Electric field effect in a Pt/Co/AlOx/Pt junction

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Abstract

Recently has been discovered that electric fields offer a new and interesting control of magnetic properties. These electric fields can be used to improve magnetic memory devices. In this report, the influence of electric fields on the magnetic properties of a Pt/Co/AlOx/Pt stack is presented. These materials had been chosen because this material combination is interesting for domain wall motion applications. To measure the electric field effect, first junctions that show perpendicular magnetic anisotropy (PMA) and have a resistance much larger than that of the leads had to be fabricated. It was difficult to fabricate such junctions. Because of this, first the thicknesses of the layers had to be optimized. During this sample optimization some interest results were found. It was found that a Ta buffer layer increases the coercivity and increases the range where the sample shows an out-of-plane magnetization. It was also found that oxygen ions penetrate into the Co layer during the deposition of a second AlOx layer on the junction. This influences the magnetic properties of the junction.

After the sample optimization the electric field effect could be measured. A junction that consists of a Ta (3 nm)/Pt (6 nm)/Co (1.5 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) stack was used to measure the electric field effect. In this junction a very small electric field induced domain wall velocity modification was measured. The found modification is very small and is much smaller than the electric field induced modification observed by Van den Brink before this project. This difference can be caused by the Ta buffer layer, the oxidation procedure and the thicknesses of the layers that are used.
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Chapter 1

Introduction

Nowadays, a lot of research is done to improve memory devices in for example computers and mobile phones. The major goals of this research are to make these memory devices faster, to create devices that can store more information on a smaller area, to make the devices cheaper and less power consuming and to make memory devices that are non-volatile. All this research has led to great improvements of the memory devices in the last 50 years. In 1956 a few megabytes were stored on a device that had a size of a large fridge. Nowadays, it is possible to store many terabytes on memory devices with a size of a few square centimetres. Two of the things that cause this improvement are the discovery of the Giant Magneto Resistance (GMR) effect and the Tunnelling Magneto Resistance (TMR) effect. Because of these two effects magnetic bits with a size of a few nanometres can be detected.

GMR is an effect found in thin films that consist of ferromagnetic layers separated by non-magnetic conducting layers. It was found that when a voltage is applied on such a thin film the current through the film depends on the magnetization direction of the ferromagnetic layers. When the ferromagnetic layers are in a parallel alignment the resistance of the film is lower than when the ferromagnetic layers are in an anti-parallel alignment. This effect is called GMR [1] [2]. In Figure 1.1 a schematic representation of the GMR effect is shown.

Figure 1.1: Two films with both two ferromagnetic layers separated by a non-magnetic conducting layer. In the first picture the ferromagnetic layers are in an anti-parallel alignment and in the second picture the ferromagnetic layers are in a parallel alignment. As can be seen, electrons with their spin in the same direction as the magnetization direction scatter much more than when the magnetization direction is anti-parallel. So when the ferromagnetic layers are in an anti-parallel alignment both the electrons with spin up and the electrons with spin down will be scattered. On the other hand when the ferromagnetic layers are in a parallel alignment only the electrons with spin up (in this case) will be scattered and the electrons with spin down will not be scattered. This will lead to a lower resistance. This figure is taken from [1].
TMR is an effect that occurs in Magnetic Tunnel Junctions (MTJs). MTJs are junctions that consist of two thin ferromagnetic layers that are separated by a thin insulating layer [3]. When the insulating layer is thin enough it is possible that electrons tunnel through the insulating layer from one ferromagnetic layer to the other ferromagnetic layer. When the two ferromagnetic layers are in parallel alignment it is more likely that an electron will tunnel through the insulating layer than when the ferromagnetic layers are in an anti-parallel alignment. So the resistance of a MTJ depends on the relative alignment of the magnetization of the ferromagnetic layers. This effect is called TMR [1].

So the resistance of a thin film that consists of magnetic and non-magnetic layers depends on the relative alignment of the magnetization of the magnetic layers. When the non-magnetic layer between the ferromagnetic layers is a conducting layer, the effect is called GMR. When the non-magnetic layer between the ferromagnetic layers is an insulating layer, the effect is called TMR.

1.1 Magnetic Random Access Memory (MRAM)

One recent application that uses the GMR effect or the TMR effect is the Magnetic Random Access Memory (MRAM). In Figure 1.2 a basic layout of a MRAM device is shown. MRAM consists of an array of magnetic bits. These magnetic bits are in most cases MTJs and consist of two ferromagnetic layers separated by a dielectric layer. Because of the TMR effect the resistance of the bit depends on the relative alignment of the magnetization of the two ferromagnetic layers. So when the bit has a low resistance (the ferromagnetic layers are in a parallel alignment) it is for example a “0” and when the bit has a high resistance (the ferromagnetic layers are in an anti-parallel alignment) it is for example a “1”. With this mechanism it is possible to store information. To read out a bit a small current can be used. With this small current the resistance of the bit can be measured and so the information of the bit. To write a bit a large spin polarized current can be used. A spin polarized current is a current of electrons with a different number of spin up electrons and spin down electrons. When such a spin polarized current is passing a ferromagnetic layer the magnetization direction can be changed. This effect is called Spin Transfer Torque (STT) [2]. With such a reading and writing process MRAM devices can realize a faster read and write speed. Other advantages of MRAM devices are their very high endurance and their low power consumption.

![Figure 1.2](image-url)
1.2 Recent developments

Another recent application that uses magnetic bits is the Magnetic Racetrack Memory (MRM). In Figure 1.3 a part of a MRM device is shown. A MRM device consists of a long magnetic nanowire that stores bits of information in the form of magnetic domains. These magnetic domains are well-defined regions in which all spins are oriented in a specific direction. The interface between two magnetic bits is called a domain wall. When an electric current flows through the nanowire these domain walls will move. This is because of the STT effect [4]. So in this way, it is possible to move the magnetic domains through the nanowire by electric currents. One advantage of this method is that the devices that write and read out the bits can stay fixed. Because of this a MRM device can operate faster than a conventional hard disk drive. Two advantages of MRM devices compared with MRAM devices are the high data density that is possible and the lower costs because MRM devices require less read and write units per bit.

![Figure 1.3: Two possible configurations to arrange the nanowire in a MRM device: a vertical racetrack that uses an U-shaped nanowire and a horizontal racetrack that uses a flat nanowire. On the right a schematic representation of the reading head and the writing head are shown. When a (pulsed) current goes through the nanowire the magnetic domains (bits) will move and will pass the reading head and writing head. In this way the bits can be read out and can be written. Also a racetrack storage array is shown on the right. In this case the U-shaped nanowire is used. In this way it is possible to store more information on a two-dimensional area. This picture is taken from [5].](image-url)
1.3 This thesis

Before MRAM and MRM can be applicable in the industry some important problems have to be solved and the devices have to be improved. For example, in MRM devices it is necessary to move magnetic domains in a controlled manner through the nanowire. Recently it has been discovered that electric fields offer a new and interesting control of magnetic properties [3] [6] [7]. This control of magnetic properties with electric fields may improve the proposed devices and may lead to new applications.

Before the MRAM and MRM devices can be improved by electric fields first the electric field induced magnetic anisotropy modification and the electric field induced magnetic domain wall motion modification have to be studied extensively. In this thesis this electric field effect is studied. During this project the electric field effect on junctions that consist of a Pt/Co/AlOx/Pt stack is studied. In the research group Physics of Nanostructures (FNA), Van den Brink has already studied the electric field effect on junctions that consist of a Pt/Co/AlOx/Pt stack [3]. However in the research group FNA little is known about the impurities in the AlOx layer and the effect of these impurities on the electric field effect. To measure these effects, junctions that show an out-of-plane magnetization and have a resistance much larger than that of the leads have to be fabricated. It turns out that it is difficult to fabricate samples with such properties. Because of this, the most important thing that has been done during this project is to fabricate samples that have such properties.

In this thesis first some important theory about magnetic anisotropy, electric field effect, charge trapping and ion migration is described in chapter 2. Chapter 3 gives a description of the sample fabrication and measuring techniques used during this project. In chapter 4 the results of the measurements are shown. In this chapter first some important results about the sample optimization are described. In the second part of chapter 4 the results about the electric field effect will be presented. Finally the conclusions of this thesis are presented in chapter 5.
Chapter 2

Theory

In this chapter relevant theory that has been used during this project to compare the magnetic properties of the samples and to understand results is discussed. First an introduction of the concept of magnetic anisotropy is given. In general, ferromagnetic objects exhibit a preferred direction of magnetization. This phenomenon is called magnetic anisotropy. In this project the magnetization direction of ferromagnetic materials is examined. It is possible to change the magnetic anisotropy with electric fields. This effect is called electric field effect and will be briefly discussed in this chapter. In this project the magnetic anisotropy of a Co layer is modified with an electric field. In this chapter the theoretical background of this electric field effect is given. During the electric field effect experiments time dependent effects are observed. These effects can be explained by different mechanisms. Two of these mechanisms are described in this section: charge trapping and ion vacancy migration.

2.1 Magnetic anisotropy

A ferromagnetic material has a magnetic moment even when no magnetic field is applied, if the temperature is below the Curie temperature $T_c$. If the temperature is above the Curie temperature the material becomes a paramagnetic material. In general, ferromagnetic objects exhibit a preferred direction of magnetization. This phenomenon is called magnetic anisotropy. In this section the origin of magnetic anisotropy is discussed. An intuitive picture of magnetic anisotropy is needed to understand the electric field induced magnetic anisotropy modification. The theoretical background of this electric field effect is described in section 2.2.

Particles can carry an intrinsic form of angular moment, which is called spin. Magnetic anisotropy is caused by the fact that spins of different particles are coupled with each other. These spins are coupled by the exchange interaction, which is described by the Heisenberg model. In this model the energy of the interaction of atom $a$ and $b$ with electrons with spin $S_a$ and $S_b$ respectively is given by [8]:

$$U = -2JS_a \cdot S_b$$  \hspace{1cm} (2.1)

where $J$ is the exchange constant that is related to the overlap of the charge distribution of atom $a$ and $b$. When $J$ is positive the most favourable configuration of the spins is parallel, as this reduces the energy of the system (see Equation 2.1). Together with the Pauli exclusion principle this leads to a
decrease of the Coulomb repulsion of the two electrons. The Pauli exclusion principle prohibits two electrons with the same spin to occupy the same state. Because of this, two electrons with parallel spins cannot occupy the same orbital. This leads to a decrease of the Coulomb repulsion of the electrons. This means that the energy of the system depends on the relative orientation of the spins. This effect is called the exchange interaction.

When only looking to the exchange interaction, the magnetization of a ferromagnetic material is isotropic and independent of the shape of the magnetized object and independent of the crystal structure of the magnetic atoms. However, in most cases a piece of ferromagnetic material is easier to magnetize in a certain direction (the easy axis) than in other directions (the hard axes). This phenomenon is called magnetic anisotropy. This magnetic anisotropy is caused by two things: shape anisotropy and magneto-crystalline anisotropy. In magnetic materials the direction of the easy axis is determined by a competition between the shape anisotropy and the magneto-crystalline anisotropy. Both types of anisotropy are discussed in the following sections.

2.1.1 Shape anisotropy

As described in the previous section, when the exchange constant $J$ is positive a parallel orientation of the electron spins is the most favourable configuration. However, the exchange interaction only says something about the direction of the spins relative to each other. The exchange interaction does not indicate the magnetization direction of the entire material.

The fact that the magnetization of a ferromagnetic material has a preferred direction with respect to the shape of the magnetic body is caused by the dipole-dipole interaction. The energy of this dipole-dipole interaction is given by [1]:

$$U = -\frac{\mu_0}{4\pi r^3} \left(\frac{3(\vec{r}_1 \cdot \vec{m}_1)(\vec{r}_2 \cdot \vec{m}_2)}{r^2} - \vec{m}_1 \cdot \vec{m}_2\right) \quad (2.2)$$

where $\vec{r}_1$ is the vector between the two spins, $r$ is the distance between the two spins, $\mu_1$ and $\mu_2$ are the magnetic moment of particle 1 and 2 respectively and $\mu_0$ is the magnetic permeability of vacuum. In Figure 2.1 four possible configurations of spins are shown. The dipole-dipole energy is lowest when both spins are aligned in a head-to-tail configuration and point in the same direction. Because of this, the magnetization will align along the longest axis of the ferromagnetic material.

![Figure 2.1: Four possible configurations of dipoles with their dipole-dipole energy. The dipole-dipole energy is calculated with equation 2.2. In this case $m$ is the magnetic moment of the dipoles. As can be seen, a head-to-tail configuration of the dipoles is energetically favourable. This picture is taken from [3].](image)
2.1.2 Magneto-crystalline anisotropy

Another form of magnetic anisotropy is magneto-crystalline anisotropy. This magneto-crystalline anisotropy depends on the crystal structure of the material. Ferromagnetism is carried by electrons in partially filled 3d shells. The interaction between the electrons and its neighbours can give rise to magnetic anisotropy via spin-orbit coupling. This spin-orbit interaction couples the isotropic spin of the electron to the anisotropic lattice of the material. A detailed explanation of the magneto-crystalline anisotropy is given by Van den Brink [3]. At the surface of a ferromagnetic material (or at the interface of two different materials) the electrons experience a highly anisotropic environment because of the interfacial bonding effects [3] [9]. This leads to surface magneto-crystalline anisotropy.

2.1.3 Magnetic anisotropy in thin ferromagnetic films

In thin ferromagnetic layers, it is useful to write the total magnetic anisotropy as:

\[ K_{\text{tot}} = K_{\text{bulk}} + 2 \frac{K_{\text{surface}}}{t} = K_{\text{tot}} = K_{\text{bulk}} + \frac{K_{\text{top}} + K_{\text{bottom}}}{t} \]  

(2.3)

where \( K_{\text{tot}} \) is the total magnetic anisotropy, \( K_{\text{bulk}} \) is the bulk anisotropy in the ferromagnetic layer, \( K_{\text{surface}} \) is the surface anisotropy, \( K_{\text{top}} \) and \( K_{\text{bottom}} \) are the top and bottom contribution to the surface anisotropy respectively and \( t \) is the thickness of the ferromagnetic layer. The bulk anisotropy includes the shape anisotropy and a weak magneto-crystalline anisotropy. The surface anisotropy is entirely determined by the magneto-crystalline anisotropy. The magneto-crystalline anisotropy is enhanced at the surface due to the interfacial bonding effects.

In this project, thin films of ferromagnetic materials are investigated. These ferromagnetic layers are magnetized along the surface or perpendicular to the surface. When the easy-axis is along the surface the magnetization is called in-plane. When the easy-axis is perpendicular to the surface the magnetization is called out-of-plane. In Figure 2.2 a schematic illustration of two thin ferromagnetic layers with an in-plane and an out-plane magnetization is given. In relatively thick magnetic layers, the shape anisotropy causes an in-plane magnetization. On the other hand in ultra-thin magnetic layers the surface magneto-crystalline anisotropy becomes more important. This can lead to an out-of-plane magnetization. This phenomenon is called perpendicular magnetic anisotropy (PMA). The balance between shape anisotropy and magneto-crystalline anisotropy determines whether the magnetization is in-plane or out-of-plane.

![Figure 2.2: Two thin ferromagnetic layers with a) an in-plane magnetization and b) an out-of-plane magnetization.](image)

The ferromagnetic layers used in this project are very thin (about 1 nm). Because of this, the contribution of the surface magneto-crystalline anisotropy is important.
2.2 Electric field effect

In the previous section, magnetic anisotropy has been discussed. In this project the electric field induced magnetic anisotropy modification and the electric field induced domain wall velocity modification in a Co layer are investigated. In this section the electric field effect is briefly discussed. When a voltage is applied on a capacitor, electrons and holes will accumulate at the interface of the conductor and the dielectric. During this project, films that consist of Pt/Co/AlOx/Pt layers will be used. In these films the Pt and Co layers are the conductors. The AlOx layer is the dielectric layer that separates the conducting layers. When a voltage is applied on the Pt layers, electrons and holes will accumulate on the Co/AlOx interface, which results in a different charge distribution at the interface. The added (removed) electrons are assumed to be distributed evenly over the orbitals. These added (removed) electrons modify the band filling profile of the interface atoms. The electrons experience a different anisotropic environment than before the voltage was applied on the film. This implies that the surface magneto-crystalline anisotropy will be different. Since the surface magneto-crystalline anisotropy is important in thin films, this electric field effect can have a significant effect on the magnetic properties of a thin Co layer. It is found that the modification of the anisotropy is linearly dependent on the applied voltage. For a thin Pt/Co/AlOx/Pt film the electric field induced change in perpendicular magnetic anisotropy is $14\pm2 \text{ fJ V}^{-1}\text{m}^{-1}$ [6]. This change in PMA is too small to accurately detect with MOKE measurements [6]. Instead of measuring the change of magnetic anisotropy, the electric field effect can be determined by measuring the variation of the domain wall motion. It is found that the domain wall velocity in the creep regime scales exponentially with the anisotropy [3]. This implies that it is easier to measure the electric field effect by measuring the electric field induced domain wall velocity modification. It is found that when a positive (negative) voltage is applied on the junction, that the domain wall velocity will decrease (increase) [6]. This implies that the domain wall motion can be controlled with an electric field.

During the electric field effect experiments, time dependent effects are observed. These effects can be explained by different mechanisms. Two of these mechanisms are described in this section: charge trapping and ion vacancy migration.

### 2.2.1 Charge trapping

Different types of charge traps with different electron and hole energy levels in AlOx are known [10]. In this project the AlOx layer is fabricated by plasma oxidation of an Al layer. This plasma oxidation procedure is described in section 3.1.2. Because of this oxidation procedure the AlOx layer is amorphous and the AlOx layer will contains a lot of lattice defects and impurities. These lattice defects and impurities are places where charge can be trapped. The energy levels of the charge traps are lying in the band gap of AlOx. The mechanism of charge trapping can be explained with a band diagram. In Figure 2.3 a representation of the band diagram of a Pt/AlOx/Co film is shown. In this band diagram the charge traps with their energy are shown. The values shown in the band diagram correspond to measured values found in the literature [10] [11]. The values of the work functions of Pt, AlOx and Co are found in [10] and [11]. The band diagram is asymmetric because the Fermi levels of both the Pt layer and the Co layer must be equal under application of 0V.
Figure 2.3: Band diagram of a Pt/AlOx/Co film. The values of the work functions and the values of the energies of the charge traps are found in [10] and [11]. This picture is taken from [12].

As can be seen in Figure 2.3 it is unlikely that electrons tunnel from the Pt layer to the charge traps, because the electrons need a higher energy to come in these charge traps. However when a voltage is applied on the Pt layer, the band diagram of the Pt/AlOx/Co film will change. In Figure 2.4 the band diagrams of the Pt/AlOx/Co film are shown when a positive voltage of +2V and a negative voltage of -2V is applied on the Pt layer.

Figure 2.4: Two band diagrams of a Pt/AlOx/Co film with a voltage of +2V and -2V applied on the Pt layer. The values of the work functions and the values of the energies of the charge traps are found in [10] and [11]. This picture is taken from [12].

As can be seen in Figure 2.4 when a voltage of -2V is applied on the Pt layer, it is more likely that electrons tunnel from the Pt layer to the charge traps. Because of the fact that the band diagram is asymmetric, the current through the AlOx layer due to tunnelling will be polarity dependent. When a voltage of -2V is applied on the Pt layer a larger current is expected then when a voltage of +2V is applied on the Pt layer.

When a voltage of -2V is applied on the Pt layer, the charge traps at the AlOx/Co interface have the lowest energy levels as can be seen in Figure 2.4. Because of this, the probability that electrons tunnel from the Pt layer to these charge traps is increased. This will increase the electron density at the AlOx/Co interface. When a voltage of +2V is applied on the Pt layer, the charge traps at the AlOx/Co interface have the highest energy levels. Because of this, it is unfavourable for electrons to tunnel to these charge traps. It follows that this will decrease the electron density at the AlOx/Co interface. These different electron densities at the AlOx/Co interface can influence the surface magneto-crystalline anisotropy. This will influence the PMA in the ferromagnetic Co layer. It is also possible that the trapped charge enhances the electric field and this increases the electric field effect.
2.2.2 Ion vacancy migration

Ion vacancy migration is another possible mechanism which affects the electric field effect. As described in the previous section a lot of lattice defects and impurities might be present in the AlOx layer. Most of these defects are places where an oxygen ion is missing (ion vacancy) or places where an oxygen ion is in excess [13]. In most cases oxygen vacancies are much more mobile than the oxygen ions in excess [10]. The oxygen vacancies are positively charged and are commonly represented by \( V_o^{2+} \). The AlOx layer is fabricated by plasma oxidation of an Al layer as described in section 3.1.2. During the plasma oxidation, oxygen ions penetrate the Al layer and an AlOx layer is created. This suggests that the density of the oxygen vacancies is higher at the bottom of the AlOx layer than at the top of this layer. When a positive voltage is applied on the top Pt layer the oxygen vacancies will accumulate at the bottom of the AlOx layer and at the AlOx/Co interface. This changes the amount of oxygen atoms at the AlOx/Co interface, affecting the energies of different 3d orbitals and therefore affecting the magnetic anisotropy. When a negative voltage is applied on the top Pt layer the oxygen vacancies will move to the top of the AlOx layer. Also in this case the amount of oxygen atoms at the AlOx/Co interface changes and the magnetic anisotropy will also be changed. In Figure 2.5 a schematic picture of ion vacancy migration in the AlOx layer is shown.

![Figure 2.5: Schematic pictures of ion vacancy migration in the AlOx layer.](image)

This ion vacancy migration predicts also an asymmetric behaviour of the current when a positive and a negative voltage are applied on the top Pt layer. When a positive voltage is applied on the top Pt layer, the oxygen vacancies will move to the AlOx/Co interface. But because of the fabrication process of the AlOx layer, the density of oxygen vacancies is already high at the AlOx interface. In this case a relatively small amount of ion vacancies will move to the AlOx/Co interface. When a negative voltage is applied on the top Pt layer, the oxygen vacancies will move from the AlOx/Co interface to the Pt/AlOx interface. In this case a relatively large amount of ion vacancies will move to the AlOx/Co interface. This movement of a large amount of ion vacancies can create a conducting filament (path) that consists of oxygen vacancies [11]. This implies that when a negative voltage is applied on the top Pt layer, the current through the AlOx layer may be increased over time.
Chapter 3

Experimental setup

In this chapter, first the sample fabrication is discussed. The samples that are made in this project are all fabricated with the CARUSO sputter coater. After this the techniques that are used to carry out measurements are discussed. During this project two important setups are used to measure the samples. The first one is the laser MOKE setup and the second one is the Kerr microscope. Both of these measuring techniques will be briefly discussed in this chapter.

3.1 Sample fabrication

In this section first the sputter technique and the oxidation procedure is discussed. After this the materials that are used are briefly discussed. In chapter 4 during the sample optimization this subject will be discussed further. Finally the fabrication of the wedge stacks and the junctions is discussed.

3.1.1 Sputter deposition

The samples that are made in this project are all fabricated with the CARUSO ultra-high vacuum (UHV) sputter facility manufactured by Kurt J. Lesker Company. The CARUSO uses the technique of DC magnetron sputtering for the deposition of thin films. This deposition technique will be briefly discussed here. First a plasma is created near the target (a disc with highly pure materials) surface. The plasma consists of argon (Ar) ions. A so called magnetron is used to concentrate the plasma. This magnetron consists of magnets placed behind the target which concentrate the ion plasma to the target. Below the target there is a ring-shaped anode. When a high voltage is applied between the target and the anode, the argon ions in the plasma are accelerated towards the target. These argon ions then hit the surface of the target and thereby shoot out target atoms. These target atoms then fall on a substrate that is placed below the targets. In Figure 3.1 a schematic illustration of this procedure is shown. The growth rate of the deposited layer is of the order of 1 Ås⁻¹. With this technique thin layers can be grown with thickness precision of 1 Å.

The targets that are used are located in the ultra-high vacuum (UHV) sputter chamber. The base pressure in this chamber is of the order of 10⁻⁸ mbar. This vacuum is needed to eliminate pollutants and reactive gasses. In this UHV sputter chamber there are six different targets (different materials).
3.1.2 Oxidation

The oxidation chamber is used to oxidize the sample after sputtering. The oxidation chamber is a part of the CARUSO sputter facility. The samples can be moved from the CARUSO sputter chamber to the oxidation chamber without breaking the vacuum. The base pressure of the oxidation chamber is in the order of $10^{-8}$ mbar. In this oxidation chamber there is a ring-shaped anode and a cathode. A pre-volume is filled with oxygen until the pressure in this pre-volume is about 21 mbar. When the pre-volume is opened, oxygen is injected in the oxidation chamber. Before the oxygen can be injected in the oxidation chamber, the valve to the vacuum pump has to be closed. The pressure in the oxidation chamber after this injection is about $10^{-1}$ mbar. When a voltage is applied between the cathode and the anode, the oxygen will ionize and this creates an oxygen plasma. The voltage limit is set to 2 kV and the steady current is set to either 7.5 mA or 15.0 mA. In Figure 3.2 a schematic illustration of the oxidation chamber is shown. When a sample is placed beneath the ring-shaped anode the oxygen ions accelerate towards the sample and hit the sample. The oxygen ions will penetrate the sample and will bond with the atoms in the sample. In this project aluminium (Al) layers are oxidized in this way to get aluminium oxide (AlOx) layers. When the sample has been oxidized sufficiently, the valve to the vacuum pump is opened and the vacuum pump removes all the oxygen in the oxidation chamber.

The oxidation chamber is also used to plasma clean the substrate. Because oxygen plasmas are very reactive it is a very efficient way to clean the substrate. In this project all the substrates are cleaned with an oxygen plasma with a voltage limit of 2 kV and a steady state current of 15 mA for 10 minutes before layers in the sputter chamber are deposited on the substrate.
Figure 3.2: A schematic illustration of the oxidation chamber. When a voltage is applied between the cathode and the anode an oxygen plasma arises and oxygen ions will hit and penetrate the sample. This picture is taken from [9].

3.1.3 Materials

In this project samples that show perpendicular magnetic anisotropy (PMA) are investigated. The samples that are used in this project consist of a Pt/Co/AlOx/Pt stack. This material stack acts like a capacitor. These materials have been chosen because this material combination turns out to be interesting for domain wall motion applications [3] [15]. Also a Ta buffer layer is used to get a perpendicularly magnetized Co layer. The reason why a Ta buffer layer is used is described in chapter 4. The AlOx layer is obtained by oxidizing an aluminium layer as described in the previous section. The samples are deposited on a SiO₂ substrate. Before layers are deposited on this SiO₂ substrate, the substrate is cleaned. The substrate is immersed in acetone and isopropanol successively and is then plasma cleaned in the oxidation room of the CARUSO for 10 minutes.

3.1.4 Wedges and junctions

All the samples that are fabricated in this project are either wedges or junctions. These samples are fabricated by using masks. The two masks that are used are the wedge mask and the junction mask. The wedge mask is a metal plate that has a large gap. This gap has one sharp edge. During sputtering the wedge mask with the sharp edge moves along the substrate. This leads to a wedge shaped sample. In Figure 3.3 a schematic illustration of this procedure is shown. The junction mask is a tungsten plate with eight slits. In Figure 3.4 a picture of the junction mask is shown. The width of each slit is about 200 μm. The junction mask can be placed on the substrate before sputtering the layers. Atoms are only deposited on places where a slit is present. It is also possible to rotate the junction mask by 90°. So junctions as shown in Figure 3.5 can be fabricated in this way.

In the CARUSO sputter facility the mean free path of the sputtered atoms is smaller than the distance between the source of the atoms and the substrate. Because of this, the sputtered atoms do not reach the substrate directly. The atoms will reach the substrate not only from above but also from
the side. This affects the sputter procedure when the wedge mask and the junction mask are used. When a mask is used, atoms can practically only come from above. Atoms that incident at a small angle to the substrate are blocked. So when a mask is used, the amount of atoms that are deposited is reduced compared with the situation without mask. So less atoms are deposited than the calibration suggest. This effect is called a tooling factor.

Figure 3.3: A schematic illustration of the wedge fabrication procedure. During sputtering the wedge mask is moving along the substrate. This leads to a deposited layer that has a gradient. This illustration is taken from [16].

Figure 3.4: a) An illustration of the junction mask. b) An illustration of the junctions that arise when the junction mask is rotated by 90°. This picture is taken from [16].

Figure 3.5: a) A schematic illustration of (Ta)/Pt/Co/AlOx/Pt junction used in this project. The (Ta)/Pt/Co layers are made with the junction mask. Then the junction mask is removed and the AlOx layer is deposited over the whole substrate (without a mask). Then the junction mask is used again to grow the upper Pt electrode. In this case the junction mask is rotated by 90°. This picture is taken from [6]. b) A picture of a junction fabricated in this project. This picture is made with the Kerr microscope.
3.2 Magneto-optic Kerr effect (MOKE)

To study the magnetic properties of the ferromagnetic Co layer in the wedges and the junctions, the magneto-optic Kerr effect (MOKE) is used. This effect describes the changes of reflected polarized light from a magnetized surface. When a linearly polarized light beam is reflected by a magnetized surface, the reflected beam can either have a different polarization direction or a change from linear to elliptical polarization or both. This is a brief description of the magneto-optic Kerr effect. In the work of Rietjens [17] a more detailed explanation of this effect is given. When light of normal incidence to the magnetic surface is used, this effect is called polar MOKE. Polar MOKE is used for perpendicularly magnetized samples. So the magnetization of the sample can be measured by measuring the change of the polarization of the incident light with respect to the reflected light.

During this project two different ways are used to measure the magnetization of the samples, both using MOKE. The first one is a laser MOKE setup, the second one is the Kerr microscope. Both of these measuring techniques will be briefly discussed here.

3.2.1 Laser MOKE

In Figure 3.6 a schematic illustration of the laser MOKE setup is shown. This laser MOKE setup is used in this project to measure magnetic hysteresis loops. In Figure 3.7 an example of a hysteresis loop is shown. With these hysteresis loops the magnetic properties of the samples such as the saturation magnetization, the coercivity field and the remanent magnetization can be determined. The saturation magnetization $M_{\text{sat}}$ is the maximum attainable magnetization. The coercivity field $H_C$, often referred as ‘the coercivity’, is the required applied magnetic field to reduce the magnetization to zero after saturation. The remanent magnetization $M_R$ is the magnetization of the sample after saturation when the applied magnetic field is switched off.

To obtain a hysteresis loop of a magnetic sample a laser beam is focussed on the sample. Before this incident beam reaches the magnetic sample the laser beam is polarized in one direction by a polarizer. Because of the Kerr effect the polarization direction of the reflected laser beam is in a different direction then the polarization direction of the incident laser beam. The reflected laser beam will have a polarization component perpendicular to the polarization direction of the incident laser beam. With another polarizer these perpendicular components will be filtered out. This filtered reflected laser beam is detected by a CCD detector.
3.2.3 Kerr microscopy

Another way to measure the magnetic properties of the samples is to use the Kerr microscope. In this project an Evico Magnetics wide-field Magneto-Optical Kerr-Microscope is used. In Figure 3.8 a picture of this Kerr microscope is shown. A Kerr microscope is a conventional microscope that uses optical filters. The Kerr microscope uses MOKE to differentiate parts of the sample with different magnetization orientation. With the Kerr microscope the magnetic switching of magnetic nanostructures can be measured. One of the main advantages of the Kerr microscope is that a better understanding can be obtained about what is happening with the sample. With the laser MOKE setup only a hysteresis loop can be measured, because only the average magnetization of a sample can be measured with the laser MOKE setup. On the other hand with the Kerr microscope a spatially resolved view of the magnetic switching and of the domain structure can be made. A difference in the magnetization direction is represented by a difference in luminosity. With an electromagnet a
A perpendicular magnetic field can be applied. This electromagnet has a range of -86 mT to +86 mT. This electromagnet can be controlled by a computer. To measure the electric field effect a voltage is applied on the Pt electrodes. This voltage is applied with the Keithley 2400 SourceMeter. Also this Keithley can be controlled by a computer. In Figure 3.9 a common picture of a magnetic sample measured with the Kerr microscope is shown.

**Figure 3.8:** Picture of the Kerr microscope that is used in this project. In this picture the yellow ring-shaped block is the electromagnet. On top of the Kerr microscope a CCD camera is placed. Picture is taken from [18].

**Figure 3.9:** A picture of a magnetic sample made with the Kerr microscope. The darker area in this picture indicates an upward out-of-plane magnetization. The brighter area in this picture indicates a downward out-of-plane magnetization. Also places where no magnetic material is present are shown.
Chapter 4

Results and discussion

In this chapter the results of the measurements performed during this project are shown. First the sample optimization is discussed. The results of this optimization are presented in section 4.1. In this section the suitable parameters of the ferromagnetic Co layer, the dielectric AlOx layer and the Pt layers are determined. After this section, the electric field effect is measured. The magnetic behaviour of the samples when an electric field is applied is discussed. These results are presented in section 4.2.

4.1 Sample optimization

The most important goal of this project is to measure the electric field effect in thin ferromagnetic layers. To measure this electric field effect, first junctions that show perpendicular magnetic anisotropy (PMA) and have a resistance much larger than that of the leads have to be fabricated. In this project, junctions that consist of a (Ta)/Pt/Co/AlOx/Pt stack are used. These materials are used because such stacks show a strong PMA and high domain wall velocities [3]. To fabricate junctions that show the properties described above, the thicknesses of the layers have to be optimized. To determine which thicknesses of the AlOx layer and the Co layer result in the best PMA, wedge samples for the AlOx layer and for the Co layer are fabricated. The fabrication of wedge samples is discussed in section 3.1. The deposition parameters of the wedges are listed in Appendix A. The wedges are investigated with the laser MOKE setup.

4.1.1 Thickness of the AlOx layer

First the dielectric AlOx layer is optimized. The AlOx layer is produced by oxidizing an Al layer as described in section 3.1.2. To determine the optimal AlOx layer thickness, a Pt/Co/Al stack is fabricated. In this stack the Al layer is a wedge. This stack is then oxidized. In this case three things will happen. At the locations where the Al layer is too thin, over-oxidation will happen. In this case a part of the Co layer is also oxidized and a CoOx layer arises. On the other hand, at the locations where the Al layer is too thick, under-oxidation will happen. In this case a part of the Al layer has not been oxidized. Between these two regions, there will be a region where the whole Al layer is oxidized but where the Co layer is not oxidized. In this case a Co/AlOx interface will arise. In Figure 4.1 schematic representations of these three situations are shown. When the whole Al layer is
completely oxidized, the Co atoms can form bonds with the oxygen atoms in the AlOx layer. This changes the surface magneto-crystalline anisotropy. The presence of oxygen atoms at the Co/AlOx interface causes PMA as explained in section 2.1.2.

Figure 4.1: Schematic pictures of the oxidation procedure in a Pt/Co/Al stack. When the Al layer is too thick or the oxidation time is too short, the oxygen ions do not reach the Co/Al interface. In this case a layer of Al remains. This is shown in picture (a). When the Al layer is too thin or the oxidation time is too long, a part of the Co layer is also oxidized. In this case a layer of CoOx arises. This is shown in picture (c). Between these two cases, there will be a region where the whole Al layer is oxidized but where the Co layer is not oxidized. This is shown in picture (b). This picture is taken from [19].

In Figure 4.1 sharp lines between the different materials are drawn. In fact, it is very likely that near the interface between two materials the transition is rough. Because of this, it is difficult to indicate which of the three situations shown in Figure 4.1 occurs in the samples. However it does not matter which of the three situations described above are happening. In this project the most important property is whether the magnetization of the Co layer is in-plane or out-of-plane.

The Al wedge structure that is investigated consists of a Pt (4.0 nm)/Co (1.0 nm)/Al (0–3.0 nm) stack and is oxidized for 10 minutes as described in section 3.1.2. The deposition parameters of this AlOx wedge are shown in Appendix A in Table 1. In Figure 4.2 typical hysteresis loops that are measured for different Al thicknesses are shown. All these hysteresis loops have been measured with the laser MOKE setup. The magnetic properties of the sample as a function of the thickness of the AlOx top layer are shown in Figure 4.3. The saturation magnetization, the coercivity and the remanent magnetization are determined from the hysteresis loops such as shown in Figure 4.2.

Figure 4.2: Typical hysteresis loops (obtained with the laser MOKE setup) for three different Al thicknesses. In the first graph the Al layer is 1 nm thick. The magnetization of the Co layer is in-plane. In this case over-oxidation has occurred. In the second graph the Al layer is 2 nm thick. The magnetization of the Co layer is out-of-plane. In the third graph the Al layer is 2.8 nm thick. In this case under-oxidation has occurred. With these hysteresis loops the saturation magnetization, the coercivity and the remanence can be determined.
Figure 4.3: Magnetic properties of a Pt (4.0 nm)/Co (1.0 nm)/Al (0-3.0 nm) wedge oxidized for 10 minutes as described in section 3.1.2. The saturation magnetization, the coercivity and the remanence are shown as a function of the Al thickness. The remanence is defined as the ratio of the magnetization at B=0 and the saturation magnetization. These properties are determined from the hysteresis loops that are obtained with the laser MOKE setup. The black graphs show the magnetic properties of the wedge as deposited. The red graphs show the magnetic properties of the wedge after annealing at 300 °C for 30 minutes.

As can be seen in Figure 4.3, the Pt/Co/AlOx stack shows perpendicular magnetization when the Al layer thickness is between 1.7 nm and 2.3 nm. The highest coercivity is about 30 mT when the Al thickness is about 1.8 nm. When the Al layer thickness is larger than 1.8 nm, the sample is under-oxidized. In this case the coercivity decreases because less oxygen atoms reach the Co/Al interface. When the Al layer thickness is less than 1.7 nm, the sample is over-oxidized. In this case the sample does not show PMA.

Annealing the sample at 300 °C increases the coercivity and increases the range where the sample shows an out-of-plane magnetization. At 300 °C the oxygen atoms are more mobile and the oxygen atoms will be distributed more homogenously in the AlOx layer. Therefore more oxygen atoms will be present at the Co/AlOx interface. This increases the PMA.
4.1.2 The use of a Ta buffer layer

In this section the influence of a Ta buffer layer is shown. In the previous section a Pt/Co/AlOx wedge was investigated. In this section a Ta layer is deposited below the Pt layer and the magnetic properties of the wedge are measured again. The magnetic properties of the Pt (4.0 nm)/Co (1.0 nm)/Al (0-3.0 nm) wedge and the Ta (2.0 nm)/Pt (4.0 nm)/Co (1.0 nm)/Al (0-3.0 nm) wedge are shown in Figure 4.4. The deposition parameters of these AlOx wedges are shown in Appendix A in Table 1 and 2.

Figure 4.4: Magnetic properties of the Pt (4.0 nm)/Co (1.0 nm)/Al (0-3.0 nm) wedge (black graphs) and of the Ta (2.0 nm)/Pt (4.0 nm)/Co (1.0 nm)/Al (0-3.0 nm) wedge (red graphs) both oxidized for 10 minutes. The saturation magnetization, the coercivity and the remanence are shown as a function of the Al layer thickness.

As can be seen in Figure 4.4, the magnetic properties of the ferromagnetic Co layer are influenced by the presence of a Ta buffer layer. The maximum coercivity of the sample with the Ta buffer layer is about twice as large as the maximum coercivity of the sample without the Ta buffer layer. Also, the range where the sample shows an out-of-plane magnetization is increased. The Ta buffer layer causes PMA even in the under-oxidized Al regime. This suggests that the Pt/Co interface is improved by the Ta buffer layer, making it contribute significantly more to the PMA. The increase in coercivity suggests that the Co film quality might also have improved, although this cannot be determined conclusively from coercivity data alone.
4.1.3 Thickness of the Co layer

In this section the ferromagnetic Co layer is optimized. To determine the optimal Co layer thickness a Co wedge is investigated. This Co wedge consists of a Ta (2.0 nm)/Pt (4.0 nm)/Co (0-2.0 nm)/AlOx (2.2 nm) stack. In this experiment a 2.2 nm AlOx layer is used as a top layer. This AlOx thickness is chosen because of the results presented in the previous section. The AlOx layer thickness is chosen as thick as possible because this will lead to a large resistance of the junction. The deposition parameters of this Co wedge are shown in Appendix A in Table 3. The magnetic properties of the Co wedge are shown in Figure 4.5.

![Figure 4.5](image-url)

**Figure 4.5:** Magnetic properties of a Ta (2.0 nm)/Pt (4.0 nm)/Co (0-2.0 nm)/Al (2.2 nm) wedge oxidized for 10 minutes. The saturation magnetization, the coercivity and the remanence are shown as a function of the Co layer thickness.

As can be seen in Figure 4.5, the stack shows PMA for a Co layer thickness in the range between 0.7 nm and 1.6 nm. The sample has the highest coercivity of about 20 mT when the Co thickness is about 1.0 nm. Such a coercivity is also found when Figure 4.4 is examined. In that case the coercivity is about 25 mT. This difference in coercivity can be caused by the fact that the calibration of the CARUSO sputter coater is not perfect. Another explanation can be that a small tooling factor is present when the wedge mask is used. In the next section, the tooling factor of the masks used in this project is discussed further. When the Co layer thickness is below the 0.7 nm, the stack does not show PMA. When the Co layer thickness is below the 0.25 nm, it even turns out that the saturation magnetization is (nearly) zero and so the Co layer is not magnetic at all. A possible explanation for this is that oxygen atoms penetrate the Co layer and a non-magnetic CoOx layer is created. When the
Co layer thickness increases the saturation magnetization also increases. This makes sense because the thicker the Co layer is, the more magnetic material is present in the sample and therefore the higher the maximum magnetization is. If the Co layer is thicker than 1.6 nm, the surface contribution to the anisotropy becomes too small to overcome the shape anisotropy, pulling the magnetization in-plane. This is also described in section 2.1.2.

To improve the resistance of junction samples, a second AlOx layer is commonly grown on top of the first AlOx layer. To investigate if this has an effect on the magnetic properties of the Co layer, two Co wedges are investigated. The first Co wedge consists of a Ta (2.0 nm)/Pt (4.0 nm)/Co (0-2.0 nm)/AlOx (2.2 nm) stack. The second Co wedge consists of a Ta (2.0 nm)/Pt (4.0 nm)/Co (0-2.0 nm)/AlOx (2.2 nm)/AlOx (2.2 nm) stack. During the fabrication of this second wedge the sample is two times oxidized after the Al layers are deposited. The deposition parameters of these Co wedges are shown in Appendix A in Table 3 and 4. The magnetic properties of the two Co wedges are shown in Figure 4.6.

![Graph showing magnetic properties](image)

**Figure 4.6:** Magnetic properties of the Ta (2.0 nm)/Pt (4.0 nm)/Co (0-2.0 nm)/Al (2.2 nm) wedge (black graph) oxidized for 10 minutes and of the Ta (2.0 nm)/Pt (4.0 nm)/Co (0-2.0 nm)/Al (2.2 nm)/Al (2.2 nm) wedge (red graphs) oxidized two times for 10 minutes after sputtering the Al layers. The saturation magnetization, the coercivity and the remanence are shown as a function of the Co layer thickness.

As can be seen in Figure 4.6 both the coercivity and the remanence deteriorate by depositing a second AlOx layer on the sample. The stack with one AlOx layer shows PMA for Co layer thicknesses between 0.7 nm and 1.6 nm. The stack with two AlOx layers shows PMA for Co layer thicknesses between 0.9 nm and 1.6 nm. Also the coercivity of the stack with one AlOx layer is about twice as
large. The second oxidation step is also seen to decrease the saturation magnetization of the stack below 0.7 nm Co layer thickness, with no magnetic moment being detected below 0.5 nm Co layer thickness. This suggests that oxygen ions again penetrate into the Co layer during the second oxidation step, increasing the non-magnetic layer thickness from 0.25 nm to 0.5 nm. This might be due to non-uniform growth of the second Al layer, which is sputtered onto AlOx.

4.1.4 Other important parameters

In the previous sections the thicknesses of the dielectric AlOx layer and the ferromagnetic Co layer were optimized. Also the influence of a Ta buffer layer on the magnetic properties of the Co layer was determined. In this section some other important optimizations are discussed. First the resistance of the AlOx layer is discussed. Then the influence of the Argon flow in the CARUSO during sputtering is discussed. Finally the tooling factor of the wedge mask and the junction mask are discussed in this section.

The main goal of this project is to measure the electric-field effect in Pt/Co/AlOx/Pt junctions. To measure this electric field effect, first junctions that show PMA and that have a dielectric layer with a resistance that is much larger than of the leads have to be fabricated. To improve the resistance of the junction, a second AlOx layer is grown on top of the first one. The resistance of the junctions that have two AlOx layers of 2.2 nm thick are in the range of 0.1 MΩ to 50 MΩ when a voltage is applied of less than 2.5 V. This resistance is orders of magnitude higher than the contact resistance. So charges will accumulate on the interfaces of the AlOx layer. Because of the variations during the fabrication of the junctions not all the AlOx layers show such a resistance. Some of the junctions have only a resistance of a few kΩ. In these cases the top Pt electrode and the under Pt electrode are in electric contact with each other. In these cases the AlOx layers do not cover the whole Pt layer and the Co layer. Another possibility is that a dirt particle is in the AlOx layer. Such a dirt particle can create a conductive path in the AlOx layer.

Another important issue that affects the resistance of the AlOx layer is the argon pressure in the CARUSO sputter facility during the sputtering of the top Pt layer. In the FNA group, it is found that when the top Pt layer is sputtered at a higher argon pressure that the junction has a higher resistance. So the sputtering pressure has an influence on the resistance of the AlOx layer. This is probably caused by the fact that the mean free path of the Pt atoms is larger when the argon pressure is low. So these atoms are more accelerated and they will penetrate deeper into the AlOx layer, decreasing junction resistance.

The last issue that is investigated during the optimization is the tooling factor of the junction mask. It turns out that the junction mask that is used is a little bit bent. Because of this, the tooling factor of the junction mask is large. This is shown in Figure 4.7.
Figure 4.7: Three junction fabricated with the CARUSO sputter facility and with the junction mask. The first junction consists of a Ta (3.0 nm)/Pt (6.0 nm)/Co (1.0 nm)/AlOx (2.0 nm)/AlOx (2.0 nm)/Pt (4.0 nm) stack. As can be seen only the brighter area in this picture shows PMA. This is strange because this suggests that the thickness of the Co layer is different in the middle of the wire than at the edge of the wire. This is caused by the tooling factor of the junction mask. The second junction consists of a Ta (3.0 nm)/Pt (6.0 nm)/Co (1.33 nm)/AlOx (2.0 nm)/AlOx (2.0 nm)/Pt (4.0 nm) stack. In this case a thicker area of the ferromagnetic wire shows PMA. The third junction consists of a Ta (3.0 nm)/Pt (6.0 nm)/Co (1.5 nm)/AlOx (2.0 nm)/AlOx (2.0 nm)/Pt (4.0 nm) stack. In this case almost the whole ferromagnetic wire shows PMA. More Co atoms are deposited in this case, so even at the edges of the wire there are enough Co atoms to show PMA.

4.1.5 Conclusion

The most important conclusions of this section are summarized here. In this section the thicknesses of the Co layer and the AlOx layer were optimized. Also the influence of a Ta buffer layer was determined. It turned out that a Ta buffer layer increases the coercivity and increases the range where the stack shows PMA. Perpendicular magnetic anisotropy is observed in a Ta/Pt/Co/AlOx stack when the AlOx layer thickness is in a range of 1.7 nm and larger and when the Co layer thickness is in a range of 0.7 nm to 1.6 nm.

Another important property of the junctions is that the dielectric layer needs to have a large resistance. To reach this two AlOx layers of 2.2 nm thick are used as a dielectric layer. It appears that oxygen ions penetrate into the Co layer during the second oxidation step. This deteriorates the magnetic properties.
4.2 Electric field effect

To measure the electric field effect a junction that consists of a Ta (3 nm)/Pt (6 nm)/Co (1.5 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) stack is used. A Co layer thickness of 1.5 nm is used because of the large tooling factor of the junction mask. An AlOx layer thickness of 2.2 nm is used because the resistance of the junction is then in the range of 0.1 MΩ to 50 MΩ. The Pt top layer is fabricated with an argon flow of 10 sccm. The deposition parameters of the junction are listed in the Appendix A in Table 5.

This current section first describes the electric properties of such a junction. After this the results of the measurements on the electric field effect are described.

4.2.1 Electric properties of the junctions

With the Keithley different voltages are applied to the junction. The I-V curve of the above mentioned junction is given in Figure 4.8. It is clear that the junction shows a non-Ohmic behaviour. The junction used in Figure 4.8 shows a resistance between 2 MΩ and 50 MΩ for voltages between 0 V and 2 V. The contacts themselves were found to display an Ohmic resistance of about 10 kΩ. It is expected that charge accumulates on both sides of the AlOx layer. The small currents through the junctions are probably caused by tunnelling.

![Figure 4.8: Typical I-V curve of the Ta (3 nm)/Pt (6 nm)/Co (1.5 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) junction. The I-V curve shows a non-Ohmic behaviour. The junction has a resistance between 2 MΩ and 50 MΩ for voltages between 0 V and 2 V.](image)

The resistance of the junction is found to change over time. In Figure 4.9 and Figure 4.10 the resistance is plotted against the time. In Figure 4.9 a voltage of +1.5 V is applied to the junction. In Figure 4.10 a voltage of -1.5 V is applied to the junction. As can be seen in Figure 4.9, when a positive voltage is applied to the junction the resistance increases when time goes on. On the other hand, as can be seen in Figure 4.10, when a negative voltage is applied to the junction the resistance decreases when time goes on. So the time dependency of the resistance of the junction depends on the polarity of the applied voltage. In these two figures the time is set to zero when the measurement was started. The voltage was applied on the junction about 5 seconds before the measurement was started.
Figure 4.9: The resistance is plotted against the time. A voltage of +1.5 V is applied on the top Pt electrode. The resistance increases when time goes on.

Figure 4.10: The resistance is plotted against the time. A voltage of -1.5 V is applied on the top Pt electrode. The resistance decreases when time goes on.

The observed resistance change can be caused by several processes. Oxygen vacancy migration is one of these processes and will be discussed briefly here. When a positive voltage is applied to the top Pt electrode the oxygen vacancies will diffuse to the bottom of the AlOx layer. These oxygen vacancies are also places where electrons can be trapped. When the oxygen vacancies (charge traps) are accumulated at the bottom of the AlOx layer, the distance between these charge traps and the top Pt layer is increased. Because of this, the probability that electrons tunnel from the charge traps to the top Pt layer decreases. So the current through the AlOx layer decreases and the resistance increases.
On the other hand, when a negative voltage is applied to the top Pt electrode the oxygen vacancies will diffuse to the top of the AlOx layer. Before a voltage is applied across the junction the density of the oxygen vacancies is higher at the bottom of the AlOx layer than at the top of the AlOx layer. This is caused by the oxidation procedure as described in section 3.1.2. Because in this case much more oxygen vacancies will diffuse to the top Pt electrode, it is possible that a conducting path of oxygen vacancies is able to arise. So in this case the current through the AlOx layer will increase over time and so the resistance of the AlOx layer will decrease over time.

### 4.2.2 Electric field induced coercivity modification

The magnetic behaviour of the junctions is investigated with the Kerr microscope. In Figure 4.11 three hysteresis loops of the junction are shown. The hysteresis loops are measured with voltages of 0 V and ±2.0 V applied to the top Pt electrode. The used region of interest is small and is defined in the centre of the junction.

![Kerr intensity vs Magnetic field](image)

**Figure 4.11:** Three magnetic loops of the Ta (3 nm)/Pt (6 nm)/Co (1.5 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) junction. The hysteresis loops are measured with voltages of 0 V and ±2.0 V applied to the top Pt electrode. The region of interest is taken small and is defined in the centre of the junction. The intensity in the region of interest is plotted against the applied magnetic field. As can be seen, no difference in coercivity is measured when different voltages are applied to the top Pt electrode.

As can be seen in Figure 4.11 no electric field effect is measured. To measure the electric field in more detail, the domain wall motion velocity is investigated. This domain wall velocity is investigated by measuring the time evolution of the magnetization in the region of interest (in this case the whole junction). The Co layer is first saturated perpendicular to the surface. Then a magnetic field is applied in the opposite direction and the time evolution of the magnetization is measured. The applied magnetic field is set to 19 mT. A domain wall propagates across the region of interest and the
average brightness increases. In figure 4.12 this measurement technique is shown. The intensity in the region of interest is measured and is plotted against the time. In Figure 4.13 this intensity is plotted against the time. The slope of the obtained graph is thus a measure of the domain wall velocity. This measurement is done with voltages of ±1V and ±2.5V applied to the top Pt electrode.

**Figure 4.12:** Four pictures of the Ta (3 nm)/Pt (6 nm)/Co (1.5 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) junction. The red rectangle is the region of interest. The junction is first saturated perpendicular to the surface. After this a magnetic field of 19 mT is applied in the opposite direction. When this is done, domain walls propagate across the junction and the average brightness in the region of interest increases. This increase in intensity is measured and is plotted against the time. With this measuring technique the electric field effect is measured.

![Image of four pictures of the Ta (3 nm)/Pt (6 nm)/Co (1.5 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) junction](image)

**Figure 4.13:** The Kerr intensity is plotted against the time. A magnetic field is set to 19 mT at Time=0. Then the magnetization of the Co layer switches gradually. The intensity in the region of interest, this time the whole junction, changes. This intensity is measured and plotted against the time. As can be seen, the Co layer is completely switched after about 35 seconds in all cases. When a negative voltage is applied on the top Pt electrode the switching goes faster. When a positive voltage is applied on the top Pt electrode the switching goes slower.

As can be seen in Figure 4.13, a positive voltage on the top Pt electrode is found to decrease the domain wall velocity, whereas a negative voltage increases it. This difference in domain wall velocity is very small however. This difference is smaller than the observed electric field induced domain wall
Van den Brink found that a positive (negative) applied voltage decreases (increases) the domain wall velocity. This is the same result that is found in this investigation, as can be seen in Figure 4.13. It is expected that the electric field effect becomes larger for junction near the in-plane to out-of-plane transition [3]. This could be a reason for the small electric field induced domain wall velocity modification.

To increase this electric field effect another junction is fabricated and investigated. A junction that consists of a Ta (3 nm)/Pt (6 nm)/Co (1.7 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) stack is used. The deposition parameters of the junction are listed in the Appendix A in Table 6. The previously described measurement was repeated for this junction. In Figure 4.14 and Figure 4.15 the results of these measurements are shown.

![Figure 4.14](image)

**Figure 4.14:** Three magnetic hysteresis loops of a Ta (3 nm)/Pt (6 nm)/Co (1.7 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) junction. The hysteresis loops are measured with voltages of 0 V and ±1.5 V applied to the top Pt electrode. The region of interest is taken small and is defined in the centre of the junction. The intensity in the region of interest is plotted against the applied magnetic field. As can be seen, no difference in coercivity is measured when a different voltage is applied on the top Pt electrode.
Figure 4.15: The Kerr intensity is plotted against the time. A magnetic field is set to 17 mT at Time=0. Then the magnetization of the Co layer switches gradually. The intensity in the region of interest slowly changes. This intensity is measured and plotted against the time. As can be seen, the Co layer is completely switched after about 30 seconds in all cases. In this case no correlation has been found between the applied voltage and the switching behaviour.

4.2.3 Discussion

The most important conclusions of this section are summarized here. It was found that in the junction that consists of a Ta (3 nm)/Pt (6 nm)/Co (1.7 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) stack no electric field effect is measured. In the junction that consists of a Ta (3 nm)/Pt (6 nm)/Co (1.5 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) stack a very small electric field effect is measured. It turned out that a thicker Co layer does not achieve an increase of the electric field effect even though the magnetization of the Co layer is near the in-plane and out-of-plane transition. Three explanations for these observations are offered:

1. The Al layer may be under-oxidized. In this research two AlOx layers are used of 2.2 nm. It is found that in this case the Co layer shows PMA and the resistance of the junction is between 0.1 MΩ to 50 MΩ. But as can be seen in Figure 4.4 a Ta/Pt/Co/AlOx stack shows PMA in an Al layer thickness range between 1.7 nm and larger. But when the AlOx is too thick, an Al layer will still be present in the junction. So the charge will be accumulated at the Al/AlOx interface and will not accumulate at the Co/AlOx interface. So an applied electric field on the top Pt electrode will not influence the PMA in the Co layer.

2. The Co layer may be too thick. Junction with a Co layer thickness of 1.5 nm and 1.7 nm are used in this research. These thicknesses are used because of the large tooling factor of the junction mask as shown in Figure 4.7 because otherwise there would be no out-of-plane magnetization at the edge of the junction. But this thick Co layer decreases the influence of
the surface magneto-crystalline anisotropy. The total anisotropy in a thin film can be written as $K_{\text{tot}} = K_{\text{bulk}} + 2 \frac{K_{\text{surface}}}{t}$. So when the thickness of the Co layer increases the surface magneto-crystalline anisotropy becomes less important. As stated in section 2.2 the electric field effect affects the surface magneto-crystalline anisotropy. So when the thickness of the Co layer is increased, the electric field induced coercivity change and the electric field induced domain wall velocity modification are decreased.

3. The presence of a Ta buffer layer influences the anisotropy of the sample too much. A Ta buffer layer increases the coercivity and increases the range where the stack shows PMA. This is caused by the fact that the Ta buffer layer causes a smooth surface. The above given equation for the total anisotropy can be rewritten as $K_{\text{tot}} = K_{\text{bulk}} + \frac{K_{\text{top}} + K_{\text{bottom}}}{t}$. As can be seen in this equation, the surface anisotropy is not only caused by the Co/AlOx interface but is also caused by the Pt/Co interface. The Ta buffer layer causes a smooth Pt/Co interface, which significantly adds to the anisotropy. Because of this the total anisotropy is relatively less affected by the Co/AlOx interface. When an electric field is applied on the top Pt electrode this Co/AlOx interface changes. But because this change affects the anisotropy relatively less, the electric field induced coercivity change and the electric field induced domain wall velocity modification will also be less.
Chapter 5

Conclusion and outlook

Conclusion

In this project experiments were performed on junctions that consist of a Ta/Pt/Co/AlOx/Pt stack. The goal of these experiments was to measure the electric field induced magnetic anisotropy modification. Before this magnetic anisotropy modification could be measured first samples that show PMA and have a resistance much larger than that of the leads had to be fabricated. To fabricate junctions that show these properties described above, the thicknesses of the layers had to be optimized. It turned out that a Ta buffer layer increases the coercivity and increases the range where the stack shows PMA. A Ta/Pt/Co/AlOx/Pt stack shows PMA when the AlOx layer thickness is in a range of 1.7 nm and larger and when the Co layer thickness is in a range of 0.7 nm to 1.6 nm. To obtain junctions with a large resistance two AlOx layers are used. It appeared that oxygen ions penetrate into the Co layer during the second oxidation step. This influences the magnetic properties of the stack.

To measure the electric field induced magnetic anisotropy modification a junction that consists of a Ta (3 nm)/Pt (6 nm)/Co (1.5 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) stack is used. In this junction a very small electric field induced domain wall velocity modification was measured. A positive (negative) voltage applied on the top Pt electrode decreases (increases) the domain wall velocity. However these differences in domain wall velocity are very small. This electric field induced domain wall velocity modification is smaller than the observed electric field induced modification measured by Van den Brink [3].

It is expected that the electric field effect becomes larger for junction near the in-plane to out-of-plane transition [3]. So to increase the electric field effect a junction that consists of a Ta (3 nm)/Pt (6 nm)/Co (1.7 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) stack was measured. In this junction no electric field induced coercivity change and electric field induced domain wall velocity modification was measured. Three explanations for these observations are:

- The Al layer may be under-oxidized.
- The Co layer may be too thick.
- The presence of a Ta buffer layer influences the anisotropy of the sample too much.
Outlook

To increase the electric field effect in Pt/Co/AlOx/Pt junctions, the three above mentioned explanations have to be investigated further. This can be done by:

- Investigate junctions with a thinner Al layer. In that case the Al layer may not be under-oxidized. This is difficult because the resistance of the junctions has to be large. One possibility can be that another oxidation procedure is used. It is possible for example to oxidize the Al layer during the sputter procedure in the CARUSO. In this case the Al layer cannot be under-oxidized.
- Investigate junctions with a thinner Co layer. This can only be done by using another junction mask, because the tooling factor of the mask used in this project is too large. Also junctions that are made with the EBL procedure can be investigated.
- Investigate junctions without a Ta buffer layer. It turned out that it was difficult to fabricate junctions that show PMA and do not have a Ta buffer layer.
Bibliography


### Appendix A

### Deposition parameters

**Table 1: Deposition parameters of the AlOx wedge.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Base pressure (mbar)</th>
<th>Argon gas flow (sccm)</th>
<th>Argon pressure (mbar)</th>
<th>Power (DC) (W)</th>
<th>Target-sample distance (mm)</th>
<th>Deposition rate (Å/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pt (4.0 nm)</td>
<td>5.2·10⁻⁸</td>
<td>2.1</td>
<td>2.5·10⁻³</td>
<td>60</td>
<td>95</td>
<td>0.94</td>
</tr>
<tr>
<td>Co (1.0 nm)</td>
<td>5.2·10⁻⁸</td>
<td>7.0</td>
<td>9.2·10⁻³</td>
<td>20</td>
<td>95</td>
<td>0.71</td>
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<tr>
<td>Al (0-3.0 nm)</td>
<td>5.2·10⁻⁸</td>
<td>7.0</td>
<td>9.1·10⁻³</td>
<td>20</td>
<td>95</td>
<td>0.60</td>
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</table>

**Table 2: Deposition parameters of the AlOx wedge with Ta buffer layer.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Base pressure (mbar)</th>
<th>Argon gas flow (sccm)</th>
<th>Argon pressure (mbar)</th>
<th>Power (DC) (W)</th>
<th>Target-sample distance (mm)</th>
<th>Deposition rate (Å/s)</th>
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<tbody>
<tr>
<td>Ta (2.0 nm)</td>
<td>5.7·10⁻⁸</td>
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<td>2.4·10⁻³</td>
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<td>95</td>
<td>0.94</td>
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<tr>
<td>Co (1.0 nm)</td>
<td>5.7·10⁻⁸</td>
<td>7.0</td>
<td>9.0·10⁻³</td>
<td>20</td>
<td>95</td>
<td>0.71</td>
</tr>
<tr>
<td>Al (0-3.0 nm)</td>
<td>5.7·10⁻⁸</td>
<td>7.0</td>
<td>9.0·10⁻³</td>
<td>20</td>
<td>95</td>
<td>0.60</td>
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</table>

**Table 3: Deposition parameters of the Co wedge with one AlOx layer.**

<table>
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<tr>
<th>Material</th>
<th>Base pressure (mbar)</th>
<th>Argon gas flow (sccm)</th>
<th>Argon pressure (mbar)</th>
<th>Power (DC) (W)</th>
<th>Target-sample distance (mm)</th>
<th>Deposition rate (Å/s)</th>
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<tbody>
<tr>
<td>Ta (2.0 nm)</td>
<td>2.9·10⁻⁸</td>
<td>10</td>
<td>1.8·10⁻¹</td>
<td>20</td>
<td>95</td>
<td>0.92</td>
</tr>
<tr>
<td>Pt (4.0 nm)</td>
<td>2.9·10⁻⁸</td>
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<td>3.5·10⁻³</td>
<td>60</td>
<td>95</td>
<td>1.12</td>
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<tr>
<td>Co (0-2.0 nm)</td>
<td>2.9·10⁻⁸</td>
<td>7.0</td>
<td>1.3·10⁻²</td>
<td>20</td>
<td>95</td>
<td>0.67</td>
</tr>
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<td>Al (2.2 nm)</td>
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<td>7.0</td>
<td>1.3·10⁻²</td>
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Table 4: Deposition parameters of the Co wedge with two AlOx layers.

<table>
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<th>Base pressure (mbar)</th>
<th>Argon gas flow (sccm)</th>
<th>Argon pressure (mbar)</th>
<th>Power (DC) (W)</th>
<th>Target-sample distance (mm)</th>
<th>Deposition rate (Å/s)</th>
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<tbody>
<tr>
<td>Ta (2.0 nm)</td>
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<td>1.8·10⁻²</td>
<td>20</td>
<td>95</td>
<td>0.92</td>
</tr>
<tr>
<td>Pt (4.0 nm)</td>
<td>3.6·10⁻⁸</td>
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<td>3.5·10⁻³</td>
<td>60</td>
<td>95</td>
<td>1.12</td>
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<tr>
<td>Co (0-2.0 nm)</td>
<td>3.6·10⁻⁸</td>
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<td>1.3·10⁻²</td>
<td>20</td>
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<td>0.67</td>
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<td>1.3·10⁻²</td>
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<td>0.44</td>
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<td>Al (2.2 nm)</td>
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<td>1.3·10⁻²</td>
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</table>

Table 5: Deposition parameters of the Ta (3 nm)/Pt (6 nm)/Co (1.5 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) junction.

<table>
<thead>
<tr>
<th>Material</th>
<th>Base pressure (mbar)</th>
<th>Argon gas flow (sccm)</th>
<th>Argon pressure (mbar)</th>
<th>Power (DC) (W)</th>
<th>Target-sample distance (mm)</th>
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<td>0.92</td>
</tr>
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<td>Pt (6.0 nm)</td>
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<td>3.4·10⁻³</td>
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<td>95</td>
<td>1.12</td>
</tr>
<tr>
<td>Co (1.5 nm)</td>
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<td>0.67</td>
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<td>1.3·10⁻²</td>
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<td>95</td>
<td>0.44</td>
</tr>
<tr>
<td>Al (2.2 nm)</td>
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<td>Pt (7.0 nm)</td>
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<td>10</td>
<td>1.8·10⁻²</td>
<td>60</td>
<td>95</td>
<td>1.12</td>
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Table 6: Deposition parameters of the Ta (3 nm)/Pt (6 nm)/Co (1.7 nm)/AlOx (2.2 nm)/AlOx (2.2 nm)/Pt (7 nm) junction.

<table>
<thead>
<tr>
<th>Material</th>
<th>Base pressure (mbar)</th>
<th>Argon gas flow (sccm)</th>
<th>Argon pressure (mbar)</th>
<th>Power (DC) (W)</th>
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<td>0.92</td>
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<tr>
<td>Pt (6.0 nm)</td>
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<td>2.1</td>
<td>3.4·10⁻³</td>
<td>60</td>
<td>95</td>
<td>1.12</td>
</tr>
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<td>Co (1.7 nm)</td>
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<td>1.3·10⁻²</td>
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<td>95</td>
<td>0.67</td>
</tr>
<tr>
<td>Al (2.2 nm)</td>
<td>2.3·10⁻⁸</td>
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<td>1.3·10⁻²</td>
<td>20</td>
<td>95</td>
<td>0.44</td>
</tr>
<tr>
<td>Al (2.2 nm)</td>
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<td>7.0</td>
<td>1.3·10⁻²</td>
<td>20</td>
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<td>0.44</td>
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<tr>
<td>Pt (7.0 nm)</td>
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<td>1.8·10⁻²</td>
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