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Towards electric field assisted spin Hall torque switching of perpendicularly magnetized bits

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Abstract

A new type of perpendicularly magnetized memory is explored, combining the spin Hall effect as a switching mechanism with the electric field effect as a selector. Calculations predict that this method is feasible. Magnetization reversal experiments show a coercivity modification between 4.5 mT and 13 mT for voltages between -2 V and +2 V. Two sensitivity regions are identified: a low sensitivity region of 0.5 mT/V for -0.8 V < V < 1.6 V and a high sensitivity region of 4.5 mT/V for higher voltages up to ±2.0 V. A logarithmic time dependence of the coercivity is found for voltages in the higher sensitivity region, which is attributed to a changing stoichiometry of the AlOx-Co interface due to migrating oxygen vacancies. The logarithmic time dependence is explained using a thermal fluctuation aftereffect model. Experimental results on spin Hall torque switching of a PMA microwire are in good agreement with the literature, showing that similar devices could be used in future projects.
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Chapter 1

Introduction

Technology plays an important role in our lives nowadays. Electrical devices such as mobile phones and laptops are commonly used and often thought to be indispensable. For all these devices to work properly, however, they need to have the ability to electronically store data in one way or another. Therefore, it is not hard to imagine that already a lot of research has been devoted to electrical data storage during the past decades. Research towards electrical data storage can be traced back to the early 1940’s, when John Vincent Atanasoff and Clifford Berry invented the first fully electric computer [35]. Since then, many new discoveries allowed the development of smaller, faster, more reliable and more efficient data storage mechanisms. Nowadays, still many researchers focus on the development of new data storage mechanisms, not in the last place because of the ever increasing demand for faster and smaller memories from technical industries.

1.1 MRAM

One of the latest types of memory is called the Magnetoresistive Random Access Memory (MRAM). This type of memory stores data magnetically and is able to individually access bits, the fundamental parts of a memory that contain the actual data in the form of “0” and “1”. To do so, MRAMs are ideally arranged in a so called crossbar memory array, of which a schematic example is shown in figure 1.1. Every bit consists of a serially connected selector and memory device. The actual data is stored in the memory device that can either have a low electrical resistance (‘0’) or high electrical resistance (‘1’). Addressing an individual bit is done by properly biasing the column and row electrodes as schematically shown in figure 1.2.
Figure 1.1: Schematic picture of a crossbar RAM. Individual memory cells are located between column and row electrodes. Note that every bit consists of a serially connected selector and memory layer. The memory '0' state corresponds to a low resistive state of the memory layer, whereas the memory '1' state corresponds to a high resistive state of the memory layer. Picture taken from [36].

Figure 1.2: Schematic picture of properly biasing the column and row electrodes to read out or write the data of one individual memory cell (in this case the cell located within the dashed circle). Note that only the selected cell experiences a voltage of 2 V, which triggers the selector to enable access to the accompanying bit.
1.2 Magnetic tunnel junctions

The memory device of a MRAM bit consists of a so called magnetic tunnel junction (MTJ). Depicted in figure 1.3, a MTJ consists of two magnetic layers with a dielectric barrier in between. Due to the tunnel magnetoresistance (TMR) effect [45], the electrical resistance of such MTJ depends on the relative orientation of the magnetization directions. The magnetization direction of one layer is fixed, whereas the magnetization direction of the other (free) layer can be manipulated to be either parallel or anti-parallel to the fixed magnetization. This enables the device to be used as a memory element of which the data can be read out electronically.

Switching the free magnetic layer of a MTJ is generally performed by either a magnetic field or an electric current. Local magnetic fields have the drawback that they cannot easily be scaled down to small dimensions, which is not the case for electric currents. Switching by an electric current is accomplished by applying a spin-polarized current through the MTJ and utilizing the so called spin transfer torque (STT) [32]. Unfortunately, this mechanism requires relatively high current densities (~ $10^7$ A/cm$^2$) to switch the free magnetic layer [25]. High current densities are not desirable for two reasons: 1) it is not energy efficient, and 2) since the current passes through the MTJ, it can be damaged by Joule heating or electromigration. For this reason, other mechanisms that are able to manipulate the free magnetic layer of a magnetic tunnel junction electrically are of great interest. Two mechanisms that could enable a more efficient and reliable manipulation of the free layer are the electric field effect and the spin Hall effect, which are introduced in sections 1.4 and 1.5, respectively. First, however, a phenomenon called perpendicular magnetic anistropy (PMA) needs to be introduced.

Figure 1.3: Schematic picture illustrating a magnetic tunnel junction consisting of two out-of-plane magnetized layers. (Left) Parallel configuration and (Right) anti-parallel configuration. Due to the TMR effect, the configuration can be determined electronically.
1.3 Perpendicular magnetic anisotropy

The magnetization direction of magnets is generally not random, but wants to align itself along a preferred direction. This phenomenon is called magnetic anisotropy and generally implies that a magnet is magnetized along its long axis. Therefore, magnetic storage devices have long worked with in-plane magnetized layers, since the magnetization naturally aligns itself in this direction. When technological advances in fabrication processes enabled the fabrication of subnanometer thick layers, however, it was observed that the magnetization of very thin magnetic layers can point out-of-plane. This phenomenon is called perpendicular magnetic anisotropy (PMA) and is attributed to electronic interactions at the interfaces between the magnetic layer and its adjacent materials. The magnetic characteristics of perpendicularly magnetized layers therefore depend strongly on the exact electronic and atomic configuration of the corresponding interfaces.

The discovery of perpendicularly magnetized layers had a great impact on electrical data storage devices. Perpendicularly magnetized layers can be scaled down more easily than in-plane magnetized layers, without compromising the stability of a bit. This allowed for the creation of memories with higher data densities, enabling smaller and more wearable devices.

1.4 Electric field effect

For many years, it was thought that the magnetic anisotropy, along with other magnetic characteristics of a magnetic layer, could only be influenced by changing the layer thicknesses or the stoichiometry of the interfaces between the magnetic layer and its adjacent layers. It was Maruyama et al. who first reported that an electric field across a solid-state Fe-MgO interface could change the perpendicular anisotropy of the iron by as much as 40%[27]. Their results, which are shown in figure 1.4 gained immediate interest since electric fields can be applied easily and efficiently. The electric field effect therefore has great potential to be used in conventional memory devices. Subsequent quantitative measurements on the electric field effect in solid-state devices showed a linear dependence of the surface anisotropy as a function of electric field in various material systems.

The electric field effect can be explained by the interfacial origin of PMA. As mentioned in the previous section, PMA arises from electronic interactions at the interfaces between a magnetic layer and its adjacent materials. An
1.5 Spin Hall effect

Figure 1.4: (Left) Schematic of the sample used by Maruyama et al. for a voltage-induced magnetic anisotropy change. (Right) Perpendicular orientation of the magnetization for different applied voltages as a function of applied field. A significant change in the hysteresis curve indicated a large change in perpendicular anisotropy following application of the bias voltage. The left inset illustrates the magnetization direction at points A and B in the hysteresis curves. Pictures taken from [27].

electric field is able to change the electron density at these interfaces, which in turn changes the surface anisotropy. Since the stability of a magnetic layer is determined by its magnetic anisotropy, an electric field can thus be used to decrease (increase) the stability of a magnetic layer, making it easier (harder) to switch the magnetization of the layer.

One of the first studies that report fast electric field driven switching of a magnetic tunnel junction was performed by Wang et al. [50]. As can be seen in figure 1.5, they were able to significantly reduce the necessary external magnetic field to switch the magnetization of the free layer by applying a voltage across the device. Their promising results paved the way for electric field assisted switching of magnetic bits.

1.5 Spin Hall effect

The spin Hall effect is an effect that involves the so called spin of an electron. Classically, the spin of an electron can be viewed as a clockwise or counterclockwise rotation around its axis, resulting in two possible magnetic moments that point opposite to each other. A current generally consists of electrons with an equal amount of spin in either direction, but certain effect can separate electrons with opposing spin, creating a spin-polarized current. One of these effects is called the spin Hall effect, which is schematically il-
Figure 1.5: (Left) Geometry of the MTJ used to study electric field driven switching of a CoFeB layer. (Right) TMR curves under different bias voltages, showing a large change in the magnetic behavior as a function of voltage. Adapted from [50].

Figure 1.6: (Left) Schematic illustration of the spin Hall effect. Electrons with opposite spin gain a velocity in opposing vertical directions, leading to a spin-polarized current at the top and bottom interfaces of the conducting microwire. (Right) Figure illustrating the direction of the spin Hall torque on the magnetization of the adjacent perpendicularly magnetized layer.

Illustrated in the left panel of figure 1.6. When a current flows through a high spin-orbit coupling material like platinum or tantalum, interactions between the electrons and the lattice cause a vertical separation of electrons with opposite spin. Due to the magnetic moment of the electrons, the resulting vertical flow of spin-polarized electrons is able to exert a torque on the magnetization of adjacent layers. This torque is called the spin Hall torque and, as illustrated in the right panel of figure 1.6, is able to rotate the magnetization towards an in-plane configuration.

The spin Hall torque can be used to switch the magnetization of adjacent layers, thereby offering a new way to manipulate thin magnetic layers. As
an example, spin Hall torque driven switching of a PMA magnetic layer was shown by Miron et al., who performed switching experiment on perpendicularly magnetized Pt-Co-AlOx devices (left panel of figure 1.7). By applying current pulses through the platinum microwires as well as a small magnetic field along the current flow direction, they were able to switch the magnetization deterministically as depicted in the right panel of figure 1.7. A drawback of spin Hall torque induced switching is that the necessary current density is of the order of $10^8$ A/cm$^2$, which is rather high. New ways to reduce this switching current are therefore of great interest.

1.6 This thesis

Although a wide range of studies has been performed focusing solely on the electric field effect or spin Hall effect, only recently they have been combined successfully by Liu et al. [24]. They performed spin Hall torque switching measurements on a MTJ as shown in the left panel of figure 1.8. As can be seen in their results in the right panel of figure 1.8, they were able to significantly reduce the spin Hall torque switching current for an in-plane magnetized free layer by applying an electric field across the MTJ. As proposed independently by Liu et al. and Van den brink [46, 24], this mechanism enables a new data writing scheme for crossbar MRAM where spin Hall torque switching is assisted by an electric field. This could significantly decrease the data writing time and energy consumption of memories, since it allows multiple bits to be written simultaneously by one single current pulse. This mechanism is depicted in figure 1.9.
Figure 1.8: (Left) Schematic picture of geometry used to examine E-field assisted spin Hall torque switching. (Right) Spin Hall torque switching curves for different values of MTJV, for 10 ms pulses. The lead resistance from the Ta contact has been subtracted. The data for different MTJV are offset vertically. Pictures from [24].

Figure 1.9: MRAM concept using in-plane current injection to switch magnetic bits. Each junction is a MTJ stack. A bias voltage supplied to the top leads is used to control which bits are switched: a positive (negative) bias voltage increases (decreases) the magnetic anisotropy to prohibit (allow) switching. All bits on a current line can be selectively switched simultaneously. Read-out is performed using the TMR effect. Picture and description from [46].

As shown by the results of Liu et al., the electric field effect and spin Hall effect have already been combined successfully. However, the device used by Liu et al. consists of in-plane magnetized layers, whereas perpendicularly magnetized layers are preferred due to their earlier mentioned superior scalability as compared to in-plane magnetized layers. The concept of electric field assisted spin Hall torque switching can therefore be improved by utilizing perpendicularly magnetized layers instead of in-plane magnetized layers.
This thesis focuses on combining the electric field effect and spin Hall effect in Pt-Co-AlOx devices with perpendicularly magnetized layers. Figure 1.10 shows a device consisting of two MTJs with perpendicularly magnetized layers that can be manipulated by both an electric field and spin Hall torque. To investigate both the physics and the feasibility of this memory device, the measurements presented in this thesis all focus on a particular aspect of the memory. This includes a theoretical study on the feasibility of the memory, material thickness dependence studies to determine the appropriate material thicknesses to create the perpendicularly magnetized layers, a comprehensive characterization of the electric field effect of a simplified magnetic bit, and finally some preliminary results on spin Hall torque switching. Along the way we will see that the electric field effect measurements reveal previously unreported behavior, which is explored in detail.

The next chapter, chapter 2, will first cover some theory applicable to general magnetism, its dynamics, the electric field effect, spin Hall torque switching, and device physics. It also includes a theoretical feasibility study on the proposed memory. An overview of the experimental setups used will be given in chapter 3, together with a description of the samples used during this project and their corresponding fabrication processes. The experimental results on
the E-field effect are described and discussed in chapter 4, after which preliminary spin Hall torque switching measurements are presented in chapter 5. Finally, chapter 6 summarizes the findings of this project and will discuss some possible future research on the E-field effect and spin Hall torque switching.
Chapter 2

Theory

This chapter covers some basic theory that is applicable to general magnetism, its dynamics, the electric field effect, spin Hall torque switching, and device physics. It starts with an introduction on magnetic anisotropy and magnetic switching, after which both the electric field effect and spin Hall effect are discussed. This knowledge is subsequently used for a feasibility study on a memory that successfully employs the electric field effect as the selector mechanism in a cross-bar memory array. The last section is devoted to physical mechanisms that could play a role during electrical measurements on a Pt-AlOx-Co structure.

2.1 Magnetic anisotropy

The direction of the magnetic moment in a ferromagnetic specimen is generally not random, but prefers to align itself along a certain easy axis or plane. This phenomenon is called magnetic anisotropy and is very important concerning the fabrication and characterization of magnetic specimens. There are three main sources that contribute to the anisotropic behavior of a magnetic film: magneto-crystalline anisotropy, shape anisotropy, and interface anisotropy. These sources will be briefly described, after which the effective magnetic anisotropy of a perpendicularly magnetized thin film will be addressed.

Magneto-crystalline anisotropy

Magneto-crystalline anisotropy is the anisotropy that arises due to a material’s crystal structure. Certain crystal structures can induce a preferred configuration for the orbital electrons due to interactions between the electrons.
of neighboring atoms. Since the orbital moment of an electron is coupled to its spin, such a preferred configuration of electron orbitals in turn induces a preferred direction for the magnetization.

The energy density associated with magneto-crystalline anisotropy is given by the volume anisotropy constant $K_v$. Since the total magneto-crystalline anisotropy energy of a magnetic material scales with its volume, this anisotropy plays a relatively bigger role in bulk magnetic materials as compared to lower dimensional structures. For lower dimensional structures, other sources for magnetic anisotropy (like the following shape and surface anisotropies) are more likely to determine the magnetic characteristics of the structure.

**Shape anisotropy**

The shape of a magnetic specimen can be of great influence on the magnetization. Due to the long range magnetic dipolar interaction between spins, a magnetic specimen can sense its outer boundaries [14]. This favors a magnetization that is aligned along the longest axis of a magnetic specimen, since this minimizes the total dipolar energy within the magnetic material. This anisotropic behavior called shape anisotropy is thus a macroscopic manifestation of the microscopic dipole-dipole interaction favoring spin alignment along internuclear axis [46].

To account for the shape anisotropy within a magnetic material, an effective magnetic field called the demagnetization field is used. The demagnetization field is defined as:

$$
H_d = -\left(\frac{N_x M_x \hat{x}}{N_x M_x}, \frac{N_y M_y \hat{y}}{N_y M_y}, \frac{N_z M_z \hat{z}}{N_z M_z}\right),
$$

with $N_d = (N_x, N_y, N_z)$ the demagnetization vector and $M = (M_x, M_y, M_z)$ the magnetization within the material. The demagnetization vector $N_d$ depends on the specific geometry of the magnetic material, for which the limiting case for a magnetic thin film is shown and discussed in figure 2.1. Since the individual values for $N_d$ are positive by definition, the demagnetization field always counteracts the effective magnetic field inside a magnetic material.
2.1 Magnetic anisotropy

Figure 2.1: The limiting case for the demagnetization vector of a magnetic thin film. For an in-plane magnetized thin film, the magnetization is aligned along the longest axis, resulting in a negligible demagnetization field and $N_{x,y} = 0$. However, the demagnetization field is maximized for an out-of-plane magnetized thin film, so $N_z = 1$. Hence, without any other source of magnetic anisotropy, the magnetization of a thin film will be in-plane. Picture adapted from [44].

Surface anisotropy

Surface anisotropy can be viewed as a special case of magneto-crystalline anisotropy. Since magneto-crystalline anisotropy originates from the anisotropic lattice structure of a material, the anisotropic behavior at a material’s surface can differ significantly from the bulk. The magnetic anisotropy that arises due to such surface interactions is called surface anisotropy and plays a significant role in perpendicularly magnetized thin films.

To illustrate the significance of surface anisotropy, again consider the case of a magnetic thin film. Without any surface anisotropy at the top and bottom interfaces, the magnetization of a thin film would prefer an in-plane alignment due to its shape anisotropy. However, when a magnetic thin film is sandwiched between two other materials, local interactions at the top and bottom interfaces are sometimes able to overcome the shape anisotropy and cause an out-of-plane easy axis for the magnetization. A perpendicularly magnetized layer is considered to have perpendicular magnetic anisotropy (PMA), of which the strength strongly depends on the specific materials used and the quality of the interfaces.

The surface anisotropy is quantitatively described by the surface anisotropy constant $K_s$, which is defined by the energy difference between the relevant magnetization directions (in-plane or out-of-plane). Surface anisotropy can only influence the magnetization significantly when the material has a relatively large surface to volume ratio, as is the case for a magnetic thin film.
Furthermore, both $K_s$ and the earlier mentioned $K_v$ are defined positive for favoring a perpendicular easy axis.

Thin film magnetic anisotropy

The effective anisotropy of a perpendicularly magnetized thin film can be deduced by combining the previously described sources for magnetic anisotropy. First, by combining the magneto-crystalline and surface anisotropy, we can write for the intrinsic volume anisotropy of a perpendicularly magnetized thin film:

$$K = K_v + \frac{K_{s,\text{top}} + K_{s,\text{bottom}}}{t},$$

(2.2)

where $K_{s,\text{top}}$ and $K_{s,\text{bottom}}$ denote the surface anisotropy values of the top and bottom surfaces, respectively, $t$ the thickness of the magnetic layer and $K_v$ the intrinsic magneto-crystalline anisotropy (without demagnetization field). As argued earlier, the relative strength of both surface anisotropies versus $K_v$ strongly depends on the layer thickness $t$. For the 1 nm thick cobalt film studied here, the expected $K_v$ ($<0.2$ MJ/m$^3$) is small compared to $\frac{2K_s}{t}$ ($\approx 2.0$ MJ/m$^3$) \[14\], thereby making it reasonable to write for $K$:

$$K \approx \frac{K_{s,\text{top}} + K_{s,\text{bottom}}}{t}.$$

(2.3)

The shape anisotropy of a magnetic thin film can be included in equation\[2.3\] by considering the resulting energy density due to the demagnetization field $H_d$. Since the magnetization is pointing out-of-plane, $H_d$ points in the opposite direction as $M$ and is equal in magnitude. Thus, $H_d$ directly lowers the effective perpendicular anisotropy of the thin film since it tends to pull the magnetization in-plane. The energy density due to $H_d$ is in that case equal to $\frac{1}{2}\mu_0 M_s^2$, with $M_s$ the saturation magnetization \[14\]. The effective anisotropy of a perpendicularly magnetized thin film can now be written as:

$$K_{\text{eff}} = \frac{K_{s,\text{top}} + K_{s,\text{bottom}}}{t} - \frac{1}{2}\mu_0 M_s^2.$$  

(2.4)

The resulting equation shows that a positive value for $K_{\text{eff}}$ means that the magnetization favors an out-of-plane magnetization, since in that case the surface contribution to the total anisotropy is bigger than the demagnetization energy. In contrast, a negative value for $K_{\text{eff}}$ results in an in-plane alignment of the magnetization. Equation\[2.4\] also shows that $K_{\text{eff}}$, for a given material, can only be manipulated by changing the layer thicknesses, the surface anisotropies, or $M_s$. 

2.2 Magnetic switching

Whereas the previous section described the general concept and origin of magnetic anisotropy, this section continues on how the magnetization of a material can be manipulated. More specifically, a qualitative discussion is given about the magnetic switching dynamics of a thin magnetic film with out-of-plane easy axis, since all devices studied during this project exhibited an out-of-plane magnetization.

2.2.1 Hysteresis

As described in the previous section, magnetic anisotropy implies a preferred axis (easy axis) along which the magnetization wants to align itself. This phenomenon therefore influences what happens to the magnetization of a magnetic specimen when placed inside a magnetic field. A magnetic system can reduce its Zeeman energy in an external magnetic field by aligning its magnetization to the external field \[44\]. However, this Zeeman energy has to compete with the anisotropy energy of the magnetic specimen. This competition can result in magnetic hysteresis: an orientation of the magnetization that depends on the history of the external magnetic field.

Figure 2.2 illustrates the origin of magnetic hysteresis. For a thin magnetic layer with PMA, the easy axis points out-of-plane. Without the application of an external magnetic field, both the “up” and “down” magnetization represent an equal local minimum in the total energy density as a function of \(\theta\). However, when a magnetic field is applied along the easy axis, the Zeeman energy results in an asymmetry between the two local minima as shown in the right graph of figure 2.2. An external field pointing in the opposite direction as the magnetization increases the total energy density of the system, but will not cause the magnetization to switch until the magnetic field is strong enough to let the local minimum of the established situation disappear. The magnetization at zero field therefore depends on the history of the external magnetic field, causing magnetic hysteresis.

Figure 2.3 shows experimental data of an easy axis hysteresis loop measured on a thin magnetic film with PMA. It clearly shows that for the easy axis loop, the magnetic component along this easy axis can find itself in two different configurations at zero magnetic field. Such hysteresis loops are characterized by the remaining magnetic saturation at zero bias field, called the remnant magnetization \(M_r\), and the magnetic field strength at which the magnetization switches, called the coercivity \(H_c\). It must however be noted that the
Figure 2.2: (Left) Schematic illustration of the geometry and significant parameters. (Right) Total energy density plotted as a function of $\theta$. The stability of the magnetic configuration is visualized by a small sphere located at an energy minimum. A negative field of $-2K/\mu_0M_s$ is required to switch the magnetization from $\theta = \pi/2$ to $\theta = -\pi/2$. Note: for clarity, the curves have been progressively shifted in vertical direction. Adapted from [44].

Figure 2.3: Experimental easy axis magnetic field loop showing hysteresis. The definition of the coercivity $H_c$ is shown, as well as the magnetic orientation of the sample.

coercivity is in practice not exact and can differ between subsequent measurements, since magnetic switching is a thermally assisted process at finite temperature.
2.2 Magnetic switching

2.2.2 Magnetic domains

In the case of an ideal magnetic thin film, it would be uniformly magnetized. In practice, however, this is rarely the case due to the existence of so-called magnetic domains. Magnetic domains are regions within a magnetic material with uniform magnetization. Many factors can cause the creation of magnetic domains, such as local defects at film edges or in the lattice. Since every magnetic domain can have slightly different magnetic characteristics, this changes the ideal picture of uniform switching of a magnetic layer as described in the previous section. Local variations in the thickness of a magnetic film, for example, result in a locally varying energy barrier between the magnetic up and down state. Switching will then first occur at places where the energy barrier is relatively low, which nucleates a magnetic domain with opposite magnetization.

The switching process of a magnetic layer can be either due to the nucleation of new magnetic domains (nucleation dominated) or by the expansion of existing domains (domain wall motion dominated). Both of these mechanisms are schematically shown in figure 2.4. Independent of the exact switching process, both processes result in a smoother easy axis hysteresis loop when the total magnetization of a layer is measured.

2.2.3 The Landau-Lifshitz-Gilbert equation

To numerically investigate the magnetization dynamics of a magnetic specimen, the Landau-Lifshitz-Gilbert (LLG) equation can be used. The LLG equation describes the precession and damping of the magnetization due to an effective magnetic field inside a material. The most general and simple LLG equation is given by [12]:

\[
\frac{d\mathbf{M}}{dt} = -\gamma (\mathbf{M} \times \mathbf{H}_{\text{eff}}) + \frac{\alpha}{M_s} \left( \mathbf{M} \times \frac{d\mathbf{M}}{dt} \right)
\]  

(2.5)

where \(\mathbf{M}\) denotes the magnetization vector, \(\gamma = \mu_0 \frac{\mu_B}{h}\) the gyromagnetic ratio, \(\mathbf{H}_{\text{eff}}\) the effective magnetic field within a magnetic specimen, \(\alpha\) the Gilbert damping constant and \(M_s\) the saturation magnetization. The first term on the right of equation 2.5 describes the precessional motion of the magnetization around an effective field \(\mathbf{H}_{\text{eff}}\), while the second term describes the damping of the magnetization to \(\mathbf{H}_{\text{eff}}\). The LLG equation can be expanded by other terms which account for different types of torques exerted on the magnetization, i.e. spin transfer torque or spin Hall torque.
Figure 2.4: Illustration of nucleation dominated and domain wall motion dominated switching by the application of an external magnetic field. The dark spots represent areas where the magnetization is switched. In case of nucleation dominated switching, increasing the magnetic field results in the creation of more magnetic domains which are relatively small and locally bounded, until whole layer is switched. In case of domain wall motion dominated switching, however, existing domains prefer to expand by domain wall motion until whole layer is switched. Adapted from [46].

The effective magnetic field $H_{\text{eff}}$ of equation 2.5 is the resulting sum of many different fields, including an effective anisotropy field $H_{K,\text{eff}}$ and any external magnetic field $H_{\text{ex}}$. Without any temperature contributions, we can generally write for $H_{\text{eff}}$:

$$H_{\text{eff}} = H_{K,\text{eff}} + H_{\text{ex}} = H_K - \left( \begin{array}{c} N_x M_x \hat{x} \\ N_y M_y \hat{y} \\ N_z M_z \hat{z} \end{array} \right) + H_{\text{ex}}, \quad (2.6)$$

with $H_K$ the intrinsic anisotropy field (due to surface and volume anisotropies).

Looking at equation 2.6, we see that $H_{\text{eff}}$ depends linearly on $\mathbf{M}$. Therefore, magnetic (switching) dynamics of magnetic components are not straightforwardly evaluated. Any change in $\mathbf{M}$ changes $H_{\text{eff}}$, which in turn influences the magnetization. For this reason, magnetization dynamics are often numerically evaluated.
2.3 Electric field effect

The electric field effect is the general term used to describe the influence of an electric field on the magnetic characteristics of a material. It has been extensively studied in the last couple of years, since the application of an electric field is a simple and energy efficient process which makes it highly suitable to be used in today’s electronics. This section gives a brief overview of the speculated origins of the electric field effect and its current research status.

It is reported in the literature that an electric field changes the perpendicular surface anisotropy $K_s$ of a magnetic layer [40]. Electric field effects are therefore only reported for devices with a thin magnetic film because of the significant surface anisotropy in such devices. An early example of the electric field effect was found by Maruyama et al., of which the results are shown in figure 2.5 [27]. As can be seen, they measured a significant change in the hysteresis curve of the device, which they attribute to a change in perpendicular anisotropy.

Basically two physical mechanisms are proposed that are able to change $K_s$ due to the application of an electric field. First of all, any change in the electron density at the magnetic interface due to an electric field is thought to influence the electron filling of the $3d$ orbitals in the magnetic thin film and thereby the PMA. The other explanation is based on the physical change of the interface stoichiometry caused by diffusing ions or redox reactions.
Maruyama et al. attribute their results, as shown in figure 2.5, to the first mechanism: a change in the electron filling of the 3d orbitals at the surface. A voltage is able to change the electron density at the barrier/Fe interface. This in turn influences the relative energies (and with that occupation) of the 3d orbitals at the interface, causing a modulation of the perpendicular magnetic anisotropy. This phenomenon is schematically shown in figure 2.6. To fully understand this phenomenon, however, first principle calculations are required that include mixing of orbitals and the spin-orbit interaction. For more information on this topic, see [31, 46].

Another interesting result on the electric field effect was reported by Bauer et al. [3]. They demonstrated that a charge-trapping layer placed in proximity to a ferromagnetic metal enables efficient electrical and optical control of the metal’s magnetic properties. This is schematically shown in figure 2.7. ZrO$_2$ is known for its high charge trap density, and the authors show that retention of charge trapped inside this layer provides non-volatility to the magnetoelectric effect and enhances its efficiency by an order of magnitude. Furthermore, it was shown that the trapped charges could also be supplied optically instead of electronically.

It is good to emphasize at this point that, in contrast to the application of a magnetic field, the application of an electric field does not cause one pre-
2.3 Electric field effect

Figure 2.7: (Left) Under positive gate bias, holes from ITO electrode can be optically pumped into ZrO$_2$ charge trapping layer. Trapped holes remain in ZrO$_2$ trapping layer after external bias is removed and generate internal electric field $E$ across MgO barrier. (Right) By partly illuminating the magnetic layer, the coercivity could be changed locally (dark blue spots in the middle). Pictures taken from [3].

Figure 2.8: Schematic representation of the effect of applied voltages and magnetic fields on the energy diagram of a bi-stable magnetic bit. An external magnetic field reduces or increases the energy barrier, depending on its direction with respect to the initial state of the magnetic layer, while the voltage dependent anisotropy reduces or increases it for both switching directions, depending only on the voltage polarity. Picture taken from [16].

As mentioned earlier, another mechanism which could influence the surface magnetic anisotropy is the physical change of the interface stoichiometry caused by diffusing ions or redox reactions. Although ionic diffusion effects...
and redox reactions are known to exist in dielectrics, only recently such mechanisms are related to the electric field effect. A study of Bauer et al. on the electric field control of domain wall propagation in Pt-Co-GdOx films suggests that the electric field effect can be divided in three different regions as shown in figure [2.9][2]. The linear and reversible effect of region I (low voltages) is attributed to the previously described change in electron filling of the 3d orbitals. For higher voltages (electric field > 0.2 V/nm), the linear behavior and reversibility no longer holds, which is attributed to a changing interface stoichiometry due the onset of oxygen vacancy migration in the GdOx which is similar to soft dielectric breakdown. For even higher voltages, hard dielectric breakdown occurs (region III). More information on dielectric breakdown phenomena is given in section 2.6.2.

Direct evidence that an electric field is able to change an interface’s stoichiometry, and with that the magnetization, was recently found by Bonell et al. [5]. By performing x-ray absorption spectroscopy and magnetic circular dichroism measurements on a FeCo-MgO interface, they report a reversible change in the oxidation state and magnetic dichroism of the iron due to the application of an electric field. Similar results were found by Leistner et al., who also report an electric field control of magnetism by reversible surface reduction and oxidation reactions [21]. These results show that electrochemical phenomena should not be neglected in the interpretation of recent results dealing with voltage control of magnetism.
Figure 2.9: Experimental results found by Bauer et al. (a) Modification of switching field $H_c$, (b) remnant to saturation magnetization ratio $M_r/M_s$, and (c) leakage current (clamped at 0.5 mA) as a function of time while gate voltage $V_g$ is ramped in steps of 0.5 V every 40 s (d). Left and right half of figure correspond to two different devices, measured under increasing negative and positive $V_g$, respectively. The effects in regime I are linear and reversible. Regime II (enlarged in inset of (a)) is marked by the onset of irreversibility and, at higher $V_g$, a steep drop in $H_c$ and $M_r/M_s$. Regime III corresponds to hard dielectric breakdown. The dashed area highlights lack of regime II for negative $V_g$. Insets in (b) show representative hysteresis loops at indicated points. Picture from [2].
Figure 2.10: Schematic illustration of the spin Hall effect. Electrons with opposite spin gain a velocity in opposing vertical directions, leading to a spin-polarized current at the top and bottom interfaces.

2.4 Spin Hall effect

When a current flows through a conducting material with a high spin-orbit coupling like platinum or tantalum, interactions between the flowing electrons and the lattice cause a vertical separation of electrons with opposite spin. This phenomenon is called the spin Hall effect and is schematically illustrated in figure 2.10. The resulting vertical flow of spin-polarized electrons is able to influence the magnetization of adjacent magnetic layers by exerting a torque on the magnetization at the interface. In such cases, the spin Hall effect always exerts a torque which is parallel to the y-direction as shown in figure 2.10.

The spin Hall effect can be accounted for in the switching dynamics of adjacent magnetic layers by adding the following term to the general LLG equation (equation 2.5):

$$\frac{\alpha_{SH} \mathbf{M} \times (\mathbf{\sigma} \times \mathbf{M})}{M_s},$$

(2.7)

where $\alpha_{SH}$ represents the spin Hall constant and $\mathbf{\sigma}$ the spin magnetic moment of the injected spins. The spin Hall constant $\alpha_{SH}$ is furthermore given by:

$$\alpha_{SH} = \frac{\mu_B \theta_{SH}}{e M_s t} J,$$

(2.8)

with $\mu_B$ the Bohr magneton, $\theta_{SH} = \frac{J}{t}$ the spin Hall angle (ratio between transverse spin current density and charge current density), $e$ the elementary charge, $t$ the thickness of the magnetic specimen and $J$ the charge current density [8]. The spin Hall angle $\theta_{SH}$ depends on the materials being used, as well as the quality of the interface between them. A typical value for the spin Hall angle of platinum is found to be 0.07 [6].
Figure 2.11: Geometry used to study the feasibility of a memory which uses the electric field effect as the selector mechanism in a cross-bar memory array. By applying different voltages across the left and right bit, the perpendicular magnetic anisotropy of each bit can be tuned. A negative voltage will decrease the necessary threshold current needed to switch the magnetization of the bit, while a positive voltage increases it.

2.5 Feasibility study E-field effect MRAM

This section describes a feasibility study on a MRAM that employs the electric field effect as the selector mechanism in a cross-bar memory array. The feasibility study is performed by comparing the spin Hall torque switching currents of two similar magnetic bits, experiencing opposite electric fields. Several key theoretical concepts discussed in the previous sections will be used, as well as some additional concepts found in the literature.

The geometry under consideration is schematically shown in figure 2.11. It consists of two magnetic bits placed on top of a single nanowire. The magnetic layers are composed of cobalt and are 100 x 100 nm in size. The layer thicknesses are 1 nm for the magnetic layers and 3.8 nm for the oxide barriers. Two different oxide barriers are evaluated: AlOx and TaOx. The top and bottom electrodes are made of platinum, of which it is assumed that the exact thicknesses do not influence the necessary current density for magnetic switching.
2.5.1 Anisotropy field

We aim to calculate the threshold current density needed for switching a magnetic bit using a spin Hall torque. We first need to find an expression for the effective, voltage dependent anisotropy field $H_{K,\text{eff}}$. As discussed in section 2.1, the intrinsic volume anisotropy of a thin magnetic film can be approximated by:

$$K \approx \frac{2K_s}{t},$$

where the top and bottom surface anisotropies are taken to be equal. This anisotropy causes an intrinsic anisotropy field $H_K$ within the material which is equal to:

$$H_K = \frac{4K_s \mu_0 M_s}{\mu_0 M_z t} \hat{z},$$

(2.10)

where $\hat{z}$ points in the direction perpendicular to the plane (as shown in figure 2.11). The demagnetization field $H_D$ is furthermore approximated by equation 2.1 with $N_x = N_y \approx 0$. The effective, voltage dependent anisotropy field $H_{K,\text{eff}}$ is then found by adding up $H_K$ and $H_D$:

$$H_{K,\text{eff}} = H_K + H_D = \left(\frac{4K_s \mu_0 M_s}{\mu_0 M_z t} - N_z M_z\right) \hat{z}.$$  

(2.11)

The next step is to include the electric field effect in equation 2.11. $K_s$ is assumed to depend linearly on the applied voltage across the magnetic device [16]. This linear voltage dependency of $K_s$ can be described algebraically as:

$$K_s(V) = K_{s,0} (1 + \xi V),$$

(2.12)

where $K_{s,0}$ denotes the anisotropy constant for $V = 0$ and $\xi$ is the coefficient that describes the sensitivity of the anisotropy change on voltage [46]. By inserting equation 2.12 into the previously found expression for $H_{K,\text{eff}}$ (equation 2.11), we find:

$$H_{K,\text{eff}} = \left(\frac{4K_s (1 + \xi V)}{\mu_0 M_z t} - N_z M_z\right) \hat{z}.$$  

(2.13)

Note that in this derivation, it is assumed that the effective anisotropy field points in the $z$-direction, which is indeed the case for the out-of-plane geometries that are under consideration in this thesis. Furthermore, the sign of $V$ is defined such that positive $V$ results in electron accumulation at the ferromagnetic-insulator interface. Looking more closely at equation 2.13, we see that positive voltages (electric field in negative $z$-direction) will thus increase $H_{K,\text{eff}}$ in this convention, increasing the energy barrier between the two out-of-plane states.
By evaluating the extended LLG equation found by incorporating equation 2.8 into equation 2.5, Lee et al. [20] found that the critical spin Hall torque switching current of a perpendicularly magnetized circular bit, as shown in figure 2.12, can be described by:

\[ J_{\text{SH}}^{C} = \frac{2e\mu_0 M_s t}{\hbar \theta_{\text{SH}}} \left( \frac{H_{K,\text{eff}}}{2} - \frac{H_x}{\sqrt{2}} \right), \]  

(2.14)

in the case that \( H_x \ll H_{K,\text{eff}} \). Equation 2.14 is found to approach the threshold currents found by numerically evaluating the extended LLG equation. Note that equation 2.14 does not include any electric field effect, and is only valid for the high-Gilbert-damping regime (\( \alpha > 0.03 \)). The low-damping regime showed less predictable and less well-defined switching events, which will not be considered here. Experimentally, \( \alpha \) is found to be higher than 0.03 in the samples of interest, as reported for instance by Mizukami et al. [30]. Lee et al. report a switching current of approximately \( 10^8 \) A/cm² for a thermal stability of the bit of \( \Delta T = E_b/k_B T = 40 \), with \( E_b \) the barrier energy between the magnetic up and down states and \( k_B T \) the thermal energy. A thermal stability of at least 40 is necessary to ensure data retention over longer periods of time.

To include the electric field effect in equation 2.14, we can insert the previously found voltage dependent expression for \( H_{K,\text{eff}} \) (equation 2.13) into equation 2.14. Thereby we obtain the following expression for \( J_{\text{SH}}^{C} \):

\[ J_{\text{SH}}^{C} = \frac{2e\mu_0 M_s t}{\hbar \theta_{\text{SH}}} \left( \frac{2K_s (1 + \xi V)}{\mu_0 M_s t} - \frac{N_z M_z}{2} - \frac{H_x}{\sqrt{2}} \right). \]  

(2.15)

According to this equation, positive voltages will thus increase \( J_{\text{SH}}^{C} \).
2.5.3 Results

Now that all the necessary theory has been introduced, we are in the position to perform calculations on the feasibility of the proposed memory depicted in figure 2.11. A value for the intrinsic surface anisotropy constant $K_s$ for a Pt(4)/Co(1)/AlOx device was determined by Van den Brink to be $0.86 \cdot 10^{-3}$ J/m$^2$ [46], which was also used for the Pt(4)/Co(1)/TaOx device. A value for $\xi$ was also found, being $0.0051$ V$^{-1}$ for AlOx. Note that this value for $\xi$ is only valid in case of an oxide thickness of approximately 3.8 nm thick, which we therefore assumed for the device under consideration here. Since $\xi$ is considered to scale with the dielectric constant of the oxide barrier, it was taken as $0.022$ V$^{-1}$ for TaOx [39, 49]. The used saturation magnetization of cobalt was $M_s \equiv M_s = 1.27 \cdot 10^6$ A/m and the spin Hall angle $\theta_{SH}$ for platinum was taken as 0.07. The demagnetization factor $N_z$ was 0.966, which was calculated for a 100 nm x 100 nm x 1 nm bit by using analytical expressions given by Aharoni [1]. The external in-plane field was chosen to be 35 mT, which is the maximum magnetic field that experimentally can be applied in our setup.

Figures 2.13 and 2.14 show the necessary threshold current density as function of voltage for a bit with AlOx or TaOx barrier, respectively. As can clearly be seen in both figures, the threshold current depends linearly on the applied voltage, with the TaOx barrier resulting in a larger electric field effect. The threshold current for $V = 0$ is already around $3 \cdot 10^9$ A/cm$^2$, which is quite high compared to, for example, typical spin-Transfer torque threshold current densities [20]. However, the current in this case flows through the low resistive platinum electrode, which can therefore be applied more energy efficiently as compared to a current flowing through a magnetic tunnel junction. Moreover, the proposed memory has the advantage of manipulating many bits with only one current pulse, which lowers the energy consumption per bit.

In order to test the feasibility of using the electric field effect as the selector in a memory array, we are predominantly interested in the difference in $J^{SH}$ between positive and negative voltage, $J^{SH}_C \equiv M_s \equiv M_s = 1.27 \cdot 10^6$ A/m and the spin Hall angle $\theta_{SH}$ for platinum was taken as 0.07. The demagnetization factor $N_z$ was 0.966, which was calculated for a 100 nm x 100 nm x 1 nm bit by using analytical expressions given by Aharoni [1]. The external in-plane field was chosen to be 35 mT, which is the maximum magnetic field that experimentally can be applied in our setup.

In order to test the feasibility of using the electric field effect as the selector in a memory array, we are predominantly interested in the difference in $J^{SH}$ between positive and negative voltage, $J^{SH}_C + J^{SH}_C$, relative to the average threshold current $J^{SH}_{C,av}$. This parameter represents the relative change in $J^{SH}$ as a function of voltage, which needs to be maximized for practical situations in order to counteract the inevitable distribution in $J^{SH}$ when many bits are placed in a memory array. The insets in figures 2.13 and 2.14 therefore show this relative percentage change.
Figure 2.13: Threshold current as a function of positive and negative voltage for a 100x100 nm Pt/Co (1nm)/AlOx magnetic junction. The applied magnetic field is 35 mT. The inset shows the percentage change with respect to the average $J_{SH}^C$ as a function of voltage.

Looking at the percentage change as a function of voltage, we see that a voltage of ±6 volts results in a change of 15 % and 40 % for the AlOx and TaOx barrier, respectively. Although relatively high voltages are needed, these results suggest that it should be possible to use the electric field effect in Pt-Co-TaOx as a selector in spin Hall torque driven switching experiments. Assuming a distribution in $J_{SH}^C$ of 20 % when many bits are placed in a crossbar MRAM arrangement [15], a stronger electric field effect is required to meet current industry standards on reliable switching. This might be overcome by using different material systems, such as Ta-CoFeB-MgO or Fe-MgO, in which stronger voltage-induced anisotropy modifications have been observed [50] [3]. Moreover, the electric field effect could always be used to assist magnetic switching by the spin Hall torque, reducing the overall energy consumption.

To reduce the value of $J_{SH}^C$, several device parameters can be changed. One of them is the material of the bottom nanowire, which changes the effective spin Hall angle of the system. Tantalum, for example, has a higher spin Hall angle than platinum and is therefore expected to reduce $J_{SH}^C$ significantly. Another way to reduce $J_{SH}^C$ is by applying a larger external field in
Figure 2.14: Threshold current as a function of positive and negative voltage for a 100x100 nm Pt/Co(1nm)/TaOx magnetic junction. The applied magnetic field is 35 mT. The inset shows the percentage change with respect to the average $J_{SH}^C$ as a function of voltage.

To summarize, calculations were performed on the spin Hall torque threshold current as a function of voltage for a 100 x 100 x 1 nm bit. The results show a linear dependence of the threshold current as function of voltage. Both AlOx and TaOx as the oxide barrier were evaluated, of which the higher di-
2.5 Feasibility study E-field effect MRAM

The electric constant of TaOx as compared to AlOx resulted in a stronger electric field effect. The feasibility study suggests that it should be possible to use the electric field effect in Pt-Co-TaOx as a selector in spin Hall effect driven switching experiments. In actual memory applications, a stronger electric field effect is required to meet industry standards. This might be achieved in different material systems, such as Ta-CoFeB-MgO or Fe-MgO, in which stronger voltage-induced anisotropy modifications have been observed [50][8].
2.6 Device Physics

When performing electrical measurements on nanoscaled devices, the electrical behavior can only be described by correctly evaluating the physical conduction mechanisms involved. These can include, for example, drift, diffusion, charge carrier generation and recombination, tunneling, ion migration, and chemical reactions. This section gives an overview of the possible physical mechanisms playing a role in the fabricated devices, where the main focus will be on the AlOx barrier. This knowledge is useful for the analysis of experimental results shown in chapter 4. The section starts with a description on the expected band diagram of our devices, followed by a discussion on dielectric breakdown and resistive switching.

2.6.1 Pt-AlOx-Co band diagram

A common way to describe and analyze the electrical behavior of a device is by considering the energy landscape felt by an electron traveling through the device. Such an energy landscape is called a band diagram. The shape of such band diagrams depends on the specific combination of materials used. In our case, we have an AlOx barrier which is sandwiched between a platinum and cobalt layer. AlOx is an insulator with a large band gap of 8.8 eV, while platinum and cobalt are metals that do not have an energy gap at the Fermi level. The so-called band alignment of the Pt-AlOx-Co can be approximated by considering the electron work functions for the different materials, which is defined as the amount of energy needed to excite an electron at the material’s surface into vacuum. Figure 2.15 schematically shows the different work functions for the materials used, for which typical values were found in the literature \[4, 55, 34, 52\]. By combining the electron work functions of platinum, aluminium-oxide, and cobalt as shown in figure 2.15, it is possible to construct the band diagram shown in figure 2.16.

As can be seen in figure 2.16, the difference in work functions for platinum and cobalt result in the AlOx having a slanted conduction band. This can be viewed as the AlOx being subjected to a bias voltage, which is commonly called the built-in voltage of a device. In this case, the built-in voltage is expected to be around 0.5 eV. The resulting asymmetric band diagram causes an asymmetry in the effective barrier height felt for electrons tunneling from the platinum to the cobalt as compared to the other way around. Therefore, the I-V curve of a Pt-AlOx-Co device is expected to be shifted towards positive voltages.
2.6 Device Physics

Figure 2.15: Schematic representation of the different work functions of the used materials. Note that the value for AlOx is in this case the electron affinity, which is the energy needed to excite an electron from the bottom of the AlOx conduction band into vacuum. Values were taken from [4, 55, 34, 52].

Figure 2.16: Band diagram obtained by leveling the Fermi energies of the conducting platinum and cobalt. Since AlOx is a poor conductor, the difference in work functions between platinum and cobalt result in the conduction band being slanted within the AlOx.
In practice, however, the band diagram as shown in figure 2.16 is not always able to explain the electrical behavior of a device. In reality, any AlOx layer is expected to contain lattice defects which result in additional energy levels lying within the AlOx band gap. Depending on the type of defect, such lattice defects can act as electron or hole traps and should therefore be included in the band diagram. Several studies already analyzed the different kinds of defects possible in AlOx, including their corresponding energies and charges \[52, 64, 85, 23\]. By including the energetically most favorable defects, the more comprehensive band diagram of figure 2.17 can be obtained.

The possible electron trap energy levels are represented in figure 2.17 by the vertical lines drawn within the AlOx band gap, which denote the energy range in which electron traps can be expected. Note that only electron traps are included in the band diagram, since the energy levels of any possible hole trap are much higher in energy as compared to the electron traps and are therefore assumed to be less significant for the electrical behavior of our device.

With the more elaborate band diagram of figure 2.17, we are now in a position to reason what we would expect for the electrical behavior. To illustrate this, figure 2.18 shows the altered band diagrams for the application of ±2 V bias voltages across the device. For positive voltages up to 2 V, the cobalt Fermi energy level is still below the lowest electron charge trap energy, which means that for these voltages direct tunneling from the Pt electrode to the Co is expected to dominate the electrical behavior. For negative voltages, the induced electric field enhances the built-in voltage and already enables trap-assisted tunneling for lower voltages. This also makes electron charge trapping at the AlOx-Co interface possible, since those charge traps will be electrically active.

**Figure 2.17:** Pt-AlOx-Co band diagram including energy levels of the most energetically favorable electron charge traps in AlOx.
2.6 Device Physics

2.6.2 Dielectric breakdown

In case that a dielectric material like AlOx is placed in a strong electric field, so called dielectric breakdown can occur. Dielectric breakdown describes the irreversible physical change of a dielectric due to a strong electric field and often destroys its functionality within a device. Basically two types of breakdown can be distinguished, being intrinsic and extrinsic breakdown [48].

The speculated physical background of these two types of breakdown will be described first, after which more information about dielectric breakdown in AlOx will be given. Unless otherwise stated, the dielectric breakdown of a highly resistive barrier that is sandwiched between two biased electrodes is considered.

Intrinsic breakdown

Intrinsic breakdown occurs predominantly in case of a high quality dielectric, which is a dielectric with a negligible amount of lattice defects, impurities or doping atoms. An intrinsic breakdown event of a highly resistive barrier is characterized by an abrupt and irreversible drop in resistance due to the application of an electric field across the dielectric. This abrupt and disruptive characteristic of intrinsic breakdown is the reason that its often referred to as hard dielectric breakdown.

The ultimate cause of intrinsic breakdown is believed to be the formation of one, or several, low ohmic path(s) [48]. The capacitor is then discharged through these paths, resulting in the final rupture. The low ohmic paths are initially formed by the creation of a chain of charged traps within the dielectric. Several mechanisms are known to exist that can cause this fast creation of traps in a high quality dielectric, such as scattering events of in-
jected electrons with the lattice. Independent of the dominant trap creation mechanism, however, an intrinsic breakdown event can only be kept under control by limiting the current through the dielectric. This namely limits the damage to the dielectric due to Joule heating, and in some cases even enables the low ohmic paths to be reduced again (see section 2.6.3).

**Extrinsic breakdown**

In contrast to intrinsic breakdown, extrinsic breakdown is characterized by a gradual, and in some cases even reversible, change of the dielectric due to the application of an electric field. Extrinsic breakdown not necessarily disrupts the dielectric properties of the material and can be controlled more easily due to the gradual nature of it. It is therefore also referred to as soft breakdown.

The physical background of extrinsic breakdown, or defect-related breakdown, is dominated by local defects in the dielectric material. These local defects can be any sort of lattice defect within the dielectric, like interstitial atoms, vacancies, or impurity atoms. The electric field needed to ionize or move such defects can be much smaller than the electric field needed to achieve this in the perfect, defect-free lattice, so extrinsic breakdown occurs at lower electric fields than intrinsic breakdown does.

In case of extrinsic breakdown, this does not necessarily mean that new ions, or defects, are created within the dielectric. It is known in literature that some defects, such as charged oxygen vacancies, are able to diffuse through a dielectric when a high enough electric field is applied. Pre-existing charged oxygen vacancies could therefore form a conductive filament across a dielectric and eventually cause an intrinsic dielectric breakdown event. This example also shows that extrinsic and intrinsic breakdown are not mutually exclusive, since local defect-related breakdown events can eventually lead to an intrinsic breakdown of the dielectric.

The creation and displacement of charged local defects causes a gradual change in the resistance of the dielectrics, since such defects increase trap assisted tunneling or can create local low ohmic paths. Therefore, the current flowing through a dielectric can be studied to learn more about the gradual breakdown of a dielectric.
Dielectric breakdown in AlOx

Earlier studies on the dielectric breakdown of thin AlOx barriers show that both intrinsic and extrinsic breakdown mechanisms can occur in amorphous AlOx [47]. The critical electric field reported in literature for intrinsic breakdown in AlOx ranges between 0.3 - 1.2 V/nm [18, 33, 37, 28]. The necessary electric field for extrinsic breakdown is not well defined due to the specific defect-related nature of it, but can already play a role at lower electric fields.

The dielectric breakdown mechanism in metal oxides is often attributed to the creation and diffusion of oxygen vacancies [47]. This also applies to AlOx, since oxygen defects are expected to be relatively mobile within AlOx [13]. Therefore, oxygen vacancies are expected to dominate any possible ionic effects within the AlOx barrier studied during this project. Moreover, since hybridization between Co 3d and O 2p orbitals is expected to play a crucial role in the PMA of the Co film [26], the PMA should be very sensitive to changes in interface oxygen stoichiometry [2].

2.6.3 Resistance modification

Besides the concept of MRAM, there are also other resistive switching phenomena proposed to be used in memories. One of these phenomena is based on the electrically stimulated change of the resistance of a metal-insulator-metal (MIM) memory cell, usually called resistance switching RAM or RRAM for short [51]. Since the Co-AlOx-Pt layers of the devices studied here also represent a MIM structure, similar modifications of the resistance can be expected as reported for resistive switching memory cells. The dominant contribution to resistive switching can be due to thermal, electronic, or ionic effects. This section will however focus on ionic effects, since such effects are most likely to occur in the devices studied during this project.

Resistive switching is typically reported as a confined, filamentary effect rather than a homogeneously distributed one [51]. It is attributed to the formation and rupture of low ohmic paths, or current filaments, between the two electrodes. Figure 2.19 schematically shows this phenomenon, in this case focusing on resistive switching in CuO (the same phenomenon holds for many metal oxides, including AlOx) [10]. The ionic effects causing such current filaments can be separated into two classes. One class has an electrochemically active electrode metal from which cations diffuse through the insulator and form the low ohmic path, while the other class relies on the migration of charged oxygen vacancies through the insulator.
Figure 2.19: Oxidation–reduction model for resistance switching according to Fujiwara et al. [10]. The forming process creates a conducting bridge, which is a mixture of filamentary Cu metal (yellow) and insulating oxide (white), by a soft breakdown. The filamentary Cu metal path can be blocked and opened repeatably by applying an electric field and/or current. If multiple bridges are produced in the forming, a permanent breakdown results that can no longer be undone by an electric field or current.

For the latter case, Xu et al. proposed a unified physical model of resistive switching in oxide based RRAM [54]. It is convincingly claimed that 1) the conduction of both the low-resistive and high-resistive state (LRS and HRS) is due to electron hopping transport among localized oxygen vacancies in the current filaments; 2) the switching between LRS and HRS is due to the formation and rupture of the current filaments; 3) SET process (switching from HRS to LRS) is similar as dielectric soft breakdown which generates and move oxygen defects (often oxygen vacancies) to form current filaments.

An experimental example of resistive switching which is attributed to diffusing oxygen vacancies can be found in the work of Wu et al. [53]. They performed measurements on TiN-Al₂O₃-Pt memory cells and report both
2.6 Device Physics

Figure 2.20: Unipolar (a) and bipolar (b) resistive switching of a TiN/Al<sub>2</sub>O<sub>3</sub>/Pt memory cell reported by Wu et al. [53]. The inset shows the proposed mechanism responsible for the resistive switching, which is in this case the formation and reduction of a current filament formed by oxygen vacancies. It is furthermore suggested that there exists an ion migration barrier between the TiN and Al<sub>2</sub>O<sub>3</sub> which explains both switching types.

unipolar (two way switching with same polarity) and bipolar switching (two way switching by different polarity), as can be seen in figure 2.20. Other examples of resistive switching in Al<sub>2</sub>O<sub>3</sub> were reported by Lin et al. [23] and Li et al. [22], in which the latter mentions a constant drift of oxygen vacancies through the Al<sub>2</sub>O<sub>3</sub>. Sleiman et al. [42] furthermore report resistive switching in a Cu-Al<sub>2</sub>O<sub>3</sub>-W stack, although in this case the copper electrode is thought to be electrochemically active and diffusing cupper ions are held responsible for the formation of a low ohmic path.

There are no reports found in literature that specifically report resistive switching in Pt-AlOx-Co stacks. However, since the creation and diffusion of oxygen defects in AlOx does not necessarily depend on the electrodes, such stacks are expected to have similar resistive switching and soft breakdown characteristics as other devices with AlOx as the main dielectric barrier. Thus, electric fields close to the dielectric breakdown field of AlOx are likely to induce the migration of oxygen vacancies, causing the device resistance to change over time. In addition, such migration of oxygen vacancies at the AlOx-Co interface could change the stoichiometry of the interface, influencing the PMA of the device.
Chapter 3

Experimental tools

This chapter describes the various experimental tools which were used during the project. The first part of this chapter describes the methods and equipment used for sample fabrication, including a detailed description of the fabricated samples. The second part continues with a description of the different measurement techniques and equipment utilized to magnetically and electrically characterize the samples.

3.1 Device fabrication

3.1.1 Sputter deposition

All thin films used during this project were fabricated by DC sputter deposition, which enables the deposition of sub-nanometer thin films. The basic principle of sputter deposition is that a material with high purity is bombarded with highly energetic argon ions, thereby knocking off some of the atoms of the highly pure material. These atoms in turn travel towards a substrate near the target, slowly coating it with the highly pure material. The thickness of this coating can be controlled within one Ångström by varying the exposure time of the sample to the released atoms.

The sputter deposition setup used had a main vacuum chamber with a base pressure below $10^{-7}$ mbar. Six different material targets can be installed in this main chamber. A load lock allows for a sample to be loaded in the system without venting the main chamber. The main chamber is also connected to an oxidation chamber, which was used for plasma cleaning and oxidation.
Chapter 3 Experimental tools

To perform quick film thickness dependence studies, a wedge mask technique was used. This technique involves placing a so called wedge mask just above a sample’s surface. This wedge mask partially covers the substrate beneath it and thereby prevents the deposition of material. This technique is schematically shown in figure 3.1. When the horizontal position of the wedge mask is changed from one side to another during the deposition of material, a wedge of the deposited material is created on top of the substrate. In a similar fashion, other masks can be used for the production of simple structures.

3.1.2 Plasma oxidation

Oxidation of the aluminium layers was performed by means of plasma oxidation. Plasma oxidation is a process in which a material is bombarded with highly energetic oxygen ions that interact with the material’s surface. By using this technique, it is possible to clean a material’s surface by burning away any surface contamination, or to create thin oxygenated films like aluminium-oxide. Both of these applications have extensively been used during this project.

While creating thin oxygenated films by means of plasma oxidation, it is important to keep in mind that the oxygen ions only interact with the material’s surface and therefore only penetrate a finite depth into the material. This means that plasma oxidation can only be used to oxidize thin layers of a material. As can be seen in figure 3.2, earlier results on the plasma oxidation of aluminium revealed that aluminium layers up to 2 nm thick can be fully oxidized, after which the oxygen density decreases gradually with increas-
3.1 Device fabrication

Plasma cleaning of a substrate was always performed with a plasma current of 15 mA, whereas the oxidation of aluminium was performed with a lower current of 7.5 mA. The oxygen pressure was kept constant at 0.1 mbar during the oxidation process. Furthermore, the oxidation time was always 10 minutes and the distance between the anode and the sample was kept constant. Since the time of oxidation was relatively long compared to the oxidation times shown in the right figure of figure 3.2, it was assumed that up to 2.0 nm could be fully oxidized.

3.1.3 Electron Beam Lithography

The micro-sized structures studied during this project were fabricated by utilizing a technique called Electron Beam Lithography (EBL). This technique enables the fabrication of self-designed microstructures and will be described in some detail first. More detailed information about the design of the fabricated structures will be given afterwards.

The general EBL process consists of several steps, which are depicted in figure 3.3. At first, the substrate at which the structure needs to be fabricated needs to be coated with an electron sensitive polymer (called “resist”).

Figure 3.2: (Left) Oxidation rate as a function of oxidized aluminium thickness according to Knechten [17]. It can be seen that the oxidized thickness approaches 2.0 nm for almost all different plasma currents used. (Right) Unoxidized aluminium as a function of the nominal aluminium thickness according to LeClair [19]. This result shows the transition of fully oxidized aluminium to underoxidized aluminium.
Figure 3.3: Schematic overview of the different steps during electron beam lithography. (1) The two resists is spin coated on the substrate. (2) Several areas are exposed to an electron beam. (3) The exposed areas dissolve, (4) exposing the substrate at those areas. (5) Material is deposited on top of the structure. (6) The resist is dissolved, thereby removing the deposited material on top of the resist. The final structure remains at the substrate.

Generally, this is done by spin coating a thin layer of such a polymer onto the substrate. In many cases, and also during this project, two different polymers are used subsequently, the first one being softer than the second one. This will become useful later on during the EBL process, since the softer polymer creates a small ‘undercut’ that eases the removal of the resist.

After the substrate is covered with resist, it is placed in an EBL setup. An EBL setup uses a focused electron beam to expose certain areas on the substrate. The molecular bonds between the resist polymers are altered at those particular areas, which softens the polymer locally. Subsequently, when the substrate is placed inside a solvent for the resist, the exposed areas of the resist dissolve first, thereby exposing the underlying substrate. This process is called developing. Note that the softer polymer on the substrate dissolves easier as compared to the harder resist, which ensures the exposed parts of the substrate to be clear of any leftover resist.

The next step in the EBL process is to deposit the desired materials on top of the whole substrate. This can be done by, for example, sputter deposition, which was used during this project. If necessary, plasma oxidation can also be used at this stage. Once the desired materials are deposited on top of the substrate, the substrate is placed in a strong solvent for the resist,
removing both the resist and the deposited material on top of it. The softer polymer at the substrate’s interface eases this separation of the hard polymer resist and the substrate. The final result is a substrate which has only the desired structure on top of it. At this point, depending on the structure under fabrication, the whole EBL process can be repeated several times to fabricate more advanced nanostructures.

The two polymers used during this project were PMMA 495 K and PMMA 950 K as the soft and hard resist, respectively. Furthermore, a FEI Nova Nanolab 600i dual beam was used for lithography and developing was performed by placing the substrate in a MIBK(1 unit)-isopropanol(3 units) solution for 45 seconds. The resist was finally removed by placing the substrate in acetone.

3.1.4 Sample geometry and fabrication

This section describes the main geometry and fabrication procedure of the samples studied during this project. Any sample-specific details, like the material thicknesses, or geometrical deviations of the measured devices will be pointed out in chapters 4 and 5.

The general geometry of the devices under investigation is shown schematically in figure 3.4. The samples consisted of a 1.5 \( \mu m \) wide magnetic Pt-Co-AlO\textsubscript{x} microwire with another 1.5 \( \mu m \) wide platinum top electrode placed on top, crossing the magnetic microwire. The material thicknesses of the magnetic microwire were chosen such that the cobalt layer experienced a perpendicular magnetic anisotropy (see sections 4.1 and 4.2). In addition, the platinum top electrode, together with the highly resistive AlO\textsubscript{x} layer, made it possible to locally create an electric field beneath the top electrode by applying a voltage across the top and bottom platinum layer. The magnetization characteristics beneath the top electrode could be measured by utilizing Kerr microscopy, which measurement technique will be highlighted in section 3.2.1.

To create samples with the geometry as shown in figure 3.4, three EBL steps as described in section 3.1.3 were performed. In the first EBL step, the magnetic microwire was created on top of a Si substrate with 100 nm of SiO\textsubscript{2}. The substrate already contained golden connection wires for wire-bonding purposes, leaving several areas of approximately 10 \( \times \) 10 \( \mu m \) free for creating the device. During the first EBL step, the bottom platinum layer, the cobalt layer, and one AlO\textsubscript{x} layer were deposited, the latter layer being created by
first depositing aluminium and subsequently oxidizing it by means of plasma oxidation.

During a second EBL step, a second AlOx layer, slightly wider than the microwire itself, was created at the place where the top electrode would be covering the microwire. The purpose of this second AlOx layer was twofold. Firstly, it prevented possible electrical shorts between the platinum top electrode and the sides of the bottom microwire. Secondly, it increased the resistance of the AlOx barrier, which reduces the leakage current through the AlOx during electric field effect measurements. This second AlOx layer was created in the same way as the first AlOx layer.

With a third and final EBL step, the top platinum electrode was created. The sputter deposition of this platinum top electrode was performed with a higher argon pressure than the bottom platinum layer, since it was experimentally determined that this increased the overall resistance of the junction. This increased resistance is probably due to reduced damage to the barrier due to reduced kinetic energy per atom. The deposition rate of platinum at this higher argon pressure was assumed to be the same as for the other case, since this was not calibrated before. However, the exact thickness of the top electrode is not expected to play a role in the experiments performed, since the top electrode is only used to create an electric field across the junction.

Figure 3.5 shows a microscope image of one of the fabricated devices, where both microwires are clearly visible. This particular device was used for the experiments found in chapter 4.
3.2 Characterization

3.2.1 Magnetic characterization

The magnetic characteristics of the devices studied were all obtained by utilizing the so called Magneto-Optical Kerr Effect (MOKE). Therefore, this effect will be briefly described first, after which the different measurement setups will be presented which utilize this effect.

Magneto-optical Kerr effect

MOKE is one of the known magneto optic effects which describes the sensitivity of light to the magnetization of a material. When a beam of linearly polarized light is reflected from a magnetic substance, the reflected beam generally has a slightly rotated polarization and ellipticity as compared to the incident beam. This phenomenon is schematically shown in figure 3.6. By analyzing the changes in polarization angle and ellipticity, information about the orientation of the magnetization can be gathered.

The magneto-optical Kerr effect can qualitatively be understood by considering an incident linearly polarized beam of light, heading to reflect from a
magnetic material. Such a linearly polarized beam of light can be considered as the superposition of two circular polarized beams of light with opposite chirality. The electric field components of these beams of light will, while reflecting from the material, interact with the orbital electrons within the material. For magnetic materials, there is an imbalance in up and down spins, which is reflected in the electron orbits due to the spin-orbit coupling. This causes an asymmetry in the system for the two reflected beams of light with opposite chirality and thereby results in the reflected beam having an altered polarization and ellipticity.

**Kerr microscopy**

The magnetic characteristics of small devices were studied with a wide-field Kerr microscope. As the name suggests, this microscope utilizes the previously described MOKE effect to measure the magnetization of a sample. The configuration of a Kerr microscope is very similar to the configuration of a normal microscope, but with some additional optical elements to make it sensitive for MOKE measurements. The main difference is that the light of a Kerr microscope first travels through a linear polarizer before illuminating the sample under investigation. The reflected light then travels through a compensator (a birefringent material that is able to linearly polarize the light again) and a second polarizer (called the analyzer), which results in the intensity of the beam being sensitive to the magnetization of the sample.
3.2 Characterization

Figure 3.7: Typical Kerr microscope image. The black areas in this picture are magnetized in the opposite direction as compared to the reference image taken, thereby revealing the magnetic behavior of the microwire. Note that the Kerr signal is less apparent at the junction itself, since the platinum top electrode partly blocks the light.

the changes in intensity are often subtle, this intensity difference is generally studied by using a video camera and digital image processing. For more in depth information about Kerr microscopy, see Schäfer [38].

To make any change of magnetization visible to the human eye by using the video camera, a simple trick can be used. The magnetic sample is first magnetically saturated in a particular direction by the application of an external magnetic field. Subsequently, a reference image at zero field of the sample is taken with the video camera. Once this image is subtracted from the live image of the video camera, the resulting image becomes very sensitive to any intensity fluctuation of the signal. Hence, any magnetization change is displayed as a region which becomes black or white, depending on the specific nature of the change in magnetization. A typical Kerr microscope image recorded by using this technique is shown in figure 3.7.

External magnetic fields were applied by utilizing two different magnets. One was only able to produce magnetic field out of the plane, while the other was able to generate magnetic fields in all three dimensions. The maximum magnetic field which could be applied was 86 mT in the out of plane direction, and 38 mT in both in plane directions. Both magnets were automatically controllable by an external computer, which made it possible to obtain similar conditions over the course of different measurements.
3.2.2 Admittance spectroscopy

Admittance spectroscopy is an electrical characterization technique which has been utilized in an attempt to learn more about the physical conduction properties of the AlOx barrier. This section describes briefly the basic concepts and equations that govern admittance spectroscopy.

The basic idea of admittance spectroscopy is to measure an electrical circuit’s dynamical response to the application of an alternating voltage with varying frequency. This way, information can be gained about the capacitances and resistances of different elements within the circuit, as well as the presence and significance of certain conduction mechanisms within capacitive elements. To understand in what way the dynamical response of an electrical circuit depends on the frequency of a signal, a theoretical analysis including the complex impedances of the different electrical elements needs to be performed. Therefore, an introduction on the complex impedances and admittances of electrical components will follow now, together with an example on how to use them to describe the dynamical response of a circuit.

The dynamical response of an ideal electrical element is given by its corresponding impedance formula. For an ohmic resistance, the impedance is given by

\[ Z = R, \]

(3.1)

and for a capacitance, it is given by

\[ Z = \frac{1}{i\omega C}, \]

(3.2)

where \( i \) is the imaginary unit, \( \omega \) the angular frequency of the electrical signal, and \( C \) the capacitance. Now, for a given circuit consisting of several resistances and capacitors, the total dynamical response can be evaluated by calculating the equivalent total impedance of the circuit. This can be done by applying the mathematical rules for combining impedances which are connected in series

\[ Z_{eq} = Z_1 + Z_2, \]

(3.3)

or in parallel

\[ \frac{1}{Z_{eq}} = \frac{1}{Z_1} + \frac{1}{Z_2}. \]

(3.4)

Since the impedance of a capacitance includes the imaginary unit, the resulting equivalent impedance of a circuit generally consists of a real part (called
3.2 Characterization

the resistance) and an imaginary part (called the reactance), which are both functions of $\omega$:

$$Z_{eq} = R_{eq} (\omega) + iX_{eq} (\omega).$$  

(3.5)

Now, the admittance of a circuit is defined as the inverse of the impedance, so is given by:

$$Y_{eq} \equiv \frac{1}{Z_{eq}} = \frac{1}{R_{eq} (\omega) + iX_{eq} (\omega)} \equiv G (\omega) + iB (\omega),$$

(3.6)

where $G$ is the real part of the admittance, called the conductance, and $B$ the imaginary part, called the susceptance.

When including capacitors in an electrical circuit, the conductance $G$ and susceptance $B$ will generally depend on the angular frequency $\omega$, as suggested by equation (3.6). Therefore, if we measure the conductance $G$ and susceptance $B$ as a function of angular frequency $\omega$, this gives us information about the total admittance of the circuit under consideration. A common way to present the data gained by admittance spectroscopy measurements is by evaluating the so called loss, $L$, and complex capacitance, $C_{com}$, as a function of frequency. These parameters are defined as the conductance and susceptance divided by the angular frequency, which means for the loss:

$$L (\omega) = \frac{G (\omega)}{\omega},$$

(3.7)

and for the complex capacitance:

$$C_{com} (\omega) = \frac{B (\omega)}{\omega}.$$ (3.8)

For the analysis and interpretation of admittance spectroscopy measurements, results are often compared to appropriate equivalent circuits. This makes it possible to quantify and study the influence of for example a DC bias voltage on one of the electrical elements within a circuit. Note that care has to be taken by doing so, since an equivalent circuit can mask the actual physical processes that cause the measured behavior. The measurements performed during this project were compared to the circuit shown in figure 3.8, which is also called the double layer circuit and can be used to simulate electrical devices consisting of two independent layers: a depletion layer and a bulk layer. For a Schottky barrier, for example, the depletion layer would represent the bent part of the band diagram, while the bulk layer would represent the bulk characteristics of the semiconductor. In our case,
Figure 3.8: Double layer circuit used to describe the dynamical response of the AlOx barrier.

the depletion part is thought to represent the AlOx near the Co interface, while the bulk layer would represent the rest of the AlOx barrier.

If we theoretically evaluate the circuit shown in figure 3.8 by applying the equations shown in this section, we find for the loss:

$$L = \left( \frac{1}{R_d R_b} - \omega^2 C_b C_d \left( \frac{1}{R_d} + \frac{1}{R_b} \right) + \frac{C_d}{R_b R_d} \omega^2 \left( C_d + C_b \right) \right), \quad (3.9)$$

and for the complex capacitance:

$$C_{com} = \left( \frac{C_d + C_b}{R_b R_d} \left( \frac{1}{R_d} + \frac{1}{R_b} \right) - \frac{C_d + C_m}{R_b R_d} \omega^2 C_b C_d \left( C_d + C_b \right) \right), \quad (3.10)$$

If we now plot equation 3.9 and equation 3.10 as a function of $\omega^2 = f$, this results in a graph with the shape as shown in figure 3.9.

As can be seen in the resulting graph, the low frequency capacitance is equal to the highest capacitance of the equivalent circuit (normally the depletion layer’s capacitance), while the capacitance at high frequencies is determined by the equivalent capacitance of the two single capacitors placed in series (in this case similar to the lower capacitance). The resistance parallel to the bulk capacitance ($R_b$) furthermore determines the relaxation frequency, which is the frequency at which the capacitance collapses (or similarly, the loss has
3.2 Characterization

Figure 3.9: Typical result for the capacitance and loss as a function of frequency for the double layer circuit as shown in figure 3.8. The inset shows the corresponding values for the resistances and capacitors.

its maximum). Finally, a decreasing depletion layer’s resistance (interface gets more leaky) results in the loss diverging for low frequencies. This for example happens when the Schottky barrier of a semiconductor collapses.

What has been left out of the discussion so far, is why admittance spectroscopy was utilized during this project. The reason for this is that admittance spectroscopy can be used to identify and characterize interface states (charge trapping energy levels near an interface). As we will see in chapter 4, the fabricated devices showed a significant electric field effect that could have been caused by trapped charges at interface states near the Co-AlOx interface. In what way admittance spectroscopy can give information about any interface states present will be discussed below.

To understand how interface states can be identified and characterized by admittance spectroscopy, take a look at figure 3.10. The figure shows a metal-insulator-semiconductor band diagram where interface states exist at the insulator-semiconductor interface [43]. Applying a bias voltage across such device changes the semiconductor’s Fermi level relatively to the metal’s Fermi level, causing the amount of trapped electrons at the interface to change. When the Fermi level is modulated by an AC component of the
Figure 3.10: Schematic band diagrams of a metal-insulator-semiconductor device with localized electronic levels at the semiconductor-insulator interface for different biases. The dashed line represents the Fermi level. For certain biases, the Fermi level is resonant with the interface states (b) and this opens conduction paths for charge to reach closer to the interface. When the interface states are empty (a) or completely filled (c), they do not contribute to the capacitance and loss. Picture taken from [43].

external field while the interface states are partly filled (figure 3.10b), charge will flow into and out of the interface states [43]. This increases the measured capacitance, since charge is then able to reach all the way up to the interface, increasing $\Delta Q/\Delta V$. Furthermore, the conduction through the interface states is highest when the probing frequency is close to the charge capture and emission rates of the interface states [43]. The presence of interface states will therefore result in extra peaks in the loss at frequencies that correspond with the capture and emission rates of the interface state. So by measuring capacitance and loss spectra for different biases, information can be gathered about whether interface states are present, as well as the corresponding capture and emission rates.

The admittance was measured with a Solartron 1260 Gain-Phase-Impedance analyzer system, which is able to apply frequencies up to 32 MHz. Furthermore, as also shown in figure 3.8, the amplitude of the alternating voltage was 10 mV and the integration time per point was kept constant at 2 seconds. Because of this constant integration time, points measured at lower frequencies were less accurate than those at higher frequencies. Therefore, only results for frequencies above 100 Hz will be presented.
Chapter 4

Exploring the electric field effect

This chapter covers measurements focusing on the electric field effect in Pt-Co-AlOx junctions. The chapter starts with two thickness dependence studies to determine the most suitable cobalt and AlOx thicknesses for the junctions. Subsequently, the I-V characteristics of the fabricated junctions is shown and discussed. After this, a comprehensive section follows showing and discussing the resulting electric field effect on the coercivity in these junctions. Here, an unexpected time dependency of the coercivity is shown that is attributed to diffusing oxygen vacancies in the AlOx. The last section of this chapter shows results of admittance spectroscopy measurements, which was utilized in an attempt to characterize the time-dependent phenomenon.

4.1 AlOx thickness study

As explained in section 3.1.2 because of the finite penetration depth of the oxygen during plasma oxidation, an AlOx thickness dependence study was performed to determine the AlOx thickness necessary to obtain an out-of-plane magnetization. The wedge sample used for this purpose was fabricated by sputter deposition in combination with the wedge mask technique as described in section 3.1.2. Figure 4.1 shows a schematic picture of the wedge sample used. The magnetic characteristics of this wedge sample were studied using laser MOKE as described in section 3.2.1, measuring out-of-plane hysteresis loops at different positions along the wedge. For each single measurement, the corresponding magnetic saturation, coercivity and remanence were determined.
Figure 4.1: Schematic picture showing the stack order and layer thicknesses of the AlOx wedge sample studied. The shaded area illustrates the oxidized part of the sample.

Figure 4.2 shows the resulting magnetic characteristics as a function of AlOx thickness. For an aluminium thickness below 1.7 nm, no magnetization is present. This is expected for thin aluminium layers, since the sample will be over-oxidized and the cobalt be destroyed. The data shows furthermore that an aluminium thickness of 1.8 nm is enough to pull the magnetization out-of-plane. The sample is in that case oxidized to a depth comparable to the depth of the Co-AlOx interface, thereby maximizing the bonding between oxygen and cobalt atoms. Increasing the aluminium thickness further increases the amount of unoxidized aluminium at the Co-AlOx interface, thereby reducing the PMA. At a certain thickness, in this case at 2.3 nm, the surface anisotropy has become too small to pull the magnetization out-of-plane and the easy axis is changed from out-of-plane to in-plane. The small effects at 3.0 nm of aluminium are measurement artifacts due to boundary effects of the sample.

It must be kept in mind that the results shown in figure 4.2 do not take domain wall motion within the wedge into account. This means that the coercivity of a homogeneous magnetic film can differ significantly from the results shown here. The measured magnetic saturation and remanence, however, are not influenced by domain wall motion and can therefore easily be characterized by using the wedge mask technique as shown in this section.

To summarize, the magnetic characteristics as a function of top AlOx layer are found to behave as one would expect. The data shown in figure 4.2 clearly shows that, for a cobalt thickness of 1.0 nm, an AlOx thickness between 1.9 nm and 2.3 nm is needed to create devices with out-of-plane magnetization. As will be discussed in section 4.3, this knowledge was subsequently used to fabricate appropriate electric field effect junctions. Note that the aluminium thickness is expected to increase during oxidation.
4.1 AlOx thickness study

Figure 4.2: Saturation magnetization, coercivity and remanence as a function of aluminium thickness in a Pt(3 nm)/Co(1 nm)/AlOx(x nm) wedge sample. Fully remanent out-of-plane magnetization is observed between 1.8 nm and 2.3 nm of aluminium.
4.2 Cobalt thickness study

As discussed in section 2.1 and made clear by equation 2.4, the cobalt thickness plays an important role in determining how sensitive the effective anisotropy $K_{\text{eff}}$ is to any change in the surface anisotropy $K_{s,\text{top}}$. Therefore, a study was performed to determine the magnetic characteristics as a function of cobalt thickness. The influence of adding an extra AlO$_x$ layer on top by a second sputter and oxidation step was also studied.

To characterize the described influences, two 0-2 nm cobalt wedge samples were fabricated by sputter deposition in combination with the wedge mask technique as described in section 3.1.2. Figure 4.3 shows a schematic picture of both wedge samples. The stack order of the first sample was Ta(2)/Pt(4)/Co(0-2)/AlO$_x$(2.2+Ox), with the numbers representing thicknesses in nm. In this case, a tantalum seed layer was used which increased the overall interface qualities. The AlO$_x$ layer was created by plasma oxidizing a 2.2 nm thick aluminium layer. The second wedge sample was identical to the first one except for an extra AlO$_x$ layer on top. The AlO$_x$ layers were chosen to be 2.2 nm in thickness, since preliminary experiments with such AlO$_x$ layers yielded acceptably high resistances for junctions, as well as PMA (see previous section).

Figure 4.4 now shows the magnetic saturation, coercivity and remanence as a function of cobalt thickness for both samples. Qualitatively, the cobalt thickness dependence corresponds well with what one would expect. A thin (in this particular case < 0.6 nm) sputter deposited cobalt layer is not yet homogeneous and therefore does not show any remanence or coercivity. As the cobalt thickness increases (0.6-1.1 nm), the cobalt layer becomes more homogeneous and the magnetization is pulled out-of-plane by the top AlO$_x$-Co and bottom Pt-Co surface anisotropies. In accordance to equation 2.4, increasing the cobalt thickness further decreases the relative strength of $K_s$ and
4.2 Cobalt thickness study

Figure 4.4: As deposited saturation magnetization, coercivity and remanence as a function of cobalt thickness for one (open circles) and two (filled squares) AlOx layer(s) on top of the cobalt. Both AlOx layers were fabricated by oxidizing a 2.2 nm thick layer of aluminium.

therefore gradually decreases the coercivity for cobalt thicknesses of 1.1-1.7 nm. Above 1.5 nm, the sharp drop in remanence signatures the out-of-plane to in-plane transition of the cobalt due to the demagnetization energy dominating over the surface anisotropy energy at increased thicknesses.

When comparing the data of the two samples in figure 4.4, a couple of differences can be noted. Both $M_{sat}$ and $M_r$ show a 0.3 nm shift of the data towards thicker cobalt thicknesses, which suggests that some cobalt is destroyed during the second oxidation step despite the fact that the cobalt was already covered by a 2.2 nm AlOx layer. The overall lower $M_{sat}$ for the sample with two layers of AlOx could also hint at this phenomenon, although care has to be taken when comparing the values for $M_{sat}$ since the MOKE can differ for two AlOx layers as compared to one. When we furthermore look at the coercivity, it can be seen that the coercivity is reduced by adding the second AlOx layer. Although highly speculative, this could suggest a decrease of $K_{eff}$ due to a decrease in $K_s$, which would agree well in case the AlOx-Co stoichiometry changes due to the cobalt being destroyed.
Chapter 4 Exploring the electric field effect

4.3 Junction layout and I-V characterization

To characterize the electric field effect on the magnetization of a thin cobalt layer, microsized junctions as described in section 3.1.4 and schematically shown in figure 3.4 were created. Based on the thickness dependence studies as shown in the previous section, the layer thicknesses were chosen as such that the cobalt was perpendicularly magnetized for a relatively thick AlOx barrier to ensure a large resistance of the junction.

The geometry and resulting stack order of the junctions is schematically shown in figure 4.5. No tantalum buffer layer was used in this case to reduce $K_{s,\text{bottom}}$ and thereby increase the sensitivity of $K_{\text{eff}}$ to any change in $K_{s,\text{top}}$ (see equation 2.4). The second AlOx layer was chosen 0.1 nm thinner than the first one to reduce the chance of any screening effect due to unoxidized aluminium in the AlOx barrier. Figure 4.5 also shows how the applied voltage was defined.

As a first characterization tool for the fabricated devices, I-V curves were obtained of which a typical example is shown in figure 4.6. First of all, we see that the electrical response is not ohmic, but typically that as expected for
4.4 E-field effect on coercivity

The electric field effect on the coercivity has been determined by using the Kerr microscope setup as described in section 3.2.1. To only be sensitive to the magnetization of the cobalt below the top electrode, a region of interest was defined that was somewhat smaller than the junction (see figure 4.7).
Figure 4.7: (Left) Kerr image depicting the small region of interest (ROI) used to extract only the Kerr signal of the cobalt beneath the platinum top electrode. (Right) Easy axis hysteresis loops for -2 V, 0 V and +2 V. Negative voltages result in a decrease of the coercivity, whereas positive voltages increase the coercivity. The device was initially saturated by a magnetic field of -50 mT before every measurement.

The voltage on the top electrode was manually applied by using a Keithley voltage source, which was also used to directly read off the current flowing through the device.

4.4.1 DC voltage coercivity change

The electric field effect on the coercivity has been characterized by measuring easy axis hysteresis loop for different applied voltages. Figure 4.7 shows three easy axis loops for voltages of -2 V, 0 V, and +2 V, respectively. As can be clearly be seen, the easy axis loop of the cobalt below the top electrode is highly sensitive to the application of a voltage. Positive voltages show an increase of the coercivity, while negative voltages decrease it. In contrast, the coercivity outside the ROI was not affected by the application of a voltage. Note that in addition to the change in coercivity, a more gradual change and reduction of the Kerr intensity for negative voltages is found. This was not studied in more detail.

The coercivity as a function of voltage is shown in figure 4.8. As can be seen, the coercivity could be changed from 4.5 mT to 13 mT by applying voltages of -2 V and +2 V, respectively. The coercivity change as a function of voltage is found not to be linear, but instead seems to be divided in two different regions. Region I is for lower voltages where the sensitivity of the coercivity is relatively small (~0.5 mT/V), and region II is for higher voltages
4.4 E-field effect on coercivity

where the coercivity change is much more sensitive to the application of a bias voltage (~4.5 mT/V). This closely resembles the different electric field effect regions found by Bauer et al. as described in section 2.3 [2]. However, in contrast to their results, the electric field effect was still found to be reversible for the higher sensitivity region.

Figure 4.8 also shows that the transition from region I to region II occurs at a lower voltage for negative polarity as compared the same transition at positive voltages. For negative polarity, this transition is found to be at -0.8 ± 0.1 V, while for positive polarity it is 1.6 ± 0.1 V. Referring back to the Pt-AlOx-Co band diagram of section 2.6.1, this horizontal shift is in good agreement with the theoretically expected built-in voltage of the device (+0.5 V). Due to this built-in voltage, a positive voltage of +0.5 V is necessary to counteract the intrinsic electric field in the AlOx, leading to a similar horizontal shift of mechanisms that depend on the electric field. Our results thus agree with the current consensus that the PMA change due to a voltage is linked to the effective electric field within the device.

If we compare the results presented here with similar electric field effect measurements performed earlier by Van den Brink (figure 4.9), we see that those results did not show different regions for the sensitivity of the coercivity to the application of a voltage [46]. The devices of Van den Brink consisted of

**Figure 4.8:** Coercivity as a function of voltage. Two sensitivity regions can be distinguished: one for lower voltages (region I), and one for higher voltages (regions II). The error bars are given by the standard deviation.
the same materials, with the exact stack order of the junction being Pt(4 nm)-Co(1 nm)-AlOx(3 nm + Ox)-Pt(4 nm). Those devices only showed one linear dependence of the coercivity with a sensitivity of approximately 0.6 mT/V. Note that this sensitivity corresponds well with the low sensitivity region of figure 4.8 and has the same sign as the results shown in this report (the voltage was defined reversely in this case). The absence, however, of any high sensitivity region raises questions about the exact differences between the devices studied by Van den Brink and the devices studied during this project other than the materials used. These main differences were the area size of the junctions and the fact that the devices of Van den Brink were annealed [46]. Both differences will be discussed briefly.

The devices of Van den Brink were approximately 200 x 200 micrometer in size and were fabricated by using sputter deposition in combination with a contact mask technique. The much larger device size naturally resulted in a lower overal resistance, but should in principal not affect any direct electric field effect when a constant voltage is applied. Bigger junctions are, however, expected to be less sensitive to any boundary effects such as smoothed edges of junctions, but it is in that case not straightforward to come up with an explanation of why the coercivity change in our devices was more sensitive for higher voltages.

As mentioned, another major difference between both kind of devices was that the devices of Van den Brink were annealed. Annealing generally increases the interface qualities within the stack, thereby increasing the PMA.
in most cases. This is also the main reason why the coercivity was much higher for the devices of Van den Brink and why a much higher voltage could be applied across the junction without causing dielectric breakdown. Because of this difference in fabrication process, it would have been interesting to anneal the devices studied during this project which showed the dependency of figure 4.8 to see whether this changes the presence of different regions in the sensitivity of the coercivity. Unfortunately, however, all devices which showed the reported time dependence were destroyed during the measurements shown and several attempts to recreate it were unsuccessful due to fabrication issues. Nevertheless, this is something to investigate in future projects.

To summarize, the electric field effect junctions studied during this project showed a significant change in coercivity as a function of voltage. Two sensitivity regions could be distinguished, being one lower sensitivity region for voltages between -0.8 - 1.6 V and one higher sensitivity region for higher positive and negative voltages. These separate sensitivity regions were not observed during earlier electric field effect measurements performed on similar devices by Van den Brink. The differences in device geometry and fabrication were discussed. An in-depth analysis of the observed behavior requires more extensive measurements, which are discussed in the following sections.

4.4.2 Coercivity time dependence

While performing electric field effect measurements on the fabricated devices, it was found that the coercivity not only depended on the applied voltage, but also on the time a certain voltage was applied. Figure 4.10 shows several easy axis loops, measured subsequently while a voltage of -2 V or +2 V, respectively, was applied. As can clearly be seen in both figures, a time dependent change in coercivity occurs on a relatively long time scale (minutes/hours) compared to the almost instantaneous electric field effects reported in literature [27]. Therefore, this coercivity time dependence has been characterized in more detail for both polarities. Note that the previously discussed results were obtained after at least 10 minutes of electroforming.

The coercivity time dependence for positive voltages has been characterized by the following measurement sequence. First, -2 V was applied for 30 minutes to electrically saturate the device into its low coercivity state. Subsequently, hysteresis loops were repeatedly recorded under constant application of a positive voltage (ranging from 0-2 V) to monitor the coercivity change over time. Comparable measurements were performed for negative
Figure 4.10: Subsequently measured Kerr intensity loops, measured subsequently under application of a negative voltage of -2 V (upper panel) or a positive voltage of +2 V (lower panel). The data clearly shows the time dependent decrease/increase in coercivity for negative/positive voltages, respectively.
voltages, where in this case +2 V was applied for 30 minutes to electrically saturate the device into its high coercivity state.

Figure 4.11 shows the resulting coercivity time dependencies for higher negative and positive voltages. The data shows a clear time dependent behavior for both polarities that furthermore depends on the applied voltage. The lines shown in both figures are logarithmic fits given by:

$$\mu_0 H_c = a + b \ln(t),$$  \hspace{1cm} (4.1)

with $a$ and $b$ fitting parameters and $t$ the time. As can be seen, equation (4.1) is able to fit the data, which suggests that the coercivity change is due to a physical mechanism with a similar logarithmic time dependence. A thermally activated process could lead to such a logarithmic time dependence. This will be discussed in more detail in section 4.4.4.

Besides the time dependent change of the coercivity, an asymmetry and time dependence was measured in the current flowing through the devices. To illustrate this, figure 4.12 shows the current evolution during the -1.8 V, -2.0 V, +1.8 V and +2.0 V time dependence measurements as shown earlier in figure 4.11. In contrast to the increasing current for negative voltages, an almost instantaneous decrease in current was observed for positive voltages up to +2 V. This asymmetry and time dependence of the current motivated subsequent studies focusing on this current evolution.

4.4.3 Current evolution

The increasing current for negative polarities has been studied in more detail. Figure 4.13 shows the current evolution for three applied voltages, being -1.5 V, -1.8 V, and -2.0 V. The data shows that a voltage of at least -1.5 V was necessary to let the current significantly increase over time. This voltage corresponds to an electric field of approximately -0.3 V/nm within the device and has the same value as that at which the transition of Region I to Region II takes place in figure 4.8. Lower voltages than -1.5 V did not result in any measurable time dependence. Moreover, similar measurements performed for positive polarities up to +2 V did not show any significant time dependence of the current, except for a quick reduction of the current to nearly zero. Note also the chaotic growth of the current.

Besides the current being dependent on the time and magnitude of the applied voltage, a hysteretic behavior of the current was observed, as shown
Figure 4.11: Coercivity as a function of time for negative voltages (upper panel) and positive voltages (lower panel). The lines are logarithmic fits through the data. Before each measurement, the sample is prepared in the electroformed state by applying $\pm$2.0 V for 30 minutes. The two data points in the upper left corner of the data for positive voltages could not be fitted well, which cannot be explained at this point.
Figure 4.12: (Left) Current evolution for negative voltages of -1.8 V and -2.0 V. The data clearly shows an increasing (negative) current over time which depends on the magnitude of the voltage. (Right) Current evolution for positive voltages of +1.8 V and +2.0 V. For positive voltages, a quick decrease of current was observed which resulted in a negligible current flow within noise levels. The +2.0 V trace showed an increase in current after 10 minutes. All lines are guides to the eye.

Figure 4.13: Current evolution as a function of voltage. Before every single measurement, the device was subjected to +2 V for 30 minutes to "reset" the device. During this “resetting” of the device, the current was negligible.
Figure 4.14: Current evolution as a function of the sequence of voltage application. Before the measurement sequence shown, the device was subjected to a +2V voltage for 30 minutes. The inset shows the applied voltage as a function of time. Between two single measurements ('a' and 'b'), the device was subjected to 0 V for only 15 seconds.

As can be seen in the inset, two measurement sequences are shown (labelled '1' and '2') which were performed 17 hours after each other. One single measurement sequence consisted of two current evolution measurements of 10 minutes each (labelled 'a' and 'b'). The result for the second measurement (1.b) shows that the current amplitude quickly recovers itself to the value as where the previous measurement (1.a) stopped. Repeating the same experiment after subjecting the device to 0 V for 17 hours (2.a and 2.b), however, resulted in exactly the same current behavior. This suggests that the device was 'resetted' by subjecting it to 0 V for 17 hours.

To summarize these results, an additional time dependent phenomenon was found for voltages corresponding to the higher sensitivity regions in figure 4.8 (regions II). The coercivity showed a logarithmic time dependent change that was furthermore accompanied by an asymmetric current evolution over time. Negative voltages increased the current over time, while positive voltages up to +2 V reduced it. More detailed measurements on this current evolution for negative voltages revealed a chaotically developing current and the presence of a hysteretic effect.
4.4 E-field effect on coercivity

4.4.4 Discussion

Now that all experimental results focusing on the electric field effect have been presented, we are in the position to discuss the different mechanisms that could cause the observed behavior. We will argue that only one phenomenon is able to convincingly explain all the measurements shown. This phenomenon is the migration of oxygen vacancies at the AlOx-Co interface. In what way such migration of oxygen vacancies could explain the results will be discussed in detail below. Other possible mechanisms will be discussed afterwards.

Referring back to figure 4.8 we identified two different regions for the sensitivity of the coercivity to an applied voltage. The sign and magnitude of the electric field effect for lower voltages (~0.5 mT/V) is comparable with previous studies on the electric field effect and is therefore attributed to a changing electron density at the AlOx-Co interface, in line with the interpretation given by the respective authors [46, 27, 2]. The transitions between both sensitivity regions were found at -0.8 V and 1.6 V, which both corresponded to electric field magnitudes of ±0.25 V/nm within the AlOx (correcting for the expected built-in voltage). As discussed in section 2.6.2 this magnitude is close to reported intrinsic breakdown fields for amorphous AlOx. Extrinsic breakdown mechanisms such as oxygen vacancy migration can therefore be expected at these field strengths. In addition, oxygen vacancies are predominantly expected at the AlOx-Co interface due to the finite penetration depth of oxygen ions during plasma oxidation. This agrees well with the idea of nondesruptive oxygen migration at the AlOx-Co interface.

Another reason why the strong electric field effect for higher voltages is thought to be a changing oxidation state of the AlOx-Co interface, is the logarithmic time dependence found in the data shown in figures 4.11 and ???. Thermally activated processes, likely the migration of ions, are namely able to produce such logarithmic time dependencies. The specific model that is able to describe the time dependencies of figure 4.11 is called the thermal fluctuation aftereffect model [[11]], which will be described in more detail below.

In order to describe the model, consider the system of figure 4.15 where a fixed amount of oxygen ions (or oxygen vacancies) are located exactly at the AlOx-Co interface and all have two possible lattice sites to occupy: one located within the cobalt and one within the aluminium. The energy landscape of one single oxygen ion would in that case consist of two similar local
Chapter 4 Exploring the electric field effect

Figure 4.15: Schematic picture illustrating oxygen ion migration at the AlOx interface. a) A fixed amount of oxygen ions and vacancies are located exactly at the AlOx-Co interface, where in this case all oxygen ions are located into the AlOx. b) The application of a high enough electric field induces the migration of oxygen ions into the cobalt. This is a thermally activated stochastic process. c) After a long time, nearly all oxygen ions are considered to have migrated into the cobalt.

minima that are separated by an energy barrier. Since the oxygen ion is charged, an electric field is able to alter this energy landscape by favoring one of the two lattice sites. An electric field will therefore induce a migration of ions, especially when assisted by thermal energy to overcome the energy barrier.

Since the migration of ions is a thermally activated process, we can write for the rate of change of the ions highest in energy to the lattice site lowest in energy [11]:

\[
\frac{dN_1}{dt} = v_0 \left[ N_2 \exp \left( -\frac{E_b - E_2}{k_b T} \right) - N_1 \exp \left( -\frac{E_b - E_1}{k_b T} \right) \right],
\]

where \(E_b\) is the energy of the barrier, \(E_1\) and \(E_2\) are the energies of the two local minima, \(N_1\) and \(N_2\) the amount of ions at lattice sites 1 and 2, respectively, and \(k_bT\) the thermal energy. Since there is a limited and constant number of ions, we furthermore know that \(N_1 + N_2 = N\). By substituting this into equation [4.2] and solving the resulting first-order differential equation, we find for the occupation rate \(n_1/N\) as a function of time:

\[
n_1(t) = n_{\infty} \left[ 1 - \exp \left( -t/\tau \right) \right] + n_0 \exp \left( -t/\tau \right),
\]

with \(n_{\infty}\) and \(n_0\) the equilibrium and initial value of \(n_1\), respectively, and \(\tau\) the relaxation time. If we now assume that, at \(t = 0\), all oxygen ions were
located at lattice site 1 and in the end all end up at lattice site 2, we can take \( n_0 = 1 \) and \( n_\infty = 0 \). Equation 4.3 can in that case be simplified to:
\[
    n_1(t) = \exp(-t/\tau).
\]
(4.4)

As can be seen, equation 4.4 does not yet show a logarithmic time dependence for the occupation rate as a function of time. What has been neglected so far, however, is that in practice not all oxygen ions will experience the same ion migration energy landscape. The AlOx-Co interface is not expected to be perfectly defined and therefore results in a distribution of energy landscapes and relaxation times \( \tau \). Assuming the distribution function can be expressed by:
\[
    \int \frac{g(\tau)}{\tau} d\tau = 1,
\]
(4.5)

with \( g(\tau) \) a uniform distribution between \( \tau_{\min} \) and \( \tau_{\max} \). Fujikata et al. showed that equation 4.4 in that case transforms into a logarithmic time dependence that can be described by [9]:
\[
    n_1(t) = a + b \ln(t),
\]
(4.6)

with \( a \) and \( b \) depending on the specific distribution of relaxation times \( \tau \). Note that \( a \) and \( b \) can be positive or negative, depending on the direction of oxygen vacancy migration.

Although equation 4.6 shows the desired logarithmic time dependence for the occupation rate of one of the two states, it does not yet link this changing stoichiometry of the AlOx-Co interface to a change in coercivity. This necessary link, however, has recently been demonstrated by Bonell et al. [5]. As also described in section 2.3, Bonell et al. successfully measured the oxidation state of a FeCo-MgO interface as a function of voltage and found 1) that the oxidation state could be controlled by an electric field and 2) that a partial oxidation of the magnetic layer resulted in a lower PMA. Such change in PMA due to a changing oxidation state of the Co-AlOx interface is also expected because of the orbital hybridization between Co \( 3d \) and O \( 2p \) orbitals at that interface (see section 2.3). The results presented here are in good agreement with the findings of Bonell: a negative voltage is expected to oxidize the cobalt over time, thereby reducing the PMA and with that the coercivity. The opposite is true for a positive voltage: this will reduce the amount of oxygen within the cobalt and will therefore increase both the PMA and the coercivity.
Note that until now, the precise switching mechanism for the magnetization has been left out of the analysis. Domain wall motion could, however, have influenced the coercivity measurements for positive voltages, since in that case the unchanged coercivity of the microwire was lower than that of the junction. This could have caused depinning domain walls at the sides of the top electrode instead of the nucleation of a new domain below the top electrode. Unfortunately, it was not possible to determine this due to the quick switching process and the small size of the junction. Nevertheless, regardless the responsible switching mechanism, this domain wall pinning (and depinning) would still mean an increase in PMA for the region below the top electrode. Moreover, domain wall motion cannot have played a role in reducing the coercivity for negative voltages, since in that case the coercivity of the junctions was lower as compared to the unchanged coercivity of the rest of the microwire.

The proposed mechanism of oxygen vacancy migration for higher voltages can also explain the measured current evolution over time. Figure 4.16 illustrates what would happen in case of significant oxygen vacancy migration within the AlOx barrier. When a sufficient negative voltage is applied across the oxide barrier, oxygen vacancies will tend to diffuse from the AlOx-Co interface into the AlOx barrier (left panel of figure 4.16). This process slowly creates a low ohmic path through the AlOx barrier over time, thereby enhancing the conduction through the barrier. The opposite is true when an opposite voltage is applied (right panel of figure 4.16). Oxygen vacancies will then diffuse (back) to the AlOx-Co interface, decreasing any low-ohmic paths in the barrier. Note that this asymmetric current dependence is enhanced by the built-in voltage.

It must be noted that the ~5 nm thick aluminium oxide barrier was created by performing two sputtering and oxidation steps. Because of the finite penetration depth of oxygen ions during plasma oxidation, it is plausible that a second region of somewhat higher oxygen vacancy density was located between both AlOx layers. However, this would not have altered the mechanism as shown in figure 4.16 since in that case this mechanism simply occurs twice (within both layers of asymmetrically oxidized AlOx layers).

As also mentioned previously, the different sensitivity regions found for the coercivity as a function of voltage closely resemble the results of Bauer et al. on electric field control of domain wall motion in Pt-Co-GdOx devices (see figure 2.9). Bauer et al. reported a direct electric field effect for electric fields <0.2 V/nm, which is similar to our low sensitivity region for electric...
fields \(<0.25\) V/nm and of equal sign. Bauer et al. furthermore reported a much stronger sensitivity region for electric fields of 0.2-0.4 V/nm, again comparable with the results presented in this thesis. However, in contrary to our results, this effect was opposite in sign as the direct electric field effect. This difference in sign could be due to a different initial stoichiometry of the Co-Oxide interfaces, since the GdOx layer was fabricated by reactive sputtering instead of plasma oxidation. Finally, Bauer et al. also report that the large coercivity change for electric fields of \(+0.2-0.4\) V/nm could be reversed by applying a negative voltage for a while. Unfortunately, no detailed information about the timescale of this effect is given, except for one single measurement on a timescale of 15-60 seconds. Since the coercivity of our devices changed predominantly within the first minutes, this could be due to a similar mechanism and therefore agrees with the results presented here.
4.4.5 Alternative explanations for the observed effects

Although the described model of oxygen vacancy migration is able to give a qualitative explanation of the measured magnetic and electronic characteristics, this does not exclude the presence of other physical mechanisms. Other mechanisms which could have influenced the presented results are charge trapping, impurity related mechanisms, the spin Hall effect, and Joule heating. These effects will be discussed below.

Charge trapping
As discussed in section 2.6.1 it is not unlikely that charge traps are present in the AlOx barrier. The presence of electron traps close to the AlOx-Co interface could have a significant impact on the local electron density and thus on the magnetization of the cobalt. Moreover, as also discussed in section 2.3 Bauer et al. demonstrated that a charge-trapping layer placed in proximity to a ferromagnetic metal enables efficient electrical and optical control of the metal’s magnetic properties [3]. The possibility of charge trapping should therefore not be ignored.

Looking at the Pt-AlOx-Co band diagram of figure 2.18 charge trapping at the AlOx-Co interface could occur. When a negative voltage of -2 V is applied, some of the electron charge trap energy levels close to the AlOx-Co interface are lowered beneath the platinum Fermi energy level (right panel of figure 2.18). This is expected to enhance electron tunnelling from the Pt top electrode to the localized charge traps at the AlOx-Co interface, thereby increasing the electron density at the interface. The opposite is true for positive voltages: when a positive voltage is applied, it is energetically unfavourable for an electron to be located at the AlOx-Co interface (left panel of figure 2.18). Therefore, a reduction of the electron density at the AlOx-Co interface is expected in this case.

Comparing the results found by Bauer et al. with the results presented here, however, there is one striking difference. Bauer et al. reported two different time scales for the change in remanence that depended on the polarity. For +3 V, for example, they report a saturation time of the remanence of 100 seconds, while -3 V had a saturation time of almost 30 minutes. This significant difference in time scales is not observed in our data, since figure 4.11 shows similar time scales for both polarities. Moreover, our devices could clearly not be saturated in 100 seconds, favoring the described model of diffusing oxygen vacancies above the charge trapping mechanism.
4.4 E-field effect on coercivity

Despite the built-in voltage within the device, the charge trapping mechanism is not able to give a convincing explanation for the asymmetric current behavior as shown in figures 4.12, 4.13 and 4.14. In case of charge trapping at the AlOx-Co interface, this is not expected to significantly lower the overall resistance over time. Moreover, the chaotic current development as shown in figures 4.13 and 4.14 strongly resembles the presence of prebreakdown current jumps as reported in literature [7]. Since the breakdown of our AlOx barrier is most likely caused by diffusing oxygen vacancies, this therefore again favors the described model of diffusing oxygen vacancies. Note, however, that although oxygen vacancy migration is thought to be the dominant mechanism for the strong electric field effect at higher voltages, the presence of any charge trapping can still not be excluded. This would therefore be something to investigate in more detail.

Impurities
Due to the fabrication procedure followed for making the electric field devices, the presence of impurities within the AlOx cannot be ruled out. Since the plasma oxidation of aluminium was performed with the PMMA resist still on the sample, this could have caused some carbon contamination in the AlOx barrier. It is not clear, however, what influence such impurities would have on the magnetization of the cobalt or the characteristics of the AlOx barrier, but they could for example cause additional charge traps in the AlOx or influence the migration of ions. This could be something to investigate in future projects.

Spin Hall effect
Another mechanism which could have influenced the magnetization during the electric field effect measurements is the spin Hall effect. It is not unlikely that such a current-induced effect could have influenced the measurements, if only because of the similarities between figures 4.6 and 4.8. Moreover, for higher negative voltages, both the current and the coercivity changed over time. The expected order of magnitude of this effect, however, is much smaller than the typical order of magnitude necessary to influence the magnetization of the cobalt. The maximum current density in the platinum microwires was of the order of $5 \cdot 10^3$ A/cm$^2$, which is five orders of magnitude smaller than typical spin Hall torque switching currents of $10^8$ A/cm$^2$ reported in literature [29]. The spin-Hall effect is therefore deemed negligible.

Joule heating
Another current-induced effect present in electrical devices is Joule heating. This effect, however, is also believed to be irrelevant in our devices. First of
all, the observed current density was very small. Moreover, in case of Joule heating, this would reduce the thermal stability of the magnetization and with that the coercivity. If we look at our results, this could have caused the decrease in coercivity for negative voltages due to the increasing current, but it does not explain the increasing coercivity for positive voltages. Therefore, Joule heating is not considered to be of importance for the results shown.

### 4.4.6 Conclusions

It has been shown that the fabricated devices showed a significant change in coercivity as a function of voltage. Two sensitivity regions could be distinguished: a lower sensitivity region for voltages between -0.8 - 1.6 V and a higher sensitivity region for higher positive and negative voltages. These separate sensitivity regions were not observed during earlier electric field effect measurements performed by Van den Brink on similar devices [46]. Differences in device geometry and fabrication process were discussed.

An additional time dependent phenomenon was found for the higher applied voltages. The coercivity showed a logarithmic time dependent change that was furthermore accompanied by an asymmetric current evolution over time. Negative voltages thereby increased the current over time, while positive voltages up to +2 V reduced it. It was argued that this time dependent behavior can be explained by the migration of oxygen vacancies at the AlOx-Co interface. The measured logarithmic time dependence of the coercivity could be explained by applying a thermal fluctuation aftereffect model.

Moreover, the presence of oxygen vacancy migration in the AlOx could convincingly explain the asymmetry in the current behavior. The results presented here therefore strongly suggest that the behavior of the current should always be shown, or at least discussed, when electric field effect measurements are presented. As we have seen, this behavior can give valuable information about the possible origin of the electric field effect. Unfortunately, this is currently not common practice in the research field. In addition, since the oxidation state of in this case the AlOx-Co interface seems to be very important, detailed information about the fabrication process should always be given so that results can be correctly compared.

Alternative explanations for the observed effects were discussed, of which none of the mechanisms was able to convincingly explain all observed dependencies. The presence of any charge trapping at the AlOx-Co interface, however, cannot be fully ruled out, as well as the possibility that the increased
coercivity for positive voltages was due to the pinning and depinning of a domain wall. Subsequent measurements could therefore focus more on these effects. A first attempt to characterize any charge trapping at the AlOx-Co interface has already been undertaken, using admittance spectroscopy. First results of this study are discussed in the next section.
4.5 Admittance spectroscopy

Since charge trapping at the AlOx-Co interface could not be ruled out as one of the mechanisms responsible for the large electric field effect for higher voltages, admittance spectroscopy measurements were performed. As discussed in section [3.2.3], any charge trapping occurring at energy states at the AlOx-Co interface is expected to cause an extra peak in the loss and capacitance graphs as a function of frequency. Therefore, frequency spectra were obtained as a function of bias voltage and time.

Before any results can be shown and discussed, one thing must be noted. Because of the small area size of our junctions, the capacitance was expected to be very small. This made them less suitable for admittance spectroscopy measurements. To put this into perspective, the geometrical device capacitance was approximated by:

\[ C_d = \varepsilon_0 \varepsilon_r \frac{A}{d} \approx 0.04 \text{ pF}, \]

(4.7)

which is much smaller than the smallest measurable capacitance of 10 pF as specified by the manufacturer of the experimental setup. In addition, the devices were connected by normal instead of coaxial cables, which means that additional contact capacitances and resistances, or external factors, could have influenced the measurements. For this reason, no quantitative analysis could be carried out on the results. The results, however, did still depend on the applied voltage and showed some features that could be of interest when investigated in future projects. We therefore include them here.

Results

The admittance spectroscopy measurements performed were very similar to those discussed in section [4.3], where we measured the coercivity time dependence as function of voltage. The devices were first subjected to +2 V for 30 minutes to electrically saturate the device. During these 30 minutes, several admittance spectra were obtained with the frequency ranging from \(10^2 - 10^7\) Hz. Subsequently, a negative voltage was applied for 30 minutes while again several admittance spectra were measured. By repeating this for many negative voltages the resulting DC spectra after 30 minutes of electroforming could be measured, as well as any time dependence of the spectra.

Figure [4.17] shows the resulting capacitance and loss graphs for different voltages after 30 minutes of electroforming. First of all, it can be seen that both
Figure 4.17: Loss (left) and capacitance (right) for different voltages as a function of frequency. Higher negative voltages shifted the loss and capacitance data to lower frequencies.

parameters show the typical behavior as expected theoretically for a double layer circuit. All loss graphs show one clear peak within the $10^4 - 10^5$ Hz range, which corresponds well with the resulting capacitance curves. However, no clear additional peaks were found, except for a small peak in the capacitance at $10^5$ Hz for the +2 V graphs. Since this was the only peak and was absent for the other voltages, this inhibited any further research on the presence of interface or bulk traps within the AlOx.

If we compare the results for different voltages, we see that increasing the negative voltage decreased the height of the peak in the loss graph and shifted it to lower frequencies. In view of the double-layer circuit as discussed in section 3.2.2, such a shift can be explained by a reduced bulk resistance in combination with a reduced depletion and/or bulk capacitance. Qualitatively, this is in agreement with what one would expect in case of a reducing overall device resistance due to migrating oxygen vacancies.

When comparing the subsequently measured spectra for one applied voltage, a time dependent change could be observed. Figure 4.18 shows a close up of the loss peaks for the -2 V spectra. In this case, it was observed that the height of the peak reduced over time and shifted to the left. This is also compatible with the idea of a reducing bulk resistance and reducing capacitances over time.

To summarize, we have seen that the admittance spectroscopy measurements were able to produce typical graphs for the loss and capacitance as a function of frequency. The absence of a significant additional peak in the loss for
more than one voltage, however, inhibited further research on the presence of interface states. Furthermore, there was also a time dependent behavior of the loss peak measured for negative voltages, which could be explained by a slowly reducing bulk resistance in combination with reducing capacitances. However, further research on more suitable (bigger) devices is needed to determine whether interface states could have influenced or caused the large electric field effect as shown in the previous section.
Chapter 5

Spin Hall torque switching

This chapter covers results on magnetic switching involving the spin Hall torque due to the spin Hall effect. The first part shows measurements of the coercivity as a function of in-plane current, which are compared with results found in the literature. The second part focuses on actual deterministic spin Hall torque switching of a magnetic microwire in the presence of an in-plane magnetic field. Note that no measurements were conducted on actual electric field assisted spin-Hall torque switching, since all junctions which showed the electric field effect as shown in chapter 2.3 were destroyed during those experiments.

5.1 Spin Hall torque assisted switching

The first phenomenon that has been characterized in our devices is spin Hall torque assisted magnetic reversal. When an in-plane current is applied through the microwire, the resulting in-plane torque due to the spin Hall effect is expected to pull the magnetization towards in-plane. This torque will therefore assist magnetization reversal by an external field, causing a reduced coercivity. This effect can therefore easily be studied with the Kerr microscope.

The devices used for this purpose were very similar to the electric field effect junctions presented earlier in chapter 2.3. In this case, however, the devices had an extra 2 nm thick tantalum seed layer beneath the platinum to ensure an out-of-plane magnetization of the cobalt. The fabricated devices also had a top platinum electrode but did not show a significant electric field effect. Therefore, only the coercivity of the microwire itself has been investigated.
To characterize the spin Hall torque assisted magnetization reversal of the microwire, the following measurement sequence was utilized. The microwire was initially magnetically saturated by applying a -50 mT out-of-plane magnetic field as defined by figure 1.6, after which an in-plane current was applied through the microwire and an out-of-plane hysteresis loop was measured. Currents up to 5 mA were applied, which corresponded to a maximum current density of approximately $5 \times 10^8$ A/cm$^2$. No in-plane magnetic fields were applied during these measurements. Note that the in-plane field was defined as being anti-parallel to the applied current.

Figure 5.1 shows several easy axis loops for different in-plane currents to illustrate the changes in magnetic reversal due to an in-plane current. As expected, an in-plane current was able to decrease the coercivity of the microwire. Furthermore, the result shows a more gradual change of the magnetization for higher currents, suggesting a tilted easy axis due to the spin Hall torque. The change in easy axis loop is characterized more systematically by determining the coercivity as a function of in-plane current.

The resulting coercivities as a function of in-plane current are presented in the left figure of figure 5.2. The data shows a direct linear decrease of the coercivity as a function of in-plane current, which shows that the spin Hall torque in our devices was immediately able to influence the coercivity. Moreover, the data shows that a current of 3.5 mA was enough to pull the magnetization completely in-plane.
5.1 Spin Hall torque assisted switching

Figure 5.2: (Left) Coercivity as a function of current amplitude. Both the negative and positive values for the coercivity are shown, which show a similar decrease as a function of current amplitude. (Right) Magnetic switching as a function of current amplitude and magnetic field according to Miron et al. Region I: conventional field-induced magnetization reversal occurs at $B = B_c$. Region II: spin Hall torque assisted reversal. Red triangles indicate the minimum external field required to reverse $M_z$ parallel to $B_z$. Region III: pulse-induced switching. Black triangles indicate the minimum field at which positive current pulses reverse the magnetization antiparallel to $B_z$. The maximum field at which switching is observed (blue open squares) coincides with the coercivity of the data. Graph and description taken from [29].

As can be seen on the right of figure 5.2, similar measurements performed by Miron et al. also showed a linear dependence of the coercivity as a function of in-plane current amplitude [29]. Note, however, that the data of Miron et al. shows an additional region (region I) for low current amplitudes where the resulting spin Hall torque was too weak to significantly alter the coercivity. This region is absent in our results, which is attributed to the much lower coercivity of our devices (~27 mT) as compared to the devices studied by Miron et al. (~300 mT). The much lower effective anisotropy present in our devices already enabled spin Hall assisted switching for lower in-plane currents. Note that region III could not be identified in our data since pulse-induced switching measurements were not performed. Furthermore, thermal effects cannot be excluded at this point.

To summarize, the results on spin Hall torque assisted magnetic reversal show that the spin Hall torque was indeed able to influence the magnetic reversal of our microwires. A linear decrease of the coercivity as function of in-plane current was found and a current density of $3.5 \cdot 10^8$ A/cm$^2$ was able to fully pull the magnetization in-plane. This current density has the same order of magnitude as those already reported for out-of-plane magneti-
zation reversal. At this point, however, thermal effects cannot be excluded. The results of this section therefore motivated subsequent measurements on deterministic spin Hall torque switching.
5.2 Deterministic spin Hall torque switching

Since the goal of this project was to investigate the possibility of electric field assisted spin Hall torque switching, subsequent measurements were performed focusing on deterministic spin Hall torque switching. As discussed in the introduction of this thesis, deterministic spin Hall torque switching in PMA systems in absence of any other symmetry breaking is only possible by using an in-plane magnetic field which points along the microwire. Since the switching chance of the magnetization depends on the values and directions of both the applied magnetic field and current, a phase diagram was constructed showing which combinations result in magnetic switching.

To create the mentioned phase diagram, the following measurements were performed. First, the device was always magnetically saturated by applying a -50 mT out-of-plane magnetic field. Subsequently, an in-plane magnetic field was applied parallel to the microwire. After this, a measurement of the Kerr intensity as a function of time was started. Figure 5.3 shows two of such measurements, together with the applied current as a function of time. As can be seen, the current was applied 10 seconds after the start of the measurement, which for some combinations of in-plane field and current caused the magnetization to switch. By performing these measurements for many magnetic field values and current amplitudes, a switching phase diagram could be constructed.

The left figure of figure 5.4 shows the resulting phase diagram. The result is asymmetric around zero in-plane field, which is expected for spin Hall torque switching. Depending on the sign of the in-plane field, the precessional torque on the magnetization due to this field counteracts or assists the spin Hall torque. This behavior was also found by Van den Brink (unpublished) by performing simulations on the switching dynamics of a $20 \times 200 \mu m$ Pt-Co-AlOx junction, of which the resulting phase diagram is shown on the right of figure 5.4.

Although the resulting phase diagram is as one would expect for spin Hall torque switching, it must be noted that Joule heating in combination with a small misalignment of the in-plane magnetic field could also result in the asymmetric phase diagram as shown on the left of figure 5.4. A small out-of-plane component would in that case also counteract or assist the switching, depending on the sign of the field. To fully rule out this possibility, subsequent measurements should be conducted.
Figure 5.3: Kerr intensity and applied current as a function of time. Two measurements for the Kerr intensity are shown, where one of the two clearly shows magnetic switching by a rapid drop in intensity once the current was applied (filled black squares). The in-plane magnetic field was applied constantly during the measurement. Whether or not the magnetization was switched was determined by comparing the average Kerr intensity of the first 5 seconds with that of the last 5 seconds. The magnetization was defined as being switched when the difference between these Kerr intensities was more than half the maximum difference measured.

Figure 5.4: (Left) Switching phase diagram showing which combination of in-plane magnetic fields and current densities were able to switch the magnetization. The result clearly shows that positive in-plane fields assisted the spin Hall torque, whereas negative fields contracts it. (Right) Switching phase diagram found by Van den Brink by performing numerical simulations on the magnetization dynamics. The dashed rectangle denotes the corresponding parameter space which was measured experimentally. Although the magnitudes differ, it shows the same qualitative behavior.
5.2 Deterministic spin Hall torque switching

To summarize, we have seen that the devices studied during this project were able to produce the expected switching phase diagram for spin Hall torque switching. The currents and magnetic fields involved were of the same order of magnitude as can be found in the literature. Although Joule heating in combination with a misalignment of the in-plane field cannot be fully ruled out as the main cause of the phase diagram presented here, the results indicate that electric field assisted spin Hall torque switching can be studied in future projects by using the same devices.
Chapter 6

Conclusions and outlook

To conclude this thesis, the findings and conclusions of the previous chapters are briefly summarized here. After this, an outlook on possible future research and applications regarding electric field assisted spin Hall torque switching is given.

6.1 Conclusions

The most important findings and conclusions of this work are:

**Co & AlOx thickness**
Thickness dependence studies regarding the Co and AlOx thickness of a Pt-Co-AlOx stack showed that, for a Co thickness of 1.0 nm, an AlOx thickness between 1.9 nm and 2.3 nm is needed to create devices with out-of-plane magnetization. Moreover, when two 2.2 nm thick layers of AlOx are utilized, a cobalt thickness between 1.0 nm and 1.5 nm is needed. The results furthermore show that, for thickness optimization studies, a single 2.2 nm thick layer of AlOx is not sufficient to fully protect the underlying layers against a second plasma oxidation step.

**I-V characterization**
I-V measurements on the fabricated devices showed a non-ohmic electrical behavior, which is expected for electric tunneling in an asymmetric metal-insulator-metal device [41]. Furthermore, the I-V curve was symmetric around +0.3 V, which is attributed to the built-in voltage within the device. Overall, the I-V measurements showed that the AlOx barriers of the devices were of high enough quality to be used for electric field effect measurement.
Electric field effect
Magnetization reversal measurements using Kerr microscopy showed a significant change in coercivity as a function of applied voltage. Two sensitivity regions could be distinguished: one lower sensitivity region for $-0.8 \, V < V < 1.6 \, V$ and one higher sensitivity region for higher positive and negative voltages up to $\pm 2.0 \, V$. Earlier electric field effect measurements performed by Van den Brink on similar devices did not show these separate sensitivity regions [46], which was attributed to the fact that the devices of Van den Brink were annealed, causing a more homogeneous and stable oxide layer. The identified sensitivity regions were in agreement with earlier results on devices with GdOx barriers [2], of which the similarities are discussed.

Time dependence
An additional time dependent change of the coercivity was found for voltages in the higher sensitivity regions. The coercivity showed a logarithmic time dependent change that was furthermore accompanied by an asymmetric current evolution over time. It was argued that this time dependent behavior could be explained by the migration of oxygen vacancies at the AlOx-Co interface. By applying a thermal fluctuation aftereffect model, the measured logarithmic time dependence of the coercivity could be explained. Moreover, the presence of oxygen vacancy migration in the AlOx barrier could also explain the asymmetry in the current behavior. The presence of oxygen vacancy migration in our devices is in agreement with the literature, where comparable electric fields are reported to cause this migration and it is reported that a changing oxidation state of a ferromagnet-oxide interface alters the surface anisotropy of the ferromagnet.

Alternative explanations
Alternative explanations for the observed effects were discussed, none of which were able to convincingly explain all observed dependencies. The presence of any charge trapping at the AlOx-Co interface, however, could not be ruled out, but can not explain the observed effects by itself.

Admittance spectroscopy
Despite the small capacitance of the devices, admittance spectroscopy measurements were performed in a first attempt to characterize any possible charge trapping at interface states near the Co-AlOx interface. Unfortunately, the absence of an additional peak in the loss and capacitance graphs for more than one voltage inhibited further research on the presence of interface states. Nevertheless, a time dependent behavior of the loss peak could be identified, as well as a shift of the graphs to lower frequencies for negative
voltages. Although highly speculative, both could be due to a reducing bulk resistance in combination with reducing capacitances.

**Critical current**
Calculations on the spin Hall torque switching current as a function of voltage for a 100 nm x 100 nm x 1 nm bit show an average critical current of \( 3 \cdot 10^9 \text{A/cm}^2 \) which depends linearly on the applied voltage. Both AlOx and TaOx as the oxide barrier were evaluated, of which the higher dielectric constant of TaOx as compared to AlOx resulted in a stronger electric field effect. The feasibility study suggests that it should be possible to use the electric field effect in Pt-Co-TaOx as a selector in spin Hall effect driven switching experiments. A stronger electric field effect is required in actual memory applications, which might be achieved in different material systems. Moreover, the electric field effect could always be used to assist magnetic switching by the spin Hall torque, reducing the overall energy consumption.

**SHE magnetization reversal**
Measurements on spin Hall torque assisted magnetization reversal showed that the spin Hall torque present in our devices was indeed able to assist the magnetization reversal of our microwires. A linear decrease of the coercivity as function of in-plane current was found and a current density of \( 3.5 \cdot 10^8 \text{A/cm}^2 \) was able to pull the magnetization in-plane. The results were in good agreement with the literature, although thermal effects could not be excluded. Subsequent measurements on deterministic spin Hall torque switching produced the expected switching phase diagram, with the necessary currents and magnetic fields having the same order of magnitude as found in the literature. Although Joule heating in combination with a misalignment of the in-plane field could not be ruled out as the main cause of the asymmetric phase diagram, the results suggest that electric field assisted spin Hall torque switching can be studied with similar devices in future projects.

**Our goal**
In view of our goal to investigate the physics and feasibility of electric field assisted spin Hall torque switching of PMA magnetic bits, it must be concluded that the high sensitivity effect for higher voltages cannot be used within a conventional crossbar MRAM arrangement. In order to be suitable for such an arrangement, the timescale must namely be in the nanosecond regime, which is simply not feasible for migrating oxygen vacancies. Moreover, since the migration of oxygen vacancies eventually causes hard dielectric breakdown of a barrier, this is expected to greatly reduce the durability of the device. In contrast, the direct (but less significant) electric field effect
for lower voltages can in principle still be utilized to assist spin Hall torque switching, as was theoretically investigated in section 2.5.2.

6.2 Outlook

Although quite some research has already been performed on both the electric field effect and the spin Hall effect, the physics behind these effects are not fully understood. In view of our goal to combine both effects in an electric field assisted spin Hall torque switching memory, the findings and conclusions of this thesis could motivate further research on this subject. Some suggestions on possible future research, as well as one possible application for the enhanced electric field effect, are given below.

Proof of principle
As discussed in the previous section, the direct, but less significant, electric field effect for lower voltages can in principle still be utilized for electric field assisted spin Hall torque switching of a PMA magnetic layer. Since only experimental results for in-plane magnetized layers are reported in the literature [24], a proof of principle study with PMA layers would be of interest to further investigate the feasibility of the proposed memory.

Current behavior
The results presented in this thesis strongly suggest that the behavior of the current should always be shown, or at least discussed, when electric field effect measurements are presented. The current evolution over time can give valuable information about the possible origin of the electric field effect. Unfortunately, this is currently not common practice in the research field. In addition, since the oxidation state of in this case the AlOx-Co interface is very important, detailed information about the fabrication process should always be given so that results can be correctly compared.

Other applications
Although the enhanced electric field effect due to migrating oxygen vacancies cannot be used for fast switching dynamics, there could still be other applications where the electric field effect does not need to operate quickly. One possible application would be to increase the thermal stability of magnetic bits while a computer is turned off. To achieve this, a relatively high voltage could be applied to all magnetic bits during shutdown to increase the coercivity. The opposite voltage could then be applied during start-up, enabling the efficient manipulation of bits.
Co-AlOx interface
Additional measurements could also be performed on the Co-AlOx interface. From a physical point of view, it would be interesting to investigate whether the addition of an oxygen migration barrier at this interface influences the measured time dependence of the coercivity. Platinum, for example, is hard to oxidize, so a thin layer of platinum between the Co and the AlOx could act as an oxygen migration barrier which inhibits the oxidation of the underlying cobalt. This could give additional information about the oxygen vacancy migration process within these devices, although this is expected to destroy the electric field effect.

Admittance spectroscopy
Since the devices studied here were too small to be used for admittance spectroscopy measurements, additional admittance spectroscopy measurements could be performed with bigger, more suitable, devices. As discussed, this could give valuable information about whether or not charge trapping at interface states near the Co-AlOx interface plays a role in causing the observed electric field effect.
Bibliography


