Photoconductivity Measurements in Yttrium Iron Garnet Thin films

Roland Rösslhuber

Master Thesis

Supervisor: PD. Dr. Sebastian T. B. Goennenwein
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1 Introduction

Oxides exhibit a rich spectrum of physical effects in both, bulk materials and in heterostructures [1]. One important aspect are the localized electrons [2] which may exhibit correlated behaviour. The electrons strongly interact with each other and the lattice ions, giving rise to unique properties. Bulk effects in oxides, such as high temperature superconductivity [3, 4] and the colossal magneto resistance effect (CMR) [5, 6], have been investigated for quite some time. On the other side, research on oxide interface effects is a rather young field in condensed matter physics since the growth of well defined interfaces with atomic layer precision is a very challenging task [7–12].

Arising fields in condensed matter physics investigating the unique properties of oxides and oxide interfaces are, among others, spin electronics (spintronics) [13] and spin caliotronics [14]. The latter in particular draw attention by the observation of two effects at a ferromagnetic insulator (FMI)/normal metal (NM) interface.

The first is the spin Seebeck effect (SSE) [15], which describes the arising of a voltage in the NM due to thermal generation of a pure spin current across the FMI|NM interface by applying a temperature gradient. It is the manifestation of a complex interplay of phonons, magnons and electrons which is not fully understood yet [16].

The second is the spin Hall magnetoresistance (SMR) [17–19], which was discovered in FMI/NM heterostructures by H. Nakayama et al. and independently by M. Althammer et al.. Due to the Spin Hall effect (SHE) [20], a current through the NM layer generates a pure spin current towards the FMI|NM interface. Depending on the direction of the magnetization of the FMI relative to the charge current direction, the spin current is either reflected at the interface or absorbed in the FMI. The reflected spin current in turn, leads to the generation of an additional charge current in the NM layer due to the inverse Spin Hall effect (ISHE) [21, 22]. This process is typically measured as a magnetization dependent change in the resistance of the NM layer.
Yttrium iron garnet (Y$_3$Fe$_5$O$_{12}$, YIG) as ferrimagnetic insulator and platinum as normal metal are commonly used for the investigation of both effects. Pt is used as NM because it exhibits a large spin Hall angle $\alpha_{\text{SH, Pt}} = 0.11$ [17] and thus facilitates the observation of the SMR and the SSE. The relatively large Curie temperature (560 K) of YIG is ideal for experiments at room temperature. Additionally, it also exhibits a very small ferromagnetic resonance line width [23, 24]. Because of these properties, YIG is also widely used in ferromagnetic resonance and spin pumping experiments.

YIG was discovered in 1956 by S. Geller and M. A. Gilleo together with various other members of the rare earth iron garnet group [25]. The low dielectric loss and the high resistivity made it to a widely used compound in microwave devices [26, 27]. Soon it was discovered, that the resistivity of YIG can be lowered by doping over a wide range and intense research was done on its electrical properties [28–32, 32]. Nevertheless, the conduction mechanism in YIG could not be identified [31, 33–36].

In this thesis, the photo-conductivity of YIG in dependence of its magnetization is investigated. Besides scientific curiosity, this is of interest because of two reasons. Firstly, because of Spin Seebeck experiments wherein the required temperature gradient is generated using laser light [37–39]. The knowledge about the electrical response of YIG to illumination and its dependence on the magnetization therefore is important for the interpretation of SSE experiments and the discussion of spurious effects. Moreover, in SMR experiments, the resistance of the Pt layer, which is in direct contact to YIG, is measured. The mechanism behind the observed magnetoresistance in these structures is currently vividly discussed in literature. Identifying the intrinsic magnetoresistance of YIG may help the interpretation of the results of SMR experiments. While YIG has a much larger resistivity ($\rho_{\text{YIG}} \approx 10^{10}$ $\Omega$ m [32, 35]) than Pt ($\rho_{\text{Pt}} \approx 10^{-7}$ $\Omega$ m [40]), a space charge region in the YIG could, in principle, also affect the measured resistance.

Secondly, the information on a possible magneto resistive effect and its amplitude may contribute to the identification of the conduction mechanism in YIG.

The thesis is organized as follows: a short introduction on the physical properties of YIG is given which is followed by a brief review of its electrical properties and a summary of its optical absorption (Ch.2). Chapter 3 describes the investigated
samples. Subsequently, in Ch. 4 the measurement setup is described and the first results are discussed. In Ch.5, a second measurement technique significantly improving the signal to noise ratio is introduced. The obtained results are summarized in Ch. 6 and followed by an outlook.
2 Theory

In this chapter a brief overview on the crystalline, magnetic and electric properties of Yttrium Iron Garnet is given (YIG). YIG is a ferri magnetic insulator with a very narrow ferromagnetic resonance line width [23, 24]. Its high resistivity and low dielectric loss makes YIG to a widely used material in high-frequency applications. It was intensively investigated in the '50s, '60s and '70s [25, 35, 41, 42]. Unfortunately, the interest in its electric properties diminished after the main prospective application (magnetic bubble memory) became obsolete [36]. Thus, no coherent, generally accepted model of the electrical transport in YIG is available. We will discuss the few available publications on photo-conductivity and magnetoresistance in YIG. Finally, to complete the picture, literature on the absorption spectra of YIG is summarized.

2.1 Structural and Magnetic Properties of YIG

Yttrium iron garnet $Y_3Fe_2(FeO_4)_3$ is an artificial compound wherein the Ca atoms of natural garnet (Ca$_3$Al$_2$(SiO$_4$)) are replaced by Y and the Al and Si atoms by Fe. It exhibits a cubic crystal structure (Ia3d space group) with a lattice constant $a = 12.376 \, \text{Å}$ [43] wherein one unit cell contains 8 formula units (160 atoms). Figure 1.1 (taken from ref. [44]) depicts the atoms associated with the environment of the [100] face of the unit cell of YIG. The Y$^{3+}$ ions occupy the c-sites which are found in the centre of of a O$^{2-}$ dodecahedron. There are two inequivalent positions for the 40 Fe$^{3+}$ ions within a unit cell: 16 a-sites, lying in the centre of a O$^{2-}$ tetrahedron, and 24 d-sites, lying in the centre of a O$^{2-}$ octahedron.

The ground state of the free Fe$^{3+}$ ion is $^6S$ with the electronic configuration $3d^5$ and a spin of $\frac{5}{2}$. Within the garnet crystal structure, the five 3d orbitals split into two $e_g$ and three $t_{2g}$ orbitals due to the crystal field (coulomb interaction with adjacent O$^{2-}$ cations). For the d-sites, the $e_g$ orbitals are pointing directly to adjacent O$^{2-}$
Figure 2.1: $Y_3Fe_5O_{12}$ (YIG) crystal structure, taken from ref. [44]. The positions of atoms lying on the [100] face of the cubic unit cell (space group Ia3d) are depicted. The $Y^{3+}$ ions on the $c$-sites are in the centre of a $O^{2-}$ dodecahedron (red shaded). The $Fe^{3+}$ occupy two inequivalent sites referring to their $O^{2-}$ environment. $Fe^{3+}$ ions on $a$-sites are surrounded by four $O^{2-}$ anions which form a tetrahedron (grey shaded), the $Fe^{3+}$ ions on $a$-sites are surrounded by six $O^{2-}$ anions which form a octahedron (black shaded).

cations which leads to an increased energy compared to the $t_{2g}$ orbitals. For the $a$-sites, the $O^{2-}$ cations lie more in the orientation of the $t_{2g}$ orbitals and therefore, the $t_{2g}$ are energetically higher then the $e_g$ orbitals. The splitting is stronger for the $d$-sites because of the higher number of surrounding $O^{2-}$ cations compared to the $a$-sites.

Optical absorption measurements indicate a band gap of about 2.85 eV [45, 46]. Numerical calculations show the band gap to be of the direct type [47].
The spin orientation of the two Fe$^{3+}$ ion sublattices is antiparallel due to the indirect super exchange coupling via the O$^{2-}$ ions. Thus, the magnetic moments of the $a$- and $d$-sites partially compensate each other which is the origin of the ferrimagnetism of YIG. It exhibits a Curie temperature of 560 K [48]. The coercive field of epitaxially grown thin films depends on the growth conditions with common values of $\mu_0H_C \leq 15$ mT [17].

2.2 Electrical Properties

The first investigation on the electrical transport properties was done in 1957 [28], soon after the discovery of YIG [25, 49]. Since then, a large number of publication followed which are summarized in the reviews of R. Metselaar et. al (1977) [35], G. Winkler (1981) [36] and A. Tucciarone et. al. (1984) [32]. The resistivity of stoichiometric YIG at room temperature is about $10^{10} \Omega$ m and can easily be lowered by doping $10^2 \Omega$ m [32] (down to $10^2 \Omega$ m for YIG:Si with 0.1 Silicon atoms/formula unit [50]). All cations have a valence of 3 so that the addition of cations with a valence less than 3 (Ca$^{2+}$,Pb$^{2+}$,Zn$^{2+}$,Mg$^{2+}$ etc.) leads to the creation of acceptor centres. Cations with a valence higher than 3 act as donors (Si$^{4+}$,Ge$^{4+}$,Sn$^{4+}$,Ti$^{4+}$ etc.). Moreover, Y and Fe vacancies act as acceptors and O vacancies and interstitial cations such as H$^+$ and Li$^+$ as donors. Thus, the conduction in YIG can be made $n$- or $p$-type and varied over several orders of magnitude.

The question, whether the conductivity of YIG should be described by an energy band model or by a localized charge transfer model (electron hopping) was discussed intensely. The conclusion was, that the investigated samples were not precisely characterized regarding their stoichiometry and crystal defects. Moreover, the measurement techniques employed for the experiments were not described sufficiently to put the comparison of the obtained results on a solid base [36]. As a result, the conclusions made in individual publications were contradictory in the sense that different conductivities for similarly doped samples were given and both hopping conduction and band conduction were proposed [35]. An overview of the publications containing information on the electrical properties of YIG is given in tab. 2.1. The main rea-
sons for the discrepancy according to Refs. [35] and [36] shall be summarized briefly.

Most of the investigations [28, 31, 51, 52] are done on polycrystalline samples which are fabricated by the standard ceramic technique of ball milling. This preparation technique produces samples with a high impurity content and introduces highly resistive grain boundaries which complicates the interpretation of dc-measurements. The examined single crystals [29, 41, 50, 53] were grown by the flux method using a PbO $-$ PbF$_2$ $-$ B$_2$O$_3$ flux or by liquid phase epitaxy (LPE) by transport from a lithium rare-earth molybdate flux [54]. In the former, Pb ions and in the latter Li ions are present and may act as a counter doping to the original doping. Moreover, the distribution coefficient of the dopants between the melt and the crystal may differ and vary depending upon the growth conditions. Therefore, the cited doping concentrations given in literature may be incorrect and an inhomogeneous distribution of the impurities is possible. Another possible source for an incorrect doping content are anion and cation vacancies, which act as donors or acceptors and compensate the original doping. These crystal defects could be introduced by a cooling procedure after a post growth heat treatment.

In the literature, the investigation of the conduction mechanism was mainly carried out by temperature dependent measurements of the resistivity $\rho$, the Seebeck coefficient $\alpha$ and the Hall mobility $\mu_H$, ranging from 77 K up to 1700 K. The main principle behind this approach is, that depending on the conduction mechanism, these quantities show different temperature behaviour [34, 35]. The problem thereby is, however, that these quantities also depend on the number of charge carriers, whose precise determination is prohibited by the reasons mentioned above. Moreover, the ionic nature of YIG leads to a small mobility of the charge carries ($\mu \sim 0.1 \text{ cm}^2/\text{Vs}$ for YIG:Si [41]) and consequently, to a small conductivity ($\rho \sim 10^7 \Omega \text{ m} - 10^{11} \Omega \text{ m}$ for undoped YIG [36]). Both may complicate accurate measurements. Similar issues are valid for the activation energy, which is determined from the plot of log $\rho$ over $1/T$ and is strongly influenced by the nature and concentration of impurities of the YIG specimen.

The overall conclusion of the intense research between the 50’s and 80’s is, that neither band conduction nor a localized charge transfer model (electron hopping) can
be ruled out as conduction mechanism in YIG and both have to be considered to de-
scribe the electrical properties [35]. Furthermore, it is possible that both mechanisms
are present but dominate at different temperatures and that the ac-conductivity is
described more appropriately by a localized charge carrier model whereas the dc-
conductivity is described more appropriately by a band model [36, 55].
The band conduction may be more appropriate for the extrinsic contribution to the
dc-conduction and may be dominant at temperatures up to 600 K. This model is
favoured by A. Tucciarone et al. [32] who mainly investigated silicon doped YIG
films with a comparable small resistivity of $\rho \gtrsim 10^2 \Omega \text{m}$. On the other hand, the
intrinsic dc-conduction may be ascribed to the hopping of localized charge carriers
[56] and may become dominant at higher temperatures [29, 31]. Initially, this model
was suggested because the concept of localized Fe$^{2+}$ ions explains the optical and
magneto-optic properties of YIG [46], although it was contradictory to some publi-
cations.

The concept of conduction via small polarons [30, 33, 34] predicts a band-like con-
duction up to a certain temperature and a thermally activated hopping for higher
temperatures. This model is used to explain more recent investigations of L. Sird-
eshmukh et. al. (1998) [55] and A. El Ata et. al. (2004) [57].

### 2.2.1 Influence of the Magnetization on the Electrical Properties

The influence of the magnetization on the electrical properties in YIG is considered
to be very weak [35]. Therefore, no special consideration is done and no external
magnetic field is applied in most of the above mentioned literature. Only in [55, 57],
a kink in the dc-conductivity over $1/T$ at the curie temperature $T_C$ is observed,
indicating an influence of the magnetic order on the electrical properties in the in-
vestigated samples.

In the literature on the photo-conductivity of YIG, no external magnetic field is
applied [52, 58] or no dependence on an external magnetic field is observed [59].
The first observation of a magnetoresitance was done by R.C. LeCraw et al. (1978)
[53] in (111) $n$-type films and bulk YIG. The largest effect is observed in a film
which is grown on gadolinium gallium garnet substrates by LPE by transport from
a lithium rare earth molybdate flux (LRM) [54] which exhibits a resistivity of \( \rho = 9 \times 10^2 \, \Omega \, \text{m} \). In the following, the results of Ref.[53] are briefly summarized. Moreover, the observation will be compared to the model of the anisotropic magneto resistance (AMR), which will be discussed briefly afterwards in Sec. 2.2.2.

In the first investigation, the current \( \mathbf{I} \) is flowing in the \([11\overline{2}]\) direction while the magnetic field is rotated in the \((11\overline{2})\) plane, so that the angle \( \theta \) between the \([1\overline{1}0]\) direction and the direction of the magnetic field \( \mathbf{H} \) is varied (see Fig. 2.2 (a), taken from [53]). This leads to a change of the relative resistance of the sample with a maximum change of \( \Delta R/R = -0.55\% \) at \( \mathbf{H} \parallel [111] \) (Fig. 2.2 (a), open circles). It has to be noted, that the effective angle between the current direction \( \mathbf{I} \) and the magnetic field direction \( \mathbf{H} \) remains 90° during the rotation of the field in the \((11\overline{2})\) plane. The measured resistance corresponds to the resistivity \( \rho_\perp \), which is perpendicular to the direction of the current \( \mathbf{I} \). The observed behaviour of \( \Delta R/R \) can not be explained with the model of the AMR because the AMR only predicts a change in the resistivity when the effective angle between \( \mathbf{H} \) and \( \mathbf{I} \) is changed.

Moreover, \( \Delta R/R \) is measured in dependence on the direction of the magnetic field which is rotated in the \((111)\) plane (Fig. 2.2 (a), solid circles). It is observed, that the in plane rotation of the magnetic field has no measurable influence on the resistance, and an isotropy in the \((111)\) plane is assumed by the author. The absence of a resistance change for the rotation in the \((111)\) plane disagrees with the model of the AMR.

Furthermore, in Ref. [53], a \((1\overline{1}0)\) bulk single crystal bar doped with silicon, which is grown from a \( \text{PbO} - \text{PbF}_2 - \text{B}_2\text{O}_3 \) flux, is investigated. The current \( \mathbf{I} \) is applied parallel to the \([1\overline{1}0]\) direction. The conduction is determined to be \( n \)-type with a resistivity of \( \rho = 1.3 \times 10^2 \, \Omega \, \text{m} \). Under the rotation of the magnetic field \( \mathbf{H} \) in the \((1\overline{1}0)\) plane, \( \Delta R/R \) exhibits a maximum at \( \mathbf{H} \parallel [001] \) and a minimum at \( \mathbf{H} \parallel [110] \) (Fig. 2.2 (b), taken from [53]). Again, the effective angle between the current direction \( \mathbf{I} \) and the magnetic field direction \( \mathbf{H} \) remains 90° while the magnetic field is rotated, so that the measured resistance corresponds to \( \rho_\perp \). Again, the observed behaviour of \( \Delta R/R \) can not be explained with the model of the AMR because the AMR only predicts a change in the resistivity when the effective angle between \( \mathbf{H} \) and \( \mathbf{I} \) is changed.
2.2 Electrical Properties

The rotation of \( \mathbf{H} \) in the (111) plane seems to reveal a small dependence of \( \Delta R/R \) on the field direction (Fig. 2.2 (c), taken from [53]). At the position of the maxima, the angle between the magnetic field \( \mathbf{H} \) and the current direction \( \mathbf{I} \) is 45°, while \( \Delta R/R = 0 \) corresponds to \( \mathbf{H} \parallel \mathbf{I} \). The observed behaviour is not consistent with the model of the AMR, since the maxima would be expected at the positions, where \( \mathbf{H} \parallel \mathbf{I} \) or where \( \mathbf{H} \perp \mathbf{I} \). According to the author of Ref. [53], the effect is within the experimental error of cutting and mounting of the bar and a dependence of \( \Delta R/R \) on \( \mathbf{H} \) rotating in the (111) plane is not confirmed. On the other hand, it is mentioned that \( \Delta R/R \) is dependent on the orientation of the magnetic field rotating in the (111) plane in measurements at 200 K which are, unfortunately, not further specified in Ref. [53].

Overall, the cited results in Ref. [53] are not expected in the model of the AMR. Moreover, an empirical model [60], which is based on the assumed isotropy of the resistance in the (111) plane of YIG and on a hopping like conduction mechanism, is applied to predict the results. Within this model, the obtained results are not consistent in regard to the observed amplitude of \( \Delta R/R \) and especially the bulk...
sample shows deviating behaviour. The empirical model is discussed in respect to YIG in Ref. [61] but no physical explanation is found. The intrinsic origin of the observed magneto resistance in YIG in Ref. [53] remains unclear.

2.2.2 Magneto Transport Measurements

In the following, a qualitative model for the discussion of the magnetic field dependent photo-conductivity measurements in Ch. ?? and Ch. ?? is introduced. The standard approach to magneto transport measurements is to consider ohmic samples and to start with Ohm’s law

\[ E = \rho \cdot J, \]

where \( E \) is the electric field, \( \rho \) the resistivity tensor and \( J \) the current density. The main point is, that the resistivity tensor \( \rho \) can depend on the orientation of the magnetization \( M \) in respect to the crystallographic axes. It is convenient to introduce the unit vectors \( j \) and \( m \) which denote the current direction and the orientation of the magnetization.

In the ansatz of Briss [62] and Muduli et al. [63] the resistivity tensor \( \rho \) is represented by a series expansion in powers of \( m_i \), which are the components of \( m \). By assuming a single crystalline ferromagnetic material and by considering its crystal symmetry, the coefficients of single terms in the series expansion vanish. As a result, general expressions for \( \rho_{\text{long}} \) and \( \rho_{\text{trans}} \), which are the resistivity parallel and perpendicular to the current direction, respectively, in dependence of \( j \) and \( m \) are obtained. It turned out, that the model obtained with this approach is a powerful tool to qualitatively predict the results of magneto transport measurements with an arbitrarily oriented magnetization \( M \) of the sample [64]. Unfortunately, this approach can not be applied on the YIG samples investigated in this thesis due to several reasons. First, we can not confirm that our samples are single crystalline. Moreover, no special consideration was put on the alignment of the electrode structure relative to the crystal symmetry. As a result, the direction of the current with respect to the crystallographic axes in the film plain is not determined.
2.2 Electrical Properties

The thesis is meant as a proof of principle to demonstrate, that a dependence of the photo-conductivity on the orientation of an external magnetic field can be measured. Therefore, a very basic approach is chosen in which the anisotropic magneto resistance (AMR) is considered.

2.2.3 Anisotropic Magneto Resistance

The AMR occurs in ferromagnetic metals and magnetic semiconductors which exhibit a finite spin-orbit coupling [65, 66]. We assume the presence of the AMR in YIG because of the Fe ions with partially filled \( d \) orbitals which are considered to exhibit a finite spin-orbit coupling. It has to be mentioned here, that we have no knowledge on the spin-orbit coupling of Fe ions incorporated in the YIG crystal structure and further consideration is beyond the scope of this thesis.

However, due to the spin-orbit coupling, the resistivity \( \rho_\parallel \) parallel to the magnetization \( \mathbf{M} \) is different to the resistivity \( \rho_\perp \) perpendicular to \( \mathbf{M} \). Whether \( \rho_\parallel < \rho_\perp \) or \( \rho_\parallel > \rho_\perp \) depends on the intrinsic structure of the material.

In the following, the dependence of \( \rho_{\text{long}} \) and \( \rho_{\text{trans}} \) on the magnetization \( \mathbf{M} \) due to the AMR is briefly deduced. We considered that an external magnetic field \( \mu_0 \mathbf{H} \) is rotated in the \( xy \)-plane corresponding to the sample surface. The structural properties of the sample play a minor and the sample may, for example, be polycrystalline. Important is, that the magnetic field is strong enough to align the magnetization of all domains or crystallites parallel to \( \mu_0 \mathbf{H} \). By considering that \( \rho_\parallel \neq \rho_\perp \) due to the AMR and a homogeneously \( \mathbf{M}, \overline{\rho} \) becomes

\[
\overline{\rho} = \begin{pmatrix}
\rho_\parallel & -\rho_\mathbf{H} & 0 \\
\rho_\mathbf{H} & \rho_\parallel & 0 \\
0 & 0 & \rho_\perp
\end{pmatrix},
\]

(2.2)

wherein the off-diagonal elements \( \rho_\mathbf{H} \) are introduced by the ordinary Hall effect and the anomalous Hall effect. Using Eq. 2.1 and Eq. 2.2, the electric field \( \mathbf{E} \) can be determined. The component of the electric field parallel to the current is \( E_{\text{long}} = \mathbf{j} \cdot \mathbf{E} \), the transverse component is \( E_{\text{trans}} = \mathbf{t} \cdot \mathbf{E} \), wherein \( \mathbf{t} \) is the unit vector with \( \mathbf{t} = \hat{\mathbf{e}}_z \times \mathbf{j} \).
2 Theory

The corresponding longitudinal resistivity $\rho_{\text{long}}$ is written as

$$\rho_{\text{long}} = \frac{E_{\text{long}}}{|\mathbf{J}|} = \mathbf{j} \cdot \mathbf{p} \cdot \mathbf{j},$$

and the transverse resistivity $\rho_{\text{trans}}$ as

$$\rho_{\text{trans}} = \frac{E_{\text{trans}}}{|\mathbf{J}|} = \mathbf{t} \cdot \mathbf{p} \cdot \mathbf{j}. \quad (2.4)$$

Inserting Eq. 2.2 in Eq. 2.5 and performing some basic vector algebra yields

$$\rho_{\text{long}} = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp}) \cos^2(\varphi), \quad (2.5)$$

wherein $\varphi$ denotes the angle between the current $\mathbf{J}$ and the magnetisation $\mathbf{M}$. It will be of advantage for the discussion of the experimental results in Ch.4 and Ch. 5 to substitute the $\cos^2(\varphi)$ with a sine function \footnote{$\cos^2(\varphi) = \frac{1}{2} + \frac{1}{2} \sin(2\varphi + 90^\circ)$} and to set $\rho_{\text{average}} = \frac{\rho_{\perp} + \rho_{\parallel}}{2}$ and $\Delta \rho = \rho_{\parallel} - \rho_{\perp}$. As a result $\rho_{\text{long}}$ becomes

$$\rho_{\text{long}} = \rho_{\text{average}} + \frac{\Delta \rho}{2} \sin(2\varphi + 90^\circ). \quad (2.6)$$

By Inserting Eq. 2.2 into Eq. 2.4, $\rho_{\text{trans}}$ is determined to

$$\rho_{\text{trans}} = (\rho_{\parallel} - \rho_{\perp}) \sin(\varphi) \cos(\varphi). \quad (2.7)$$

The observation that in general $\rho_{\text{trans}} \neq 0$ is denoted as the planar Hall effect (PHE).

The above obtained two fold symmetry of $\rho_{\text{long}}$ and $\rho_{\text{trans}}$ is the most basic one which can be observed. In single crystals and epitaxial films, additional features due to the magneto crystalline anisotropy may be observed which leads to a deviation of the $\sin(2\varphi + 90^\circ)$ dependence of $\rho_{\text{long}}$ \cite{67}. This also means, that if the $\sin(2\varphi + 90^\circ)$ dependence of $\rho_{\text{long}}$ is not observed, it is not possible to observe an AMR effect of higher symmetry as well. Therefore, we will check our magneto photo-conductivity measurements in dependence of the orientation of $\mathbf{M}$ relative to $\mathbf{J}$ on the observation of the $\sin(2\varphi + 90^\circ)$ dependence to search for the presence of the AMR in our samples.
2.3 Optical Absorption

The optical and magneto-optical properties of YIG were intensively investigated between the 1960s and 1980s. A coherent model for the spectral dependence of the major dielectric tensor elements $\epsilon_0$ and $\epsilon_1$ could be developed [46]. Here, the absorption spectra shall be discussed briefly since it will be of importance for the photo-conductivity measurements in Ch. 4.

In Fig. 2.3 (taken from Ref. [46], p.450), the absorption spectra of a thin section of YIG bulk crystals at 77 K according to the data of Refs. [68] and [69] is depicted. In the following, the results summarized in Ref. [46] are paraphrased.

The absorption spectra are split into regions according to the origin of the relevant transitions [46]. In the region between 10 000 cm$^{-1}$ (1.24 eV) and 23 000 cm$^{-1}$ (2.85 eV), the absorption is ascribed to the crystal field transition of a $[\text{Fe}^{3+}],(\text{Fe}^{3+})$ ion pair, wherein the former is octahedrally and the latter tetrahedrally coordinated. The total spin of this pair is zero. The excitation of one of the ions from the crystal field split ground state, $^6A_1$ for $(\text{Fe}^{3+})$ and $^6A_{1g}$ for $[\text{Fe}^{3+}]$, to the higher states (which correspond to the spin quartet states $^4G, ^4P, ^4D, ^4F$ of the free Fe$^{3+}$ ion) is connected with inverting one spin, so that $s = \frac{3}{2}$. As a result, the total spin of the ion pair is changed $\Delta S = -1$. According to the selection rules for dipole radiation, this transition is allowed with a small transition probability for electron systems with finite spin orbit coupling. Therefore, to explain the value of the absorption in this region, the inverting of one spin on the second ion is suggested, since that would avoid the change of the total spin of the ion pair and result in an increased transition probability.

Starting from 23 000 cm$^{-1}$ (1.24 eV), the absorption may be explained by inter-sublattice charge transfer transitions [46, 70, 71]. An electron in the ground state located at a $(\text{Fe}^{3+}),(\text{Fe}^{3+})$ ion is excited into one of the crystal field split orbitals of an adjacent ion, thus creating $[\text{Fe}^{2+}),(\text{Fe}^{2+})$. It is suggested, that the formation of Fe$^{4+}$ is suppressed [69] and that the produced hole is associated to O$^{2-}$ due to a hybridization between the filled 3$d$ and 2$p$ bands [46].

The region at about 35 000 cm$^{-1}$ (4.34 eV) and above is assigned to charge transfer...
transitions from the $2p$ band of $O^{2-}$ into the $3d$ of $Fe^{3+}$. It is suggested that a transition into the octahedrally coordinated $[Fe^{3+}]$ sites is preferred [46].
<table>
<thead>
<tr>
<th>Ref.</th>
<th>(year)</th>
<th>growing technique</th>
<th>crystal</th>
<th>doping (concentration)</th>
<th>resistivity (type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[28]</td>
<td>(1957)</td>
<td>ceramic polycrystalline</td>
<td>Cu + V (3.75 mol%)</td>
<td>8 × 10^9 Ω m (unknown)</td>
<td></td>
</tr>
<tr>
<td>[51]</td>
<td>(1959)</td>
<td>ceramic polycrystalline</td>
<td>none</td>
<td>1.5 × 10^3 Ω m (unknown)</td>
<td></td>
</tr>
<tr>
<td>[29]</td>
<td>(1968)</td>
<td>flux singly crystal</td>
<td>Hf (0.04 atoms/formula unit)</td>
<td>5 × 10^3 Ω m (n-type)</td>
<td></td>
</tr>
<tr>
<td>[41]</td>
<td>(1970)</td>
<td>unknown single crystal</td>
<td>Si (0.03 - 0.3 atoms/formula unit)</td>
<td>10^4 - 10^5 Ω m (n-type)</td>
<td></td>
</tr>
<tr>
<td>[52]</td>
<td>(1972)</td>
<td>ceramic polycrystalline</td>
<td>Si (1 mol%)</td>
<td>2.9 × 10^5 Ω m (n-type)</td>
<td></td>
</tr>
<tr>
<td>[58]</td>
<td>(1972)</td>
<td>unknown single crystal</td>
<td>unknown</td>
<td>3.5 × 10^9 Ω m (unknown)</td>
<td></td>
</tr>
<tr>
<td>[59]</td>
<td>(1974)</td>
<td>flux and LPE bulk and films</td>
<td>unknown</td>
<td>R ∼ 10^{10} Ω ¹(unknown)</td>
<td></td>
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<tr>
<td>[53]</td>
<td>(1978)</td>
<td>Li RE molybdate flux (111) film</td>
<td>Si (unknown)</td>
<td>9 × 10^2 Ω m (n-type)</td>
<td></td>
</tr>
<tr>
<td>[53]</td>
<td>(1978)</td>
<td>flux single crystal</td>
<td>SiO₂ (20 mol%)</td>
<td>1.3 × 10^2 Ω m (n-type)</td>
<td></td>
</tr>
<tr>
<td>[31]</td>
<td>(1982)</td>
<td>ceramic polycrystalline</td>
<td>none</td>
<td>9.7 × 10^4 Ω m (unknown)</td>
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</tr>
<tr>
<td>[50]</td>
<td>(1983)</td>
<td>flux single crystal</td>
<td>Si (0.03 atoms/formula unit)</td>
<td>10^2 Ω m (n-type)</td>
<td></td>
</tr>
<tr>
<td>[50]</td>
<td>(1983)</td>
<td>flux single crystal</td>
<td>Sn (0.06 atoms/formula unit)</td>
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</tr>
<tr>
<td>[55]</td>
<td>(1998)</td>
<td>flux bulk crystal</td>
<td>none</td>
<td>10^{11} Ω m (n-type)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ref.</th>
<th>(year)</th>
<th>growing technique</th>
<th>crystal</th>
<th>Y_{3-2x}Ca_{2x}Fe_{5-x}V_xO_{12}</th>
<th>resistivity (type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[57]</td>
<td>(2004)</td>
<td>ceramic poly crystalline</td>
<td>x=0.0</td>
<td>2 × 10^{11} Ω m (p-type)</td>
<td></td>
</tr>
<tr>
<td>[57]</td>
<td>(2004)</td>
<td>ceramic poly crystalline</td>
<td>x=0.2</td>
<td>1 × 10^{11} Ω m (p-type)</td>
<td></td>
</tr>
<tr>
<td>[57]</td>
<td>(2004)</td>
<td>ceramic poly crystalline</td>
<td>x=0.4</td>
<td>8 × 10^{11} Ω m (p-type)</td>
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</tr>
<tr>
<td>[57]</td>
<td>(2004)</td>
<td>ceramic poly crystalline</td>
<td>x=0.6</td>
<td>1 × 10^{12} Ω m (p-type)</td>
<td></td>
</tr>
<tr>
<td>[57]</td>
<td>(2004)</td>
<td>ceramic poly crystalline</td>
<td>x=0.8</td>
<td>1 × 10^{10} Ω m (n-type)</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Overview of the YIG samples investigated in literature. The flux method is referred to the growth technique using a PbO – PbF₂ – B₂O₃ flux. ¹ Several YIG samples, films and bulk crystals, were investigated wherein only the magnitude of the resistance is mentioned. The electrode design was not describe sufficiently to determine the resistivity ρ.
3 Samples

In this thesis, the magnetic field dependent photo-conductivity of five magnetic insulator samples is investigated. Additional, one sample is used for reference. The five photo-conductivity samples are based on the ferrimagnetic insulator yttrium iron garnet (Y$_3$Fe$_5$O$_{12}$, YIG) and were grown in-house at the Walther-Meißner-Institute (WMI) by Sibylle Meyer, Marc Ross, Evgeny Zamburg, Andreas Erb and Stephan Geprägs. An detailed overview of all samples is given in Tab. 3.1.

Photoconductivity Samples

The samples 1 to 3 were grown by Marc Ross. They consist of (111) YIG thin films grown epitaxially by UHV laser molecular beam epitaxy (laser MBE) [10, 12] on (111) oriented yttrium aluminium garnet (Y$_3$Al$_2$(AlO$_4$)$_3$, YAG) substrates. The samples were grown at $T = 500\,^{\circ}\mathrm{C}$ in an O$_2$ atmosphere at $p = 25\,\mu\mathrm{bar}$. Albeit the lattice mismatch between YIG ($a = 12.376\,\AA$) and YAG ($a = 12.01\,\AA$ [72]) is comparably large, the weaker paramagnetism [73] of this material is beneficial for the determination of the YIG’s own magnetic properties. The band gap of YAG is about $6.5\,\mathrm{eV}$ [74] and much larger than the one of YIG ($2.85\,\mathrm{eV}$). Therefore, conduction across the YAG substrate is negligible in the measurements in Ch.4 and Ch.5.

Sample 4 was grown by Evgeny Zamburg. It is a (111) YIG thin film grown epitaxially with UHV laser molecular beam epitaxy on (111) oriented gadolinium gallium garnet (Gd$_5$Ga$_5$O$_{12}$, GGG) substrate. The sample was grown at $T = 550\,^{\circ}\mathrm{C}$ in an O$_2$ atmosphere at $p = 25\,\mu\mathrm{bar}$. Due to the small lattice mismatch of GGG ($a = 12.383\,\AA$ [75]) with YIG ($a = 12.376\,\AA$), it is widely used as substrate for YIG. The large band gap of $4.03\,\mathrm{eV}$ [76] ensures, that the conduction is mainly carried by the YIG film.
Andreas Erb and his team fabricated sample 5 in the crystal laboratory at the Walther-Meißner Institut. It is a YIG bulk crystal which was grown by the travelling solvent floating zone (TSFZ) \[77, 78\] method using a YFeO$_3$ solvent with 20 mol\% Y$_2$O$_3$. The growth direction was determined to be along the \((111)\) direction \[79\]. The actual sample is a 2mm thick disk, cut in the plane normal to the \((111)\) direction. The sample surface was polished afterwards to increase the smoothness of the surface. As a result of the applied fabrication technique, sample 5 does not have a substrate layer.

To enable the transport measurements, Au electrodes consisting in two interengaging combs \(^1\) (see Fig. 3.1 ((a))), are deposited ex-situ onto the samples 1-5 by optical lithography. The pattern is transferred into a photoresist layer covering the YIG film by means of a image removal process in the clean room facility at the WMI. Subsequently, the obtained cutout is filled with a 50 nm Au layer using the sputtering method. Finally, the remaining photoresist is removed by treating the sample with acetone and subsequently with isopropanol in a ultrasonic bath. A detailed description of the procedure can be found in Ref. [80]. A schematic of the samples and a microscope picture (of sample 4) showing the electrode design are depicted in Fig. 3.1 ((a) and (b)), respectively.

IDT-structures of 3 different dimensions are deposited onto the samples. All samples exhibit patterns with \(d_{\text{IDT}} = 5\,\mu\text{m}\) and \(d_{\text{W}} = 5\,\mu\text{m}\), denoting the distance between the fingers and the finger width. Onto sample 1, sample 3 and sample 4, a pattern with \(l_{\text{IDT}} = 838\,\mu\text{m}\) and \(N = 60\), denoting the length of the fingers and the total number of fingers, respectively, is deposited. The pattern on sample 2 and sample 5 both exhibit \(l_{\text{IDT}} = 1700\,\mu\text{m}\) but a different number of fingers with \(N = 300\) and \(N = 120\), respectively. The electrode design will be discussed in detail in Sec. 4.2.

At room temperature, Au is weakly diamagnetic \[81\] and does not feature magneto resistive effects within the limits of our experiment. A magnetic proximity effect in the Au as a source of magneto resistive effects can be neglected \[82, 83\].

\(^1\)The pattern corresponds to an interdigital transducer (IDT), whereas the ability of generating surface acoustic waves (SAW) is not relevant for the experiments in this thesis.
Figure 3.1: a) Schematic of the photoconductivity samples. b) Microscope picture of sample 4 showing the dimensions of the Au electrodes with the IDT pattern. The YIG thin layer is grown epitaxially on conventional YAG or GGG substrates by UHV laser molecular beam epitaxy. The Au electrodes with the IDT pattern are deposited onto the samples ex-situ by means of optical lithography in clean room environment and the sputtering technique.

**Spin Hall Magnetoresistance Sample**

As mentioned above, an additional sample was used for reference purposes. More specifically, spin Hall magnetoresistance [17–19] (SMR) measurements using the scheme presented in Sec.5.4 were performed and compared with results obtained from conventional magnetotransport experiments. The sample consists in a (111) YIG thin film grown on GGG substrate with a orientation of (111). Sample A was fabricated by Sibylle Meyer. A Pt film was deposited on top in-situ, without breaking the vacuum, ensuring the best possible transparency of the YIG/Pt interface for spin transport. For the measurements, the Pt film is patterned into Hall bar structures using photo lithography and ion beam etching. A schematic of the sample and a microscope picture including a scheme of the Hall bar structure are depicted in Fig. 3.2 (a) and (b), respectively.
Figure 3.2: a) Schematic of the sample used for the SMR measurements. b) Microscope picture of sample A showing the dimensions of the Pt Hall bar. The YIG thin layer is grown epitaxially on conventional GGG substrates by UHV laser molecular beam epitaxy. The Pt layer is deposited onto the YIG thin film in-situ and patterned into a Hall bar structure by means of photo lithography and ion beam etching.

<table>
<thead>
<tr>
<th>sample #</th>
<th>lab name</th>
<th>$d_{\text{YIG}}$</th>
<th>$d_{\text{Au}}$</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>YY46#1</td>
<td>53.5 nm</td>
<td>50 nm</td>
<td>YAG</td>
</tr>
<tr>
<td>2</td>
<td>YY48</td>
<td>82 nm</td>
<td>50 nm</td>
<td>YAG</td>
</tr>
<tr>
<td>3</td>
<td>YY54</td>
<td>37 nm</td>
<td>50 nm</td>
<td>YAG</td>
</tr>
<tr>
<td>4</td>
<td>YIG84</td>
<td>71.5 nm</td>
<td>50 nm</td>
<td>GGG</td>
</tr>
<tr>
<td>5</td>
<td>YIG Bulk</td>
<td>2 mm</td>
<td>50 nm</td>
<td>NONE</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>sample #</th>
<th>lab name</th>
<th>$d_{\text{YIG}}$</th>
<th>$d_{\text{Pt}}$</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>YIG70</td>
<td>55 nm</td>
<td>17 nm</td>
<td>GGG</td>
</tr>
</tbody>
</table>

Table 3.1: Overview of the samples investigated in course of this thesis.
4 Magnetic Field Dependent Measurements

The first of two techniques to investigate the magnetic field dependence of the photo-conductivity in YIG will be introduced in this chapter. First, the experimental setup and the electrode design are discussed. Then, the resistivity of the samples and the response to illumination with light of different wavelengths in absence of a magnetic field are presented, followed by a discussion of the magnetization dependent data.

4.1 Experimental setup

A setup for magnetic field dependent conductivity and photo-conductivity measurements has to provide the means for the illumination of the sample, for measuring the current through the sample and for applying the magnetic field.

The optics part of the setup used in this thesis (assembled by Michael Schreier and the author) is depicted in Fig. 4.1 and consists of a light source and two lenses. Light emitting diodes (LED) with maxima in their spectral emission at 365 nm, 405 nm, 450 nm, 500 nm, 530 nm and 590 nm, respectively, and a laser diode with a wavelength of 405 nm are used as light sources.

Lens 1 and lens 2 are both biconvex and have focal lengths of 60 mm and 125 mm respectively. The light beam is collimated by lens 1 and focused on the sample by lens 2. The positions are set such as to obtain a beam spot on the sample with a diameter of approximately 5 mm, large enough to illuminate the whole electrode structure. This avoids local heating effects and guarantees the reproducibility of the experiment.

The magnetic field $\mathbf{H}$ lies in the $xy$-plane perpendicular to the incident light beam.
**Figure 4.1:** Scheme of the experimental setup used for the magnetic field dependent photo-conductivity measurements. Several different LED as well as a laser diode are available as light sources. The light is focused onto the sample by two biconvex lenses so that the whole electrode structure of the electrodes is illuminated. Next to the sample are the pole shoes belonging to the two coil pairs used to apply the magnetic field, which can be rotated in-plane.

and is applied by means of two pairs of coils, through which an electrical current is driven. One coil pair generates the magnetic field component in the $x$-axis and the other the magnetic field component in the $y$-axis. Thus, by adjusting the current through the coils, the magnetic field can be rotated in the $xy$-plane. The current in each coil pair is supplied by a *Kepco BOP 20-20M* power supply. Two *LakeShore 475 DPS* Hall probes measure the magnetic field magnitudes in $x$- and $y$-direction and give feedback to the power supplies to adjust the field. We measure as a function of the angle $\alpha$ between the orientation of the magnetic field $\mathbf{H}$ and the $x$-axis while the magnitude is kept constant at $\mu_0 H = 70 \text{ mT}$. This magnetic field strength is strong enough to align the magnetization of the sample along the external field (the coercive field of YIG thin films to change the magnetization in-plane is of the order of a few mT [17]).
A *Keithley K2400 source meter* is used to apply a voltage of $U_{\text{src}} = 5\, \text{V}$ across the sample, thereby forcing a current $I$ to flow through the sample. Due to the insulating nature of YIG, the resistance of the samples $R$ is of the order of $10^7\, \Omega$ to $10^{12}\, \Omega$, resulting in a current $I$ of some hundred nanoamperes to a few picoamperes. By means of a *FEMTO DDPCA-300* transimpedance amplifier, the current $I$ is amplified and converted into a voltage $U$, which is measured with a *Fluke 2182 Nanovoltmeter*. A scheme of the equivalent circuit is shown in fig. 4.2.

The ohmic behaviour of the samples is tested up to $U_{\text{src}} = 8\, \text{V}$. The distance $d_W = 5\, \mu\text{m}$ and does not allow a further increase of $U_{\text{src}}$ because this would result in a spark-over. The ohmic behaviour of the samples

$$I = \frac{U_{\text{src}}}{R}$$

(4.1)
and the transimpedance amplifier

\[ U = I \cdot G, \quad (4.2) \]

where \( G \) is the gain of the amplifier, lead to

\[ U = \frac{U_{\text{src}} G}{R}. \quad (4.3) \]

The gain is tunable from \( 10^4 \) to \( 10^{13} \) in powers of 10. According to Eq. 4.3, the voltage \( U \) measured in our setup is a measure for the resistance \( R \) and is used to detect changes due to the illumination or the external magnetic field.

### 4.2 Dark Current Measurements

The high resistivity of YIG results in a small current flowing through the samples which is difficult to measure. To overcome this issue, the conductor cross section through the sample is increased by using the electrode design describe in Ch.3. Hereby, the effective resistance of the sample is reduced, resulting in an increased current which is easier to measure and less affected by noise.

In contrast to a conventional electrode design, where an overall direction of the current density \( \mathbf{J} \) can be identified, this is not possible here. Due to the interengaging fingers of the electrodes, a current density \( \mathbf{J} \) is generated which is pointing from one finger to both adjacent fingers and to the main body of the opposite electrode. The component of the current density which is pointing from one finger to its adjacent fingers is defined as \( \mathbf{J}_{\text{long}} \), as depicted in Fig. 4.3. The component of the current density directly pointing from one finger to the main body of the opposite electrode is defined as \( \mathbf{J}_{\text{dir}} \).

The measured voltage \( U \) contains contributions corresponding to both current density components \( \mathbf{J}_{\text{long}} \) and \( \mathbf{J}_{\text{dir}} \). Due to the small value of \( \frac{\text{dir}}{\text{long}} \ll 0.01 \) (c.f. Ch. 3, Fig. 4.3 is not true to scale), the contribution due to \( \mathbf{J}_{\text{dir}} \) is negligible.

In Sec. 4.4.1, Sec. 4.4.2 and in Ch. 5, an external magnetic field is used to align the magnetization of the investigated samples. Since we assume the presence of the AMR in Sec. 2.2.2, the planar Hall effect (PHE) has to be considered as well. The
4.2 Dark Current Measurements

Figure 4.3: Scheme for the determination of the conductor cross section $A$ of the samples including a small part of the IDT structure which is used as electrodes. Due to the symmetry of the IDT structure, the current density $j$ is pointing into the two in-plane directions perpendicular to the IDT finger elongation.

PHE gives rise to a current density $J_{\text{PHE}}$ (not shown in Fig. 4.3) which is perpendicular to $J_{\text{long}}$. The difference between $J_{\text{dir}}$ and $J_{\text{PHE}}$ is their origin, the former arises from applying the source voltage $U_{\text{src}}$ and is pointing from one finger to the main body of the opposite electrode, whereas the latter arises from the presence of the PHE and is pointing from one main body of the electrode to the main body of the opposite electrode. The contribution of $J_{\text{PHE}}$ to the measured voltage $U$ depends in our case, aside from the relative amplitude of the PHE, also on the geometrical
form of the electrode structure and therefore is neglected as well.

The overall conclusion is, that the contributions to the measured voltage $U$ from a current flowing parallel to the fingers of the electrode structure are neglected and that we ascribe $U$ to the longitudinal current density $J_{\text{long}}$. Consequently, the resistivity which is determined by measuring $U$ corresponds to $\rho_{\text{long}}$ introduced in Sec. 2.2.2. As a result, it is not possible to perform hall measurements to identify the type of charge carriers and to estimate the charge carrier mobility because the contribution to $U$ from a current transverse to the fingers can not be determined.

To compare our samples with literature, it is necessary to determine the longitudinal resistivity $\rho_{\text{long}}$ of our samples, since it is a quantity independent of electrode design and sample dimensions. In general, the resistivity $\rho$ is given as

$$\rho = R \cdot \frac{A}{d}, \quad (4.4)$$

where $R$ is the resistance, $d$ is the length of the conductor, i.e. distance between the electrodes, and $A$ is the conductor cross section.

For the electrode design used in this thesis, the length of the conductor corresponds to the distance $d_{\text{IDT}}$ between two neighbouring fingers. It is assumed that the current density $J_{\text{long}}$ does not depend on the distance to the film surface and that the entire YIG layer is responsible for the conduction. The conductor cross section is estimated as the product of the film thickness $d_{\text{YIG}}$, the length of the electrode fingers $l_{\text{IDT}}$ and a factor $N$ for the number of the fingers. Therefore, the longitudinal resistivity $\rho_{\text{long}}$ is estimated as

$$\rho_{\text{long}} = R \cdot \frac{(N - 1) \cdot d_{\text{YIG}} \cdot l_{\text{IDT}}}{d_{\text{IDT}}}. \quad (4.5)$$

A scheme for the determination of the conductor cross section is pictured in fig. 4.3. It is reminded here, that according to Eq. 4.3, $R$ is determined by measuring $U$. It is possible that single fingers are not connected because of defects in the lithography process or from sample handling etc. Therefore, Eq. 4.5 only allows an approximation of $\rho_{\text{long}}$. The film thickness is determined by x-ray reflectometry after the growth by Stephan Geprägs. The thickness of sample 5 was determined by means of a caliper.

The measurements of $U$ are performed at room temperature in absence of an exter-
nal magnetic field. The measured values for the resistance $R$ and the determined values for the $\rho_{\text{long}}$ are given in tab. 4.1.

The increase of the resistance $R$ with decreasing $d_{\text{YIG}}$ for sample 1 to 3 should not mislead to any dependence on the sample thickness because the electrode structure of sample 2 exhibits other dimensions than for sample 1 and sample 3. The values for $\rho_{\text{long}}$ are independent on the sample thickness. This supports the assumption made in eq. 4.5, that the whole YIG layer is contributing to the conduction and no layer model has to be applied. In literature, the resistivity of stoichiometric YIG bulk crystals is assumed to be $\rho_{\text{Bulk,YIG}} = 10^{10} \, \Omega \, \text{m}$ [32] and greater. For YIG thin films grown by UHV laser molecular beam epitaxy, no values from literature are available. The values of $\rho_{\text{long}}$ for sample 1 to 3 are decreased compared to $\rho_{\text{Bulk,YIG}}$, which we attribute to crystal effects introduce by the thin film growing technique rather than to impurities.

Sample 4 is the only one grown on GGG and exhibits a lower value of $\rho_{\text{long}}$ in comparison with the films grown on YAG. Since the lattice mismatch between GGG and YIG is smaller compared to YAG, an decreased $\rho_{\text{long}}$ due to an higher number of crystal defects, which may act as acceptor or donor centres, for sample 4 because of the substrate is unlikely.

We attribute the decreased resistivity of sample 4 to specific film properties which are introduced by deviations in the growth process. A Comparison of sample 4 with other samples (which are not investigated in course of this thesis) grown in the same setup under the same condition shows, that the obtained film thickness of 71.5 nm is below the expected film thickness of 140 nm. This is traced back to a decreased performance of the excimer laser, which is used in the UHV laser molecular beam epitaxy setup, during the growth process of sample 4. How this exactly influences

<table>
<thead>
<tr>
<th>sample</th>
<th>$d_{\text{YIG}}$ (nm)</th>
<th>$R$ ($\Omega$)</th>
<th>$\rho_{\text{long}}$ ($\Omega , \text{m}$)</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>53.5 ± 0.5</td>
<td>$5.68 \pm 0.07 \times 10^{10}$</td>
<td>$3.01 \pm 1.35 \times 10^7$</td>
<td>YAG</td>
</tr>
<tr>
<td>2</td>
<td>82 ± 0.5</td>
<td>$2.73 \pm 0.02 \times 10^{10}$</td>
<td>$2.28 \pm 0.92 \times 10^8$</td>
<td>YAG</td>
</tr>
<tr>
<td>3</td>
<td>37 ± 0.5</td>
<td>$1.04 \pm 0.02 \times 10^{11}$</td>
<td>$3.81 \pm 1.72 \times 10^7$</td>
<td>YAG</td>
</tr>
<tr>
<td>4</td>
<td>71.5 ± 0.5</td>
<td>$1.25 \pm 0.31 \times 10^9$</td>
<td>$8.84 \pm 4.54 \times 10^5$</td>
<td>GGG</td>
</tr>
<tr>
<td>5</td>
<td>2 ± 0.5</td>
<td>$1.78 \pm 0.06 \times 10^7$</td>
<td>$1.93 \pm 0.79 \times 10^9$</td>
<td>NONE</td>
</tr>
</tbody>
</table>

Table 4.1: Overview of the resistive properties of the investigated samples including the thickness of the YIG film $d_{\text{YIG}}$, the resistance $R$ and the longitudinal resistivity $\rho_{\text{long}}$. 

4.2 Dark Current Measurements
the growth process and the film properties is not clear. It has to be mentioned here, that XRD measurements for the investigated thin film samples, including sample 4, reveal no other phase than YIG and show no differences to other samples grown in the same setup under the same condition.

The resistance of sample 5 is relatively low due to the use of a comparably large electrode structure (Ch. 3) whereas $\rho_{\text{long}}$ is the highest. The value of $\rho_{\text{long}}$ for sample 5 agrees with literature and indicates a crystal of good quality.

### 4.3 Photocurrent measurements

One of the most relevant property of photoconductive transport measurements is the ratio by which a material’s conductivity is increased under illumination. For a semiconductor with a direct band gap, an increase in the photo-conductivity is expected when the photon energy of the incident light is higher than the band gap.

In this case, the energy of a photon is sufficient to excite an electron from the valence band into the conduction band. The resulting increased number of charge carriers in the conduction band leads to an increased conductivity. With a photon energy below the band gap, it is not possible to excite additional charge carriers into the conduction band and as a result, an increase of the conductivity is not expected for an ideal semiconductor.

Therefore, measurements of the photo-conductivity in dependence of the photon energy are performed to obtain information on the conduction model in the investigated samples. An abrupt increase with increasing photon energy indicates band conduction.

To variate the photon energy of the incident light, LEDs with different maxima in their spectral emission and a laser diode are used. The energy of the incident light is $E = \frac{h c}{\lambda}$ and therefore, a decreasing wavelength corresponds to an increasing photon energy. The literature value for the band gap of YIG $E_{\text{gap}} = 2.85 \text{ eV}$ corresponds to a wavelength of $\lambda_{\text{gap}} = 435 \text{ nm}$. To compare the influence of the different photon energies of the light sources on the photo current, it is important to take into account the intensity of the incident light. Therefore, the ratio $\frac{P_{\text{opt.}}}{P_{\text{DC}}}$ of photo current (PC) to dark current (DC) per mW optical power ($P_{\text{opt.}}$) is determined and plotted over the light source in Fig. 4.4.
4.3 Photocurrent measurements

The optical power deposited onto the sample and the chip carrier system is de-

![Graph]

**Figure 4.4:** The ratio photo current (PC) to dark current (DC) per mW optical power $P_{opt}$. The optical power of the light source is depicted along the horizontal axis. The band gap of YIG is 2.85 eV, which corresponds to a wavelength of 435 nm, and is located between the 405 nm LED and the 450 nm LED. Therefore, the optical power deposited by the 365 nm LED is approximated to be about 3% of the electrical power, since this value was determined for the other LEDs. Due to the approximation, the error bars of the 365 nm LED data points are increased.

For all samples, the values of $\frac{PC}{DC} P_{opt}$ determined for the 405 nm LED are about 3.5 times larger than the values for the 450 nm LED. By changing the light source from the 450 nm LED to the 405 nm LED, the photon energy becomes larger than the band gap. As a result, additional charge carrier can be excited into the conduction band which increases the photo current. Replacing the light sources other than
4 Magnetic Field Dependent Measurements

from the 450 nm LED to the 405 nm LED does not result in an increase of $\frac{PC}{DC \cdot P_{opt}}$ of comparable size for all samples. We attribute the observed behaviour of $\frac{PC}{DC \cdot P_{opt}}$ to band conduction in all investigated samples. For sample 4, the decrease of $\frac{PC}{DC \cdot P_{opt}}$ with increasing wavelength starting at the 450 nm LED is qualitatively consistent with the decreasing absorption coefficient shown in Sec. 2.3. For the other samples, a complete data set is not available but the decrease observed for sample 4 is not present.

In the ratio $\frac{PC}{DC \cdot P_{opt}}$, the different resistivities of the samples are already taken into account. The increased values of $\frac{PC}{DC \cdot P_{opt}}$ for sample 4 compared to the other samples are attributed to the specific film properties, mentioned in Sec. 4.3. Since we have no exact knowledge on this specific film properties, it is not possible to give an intrinsic explanation for the increased values of $\frac{PC}{DC \cdot P_{opt}}$ for sample 4. The values of $\frac{PC}{DC \cdot P_{opt}}$ for sample 5, the YIG bulk sample without substrate, are similar to that of the thin film samples 2 and 3. Therefore, an influence of the substrate on $\frac{PC}{DC \cdot P_{opt}}$ is excluded.

The results of the photo-conductivity measurements in dependence of the light source indicate band conduction in all samples. Sample 4 exhibits increased values of $\frac{PC}{DC \cdot P_{opt}}$ compared to the other samples, which we attribute to specific film properties of sample 4.

4.4 Magneto-Photo-Conductivity Measurements

The topic of a magneto resistive effect in YIG has been addressed only once before [53] in highly doped samples with low resistivity ($\rho = 9 \times 10^2 \Omega \text{m}$). A dependence of the resistivity on an external magnetic field in stoichiometric YIG samples has not been observed yet. This is not surprising, because the magnitude of most intrinsic magneto resistive effects is very small, usually $\Delta \rho / \rho \leq 0.01$, and the high resistivity of undoped YIG complicates accurate resistance measurements. As a result, a possible presence of a magneto resistive effect in stoichiometric YIG is easily obscured by noise and thermal drift. Consequently, revealing whether a magneto resistive effect can be observed in stoichiometric YIG or not, is a formidable task. But knowledge on an intrinsic magneto resistive effect in YIG may help the interpretation of SMR experiments.
To overcome the above mentioned issue, the samples are illuminated to increase the conductivity and to facilitate the measurement of small changes of the conductivity due to an external magnetic field.

The measurements in the following Secs. 4.4.1 and 4.4.2 are performed under ambient conditions. The samples are illuminated throughout the entire measurements. The high resistivity of the samples makes them sensitive to external influences such as temperature changes and air humidity which may prohibit the observation of a dependence of the photo-conductivity on the applied external magnetic field. Therefore, measurements in a cryostat providing constant external parameters are required. Unfortunately, the investigation of the photo-conductivity of the samples in a cryostat was not possible because a corresponding dip stick providing the illumination of the samples was not available. Assembling the dip stick was not possible during this thesis because the in-house workshop of the WMI had no capacities to manufacture the required components.

Therefore, we perform the measurements at ambient conditions and try to remove the influence of external parameters by averaging. As discussed in Sec.2.2.3, we test the investigated samples on the signature of the AMR. If the resolution of the measurements is increased sufficiently, the change of the photo-conductivity in dependence of the direction of an external magnetic field should be observed if the samples exhibit an AMR.

4.4.1 Magneto-Photo-Conductivity Measurements in Dependence of the Magnetic Field Direction

In our measurements, we rotate the magnetic field in the film plane of the investigated sample while the magnitude is held constant at $\mu_0 H = 70$ mT. The angle between the horizontal and the magnetic field is defined as $\alpha$. The rotation is performed in discrete steps of $\alpha$, and for each of which the resistance $R(\alpha)$ of the sample is determined. To increase the signal to noise ratio, several field rotations are performed and a mean value $\overline{R}(\alpha)$ of the resistance for each value of $\alpha$ is obtained. To allow for a comparison between samples with different resistances, it is convenient
to determine the relative change

\[
\frac{\bar{R}(\alpha) - R_{\text{average}}}{R_{\text{average}}} = \frac{\Delta R(\alpha)}{R_{\text{average}}},
\]

wherein \(R_{\text{average}}\) is the average of \(\bar{R}(\alpha)\) over a full rotation of the magnetic field and \(\Delta R(\alpha) = \bar{R}(\alpha) - R_{\text{average}}\). Using this representation, the magnitude of the change of the photo-conductivity is easily readable.

The equivalent of Eq. 4.6 in the model of the AMR according to Eq. 2.7 is

\[
\frac{\rho_{\text{long}} - \rho_{\text{average}}}{\rho_{\text{average}}} = \frac{\Delta \rho}{2\rho_{\text{average}}} \sin(2\varphi + 90^\circ),
\]

with \(\Delta \rho = \rho_\parallel - \rho_\perp\). Consequently, if the AMR is present in the investigated sample, a dependence of \(\Delta R(\alpha)/R_{\text{average}}\) on \(\alpha\) similar to \(\sin(2\alpha)\) is expected. It has to be reminded here, that \(\alpha\) is the angle between the horizontal and the magnetic field, whereas \(\varphi\) is the angle between the sample magnetization and the current direction.

The obtained values of \(\Delta R(\alpha)/R_{\text{average}}\) for sample 4 under the illumination of the 405 nm laser diode are plotted over \(\alpha\) in Fig. 4.5 as the black line. A dependence similar to a \(\sin(2\alpha)\) function with an amplitude of \(\Delta R(\alpha)/R_{\text{average}} = 6 \times 10^{-4}\) is observed. The position of the maxima are at \(\alpha = 28^\circ\), denoted as maximum A, and at \(\alpha = 210^\circ\), denoted as maximum B.

The observed behaviour of \(\Delta R(\alpha)/R_{\text{average}}\) is in agreement with the model of the AMR according to Eq.4.7. The difference between the maxima of 182° qualitatively agrees with the expected two fold symmetry of the AMR. Due to the mounting of the sample, the value of \(\alpha\) for which \(J_{\text{long}} \parallel H\) is shifted, as illustrated on the right hand side of Fig. 4.5. The positions of the maxima agree with the expected values of \(\alpha\) for which \(J_{\text{long}} \parallel H\). Therefore, it is obtained that \(\Delta \rho > 0\), because otherwise, minima would be observed at the values for \(\alpha\) where \(J_{\text{long}} \parallel H\).

To verify this and to exclude any artefacts introduced by the setup, the same measurement is performed with the sample rotated clockwise by 90°, which is plotted in Fig. 4.5 as the red line. The rotation changes the direction of \(J_{\text{long}}\) and as expected, the positions of the maxima are shifted by about 90°. The deviation from the expected exact 90° is attributed to a small misalignment introduced by remounting of
4.4 Magneto-Photo-Conductivity Measurements

Figure 4.5: Measurement of $\Delta R(\alpha)/R_{\text{average}}$ for sample 4 under the illumination of the 405 nm laser diode. $\alpha$ is defined as the angle between the horizontal and the orientation of the magnetic field $\mathbf{H}$, as depicted on the right hand side of the figure. $\Delta R(\alpha)/R_{\text{average}}$ exhibits a $\sin(2\alpha)$ dependence wherein the maxima are denoted as maximum A and B (see text) and are located where $\mathbf{H} \parallel J_{\text{long}}$. This is confirmed with a clock-wise rotation of the sample by 90° (red line). The values for $\alpha$ where $\mathbf{H} \parallel J_{\text{long}}$ are illustrated on the right hand side of the figure. The observed behaviour is in agreement with the presence of the anisotropic magneto resistance.

the sample. The value of the amplitude $\Delta R(\alpha)/R_{\text{average}} = 6 \times 10^{-4}$ is the same as before.

With the results obtained above, a short preliminary conclusion can be given. The presence of the AMR is confirmed for sample 4 under the illumination of the 405 nm laser diode. The sign of the effect is positive, $\Delta \rho > 0$, and the obtained value of $\Delta \rho/\rho_{\text{average}} = 1.2 \times 10^{-3}$ is of the same order of magnitude as the AMR observed in Fe$_3$O$_4$ thin films with $\Delta \rho/\rho = 4 \times 10^{-3}$ [84].

Corresponding measurements for the other samples show a qualitatively different behaviour. The angle dependence of $\Delta R(\alpha)/R_{\text{average}}$ seems to contain an additional contribution proportional to $\sin(\alpha)$, which obscures the possible presence of a $\sin(2\alpha)$ dependence with smaller amplitude. The measurements suffer in a lack of reproducibility in the sense that the amplitude and phase of the $\sin(\alpha)$ contribution changes from measurement to measurement for each sample. Therefore,
measurements with a rotated sample were not performed. Hence, a dependence of $\Delta R(\alpha)/R_{\text{average}}$ on $\alpha$ similar to $\sin(2\alpha)$ is not observed for the other samples by means of the available data and consequently, the presence of the AMR in samples 1 to 3 and sample 5 can not be confirmed. The origin of the $\sin(\alpha)$ contribution is discussed in Sec. 4.4.2, but for now a magneto resistive effect can be excluded as origin because the symmetry in $\alpha$ due to a magneto resistive effect is always twofold or higher but never $\sin(\alpha)$.

The measurements of $\Delta R(\alpha)/R_{\text{average}}$ under illumination of the 405 nm LED and 365 nm LED for sample 4 are shown in Fig. 4.6 (a) and (b), respectively. The measurement under illumination of the 405 nm LED exhibits two peaks, one at about 25°, referred to maximum A in Fig.4.5, and the other at 248°, referred to maximum B, with amplitudes of $1.5 \times 10^{-4}$ and $5 \times 10^{-4}$, respectively. The difference between them of 137° deviates form the 180° symmetry. Under a counter-clock wise rotation of the sample by 90°, maximum A shifts by about 85° to 110° and maximum B for 59° to about 307°. The amplitudes are slightly increased to $3 \times 10^{-4}$ and $6.4 \times 10^{-4}$, respectively.

The behaviour of $\Delta R(\alpha)/R_{\text{average}}$ under illumination of the 365 nm LED deviates from the one under the illumination of 405 nm laser diode. The peak referring to maximum A is located around 22° and exhibits a broadened shape and an increased amplitude of $6.6 \times 10^{-4}$. At around 247°, a peak referring to maximum B, with an amplitude of $5.8 \times 10^{-4}$ is observed. Again, the sample is rotated counter-clockwise by 90° and as a result, not only the position is shifted, but also the shape of the peak is influenced. Peak A is shifted for about 79° to a position around 101° and exhibits a different shape. Peak B is shifted for 73° to 320° and shows an increased width. The amplitudes are $2.6 \times 10^{-4}$ and $7.6 \times 10^{-4}$ for peak A and peak B, respectively. It has to be mentioned here, that the measurements under illumination of the 405 nm LED or the 365 nm LED for the same current direction were performed one after the other without changing the sample position in the setup. Before performing the measurements for the rotated sample, the sample holder had been modified to fix an issue with the sample adapter. As a result, the orientation of the sample relative to the setup is slightly changed, leading to the increased deviation of the shifts compared to 90°.

Under illumination of the 405 nm LED and 365 nm LED, the previously observed $\sin(2\alpha)$ dependence on the external magnetic field orientation can not clearly be
4.4 Magneto-Photo-Conductivity Measurements

Figure 4.6: Measurement of $\Delta R(\alpha)/R_{\text{average}}$ for sample 4 under the illumination of the 405 nm LED a) and the 365 nm LED b). $\alpha$ is defined as the angle between the horizontal and the orientation of the magnetic field $H$, as depicted on the right hand side of the figure. The maxima are denoted as maximum A and B (see text) and correspond to the maxima observed in the measurement under the illumination of the 405 nm laser diode in Fig. 4.5. In a), $\Delta R(\alpha)/R$ exhibits two maxima whereas the amplitude and the difference of their position of $137^\circ$ deviate from a $\sin(2\alpha)$ dependence. In b), the location of the maxima coincide with the maxima in a), but are less distinct and exhibit different shapes. A possible $\sin(2\alpha)$ dependence of $\Delta R(\alpha)/R_{\text{average}}$ seems to be obscured by an additional signal (see text).

observed. While one may recognize a number of similar features in Fig. 4.5 and Fig. 4.6 (maxima at similar positions which shift under rotation of the sample) the
4 Magnetic Field Dependent Measurements

curve is heavily affected by some kind of drift that blurs the full magnetization dependence. Its nature and origin can not be determined absolutely certain and will be discussed in Sec. 4.4.2. The form of this additional contribution is assumed to be proportional to \( \sin(\alpha) \), as it is observed in the measurements for the samples 1 to 3 and sample 5 under the illumination of the 405 nm laser diode.

The measurements for the other samples under the illumination of the 405 nm LED suffer under a lack of reproducibility as it is case for the measurements under illumination of the 405 nm laser diode. It seems that a \( \sin(\alpha) \)-type contribution is present as well. For sample 1 and sample 5, two distinct peaks with different width and amplitude are observed. The difference between the peaks strongly deviates from 180°. The measurements for sample 2 and sample 3 only reveal one dominating peak around \( \alpha = 180^\circ \) with an amplitude of about of \( 1.5 \times 10^{-4} \).

With the results obtained so far a short summary shall be given. For sample 4, the obtained results are consistent and confirm the presence of a magneto resistive effect. The dependence of the resistance on the in-plane rotation of the magnetic field fits to the anisotropic magneto resistance (AMR) [66]. The position and the amplitude of the extrema match for all light sources investigated as well as for the measurements with rotated samples. It is observed, that in sample 4, the sign of the AMR under illumination of the 405 nm laser diode is positive, i.e. \( \Delta \rho > 0 \). The obtained value \( \Delta \rho/\rho_{\text{average}} = 1.2 \times 10^{-3} \) under illumination of the 405 nm laser diode is of the same order of magnitude as the AMR observed in Fe\(_3\)O\(_4\) thin films with \( \Delta \rho/\rho = 4 \times 10^{-3} \) [84].

A contribution similar to a \( \sin(\alpha) \) is observed for the measurements under illumination of the 405 nm LED and the 365 nm LED, which seems to affect the measurements of the rotated sample in a similar way. The presence of the additional \( \sin(\alpha) \) contribution is observed for the other samples as well. It is possible, that the expected behaviour of \( \Delta R(\alpha)/R_{\text{average}} \) similar to \( \sin(2\alpha) \) is obscured by this \( \sin(\alpha) \) contribution. For sample 1 and sample 5, two peaks of \( \Delta R(\alpha)/R_{\text{average}} \) in dependence of \( \alpha \) are observed under illumination of the 405 nm laser diode whereas the difference between their positions deviates from the expected 180°. It is possible, that the maximum of the \( \sin(\alpha) \) contribution obscures only one maximum of the expected \( \sin(2\alpha) \).

The observed behaviour of \( \Delta R(\alpha)/R_{\text{average}} \) similar to a \( \sin(\alpha) \) could originate from
the current driven through the coils in order to generate the magnetic field. This current is necessary to apply the rotating field and reads as $I_{\text{vertical}} \propto \sin(\alpha)$ for the vertical coil pair and $I_{\text{horizontal}} \propto \cos(\alpha)$ for the horizontal coil pair. We can access the temperature, since the Hall probes measure temperature as well as magnetic field, in order to remove thermal effects contributing to the Hall voltage, which is used to determine the field. It is observed in Sec. 4.4.2, that the Hall probe temperature correlates with the measured sample resistance for magnetic fields along a

![Figure 4.7](image.png)

**Figure 4.7**: Measurement of the resistance $R$ (black line) of sample 4 under the illumination of the 365 nm LED plotted over time. **a**) corresponds to $\mathbf{H} \parallel \mathbf{j}$ at 105°, **b**) corresponds to $\mathbf{H} \parallel \mathbf{J}_{\text{long}}$ at 25° (rotated sample). Additional to the sample resistance, the expected $\sin(2\alpha)$ dependence (red line) due to the AMR, the temperature measured by the vertical (green line) and the horizontal (teal line) Hall probe and the current through the vertical coil pair (blue line) and the horizontal coil pair (magenta line) are plotted. In **b**), a oscillation of the resistance is observed which correlates with the measured temperatures. In **a**), the resistance seems to exhibit a $\sin(\alpha)$ dependence instead of the expected $\sin(2\alpha)$. 

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static axis. It is thus reasonable to assume that this is also the case for the relatively slow field rotations presented in this section. Therefore, it is necessary to present the data of the resistance and the measured temperatures in dependence of the time to check, if the observed correlation in Sec. 4.4.2 is also present in the measurements presented in this section.

In Fig. 4.7, the resistance and the measured temperatures of the vertical and horizontal Hall probes from the measurements of sample 4 under illumination of the 365 nm LED are plotted over time. Additionally, the expected behaviour of $\Delta R(\alpha)/R_{\text{average}}$ proportional to $\sin(2\alpha)$ and the currents $I_{\text{vertical}}$ and $I_{\text{horizontal}}$ are shown.

Fig. 4.7 (a) corresponds to the measurement with $H \parallel J_{\text{long}}$ at $105^\circ$ and Fig. 4.7 (b) to the measurement with $H \parallel J_{\text{long}}$ at $25^\circ$ (rotated sample). An entire field rotation is performed in approximately 14 min, so that the values between a blue and a grey grid line are used for the averaging. In fig. 4.7 b, a oscillation of the measured temperature is visible, which is more distinct for the temperature measured by the vertical Hall probe. The currents and the temperatures are not in phase, but exhibit similar frequencies. A correlation of the measured resistance and the measured temperatures is observed.

In Fig. 4.7 (a), a clear correlation over time between the temperature and the resistance of the samples is not observed. We now turn to the measurements in dependence of the magnetic field magnitude along a static axis since they reveal important information on this issue as well.

4.4.2 Magneto-Photo-Conductivity Measurements in Dependence of the Amplitude of the Magnetic Field

In Sec. 2.2.3 it is introduced, that measurements of $\rho_{\text{long}}$ in dependence of the relative orientation of the magnetic field $H$ to the current density $J_{\text{long}}$, which are commonly called field rotation measurements, can reveal the presence of the AMR. Measurements of this type were performed in Sec. 4.4.1 and confirmed the presence of the AMR for sample 4 under the illumination of the 405 nm laser diode.

Aside from field rotation measurements, the AMR can be observed as well in measurements of $\rho_{\text{long}}$ wherein the amplitude of the magnetic field $\mu_0 H$ is changed and the angle $\varphi$ between $H$ and $J_{\text{long}}$ is constant. Consequently, the results obtained in
Sec. 4.4.1 can be verified by performing measurements in dependence of $\mu_0 H$.

Before we present our results, a short introduction of what is expected for this measurements is given. The dependence of $\rho_{\text{long}}$ on $\varphi$ according to Eq. 2.7 is

$$\rho_{\text{long}} = \rho_{\text{average}} + \frac{\Delta \rho}{2} \sin(2\varphi + 90^\circ),$$  \hspace{1cm} (4.8)

wherein $\Delta \rho = \rho_\parallel - \rho_\perp$. Equation 4.8 is plotted over $\varphi$ in Fig. 4.8 (a) for $\Delta \rho > 0$ and in Fig. 4.8 (d) for $\Delta \rho < 0$.

The observed behaviour of $\rho_{\text{long}}$ in dependence of $\mu_0 H$ depends on whether $\Delta \rho > 0$ or $\Delta \rho < 0$. First we assume $\Delta \rho > 0$ and $\mathbf{H} \parallel \mathbf{J}_{\text{long}}$ ($\varphi = 180^\circ$ or $\varphi = 0^\circ$). At the beginning, the field amplitude is set to the value $+\mu_0 H_{\text{max}}$, so that the magnetic moments of all magnetic domains are aligned parallel to $\mathbf{H}$. Since $\mathbf{H} \parallel \mathbf{J}_{\text{long}}$, the measured value of $\rho_{\text{long}}$ corresponds to $\rho_\parallel$. Decreasing $\mu_0 H$ has no influence on $\rho_{\text{long}}$ as long as $\mu_0 H > -\mu_0 H_C$, wherein $\mu_0 H_C$ is the coercive field. Little above $-\mu_0 H_C$, the field is strong enough to change the orientation of the magnetic moments. By further decreasing $\mu_0 H$, the magnetic moments are forced to rotate so that their orientation becomes parallel to $\mathbf{H}$ again. During the rotation, the orientation of the magnetic moments is distributed randomly and the orientation of each magnetic moment relative to the current direction has to be considered. With deceasing $\mu_0 H$, the components of the magnetic moments perpendicular to $\mathbf{J}$ increase and as a result, $\rho_{\text{long}}$ drops from $\rho_\parallel$ to $\rho_\perp$. At $-\mu_0 H_C$, the magnetic moments become perpendicular to $\mathbf{J}_{\text{long}}$, so that $\rho_{\text{long}}$ corresponds no longer to $\rho_\parallel$ but to $\rho_\perp$, as depicted in Fig. 4.8 (b). A further decrease of $\mu_0 H$ aligns the magnetic moments parallel to $\mathbf{H}$, and consequently also parallel to $\mathbf{J}_{\text{long}}$, so that $\rho_{\text{long}}$ increases from $\rho_\perp$ to $\rho_\parallel$. The same mechanism is responsible for the dip of $\rho_{\text{long}}$ while increasing $\mu_0 H$ from $-\mu_0 H_{\text{max}}$ to $+\mu_0 H_{\text{max}}$. But this time, the dip is located at $+\mu_0 H_C$.

The mechanism for the behaviour of $\rho_{\text{long}}$ of with $\Delta \rho > 0$ and $\mathbf{H} \perp \mathbf{J}_{\text{long}}$, so that $\rho_{\text{long}}$ corresponds to $\rho_\perp$, is the same. Peaks are observed instead of dips because at $-\mu_0 H_C$ and $+\mu_0 H_C$, $\rho_{\text{long}}$ increase from $\rho_\perp$ to $\rho_\parallel$ and drops back to $\rho_\perp$ for a further change is $\mu_0 H$, as it is depicted in Fig. 4.8 (c). The expected behaviour of $\rho_{\text{long}}$ for $\Delta \rho < 0$ with $\mathbf{H} \parallel \mathbf{J}_{\text{long}}$ and $\mathbf{H} \perp \mathbf{J}_{\text{long}}$ is shown in Fig. 4.8 (e) and in Fig. 4.8 (f), respectively.

For our measurements, the magnetic field magnitude $\mu_0 H$ is varied from 70 mT to $-70$ mT and back to 70 mT while the angle $\alpha$ is kept constant. After each step, in
which $\mu_0 H$ is changed, the resistance $R(\mu_0 H)$ is determined. Several field sweeps are performed to obtain a mean value $\overline{R}(\mu_0 H)$ for each value of $\mu_0 H$. To allow for a comparison between samples with different resistances, it is convenient to determine the relative change

$$\frac{\overline{R}(\mu_0 H) - R_{\text{aver.}}}{R_{\text{aver.}}} = \frac{\Delta R(\mu_0 H)}{R_{\text{aver.}}},$$

wherein $R_{\text{aver.}}$ is the average of $\overline{R}(\mu_0 H)$ over the full cycle of $\mu_0 H$ from $70 \text{ mT}$ to $-70 \text{ mT}$ and back to $70 \text{ mT}$.

The measurement for sample 4 under the illumination of the 405 nm laser diode and with $J_{\text{long}} \perp H$ is shown in Fig. 4.9. The behaviour of $\Delta R(\mu_0 H)/R_{\text{aver.}}$ is composed of peaks of increased resistance and an additional contribution, which
4.4 Magneto-Photo-Conductivity Measurements

Figure 4.9: Measurement of $\Delta R(\mu_0 H)/R_{\text{aver.}}$ with $J_{\text{long}} \perp H$ for sample 4 under the illumination of the 405 nm laser diode. The shape of $\Delta R(\mu_0 H)/R_{\text{aver.}}$ is composed of resistance peaks and an additional contribution, which seems to exhibit some kind of oscillating behaviour in dependence of $\mu_0 H$. The resistance peaks are located at the field amplitudes corresponding to the coercive field and are in agreement with the signature of the AMR. The additional contribution is most probably due to thermal effects caused by the current flowing through the coils.

seems to exhibit some kind of oscillating behaviour in dependence of $\mu_0 H$. The resistance peaks are located at $\mu_0 H = 4.3 \text{ mT}$ and $\mu_0 H = -5.2 \text{ mT}$. With an offset of $\mu_0 H_{\text{offset}} = -0.5 \text{ mT}$, which may be introduced by the setup, these values fit to a coercive field of $\mu_0 H_C = 4.8 \text{ mT}$. The typical value for our YIG thin films grown in the WMI is $\mu_0 H_C \leq 15 \text{ mT}$ [17], which is in agreement with the value observed for sample 4. The difference between the maximum of the resistance peak and the interpolated curve of the additional contribution is determined to $3.5 \times 10^{-4}$ for the down sweep and $3.8 \times 10^{-4}$ for the up sweep, which is of the same order of magnitude...
as the amplitude of the field dependent measurement of $\Delta R(\alpha)/R_{\text{aver.}} = 6 \times 10^{-4}$.

The behaviour of $\Delta R(\mu_0 H)/R_{\text{aver.}}$ with the resistance peaks at the coercive field is in agreement with the expected behaviour of $\rho_{\text{long}}$ with $\Delta \rho > 0$ and $\mathbf{H} \perp \mathbf{J}_{\text{long}}$, which is depicted in Fig. 4.8 (c). It is reminded here that in Sec. 4.4.1, $\Delta \rho > 0$ was obtained for sample 4.

The additional contribution to $\Delta R(\mu_0 H)/R_{\text{aver.}}$ in Fig. 4.9 seems to be inverted for the field sweep into the other direction whereas the position of the maximum respectively the minimum does not coincide with the position of the minimum respectively the maximum. The measurements of $\Delta R(\mu_0 H)/R_{\text{aver.}}$ in dependence of $\mu_0 H$ for the other samples show the same behaviour as sample 4, whereas the resistance peaks at $-\mu_0 H_C$ and $+\mu_0 H_C$ could not be observed.

In Fig. 4.10, the resistance $R$ of sample 4, the magnetic field amplitude $\mu_0 H$ and the temperatures $T_{\text{vertical}}$ and $T_{\text{horizontal}}$, measured by the vertical and horizontal Hall probe, respectively, of the measurement of sample 4 are plotted over time. The temperatures $T_{\text{vertical}}$ and $T_{\text{horizontal}}$ show a distinct oscillation with a period which equals the time for on magnet up(down)-sweep. Clearly, the heat dissipated by the current through the coils is transported to and detected by the Hall probes. The temperature peak positions do not coincide with the maxima of the field amplitude $\mu_0 H$ respectively the current. This indicates, that the thermal conduction is not instantaneous, leading to a delay and de-phasing with respect to the applied magnetic field, respectively to the current. On the other hand, a clear correlation of the temperature and the resistance is observed. The temperature changes due to the current influence the measurement and cause the additional contribution to $\Delta R(\mu_0 H)/R_{\text{aver.}}$ observed in Fig. 4.9. The values of $R(\mu_0 H)$ between a grey line and a blue line are used to determine $\overline{R}(\mu_0 H)$ for the down sweep (black line) Fig. 4.9, the values $R(\mu_0 H)$ between a blue line and a grey are used to determine $\overline{R}(\mu_0 H)$ for the up sweep (red line) in Fig. 4.9. The phase shift of the temperature in respect with the sweeps of the magnetic field leads to the seeming inversion of the additional contribution of $\Delta R(\mu_0 H)/R_{\text{aver.}}$ in Fig. 4.9.

In view of these observations, the measurements in Sec. 4.4.1 have to be reviewed. The observed behaviour of $\Delta R(\alpha)/R_{\text{average}}$ with the $\sin(\alpha)$ contribution could be explained by the the temperature change caused by the current. The current driven
4.4 Magneto-Photo- Conductivity Measurements

Figure 4.10: Fieldsweep measurement of sample 4 under the illumination of the 405 nm plotted over the time. Additional to the resistance (blue line), the field amplitude (black line) and the temperature measured by the vertical (green line) and the horizontal (red line) hall probe are plotted. The measured resistance exhibits narrow peaks when the field amplitude is close to zero. They correspond to the symmetric tips observed in Fig. 4.9 and indicate the anisotropic magneto resistance. The anti-symmetric part of the resistance is correlated with the measured temperatures indicating thermal effects influencing the resistance. The peaks of the temperatures are not in phase with the extrema of the field amplitude, thus neglecting an influence of fields induced by the current flowing through the coils.

through the horizontal coil pair is $I_{\text{horizontal}} \propto \cos(\alpha)$, the current driven through the vertical coil pair is $I_{\text{vertical}} \propto \sin(\alpha)$.

If we assume, that the influence on $\Delta R(\alpha)/R_{\text{average}}$ due to $I_{\text{horizontal}}$ and due to $I_{\text{vertical}}$ are superimposed and if we neglect the contribution due to the AMR, we can write

$$\Delta R(\alpha)/R_{\text{average}} \propto A \cos(\alpha) + B \sin(\alpha),$$

(4.10)
4 Magnetic Field Dependent Measurements

wherein $A$ and $B$ are parameters taking into account a different influence of $I_{\text{horizontal}}$ and $I_{\text{vertical}}$ on $\Delta R(\alpha)/R_{\text{average}}$. By introducing

$$k = \sqrt{A^2 + B^2}$$  \hspace{1cm} (4.11)

with

$$\sin(\gamma) = \frac{A}{k}$$  \hspace{1cm} (4.12)

and

$$\cos(\gamma) = \frac{B}{k},$$  \hspace{1cm} (4.13)

we can write

$$A \cos(\alpha) + B \sin(\alpha) = k \sin(\gamma) \cos(\alpha) + k \cos(\gamma) \sin(\alpha).$$  \hspace{1cm} (4.14)

By using the trigonometric identities

$$\sin(x) \cos(y) = \frac{1}{2} (\sin(x - y) + \sin(x + y)),$$  \hspace{1cm} (4.15)

and

$$\sin(-x) = -\sin(x),$$  \hspace{1cm} (4.16)

we can write

$$A \cos(\alpha) + B \sin(\alpha) = k \sin(\gamma) \cos(\alpha) + k \cos(\gamma) \sin(\alpha) = k \sin(\alpha + \gamma).$$  \hspace{1cm} (4.17)

Inserting Eq. 4.17 in Eq. 4.10 yields

$$\Delta R(\alpha)/R_{\text{average}} \propto k \sin(\alpha + \gamma).$$  \hspace{1cm} (4.18)

Now, the origin of the additional contribution similar to the $\sin(\alpha)$ in the measurements in dependence of the magnetic field orientation in Sec. 4.4.1 can be explained by the influence of thermal effects caused by the current driven through the coils. The values for $A$ and $B$ depend on the sample position between the pole shoes and as a result, the value of the additional phase $\gamma$ depends on the sample position as well. This explains the lack of reproducibility of the measurements in Sec. 4.4.1 when the sample position is changed between two measurements.
Sample 4 possibly is less affected due to specific film properties which support the presence of the AMR causing the \( \sin(2\alpha) \) dependence. Otherwise, the increased resistivity of the samples 1, 2, 3, and 5 compared to sample 4 makes them more sensitive to external influences such as temperature changes which could explain, why in these samples the possible presence of the AMR is obscured by the \( \sin(\alpha + \gamma) \) contribution.

Since this influence is affecting every single field rotation and field sweep in the same way, it is not possible to remove the \( \sin(\alpha + \gamma) \) contribution to \( \Delta R(\alpha)/R_{\text{average}} \) by averaging.

**Conclusion**

The observation of the \( \sin(2\alpha) \) dependence in the measurements in dependence of \( \alpha \) and the observation of the resistance peaks in the measurements in dependence of \( \mu_0 H \) confirm the presence of the AMR in sample 4. Unfortunately, the presence of the AMR can neither be confirmed nor denied for the other samples. The influence of the thermal effects caused by the current driven through the coils obscures the possible presence of the signature of the AMR.

One approach for the investigation of the other samples is the temperature decoupling by means of a cryostat providing constant external parameters. Thereby, the \( \sin(\alpha + \gamma) \) contribution to \( \Delta R(\alpha)/R_{\text{average}} \) would be removed and the possible presence of the AMR could be observed. Unfortunately, this was not possible because a corresponding dip stick providing the illumination of the samples was not available. Therefore, another approach using the lock-in measurement technique is made in the next chapter.
5 Magneto-Photo-Conductivity Measurements Using Lock-In Detection

As mentioned in the previous section, temperature fluctuations and noise affect the magnetic field-dependent photo-conductivity measurements. In order to unambiguously determine whether or not an AMR-type effect is present in the magneto-photo-conductivity of the YIG thin films, it is necessary to remove noise and signal components induced by the setup. To minimize the contribution of spurious signals, a measurement technique, developed by Michal Schreier and the author, using two lock-in amplifiers simultaneously is applied.

One lock-in amplifier measures the magnetic field dependent photo-conductivity of the samples. The necessary modulation of the photo-conductivity signal is provided by a rotating (oscillating) magnetic field. The second lock-in amplifier is used to measure the magnetic field. Additional to the amplitude of the measured quantity, the lock-in technique provides a phase information. The obtained phase information will be used to determine the angle $\varphi_0$ at which the resistance $R$ of the investigated sample has a maximum. This information will be required to determine the sign of the AMR in the investigated sample.

In combination with the measured amplitude, the sample can be characterized in terms of magneto resistive effects with the advantages of an increased signal to noise ration and a reduced measurement time.

Although the lock-in technique is established in the literature, we start with a small excursion on its principles to make the applied technique comprehensible. Subsequently, the setup used for the experiments and the derivation of the angle $\varphi_0$ are described. Measurements of the photo-conductivity samples 1 to 5 are presented.
and discussed. The validity of the lock-in scheme is cross-checked with a reference measurement of sample A, which had been investigated before in Ref. [17] by measurements in dependence of the magnetic field orientation.

### 5.1 Phase Sensitive Detection

By applying the lock-in technique, the investigated system is excited periodically and the response of the system is detected in form of a voltage signal $U_{\text{response}}(t)$ by the lock-in amplifier. Due to the periodic excitation, the response is considered to be identically periodic as well. Usually, an external source like a frequency generator generates a voltage signal $U_{\text{excitation}}(t)$, which applies the excitation on the experiment depending on the nature of the experiment. The external source also provides a reference signal $U_{\text{ref}}(t)$. The reference signal and the response signal are depicted in Fig. 5.1. By means of a phase-locked loop (PPL), the internal reference oscillator of the lock-in is locked to the reference signal $U_{\text{ref}}(t)$ and an internal reference sine function $U_{\text{ref,int}}(t) \propto \sin (\omega_{\text{ref}} t + \theta_{\text{ref}})$ is generated with an adjustable phase $\theta_{\text{ref}}$. Due to the active tracking of the PPL, a change in the reference frequency is simultaneously transferred to the lock-in reference frequency. The signal of interest which arises from the experiment is the response signal $U_{\text{response}}(t)$, which typically exhibits a phase $\theta_{\text{res}}$ relative to the reference signal caused by sample, setup and experiment specific factors. In the most basic case, the response signal is $U_{\text{response}}(t) \propto \sin (\omega t + \theta_{\text{res}})$, which is depicted in Fig. 5.1.

The lock-in detects and amplifies the response signal $U_{\text{response}}(t)$ and multiplies it with its internal reference signal $U_{\text{ref,int}}(t)$. This step is commonly known as phase sensitive detection (PSD) [85] and its output is $U_{\text{PSD}}$, as given by

$$
U_{\text{PSD}} = V_{\text{response}} \cdot V_{\text{ref}} \sin (\omega t + \theta_{\text{res}}) \sin (\omega_{\text{ref}} t + \theta_{\text{ref}}),
$$

$$
= \frac{V_{\text{response}} \cdot V_{\text{ref}}}{2} \cos ([\omega - \omega_{\text{ref}}] t + [\theta_{\text{res}} - \theta_{\text{ref}}])_{\approx 0}
$$

$$
+ \frac{V_{\text{response}} \cdot V_{\text{ref}}}{2} \cos ([\omega + \omega_{\text{ref}}] t + [\theta_{\text{res}} + \theta_{\text{ref}}])_{\text{lowpass}}
$$

$$
= \frac{V_{\text{response}} \cdot V_{\text{ref}}}{2} \cos (\theta_{\text{res}} - \theta_{\text{ref}}),
$$

(5.2)
5.1 Phase Sensitive Detection

Figure 5.1: a.) Simplified block diagram of the lock-in technique. b.) Illustration of the reference generated by the function generator (upper most line), of the reference signal generated by the lock-in amplifier (middle line) and the resulting signal due to the response of the experiment to the periodic excitation. The phase $\theta_{\text{ref}}$ of the reference signal can be freely adjusted and the phase $\theta_{\text{res}}$ is returned by the lock-in amplifier.

wherein $V_{\text{response}}$ and $V_{\text{ref}}$ denote the amplitudes of $U_{\text{response}}(t)$ and $U_{\text{ref,int}}(t)$, respectively. The PSD is followed by a low-pass filter which removes all signal components with frequencies different from the reference frequency. Since the PPL ensures that the reference frequency $\omega_{\text{ref}}$ equals the excitation frequency $\omega$, only the response to the excitation is near DC and not removed. The reference phase $\theta_{\text{ref}}$ can be adjusted so that $\phi = \theta_{\text{res}} - \theta_{\text{ref}} = 0$ and a signal $U_{\text{PSD}} = V_{\text{response}}V_{\text{ref}}/2$ is obtained, which is proportional to the amplitude of the response signal.

To obtain the phase difference $\phi$, a second multiplication of the response with the reference is performed. This time, a phase of 90° is added to the reference phase which results in a signal proportional to $\sin(\phi)$. The PSD signals can thus be interpreted as the components of a vector relative to the reference oscillator. After the amplitude of the internal reference sine function is taken into account, the lock-in amplifier returns the measured response signal according to

\[ X = V_{\text{response}} \cos(\phi), \quad (5.3) \]
\[ Y = V_{\text{response}} \sin(\phi), \quad (5.4) \]
\[ R = \sqrt{X^2 + Y^2}, \quad (5.5) \]
\[ \phi = \arctan \frac{Y}{X}, \quad (5.6) \]
wherein the output of cartesian coordinates $X$ and $Y$, respectively of polar coordinates $R$ and $\phi$ is possible. Thereby, it is possible to determine the amplitude of the response as well as the phase relative to the reference signal. Using the lock-in technique enables accurate measurements because the PSD and low pass filter only detect signals whose frequencies are very close to the lock-in reference frequency, and thus noise with $|\omega_{\text{noise}} - \omega_{\text{ref}}|$ smaller than a bandwidth, which depends on the low-pass filter setting, is removed [85].

In reality, the response of the system to the excitation can be more complex than the sine function assumed above. For further examination, it is convenient to express such an arbitrary response by a Fourier series

$$U_{\text{response}}(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} A_n \sin(n\omega t + \theta_n), \quad (5.7)$$

where $a_0$, $A_n$ and $\theta_n$ are the zeroth Fourier coefficient, the $n^{th}$ Fourier coefficient and the phase of the $n^{th}$ harmonic, respectively.

The lock-in offers the possibility to analyse all harmonics of the measured signal. Thereby, the input reference signal remains the same with the PPL still tracking the signal so that the reference phase stays identical. The internally generated sine function, however, is changed to $V_{\text{ref}} \sin(m\omega_{\text{ref}} t + \theta_{\text{ref}})$, where $m$ denotes the harmonic one wishes to investigate. The multiplication of the response in form of the Fourier series and the internal generated reference with variable $m$ now delivers terms proportional to $\cos([n\omega - m\omega_{\text{ref}}]t + [\theta_n - \theta_{\text{ref}}])$ and $\cos([n\omega + m\omega_{\text{ref}}]t + [\theta_n + \theta_{\text{ref}}])$. Again, the low pass filter removes all components except the one with $n = m$. By doing this, any $A_n$ and $\theta_n$ can be determined.

### 5.2 Lock-in Setup

The measurements in dependence of the angle between the magnetic field and the current direction in Sec. 4.4.1 and in dependence of the magnetic field magnitude in Sec. 4.4.2 for sample 4 exhibit an AMR like signature. For the other samples, the presence of an AMR-like contribution to the magneto-photo-conductivity could
neither be confirmed nor excluded due to the small signal to noise ratio of the measurements. As a first attempt to enhance the signal to noise ratio, a lock-in amplifier and a chopper wheel were inserted into the setup. By periodically modulating the light intensity with the chopper wheel at constant external magnetic field, a periodic photo-conductivity response is expected. In other words, the PSD introduced in Sec. 5.1 detects the modulated number of charger carriers (in the band model) or the increased mobility of the charge carriers (in the hopping model). In this scheme, noise with frequencies $\omega_{\text{noise}} \neq \omega_{\text{chopperwheel}}$ is strongly suppressed. As the rotation of the external magnetic field takes place on very long timescales (minutes), however, thermal drift obscuring the magnetic field dependence of the photo-conductivity is not removed.

A more elegant and effective way to improve the signal to noise ratio is to use a rotating magnetic field as excitation. Due to the AMR, the longitudinal resistivity $\rho_{\text{long}}$ parallel to the current density depends on the angle $\varphi$ between the orientation of the magnetic field $\mathbf{H}$ and the current density $\mathbf{j}$. In Sec. 4.2 it is showed, that the measured resistance $R$ corresponds to $\rho_{\text{long}}$ and in Sec. 4.4.1, it is confirmed for sample 4, that $R$ also exhibits a dependence on $\varphi$ according to

$$R = R_{\text{average}} + \frac{\Delta R}{2} \sin(2\varphi + 90^\circ). \quad (5.8)$$

The dependence of $R$ on $\sin(2\varphi + 90^\circ)$ is used to obtain the necessary modulation to apply the lock-in technique. The periodic rotation of the external magnetic field with frequency $\omega$ leads to $\varphi = \omega t$ and as a result, the resistance $R$ is modulated as $\frac{\Delta R}{2} \sin(2\omega t)$ due to the AMR. As the PSD is only sensitive to the modulated part of $R$, the lock-in directly detects the change $\frac{\Delta R}{2}$ in the resistance. As the field can be rotated at periods $(2\pi/\omega)$ much smaller than the timescale on which thermal drift significantly influences the measurement, a large gain in the signal to noise ratio is achieved.

For this purpose, the setup in Sec. 4.1 is modified by incorporating two *Stanford Research 830* Lock-in amplifiers. One lock-in amplifier is used to measure the signal corresponding to the resistance $R$ of the sample and the other is used to measure the rotating (oscillating) magnetic field. The phases obtained thereby can be used to determine the angle $\varphi_0$ at which the resistance $R$ of the sample has a maximum.
Figure 5.2: Block diagram of the setup for the magneto-photoconductivity measurements using the lock-in technique. The signals generated by the function generator regulate the power supplies for the coil pairs. A \( \sin(\omega t) \) signal is input to the horizontal and a \( -\cos(\omega t) \) into the vertical power supply, and as a result, a rotating magnetic field is obtained. The resistance of the sample changes due to the anisotropic magneto resistance (AMR). The voltage signal corresponding to the resistance change is pre-amplified by a transimpedance amplifier and finally input into the first lock-in amplifier (lock-in signal). The first lock-in amplifier returns the amplitude of the resistance change and the phase of the resistance change relative to the reference provided by the function generator. The magnetic field components are detected by Hall probes which generate a voltage proportional to the field strength at any given time \( t \). The voltage signals corresponding to the field components are input into the second lock-in amplifier (lock-in field) measuring the magnetic field. The second lock-in returns the amplitude and the phase of the oscillating magnetic field relative to the reference.

This information is necessary to determine whether \( \Delta \rho > 0 \) or \( \Delta \rho < 0 \) is valid for the investigated sample, since the first lock-in only measures the absolute value of \( \frac{\Delta R}{2} \). If \( \varphi_0 \) qualitatively coincides with the angle at which \( \mathbf{H} \parallel \mathbf{j} \), then it can be concluded that \( \Delta \rho > 0 \). In the case that \( \varphi_0 \) qualitatively coincides with the angle at which \( \mathbf{H} \perp \mathbf{j} \), \( \Delta \rho < 0 \) is found to be valid. A block diagram of the setup used for the lock-in measurements is depicted in fig. 5.2.

Apart from the two additional lock-in amplifiers, the detection electronics remain the same as in the setup for the measurements in dependence of the magnetic field orientation and the magnetic field amplitude in Sec. 4.1. Under a voltage bias \( U_{\text{src}} \), a current \( I \) flows through the sample which is pre-amplified by the FEMTO DDPCA-300 transimpedance amplifier. The relation between the current \( I \), the applied
source voltage $U_{\text{src}}$ and the measured voltage $U$ is

$$ U = \frac{U_{\text{src}} G}{R}, \quad (5.9) $$

wherein $G$ is the gain of the transimpedance amplifier. The voltage signal $U$ is detected by the first lock-in amplifier and simultaneously by a Fluke 2182 Nanovoltmeter. The former detects the magnetic field induced change $U_{\text{AMR}}$ of $U$ due to the AMR, while the latter detects the (time) average $< U >$. To determine the relation between $U_{\text{AMR}}$ and $\Delta R$, we first have to insert Eq. 5.8 in Eq. 5.9, leading to

$$ U = \frac{U_{\text{src}} G}{R} = \frac{U_{\text{src}} G}{R_{\text{average}} + \frac{\Delta R}{2} \sin(2\varphi + 90^\circ)}. \quad (5.10) $$

In Sec. 4.4.1 we obtain $R_{\text{average}} \gg \Delta R$, prohibiting the denominator to become zero and allowing us to assume $U$ to be of the form of

$$ U = < U > + U_{\text{AMR}} \sin(2\varphi + 90^\circ). \quad (5.11) $$

The dependencies of $R$ and $U$ on $\varphi$ according to Eq. 5.8 and according to Eq. 5.11 are depicted in Fig. 5.4 (a) and (b), respectively. Now we set the right hand sides of Eq. 5.10 and Eq. 5.11 equal, leading to

$$ U_{\text{src}} G = (< U > + U_{\text{AMR}} \sin(2\varphi + 90^\circ)) \left( R_{\text{average}} + \frac{\Delta R}{2} \sin(2\varphi + 90^\circ) \right). \quad (5.12) $$

Expanding the terms on the right hand side of Eq. 5.12 leads to

$$ U_{\text{src}} G = < U > R_{\text{average}} + \left( \frac{< U > \Delta R}{2} + U_{\text{AMR}} R_{\text{average}} \right) \sin(2\varphi + 90^\circ) + \frac{U_{\text{AMR}} \Delta R}{2} \sin^2(2\varphi + 90^\circ). \quad (5.13) $$

The left hand side of Eq. 5.13 is constant and does not depend on $\varphi$. The $\sin(2\varphi+90^\circ)$ and the $\sin^2(2\varphi+90^\circ)$ are orthogonal and consequently, we can perform a comparison of the coefficients for Eq. 5.13, which leads to

$$ < U > R_{\text{average}} = U_{\text{src}} G, \quad (5.14) $$
Figure 5.3: a) The modulation of the sample resistance $R(\varphi(t))$ due to the anisotropic magneto resistance plotted over $\varphi(t)$, which is the angle between the rotating magnetic field and the current direction. $R(\varphi(t))$ exhibits maxima when the magnetic field is parallel or anti-parallel to the current direction. b) The measured voltage $U(\varphi(t))$ signal corresponding to the sample resistance plotted over $\varphi(t)$. The inversion of the voltage signal $U(\varphi(t))$ due to the use of a transimpedance amplifier is taken into account by phase shifting the signal by $\pm 180^\circ$. c) The reference provided by the function generator. d) Scheme of the voltage signal in the second harmonic processed by the lock-in amplifier. The phase $\theta_{PC}$ returned by the lock-in amplifier denotes the zero crossing of the signal.

\[
\frac{<U>\Delta R}{2} + U_{AMR}R_{average} = 0 \quad (5.15)
\]

and

\[
\frac{U_{AMR}\Delta R}{2} = 0 \quad (5.16)
\]
5.2 Lock-in Setup

Solving Eq. 5.15 for $U_{AMR}$ gives

$$U_{AMR} = -\frac{<U> \Delta R}{2 R_{average}}.$$  \hspace{1cm} (5.17)

Inserting Eq. 5.17 into Eq. 5.16 yields

$$\frac{U_{AMR} \Delta R}{2} = -\frac{<U> (\Delta R)^2}{4 R_{average}} \sim 0.$$  \hspace{1cm} (5.18)

Equation 5.18 confirms the assumption made in Eq. 5.11, because $R_{average} >> \Delta R$ allows us to neglect terms of the order $O(\Delta R^2)$ and as a result, the term $\frac{U_{AMR} \Delta R}{2} \sin^2(2 \varphi + 90^\circ)$ in Eq. 5.13 is neglected.

We now consider the time dependence of $\varphi = \omega t$ due to the rotating magnetic field. As a result, $U$ is modulated at $2 \omega t$ and the first lock-in’s PSD will detect a signal directly proportional to $U_{AMR}$ as the second harmonic in $U$. More precisely, the first lock-in returns an amplitude $R_{PC}$ and a phase $\theta_{PC}$ according to

$$U_{2nd}(t) = R_{PC} \sin(2 \omega t + \theta_{PC}),$$  \hspace{1cm} (5.19)

wherein the voltage $U_{2nd}(t)$ corresponds to the second harmonic of $U$. The exact dependence of $U_{AMR}$ on $R_{PC}$ will be determined later in Sec. 5.2.2 when the influence of the transimpedance amplifier on the lock-in measurements is discussed. The magnetic field rotates according to a signal output by a frequency generator, which also provides the reference signal $U_{ref}$ required for the PSD. The experimental means to apply the rotating magnetic field are described in detail later. $U_{ref}$ and $U_{2nd}(t)$ are depicted in Fig. 5.3 (c) and (d), respectively.

The conclusion of the above made considerations is, that we measure $U_{AMR}$ using the first lock-in amplifier and determine $\Delta R/R_{average}$ according to

$$\frac{2U_{AMR}}{<U>} = \frac{\Delta R}{R_{average}} = \frac{\Delta \rho}{\rho}.$$  \hspace{1cm} (5.20)

Since the measured value for $U_{AMR}$ is an absolute value, the minus sign present in Eq. 5.17 is removed in Eq. 5.20 and we additionally have to determine $\varphi_0$ to obtain information on the sign of $\Delta R$. For the determination of $\varphi_0$, we use the phase $\theta_{PC}$, obtained by the first lock-in measuring $U$, and the phase $\theta_{field}$, which is the phase
detected by the second lock-in measuring the rotating magnetic field. The final result for $\varphi_0$ is

$$\varphi_0 = -|\theta_{\text{field}}| + 135^\circ - \frac{\theta_{\text{PC}} + 45^\circ}{2}. \quad (5.21)$$

In the following subsections, the derivation of Eq. 5.21 is described in detail.

### 5.2.1 Rotating Magnetic Field

The *Kepco BOP 20-20M* power supply of each coil pair is now regulated according to a signal which is outputted by an *Agilent 81160A* frequency generator. The signal for the horizontal coil pair is proportional to $\sin \omega t$, whereas the signal for the vertical coil pair is phase-shifted by $-90^\circ$, resulting in $\sin \omega t - 90^\circ = -\cos \omega t$. Consequently, the components of the fields are

$$H_x = A_x \sin(\omega t + \theta_{\text{field}}), \quad (5.22)$$

and

$$H_y = -A_y \cos(\omega t + \theta_{\text{field}}), \quad (5.23)$$

wherein $\theta_{\text{field}}$, $A_x$ and $A_y$ are the phase shift due to the inductance of the coils and the power supply and the field amplitude of the horizontal and the vertical field component, respectively. For this configuration, at $t = 0$ the field points into the negative $y$-direction with a deviation due to $\theta_{\text{field}}$ and rotates counter-clockwise, as depicted in fig. 5.4.

The field components are detected by Hall probes which generate a voltage proportional to the field strength at any given time $t$. The voltage signal corresponding to the $x$-component of the magnetic field is input into the $A$-channel, the one corresponding to the $y$-component of the magnetic field into the $B$-channel of the second lock-in amplifier. The lock-in amplifier determines the difference of the signals $A - B$ and compares the result to its internal reference signal obtained from the sync output of the frequency generator. The measurement of $A - B$ is chosen to obtain a signal which contains both magnetic field components so that a possible de-phasing over time between the $x$-component and $y$-component of the magnetic field is detected.
5.2 Lock-in Setup

![Diagram](image)

**Figure 5.4:** Illustration of the rotating magnetic field $\mathbf{H}$ including a scheme of the sample and the direction of the current $J_{\text{long}}$ flowing through the sample. The rotating magnetic field $\mathbf{H}$ is phase shifted by $\theta_{\text{field}}$ relative to the reference, which is along the negative $y$-axis. The angle between the current direction $J_{\text{long}}$ and the rotating magnetic field $\mathbf{H}$ is denoted as $\varphi(t)$. The angle $\varphi_0$ denotes the angle between the reference and the current direction and is independent of the rotation frequency $\omega$.

With the phase detected by the lock-in amplifier, the required $\theta_{\text{field}}$ can be determined. The necessary calculation to obtain $\theta_{\text{field}}$ is done in the appendix A.

As depicted in Fig. 5.4, $\theta_{\text{field}}$ is the angle between the negative $y$-axis and the magnetic field at $t = nT$, where $n$ is an integer and $T = 2\pi/\omega$. This becomes clear when $\theta_{\text{field}} = 0^\circ$ is assumed. In this case, the horizontal field and the reference signal are in phase and $H_x(t = nT) = 0$ and $H_y(t = nT) = -A_y$, so that the field is pointing into the negative $y$-direction. For $\theta_{\text{field}} \neq 0^\circ$, $H_x(t = nT) = A_x \sin(\theta_{\text{field}})$ and $H_y(t = nT) = A_y \sin(\theta_{\text{field}} - 90^\circ)$. Therefore, the negative $y$-axis corresponds to the reference signal, which is used to define the obtained angles. Thereby positive and negative angles are defined by the red and blue shading in Fig. 5.4. It is intuitive that $\theta_{\text{field}} \leq 0$, which is confirmed by the values obtained in the measurement.
5.2.2 Transimpedance Amplifier

We now turn to the contribution of $\theta_{PC}$ to $\varphi_0$. First, we assume $\Delta \rho > 0$. In this case, the resistance $R$ has a maximum at $\mathbf{H} \parallel \mathbf{J}_{\text{long}}$, and consequently $\varphi_0$ denotes the angle at which $\mathbf{H} \parallel \mathbf{J}_{\text{long}}$, as it is illustrated in Fig. 5.4. As a result, it is possible to write

$$\varphi(t) = \omega t - |\theta_{\text{field}}| - \varphi_0. \quad (5.24)$$

By substituting $\varphi(t)$ in Eq. 5.11, the exact time dependence of $U$ is determined to

$$U = <U> + U_{\text{AMR}} \sin(2\omega t - 2|\theta_{\text{field}}| - 2\varphi_0 + 90^\circ). \quad (5.25)$$

Now it is important to take the influence of the transeimpedance amplifier into account. As it is denoted in Eq. 5.9, the measured voltage $U$ is inversely proportional to the sample resistance $R$, which yields the minus sign in Eq. 5.17. For the determination of $\varphi_0$, it will be of advantage to take the absolute value $|U_{\text{AMR}}|$ as the pre factor of the sine function. To take the transeimpedance amplifier into account, we therefore add $180^\circ$ to the phase of the sine function in Eq. 5.25. As a result, the time dependence of $U$ is written as

$$U = <U> + |U_{\text{AMR}}| \sin(2\omega t - 2|\theta_{\text{field}}| - 2\varphi_0 + 270^\circ). \quad (5.26)$$

As $U$ is modulated at $2\omega t$, the first lock-in’s PSD will detect a signal directly proportional to $U_{\text{AMR}}$ as the second harmonic in $U$. More precisely, the lock-in returns an amplitude $R_{PC}$ and a phase $\theta_{PC}$ according to

$$U_{2nd}(t) = R_{PC} \sin(2\omega t + \theta_{PC}), \quad (5.27)$$

wherein $U_{2nd}$ is the second harmonic of $U$. We identified $R_{PC}$ with $U_{\text{AMR}}$, but it has to be reminded here that the lock-in introduces an additional factor according to $U_{\text{AMR}} = \sqrt{2} R_{PC}$. It seems straightforward to set the phases of $U$ and $U_{2nd}(t)$ equal to obtain $\varphi_0$. But it is important to remember, that the phase $\theta_{PC}$ denotes the zero crossing of $U_{2nd}(t)$, whereas the zero crossing of $U$ is located at $\varphi(t) = 45^\circ$, as depicted in Fig. 5.3. Since $\varphi_0$ is defined as the angle at which the resistance $R$ of the sample has a maximum, the phase which corresponds to $\varphi(t) = 0^\circ$ has to be determined. Therefore, the additional term of $-45^\circ$ is added to the phase of $U_{2nd}(t)$. 

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Then the arguments of $U$ and $U_{2\text{nd}}(t)$ are set equal, leading to

$$\theta_{PC} = -2|\theta_\text{field}| - 2\varphi_0 - 45^\circ + 270^\circ,$$  \hspace{1cm} (5.28)

which finally yields

$$\varphi_0 = -|\theta_\text{field}| + 135^\circ - \frac{\theta_{PC} + 45^\circ}{2}.$$  \hspace{1cm} (5.29)

At the beginning, we assumed that $\Delta \rho > 0$, so that $\varphi_0$ denotes the angle at which $\mathbf{H} \parallel \mathbf{J}_\text{long}$. If we consider $\Delta \rho < 0$, $\varphi_0$ still denotes the angle where the resistance $R$ has a maximum, but this time the maximum of $R$ is located at the angle where $\mathbf{H} \perp \mathbf{J}_\text{long}$. Therefore, for $\Delta \rho < 0$ the obtained $\varphi_0$ should coincide with the angle where $\mathbf{H} \perp \mathbf{J}_\text{long}$.

The FEMTO DDPCA-300 transimpedance amplifier not only amplifies the magnitude of the signal, but also influences the phase $\theta_{PC}$. This phase of course has to be taken into account for the determination of $\varphi_0$. To determine the influence of the pre-amplification on the measurement of $\theta_{PC}$ and $U_{AMR}$, a resistor is connected between the output channel 1 of the frequency generator and the transimpedance amplifier. The amplified signal is then input into the A channel of the lock-in. Two different resistors with a resistance $R_{\text{cal}}$ of 12.4 M$\Omega$ and 10 G$\Omega$ are available. The appropriate resistor is chosen according to the gain of the transimpedance amplifier so that the amplified signal does not exceed the allowed maximum input voltage of 1 V of the lock-in amplifier. The settings for the frequency generator and the lock-in amplifier remain the same as for the lock-in measurements in Sec. 5.3. The amplitude and phase are recorded while the frequency of the output signal is varied. Since the signal generated by the frequency generator is a pure sin($\omega t$) signal, it is not possible to determine the amplitude and the phase in the second harmonic. Therefore, the determination is done in the first harmonic and the obtained values are used to calibrate the values which correspond to the frequency $\omega/2$.

Moreover, a calibration for the amplitude is provided. $U_{AMR}$ is determined according to

$$U_{AMR} = R_{PC} \cdot \frac{V_{\text{sig}} \cdot G}{V_{\text{cal}} \cdot R_{\text{cal}}},$$  \hspace{1cm} (5.30)

where $V_{\text{cal}}$ is the amplitude measured in the calibration, $V_{\text{sig}}$ is the amplitude of the output signal of the frequency generator and $G$ is the gain of the transimpedance amplifier.
amplifier. The $\sqrt{2}$ factor introduced by the lock-in amplifier [85] and deviations of the amplifier gain are taken into account by Eq. 5.30.

5.3 Lock-in Measurements

After the deduction of $\varphi_0$ and $\Delta R$, it is possible to characterize the samples 1 to 5 with respect to the presence of a magneto resistive effect. For all measurements, the frequency $f = \omega/2\pi$ of the signal which is generated by the frequency generator is varied between 1 Hz and 25 Hz. Each change in frequency $f$ leads to a change in $\theta_{\text{field}}$, which stabilizes after a few seconds. Once a new frequency is adjusted, $\theta_{\text{field}}$ is determined by the second lock-in after a certain period of time when the value is stable due to the small signal to noise ration. On the contrary, the value of $\theta_{\text{PC}}$ may fluctuate even after a time period much larger than the chosen integration time. Therefore, the values of $\theta_{\text{PC}}$ and $R_{\text{PC}}$ are averaged over a few minutes. The averaging procedure also yields the standard deviation depicted in the graphs to follow. In Fig. 5.5, the obtained values of $\theta_{\text{field}}$, $\theta_{\text{PC}}$ and $\varphi_0$ of all samples under the illumination of the 405 nm laser diode are plotted over $f$.

The obtained values for $\theta_{\text{field}}$ only differ by about $2^\circ$ for all measurements of all samples because the means for applying the rotating magnetic field remain the same for all measurements. Therefore, the $\theta_{\text{field}}$ for sample 1 is plotted in Fig. 5.5 (a) and is representative for all measurements of all samples. The influence of the inductance of the coils increases with increasing $f$ resulting in a decreasing $\theta_{\text{field}}$. According to the definition of $\theta_{\text{field}}$, which is also depicted in in Fig. 5.4, this indicates an increasing time delay of the rotating magnetic field relative to the reference signal.

In Fig. 5.5 (b), the frequency dependence of $\theta_{\text{PC}}$ of all samples under the illumination of the 405 nm laser diode is shown. A monotonic decrease similar to that of $\theta_{\text{field}}$ is observed for all samples for frequencies up to $f = 10$ Hz. For Samples 2 and 5, the values of $\theta_{\text{PC}}$ fluctuate compared to the behaviour of sample 4, which we attribute to temperature changes between the measurements with different $f$. The increased standard deviation of the obtained values for sample 1 and sample 5 compared to the ones of sample 4 indicate a small signal to noise ratio. The monotonic decrease of $\theta_{\text{PC}}$ is related to the one of $\theta_{\text{field}}$, as the latter determines the time $t$ for which $\mathbf{J}_{\text{long}} \parallel \mathbf{H}$. 
5.3 Lock-in Measurements

Figure 5.5: The measured values of $\theta_{\text{field}}$, $\theta_{\text{PC}}$ and the determined values of $\varphi_0$ for all samples under the illumination of the 405 nm laser diode plotted over frequency. a) $\theta_{\text{field}}$ is plotted for sample 1 and is representative for all samples. The means for applying the rotating magnetic field remain the same and therefore the values of $\theta_{\text{field}}$ do not change significantly from sample to sample. The decreasing behaviour of $\theta_{\text{field}}$ reflects the increasing phase shift relative to the reference due to the inductance of the coils. This behaviour is transferred to $\theta_{\text{PC}}$ (panel (b)) since the time $t$ for which $\mathbf{H} \parallel \mathbf{J}_{\text{long}}$ is determined by $\theta_{\text{field}}$. The deviation from the monotonic decrease for sample 1 and sample 5 indicate a small signal to noise ratio. $\varphi_0$ (panel (c)) denotes the angle relative to the reference where the maximum of the sample resistance $R$ is located and is expected to be independent of the frequency.
Figure 5.6: The average value of $\varphi_0$ over $f$ for the different samples in dependence of the wavelength of the incident light. The data points for sample 1 to 4 lie between 0° and 90°, indicating the presence of the AMR in these samples. For sample 5, strong fluctuations are observed. For sample 4, the obtained values exhibit a small error bar and are not dependent on the light source. The determined values are in good agreement with the field dependent measurements in Sec. 4.4.1. For the other samples, measurements were only performed up to the 450 nm LED because otherwise the values of $R_{PC}$ and $\theta_{PC}$ were not stable enough for a reasonable measurement. The variation of $\varphi_0$ and the relative large error bars for sample 1 and sample 5 indicate a small signal to noise ratio.

In Fig. 5.5 (c), the frequency dependence of $\varphi_0$ for all samples according to Eq. 5.21 is plotted. For sample 4, $\varphi_0$ is not dependent on the frequency. For sample 3, only small fluctuations around an average value are observe for frequencies up to $f = 20$ Hz. The dependence of sample 1, sample 2 and sample 5 exhibit fluctuations around a constant value for $\varphi_0$ which are transferred from the dependence of $\theta_{PC}$ on $f$.

Now the advantages of determining the value $\varphi_0$ in dependence of $f$ become obvious. The first is, that $\theta_{field}$ and $\theta_{PC}$ both change under a variation of $f$, whereas
5.3 Lock-in Measurements

Figure 5.7: Graphical representation of $\alpha$, which is the variable in the field dependent measurements in Sec. 4.4.1, and of $\varphi_0$. Moreover, the current direction $J_{\text{long}}$ is depicted, which is defined by the alignment of the electrode structure on the sample.

the determined value for $\varphi_0$ should not change. Consequently, the changing of $\varphi_0$ over frequency indicates, whether the signal detected by the lock-in is caused by noise or the AMR. The second advantage is, that the availability of several data points enables averaging and therefore increases the measurement accuracy for $\varphi_0$ and $\Delta R/R_{\text{average}}$.

Nearly all data points in Fig. 5.5 (c) lie between 0° and 90°, which is a clear indication for the presence of the AMR in all samples. Because in absence of the AMR, the values of $\varphi_0$ would be expected to be randomly distributed over the entire range from $-180^\circ$ to $180^\circ$.

The average values of $\varphi_0$ for all samples under the illumination of the available light sources are depicted in Fig. 5.6 (b). Again, the data points for sample 1 to 4 lie between 0° and 90°. For sample 5, strong fluctuates are observed. By optical inspection it was ensured, that all samples were aligned in a way such that the angle between the direction of $J_{\text{long}}$ and the negative $y$-axis is about $45^\circ \pm 30^\circ$, as depicted in Fig. 5.7. Since the electrode structure on each sample is aligned differently, the exact value depends on the sample.

It is reminded here that $\varphi_0$ is defined as the angle where the resistance $R$ exhibits a maximum. That means that in case of $\Delta \rho/\rho > 0$, $\varphi_0$ denotes the angle where $H \parallel J_{\text{long}}$. For $\Delta \rho/\rho < 0$, $\varphi_0$ corresponds to the angle where $H \perp J_{\text{long}}$.

For sample 4, $\Delta \rho/\rho > 0$ is determined in Sec. 4.4 so that $\varphi_0$ denotes the angle where $H \parallel J_{\text{long}}$. The obtained values for sample 4 of $\varphi_0$ lie between 67.5° for the 405 nm laser diode and 57.5° for the 590 nm LED. This agrees with the expected...
value of \( \varphi_0 = 45^\circ \pm 30^\circ \) and confirms that \( \Delta \rho/\rho > 0 \) is valid for sample 4. With this result it can be concluded that \( \Delta \rho/\rho > 0 \) is valid for the other samples as well, since the obtained values for \( \varphi_0 \) all qualitatively agree to the expected value of of \( \varphi_0 = 45^\circ \pm 30^\circ \) where \( \mathbf{H} \parallel \mathbf{J}_{\text{long}} \).

No dependence of \( \varphi_0 \) on the wavelength of the incident light is observed. To transform \( \alpha \) into \( \varphi_0 \) and vice versa \( \alpha = 270^\circ - \varphi_0 \) has to be used. For sample 4, the obtained values of \( \varphi_0 \) correspond to \( \alpha = 202.5^\circ \) for the 405 nm laser diode and 212.5° for the 590 nm LED, respectively. The value for the 405 nm laser diode is in good agreement with the value of \( \alpha = 205^\circ \) from the field rotation measurement in Fig. 4.5 in Sec. 4.4.1.

The values of \( \varphi_0 \) for sample 3 range from 68° for the 405 nm laser diode to 56° for the 405 nm LED. No measurements for the LED with wavelengths greater than 450 nm were performed because the obtained values of \( \theta_{PC} \) were not stable and prohibited an accurate measurement. For sample 1, the large fluctuations of \( \theta_{PC} \) during the measurement only allowed reasonable measurements up to the 450 nm LED. The values for \( \varphi_0 \) range from 19° for the 365 nm laser diode to 57° for the 405 nm LED. Sample 2 exhibits values for \( \varphi_0 \) in the range between 14° and 34° with relative small error bars compared to sample 1, sample 3 and sample 5. The values obtained for sample 5 are spread over a wide range and exhibit relatively large error bars. The expected value for \( \varphi_0 \) from the current direction is around 45°. The large deviation from this value indicates the absence of the AMR in sample 5.

The conclusion of the above made considerations is, that we obtain knowledge of the sign of \( \Delta \rho/\rho \) by determining \( \varphi_0 \). The resolution of the determination of \( \varphi_0 \) depends on the wavelength of the incident light, but can be estimated to exhibit deviations smaller than 30° by considering the data shown in Fig. 5.6.

In Fig. 5.8, \( \Delta R/R_{\text{average}} \) in dependence of the light source is shown. For sample 4, the obtained results clearly indicate the presence of the AMR and confirm the results of the measurements in dependence of the magnetic field orientation in Sec. 4.4.1. For the measurements of sample 4 under illumination of the 405 nm laser diode, the value of \( \Delta \rho/\rho = 1.2 \times 10^{-3} \) determined by means of the measurements in dependence of the magnetic field orientation in Sec. 4.4.1 and the value of \( \Delta \rho/\rho = 5.6 \times 10^{-4} \) determined by the lock-in measurement differ by factor 2. This factor is most probably introduced by the derivation of Eq. 5.20 in Sec. 5.2. Although the considerations in Sec. 5.2 to obtain Eq. 5.20 were reviewed several times
5.3 Lock-in Measurements

Figure 5.8: $\Delta R/R_{\text{average}}$ for all samples in dependence of the light source. For sample 4, the presence of the AMR in the photo-conductivity under illumination of every light source can be confirmed. The presence of the AMR is also confirmed for sample 2 and sample 3 under the illumination of the 405 nm laser diode, the 365 nm LED, 405 nm LED and the 450 nm LED. For sample 4, a decreases of $\Delta R/R_{\text{average}}$ with increasing wavelength of the incident light is observed, revealing that the relative amplitude of the AMR still depends on the wavelength. The increased values of $\Delta R/R_{\text{average}}$ for sample 2 and sample 3 under the illumination of the 450 nm laser diode may be attributed to a polarization dependence of the AMR in sample 2 and sample 3.

by the author, it was not possible to determine the exact origin of the additional factor 2. However, a decreases with increasing wavelength of the incident light is observed for sample 4. In $\Delta R/R_{\text{average}}$, effects due to the band gap and the intensity of the light source are already taken into account. The decrease with increasing wavelength (decreasing photon energy) indicates that the relative amplitude of the AMR still depends on the wavelength of the incident light. It is possible, that the small ratio of the charge carriers, which is influenced by the magnetization of the
sample, exhibits a different conduction mechanism than the charge carriers responsible for \( <U> \), respectively \( R_{\text{average}} \).

The other samples show different behaviour. For sample 2 and sample 3, the value of \( \Delta R/R_{\text{average}} \) for the 405 nm laser diode is increased compared to the other values, whereas the values of the 405 nm LED and 450 nm LED indicate the decrease as it is observed for sample 4. It is interesting, that for sample 2 and sample 3, the photo-conductivity measurement under the illumination of the 405 nm laser diode in Sec. 4.3 does not show an increased value compared to the other light sources.

It is possible, that the AMR in sample 2 and sample 3 is more sensitive to the polarization of the incident light. As already assumed for sample 4, it is possible for sample 2 and sample 3 that the magnetization dependent part of the resistance is carried by a different type of conduction than the part responsible for \( <U> \), respectively \( R_{\text{average}} \). The obtained values for sample 1 and sample 5 are small compared to the other samples, with \( \Delta R/R_{\text{average}} < 5 \times 10^{-5} \), and seem independent on the wavelength.

The results obtained by the lock-in measurement technique confirm the observation of the AMR in sample 4, sample 3 and sample 2. The data in Fig. 5.8 show, that a change in the photo-conductivity due to an external rotating magnetic field can be detected with a resolution of \( \Delta R/R_{\text{average}} \geq 5 \times 10^{-5} \). For sample 1 and sample 5, the detected values for \( \Delta R/R_{\text{average}} \) are too small to unambiguously distinguish them from noise. As a result, for sample 1 and sample 5 the presence of the AMR in the photo-conductivity can neither be confirmed nor denied and a further increase of the signal to noise ratio is required for further investigation.

Temperature dependent measurements could give information on the conduction mechanism in general and if the magnetization dependent resistance change shows a different behaviour. Additionally, the identification whether the conduction is \( n \)-type or \( p \)-type and if the magnetization dependent change of the photo-conductivity is carried by a different type of charge carriers could be determined by Hall measurements. Unfortunately, both were not possible in the course of this thesis. A dip stick for the low temperature measurements providing the illumination of the samples was not available and the used electrode structure prohibits Hall measurements.
5.4 Reference Measurement

To verify the values of $\Delta R/R_{\text{average}}$ obtained by the lock-in technique, it is necessary to perform a reference measurement of a sample which has been investigated before by conventional measurements in dependence of the magnetic field orientation. The reference sample for this purpose is sample A, which is a YIG/Pt thin film heterostructures, in which the Pt is patterned into a Hall bar structure. The sample is described in detail in Ch. 3. The magnetic field rotates in-plane and is applied and measured by the second lock-in amplifier in the same way as in Sec. 5.2. The effect causing the field dependent modulation of the resistance of the Pt Hall bar is the spin Hall magnetoresistance (SMR) [17–19].

For the SMR measurement, the configuration of the detection electronics is changed compared to the setup in Sec. 5.2. This time, the Keithley K2400 source meter is used to source a current $I_{\text{src}}$ across the longitudinal direction of the Hall bar. The Fluke 2182 Nanovoltmeter and the first lock-in amplifier are used to detect the voltage $U_{\text{long}}$ across the longitudinal direction. As in Sec. 5.2, the former determines the (time) average $< U_{\text{long}} >$ and the latter the field induced change $U_{\text{SMR}}$ across the longitudinal direction. The sample is considered to be ohmic and therefore

$$R_{\text{long}} = \frac{U_{\text{long}}}{I_{\text{src}}} \quad (5.31)$$

is valid, where $R_{\text{long}}$ denotes the longitudinal resistance of the Hall bar. In Fig. 5.9, the equivalent circuit of the experiment is depicted. The resistance $R_{\text{long}}$ of the Hall bar in absence of an external magnetic field is 136 $\Omega$. The current flowing through the sample is $I_{\text{src}} = 4$ mA. Therefore, $U_{\text{long}} = 545$ mV and a pre amplification is not necessary.

Due to the SMR, the resistance of the Pt Hallbar depends on the angle $\varphi$ between the current direction $j$ and the magnetic field $H$. For a rotation of the magnetic field $H$ in the plane of the YIG thin film, $R_{\text{long}}$ depends on $\varphi$ according to

$$R_{\text{long}} = R_0 + \frac{\Delta R_{\text{SMR}}}{2} \sin(2\varphi + 90^\circ), \quad (5.32)$$

wherein $\Delta R_{\text{SMR}}$ denotes the amplitude of the change of $R_{\text{long}}$ due to the SMR. By comparison of Eq. 5.32 with Eq. 5.8, it becomes obvious, that in the in-plane con-
Figure 5.9: Equivalent circuit of the setup used for spin Hall magneto resistance (SMR) measurements. The voltage $U_{\text{long}}$ corresponding to the (time) average of the sample resistance $R_{\text{long}}$ is measured by a voltmeter, the modulation $U_{\text{SMR}}$, which is proportional to the resistance change due to the SMR, is measured by a lock-in amplifier.

figuration the SMR exhibits the same signature as the AMR. Nevertheless, a direct application of the results from Sec. 5.2 on sample A is not possible because of the absence of the FEMTO DDPCA-300 transimpedance amplifier. The measured voltage signal is not inversely proportional to the resistance any more. According to Eq. 5.31 and Eq. 5.32, the dependence of $U_{\text{long}}$ on $\varphi$ is

$$U_{\text{long}} = <U_{\text{long}}> + U_{\text{SMR}} \sin(2\varphi + 90^\circ).$$

(5.33)

It is straightforward to determine

$$R_0 = \frac{<U_{\text{long}}>}{I_{\text{src}}},$$

(5.34)

and

$$\Delta R_{\text{SMR}} = \frac{2U_{\text{SMR}}}{I_{\text{src}}},$$

(5.35)

$U_{\text{long}}$ is modulated at $2\omega t$ and the PSD of the second lock-in detects a signal directly proportional to $U_{\text{SMR}}$ as the second harmonic in $U_{\text{long}}$. With the determined values of $U_{\text{SMR}}$ and $U_{\text{long}}$, the relative amplitude of the SMR can be determined according
5.4 Reference Measurement

Figure 5.10: \( \Delta R/R_{\text{average}} \) for sample A. The change in the resistance of sample A originates from the spin Hall magnetoresistance. The obtained values for \( \Delta R/R_{\text{average}} \) are in good agreement with literature [17].

To

\[
\frac{2 U_{\text{SMR}}}{U_{\text{long}}} = \frac{\Delta R_{\text{SMR}}}{R_{\text{long}}}. \tag{5.36}
\]

In Fig. 5.10, the obtained values for \( \Delta R_{\text{SMR}}/R_{\text{long}} \) for sample A are plotted over the frequency \( f \). We attribute the slight decrease of \( \Delta R_{\text{SMR}}/R_{\text{long}} \) for increasing \( f \) to the influence of the internal 25 Hz notch of the lock-in amplifier which was set active during the measurements. The average value is determined to \( \Delta R_{\text{SMR}}/R_{\text{long}} = (2.350 \pm 0.005) \times 10^{-4} \). In Ref. [17], a detailed study of the SMR in YIG/Pt heterostructures is performed and a model to quantitatively predict \( \Delta R_{\text{SMR}}/R_{\text{long}} \) in dependence of the Pt thickness is introduced. The investigated samples in Ref. [17] were fabricated in the Walther Meißner Institute by means of the same setup and fabrication process as for sample A. We therefore assume, that the obtained results in Ref. [17] are also valid for sample A. According to Ref. [17], a value of \( \Delta R_{\text{SMR}}/R_{\text{long}} = 3 \times 10^{-4} \) for sample A is expected, which is in good agreement with the obtained results using the lock-in technique.
6 Summary and outlook

In course of this thesis, the photoconductivity of Yttrium iron garnet (Y$_3$Fe$_5$O$_{12}$, YIG) in dependence of the magnetization was investigated. It is the first work related to this topic at the Walther-Meißner-Institut and revisits a research topic which was mainly examined in the 1970’s [52, 58, 59]. At that time, considerable effort was put into the identification of the conduction mechanism but the mechanism responsible for the conduction in YIG could not be identified. An influence of an external magnetic field on the photo-conductivity was not investigated or could not be observed.

The main focus of this thesis was put onto the search for a magneto resistive effect at room temperature in (111) YIG thin films grown epitaxially by UHV laser molecular beam epitaxy (laser MBE). The dependence of the photo-conductivity on a magnetic field rotating in the (111) plane of the samples is investigated. In a previous study [53], the magnetization dependent resistance of films with large impurity concentrations was investigated. To the best of the author’s knowledge, however, no magneto resistive effect in undoped YIG has been observed before. This is not surprising, because the magnitude of most intrinsic magneto resistive effects is very small, usually ($\Delta \rho / \rho \leq 0.01$), and the high resistivity of undoped YIG complicates accurate resistance measurements.

In contrast to literature, the investigated samples in this thesis are stoichiometric and exhibit a relatively high resistivity ($\rho \sim 1 \times 10^7 \, \Omega \, \text{m}$). As a result, the current flowing through the samples is very small and as a result, the possible presence of a magneto resistive effect is easily obscured by noise and thermal drift. To overcome this issue, the samples were illuminated to increase the conductivity and to facilitated the measurement of small changes of the conductivity due to an external magnetic field. Considerable effort was put in establishing a setup capable of detecting current changes of a few nA under ambient conditions.
At the beginning of the thesis, the photo-conductivity in dependence of the wavelength of the incident light was investigated (Sec. 4.3). In order to reveal the possible presence of a magneto resistive effect in the samples, measurements of the photo-conductivity in dependence of an external magnetic field which is rotated in-plane and in dependence of the wavelength of the incident light were performed (Sec. 4.4.1). Moreover, the photo-conductivity was measured while the amplitude of the external magnetic field is varied along a static axis (Sec. 4.4.2).

Furthermore, the lock-in technique is applied to increase the signal to noise ratio of the change of the photo-conductivity due to an external magnetic field rotating in the thin film plane of the investigated samples. It is obtained, that a change in the photo-resistivity can be detected for $\Delta \rho/\rho \geq 5 \times 10^{-5}$. The phase information obtained by using the lock-in technique is used to determine whether $\Delta \rho/\rho > 0$ or $\Delta \rho/\rho < 0$ is valid for the investigated samples.

The resistivity of the investigated samples is not dependent on the film thickness, indicating a high crystalline quality (sec. 4.2). The photo conductivity measurements in dependence of the wavelength of the incident light (Sec. 4.3) indicate an increased conductivity between $\hbar \omega = 2.76 \text{ eV} (\lambda = 405 \text{ nm})$ and $\hbar \omega = 3.06 \text{ eV} (\lambda = 450 \text{ nm})$. This is in agreement with the band gap $E_g = 2.85 \text{ eV}$ given in literature [45, 46] and is attributed to band like conduction in the samples at room temperature. A decrease in the conductivity under the illumination with light with $\lambda > 450 \text{ nm}$ resembles the decreasing absorption in this region [46].

In the sample with the lowest resistivity ($\rho = 8.84 \times 10^{-5} \Omega \text{ m}$), the presence of an anisotropic magneto resistance (AMR) is observed. The relative amplitude of the effect $\Delta \rho/\rho = 1.2 \times 10^{-3}$ is of the same order of magnitude as in the one paper available in literature [53]. Notably, the amplitude of the effect exhibits a dependence on the wavelength of the light source different to the one observed in the photo-conductivity measurements (Sec.5.3). It is possible, that the magnetization orientation dependent change of the photo-conductivity may be carried by a different type of conduction mechanism.

For two more samples ($\rho \sim 1 \times 10^7 \Omega \text{ m}$), the presence of the AMR is observed as well. The values of $\Delta \rho/\rho$ under illumination of a 405 nm laser diode are increased compared to the values obtained under illumination of a 405 nm LED, leading to the assumption that the polarization of the light might influence the amplitude of
the AMR (Fig. 5.8). For all samples exhibiting the AMR, $\Delta \rho / \rho > 0$ is obtained. It is observed, that thermal effects originating from the current flowing through the coils influence the measurements in dependence of the orientation of an external magnetic field and in dependence of the magnetic field amplitude.

**Outlook**

The key outcome of this thesis, the observation of an AMR like magneto resistance in undoped YIG thin films, raises several questions. First of all, the conduction mechanism in YIG is still not fully identified. Recent investigations indicate a conduction via small polarons. How the observation of the AMR can be included into this model is still open.

A first step would be to obtain information on the conduction mechanism and on the type of charge carries in the investigated samples by temperature dependent measurements of the resistivity and of the mobility. Measurements in a cryostat under controlled external parameters would minimize the above mentioned temperature effects. As a result, the presence of the AMR could be determined more precisely. Furthermore, measurements at elevated temperatures could monitor the behaviour at $T_C$, which may give valuable information on the influence of the magnetic ordering on the conduction. With the lock-in amplifier based measurement technique introduced in Ch. 5, measuring $\Delta \rho / \rho$ in dependence of the temperature is possible in reasonable time.

The spectral dependence of the photo-conductivity should be measured more accurately by using a white light source in combination with a monochromator instead of LEDs. Furthermore, thicker samples would enable the measurement of absorption spectra which would provide additional information on the creation of charge carriers due to the illumination. A systematic study of the dependence of $\Delta \rho / \rho$ on the polarization of the incident light could also prove valuable.

While the data are sparse, a dependence of the amplitude of the AMR on the film properties of the investigated samples is indicated. Investigating samples with differing properties such as doping, growth orientation, film thickness and cation or
anion vacancies could provide information to clarify the origin of the AMR in YIG. A possible influence of the electrode material on the measurements was not considered, except by using AU as electrode material to remove a possible influence of a magnetic proximity effect [82, 83]. To exclude contributions from the metal insulator interface at the electrodes, samples with different electrode material have to be investigated.

A deeper understanding of the charge transport in YIG and its dependence on the magnetization might help to interpret experiments on hybrid structures which include YIG, such as the spin Hall magneto resistance effect [17–19] or the spin Seebeck effect [37–39].
Appendix

In the following, the calculations to obtain $\theta_{\text{field}}$ are performed. The magnetic field components are

$$H_x = A_x \sin(\omega t + \theta_{\text{field}}),$$

and

$$H_y = -A_y \cos(\omega t + \theta_{\text{field}})$$

The field components are detected by Hall probes which generate a voltage proportional to the field strength at any given time $t$. The voltage signal corresponding to the $x$-component of the magnetic field is input into the $A$-channel, the one corresponding to the $y$-component of the magnetic field into the $B$-channel of the lock-in amplifier. The lock-in amplifier determines the difference of the signals $A - B$ and applies the PSD on it using the reference signal provided by the frequency generator. The lock-in returns the amplitude $R_{\text{Mag}}$ and the phase $\theta_{\text{Mag}}$. How exactly $\theta_{\text{field}}$ can be determined from $\theta_{\text{Mag}}$ is deduced here. First, the output channel $X_{\text{Mag}}$ of the PSD is determined.

$$X_{\text{Mag}} = [A - B] \ V_{\text{ref}} \ \sin(\omega_{\text{ref}} t + \theta_{\text{ref}})$$

$$= [A_x \sin(\omega t + \theta_{\text{field}}) - A_y \sin(\omega t + \theta_{\text{field}} - 90^\circ)] \ V_{\text{ref}} \ \sin(\omega_{\text{ref}} t + \theta_{\text{ref}})$$

$$= A_x V_{\text{ref}} \ \sin(\omega t + \theta_{\text{field}}) \sin(\omega_{\text{ref}} t + \theta_{\text{ref}})$$

$$- A_y V_{\text{ref}} \ \sin(\omega t + \theta_{\text{field}} - 90^\circ) \sin(\omega_{\text{ref}} t + \theta_{\text{ref}})$$

$$= \frac{A_x V_{\text{ref}}}{2} \ \cos([\omega - \omega_{\text{ref}}] t + [\theta_{\text{field}} - \theta_{\text{ref}}])$$

$$- \frac{A_y V_{\text{ref}}}{2} \ \cos([\omega + \omega_{\text{ref}}] t + [\theta_{\text{field}} + \theta_{\text{ref}}]) \Rightarrow \text{lowpass}$$
Appendix

\[- \frac{A_y V_{\text{ref}}}{2} \cos((\omega - \omega_{\text{ref}})t + [\theta_{\text{field}} - \theta_{\text{ref}} - 90^\circ]) \]
\[+ \frac{A_y V_{\text{ref}}}{2} \cos((\omega + \omega_{\text{ref}})t + [\theta_{\text{field}}] + [\theta_{\text{ref}} - 90^\circ]) \Rightarrow \text{lowpass} \]

\[X_{\text{Mag}} = \frac{V_{\text{ref}}}{2} (A_x \cos(\theta_{\text{field}} - \theta_{\text{ref}}) - A_y \sin(\theta_{\text{field}} - \theta_{\text{ref}})) \]

The determination of \(Y_{\text{Mag}}\) is analogous.

\[Y_{\text{Mag}} = [A - B] V_{\text{ref}} \cos(\omega_{\text{ref}}t + \theta_{\text{ref}}) \]
\[= [A_x \sin(\omega t + \theta_{\text{field}}) - A_y \sin(\omega t + \theta_{\text{field}} - 90^\circ)] \times V_{\text{ref}} \cos(\omega_{\text{ref}}t + \theta_{\text{ref}}) \]
\[= A_x V_{\text{ref}} \sin(\omega t + \theta_{\text{field}}) \cos(\omega_{\text{ref}}t + \theta_{\text{ref}}) \]
\[+ A_y V_{\text{ref}} \sin((\omega + \omega_{\text{ref}})t + [\theta_{\text{field}} + \theta_{\text{ref}}]) \Rightarrow \text{lowpass} \]
\[= \frac{A_x V_{\text{ref}}}{2} \sin((\omega - \omega_{\text{ref}})t + [\theta_{\text{field}} - \theta_{\text{ref}}]) \]
\[+ \frac{A_y V_{\text{ref}}}{2} \sin((\omega + \omega_{\text{ref}})t + [\theta_{\text{field}} + \theta_{\text{ref}} - 90^\circ]) \Rightarrow \text{lowpass} \]
\[Y_{\text{Mag}} = \frac{V_{\text{ref}}}{2} (A_x \sin(\theta_{\text{field}} - \theta_{\text{ref}}) - A_y \cos(\theta_{\text{field}} - \theta_{\text{ref}})) \]

With the obtained results, the polar coordinates representation of the PSD output can be determined.

\[R_{\text{Mag}} = (X^2 + Y^2)^{1/2} \]
\[= \frac{V_{\text{ref}}}{2} ((A_x \cos \phi + A_y \sin \phi)^2 + (A_x \sin \phi - A_y \cos \phi)^2)^{1/2} \]
\[= \frac{V_{\text{ref}}}{2} (A_x^2 \cos^2 \phi + 2A_xA_y \cos \phi \sin \phi + A_y^2 \sin^2 \phi \]
\[+ A_x^2 \sin^2 \phi - 2A_xA_y \sin \phi \cos \phi + A_y^2 \cos^2 \phi)^{1/2} \]
\[= \frac{V_{\text{ref}}}{2} (A_x^2 + A_y^2)^{1/2} \]
\[ \theta_{\text{Mag}} = \tan^{-1} \left( \frac{Y}{X} \right) \]  
(29)

\[ = \tan^{-1} \left( \frac{\frac{V_{\text{ref}}}{2} \left( A_x \sin(\theta_{\text{field}} - \theta_{\text{ref}}) + A_y \cos(\theta_{\text{field}} - \theta_{\text{ref}}) \right)}{\frac{V_{\text{ref}}}{2} \left( A_x \cos(\theta_{\text{field}} - \theta_{\text{ref}}) - A_y \sin(\theta_{\text{field}} - \theta_{\text{ref}}) \right)} \right) \]  
(30)

\[ A_x = A_y, \quad \tan^{-1} \left( \frac{\sin(\theta_{\text{field}} - \theta_{\text{ref}}) + \cos(\theta_{\text{field}} - \theta_{\text{ref}})}{\cos(\theta_{\text{field}} - \theta_{\text{ref}}) - \sin(\theta_{\text{field}} - \theta_{\text{ref}})} \right) \]  
(31)

It is assumed that the amplitudes \( A_x \) and \( A_y \) are equal since the amplitude of the driving signal is the same and the power supply and the coil pairs are identical. Using the trigonometric identities

\[ \cos(x) - \sin(x) = \sqrt{2} \cos(x + \frac{\pi}{4}), \]  
(32)

and

\[ \sin(x) + \cos(x) = \sqrt{2} \sin(x + \frac{\pi}{4}), \]  
(33)

this becomes

\[ \theta_{\text{Mag}} = \tan^{-1} \left( \frac{\sqrt{2} \sin(\theta_{\text{field}} - \theta_{\text{ref}} + \frac{\pi}{4})}{\sqrt{2} \cos(\theta_{\text{field}} - \theta_{\text{ref}} + \frac{\pi}{4})} \right) \]  
(34)

\[ = \tan^{-1} \left( \tan(\theta_{\text{field}} - \theta_{\text{ref}} + \frac{\pi}{4}) \right) \]  
(35)

\[ \theta_{\text{Mag}} = \theta_{\text{field}} - \theta_{\text{ref}} + \frac{\pi}{4}, \]  
(36)

and finally \( \theta_{\text{field}} \) can be according to

\[ \theta_{\text{field}} = \theta_{\text{Mag}} + \theta_{\text{ref}} - \frac{\pi}{4}. \]  
(37)

Throughout the entire thesis, \( \theta_{\text{ref}} = 0 \) was set.
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Erklärung

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