Dependence of the Spin Hall Magnetoresistance on the Interface Magnetic Moment Density in Pt|$Y_3Fe_5O_{12}$ Bilayers

Abhängigkeit des Spin Hall Magnetwiderstandes von der Magnetischen Grenzflächen-Momentdichte in Pt|$Y_3Fe_5O_{12}$

Aderneuer, Tamara Michelle


Betreuer: Dr. Stephan Geprägs
Erstgutachter (Themensteller): Prof. Dr. Rudolf Gross

Zweitgutachter: Prof. Dr. Ulrich Stroth
Chapter 1
Introduction

Spintronics is an important research area for the improvement or development of new electronic devices. In addition to the charge of electrons, information is also transferred by the spin degree of freedom in spintronic devices. Spin-based effects are already finding application. In 2007 Albert Fert and Peter Grünberg were awarded the Nobel prize for discovering the giant magnetoresistance (GMR) (Ref. [1], [2]), which is an effect that is based on thin-film multilayers of ferro- and non-magnetic materials. The GMR effect is utilized in hard disk drives.

Very recently a new magnetoresistance has been discovered, which is fundamentally different to the conventional magnetoresistance effects. This so-called spin Hall magnetoresistance (SMR) (Ref. [3]) is based on the spin Hall effect (the conversion of a charge current into a spin current) and the inverse spin Hall effect. Bilayers consisting of a ferromagnetic insulator (FMI) and a non-ferromagnetic metal (NM) are required in order for measurements to be made. By applying a charge current through the NM layer it can be observed that the resistance of the NM depends on the magnetization direction of the FMI underneath. This is surprising, as it is not possible for the charge current to pass through the interfaces. In contrast to other magnetoresistance effects, no electric current needs to pass through the magnetic material because the SMR is based on the reflection or absorption of a spin current at the NM|FMI interface. Several groups are still investigating the influence of different parameters and materials involved. In the course of this thesis we want to examine if different terminations of the FMI layer have an impact on the SMR effect, since the SMR is sensitive on the FMI|NM interface.

In the framework of this thesis, $Y_3Fe_5O_{12}$ (YIG) is used as the ferromagnetic insulator (FMI). YIG thin films are fabricated by pulsed laser deposition (PLD) on Gd$_3$Ga$_5$O$_{12}$ (GGG) substrates. The films are coated with the non-ferromagnetic metal platinum (Pt) by electron beam evaporation (EVAP) in an ultra high vacuum (UHV) system, creating YIG|Pt bilayers. The crystalline quality and structural properties are analyzed by reflection high-energy electron diffraction (RHEED), X-ray diffractometry (XRD), atomic force microscopy (AFM), and by ferromag-
Chapter 1 Introduction

Magnetic resonance (FMR). SMR is investigated by angle dependent magnetoresistance (ADMR) measurements.

The structure of this thesis is as follows. The first chapter discusses the theory of SMR (chapter 2.1). The material properties of Pt and the ferromagnetic insulator YIG are also described (chapter 2.2). The second chapter (chapter 3) describes the fabrication of YIG thin films with (001)- and (110)-orientation in order to optimize the growth process. The next chapter (chapter 4) then considers the fabrication of YIG|PT bilayers on GGG substrates to analyze them with regard to SMR. The last chapter gives a brief summary of the experimental results and a look at further steps (chapter 5).
Chapter 2

Theory

In this chapter the theory of the spin Hall magnetoresistance (SMR) as well as its dependence on the interface magnetic moment density in bilayers of a ferromagnetic insulator (FMI) and a non-ferromagnetic metal (NM) is discussed. The materials used for the FMI|NM bilayers are also presented.

2.1 Spin Hall magnetoresistance

Spin Hall magnetoresistance (SMR) (Ref. [3]) is based on the spin Hall effect (SHE) and the inverse spin Hall effect (ISHE). The spin Hall effect is the conversion of a charge current $J_q$ into a spin current $J_s$. The induced spin current is given by (Ref. [4]):

$$J_s = \alpha_{\text{SH}} \left( -\frac{\hbar}{2e} \right) J_q \times s$$  \hspace{1cm} (2.1)

where $\alpha_{\text{SH}}$ is the spin Hall angle, $e$ the positive elementary charge, $J_q$ the charge current and $s$ the spin polarization. A schematic illustration of the SHE is shown in Fig. 2.1(a). The charge current $J_q$ (blue arrow) flowing along $x$ induces the spin current $J_s$ (pink arrow), which is directed in $y$. The electrons with spin up and the ones with spin down shift to opposite sides creating a gradient in the spin-dependent chemical potential $\mu_s$. Fig. 2.1(b) illustrates that for open circuit conditions, the induced spin current is compensated due to diffusion. Thus the longitudinal resistance is independent of the SHE in equilibrium. But in case of a short circuit (cf. Fig. 2.1(c)) there is an additional spin current $J_s$. As a consequence the inverse spin Hall effect induces a charge current. This results in a change in the longitudinal resistance, which can be identified as the SMR effect.

In order to analyse the SMR effect, it is necessary to have bilayers that consist of a ferromagnetic insulator (FMI) and a non-ferromagnetic metal (NM). If the SHE and ISHE effects were not considered, we would not expect that the ferromagnetic insulator (FMI) has an influence on the electrical resistivity of the NM layer. Figs. 2.2(a) and (b) show the SMR in FMI|NM bilayers. $J_q$ (light blue arrow) and $s$ (dark
Chapter 2 Theory

Figure 2.1: Schematic illustration of the spin Hall effect. (a) A charge current $J_q$ induces a spin current $J_s \parallel y$. (b) The induced spin current is compensated for open circuit conditions. Because of the spin accumulation there is a difference in the potential $\mu_s$. The gradient $\nabla \mu_s$ leads to a compensating diffusion current. (c) In the case of short circuit conditions the additional spin current leads to a change of the longitudinal resistance (Figures are taken from Ref. [4]).

Figure 2.2: (a) Spin Hall effect in FMI|NM bilayers with the spin polarization $\mathbf{M} \perp \mathbf{s}$. (b) SHE in FMI|NM bilayers with $\mathbf{M} \parallel \mathbf{s}$. (c) Hall bar structure on a bilayer. The coordinate system is defined with $\mathbf{n}$ normal to the layer interface, $\mathbf{j}$ in the direction of $J_q$ and with $\mathbf{t}$ transverse with $\mathbf{t} = \mathbf{n} \times \mathbf{j}$ (Figures taken from Ref. [4]).
2.1 Spin Hall magnetoresistance

blue arrow) induce $J_s$ (pink arrow) which is directed normal to the interface between
the layers. The absorption and reflection of the spin current at the interface depends
on the direction of the magnetization of the FMI. Where $M \perp s$ (Fig. 2.2(a))
spin angular momentum can be transferred to the magnetization of the FMI and
the spin current is absorbed (spin torque effect). If $M \parallel s$ (cf. Fig. 2.2(b)) $J_s$ is
reflected and the ISHE leads to charge current $J_q$ in the NM layer again. In this
simple model, we expect a different resistance state for $M \perp s$ and $M \parallel s$, such
that $R_{M \perp s} > R_{M \parallel s}$. The spin current flowing across the NM|FMI interface can be
regarded as an additional dissipation channel, which affects the resistance of the NM
layer.

In order to evaluate the SMR it is necessary to use a Hall bar geometry as it is
shown in Fig. 2.2(c). A right-handed coordinate system is defined with the unit
vector $n$ normal to the layer interface, $j$ in the direction of $J_q$ and the vector $t$. The
resistivities can be calculated from the measured longitudinal $V_{\text{long}}$ and transverse
$V_{\text{trans}}$ voltages by:

$$\rho_{\text{long}} = V_{\text{long}}(I_q)^{-1} \cdot b \cdot d_{\text{Pt}}(l)^{-1} \tag{2.2}$$

$$\rho_{\text{trans}} = V_{\text{trans}}(I_q)^{-1} \cdot d_{\text{Pt}} \tag{2.3}$$

where $b$ is the width of the Hall bar and $d_{\text{Pt}}$ the thickness of the NM layer (cf.
Fig. 2.2(c)). The equations for the resistivities can be further parametrized regarding
Ref. [4] to:

$$\rho_{\text{long}} = \rho_0 + \Delta \rho m^2_t \tag{2.4}$$

$$\rho_{\text{trans}} = \rho_2 m_n + \rho_3 m_j m_t \tag{2.5}$$

where $m = M/M_{\text{sat}}$ defines the orientation of the magnetization. Therefore, the lon-
gitudinal resistivity $\rho_{\text{long}}$ depends on the magnetization component $m_t$ of the FMI
layer along $t$: If $m \parallel t$ the spin current is reflected (cf. Fig. 2.2). In case of $m \parallel j$ or
$m \parallel n$, the absorption of the spin current occurs. This behavior of the resistivity is
fundamentally different to the angular dependence of a conventional anisotropic mag-
etoresistance (AMR). The AMR depends on the magnetization component along
the current direction $j$. Therefore, we can distinguish experimentally between the
SMR and AMR by performing angular-dependent magnetoresistance (ADMR) mea-
surements in the $t-n$ plane, which results in an angular dependence of $\rho_{\text{long}}$ in the
case of SMR, and in the $j-n$ plane, which gives an angular dependence of $\rho_{\text{long}}$ in the
case of AMR.

The analyzed spin Hall magnetoresistance can be compared by calculating the rela-
tive magnitude $|\Delta \rho/\rho_0|$. $\Delta \rho$ is defined as the maximum difference of the longitudinal
resistivity for $m \perp s$ and $m \parallel s$. $\rho_0$ corresponds to the resistivity of the NM layer
Chapter 2 Theory

with \( \mathbf{m} \parallel \mathbf{j} \). If Pt is used as the NM an order of \( 10^{-4} \) is expected for \( |\Delta \rho/\rho_0| \). The theoretical formula for \( \Delta \rho/\rho_0 \) states that it is dependent on the type and thickness of the NM layer and on the so-called spin mixing interface conductance \( G \) (Ref. [4]). \( G \) can be understood as possible spin channels for the spin torque effect between NM and FMI layers. We can conclude that not only the type of FMI and NM is significant for the SMR, but also the quality of the interface and the number of spin current channels as it results in a better spin mixing conductance (Ref. [15]).

2.2 Material properties

As discussed in the previous section, bilayers consisting of a ferromagnetic insulator (FMI) and a non-ferromagnetic metal (NM) are required to analyze spin Hall magnetoresistance. In the framework of this thesis \( Y_3Fe_5O_{12} \) (YIG) is used as the FMI, and Pt as the NM since it has a strong spin-orbit coupling. This is relevant for a strong spin Hall effect (SHE), which is the conversion of a charge current to a spin current. \( Gd_3Ga_5O_{12} \) (GGG) is used as substrate which has a lattice constant of \( a_{GGG} = 1.2380 \text{ nm} \) (Ref. [19]). YIG exhibits a ferrimagnetic long-range ordering with a high Curie temperature of 559 K and a high saturation magnetization of 141.65 kA/m at room temperature (Ref. [17]). Furthermore, due to the low coercive field of less than 10 mT and the low linewidth of the ferromagnetic resonance of less than 1 mT, it is often used in microwave applications.

Figure 2.3: (a) YIG unit cell along [001] \( \parallel z \). It consists of yttrium-(\( Y^{3+} \)), iron-(\( Fe^{3+} \)) and oxygen-(\( O^{2-} \)) ions. (b) The (001)-plane at \( z = 0.0 \text{ nm} \) seen from a different direction visualizes that iron is either tetrahedrally (\( Fe^{3+}_{tet} \)) or octahedrally (\( Fe^{3+}_{oct} \)) coordinated.
YIG has a garnet structure (cf. Fig. 2.3(a)) with a lattice constant of $a_{\text{YIG}} = 1.2376$ nm (Ref. [18]). In more detail, two different Fe sites exist in the unit cell. As shown in Fig. 2.3(b), two Fe$^{3+}$ ions reside on octahedrally coordinated sites while three Fe$^{3+}$ ions are tetrahedrally coordinated. The magnetic moment on these two sites are coupled antiferromagnetic via the superexchange interaction resulting in a strong ferrimagnetic order. Since theoretically the SMR effect is sensitive to the number of spin channels and therefore the magnetic moment density at the interface between YIG and Pt, two different crystallographic orientations of the YIG layer will lead to differently terminated YIG|Pt interfaces.

The YIG unit cell along [001] without oxygen is shown in Fig. 2.4. It can be seen that the layers, indicated in Fig. 2.4(a) on the z-axis, contain different types of atoms. The unit cell can be divided into four chemically equivalent parts, neglecting symmetry which is shown in Fig. 2.4(a) by horizontal blue lines. In Figs. 2.4(b)-(d) the upper three (001)-planes are shown. Comparing these cuts, theoretically two different terminations might be possible. However, the deposition of sub-unit cell blocks with a thickness of 0.3095 nm (indicated by the blue horizontal lines in Fig. 2.4) can be controlled by using pulsed laser deposition with in-situ reflection high-energy electron diffraction to control the growth process. Therefore, with a two dimensional layer-by-layer growth made of YIG along the [001] direction, the termination of the YIG|Pt interface as shown in Fig. 2.4(b) can be adjusted. For this termination two tetrahedrally and two octahedrally coordinated Fe$^{3+}$ ions reside on the YIG surface. Due to the antiparallel alignment of the magnetic moment of Fe$^{3+}_{}$oct and Fe$^{3+}_{}$tet we get a magnetically compensated YIG surface in first order considering Y$^{3+}$ as non-magnetic.

This situation changes by considering the (110)-crystallographic orientation (see Fig. 2.5). Again the unit cell can be divided into four chemically equivalent parts indicated by blue horizontal lines. Figs. 2.5(b)-(d) show the upper three (110)-planes. In analogy to the [001] crystallographic direction the growth process can only be controlled blockwise. Therefore, assuming a two dimensional layer-by-layer growth the termination of the YIG surface along the [110] direction should be the same as illustrated in Fig. 2.5(b). In this case only Fe$^{3+}_{}$oct ions are present resulting in a magnetic moment density of $20 \mu_B$ per $\sqrt{2} \cdot (1.238 \text{ nm})^2$.

To sum up, the fabrication of YIG|Pt bilayers with [001]- and [110]-orientation of the YIG layer can be used to investigate the influence of the magnetic moment density at the interface on the SMR effect (Ref. [15]).
YIG unit cell along [001] displayed without oxygen. The z-axis indicates the different layers. Fe$^{3+}_{\text{oct}}$ occupies octahedral sites and Fe$^{3+}_{\text{tet}}$ tetrahedral sites. (b)-(d) Upper three planes of the unit cell at $z = 0.619$ nm, $z = 0.464$ nm, and $z = 0.310$ nm.
Figure 2.5: (a) YIG unit cell along [110] without oxygen. The different layers are indicated by the distance in the [110]-axis. (b)-(d) Upper three planes at a distance on the [110]-axis of 0.875 nm, 0.766 nm, and 0.657 nm.
Chapter 3

Fabrication of $Y_3Fe_5O_{12}$ thin films on (001)- and (110)-oriented $Gd_3Ga_5O_{12}$ substrates

As described in the theoretical part, bilayers of the ferromagnetic insulator $Y_3Fe_5O_{12}$ (YIG) and the non-ferromagnetic metal Pt are needed to analyze spin Hall magnetoresistance (SMR). In this chapter we discuss the optimal parameters for fabricating thin YIG films. In the first part, growth of YIG films on (001)-oriented $Gd_3Ga_5O_{12}$ (GGG) substrates is analyzed and in the second part we continue with (110)-oriented GGG substrates.

The whole growth process is monitored in-situ by reflection high-energy electron diffraction (RHEED) (see A.2.1 for more details). The structural and surface properties of the samples are analyzed by X-ray diffractometry (XRD) (see A.2.2), atomic force microscopy (AFM) (see A.2.3), and by ferromagnetic resonance (FMR) (see A.2.4).

Growth parameters

If not otherwise indicated the films described in this chapter have the following growth parameters in common: They are fabricated by pulsed laser deposition (PLD) (detailed description in A.1.2) in a pure oxygen atmosphere with a pressure of $p = 25\mu\text{bar}$. The energy fluence caused by the excimer laser at the target is $\rho_L = 2.0\ \text{J/cm}^2$. The laser hits the stoichiometric YIG target with a number of pulses in the range from 11000 to 12000 and a repetition rate of $f = 10\ \text{Hz}$ (see table B.1 for a detailed overview of the samples).

3.1 $Y_3Fe_5O_{12}$ on (001)-oriented $Gd_3Ga_5O_{12}$ substrates

3.1.1 Reflection high-energy electron diffraction

RHEED is used to analyze the growth process of YIG films on GGG substrates in the PLD chamber.
Chapter 3 Fabrication of $Y_3Fe_5O_{12}$ thin films on (001)- and (110)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates

Figure 3.1: RHEED pattern recorded during the growth process at $T_S = 360^\circ$C of a GGG(001)|YIG film. The direction of view is [010]. (a) The RHEED pattern of the GGG substrate at room temperature. Three Laue circles $L_1$, $L_2$ and $L_3$ can be resolved. (b) Reflexes after heating the sample to $360^\circ$C. During the growth process the intensity was recorded within the red rectangle around the (0,0) reflection. (c) RHEED pattern after 665 pulses on the target. The analysis of intensity tells us that this corresponds to four oscillations. (d) After deposition with 11530 pulses, which corresponds to a thickness of 22.3 nm.

In Figs. 3.1(a)-(d) RHEED patterns are exemplary shown of a 22.3 nm thick YIG film fabricated at a substrate temperature of $T_S = 360^\circ$C on a (001)-oriented GGG
substrate. At room temperature (Fig. 3.1(a)) the first three Laue circles $L_1$, $L_2$ and $L_3$ of the GGG substrate can be resolved (cf. Ref. [14]). During heating the reflections of the Laue circles sharpen (cf. Fig. 3.1(b)). Comparing the pattern before the deposition (cf. Fig. 3.1(b)) and after the first four oscillations (cf. Fig. 3.1(c)), we see that the intensity decreases. At the end of the deposition (cf. Fig. 3.1(d)) the punctual reflexes changed to lines. In Fig. 3.2 the intensity of the central (0,0) RHEED-reflex as a function of time is shown, as recorded during the same growth process. The highest intensity is found at the beginning of the growth process. The

![RHEED-intensity of the central (0,0) reflection in the RHEED pattern during the growth process of a GGG(001)|YIG sample at $T_S = 360^\circ$C. The letters (b), (c) and (d) indicate when the images in Fig. 3.1 are taken. The asterisks point out when the intensity has been adjusted by the aperture of the RHEED camera. The drop indicated by the circle is caused by a shaking of the instrument.](image)

letters (b), (c) and (d) indicate where pictures of the RHEED screen are taken (cf. Fig. 3.1). After 4x4 oscillations the aperture was adjusted which is the reason for the increase in intensity. The oscillations start to vanish after a certain time. When they are no longer visible the type of growing is no longer two dimensional (layer by layer). But as the oscillations are seen for several packets of pulses we can conclude that the crystalline quality is high. After the deposition the reflections are barely visible (cf. Fig. 3.3). They are the most clearly evident for $T_S = 320^\circ$C (Fig. 3.3(a)). Ideal punctual reflexes would indicate a perfect film surface (cf. Ref. [5]). At $T_S = 360^\circ$C the reflexes are partially punctual and line-like (Fig. 3.3(b)), indicating a weak roughness. In Fig. 3.3(c) the Laue circles are no longer visible. The pattern can be interpreted as the reciprocal lattice of YIG and consequently as three dimensional growth. The reflections vanish completely for $T_S = 450^\circ$C (Fig. 3.3(d)). One purpose of using RHEED is for information concerning the surface termination. We expect
Chapter 3 Fabrication of $Y_3Fe_5O_{12}$ thin films on (001)- and (110)-oriented $Gd_3Ga_5O_{12}$ substrates

Figure 3.3: RHEED pattern recorded at the end of the deposition of GGG(001)|YIG samples. The substrate is heated for the process to temperatures of (a) 320°C, (b) 360°C, (c) 400°C, and (d) 450°C.
that four oscillations are equivalent to one unit cell of the corresponding orientation of YIG (cf. chapter 2.2). We want to show one verification exemplary for the YIG film fabricated at $T_S = 360^\circ$C: The intensity analysis shows 17x4 oscillations (cf. 3.2). If our assumption is correct $d_{\text{YIG}} = 17 \cdot a_{\text{YIG}} = 21.1$ nm. From XRD measurements we obtain that the thickness of the YIG film is $d_{\text{YIG}} = 22.3$ nm. This is in excellent agreement and we conclude that one RHEED-oscillation can be interpreted as one chemically equal part of a unit cell (cf. chapter 2.2).

### 3.1.2 X-ray diffractometry

After the growth process the samples are analyzed with X-ray diffractometry. A detailed description of the method and its different scan types can be found in A.2.2. In Fig. 3.4(a) X-ray reflectometry measurements of YIG films grown at substrate temperatures from 320°C to 450°C are shown. We can use LEPTOS software to determine the thickness and roughness of the YIG films, which are seen in Fig. 3.4(b). An overview of the corresponding simulations is plotted in Fig. 3.5. It can be seen, that the simulations are in very good agreement with the measurements. But in order to obtain these results we always changed the density of YIG in the fit curves. To demonstrate the change two simulation curves are exemplary shown for all fabricated YIG films in Fig. 3.6(b).

![Figure 3.4](image-url)
Chapter 3 Fabrication of $Y_3Fe_5O_{12}$ thin films on (001)- and (110)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates

Figure 3.5: X-ray reflectometry measurements and simulations of GGG(001)|YIG films grown at (a) $T_S = 320^\circ C$, (b) $360^\circ C$, (c) $400^\circ C$, and (d) $450^\circ C$.

Figure 3.6: (a) $2\theta - \omega$-scans of the GGG(001)|YIG samples around the YIG (004) reflection grown at $320^\circ C - 450^\circ C$. (b) X-ray reflectometry-scan of a GGG(001)|YIG sample and two corresponding simulations. The red function is done with the correct density of YIG and the blue simulation curve with $\rho_{YIG} = 5.17 \, g/cm^3$. 

16
3.1 $Y_3Fe_5O_{12}$ on (001)-oriented $Gd_3Ga_5O_{12}$ substrates

Theoretically the density of YIG should be $\rho_{\text{YIG}} = 5.17 \text{ g/cm}^3$ which results in the red curve. But the fit improves significantly if the density is changed to $\rho_{\text{YIG}} = 7.30 \text{ g/cm}^3$ which is seen in the blue simulation. Nevertheless we see that the main change is a shift on the x-axis at the initial decrease of intensity. There is a negligible change in the period of oscillations, which means no change for the resulting values of the thickness. A modified density might be caused by non-stoichiometry or a different phase of the YIG films, which we will keep in mind for the following analysis. In Fig. 3.4(b) correlation between the thickness and temperature can be determined, also the same growth parameters were used. But it is also visible that there is a roughness of $R_{\text{RMS}} < 0.3 \text{ nm}$ for $T_S = 320^\circ\text{C}$ and $360^\circ\text{C}$ which increases for $T_S > 360^\circ\text{C}$.

Fig. 3.6(a) contains the $2\theta - \omega$ - scan around the YIG (004) reflection of the GGG(001)|YIG samples grown at $320^\circ\text{C} \leq T_S \leq 450^\circ\text{C}$. The (004) reflection is chosen because it has the highest intensity in [001] direction. The Laue oscillations visible in all scans indicate a coherent growth and high crystalline quality in all YIG thin films. In addition we can calculate the theoretical location of the (004) reflection angle by the Bragg equation (cf. equation A.1), leading to a value of $2\theta = 28.82^\circ$. Because this is in good agreement with our $2\theta - \omega$ - scan, we can conclude a correct lattice constant for the fabricated YIG films. Therefore we can exclude non-stoichiometry for the density change. From the rocking curves of the YIG reflection, we can get information about the mosaic spread of the GGG(001)|YIG samples. This can be seen in Fig. 3.7(a).

![Figure 3.7: (a) Rocking curves around the peak of the first Laue oscillation to the right of the GGG (004) reflection (cf. Fig. 3.6) with Gaussian fits. $\Delta \omega = \omega - \omega_{\text{max}}$ where $\omega_{\text{max}}$ is the maximum of the respective Gaussian fit. (b) The full width at half maximum (FWHM) determined by the Gaussian fits. The FWHM is lower than 0.04° for all YIG thin films, demonstrating high crystalline quality.](image)
Since the YIG (004) reflections fall beneath the GGG (004) reflection, the rocking curve is carried out at the first Laue oscillation to the right (cf. 3.6). The Gaussian fits and the full width determined at half maximum (FWHM) are shown in Fig. 3.7(b). Because the value for all four samples is lower than 0.04° the YIG thin films have a high crystalline quality independent of the substrate temperature used for the growth process. This was already expected, because it could be deduced from the existing RHEED oscillations that the structural quality is high. One reason for the low FWHM values is the choice of the substrate. GGG is very good for growing YIG films on top, because the materials have a small lattice mismatch.

3.1.3 Atomic force microscopy

In Fig. 3.8 the surface topographies measured by atomic force microscopy (AFM) and the resulting roughnesses are shown. The lowest roughness with $R_{\text{RMS}} = 0.86$ nm is determined for the YIG film grown at $T_S = 360$°C. The results are not in accordance with the roughness values determined by X-ray diffractometry. As for the (110)-orientation, at the (001)-orientations facets emerge for temperatures higher than 400°C (in agreement with Ref. [14]). Related to this, the roughness increases too. It is interesting that the facets at the GGG|YIG film with (001)-orientation seem to have a preferred orientation. This is seen in Fig. 3.8(d).

3.1.4 Ferromagnetic resonance

By using ferromagnetic resonance (FMR) measurements we are able to obtain further information about the film quality. Fig. 3.9 shows the FMR signals of (001)-oriented GGG|YIG films fabricated at two different substrate temperatures dependent on an external magnetic field $\mu_0 H$. 

18
3.1 $Y_3Fe_5O_{12}$ on (001)-oriented $Gd_3Ga_5O_{12}$ substrates

Figure 3.8: Surface topographies of the YIG thin films measured by AFM. The films are grown at (a) $T_S = 360^\circ C$, (b) $400^\circ C$, and (c) $450^\circ C$. (d) Top view of the YIG-surface of the sample fabricated at $450^\circ C$. The preferred orientation of the facets along the [110] direction is clearly visible.
Chapter 3 Fabrication of $Y_3Fe_5O_{12}$ thin films on (001)- and (110)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates

(a) FWHM = (3.04 ± 0.03) mT
H in plane
Lorentzian fit
$T_S = 360^\circ$C
$p = 25$ µbar

(b) FWHM = (3.88 ± 0.15) mT
H in plane
Lorentzian fit
$T_S = 400^\circ$C
$p = 25$ µbar

Figure 3.9: Ferromagnetic resonance signals of YIG films on (001)-oriented GGG substrates. (a) Resonance and Lorentzian fit of a YIG layer grown at $T_S = 360^\circ$C. (b) Resonance and Lorentzian fit of a YIG layer grown at $T_S = 400^\circ$C. The deviation is calculated by two times the statistical error of the simulation.

The measurements are carried out at room temperature and using a constant microwave frequency of 9.7 GHz. The external magnetic field $\mu_0 H$ is applied in the plane of the YIG thin films. The resonance has the shape of a Lorentzian function as can be seen in Fig. 3.9. The lower the FWHM, the better the quality of the films. For a GGG(001)|YIG sample grown at $T_S = 360^\circ$C we receive a FWHM of $(3.88 \pm 0.15)$ mT (cf. Fig. 3.9(a)) and for $T_S = 400^\circ$C the FWHM has a value of $(3.04 \pm 0.03)$ mT (cf. Fig. 3.9(b)). This is in agreement with the FMR measurements on (110)-oriented YIG thin films (cf. 3.18).

3.2 $Y_3Fe_5O_{12}$ on (110)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates

In comparison to the (001)-oriented GGG|YIG films initially examined, now YIG films are grown on (110)-oriented GGG substrates.

3.2.1 Reflection high-energy electron diffraction

Again we use RHEED for analysing the growth process of the YIG films on the GGG substrates in the PLD chamber. Fig. 3.10 shows RHEED patterns taken at different steps of the growth process with a substrate temperature of $T_S = 360^\circ$C of a 35.3 nm thick YIG film. Fig. 3.10(a) shows the RHEED pattern of a GGG(110) substrate at room temperature. The first three Laue circles are clearly resolved. After the sample is heated to a temperature $T_S = 360^\circ$C the intensity of the reflections was adjusted by the aperture of the camera (cf. Fig. 3.10(b)). During deposition oscillations of
Figure 3.10: RHEED pattern during the growth process at a substrate temperature of $T_S = 360^\circ$C of a 35.3 nm thick GGG(110)|YIG sample. The direction of view is [110]. (a) RHEED pattern of a GGG substrate before it is heated by the IR laser. Three Laue circles $L_1$, $L_2$ and $L_3$ are visible. (b) The GGG sample is heated to 360°C. During the growth process the intensity was recorded within the red rectangle around the $(0,0)$ reflection. (c) RHEED pattern of the GGG(110)|YIG sample after 617 pulses on the target which corresponds to four RHEED oscillations. (d) RHEED pattern after the deposition with 11106 pulses which results in a thickness of 35.3 nm.
Chapter 3 Fabrication of $Y_3Fe_5O_{12}$ thin films on (001)- and (110)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates

the intensity occur which means that the YIG film grows layer by layer. Fig. 3.10(c) shows the RHEED pattern after the first four oscillations. It can be seen that the intensity of the reflexes before the deposition (cf. Fig. 3.10(b)) and after the four RHEED oscillations (cf. Fig. 3.10(c)) decreases significantly. At the end of deposition (cf. Fig. 3.10(d)) the reflexes changed from punctual to lines because the roughness of the surface increased moderately. There is a higher brightness of the images again because the aperture has been adjusted a couple of times to ensure enough intensity for the analysis. At the analysis of the intensity of the (0,0) RHEED-reflex, we see oscillations for the whole growth process (cf. Fig. 3.11). Analogue as for the (001)-

Figure 3.11: Intensity of the (0,0) reflex during the growth process of the GGG(110)|YIG sample at $T_S = 360^\circ$C. The letters (b), (c) and (d) indicate the points of the RHEED pattern in Fig. 3.10. The asterisks denote an adjustment of the aperture of the RHEED camera.

oriented YIG films, we want to show that information about the termination can be obtained by the RHEED method. For the (110)-oriented YIG sample there were $20 \times 4$ oscillations (cf. 3.11). For YIG along [110] (cf. 2.2) we expect a thickness of $d_{YIG} = \sqrt{2} \cdot 20 \cdot a_{YIG} = 35.0 \text{ nm}$ for the deposited YIG film. This is in high agreement with the thickness of 35.3 nm obtained by XRD measurements. We can tell from the number of oscillations how many unit cells are deposited on the substrate. The time at which the RHEED pattern of Fig. 3.10 was taken, is indicated by (b), (c) and (d). The RHEED oscillations can be seen most clearly during the growth process of the GGG(110)|YIG film with a substrate temperature of $T_S = 360^\circ$C compared to higher substrate temperatures. In general the appearance of oscillations indicates a two dimensional layer-by-layer growth and therefore an excellent quality of the films, with low surface roughness. Fig. 3.12 shows the RHEED pattern after the deposition for substrate temperatures from 360°C to 600°C.
Figure 3.12: RHEED patterns taken at the end of the deposition for GGG(110)|YIG samples at a substrate temperature of (a) 360°C, (b) 400°C, (c) 450°C, (d) 500°C, (e) 550°C, and (f) 600°C.
Chapter 3 Fabrication of $Y_3Fe_5O_{12}$ thin films on (001)- and (110)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates

The reflexes are less sharp than before the deposition and sometimes vanish completely.

3.2.2 X-ray diffractometry

Fig. 3.13(a) shows the reflectometry-scans of the GGG(110)|YIG films grown at a range of different temperatures. The thickness and roughness values extracted by simulations of the X-ray measurements as stated before are shown in Fig. 3.13(b). When the substrate temperature increases, the thickness of the YIG layers seems to decrease. A roughness of $R_{\text{RMS}} < 0.3$ nm is expected from the evaluation of simulations with LEPTOS. Experiment and simulation of X-ray reflectometry for four different substrate temperatures can be seen in Fig. 3.14. The concordance of the simulations with the measurements is excellent, but as for the (001)-oriented YIG layers, the density of YIG was increased (cf. 3.6(b)). Possible consequences are discussed with the measurements of the following $2\theta-\omega$ scan.

Fig. 3.15(a) contains the $2\theta-\omega$-scan at an angle from $10^\circ$ to $95^\circ$ of a GGG(110)|YIG sample grown at $T_S = 500^\circ$C. The reflections indicated by asterisks in Fig. 3.15(a) are caused by the vacuum stage. Therefore no parasitic phases are visible. Analogue to the (001)-oriented YIG films $2\theta$ for the (880) reflection can be determined with the Bragg equation (cf. A.1) and the lattice constant $a = a_{\text{YIG}}$. We receive $2\theta = 89.48^\circ$. Again the location is in agreement with our $2\theta-\omega$-scan (cf. Fig. 3.15). Therefore the density change in the reflectometry simulation is not caused by non-stoichiometry. Other phases of YIG can be excluded too, because only GGG and YIG reflections are seen. The (880) reflection has in [110] direction the highest intensity therefore for further observation, $2\theta-\omega$-scans around the YIG (880) reflex are carried out. In
3.2 $\text{Y}_3\text{Fe}_5\text{O}_{12}$ on (110)-oriented $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ substrates

Figure 3.14: Experiment and simulation of X-ray reflectometry-scans of GGG(110)|YIG films grown at (a) $T_S = 360^\circ\text{C}$, (b) 400°C, (c) 500°C, and (d) 600°C.

Fig. 3.15 (b) $2\theta - \omega$-scans around the (880) reflections for YIG thin films fabricated at $T_S = 360^\circ\text{C}$, 400°C, 500°C and 600°C are shown. The Laue oscillations can be seen even better than for the (001) orientation, indicating a coherent growth and high crystalline quality of all YIG thin films. Since the YIG (880) reflections are beneath the GGG (880) reflections, the rocking curve scan is carried out from the first Laue oscillation to the right. The measurements are seen in Fig. 3.16(a) for a series of substrate temperatures between 360°C and 600°C. Because all rocking curves are very similar only the main temperatures are shown. The Gaussian fits and the determined FWHM are shown in Fig. 3.16(b). Because the value for all samples is lower than 0.05° the YIG thin films have a high crystalline quality independent of the substrate temperature used for the growth process.
Chapter 3 Fabrication of $Y_3Fe_5O_{12}$ thin films on (001)- and (110)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates

Figure 3.15: (a) $2\theta - \omega$−scan of a GGG(110)|YIG sample grown at $T_\text{S} = 500^\circ$C. The reflections indicated by asterisks are caused by the vacuum stage. (b) Enlargement of the YIG (880) reflection because it has the highest intensity. The $2\theta - \omega$−scans of the film with the growth parameter $T_\text{S}$ from 360°C to 600°C is shown.

Figure 3.16: (a) Rocking curves around the YIG (880) reflection of the GGG(110)|YIG samples grown at four different temperatures including Gaussian fits. Since the YIG (880) reflection is beneath the GGG (880) reflection, the measurement is carried out around the maximum of the first Laue oscillation to the right. For a better comparison $\Delta \omega$ is determined as described in Fig. 3.7. (b) The small FWHM determined by the Gaussian fits with a value lower than 0.05° shows a high crystalline quality.
3.2.3 Atomic force microscopy

As the values for the roughness of the YIG films we get by X-ray diffractometry analysis aren’t very precise, we additionally use AFM (see A.2.3 for details). In Fig. 3.17 AFM measurements are shown for the temperature serie with $360^\circ\text{C} \leq T_S \leq 600^\circ\text{C}$. The AFM results are important because the following spin-based experiments depend highly on the interfaces between the Pt and the YIG layers. The illustrations show very clearly that the increase of temperature is accompanied with an increase of roughness. Whereas the sample grown at $360^\circ\text{C}$ has a roughness of $R_{\text{RMS}} = 1.08 \text{ nm}$, the one at $600^\circ\text{C}$ has $R_{\text{RMS}} = 7.02 \text{ nm}$. We see that facets emerge. They occur in high quantity and low height at lower temperatures. But with increase of heating the facets combine and become higher. This is in theoretical accordance because with higher temperature there is a higher surface energy and therefore more energy available for the atoms to move. Comparing the $R_{\text{RMS}}$ evaluated by reflectometry simulations with LEPTOS and the ones from AFM observations we see that they are very different. Because atomic force microscopy is the more precise method we mainly take AFM roughness values into account.

3.2.4 Ferromagnetic resonance

Fig. 3.18 shows the FMR signals of (110)-oriented GGG|YIG films fabricated at substrate temperatures from $T_S = 360^\circ\text{C}$ to $T_S = 600^\circ\text{C}$ dependent on an external magnetic field $\mu_0 H$. 

27
Chapter 3 Fabrication of $Y_3Fe_5O_{12}$ thin films on (001)- and (110)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates

Figure 3.17: Topological properties of the YIG surfaces measured by AFM. The film is grown at (a) $T_s = 360^\circ$C, (b) $400^\circ$C, (c) $450^\circ$C, (d) $500^\circ$C, (e) $550^\circ$C, and (f) $600^\circ$C. Furthermore the roughness $R_{RMS}$ is indicated.
3.3 Conclusion

The RHEED analysis reveals a two dimensional layer-by-layer growth and therefore that the quality of YIG films is excellent for substrate temperatures of $T_S = 360^\circ$C. For (001)-oriented YIG films we can conclude from the RHEED patterns after the growth process (cf. Fig. 3.3) that a two dimensional growth mode is present with $T_S = 360^\circ$C and is already three dimensional at $T_S = 400^\circ$C. RHEED oscillations can be seen for all temperatures, but for a longer time in (110)-orientation. The clearest oscillations occurred for the growth process of the GGG(110)|YIG film seen in Fig. 3.11 and GGG(001)|YIG film seen in Fig. 3.2 at $T_S = 360^\circ$C. XRD mea-

Figure 3.18: Ferromagnetic resonance signals in dependence on an external magnetic field $\mu_0 H$ of YIG films on (110)-oriented GGG substrates. (a) Resonance and Lorentzian fit of a YIG layer grown at $T_S = 400^\circ$C. (b) Analyzed FWHM of YIG(110) layers grown at different substrate temperatures $T_S$. The deviation is calculated by two times the statistical error of the simulations.

A constant microwave frequency of 9.7 GHz was applied. The external magnetic field is applied in the plane of the YIG thin film for all measurements which are carried out at room temperature. The resonance is analyzed by a Lorentzian fit (cf. Fig. 3.18 a)), out of which the FWHM value can be obtained. When the FWHM of the GGG(110)|YIG layers (Fig. 3.18 b)) are compared, it can be seen that there is an increase of the line width with the substrate temperature during the growth. Only the value of the layer grown at $T_S = 400^\circ$C differs, but as we can see in Fig. 3.18 a) there is an asymmetry in the signal which leads to a significant error. The FWHM value for the YIG thin film fabricated at $T_S = 360^\circ$C is lower than 3 mT which indicates a good quality of the film and is in agreement with FMR measurements for (111)-oriented GGG|YIG samples (Ref. 6).

3.3 Conclusion

The RHEED analysis reveals a two dimensional layer-by-layer growth and therefore that the quality of YIG films is excellent for substrate temperatures of $T_S = 360^\circ$C. For (001)-oriented YIG films we can conclude from the RHEED patterns after the growth process (cf. Fig. 3.3) that a two dimensional growth mode is present with $T_S = 360^\circ$C and is already three dimensional at $T_S = 400^\circ$C. RHEED oscillations can be seen for all temperatures, but for a longer time in (110)-orientation. The clearest oscillations occurred for the growth process of the GGG(110)|YIG film seen in Fig. 3.11 and GGG(001)|YIG film seen in Fig. 3.2 at $T_S = 360^\circ$C. XRD mea-
measurements point out that there is a high crystalline quality for the complete series of temperatures for both orientations. The FWHM values of the rocking curves are lower than 0.04° for GGG(001)|YIG films (320°C ≤ T_S ≤ 450°C) and lower than 0.05° for GGG(110)|YIG films (360°C ≤ T_S ≤ 600°C). AFM confirms the temperature where no facets are formed. There is a low surface roughness for both orientations at 360°C and 400°C (cf. Figs. 3.8 and 3.17). The FWHM value of the FMR signals point out a high crystalline quality for lower temperatures, too. For (110)-oriented YIG films a value lower than 3 mT is only measured for T_S = 360°C. We conclude that T_S = 360°C is the optimized substrate temperature for the fabrication of YIG thin films on GGG(001) as well as on GGG(110). In the next section we use this substrate temperature for the fabrication of YIG|Pt bilayers, which are then analyzed with respect to the SMR effect.
Chapter 4

Spin Hall magnetoresistance in $Y_3Fe_5O_{12}|Pt$ bilayers

After we optimized the fabrication parameters of YIG thin films on GGG substrates, this chapter is about the electrical transport measurements on YIG|Pt bilayers on GGG substrates. The first part analyzes the fabrication of YIG(110)|Pt and YIG(001)|Pt bilayers. In the second part, electrical transport measurements on these bilayers are discussed as regards the spin Hall magnetoresistance (SMR).

4.1 Fabrication of $Y_3Fe_5O_{12}|Pt$ bilayers

In the framework of this thesis, two YIG(110)|Pt bilayers as well as one YIG(001)|Pt bilayer were fabricated by pulsed laser deposition (PLD) (see A.1.2) and subsequent electron-beam evaporation (EVAP) (see A.1.3) on GGG substrates. First, the YIG thin films were grown via PLD using the optimized parameters as discussed in the previous chapter.

4.1.1 Pt on $Y_3Fe_5O_{12}$ on (001)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates

Reflection high-energy electron diffraction

The growth process of the YIG layer, which is first deposited on the GGG substrate, is analyzed by the (0,0) RHEED-reflex in analogy to chapter 3.1.1. The RHEED pattern is seen in Fig. 4.1 at different stages of the fabricating process. The central (0,0) RHEED-reflex is used for the intensity analysis which is shown in Fig. 4.2. In Fig. 4.1b) the first and parts of the second Laue circle are visible. The intensity of the RHEED reflections decreases from the beginning of deposition until the end with 5 unit cells shown in Fig. 4.1d). Only the first 2x4 oscillations (of the 5x4 in total) are clearly visible. Each four oscillations should be equivalent to one unit cell grown in (001)-orientation. Therefore, the thickness of 6.6 nm of the YIG layer should correspond to five YIG unit cells.
Figure 4.1: RHEED screen during YIG deposition of a GGG(001)|YIG|Pt sample. (a) RHEED pattern of a GGG substrate at room temperature. (b) RHEED pattern after deposition with 1923 laser pulses, which results in 5x4 RHEED oscillations and a 6.6 nm thick YIG film.

Figure 4.2: Intensity of the (0,0) RHEED-reflex during the YIG deposition of the GGG(001)|YIG|Pt sample.
X-ray diffractometry

The evaluation of the GGG(001)|YIG|Pt samples by X-ray diffractometry is shown in Fig. 4.3. The reflectometry-scan (Fig. 4.3(a)) is used to determine the thickness.

By means of the LEPTOS simulation software we get $d_{\text{YIG}} = (6.6 \pm 2.0) \text{ nm}$ and $d_{\text{Pt}} = (5.3 \pm 0.5) \text{ nm}$ as well as a surface roughness of $R_{\text{RMS}} = (0.5 \pm 0.1) \text{ nm}$. The reflection of the platinum layer is a lot greater than that of the YIG layer, which leads to a higher error for the thickness of the YIG layer. The $2\theta-\omega$-scan in Fig. 4.3(b) is shown around the YIG (004) reflection. Because the lattice mismatch is very small between the GGG substrate and the YIG film, the GGG (004) reflection overlays the one of YIG. However small Laue oscillations may be discernible.

Atomic force microscopy

The topography of the sample surface can be seen in Fig. 4.4. The roughness determined with AFM has a value of $R_{\text{RMS}} = 1.22 \text{ nm}$. This indicates a good surface quality with low surface roughness. It can be seen that the surface has no facets. We know that we have a GGG(110)|YIG|Pt sample of high quality regarding the subsequent analysis of the Spin Hall magnetoresistance.
Figure 4.4: Topological properties of the GGG(001)|YIG|Pt sample. The image was created by AFM. A roughness of $R_{\text{RMS}} = 1.22\,\text{nm}$ is determined.

4.1.2 Pt on $\text{Y}_3\text{Fe}_5\text{O}_{12}$ on (110)-oriented $\text{Gd}_3\text{Ga}_5\text{O}_{12}$ substrates

Reflection high-energy electron diffraction

In analogy to the previous described fabrication of YIG thin films on GGG(001), a YIG film is now grown on a (110)-oriented GGG substrate and analysed during the deposition. Information about the (0,0) RHEED-reflex can be obtained as in chapter 3.2.1 which is shown in Fig. 4.6. Pictures of the RHEED pattern are taken at several interesting points, and these are shown in Fig. 4.5. The brightest five reflections are part of the first Laue circle $L_1$. The second Laue circle $L_2$ is also visible. Fig. 4.5(a) shows the reflection pattern while the GGG substrate is still at room temperature. After heating to $360^\circ\text{C}$ the reflexes do not significantly change. But we see that punctual reflexes from the beginning of deposition change form to become more line-like reflexes at the end of deposition (cf. Fig. 4.5(b)). In the intensity analysis, we see that the first 4 oscillations which corresponds to the first packet of laser pulses, appear very clear, while they seem to vanish afterwards. The last four oscillations are more visible again because of a readjustment of the aperture of the RHEED camera. In total there are 5 packets of 4 oscillations, which is equivalent to 5 (110)-oriented YIG unit cells.
4.1 Fabrication of $Y_3Fe_5O_{12}|Pt$ bilayers

Figure 4.5: RHEED pattern during the YIG deposition with $T_S = 360^\circ$C of a GGG(110)|YIG|Pt sample. (a) RHEED pattern of the GGG substrate at room temperature. (b) RHEED pattern after the YIG deposition with 5317 laser pulses, which corresponds to 5x4 RHEED oscillations and a thickness of 6.0$nm$ of the YIG film.

Figure 4.6: Intensity of the (0,0) RHEED-reflex during the YIG deposition of the GGG(110)|YIG|Pt sample at $T_S = 360^\circ$C. The asterisk points out where the intensity has been adjusted. The drop indicated by the circle is caused by a shaking of the instrument.
Chapter 4 Spin Hall magnetoresistance in Y\textsubscript{3}Fe\textsubscript{5}O\textsubscript{12}/Pt bilayers

X-ray diffractometry

The GGG(110)|YIG|Pt bilayers are analyzed by X-ray diffractometry. The Reflectometry- and 2θ−ω−scans of two bilayers are shown in Fig. 4.7. The thickness and roughness is determined by the simulation curves. For sample YIG#156 we get $d_{\text{YIG}} = (6.0 \pm 2.0)\ \text{nm}$, $d_{\text{Pt}} = (5.0 \pm 0.5)\ \text{nm}$ and a surface roughness of $R_{\text{RMS}} = (0.4 \pm 0.1)\ \text{nm}$. For sample YIG#158 we obtain $d_{\text{YIG}} = (8.7 \pm 2.0)\ \text{nm}$, $d_{\text{Pt}} = (4.9 \pm 0.5)\ \text{nm}$ and a roughness of $R_{\text{RMS}} = (0.5 \pm 0.1)\ \text{nm}$. As for the bilayer grown in a different orientation, the high error for $d_{\text{YIG}}$ is because the platinum dominates the X-ray reflectometry due to its high reflection. The 2θ−ω−scans are done around the YIG (880) reflection, but we see mainly the GGG (880) reflection. Because the lattice mismatch is very small, the reflection of the substrate GGG overlaps that of the YIG film. However, small Laue oscillations in the vicinity of the YIG (880) reflections can be resolved.

Atomic force microscopy

The topographies of both layers are shown in Fig. 4.8. The determined roughnesses are $R_{\text{RMS}} = 3.12\ \text{nm}$ for the sample YIG#156 (cf. Fig. 4.8(a)) and $R_{\text{RMS}} = 1.64\ \text{nm}$ for YIG#158 (cf. Fig. 4.8(b)). The latter in particular has a low surface roughness. One can see that there is a difference between the roughness values determined by AFM and those determined by the LEPTOS simulations. Surfaces with a low roughness are wanted because the following measurements analyze interface based effects.

Figure 4.7: (a) Reflectometry-scans of two GGG(110)|YIG|Pt samples. The thickness is determined by the simulation curves. (b) 2θ−ω−scans of the same samples around the GGG (880) reflection.

36
4.2 Spin Hall magnetoresistance

In the following we will analyze the fabricated bilayers with regard to the spin Hall magnetoresistance (see chapter 2.1) by angle-dependent magnetoresistance (ADMR) measurements (cf. [4]). To make this analysis, it is necessary to pattern the sample with a Hall bar geometry as shown in Fig. 4.9 using photolithography and Ar ion milling. The measurements are carried out at $T = 300$ K and subject to an external magnetic field of $\mu_0 H = 1$ T. The coordination system $(n, t, j)$ is defined with the unit vector $n$ which is normal to the layer interface, $j$ which points in the direction of the charge current $J_q$ (cf. (2.2)) and with $t = n \times j$. The orientation of the external magnetic field $h = H/|H|$ is either rotated in the $n$-$t$-plane (oopj geometry) or in the $n$-$j$-plane (oopt geometry). ADMR analysis of a (001)-oriented YIG|Pt bilayer can be seen in Fig. 4.9 and of a (110)-oriented one in Fig. 4.10. The longitudinal $\rho_{\text{long}}$ and transversal $\rho_{\text{trans}}$ resistivities are defined by Eq. (2.2) and Eq. (2.3). To evaluate them voltage and current are measured as illustrated in Fig. 2.2(c). For both Hall bars there is a width of $b = 80 \mu m$ and a length of $l = 600 \mu m$. A thickness of $d_{\text{Pt}} = 5.3 \text{ nm}$ for the YIG(001)|Pt bilayer and $d_{\text{Pt}} = 4.9 \text{ nm}$ for the YIG(110)|Pt sample is determined by X-ray diffractometry (cf. Figs. 4.3 and 4.7).

In accordance with Eq. (2.4) the oopj measurements show a $\cos^2(\beta)$ dependency for $\rho_{\text{long}}$. The minima of $\rho_{\text{long}}$ occur at $\beta = -90^\circ$ ($h \parallel +t$) and $\beta = -270^\circ$ ($h \parallel -t$). And as expected from Eq. (2.5) $\rho_{\text{trans}}$ shows a $\cos(\beta)$ dependency. As obvious from the ADMR measurements in oopt geometry (cf. Figs. 4.9(b) and 4.10(b)) no angle-dependent longitudinal magnetoresistance can be observed. This confirms the
Figure 4.9: Angle-dependent magnetoresistance measurements of a (001)-oriented YIG|Pt bilayer, carried out at $T = 300 \text{ K}$ and an external magnetic field of $\mu_0 H = 1 \text{T}$. (a),(b) The angles and axis are defined in the schematic pictures of the Hall bars. The unit vector $\mathbf{n}$ is normal to the layer interface, $\mathbf{j}$ points towards the direction of the charge current $\mathbf{J}$, and $\mathbf{t}$ is transverse with $\mathbf{t} = \mathbf{n} \times \mathbf{j}$. The orientation of the external magnetic field $\mathbf{h} = \mathbf{H}/|\mathbf{H}|$ is either rotated (a) in the $\mathbf{n} - \mathbf{t} - \mathbf{j}$ plane (oopj geometry) or (b) in the $\mathbf{n} - \mathbf{j} - \mathbf{t}$ plane (oopt geometry). (c),(d) Longitudinal resistivity $\rho_{\text{long}}$ (black) and transverse resistivity $\rho_{\text{trans}}$ (red) for an oopj geometry ($\mathbf{h} \perp \mathbf{j}$) and an oopt geometry ($\mathbf{h} \perp \mathbf{t}$).

theoretical assumption (cf. chapter 2.1) that the ADMR results can be explained solely by a spin Hall magnetoresistance (SMR), and conventional anisotropic magnetoresistance (AMR) is not the source of the observed magnetoresistance. This is in agreement with (111)-oriented YIG|Pt bilayers (Ref. [4]) and confirms that in YIG|Pt bilayers spin currents are the driving force of the magnetoresistance in Pt. Because SMR is an interface sensitive effect, it is of interest to compare the ADMR results of (001)- and (110)-oriented YIG|Pt bilayers. In order to do so the ratio $\Delta \rho/\rho_0$ is calculated. $\Delta \rho$ is the maximum difference of $\rho_{\text{long}}$ in the oopj geometry and $\rho_0$ is the value of $\rho_{\text{long}}$ at $\mathbf{h} \parallel \mathbf{j}$. The results of the ADMR measurements on the fabricated YIG|Pt bilayers are shown in table 4.1. There is only a small difference between the analysed ratios. Contrary to expectations, the orientation of the bilayers seems to have no influence on the SMR. But in order to make a well-founded
4.3 Conclusion

The RHEED, XRD, and AFM methods of analysis confirm that the growth parameters optimized in chapter 3 were well chosen. Compared to the growth of a single YIG thin film at \( T_S = 360^\circ \text{C} \), the RHEED-oscillations are not as clearly visible during the fabrication of the YIG film (cf. Figs. 4.2 and 4.6) and the surface roughness \( R_{\text{RMS}} \) is slightly higher (cf. Figs. 4.4 and 4.8) for the bilayers. Nevertheless the additional Pt thin film does not change the crystalline properties of the YIG layer underneath as it can be confirmed by the XRD analysis.

The ADMR measurements seem to show that the YIG orientation does not influence the SMR effect (cf. Table 4.1). This is in contrary to our expectations (see chapter 2.2). Since the SMR effect is sensitive to the interface of the YIG|Pt bilayer,
which is described theoretically by the so-called spin mixing conductance (see chapter 2), we expected a large difference between the SMR amplitudes for YIG(001) and YIG(110) oriented bilayers. In these two cases the interface changes from a magnetically compensated one to a ferromagnetic coupled interface with a large magnetic moment density at the interface. Our results suggest that the SMR might depend on the absolute value of the magnetic moment density of each magnetic sub-lattice of YIG, resulting in $|\mathbf{m}| = |\mathbf{m}_{\text{Fe}^{3+}_{\text{oct}}}| + |\mathbf{m}_{\text{Fe}^{3+}_{\text{tet}}}| = 20\,\mu\text{bar}$ for the YIG (001)- and (110)-orientation. But it would be necessary to analyze a greater number of comparable GGG|YIG bilayers to exclude statistical error. The ratio $\Delta \rho/\rho_0$ of the three fabricated bilayers is in between $2.1 \times 10^{-3}$ and $2.2 \times 10^{-3}$ (cf. table 4.1). We are able to compare the values with the ADMR results of (111)-oriented GGG|YIG layers (cf. Ref. 4). It is interesting that the values we get for (110)- and (001)-oriented samples are more than a factor of two larger than the values for (111)-oriented YIG|Pt layers. The main reason for the increase of the SMR might be the different thickness of the YIG layers of about $50-60\,\text{nm}$ in Ref. 4 compared to our YIG layers of about $5\,\text{nm}$. So far there has been no research of the influence of the YIG thickness in YIG|Pt bilayers on the SMR.

Besides the impact of the sample properties another important point might be the spin mixing conductance $G$. $G$ is further divided into the real part $G_r$ and the imaginary part $G_i$. $\Delta \rho/\rho_0$ is only sensitive to the $G_r$ and therefore in the ADMR measurements we are only sensitive to the real part. This might also be a reason for the absence of a difference between (110)- and (001)-orientation. To get information about $G_i$ it would be necessary to carry out ordinary Hall effect (OHE) measurements (cf. Ref. 4).
Chapter 5
Summary and outlook

The newly discovered spin Hall magnetoresistance (SMR) is the topic of current research. The behavior is not yet completely understood, and influencing parameters are still investigated. The small magnitude of the SMR compared to other magnetoresistance effects like GMR makes the analysis challenging.

In this thesis YIG|Pt bilayers with different crystallographic orientations of the YIG layer were fabricated, because FM|NM bilayers are necessary for the investigation of the SMR. Therefore thin YIG films were deposited on GGG substrates in (001)- and (110)-orientation. The aim was to control the termination of the surface and hence the magnetic moment density of the interface between YIG and Pt.

The first step was the deposition of YIG on (001)- and (110)-oriented GGG substrates to optimize the growth process. It was found out that for both orientations the optimal substrate temperature is $T_S = 360^\circ C$. The experimental methods RHEED, XRD, AFM and FMR revealed the quality of the films to be excellent. We were able to fabricate layers with a low roughness. This is an important step for further multilayer experiments. Therefore fabrication of YIG|Pt bilayers on GGG was continued in order to analyze SMR. From the angle dependent magnetoresistance measurements it was found that the ratio $\Delta \rho/\rho_0$ for the three fabricated bilayers is in the order of $2 \times 10^{-3}$. There was no significant difference between the two orientations. This could mean that the orientation has no influence on SMR, which is against our initial expectation. Our results suggest that the SMR might depend on the absolute value of the magnetic moment density $|\mathbf{m}|$ of each magnetic sub-lattice of the (001)- and (110)-oriented YIG bilayers.

A next step might be to carry out further measurements, as it would be necessary to have a significant number of results to make a convincing comparison of the SMR ratio $\Delta \rho/\rho_0$. There may be also other explanations for the absence of a difference. The spin mixing conductance $G$ has an influence on $\Delta \rho/\rho_0$. In our experiments we were only sensitive on the real part $G_r$, therefore investigation of the Hall effect in Pt could give information about the imaginary part $G_i$. Moreover the thickness of YIG could possibly have an impact. So far there has been no investigation of its influence.
In summary the investigation of the SMR will remain important as in contrast to other magnetoresistances no electrical currents needs to pass through the magnetic material. Only the spin current has an effect, which suggests a high potential for application in electronic devices.
Appendix A

Experimental methods

In this part the experimental methods used will be explained. We differentiate between methods used to fabricate thin films and those used to analyze them. The films are grown by pulsed laser deposition (PLD) and electron beam evaporation (EVAP). Those two fabrication methods are carried out in an ultra high vacuum (UHV) cluster system. During the growth process the thin films are analyzed by reflection high-energy electron diffraction (RHEED). We obtain information about the thickness, crystalline quality and roughness by x-ray diffractometry (XRD). Atomic force microscopy (AFM) is used additionally to analyze the surface, and to get more precise information about the roughness. More information about the quality of the films can be obtained by ferromagnetic resonance (FMR).

A.1 Fabrication methods

A.1.1 Ultra high vacuum (UHV) cluster

In the framework of this thesis thin films were fabricated by pulsed laser deposition (PLD) and electron beam evaporation (EVAP) in two different chambers which are part of an ultra high vacuum (UHV) cluster system (see Fig. A.1).
Appendix A Experimental methods

Figure A.1: Schematic illustration of the ultra high vacuum cluster with different chambers, used to fabricate different thin films (Figure taken from Ref. [7]).

The system consists of a so called load-lock where the samples can be inserted. The sample holders are cleaned beforehand with acetone and isopropanol, and so are the substrate surfaces. When they are inside the cluster the samples can be moved to different chambers by the transfer arm without breaking the vacuum. Therefore different growth processes can be done one after another, without any polluting substances reaching the interfaces. The sputter chamber is part of the cluster but not used for the growth of the YIG|Pt bilayers.

A.1.2 Pulsed laser deposition (PLD)

Pulsed laser deposition (PLD) allows the fabrication of epitaxial thin films. Crystalline layers which grow in an orientation related to the substrates can be fabricated. The set-up can be seen in Fig. A.2.
A pulsed laser beam hits the chosen target. A stochiometric, polycrystalline Y$_3$Fe$_5$O$_{12}$(YIG)-target is used in all processes. The laser has a wave length of $\lambda = 246$ nm. Due to the high intensity of the excimer laser, enough energy is provided for a plasma plume to emerge. The plasma plume propagates towards the substrate, which is located above (cf. Fig. A.2(a)). The process gas is oxygen and a pressure of $p = 25\, \mu\text{bar}$ was set during the deposition. To allow the atoms to move on the interface of the substrate, energy is provided by heating the sample with an infrared heating laser. Because platinum absorbs the laser light better, an 180 nm thick Pt layer is sputtered on the back side of the Gd$_3$Ga$_5$O$_{12}$(GGG) substrates before the PLD process. The infrared heating laser hits the substrate on the back side. A pyrometer can be used to measure the actual temperature of the substrate. In addition a RHEED-system (reflection high-energy electron diffraction) is used to analyze the growth process in-situ. In Fig. A.2(a) it can be seen that a high energy electron beam hits the substrate, is reflected and causes a pattern on the fluorescence screen. The method will be later explained in more detail.

A.1.3 Electron beam evaporation (EVAP)

For the fabrication of YIG|Pt bilayers the sample is transferred from the PLD chamber to the EVAP chamber without breaking the vacuum. In the EVAP chamber a Pt thin film with a thickness of around 5 nm is deposited on the YIG layer. A schematic set-up of the EVAP chamber can be seen in Fig. A.3.
The generated electrons are focused and accelerated by an electrode. The electron beam is directed by a magnetic field to the Pt crucible. When the electron current is high enough, the platinum evaporates and condenses at the surface of the sample. During the growth process the thickness can be measured by an oscillating crystal. The shutter closes automatically when the final thickness is reached.

A.2 Analysing methods

A.2.1 Reflection high-energy electron diffraction (RHEED)

Reflection high-energy electron diffraction (RHEED) makes it possible to analyze the growth mode and quality of the films while the process takes place (see Fig. A.2). High energy electrons hit the surface at a low angle, are reflected and reach a fluorescence screen. The diffraction of the electrons on the surface leads to a RHEED pattern. The pattern varies depending on the type of substrate and orientation. The images in Fig. A.4 show the RHEED patterns of (110)- and (001)-oriented Gd$_3$Ga$_5$O$_{12}$ substrates.
A.2 Analysing methods

Figure A.4: (a) RHEED pattern from the surface of a clean (110)-oriented GGG substrate. The direction of view is [110]. (b) RHEED pattern from the surface of a clean (001)-oriented GGG substrate. The direction of view is [010].

A pattern can be clearly seen if the crystalline quality is high and the surface is very smooth. The formation of the pattern can be explained by the Ewald construction (see Fig. A.5).

Figure A.5: Ewald construction. $k_0$ is the incoming wave vector, $k_{ij}$ the outgoing wave vector after diffraction at the reciprocal lattice (Illustrations from Ref. [8]).

Because of elastic scattering at the lattice $|k_0| = |k_{ij}|$. $k_0$ describes the incoming, $k_{ij}$ the scattered wave vector. The initial beam $k_0$ is defined with $|k| = \frac{2\pi}{\lambda}$ and determines the radius of the sphere.
A three dimensional view is shown in Fig. A.6 where it can be seen how the Ewald construction defines the reflexes at the RHEED screen. Because of the low angle reflection only occurs on the surface of the lattice. The two dimensional layer leads to lattice rods instead of points. The intersections of the Ewald sphere with the lattice rods define the RHEED pattern. The reflection pattern on the screen and their intensity during the fabrication process can be analyzed. They give information about the type of the growth. RHEED-oscillations emerge in case of a two dimensional layer-by-layer growth. One oscillation corresponds to one chemically completed unit (cf. chapter 2.2). When a layer is complete the intensity reaches its maximum, when the surface is the roughest it has its minimum.

**A.2.2 X-ray diffractometry (XRD)**

X-ray diffractometry (XRD) is used in order to determine the thickness, the crystalline quality and the roughness of the films grown. Fig. A.7(a) depicts a sketch of the set-up.
A.2 Analysing methods

The incoming monochromatic X-ray beam has a wavelength of $\lambda = 0.154056$ nm. It hits the sample at an angle $\omega$. The axe of rotations and angles of the X-ray diffractometer are depicted in Fig. A.7(b). Before starting a measurement the position of the detector and the sample have to be aligned. The sample is centred in the $x,y$ and $z$-axis and the position is found where the maximum intensity reaches the detector.

The samples are examined with three different types of scans:

Reflectometry
The reflectrometry scan measures the diffraction at the surface of the sample and at the interfaces between different layers. The intensity at the $2\theta$ angles from 0.5° to 5° is measured. Interference of the reflected beams causes the oscillations seen, whose pattern varies depending on the type of material. Simulations of the data are done with the LEPTOS software. The period of the oscillations is related to the thickness of the layers. The decrease of the intensity gives information about the roughness of the surface. Because the result for roughness is not very precise, the samples are additionally analyzed by atomic force microscopy.

$2\theta - \omega - \text{scan}$
For the $2\theta - \omega - \text{scan}$ the sample is aligned with respect to the lattice planes. To understand the reflection at the lattice planes we have to consider the Bragg equation (Ref. [9]) for constructive interference:

$$2d_{hkl} \sin \theta = n\lambda \quad (A.1)$$

where $n$ is the diffraction order of the maximum, $\lambda$ the wavelength of the x-ray and $\theta$ the angle as shown in Fig. A.7. For cubic lattice structures the lattice plane distance $d_{hkl}$ with the Miller indices $h, k, l$ is defined as (Ref. [9]):

$$d_{hkl} = \frac{a}{\sqrt{h^2 + k^2 + l^2}} \quad (A.2)$$

Figure A.7: (a) Schematic figure of a X-ray diffractometer (taken from Ref. [9]). (b) Illustration of the axis and angles of a four-circle X-ray diffractometer (from Ref. [7]).
Appendix A Experimental methods

where $a$ is the lattice constant. It can be seen that depending on the material and the orientation the reflection maxima are found at different angles. Therefore the reflexes of the YIG thin films differ, depending whether they are grown in (110)- or (001)-orientation.

**Rocking curve**

The crystalline quality can be analyzed with a rocking curve. The detector is located at a fixed $2\theta$ – angle where a reflex with high intensity is expected. The sample is then rotated around $\omega$. The more parallel the lattice planes the better the crystalline quality. The intensity that is measured by the detector results in a graph that is similar to a Gaussian curve. The sharper the peak which is equal to a low full width at half maximum (FWHM), the better the crystalline quality.

### A.2.3 Atomic force microscopy (AFM)

Atomic force microscopy (AFM) is used to get information about the topography and roughness of the sample surface. A schematic picture of the AFM method is shown in Fig. A.8.

![Figure A.8: Function of atomic force microscopy (AFM). (a) Schematic illustration of the AFM method in general. (b) Laser beam technique to monitor the deflection of the cantilever (Illustration taken from Ref. [10]).](attachment:figa8.png)

A cantilever is located in a certain distance above the sample. This metering needle is anchored at one side and has a tip on the other side which is used to scan the surface. The deflection sensor, the feedback electronic and the x,y,z piezo scanner ensures the gap to be always constant. The deflection of the cantilever due to interatomic forces between tip and surface is analyzed. A change is equal to
a change in the distance and the elements take care that the needle is kept at a position where the distance is the same as the initial value. To analyse the deflection of the cantilever there are different techniques. For YIG films, laser beam deflection (cf. Fig. A.8(b)) is used. A beam hits the top of the tip and is reflected to a photo detector. The signal is evaluated with control software to extract informations about the sample surface.

A.2.4 Ferromagnetic resonance (FMR)

Ferromagnetic resonance (FMR) is used to analyze the magnetic properties of ferromagnetic materials. Information about the crystalline quality can be obtained as well. Analogue to the electron spin resonance (ESR), FMR is based on the absorption of microwave radiation dependent on an external magnetic field $\mu_0 H_0$.

Figure A.9: Fundamental principle of FMR (Figure taken from Ref. [11]).

Fig. A.9 shows an illustration of the fundamental principle. A microwave radiation with a constant frequency is absorbed at an external magnetic field $H_{res}$ if the resonance condition $\hbar \omega = g_J \mu_B H_{res}$ is fulfilled (cf. Ref. [12]). $g_J$ is the g-factor and $\mu_B$ is the Bohr magneton. For FMR the value of $H_{res}$ changes due to exchange interaction and magnetic anisotropy of the ferromagnetic material.
Appendix B

Sample view

<table>
<thead>
<tr>
<th>sample</th>
<th>layers</th>
<th>orientation</th>
<th>$T_S$ ($^\circ$C)</th>
<th>laser pulses</th>
<th>thickness $d$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YIG#137</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>500</td>
<td>11970</td>
</tr>
<tr>
<td>YIG#139</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>450</td>
<td>11437</td>
</tr>
<tr>
<td>YIG#140</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>500</td>
<td>11456</td>
</tr>
<tr>
<td>YIG#141</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>550</td>
<td>11209</td>
</tr>
<tr>
<td>YIG#142</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>600</td>
<td>11283</td>
</tr>
<tr>
<td>YIG#143</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>360</td>
<td>11106</td>
</tr>
<tr>
<td>YIG#144</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>400</td>
<td>11658</td>
</tr>
<tr>
<td>YIG#146</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(001)</td>
<td>360</td>
<td>11530</td>
</tr>
<tr>
<td>YIG#147</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(001)</td>
<td>400</td>
<td>11165</td>
</tr>
<tr>
<td>YIG#148</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(001)</td>
<td>450</td>
<td>11264</td>
</tr>
<tr>
<td>YIG#151_N</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(001)</td>
<td>360</td>
<td>3588</td>
</tr>
<tr>
<td>YIG#152</td>
<td>GGG$</td>
<td>$YIG$</td>
<td>$Pt</td>
<td>(001)</td>
<td>360</td>
</tr>
<tr>
<td>YIG#153</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(001)</td>
<td>320</td>
<td>11039</td>
</tr>
<tr>
<td>YIG#154_N</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>360</td>
<td>2817</td>
</tr>
<tr>
<td>YIG#155_N</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>360</td>
<td>4549</td>
</tr>
<tr>
<td>YIG#156</td>
<td>GGG$</td>
<td>$YIG$</td>
<td>$Pt</td>
<td>(110)</td>
<td>360</td>
</tr>
<tr>
<td>YIG#157</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(110)</td>
<td>360</td>
<td>5454</td>
</tr>
<tr>
<td>YIG#158</td>
<td>GGG$</td>
<td>$YIG$</td>
<td>$Pt</td>
<td>(110)</td>
<td>360</td>
</tr>
<tr>
<td>YIG#159_N</td>
<td>GGG$</td>
<td>$YIG</td>
<td>(001)</td>
<td>360</td>
<td>1528</td>
</tr>
</tbody>
</table>

Table B.1: List of fabricated samples. A detailed description is given below.

A list of all fabricated samples is shown in table B.1. The samples indicated with a subscripted $N$ are not used for further evaluation. They have a YIG layer.
of less than 10 nm and have a low crystalline quality, as indicated known from the RHEED analysis. Therefore X-ray diffractometry was not used and there is no information about the thickness of the Y$_3$Fe$_5$O$_{12}$ films. $T_S$ indicates the temperature of the substrate during the growth process in the PLD chamber and $d$ defines the thickness of the YIG and if existing the Pt layer. All samples are grown in an oxygen atmosphere with a pressure of $p = 25 \, \mu\text{bar}$ and with an energy density of $\rho = 2.0 \, \frac{J}{\text{cm}^2}$. The YIG films grown in the PLD chamber with a thickness between 20-30 nm are fabricated with 11000-12000 pulses of the excimer laser, the ones with a thickness lower than 10 nm with 1500-5500 pulses. The frequency of the laser was always $f = 10 \, \text{Hz}$. 

Appendix B  Sample view
## List of Figures

2.1 Fundamental principle of the Spin Hall effect. ........................................ 4
2.2 Spin Hall effect in FMI|NM bilayers. .................................................. 4
2.3 YIG unit cell along direction (001). ..................................................... 6
2.4 YIG unit cell along direction (001) without oxygen. ............................... 8
2.5 YIG unit cell along direction (110) without oxygen. ............................... 9

3.1 RHEED patterns during the growth process of GGG(001)|YIG. ................. 12
3.2 RHEED-intensity during the growth process of GGG(001)|YIG. ................ 13
3.3 RHEED patterns at the end of the deposition of (001)-oriented YIG. .......... 14
3.4 X-ray reflectometry-scans of GGG(001)|YIG samples. ............................ 15
3.5 X-ray reflectometry and simulations of GGG(001)|YIG samples. .............. 16
3.6 2θ − ω−scans of the GGG(001)|YIG samples. ............................... 16
3.7 Rocking curves of GGG(001)|YIG samples. ......................................... 17
3.8 AFM illustrations of GGG(001)|YIG film surfaces. ............................... 19
3.9 FMR signals of GGG(001)|YIG samples. ............................................. 20
3.10 RHEED patterns during the growth process of GGG(110)|YIG. ............... 21
3.11 RHEED-intensity during the growth process of GGG(110)|YIG. ............... 22
3.12 RHEED patterns at the end of the deposition of GGG(110)|YIG. ............. 23
3.13 X-ray reflectometry-scans of GGG(110)|YIG samples. ........................ 24
3.14 X-ray reflectometry-scans and simulations of GGG(110)|YIG samples. .... 25
3.15 2θ − ω−scans of GGG(110)|YIG samples. ......................................... 26
3.16 Rocking curves of GGG(110)|YIG samples. ......................................... 26
3.17 AFM illustrations of GGG(110)|YIG surfaces. ...................................... 28
3.18 FMR signals of GGG(110)|YIG samples. ............................................. 29
4.1 RHEED patterns during the growth process of GGG(001)|YIG|Pt. ............... 32
4.2 RHEED-intensity during the growth process GGG(001)|YIG|Pt. ................. 32
4.3 X-ray reflectometry- and 2θ − ω−scan of GGG(001)|YIG|Pt. .................. 33
4.4 AFM illustration of a GGG(001)|YIG|Pt surface. ................................... 34
4.5 RHEED patterns during the growth process of GGG(110)|YIG|Pt. ............... 35
4.6 RHEED-intensity during the growth process of GGG(110)|YIG|Pt. ............... 35
4.7 X-ray reflectometry- and 2θ − ω−scans of GGG(110)|YIG|Pt. ................. 36
4.8 AFM illustrations of GGG(110)|YIG|Pt surfaces. ................................... 37
4.9 ADMR analysis of YIG(110)|Pt bilayers. ............................................ 38
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.10</td>
<td>ADMR analysis of YIG(110)</td>
<td>Pt bilayers.</td>
</tr>
<tr>
<td>A.1</td>
<td>Ultra high vacuum cluster (Ref. [7]).</td>
<td>44</td>
</tr>
<tr>
<td>A.2</td>
<td>Set-up for pulsed laser deposition (Ref. [5]).</td>
<td>45</td>
</tr>
<tr>
<td>A.3</td>
<td>Components of the electron beam evaporation chamber (Ref. [7]).</td>
<td>46</td>
</tr>
<tr>
<td>A.4</td>
<td>Reflection high-energy electron diffraction patterns.</td>
<td>47</td>
</tr>
<tr>
<td>A.5</td>
<td>Ewald construction in 2D view (Ref. [8]).</td>
<td>47</td>
</tr>
<tr>
<td>A.6</td>
<td>Ewald construction and the RHEED set-up in 3D view (Ref. [8]).</td>
<td>48</td>
</tr>
<tr>
<td>A.7</td>
<td>X-ray diffractometer (Ref. [9], [7]).</td>
<td>49</td>
</tr>
<tr>
<td>A.8</td>
<td>Atomic force microscopy (Ref. [10]).</td>
<td>50</td>
</tr>
<tr>
<td>A.9</td>
<td>Fundamental principle of FMR (Ref. [11]).</td>
<td>51</td>
</tr>
</tbody>
</table>
Bibliography


Bibliography


Acknowledgement

Of course this thesis would not have been possible without the involvement of many others. In particular I want to thank:

Prof. Dr. Rudolf Gross who gave me the opportunity to write my bachelor thesis at the Walther-Meißner-Institut (WMI) für Tieftemperaturforschung.

Dr. Stephan Geprägs ("Steve") for his extraordinary supervision. I cannot imagine someone being more contributed. He always made time to explain theoretical and experimental issues. I want to thank for his great commitment despite his many other tasks. His constant good mood made it a great pleasure to work at the WMI.

Dr. Matthias Opel as I would not have come to the WMI without his commitment to make it possible that I get to know the WMI as a working student. Furthermore I want to thank for the help concerning all kind of technical questions.

All other researching people I got to know at the WMI. It was very nice that could always ask them questions and knew that they would help willingly. I enjoyed the coffee talks and the hierarchyless atmosphere. In particular I want to thank Francesco, Andi, Michi, Adrian and Sascha, that everything worked out as uncomplicated although all of us were using the PLD during the "high season" of bachelor students. I also want to thank Felix for his excellent work for his bachelor thesis one year in advance to mine because it simplified many steps.

Not to forget I want to mention my parents. I am very grateful for their support during my studies.