Waals information is encoded in the trace only and the magnetic information is encoded in the retrace phase image. In our case, the lift height was set to 65 nm. MFM measurements were conducted on the JPK NanoWizard AFM [27].
Chapter 5

Transport Measurements

In this chapter, we will discuss first the results from RT measurements together with the corresponding DC Joule heating measurements. Second, the results from the AMR characterization are shown, together with the results from a DW pinning experiment. In the discussion, the analogy is made between the AMR experiment and the field sweep simulations. Finally, the temperature dependence of the AMR signal is investigated and discussed.

5.1 Joule heating

Figure 5.1: The measured values for the resistance are converted into resistivity. The corresponding nanowire dimensions are: length = 825 nm, width = 600 nm, height = 35 nm. In figure (a), the red line through the data points represents a fit with equation 4.2, of which the results are listed below. The red line in figure (b), corresponds to the linear fit, we used to approximate the temperature increase in the Joule heating experiment.
In figure 5.1, the results from an RT measurement are shown. Lock-in techniques are used to apply a low frequency AC signal and probe the voltage around the notch. The clear parabolic temperature dependence points at normal metal behaviour, where the resistance is dominated by electron-electron scattering. The parabolic fitting parameters are listed in table 5.1. The phase difference between the driven and measured AC signal, stayed below 0.15°, over the entire temperature range, pointing at a pure resistive impedance between the contacts.

Resistivity is determined from the resistance, by taking into account the wire dimensions between the contacts: a length of 825 nm, a height of 35 nm and a width of 600 nm.*

$\alpha = 1.3 \times 10^{-6} \text{Ω m}$

$\beta = 9.32 \times 10^{-12} \pm 7.64 \times 10^{-14} \text{Ω m K}^{-2}$

$\gamma = -1.20 \times 10^{-19} \pm 5.01 \times 10^{-21} \text{Ω m K}^{-3}$

$\delta = 2.55 \times 10^{-9} \text{Ω m K}^{-1}$

**Table 5.1:**

Fitting parameters for figure 5.1. The coefficient $\gamma$, is small enough to neglect. To be noted is, that it is a negative contribution, which is not in line with the physical explanation of a positive phonon contribution. We believe this negative contribution is an error in the measurement, due to an ineffective cooling and warming mechanism of the PPMS at high temperatures.

![Figure 5.2: Joule heating measurements](image)

Curves are separated over two graphs, because of the similar shape of the low initial temperature curves.

During the IV measurements, the current was swept between -5 mA and 5 mA, the voltage was measured between the gold contact lines. For low current densities, the resistance behaves ohmic (constant resistance). However, for higher current densities, also heat is generated. In figure 5.2, dissipation is already visible for current densities starting from $0.5 \times 10^{11} \text{A/m}^2$.

---

*After inspection with AFM*
In order to determine the increase in temperature from the heat generated by the current \((P = IR^2)\) in figure 5.2, the high temperature limit of the RT curve (in figure 5.1) is approximated by a linear fit, where we neglect the parabolic low temperature behaviour.

\[ \Delta T = \left( \frac{dR}{dT} \right)^{-1} \Delta R = \delta \Delta R \] (5.1)

The corresponding coefficient, \(\delta\), found from the linear fit, is listed in table 5.1.

It is observed that, especially for the \(T_0 = 250\) K curve, the temperature increase reaches a very high temperature. Taking into account its initial temperature, the total temperature of the wire due to the current is almost 800 K, hereby (closely) reaching the Curie temperature of Permalloy, which is between 480 - 900 K\(^\dagger\).

A curve with initial temperature of 300 K is not shown, as the temperature increase of the wire at currents of 5 mA, corresponding to \(\sim 3.3 \times 10^{11}\) A/m\(^2\), was high enough to break the contacts, hereby destroying the device.

The Joule heating experiments show that room temperature experiments are not only more susceptible to thermal activation that can influence the DW motion, but also they show the maximum current densities allowed to be applied before heating the sample.

### 5.2 Anisotropic magnetoresistance

AMR measurements were conducted, in which the resistance around the notch was monitored for fields applied from 30 mT to -30 mT and from -30 mT to 30 mT along the wire axis.

The AMR signal for a 440 nm wide nanowire with a notch depth of 90%, performed at 10 K, is shown in figure 5.3a. We define the AMR signal here as:

\[ AMR = \frac{\rho(B) - \rho(0)}{\rho(0)} \times 100\% \] (5.2)

The direction of the spin polarization of the conduction electrons is along the wire axis of the nanowire. The AMR signal arises due to a fluctuation in the angle of the magnetization and the direction of the conduction electrons. The AMR signal for a Permalloy nanowire in a field that is applied parallel to the wire axis, is therefore proportional to the deviation from parallel alignment with the wire axis.

The AMR experiment reproduce the behaviour observed already in OOMMF simulations (figure 5.3a). We can, therefore, attribute the non-constant value of the AMR signal in the pinned region to a single domain wall that is being transformed while being pushed through the region with the notch.

\(^\dagger\)depending on its crystal structure [28]
5.2.1 Anisotropic magnetoresistance domain wall pinning

After determining the pinning field of the nanowire in the previous measurement at 5 mT, a domain wall pinning experiment was performed, from which the results are shown in figure 5.3b. The sample was first magnetized in the positive field direction at a field of 200 mT. The field was then linearly reduced to zero. Then the resistance was monitored in a field sweep in which the field was slowly reduced to -5 mT, at which a domain wall was created and pinned. At this point, the field was brought back to zero. The results show a drop in the AMR signal at the pinning field, which remains after the field is brought back to zero. From this we can deduce that the two-domain state is stable at zero field, which corresponds to one domain wall pinned under the notch and for which the resistance is determined to be 0.17 Ω.

Figure 5.4: MFM characterization of the Permalloy wire and the contact line. Figure (a) shows the AFM trace image, in which no magnetic information is encoded, as the van der Waals forces are dominating in this region. Figure (b), shows the retrace of the same image and the retrace at a smaller magnification of the contact line. The retrace is taken at 65 nm away from the surface, outside the van der Waals regime. This is confirmed by the fact that the gold contact lines are (almost) no longer visible in the retrace, as they do not possess any magnetic information.
MFM measurements were conducted on a pinned domain wall in order to confirm this. Before examining the structure with MFM, the sample had to be taken out of the PPMS. The PPMS was therefore warmed up and the sample was taken from the puck, the sample holder, hereby removing all the wiring that was connected to the contact pads.

Figure 5.4 shows the phase images for a Permalloy nanowire for which a domain wall was pinned at the notch by means of the AMR measurement. For this specific wire, the domain wall pinning measurement was done at a temperature of 300 K, before taking it out of the PPMS. The lift height, in the MFM mode of the JPK AFM, was set to 65 nm. We compare the trace of the phase image with its corresponding retrace phase image. The retrace phase image, for which the tip was lifted 65 nm away from the surface, shows a different contrast than its trace. This is because the van der Waals forces are no longer distorting the signal, and only magnetic information is encoded in the retrace phase.

In the contact pad, which has a relatively smooth surface, the contrast in the retrace image is good enough to distinguish magnetic domains. The surface of the wire, is less uniform, it was therefore more difficult to obtain a more detailed phase image, that did not show any information about the height itself. Nevertheless, Permalloy does show a slight deviation at the position of the notch, which might point at the presence of a domain wall.

5.2.2 Anisotropic magnetoresistance temperature dependence

In the domain wall pinning measurements, we noticed that the pinning field changed significantly at 300 K from the pinning field measured at 10 K. We, therefore, conducted several field sweeps at different temperatures for the same device, in order to quantify this difference of which the results are summarized in the figure below. The AMR signal is here defined as in equation 5.2. The Permalloy wire has a length of 3.95 $\mu$m, a width of 400 nm and a thickness of 35 nm, with a notch depth of 70%. From figure 5.5, an apparent change in the shape of the AMR signal is visible. This difference is quantized in figure 5.6a where the pinning and depinning fields are plotted as a function of temperature. As the shape of the curve is not symmetric, a distinction is made between the left and the right AMR drop. Moreover, the width of the drops is plotted in figure 5.6b. The figures show a temperature dependence, which is most significant for the depinning field.

An apparent decrease in the depinning fields as a function of increasing temperature is observed. However, the $T = 10$ K measurement shows a more sensitive behaviour to pinning sites that is not observed in the other measurements for higher temperatures. Because the total resistance is lower at lower temperatures (we determined the RT curve in figure 5.7), the relative AMR signal is higher for low temperatures.
From the AMR signals at different temperatures, it can be concluded that domain walls are more easily depinned from the notch due to thermal fluctuations. But, at room temperature, Joule heating is more efficient in heating the nanowire at these high current densities.
Figure 5.7: Characterization of nanowire quality. (a) Resistivity in zero field as a function of temperature. (b) In this SEM image, only the part around the notch is visible, together with the gold contact lines, that show up brighter. The dimensions of the wire are: width = 400 nm, length = 3.95 µm and thickness = 35 nm.
Chapter 6

Preliminary results: domain wall velocity experiments

Anisotropic magnetoresistance measurements show that the resistance of the nanowire drops when a domain wall enters the region of interest, due to the transverse components in the vortex-mode of magnetization reversal inside the domain wall.

6.1 DC currents

Figure 6.1: DC current domain wall depinning tests. Figure (a), shows the AMR signal from a 440 nm wide wire (same device as in figure 5.3b). Resistance as a function of current for a one- and a two-domain state is plotted in (b).

As a first step in order to move a domain wall, we conducted tests in which we applied a DC current with different amplitudes. A shift in the corresponding IV curve, with respect to an IV
Preliminary results: domain wall velocity experiments

curve taken in a saturated state, can be interpreted as a motion of the domain wall out of the probed region.

We prepared a domain wall, the signal of which is plotted in figure 6.1a. The corresponding two-domain resistance as a function of current is plotted in figure 6.1b. Together with the two-domain resistance, the one-domain resistance of a saturated wire is shown in the figure. The IV-curves are taken at a temperature of 50 K.

In these curves, however, no difference was observed between the saturated state and the two-domain state, from which we concluded that the domain wall was not depinned from the notch.

In order to confirm this, the AMR signal was obtained from a field sweep from zero field up to a saturation field of -12 mT. As can be seen from figure 6.2, the IV amplitude range was not sufficient to depin the domain wall from the notch as the DW was still present even after applying the high current densities. Tests with higher current densities were not possible, as the wire broke for current densities higher than $4.5 \times 10^{11} \text{ A/m}^2 (> \pm 6.5 \text{ mA})$. What has to be noted is that the AMR signal of the domain wall in the depinning sequence is 0.05% larger than in the pinning sequence. At the moment, we cannot explain the reason for this change.

![Figure 6.2: Confirmation DW configuration unaffected by IV sequence](image)

AMR signal of a domain wall that is depinned from the notch due to field. Same device as characterized in figure 5.3.

6.2 High-frequency pulses

In order to prevent the wire from heating, pulses are favoured over DC signals. Moreover, by means of high-frequency pulses, the dynamics of the domain wall velocity can be probed. Previous research with real-time measurements probing domain wall velocities, has shown that domain wall velocities reach values around 50 - 150 m/s [29] under the influence of a current. Assuming a region of 10 µm between two different contacts, a 65 ns resolution is needed.
6.3 Experimental set-up

The use of pulses will allow to probe the voltage in a narrow time region, as well as to trigger at the corresponding time region. Voltage pulse generators can create pulses of nanosecond width, whereas current pulse generators create pulses with a width of at least a few hundreds of nanoseconds. For that reason, voltage pulses seem to allow for a more accurate time resolution. The voltage can be probed by means of an oscilloscope. At these short time scales, the edges of the pulse are described by high frequencies and thus very small wavelengths. These wavelengths can become so small, that they become on the order of the size of the cables, or even shorter. In this case, cables start behaving as transmission lines. Transmission lines come with their own characteristic impedance, that is dependent of the inductance and the capacitance of the line [30]. It is, therefore, imperative that one takes a closer look at the experimental set-up.

6.3 Experimental set-up

6.3.1 Impedance matching

It was necessary to adapt the usual PPMS external electronics. The breakout box that connects the external electronics with the PPMS lemo acts as a low-pass filter, unfit for high-frequency measurements. Moreover, the twisted pairs of wires leading to the puck and the sample have a resistance that does not match the resistance of the coaxial cables and the output of the pulse generator (50Ω). In order to have a properly defined pulse shape and width, we need to prevent reflections (and standing waves).

For this purpose, Ing. Bert Crama, from the Electronic Department, built an impedance matcher,
that matches the impedance of the 50 Ω output of the pulse generator and the BNC cables with the \( \approx 93 \Omega \) impedance of the twisted pair leading to the sample, of which a sketch is shown in figure 6.4. The numbers 13 and 14 correspond to the twisted pair numbering of the PPMS insert, where 14 is the shield and 13 is the signal. The same matching is done for the pair 11 and 12.

The impedance matcher introduces a voltage drop. The actual voltage, across the 93 Ω termination resistor, is actually:

\[
U_{93\Omega} = \frac{75 \parallel (64.9 + 93)}{50 + 75 \parallel (64.9 + 93)} U_{in} = \frac{50.8}{50 + 50.8} \approx \frac{1}{2} U_{in} \quad (6.1)
\]

The current that will actually flow through the experiment is therefore given by:

\[
I_{\text{sample}} \approx \frac{1}{2} \frac{U_{in}}{R_{\text{exp}}} \quad (6.2)
\]

One requisite is that \( R_{\text{exp}} \) must be, preferably one order of magnitude, larger than the 93 Ω resistance, allowing to neglect reflection coming from mismatch on that part of the circuit. The voltage coming from the pulse generator is limited to maximum voltage of 10 V. The maximum current density for a 1 kΩ resistor (assume 300 nm width and 35 nm thickness) is then:

\[
j = \frac{1}{2} \frac{10 \text{ V}}{1 \text{ kΩ} \cdot 300 \text{ nm} \cdot 35 \text{ nm}} = 4.7 \times 10^{11} \text{ A/m}^2 \quad (6.3)
\]

From the DC measurements, however, we found that a current density of \( 4.5 \times 10^{11} \text{ A/m}^2 \) was not sufficient to depin the domain wall from the notch.

Moreover, when probing the voltage across the 93 Ω resistance with another twisted pair, the signal will again experience a loss in the voltage due to the impedance matcher. In this case, the actual voltage measured is given by:

\[
U_{\text{out}} = \frac{50 \parallel 75}{50 \parallel 75 + 64.9} U_{93\Omega} = \frac{30}{30 + 64.9} U_{93\Omega} \approx 0.3 U_{93\Omega} \quad (6.4)
\]

This additional loss might be problematic too, as the difference due to the presence of a domain wall in the AMR signal is less than 1%.

**Figure 6.4: Impedance matching circuit.** The impedance matching circuit is incorporated inside a Fisher plug. An equal pair exists for twisted pair 11 and 12 (shield).
6.3.2 Trial results

Quasi-static tests were conducted by sending voltage pulses and then probing the resistance by means of AC lock-in techniques on a 400 nm wide nanowire with a notch with 90% depth. A sketch of the experimental set-up is shown in figure 6.5.

A small, low frequency AC signal is used to probe the resistance around the notch (1 V with 100 kΩ in series). Different amplitude pulses of 1 μs width are applied to depin the domain wall from the notch. The AC lock-in signal and RF signal from the pulse generator are combined using a bias-tee. Here the low frequency AC lock-in signal is connected to the DC input of the bias-tee, which has a 100 Hz – 1000 MHz frequency range.

![Figure 6.5: Experimental set-up. Outputs 13 and 14 are connected to one BNC input cable of the Fisher plug to apply the signal. 11 and 12 are connected to the remaining BNC cable in the Fisher plug in order to probe the voltage around the notch.](image)

![Figure 6.6: Three-probe resistance after 1 μs voltage pulses. The x axis reads the amplitude of the voltage pulses. Width of the pulse is 1 μs. A previous measurement with 100 ns pulses did not change the resistance of the nanowire at all.](image)

Test results show that indeed 10 V pulses, the maximum the pulse generator can deliver, with
1 µs width are not able to move the domain wall from the notch. This was again confirmed by an AMR measurement. However, after the 1 µs-voltage pulse with a 10 V amplitude, we do see a decrease, rather than an increase, in the resistance. Currently, we do not have an explanation for this decrease in overall resistance. Note however, that for this device, the wire resistance is on the same order as the 93 Ω termination resistance, hereby acting as a voltage divider, with an effective termination resistance of $\frac{1}{2} \times 93 \Omega$. The line is, therefore, no longer properly terminated and part of the power might be lost in reflections here too, resulting in an even lower current density than found in equation 6.3 and an ill-defined pulse shape. For future experiments, the resistance of the sample that contributes to the termination of the wire should be taken into account more carefully.

6.4 Outlook

Because the maximum applicable current density is limited, it seems that the current design with a 90% notch creates a pinning potential that is too strong for the current to overcome. Moreover, higher current densities might even destroy the sample due to the increase in temperature. In future experiments, a device should be fabricated that allows for lower current density thresholds. This can be accomplished by:

- Reduce the size of the pinning potential: improve smoothness of the wires by improving the fabrication process and/or reduce the depth of the notch.
- Assist the domain wall depinning using a small field, just below the depinning field.
- Induce a domain wall without the use of a notch.

The later option has been explored already by M. Hayashi [29], for example. M. Hayashi induces a domain wall by sending a current through a contact line perpendicular to the wire, hereby employing Ampère’s law, in order to create a domain with a different polarization with respect to the original direction of the magnetization in the wire.
Conclusion

During this project, we have made a start for a future experiment to study the dynamics of domain wall velocity in Permalloy nanowires.

Notched Permalloy wires with nanometer dimensions were fabricated by means of Electron Beam Lithography and Ultra High Vacuum sputtering techniques. The devices contained a single Permalloy contact pad, which served for the creation of the domain wall in the AMR field sequence. Three gold contact pads, were fabricated subsequently, using evaporation as material deposition technique.

Atomic Force Microscopy measurements, showed that, although switching from sputtering machine reduced the size of the ears at the sides of the wire, the surface and the edges of the Permalloy wire remained rough. In domain wall motion experiments, this can induce additional pinning sites, especially at low temperatures, which will make it difficult to control the domain wall motion. In order to reliably produce uniform nanowires, the current fabrication recipe has to be improved further. This will also greatly improve the signal in the MFM images, making it easier to study the complex modes of the various domain walls.

Numerical simulations have shown the transformation of the shape of the domain wall, while it is being pushed under the notch. The corresponding trace of the magnetization, has a good resemblance with the AMR signal obtained from transport measurements of a fabricated device with a similar shape and dimensions.

Moreover, the numerical simulations show that there is a high current density necessary in order to depin the vortex domain wall from a notch with 80% depth. Domain wall velocities can thus only be obtained in the high current density regime. The obtained domain wall velocities show a linear trend as a function of current density.

Experiments on current-induced domain wall motion showed that for the current design with a 90% notch depth, the current density threshold was too high to depin the domain wall. A design with a smaller pinning potential is necessary in order to do domain wall velocity measurements with a reasonable current density, that does not heat the device too much.
Although, a start of the experimental realisation on actual domain wall velocity experiment has been made, much effort is still needed in order to do a reliable experiment in the PPMS. The advantage, however, of using a setup as the PPMS is that it can vary and control the temperature accurately, and that it can cool down to as low as 2 K. We were able to show the temperature dependence of the AMR signal, and were able to quantize the (de-)pinnig fields’ temperature dependence, which we found to be very strong. We expect, that temperature will therefore also have large influence on the domain wall velocities as well. This is in agreement with conclusions from Schieback et al. [31] who conducted numerical simulations on current-induced domain wall motion incorporating thermal fluctuations. An addition to the conventional LL(G) equation was made, by adding a longitudinal relaxation term. This equation is also known as the Landau-Lifshitz-Bloch equation. Similar to $T_1$ relaxation in Nuclear Magnetic Resonance, it describes the relaxation of the magnetic moment due to thermal interactions with its surroundings.

Schieback et al. found a strong temperature dependence of the domain wall velocities. Moreover, the relative strengths of the adiabatic and non-adiabatic terms showed a strong temperature dependence as well. We therefore agree with Schieback et al., that it is crucial to perform more temperature dependent studies on actual domain wall velocity experiments, in order to identify the relevant damping mechanism in current-induced domain wall motion.
Acknowledgements

I would like to use this opportunity to acknowledge a few people important in the realisation of this thesis and the corresponding research. First of all, I would like to express my deepest gratitude to my direct supervisor Dr. Aymen Ben Hamida, for all his patience and guidance during this project and his insight into the theory.

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Finally, I would like to thank the whole MSM group for all their support and kindness.
Appendix

Sample fabrication recipe

In table A.1, one can find all parameters used in the sample fabrication process. As substrates we use diced 1 cm$^2$ Si wafers with 300 nm of thermalized SiO$_2$ on its surface.

Samples are cleaned by rinsing with demi water, sonicating 3-6 minutes in acetone, rinsing with IPA and drying with nitrogen. In the developing step, it was sometimes necessary to add some demi-water to the MIBK for the copolymer layer to be developed fully. This also increased the undercut. We added enough demi-water until the copolymer was completely removed from the big contacts.
### Sample fabrication summary

<table>
<thead>
<tr>
<th>Layer 1</th>
<th>Permalloy nanowires</th>
<th>Permalloy contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin coating</td>
<td>resist</td>
<td>frequency</td>
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<tr>
<td>Copolymer</td>
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<td>200 °C</td>
</tr>
<tr>
<td>PMMA 950 K</td>
<td>4000 rpm</td>
<td>150 °C</td>
</tr>
<tr>
<td>(3x) PEDOT</td>
<td>4000 rpm</td>
<td>-</td>
</tr>
<tr>
<td>EBL spotsize</td>
<td>Permalloy nanowire</td>
<td>Permalloy contact</td>
</tr>
<tr>
<td>PC 14 (PC 12)</td>
<td>PC 1</td>
<td>100 µC/cm²</td>
</tr>
<tr>
<td>Developing</td>
<td>Developer</td>
<td>time</td>
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<tr>
<td>MIBK 1:3 IPA</td>
<td>60 s</td>
<td>IPA</td>
</tr>
<tr>
<td>Material Deposition</td>
<td>Material</td>
<td>Technique</td>
</tr>
<tr>
<td>Permalloy</td>
<td>UHV magnetron sput.</td>
<td>time</td>
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<tr>
<td></td>
<td>setpoint I = 150 mA</td>
<td>7 min 30 s</td>
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<tr>
<td></td>
<td>I = 146 mA</td>
<td>35 nm</td>
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<tr>
<td></td>
<td>V = 335 V</td>
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<tr>
<td>Gold (cap)</td>
<td>RF diode sput.</td>
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<tr>
<td></td>
<td>V = 1kV</td>
<td>10s</td>
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<td></td>
<td>P = 5·10⁻³ mbar</td>
<td>3 nm</td>
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<tr>
<td>Lift-Off</td>
<td>Aceton</td>
<td>30 min</td>
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<table>
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<td>Copolymer</td>
<td>6000 rpm</td>
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<td>PMMA 950 K</td>
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</tr>
<tr>
<td>(3x) PEDOT</td>
<td>4000 rpm</td>
</tr>
<tr>
<td>EBL spotsize</td>
<td>Permalloy nanowire</td>
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<tr>
<td>PC 14 (PC 12)</td>
<td>PC 1</td>
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<td>Developing</td>
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<td>Material</td>
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<tr>
<td>(sticking layer)</td>
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</tr>
<tr>
<td>Gold</td>
<td>UHV resistance evap.</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Lift-Off</td>
<td>Aceton</td>
</tr>
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</table>

*Table A.1: Sample fabrication summary*
Bibliography


