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van der Heijden, M.A.J.

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Domain wall pinning by EBID iron nanopillars

M.A.J. van der Heijden
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Supervisors:
ir. J.H. Franken
prof.dr.ir. H.J.M Swagten
Abstract

In this report, the influence of iron pillars on domain wall movement in perpendicularly magnetized nanowires is investigated. Several iron pillars with different heights are electron beam induced deposited onto Pt-Co-Pt nanowires. Results show that the magnetic stray field of magnetized iron pillars create domain wall pinning sites and that, as a function of pillar height, the pinning strength first increases and then levels off. Results also show that the field needed to move a domain wall back from a pillar first decreases with increasing pillar height and saturates thereafter. This behavior is consistent with theory.

Furthermore, an experimental approach is introduced to determine the coercive fields of the pillars. Results show that the coercivity of the pillars increases with increasing pillar height and decreases with increasing pillar diameter. This behavior is also theoretically expected, with the exception that the predicted saturation of the coercive field is not yet observed.
Chapter 1

Introduction

Nowadays, a lot of research is being done on the movement of magnetic domain walls inside small nanowires. Domain walls (DWs) are interfaces separating magnetic domains and the main motivation to study their motion is found in its potential application to new data storage and logic technologies. One conceptual data storage device which makes use of DW movement to handle its data is called the Racetrack Memory, of which a schematic overview is shown in figure 1.1. The idea of the Racetrack Memory is to induce DW motion in nanowires by sending current pulses through the wires. This way, data could be transferred through the wires and read out by fixed sensors. Advantages of the Racetrack Memory over conventional memory devices would be that it has the potential to operate faster, has no moving parts and makes use of the third dimension to obtain a higher data density.

Although the idea of the Racetrack Memory is quite obvious, there are still some major issues that have to be remedied before the basic concept could be applicable for industrial use. One of these problems is that it appears to be difficult to exactly control DW movement with current pulses. The mechanism by which current pulses initiate DW movement is not yet fully understood and there is always randomness in the DW displacement. Therefore, other methods which influence DW movement are also subject to study. One way to influence DW movement is by introducing fixed places along a nanowire where DWs are most likely to stop: so called "DW pinning sites". These pinning sites come in many shapes and sizes and a common method to generate them is by geometrically altering or damaging a nanowire (see figure 1.2 for an example). Although this method works fine for most cases, it is not always desirable to have a geometrically altered nanowire. Therefore, other possible ways to induce DW pinning are of great interest.
Figure 1.1: Two versions of the Racetrack Memory concept: a vertical racetrack and a horizontal racetrack. The blue and red areas of the nanowires indicate regions with opposite magnetization.

Figure 1.2: Domain wall pinning by a geometrically altered nanowire. The middle picture shows domain wall pinning.
1.1 This and previous work

The goal of this work is to characterize DW pinning by small magnetized iron pillars placed on top of perpendicularly magnetized nanowires. Hereby, this report continues the work by Ellis on Electron Beam Induced Deposition (EBID) of iron. EBID is a fabrication method by which an electron beam in combination with a precursor gas is used to fabricate small structures. Figure 1.3 shows the basic principle of EBID.

The research of Ellis focused on the characterization of a new iron precursor gas, Fe$_2$(CO)$_9$, and some preliminary investigations into practical magnetic deposits. One of his last experiments consisted of several iron nanopillars placed on top of a perpendicularly magnetized nanowire (see figure 1.4). The goal was to study the DW movement through the wire under influence of an external magnetic field. During this experiment, DW pinning was observed at the places where the iron pillars were positioned, as shown in figure 1.5. This DW pinning was thought to be caused by the magnetic stray fields of the magnetized iron pillars. To exclude that this pinning was caused by the EBID process itself rather than the magnetic properties of the iron pillars, a similar experiment was done with EBID platinum pillars. No DW pinning was observed for this latter case, which strongly suggested that EBID iron deposits show magnetic behavior, inducing pinning sites for DWs. For more detailed information about the experiments performed by Ellis and the EBID of iron with Fe$_2$(CO)$_9$, see his report [1].
Chapter 1 Introduction

Figure 1.4: Sample geometry of the experiment done by Ellis. Three iron pillars were grown on a perpendicularly magnetized nanowire, each with a different height. Picture taken from [1].

Figure 1.5: Domain wall pinning by EBID iron pillars as observed by Ellis. The picture shows three DW pinning stages for different external magnetic field strengths. The dark area of the nanowire has opposite magnetization as the bright area. The arrows indicate where the iron pillars were positioned. Picture taken from [1].
1.1 This and previous work

Although Ellis observed DW pinning by EBID iron pillars, he had only investigated one sample which was not sufficient enough to fully understand and characterize the pinning mechanism. Therefore, more research towards DW pinning by iron pillars was needed, which is the direct motivation of this work.

Another motivation for this project is the recently published article by O’Brien et al [2]. They demonstrated DW pinning with in-plane magnetized nanowires using nanometer scale magnetic stray fields. The localized stray fields arised from multiple uniformly magnetized nanostubs, very similar to Ellis’ experiment where the iron pillars created the localized stray fields. One of the experimental structures studied by O’Brien et al is shown in figure 1.6. The figure also shows a schematic of the magnetization evolution under applied global magnetic field. O’Briens results indeed underline the hypothesis that DW pinning can be achieved by placing nano-magnets in the vicinity of a nanowire.

During this project, the influence of differently sized EBID iron pillars on DW movement in perp endicularly magnetized nanowires is investigated. It is found that the stray fields of these iron pillars indeed effectively create DW pinning sites. Furthermore, calculations are performed on the stray fields of these iron pillars and the potential landscape they produce for a DW to explain the experimental results. Moreover, an experimental approach is introduced to determine the coercive fields of the pillars. It appears that the coercive field strongly depends on the geometry of a pillar and the results also show that a magnetic DW succesfully can be used to sense magnetic properties of nano-objects.

In addition to this introduction, this report is divided into four chapters. Chapter 2 first treats some useful theory on the subject, including theory about how to calculate the stray field of a pillar and an introduction to the Stoner-Wohlfarth model. The experimental toolbox used and the sample fabrication process are subsequently described in chapter 3. More detailed information about the experiments and the results is found in chapter 4 and finally a conclusion and outlook on the subject is given in chapter 5.
Figure 1.6: (a) SEM image of an experimental structure studied by O’Brien et al (b) Schematic of the magnetization evolution under applied global magnetic field sequence. First, a DW was created inside the corner of the nanowire by applying an oblique global magnetic field. Subsequently, the global magnetic field was increased in the direction as shown in the middle picture to move the DW towards the nanostub(s). DW pinning was observed for a global magnetic field strength which was between two certain experimentally determined magnetic field strengths \(H_D\) and \(H_P\). Picture partly taken from [2].
Chapter 2

Theory

This chapter covers some theory that has been used during this project to predict and compare outcomes of the experiments performed. First some theory is given about how to calculate the magnetic stray field of a small iron pillar. After that, the chapter continues with a brief introduction to the Stoner-Wohlfarth model to get an estimation for the coercive field of a pillar. Finally, a discussion is given about which mechanisms can actually cause domain wall pinning by an iron pillar.

2.1 Magnetic stray field

In order to say something about the way iron pillars can influence the movement of a domain wall, knowledge is needed about the shape and magnitude of the stray field these pillars produce. This shape of the stray field can be determined with formulas known from the field of electromagnetism.

From electromagnetism it is known that the stray field of a magnetized object can be calculated by first determining the volume bound current $\vec{J}_b = \nabla \times \vec{M}$ and the surface bound current $\vec{K}_b = \vec{M} \times \hat{n}$, and then find the magnetic field these bound currents produce. The magnetic field produced by these bound currents can be calculated with the Biot-Savart law, most generally given by [3]:

$$\vec{B}(r) = \frac{\mu_0}{4\pi} \int \frac{Id\vec{l} \times \hat{r}}{r^2},$$ (2.1)

with $r$ the distance between a small current element $d\vec{l}$ to the point where the field is under investigation.
Figure 2.1: The magnetic field produced by the bound current $\vec{K}_b$ is approximated by adding up the magnetic fields of several current loops placed on top of each other. The total current that flows through the current loops must equal the total bound current for a good approximation of the magnetic field.

Most ideally, the iron pillars can be imagined as tiny finite cylindrical magnetic structures. By investigating the magnitudes and directions of the bound currents $\vec{J}_b$ and $\vec{K}_b$ for a cylinder which is homogeneously magnetized in the positive $z$ direction, it can be found that $\vec{J}_b = 0$ and $\vec{K}_b = M \hat{\phi}$ (cylindrical coordinates), with $M$ the magnitude of the magnetization $\vec{M}$. As already mentioned, the next step is to find the magnetic field these bound currents, in this case only $\vec{K}_b$, produce. Since the surface current is circumferential in nature, the magnetic field due to this current can be approximated by calculating the total magnetic field from a lot of current loops placed on top of each other. This latter is illustrated in figure 2.1.

Our task now is to calculate the magnetic field due to one current loop, after which we can add up the magnetic fields from all the current loops to get to our final answer. The stray field of one current loop can be calculated by applying the Biot-Savart law. For the calculation, let us put a current loop with radius $a$ on the $xy$-plane and center it at the origin. By first taking symmetry arguments into account, we can conclude that the magnetic field this current loop produces has no circumferential component. Therefore, we are only interested in the $r$ and $z$ component of the magnetic field (cylindrical coordinates). See also figure 2.2 for a definition of the parameters used.

By applying the Biot-Savart law, we find for the $r$ and $z$ component of the
2.1 Magnetic stray field

**Figure 2.2:** Current loop geometry: cylindrical coordinates $r, \phi, z$ are used to calculate the field due to the loop in the $xy$-plane. Picture taken from [4].

The magnetic field \[B\] is given by:

\[B_r = B_0 \frac{\gamma}{\pi \sqrt{Q}} \left( E(k^2) \frac{1 + \alpha^2 + \beta^2}{Q - 4\alpha} - K(k^2) \right), \quad (2.2)\]

\[B_z = B_0 \frac{1}{\pi \sqrt{Q}} \left( E(k^2) \frac{1 - \alpha^2 - \beta^2}{Q - 4\alpha} + K(k^2) \right), \quad (2.3)\]

where

\[\alpha = \frac{r}{a}, \quad (2.4)\]

\[\beta = \frac{z}{a}, \quad (2.5)\]

\[\gamma = \frac{z}{r}, \quad (2.6)\]

\[Q = (1 + \alpha)^2 + \beta^2, \quad (2.7)\]

\[k^2 = \frac{4ar}{(a + r)^2 + z^2}, \quad (2.8)\]

\[B_0 = \frac{I\mu_0}{2a}, \quad (2.9)\]

with $I$ the current running through the loop. $K(k^2)$ and $E(k^2)$ furthermore represent the complete elliptical integrals of the first and second kind, defined as [4]:

\[K(k^2) = \int_{\vartheta=0}^{\frac{\pi}{2}} \frac{d\vartheta}{\sqrt{1 - k^2 \sin^2 \vartheta}}, \quad (2.10)\]

\[E(k^2) = \int_{\vartheta=0}^{\frac{\pi}{2}} \sqrt{1 - k^2 \sin^2 \vartheta} d\vartheta. \quad (2.11)\]
To get more feeling for the formula’s given, let us consider the case where \( r = 0 \) and \( z = 0 \). In that case \( \alpha = \beta = 0 \) and for \( B_r \) we are left with (after substitution of \( Q \)):

\[
B_r = B_0 \frac{\gamma}{\pi \sqrt{Q}} \left( E(k^2) - K(k^2) \right).
\]  

(2.12)

Moreover, \( k^2 = 0 \) since \( r = 0 \), resulting in the same values for \( E(k^2) \) and \( K(k^2) \):

\[
E(k^2) = K(k^2) = \left( \frac{\pi}{2} \right).
\]

(2.13)

Therefore we find for \( B_r \):

\[
B_r = 0,
\]

(2.14)

just as expected when taking symmetry into account. For \( B_z \) we find for this latter case:

\[
B_z = B_0 \frac{1}{\pi \sqrt{Q}} \left( E(k^2) + K(k^2) \right) = B_0 = \frac{I \mu_0}{2a}.
\]

(2.15)

This result is indeed the magnetic field at the origin of a current loop with radius \( a \).

Figure 2.3 shows the magnetic field lines produced by (a) one current loop and (b) 25 current loops placed on top of each other. In chapter 4.1 we use the magnetic stray field for our experimental geometry to estimate the DW potential landscape and compare it with experimental results.
2.2 Stoner-Wohlfarth theory

This section gives an introduction to the Stoner-Wohlfarth model, generally following the introduction found in [4]. The Stoner-Wohlfarth theory describes the total energy of a macroscopic magnetic system with uniform magnetization placed in an external magnetic field. In our case, we are interested in the main magnetic characteristics, or more explicitly the coercive field, of an iron pillar. Basically there are two different energies that the Stoner-Wohlfarth model takes into account. First of all, there is the Zeeman energy which describes the potential energy of a magnetized object placed in an external magnetic field. In this case, the zeeman energy is given by:

\[ E_z = -\mu_0 M_{sat} H_{ext} \cos(\phi - \theta), \]  

(2.16)

with \( M_{sat} \) the local saturation magnetization, \( H_{ext} \) the external magnetic field, \( \phi \) the angle between the external magnetic field and the easy axis of the object and \( \theta \) the angle between the magnetization vector and the easy axis of the object. The easy axis is the direction in which an object is most easily magnetized and is defined by a second term in the Stoner-Wohlfarth model. See also figure 2.4 for a definition of the geometry in the Stoner-Wohlfarth model. In case of a single easy axis, for example the long axis of a cylinder, this anisotropy energy is given by:

\[ E_a = K \sin^2 \theta, \]  

(2.17)

with \( K \) the anisotropy constant, which we will discuss later. The total energy of a magnetic object placed in an external magnetic field is now given by the sum of the Zeeman energy and the anisotropy energy, thus:

\[ E_{total} = E_z + E_a. \]
\[ U = E_a + E_z = K \sin^2 \theta - \mu_0 M_{sat} H_{ext} \cos(\phi - \theta). \]  

We now assume that the magnetization of our iron pillars is in the same direction as the easy axis of the pillar, or in other words: \( \phi = 0 \). In that case the total energy reads:

\[ U = K \sin^2 \theta - \mu_0 M_{sat} H_{ext} \cos \theta. \]  

Equation 2.19 is now ready for inspection. According to the Stoner-Wohlfarth theory, the magnetization direction of a magnetized object is inverses when a sign reversal occurs from the second derivative of the total energy in respect to \( \theta \). The second derivative of the total energy (eq 2.19) for the case that \( \theta = 0 \) is given by:

\[ \frac{\partial^2 U}{\partial \theta^2} \bigg|_{\theta=0} = 2K + \mu_0 M_{sat} H_{ext}, \]  

and this becomes zero at an external magnetic field of:

\[ H_{ext} = H_c = \frac{-2K}{\mu_0 M_{sat}}, \]  

with \( H_c \) the coercive field.

The one remaining task is to find an expression for the anisotropy constant \( K \). In general, anisotropy can be induced by properties (i.e. the crystal structure) of the material itself, or by the shape of the magnetic object. We expect no well-defined crystal axis of our iron pillars because of their chaotic structure, leaving the cylindrical shape of our pillars as the main property which influences the anisotropy constant \( K \). Shape anisotropy takes into account that its easier to magnetize an object along a long axis, the so called easy axis. This geometry dependent behavior is characterized by the demagnetization factor \( N \), which can have a different value for every direction and lies between 0 and 1. A high demagnetization factor along a certain axis of an object implies that it is hard to magnetize the object in that direction. Thus, considering the iron pillars used during this project, a low demagnetization factor is expected along the long (easy) axis of a pillar, as shown in figure 2.4.

For simple shapes where \( z \gg x \), the shape anisotropy of a magnetized object scales with the difference between the demagnetization factors along the easy and hard axis, or more explicitly [6]:

\[ K_{shape} = \frac{\mu_0 M_{sat}^2}{2} (N_x - N_z) = \frac{\mu_0 M_{sat}^2}{4} (1 - 3N_z), \]
where $N_x$ and $N_z$ represent the demagnetization factors in respectively the $x$ (hard axis) and $z$ (easy axis) direction. Note that also $N_x + N_y + N_z = 1$ and $N_x = N_y$ have been used to rewrite the expression.

Finally, to get the total coercive field of a pillar, we combine equations 2.21 and 2.22 to get:

$$H_c = \frac{-2K_{\text{shape}}}{\mu_0 M_{\text{sat}}} = \frac{-1}{2}(1 - 3N_z)M_{\text{sat}}.$$  (2.23)

Now we are left with only the demagnetization factor $N_z$ and the saturation magnetization $M_{\text{sat}}$ which determine the coercive field of a pillar. Values for $N_z$ for different shaped pillars can be calculated by evaluating [7]:

$$N_z = 1 - \left(\frac{2}{\pi}\right)\left(\frac{p}{k}\right)[K(k) - E(k)],$$  (2.24)

with

$$k^2 = \left(1 + \frac{1}{4}p^2\right)^{-1}$$  (2.25)

and

$$p \equiv \frac{L}{2a}$$  (2.26)

$K(k)$ and $E(k)$ again represent the complete elliptic integrals of the first and second kind and $L$ and $a$ are respectively the length and radius of the cylinder. For more information on the calculation of the demagnetization factor, see [7].

Figure 2.5 now shows the coercive field as a function of pillar height for pillars with a constant base diameter of 100 nm. Numerical values for the demagnetization factor are taken from [7] and the saturation magnetization of the iron pillars is estimated on $M_{\text{sat}} = 1000$ kA/m, corresponding to an iron content of approximately 60%. In chapter 4.3, we compute the coercive field for our experimental geometry, in order to compare with experimental results.

### 2.3 Domain wall pinning

When we look closer to the shape of the magnetic field due to a magnetized iron pillar, it is possible to reason in what way a pillars’ stray field influences domain wall movement. Figure 2.6 shows a schematic profile view of a pillar...
placed on top of a perpendicularly magnetized nanowire to illustrate this, including the magnetic field lines from the pillar. When a domain wall is nucleated on the left side of the wire and an external field is applied as shown in the figure, a domain wall tends to propagate towards the pillar until the situation shown in the figure is reached. At that point, the magnetic field of the pillar points upward in the region left of the domain wall, favoring an upward magnetization of the wire. At the same time, the magnetic field of the pillar points downward right beneath the pillar (to the right of the domain wall), favoring a downward magnetization of the wire. This results in domain wall pinning until the external field is strong enough to overcome the downward field beneath the pillar or exceeds the coercive field of the pillar.

By looking to figure 2.6, it is also possible to estimate how the potential energy landscape for a DW would look like. When we consider the situation where both the pillar and the wire are initially magnetized downwards, a nucleated domain wall on the left of the wire would first be attracted slightly towards the pillar since the large region on the left of the pillar favors an upward magnetization of the wire. This relatively weak attraction (weak since the upward magnetic field is not expected to be very strong) causes a small decrease of energy in the energy landscape. The domain wall needs
Figure 2.6: Schematic profile view of a magnetic iron pillar placed on top of a perpendicularly magnetized wire. Note that above "A" the magnetic field of the pillar points upward, favoring an upward magnetization of the wire. Above "B", right beneath the pillar, the magnetic field points downward, favoring a downward magnetization of the wire. This results in domain wall pinning until the external field is strong enough to overcome the downward field beneath the pillar or exceeds the coercive field of the pillar.
to have minimum energy when the situation of figure 2.6 is reached, since then domain wall pinning occurs. Further along the wire, the domain wall energy strongly increases beneath the pillar (because of the strong localized magnetic field pointing downwards) and eventually slightly decreases again in the region on the right of the pillar because there the DW is repelled from the pillar. To summarize, the energy landscape for a domain wall is expected to be the combination of an energy well and an energy barrier, as schematic shown in figure 2.7. Note that this energy landscape is also expected for the opposite case when the pillar and wire are initially magnetized upwards. In chapter 4.1 we will calculate the shape of the energy landscape with use of the exact stray field of a magnetized iron pillar.
Chapter 3

Experimental setup

This chapter describes the various experimental tools which are used during the project. The chapter begins with a short description of the FEI Nova Nanolab 600i dual beam, which is used to deposit iron pillars on top of nanowires by means of Electron Beam Induced Deposition (EBID). Subsequently, the Kerr microscope set-up which is used to study the DW motion through nanowires is described. Finally, information is given about the fabrication process and the geometry of the samples used.

3.1 FEI Nova Nanolab 600i dual beam

For the fabrication of EBID iron nanopillars, a FEI Nova Nanolab 600i dual beam has been used. A schematic representation of the device and a picture from the interior of the vacuum chamber is shown in figure 3.1. The system is called a dual beam since the total system consists of two beams which can be controlled separately: an electron beam and an ion beam. As can be seen in figure 3.1, these beams are positioned with a fixed angle of 52 degrees between them. Samples can be loaded directly inside the vacuum chamber and the sample stage is able to rotate precisely 52 degrees towards the ion beam.

The dual beam has furthermore a couple of Gas Injection Systems (GIS’s) installed which can be inserted separately. These GIS’s make it possible to inject different precursor gases for the deposition of various materials by means of EBID or IBID (Ion Beam Induced Deposition). For the fabrication of our iron pillars, a Fe$_2$(CO)$_9$ precursor is used. More information about the EBID process itself and the dual beam can be found in [8].
The dual beam has also an Energy Dispersive X-ray (EDX) measurement system installed. This system makes it possible to determine the composition of a certain area on a sample by analyzing the characteristic X-rays emitted from that area. Unfortunately it is not possible to do reliable EDX measurement on EBID iron pillars due to their small size. Other iron structures grown with the same precursor gas and settings as used for the fabrication of the pillars showed that the iron content of the fabricated structures is approximately 60 percent [%]. Therefore, it is assumed that the iron pillars have an iron content of 60 percent.

One characteristic of EBID with Fe$_2$(CO)$_9$ is that the precursor gas flow decreases while working with it. This decreasing precursor gas pressure results in a decreasing grow speed of the deposition. Therefore, in order to make iron nanopillars with a specific geometry, this dependence has to be taken into account during the EBID process.

### 3.2 Kerr Microscope

The DW movement is studied with a wide-field Kerr microscope. A Kerr microscope makes use of the Magneto-optical Kerr effect (MOKE) to differentiate parts of a surface with another magnetization. To do so, a beam of polarized light is reflected off a magnetized surface. Due to the MOKE,
3.2 Kerr Microscope

Figure 3.2: Typical image recorded with the Kerr microscope. The seven vertical lines represent seven different nanowires. The dark area of a wire has opposite magnetization as the bright area of a wire.

Figure 3.3: Picture of the Kerr microscope used. The yellow part in the middle represents the solenoid with which a perpendicular field can be applied.

the polarization of the reflected beam is slightly rotated and this rotation gives information about the magnetic orientation of the surface. A typical image recorded with the Kerr microscope is shown in figure 3.2. Figure 3.3 furthermore shows a picture of the Kerr microscope used. More information about the Magneto-optical Kerr effect and Kerr microscopy in general can be found in [9].

To apply a perpendicularly oriented magnetic field during measurement with the Kerr microscope, a solenoid is used wherein the sample can be placed (see
Figure 3.4: Basic geometry of one sample consisting of a perpendicularly magnetized nanowire with an EBID iron pillar placed on top.

also figure 3.3). The magnet has a range of approximately ± 100 mT and is (automatically) controllable by an external computer. This latter makes it possible to maintain similar conditions over the course of different measurements. For more detailed information about the Kerr microscope set-up, see [10].

3.3 Sample fabrication

Figure 3.4 shows the basic geometry of one sample, consisting of a perpendicularly magnetized nanowire with an EBID iron pillar placed on top. For this project, Pt(4 nm)-Co(0.5 nm)-Pt(2 nm) nanowires are used for the measurements. For fabrication, the nanowires are first patterned onto a Si-SiO$_2$ substrate using Electron Beam Lithography (EBL) and the different layers are sputtered onto the sample thereafter. The wires have a length of 55 µm and the width of the wires is chosen to be 0.5 µm. This differs from the 1 µm nanowires used earlier by Ellis, because a more pronounced pinning effect is expected for narrower wires. In that case it is expected that it is energetically less favorable for the two DW ends at both sides of the nanowire to sneak around the pillar since they are closer to the iron pillar and hence are more influenced by the stray field of the pillar.

To ensure a clean injection of a DW inside the nanowire, one side of each nanowire is irradiated with a defocused gallium ion beam, for which the ion beam from the FEI dual beam is used. This irradiation destructively modifies the Co-Pt interface, which results in a lower perpendicular oriented anisotropy and thereby makes it easier for the magnetization to switch and nucleate a DW. A defocused beam is used to minimize the DW depinning field at the boundary between the irradiated part of the wire and the rest of the wire. For more information about the fabrication of the nanowires and the use of gallium irradiation for a clean DW injection, see [11].
3.3 Sample fabrication

For this report, several iron pillars with different heights are deposited onto the Pt-Co-Pt nanowires. Each wire contains only one iron pillar (as can be seen in figure 3.4) and the pillars are fabricated by means of EBID with the FEI dual beam in combination with the Fe$_2$(CO)$_9$ precursor gas. For the deposition process, a beam energy and current of respectively 5.0 kV and 0.40 nA are used, which results in iron nanopillars with a nearly constant base diameter of $60 \pm 10$ nm. By varying the beam exposure time at one position (dwell time), the height of the iron pillars is varied, ranging from $\sim 100$ nm up to $\sim 1$ µm. By doing this, the dependence between the precursor gas pressure inside the vacuum chamber of the dual beam and the grow speed of the depositions as described earlier is taken into account. This is done by keeping the dwell time constant for some pillars, thereby creating pillars with different heights. The depositions are furthermore performed in a single run to ensure similar fabrication conditions for the pillars. Some fabricated iron pillars are shown in figure 3.5.
Chapter 4

Results and discussion

In this chapter the results of calculations and measurements performed during this project will be shown. The chapter starts with results of calculations on the magnetic stray field produced by an iron pillar. The second part of this chapter discusses experiments on the influence of a pillars’ height on some DW pinning characteristics. The third and last section of this chapter introduces a method to indirectly determine the coercive fields of EBID iron pillars and experimental results are shown and discussed.

4.1 Calculation of the magnetic stray field

By applying the theory of section 2.1, the magnetic stray field of a pillar has been calculated. The calculations were done with Matlab and have been performed for pillars with a variety of heights. The base diameter of the pillar was held constant at 60 nm. Since the nanowires used are perpendicularly magnetized, we only focus in this report on the perpendicular component of the magnetic field since that component is expected to influence DW movement the most. This is due to the small dimensions of the DW. For the calculations it is assumed that the pillars have a saturation magnetization $M_s = 1000 \text{kA/m}$, corresponding to an iron content of approximately 60%. It is furthermore assumed that the cobalt layer, where the stray field can interact with a DW, lays 2 nm below the pillar.

Figures 4.1a and 4.1b show the perpendicular component of the magnetic field for pillars with a height of 10 and 100 nm respectively and a constant base diameter of 60 nm. The pillar height for these calculations have been chosen very low to illustrate that, due to flux closure, there is a large area with negative $B_z$ around the pillar, and the magnitude of this field decreases
Chapter 4 Results and discussion

Figure 4.1: Perpendicular component of the magnetic field (in Tesla) 2 nm beneath a pillar as a function of the position. The pillars have a height of (a) 10 nm and (b) 100 nm. Both pillars have a base diameter of 60 nm. The spikes in the middle of the first figure arise because the distance between the data points and the circumferential current loops varies between data points.

with pillar height. One can also see that, as can be expected, the maximum field strength right under a pillar increases for increasing pillar height.

Since the domain wall inside a nanowire is generally all across the width of the wire, calculations like 4.1a and 4.1b do not give us the effective field a domain wall feels. To get an estimation of this effective field, the perpendicular component has to be averaged across the width of a wire. Therefore, figure 4.2b also shows the perpendicular component of the magnetic field, but now averaged across the width of a 500 nm wide nanowire. This time the calculation has been performed for a pillar height and pillar base diameter of 300 and 60 nm respectively, comparable to the pillars studied. When, for example, figure 4.1 and figure 4.2b are compared, it can be seen that they show the same behavior for the magnetic field as a function of the distance from the pillar, although the magnitude of the effective field shown in figure 4.2b is smaller. Therefore, the pinning field experienced by a DW is thus much lower than the maximum stray field of the pillar.

By integrating the data from figure 4.2b it is also possible to get a qualitative estimation for the energy landscape felt by a domain wall with a certain polarity. This is because the zeeman energy scales linearly with the prevailing magnetic field. Figure 4.2c shows the result of integrating the effective field as shown in figure 4.2b. One remarkable thing about the result is that the two energy saturation levels of both sides are not on the same level. This difference in energy is due to the fact that when the magnetization of a pillar
4.1 Calculation of the magnetic stray field

Figure 4.2: (a) Sample situation which is under investigation. (b) Calculated average perpendicular component of the magnetic field as a function of the position along the underlying wire of a 300 nm high, 60 nm wide pillar. The perpendicular component is averaged across the width of the wire, in this case 500 nm. (c) Calculated energy landscape for the DW from integration of the data shown in figure 4.2b. The energy landscape distortion caused by the stray field of a pillar is the combination of a small energy well and a big energy barrier.
has another orientation as the region of the wire just beneath it, the Zeeman energy of the system is higher compared to the opposite case. When the width of the nanowire is increased, the difference between the two saturation levels decreases. This must also be the case, since then the total magnetic flux through the nanowire due to the stray field of the pillar approaches zero. To conclude, the energy landscape shown in figure 4.2c shows indeed the combination of a small energy well and a big energy barrier, as was also reasoned in section 2.3.

4.2 DW pinning characteristics

To determine the influence of pillar height on the DW pinning characteristics, experiments comparable to the pilot experiment by Ellis (see introduction) have been performed. A variety of iron pillars have been grown on perpendicularly magnetised nanowires and, under influence of an external magnetic field, the domain wall movement has been studied. This section will begin with a short introduction about the different DW pinning characteristics that have been studied and the experimental approach for the determination of these characteristics will be explained. After that, more detailed information will be given about the geometry and fabrication process of the samples used for this project. Finally, the results found for the DW pinning characteristics will be shown and discussed.

During the measurements performed, two different DW pinning characteristics have been determined: (1) the difficulty for a DW to overcome the energy barrier caused by an iron pillar (from now on, this characteristic will be called the "depinning field of a pillar") and (2) the difficulty for a DW to move back from a pillar after DW pinning was observed (the "pulling field of a pillar"). Both characteristics were determined with the same samples, although with a slightly different experimental approach.

Figures 4.3 and 4.4 schematically show the experimental approaches for the determination of the depinning field and the pulling field of the iron nanopillars respectively. First, for the determination of the depinning field of a pillar, the sample is magnetically saturated by applying a high perpendicular oriented external magnetic field of ±100 mT. This first step ensures that the nanowire and the pillar are properly magnetized in the same direction. Then, a domain wall is nucleated at one irradiated end of the nanowire by applying a small magnetic field in the opposite direction as the initial saturation field. Subsequently, by further increasing the magnetic field, the domain wall
4.2 **DW pinning characteristics**

**Figure 4.3:** Experimental approach for the determination of the depinning field of EBID iron nanopillars. The magnitude of the external magnetic field at which the domain wall, after pinning, continues its propagation through the nanowire is called the depinning field.

**Figure 4.4:** Experimental approach for the determination of the pulling field of EBID iron nanopillars. The magnitude of the external magnetic field at which the domain wall, after pinning, began to move back from the iron pillar is called the pulling field of the pillar.

propagates through the nanowire until it pins somewhere or reaches the end of the wire. In most cases the domain wall pins beneath the pillar position since the stray field of the pillar creates an energy landscape distortion for the domain wall. When at that point the external magnetic field is increased even more, the domain wall eventually overcomes the energy barrier of the iron pillar and continues its propagation through the nanowire. The magnetic field strength at which this happens, is labeled as the depinning field of the pillar in question.

The experimental approach for the determination of the pulling field is schematically shown in figure 4.4. This pulling field was determined with the same samples as used for the determination of the depinning field. After the same saturation and DW nucleation procedure was performed as described earlier, the external magnetic field was increased until DW pinning could be observed at the pillars’ position. At that point, the magnetic field was decreased towards the initial saturation direction. The magnitude of the negative external magnetic field at which the DW began to move away from the pillar is in this report called the pulling field of the pillar.

As described in chapter 3, the DW movement under influence of the external
Chapter 4 Results and discussion

Figure 4.5: Overview of the typical stages which could be observed with the Kerr microscope during a measurement to determine the depinning field of a pillar. The dark area inside the nanowire represents the part of the wire which has switched in the direction of the external magnetic field. The dark area during domain wall nucleation is the irradiated part of the wire.

Several nanowires which lie next to each other could be studied at once during one measurement by video recording the domain wall movement as a function of the applied field and performing video analysis thereafter. Hereby the total brightness of the video image inside a region of interest was a measure for the orientation of the magnetization, as can clearly be seen in figure 4.5. Figure 4.6 gives a visual explanation of how the regions of interest were chosen. Figure 4.7 furthermore shows a typical hysteresis loop found with this method. The data in the figure represents the average brightness of a region of interest during the measurement. The entire course of the data shown in figure 4.7 will be discussed later, for the determination of the depinning and pulling field we were only interested in the magnetic field strength needed to depin or retrieve the DW, respectively. To ensure similar conditions over the course of the measurements, the external magnetic field was automatically...
4.2 DW pinning characteristics

Figure 4.6: Visual explanation of how the regions of interest were chosen. The red rectangles represent the regions of interest from which the average brightness as a function of the external field was determined. There was only one region of interest per nanowire and each region of interest resulted in hysteresis loops as shown in figure 4.11. The left nanowire inside the magnified image shows DW pinning.

controlled by a computer and increased linearly with time. The depinning and pulling fields were determined with a field sweep rate of approximately 0.07 mT per second and a step size of 0.02 mT. Both the depinning and pulling field are expected to slightly increase by increasing sweep rate, since the chance of depinning scales with the applied magnetic field and the time a certain magnetic field holds.

Figure 4.8 shows the experimental results for the depinning and pulling field as a function of the pillar height. When looking at the result in the figure, a few phenomena can be noticed and will be discussed now. These phenomena are:

- For lower pillars, the depinning field increases with increasing pillar height.
- The depinning field seems to saturate for higher pillars.
- The pulling field decreases slightly for lower pillars and tends to saturate for higher pillars.
- The depinning field is higher than the pulling field.
- There is a large distribution of data points.

First there is the increase of the depinning field for pillars with a height of 150 nm up to 300 nm. This increase is not very surprising since higher iron
Figure 4.7: Typical data found for the average brightness of a region of interest during one measurement. First, a high negative magnetic field was applied to magnetically saturate the sample. After that, a hysteresis loop was started which resulted in the data shown. In this case the depinning field was approximately 7 mT.
pillars are expected to produce stronger stray fields compared to smaller iron pillars and therefore have more potential to influence the domain wall movement. Nevertheless, although the height of the pillars increases, saturation of the depinning field seems to occur for higher pillars. For higher pillars this result is also as expected since for these pillars the shape of the stray field produced by the pillar - which in turn determines the shape of the energy barrier - does not change that much anymore with a changing pillar height (see also theory section). If these explanations are true, then figure 4.8 suggests that saturation of the depinning field is first achieved for pillars with a height of approximately 300 nm.

A nice comparison can be made between the results shown in figure 4.8 and the results which we theoretically would expect. Figure 4.9 shows the theoretical result for both the depinning and pulling fields. These fields have been calculated by finding the maximum and minimum values of the average (across the width of the wire) perpendicular magnetic field for different pillar heights. Note that, except for the magnitudes of the fields, the similarity between the experimental results and the theoretical results is striking. Theoretically we also find saturation for both the depinning and pulling fields of relatively high pillars. This saturation begins at a pillar height of approxi-
Figure 4.9: Calculated depinning and pulling field as a function of the pillar height. The calculation has been performed for pillars with a constant base diameter of 60 nm.

mately 300 nm, just like our experimental result.

Although the explanation for the increase and stabilization of the depinning field sound very plausible, there could still be another reason for this behavior. One possible reason could be that most smaller pillars, although fabricated on the same day, were grown with a somewhat lower precursor gas pressure compared to the prevailing gas pressure during the fabrication of most of the higher pillars (see the experimental setup section for the decreasing precursor gas pressure). This difference in fabrication conditions could have caused the iron pillars to have slightly different compositions, which in turn causes possible differences in the DW depinning field. Unfortunately, due to the small dimensions of the pillars, it was not possible to directly measure the composition of the individual pillars accurately and learn more about the influence of the decreasing precursor gas pressure on the composition and the magnetic properties of the deposits.

When looking at the trend of the pulling field in figure 4.8, it decreases slightly for lower pillars and seems to saturate for higher pillars. As already discussed and shown in section 2.3 and figure 4.9, this general behavior can also be expected when the energy landscape distortion caused by a pillar looks
4.2 DW pinning characteristics

like an energy barrier with a relative small energy dip in front of it, as shown in figure 4.2c. The bottom of the energy dip just in front of a pillar is deeper and narrower for smaller pillars compared to higher pillars, causing a higher pulling field for smaller pillars. The saturation of the pulling field for higher pillars could be explained by the same argument as the argument for the earlier discussed saturation of the depinning field: height changes of higher pillars have less influence on the shape of the stray fields they produce when compared to smaller pillars and hence the pinning characteristics change less.

Nevertheless, it is still not certain whether the dip in the energy landscape just in front of a pillar actually has influence on the pulling field. The main reason for this is that, during this project, no experiments have been performed yet to determine what magnetic field is needed to initiate movement of a domain wall that is not pinned. If this field would be slightly lower (especially for lower pillar) then the pulling field as shown in figure 4.8, this would be strong evidence that indeed the deepness of the dip in the energy landscape just in front of a pillar influences the pulling field.

Another thing that can be mentioned by looking at figure 4.8 is that the depinning field is much higher than the pulling field. This result strongly underlines the idea that the energy landscape distortion caused by the stray field of the pillar looks like the combination of a relatively small energy well followed by a relatively big energy barrier, as calculated in section 4.1.

Finally, the results for the depinning field and the pulling field as shown in figure 4.8 show a large distribution of data points, even when pillars with approximately the same height are compared. One important thing to mention here is that the data points shown in the figure are averages of multiple measurements (typically six) done on individual iron pillars. No large distribution of the depinning field could be observed between repeated measurements on the same pillar (as reflected in the error bars in figure 4.8), which excludes a major influence of, for example, thermally induced depinning events. Therefore, the different results found for similarly high iron pillars are most likely caused by a lacking reproducability of the nanowires and/or the iron pillars.

One possible explanation for the distribution of data points is found in the fabrication process of the iron pillars. First of all, since the EBID growing process is in essence very chaotic, it could be that the atomic structure and thereby the magnetic properties of two similarly shaped iron pillars can differ much. Furthermore, the decreasing gas pressure influenced the grow speed of the iron pillars and with that most likely also the structure and composition.
of the iron pillars. These two phenomena affect the reproducibility of the fabrication process, which makes it harder to successfully fabricate a lot of similar iron pillars. It could also be the case that there are structural differences between the nanowires, since every iron pillar was grown on another nanowire. Nevertheless, all the nanowires were fabricated the same way so no significant differences between them are expected.

4.3 Coercive field of EBID iron pillars

During the earlier discussed experiments on the pinning characteristics of EBID iron pillars, it was discovered that in most cases no domain wall pinning could be observed when, at the end of a measurement, the orientation of the external magnetic field was set to zero and subsequently was increased slowly in the opposite direction. This phenomenon was even observed for cases when the external field was reversed after the domain wall had already overcome the energy barrier of the iron pillar and the entire Pt/Co/Pt strip was switched. This observation suggests that the depinning field of the iron pillars was in most cases lower than the coercive field of the iron pillars. Below, we will exploit this observation to measure the coercive field of the pillar itself.

Figure 4.10 gives a schematic overview of the experimental approach to determine the coercive fields of the EBID iron pillars. First, exactly the same procedure is followed as the earlier described experiment from section 4.1. After the magnetization of the nanowire is totally switched in the direction opposite to the initial saturation direction, the external magnetic field is increased even more until a certain maximum magnitude. At that point, two different states of the sample can be distinguished. When the maximum applied magnetic field is lower than the coercive field of the iron pillar, the magnetization of the pillar will not switch and theoretically there is only pinning due to the small field just in front of a pillar by repeating the same experiment with a reversed magnetic field (see (I) in figure 4.10). Note that, in our case, no pinning was observed by repeating the same experiment with a reversed magnetic field since the field needed to inject the DW inside the wire was generally higher than the pulling field. For the case that the maximum applied magnetic field is higher than the coercive field of the iron pillar, the magnetization of the pillar will switch and pinning can be observed by repeating the same experiment with a reversed magnetic field (see (II) in figure 4.10). So by determining the minimum magnetic field at which domain wall pinning can be observed after reversal of the magnetic field, the coercive fields of the iron pillars can be determined.
For the determination of the coercive fields of EBID iron pillars, the same samples have been used as for the determination of the depinning and pulling fields of EBID iron pillars. The samples were first saturated with a magnetic field of $\pm 100$ mT, whereafter a hysteresis loop was started. The hysteresis loop, and thereby the external magnetic field, was automatically controlled by a computer and the maximum field was increased with 2 mT each time between measurements. This was continued until pinning was observed by all domain walls which were under investigation. Similar to the earlier described measurements, several nanowires could be investigated at once by video recording the domain wall movement and performing video analysis thereafter. Figure 4.11 shows typical hysteresis loops for the two distinguishable cases. The data in the figures again represent the average brightness of a region of interest during the measurement.

Figure 4.12 shows the measured coercive fields of the iron pillars as a function of the pillar height. One of the first things to note is a strong dependency
Figure 4.11: (a) Typical hysteresis loop for the case that the maximum external magnetic field was lower than the coercive field of the pillar. Stepwise explanation of the data: (1) the external magnetic field begins at the minimum magnetic field and increases. When positive, it nucleates a DW in the nanowire. (2) The DW overcomes the barrier between the with gallium irradiated part of the wire and the rest of the wire and gets pinned by the iron pillar. (3) The external magnetic field has reached the depinning field of the pillar and the DW overcomes the energy barrier caused by the iron pillar. (4) The external field increases to the set maximum field and decreases again. (5) The external field continues its decrease. (6) After nucleation, the DW breaks through the pinning spot between the irradiated part of the wire and the rest of the wire. Since the magnetization of the pillar was not switched, no pinning is observed. (b) Typical hysteresis loop for the case that the maximum external magnetic field exceeds the coercive field of the pillar. Note the additional pinning contribution in the upper left corner of the graph.
between the height of a pillar and its coercive field. According to the results, the coercive field tends to increase linearly with the height of the pillars. Theoretically an increase is also expected, although not linearly. When applying the Stoner-Wohlfarth model to this problem, a dependency between the height of a pillar and its coercive field is found as shown in figure 4.13. When comparing the experimental and theoretical results from figures 4.12 and 4.13, the results differ on two major points: (1) the coercive fields according to the Stoner-Wohlfarth model are much higher than found in the experimental results and (2) in contrast to the theoretical results, the experimental results do not show saturation of the coercive field for higher pillars. The first difference between the magnitudes of the coercive fields can, to a large extent, be explained by the fact that for the Stoner-Wahlfarth model it is assumed that the iron pillars consist of one magnetic domain. In practice, this is almost never the case and especially not for the EBID iron pillars because of impurities in the deposition. The second difference, that no saturation is observed for higher pillars, is at this point not yet understood and needs further investigation. Still, although mentioned differences between the experimental and theoretical results exist, the general behavior of the coercive field is there: the coercive field increases with an increasing iron
Figure 4.13: Coercive field as a function of the pillar height, according to the Stoner-Wohlfarth model. The base diameter of the pillars is held constant at 60 nm. The line is a guide to the eye.

One thing also worth mentioning is that for lower pillars (with a height between 130 - 300 nm) a large variety of the coercive fields was found. In fact, one could recognize two different trends in the data, which are made more visible in figure 4.14. Further investigation of the data points revealed that the associated pillars belong to two different sample groups, which will now be explained in more detail. The sample used contained different sections with nine nanowires each. During the fabrication process of the iron pillars, one section was provided with iron pillars without interrupting the precursor gas flow. After this, the precursor gas flow was temporarily stopped and preparations were made to provide another section with iron pillars. The described fabrication method resulted in different fabrication conditions for the different sections of the sample, more explicitly because of the decreasing precursor gas pressure issue (see section 3.2). These different conditions during sample fabrication could have caused differences in composition and geometry of pillars from different sections, which in turn could have caused differences in their magnetic characteristics and hence their coercive fields.

When looking closer to the relative position and the geometry of the pillars
4.3 Coercive field of EBID iron pillars

Figure 4.14: Coercive field as a function of the pillar height. This figure is a magnification of the data shown earlier in figure 4.12 for pillars with a height between 130 - 300 nm. The two dashed lines are guides to the eye and represent two different trends that can be recognized in the data. The two different colours indicate data points which belong to the same set of pillars, all located inside the same region on the sample. The black data is from pillars which were grown in ten seconds with a precursor gas pressure of $2.4 \times 10^{-6}$ millibar at the beginning of the EBID process. The red data is from pillars which were grown in twenty seconds with a precursor gas pressure of $3.0 \times 10^{-6}$ millibar at the beginning.
Figure 4.15: Two iron pillars with approximately the same height. The pillars were positioned in another section on the sample. The first pillar was grown in ten seconds with a precursor gas pressure of approximately $2.3 \times 10^{-6}$ millibar at the beginning of the EBID process. The second pillar was grown in twenty seconds with a precursor gas pressure of $2.4 \times 10^{-6}$ millibar at the beginning. Note that the first pillar was fabricated closer to opening of the GIS, since the first pillar was third in row and the second pillar was nineth in row. By comparing the geometry of the pillars, it can clearly be seen that the first pillar is smaller than the second one. This difference is thought to cause the difference in coercive fields.

From which the coercive fields are shown in figure 4.14 it is first found that both trends are due to two different sets of pillars. The higher coercive fields are from pillars located inside another section of the sample than those with the lower coercive fields, which means that they experienced different fabrication conditions because of the earlier described precursor gas issue. This possibly causes differences in the structure and composition of the pillars (similar as described in the previous section). When comparing the geometry of the associated pillars, it can be concluded that the pillars with the lower coercive fields are slightly wider than those with the higher coercive fields. Figure 4.15 shows two pillars with approximately the same height to illustrate this. The pillars shown in the figure were positioned on a different section of the sample and it can clearly be seen that the first pillar is smaller than the second one. This difference in geometry alters the shape anisotropy, resulting in a higher coercive field for the smaller iron pillar, which is in agreement with the Stoner-Wohlfarth theory.

When we look closer to the diameters of the higher pillars, we find that these are constantly between 60 - 70 nm. The results for higher pillars shown in fig-
figure 4.12 underline this, since the higher pillars nicely follow one trend. Note that the influence of the base diameter is also expected to be less significant for higher pillars, since the shape anisotropy of a pillar is determined by the ratio between its width and height. This ratio changes less for higher pillars when the base diameter changes.
Chapter 5

Conclusions and outlook

To conclude this report, the findings and conclusions of the previous chapter are briefly summarized here. Furthermore, a small outlook on possible future research is presented.

Conclusions

The most important findings and conclusions of this work are:

- EBID iron deposits show magnetic behavior. The experimental results show that an EBID pillar’s magnetic stray field influences DW movement and that these pillars show magnetic hysteresis.

- DWs can be used to detect localized stray fields of nanoscaled magnetic objects and to determine the coercive fields of such objects. In this report DWs were successfully used to characterize the magnetic behavior of small iron pillars.

- Magnetized EBID iron pillars placed on top of perpendicularly magnetized nanowires create DW pinning sites. This pinning is expected to be stronger for smaller nanowires, since then its harder for a DW to bend around the pinning site.

- For low EBID iron pillars, the depinning field of a pillar increases with increasing pillar height. For higher pillars, saturation of the depinning field occurs. Saturation of the depinning field is first achieved by pillars with a height of approximately 300 nm, for a base diameter of 60 nm. This general behavior is consistent with theory.
• For low EBID iron pillars, the pulling field of a pillar decreases with increasing pillar height. For higher pillars, saturation of the pulling field occurs. Similar as the saturation of the depinning field, saturation of the pulling field is first achieved by pillars with a height of approximately 300 nm, again for a base diameter of 60 nm. This general behavior is also consistent with theory.

• The coercive field of an EBID iron pillar increases with increasing pillar height. This is consistent with the Stoner-Wohlfarth model including shape anisotropy. Nevertheless, no saturation of the coercive field is observed for higher pillars as theoretically is expected. This behavior is not well understood yet.

• The coercive field of an EBID iron pillar seems to decrease with increasing pillar diameter. Although not explicitly examined, this is strongly suggested by the two trends found for the coercive field of lower pillars. In theory this should also be the case.

• EBID of iron with Fe\(_2\)(CO)\(_9\) as the precursor gas is not good in terms of reproducibility. The decreasing precursor gas pressure during pillar fabrication resulted in different fabrication conditions for different pillars, which in turn resulted in pillars with a slightly different geometry and/or composition. Furthermore, the chaotic nature of EBID itself also induces possible differences between the composition of on first sight similar pillars. These differences are reflected in the magnetic behavior of the pillars by a large distribution of datapoints for the depinning and pulling field of a pillar.

**Outlook**

The research on DW pinning and more explicitly on DW pinning by nanoscaled magnetic EBID deposits is still in its infancy. Findings and conclusions comparable of those found in this work are reasons for more research on this subject, since not everything is understood yet and the research possibilities seem endless. Possible future research on this subject could have as goal to:

• Examine if indeed saturation of the coercive field occurs for higher (iron) pillars, as theoretically is expected. This is not (yet) observed for a pillar height of 1 micrometer.

• Examine if depositions made with other precursor gases also show magnetic behavior and characterize this behavior. For example, Cobalt can
also be deposited and Cobalt depositions are expected to have magnetic properties as well.

- Examine if the magnetic orientation of a DW influences DW pinning by EBID iron pillars. This can be done both experimentally and theoretically.

- Examine the possibilities in designing specific localized stray fields by creating exotic nanoscaled magnets, like a horseshoe magnet. The beauty of EBID is that it enables us to manufacture deposits with almost any shape.
Bibliography


