Diplomarbeit

Non-local Phenomena in Metallic Nanostructures

On the Search for the Spin Hall Effect

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Abstract

Spin electronics has attracted a lot of interest in recent time, not only because of its rich physics, but also because of possible applications like magnetic memory or logic. In many spintronic concepts, highly spin-polarized currents are needed or advantageous. One promising approach for the generation of pure spin currents is the use of the Spin Hall Effect. Extending pioneering experiments by Mihajlović et al. [1], in this work a concept for a fully electrical generation and detection without the need for ferromagnetic spin injectors or detectors is investigated. If the ratio of spin Hall and electrical conductivity and the spin diffusion length are large enough, an interesting non-local charge transport should be observed. This effect is mediated by diffusive spin transport employing a combination of Spin Hall Effect and Inverse Spin Hall Effect and leads to a detectable non-local voltage in non-magnetic materials.

To thoroughly test this concept, H-shaped nanostructures with feature sizes as small as 50 nm are fabricated and characterized. Nanostructures made of gold, aluminum and ferromagnetic nickel were compared. In order to detect the exponentially decaying non-local voltage signal a high resolution voltage measurement setup is mandatory. An existing lock-in amplifier setup was replaced by a new current reversal setup, leading to an improvement in the signal to noise ratio and minimal detectable voltage.

In stark contrast to the rationale of the concept, the non-local voltage signal showed a sign change for low temperatures. Furthermore the negative signal exhibited reproducible fluctuations. In contrast the nickel samples do not show a negative voltage sign, but another interesting phenomenon: an enhanced anisotropic magneto resistance in non-local configuration.

To address the physical mechanisms being responsible for the experimental observations, we critically compare the Spin Hall Effect concept to three other possibly influencing effects: current spreading, ballistic transport and universal conductance fluctuations. Indeed, current spreading can account for many of the features found in the non-local voltage. However, sign change remains unexplained up to now.
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Chapter 1

Introduction

The emerging technology called Spintronics is heralding a paradigm shift for electronic devices. Although being a quite new research area, its basics date back to 1922, when Otto Stern and Walter Gerlach conducted their famous experiment [2] which eventually led to a new understanding of physics. By this experiment it was discovered that the electron must have an additional degree of freedom, which is now called the spin. The spin can take two values with respect to a quantization axis, which are often referred to as spin up and spin down. Today, research in spintronics is aiming to use this additional degree of freedom and thus revolutionize electronic devices. The possibilities are manifold: they reach from further down-scaling of device size over lower power consumption to non-volatile high speed memory.

The importance of spin based devices was underlined two years ago in 2007, when the discovery of the giant magneto resistance (GMR) by Albert Fert and Peter Grünberg on magnetic multilayers were honored with the Nobel Prize in Physics. The GMR-based readout enabled the extreme data densities of modern computer hard drives, and can thus be seen as the first great success of Spintronics. Now, improved fabrication techniques allow access to the nanoscale, fueling hope that this success can be repeated with other devices. Most of the new concepts rely on spin currents or spin-polarized currents. A spin current is a movement of spin polarization without any net charge translation.

A very promising approach to generate such spin currents is the Spin Hall Effect (SHE). It refers to a separation of spin up and down in a direction transverse to a charge current due to spin orbit coupling. The name indicates an analogy to the standard Hall effect, where a magnetic field leads to a transverse charge accumulation. However, the SHE needs no external field and no charge, only spin, is accumulated. According to the Onsager relations [3, 4], an equivalent inverse effect exists, the Inverse Spin Hall Effect (ISHE), which is the generation of a charge current transverse to a spin current.

The first theoretical prediction were made already more than three decades ago by D’yakonov and Perel’ [5]. However, it took twenty years to regain attention after a publication by Hirsch in 1999 [6], where the name Spin Hall Effect was mentioned for the first time and an idea for a detection method expressed. Some years later, in 2004, the first experimental proof of spin accumulation due to the SHE was given by Kato et al. [7]. The experiment used scanning Kerr rotation to detect optically the accumulation of opposite spins at the lateral edges of GaAs and InGaAs samples. With this experiment not only a intuitive proof for the existence of the SHE was
given but also the focus of many research groups around the world was drawn onto the topic. The impact of the SHE on the generation of spin current was realized soon and, as a next step, the realization of a fully electrical detection was undertaken. One of the first successful experiments was the one conducted by Valenzuela and Tinkham in 2006 \[8\]. As in many following experiments (e.g. \[9, 10, 11\]), magnetic contacts were used to inject a spin current into a wire, in this case aluminum, which subsequently generated a transverse, measurable voltage due to the ISHE.

However, with the use of magnetic probes additional complexity and problems are introduced. In particular, the influence of spurious signals due to stray fields of the probes themselves or the additional interfaces is often difficult to understand. As a next step, the goal is to avoid magnetic materials all together and to generate spin currents by the SHE which are subsequently detected by use of the ISHE. This way a design with impressive simplicity can be used: the layout only consists of an H-shaped structure, made of a single material. Obviously, this is also interesting for applications, as it would lower the production complexity. A first proposal of this layout for GaAs was given by Hankiewicz et al. \[12\] and extended by Abanin et al. \[13\] to the diffusive regime, which is expected e.g. in metals. The recent publication of a “giant spin hall effect” in gold by Seki et al. \[11\] stated an extremely high value for the ratio of spin hall to charge conductivity. With these values, the fully electrical and magnet-free detection of the SHE in H-shaped gold nanostructures should be possible. Nevertheless, so far an experimental proof is missing. The search for this experimental verification of the SHE and the ISHE in gold gave the motivation for this thesis.

After the introduction,

**Chapter 2** introduces to the fundamental physics required to understand the SHE. This includes an introduction to spin currents and spin orbit coupling. Based on these fundamentals it is explained how the microscopic spin transport leads to the macroscopic SHE, e.g. a spin accumulation. Finally we discuss the sample design and estimate the expected signal magnitude.

**Chapter 3** gives an overview of the underlying experimental methods. This includes the overview over the sample preparation as well as a description of the measurement setup.

As the measurement results are surprising and up to now not understood in every detail, the presentation of the results and their discussion is divided into two chapters. While **Chapter 4** deals with the results, **Chapter 5** discusses possible mechanisms and attempts to give an interpretation of the experimental outcome.

The important points are always summarized at the end of each chapter. Finally, this thesis concludes with a brief summary and an outlook.
Chapter 2
Theoretical Background

In this chapter, we discuss the fundamental physics behind the Spin Hall Effect (SHE). As this is a macroscopic transport effect it is useful to define the so called spin current, which is done in the first section. In Sec. 2.2 the microscopic mechanisms leading to a spin current will be explained. With this fundament one can introduce the SHE itself in Sec. 2.3. Finally the non-local detection and the geometry used in this thesis will be presented.

2.1 Spin Currents

For the experimental environment one wants to define macroscopic quantities. In analogy to the carrier and charge density, $\langle n \rangle$ and $\langle qn \rangle$, we define the spin density for a quantization parallel to the z-axis as

$$S_z = \langle s_z n \rangle$$  \hspace{1cm} (2.1)

where $s_z$ denotes the the z-component of the spin operator and $q$ the electric charge. While the transport of charge is described by the charge current density $j_c = \langle qn v_k \rangle$, the transport of spins can be described by the spin current density

$$j_s = \langle s_z n v_k \rangle.$$  \hspace{1cm} (2.2)

Here $v_k$ denotes the velocity. In the two spin channel model, where an independent transport channel is defined per spin species, the spin density is equal to the difference of the densities of the species, $S_z = n_\uparrow - n_\downarrow$, while the total carrier density is the sum $n = n_\uparrow + n_\downarrow$. $n_\uparrow$ and $n_\downarrow$ denote the carrier density of spin up or spin down charge carriers. In this model, the spin current density can be defined easily as the difference of the indivual charge currents

$$j_s = \frac{1}{q} (j_\uparrow - j_\downarrow)$$  \hspace{1cm} (2.3)

\footnote{This definition is consistent with most theoretical papers \cite{14,15,16} and basic understanding of a particle current. However lately, the spin current density is defined as $j_s = \langle qs_z n v_k \rangle$ in many experimental papers \cite{17}, giving it the same dimensionality as $j_c$. For the author this seems unintuitive, as no charge is transported and this definition can lead to consistence problems with the spin density.}
In contrast, charge current density is defined as the sum:

\[
j_c = (j_↑ + j_↓).
\]  

(2.4)

By Eq. (2.3) & (2.4) three different types of experimentally important current configurations can be defined (cf. Fig. 2.1). If the same amount of carriers with up-spin and down-spin travel in one direction, i.e. \( j_↑ = j_↓ \), effectively only charge is transported and thus a pure charge current exists (cf. Fig. 2.1a). A spin polarized current can be found (cf. Fig. 2.1b), if in a current one species prevails. This means, that a combination of \( j_s \) and \( j_c \) and thus a net movement of magnetic moments prevails. In the extreme case of \( j_↑ = -j_↓ \) a spin transport without any net charge transport can be found and is called a pure spin current (cf. Fig. 2.1c).

As in a spin orbit (SO) coupled system the projection of the spin, \( s_z \), is not conserved, the spin current is likewise not a conserved quantity and the simple equation of continuity holds not true, but must be extended to incorporate additional source terms (cf. Sec. 2.3.3). Already the assumption that the spin channels do not mix does not hold true. However, for the next considerations this will not be important, as only the generation of spin currents, but not the evolution in space will be discussed. In a semiclassical approach, one can describe the transport of the carriers with spin \( \sigma = \uparrow / \downarrow \), velocity \( v_k \) and mass \( m \) under influence of an electric field \( E \) with the classical Boltzmann transport equation [18]

\[
v_k \cdot \nabla f_{k\sigma} + \frac{qE}{\hbar} \cdot \nabla f_{k\sigma} = \left( \frac{\partial f_{k\sigma}}{\partial t} \right)_{\text{scatt}},
\]  

(2.5)

where \( \frac{\partial f_{k\sigma}}{\partial t} \) is the collision term and \( f_{k\sigma} \) the distribution function. One can write the current densities (cf. Eq. (2.3) & (2.4)) as

\[
j_c = q \sum_k \frac{\hbar}{m} k (f_{k\uparrow} + f_{k\downarrow})
\]  

(2.6)

\[
j_s = \sum_k \frac{\hbar}{m} k (f_{k\uparrow} - f_{k\downarrow}).
\]  

(2.7)

Thus, for a known collision term, one can determined in a similar way both, the charge and the spin current.
2.2 Generation of Spin Currents

In this section, it will be discussed, how a spin current can be generated by spin orbit (SO) coupling. Therefore a short introduction of the SO coupling will be given. Afterwards this formalism will be applied to derive the transport of spins.

2.2.1 Spin Orbit Coupling

The spin orbit coupling describes any interaction of a particle’s spin with its angular momentum. The corresponding term in the Hamiltonian for a particle with momentum $\mathbf{k}$ can be deduced using the Dirac equation \[19\]. In first order perturbation theory relativistic effects are included and lead to the Pauli spin-orbit term \[20, 21\]

$$\hat{H}_{\text{SO}} = \eta_{\text{SO}} \mathbf{s} \cdot \left( \nabla \tilde{V} (\mathbf{r}) \times \frac{\nabla}{i} \right)$$

(2.8)

where $\mathbf{s}$ is the Pauli spin operator, $\hbar/i\nabla$ the momentum operator and $\eta_{\text{SO}}$ the coupling parameter, which takes the value of $\frac{\hbar^2 k_F^2}{4m_e^2c^2}$ in the free-electron model and can be $10^2 - 10^3$ times higher in metals \[17\]. Here, $k_F$ denotes the Fermi wave vector, $c$ the velocity of light and $m_e$ the mass of the electron. The total potential $\tilde{V} = V_{\text{crys}} + V_{\text{imp}}$ can be split into the crystal potential $V_{\text{crys}}$ and an aperiodic part $V_{\text{imp}}$, containing the potential created by impurities. Generally one distinguishes between the extrinsic and the intrinsic contributions to the SO coupling. The extrinsic part takes into account the influence of impurity potentials as opposed to the intrinsic, which describes the influence of the band structure of the solid.

Extrinsic Coupling

The extrinsic contribution can be described in a semi-classical approach \[22\]. When a charge carrier with spin $\mathbf{s}$, effective mass $m$ and charge $q$ travels through a solid with velocity $\mathbf{v}_k = \frac{\hbar}{m} = \frac{\hbar}{i m} \nabla$ in presence of an impurity potential $V_{\text{imp}} (\mathbf{r})$, it feels an effective magnetic field $\mathbf{B}_\text{eff} = \mathbf{E} \times \frac{\mathbf{k}}{mc}$. Here, $\mathbf{E} = -q^{-1}\nabla V_{\text{imp}} (\mathbf{r})$ is the electric field, which arises due to $V_{\text{imp}} (\mathbf{r})$. The interaction of $\mathbf{B}_\text{eff}$ with the magnetic moment $\mathbf{\mu} = -\frac{q^{-1} \hbar}{2m} \mathbf{s}$ of the carrier gives rise to to a perturbation Hamiltonian $\hat{\mathcal{H}}_{\text{Zeeman}} = -\mathbf{\mu} \cdot \mathbf{B}_\text{eff}$. Here $\mu_B = \frac{e \hbar}{2m}$ is the Bohr magneton and $g$ the $g$-factor. The magnetic field $\mathbf{B}_\text{eff}$ equals $\frac{1}{2} \mathbf{B}_\text{eff}$, because a relativistic correction of $\frac{1}{2}$, known as the Thomas factor$^2$, must be applied. The resulting Hamiltonian

$$\hat{\mathcal{H}}_{\text{ext}} = \frac{1}{4} \frac{g \hbar^2}{m^2 c^2} \mathbf{s} \cdot \left( \nabla V_{\text{imp}} (\mathbf{r}) \times \frac{\nabla}{i} \right)$$

$$= \eta_{\text{SO}} \mathbf{s} \cdot \left( \nabla V_{\text{imp}} (\mathbf{r}) \times \frac{\nabla}{i} \right)$$

(2.9)

$^2$A simple and pedagogical argument can be found in \[23\].
has the similar form as Eq. (2.8), but with a different potential. It describes all the contributions due to impurities.

**Intrinsic Coupling**

A SO coupling can not only occur in presence of impurities, but also by the influence of band-structure. In semiconductors an inversion asymmetry, which removes the two-fold spin degeneracy of the band structure, can lead to SO coupling. The asymmetry can be a consequence of the crystal or of a confining potential. The first is called *bulk inversion asymmetry* (BIA) and can be found, e.g., in the zinc blende structure. The second is typically referred to as the *structure inversion asymmetry* (SIA) and can be introduced by a built-in or external potential. Therefore it even can be tuned by external gates \[24\]. The contributions by SIA can be described by the *Rashba* term \[21, 25\]

\[
\hat{H}_{\text{Rashba}} = \frac{\alpha_R}{\hbar} \mathbf{s} \cdot \mathbf{k} \times \mathbf{E},
\]

with \(\alpha_R\) as a tunable material constant describing the SO coupling. The *Dresselhaus* term \[21, 26\] is more complicated. As an example, one can deduce it for the zinc blende structure to

\[
\hat{H}_{\text{Dresselhaus}} = \frac{\alpha_D}{\hbar^3} \left( \{k_x, k_y^2 - k_z^2\} \sigma_x + \text{cp} \right).
\]

Here \(\{k_x, k_y^2 - k_z^2\}\) is the symmetrized product \(\frac{1}{2} \left( k_x (k_y^2 - k_z^2) + (k_y^2 - k_z^2) k_x \right)\), \(\text{cp}\) the cyclic permutation of the preceding term and \(\alpha_D\) an effective coupling parameter.

### 2.2.2 Spin Transport in Spin Orbit Coupled Systems

Which microscopic mechanism dominates the transport will depend strongly on the specific material. As this thesis is only concerned with metallic structures where intrinsic effects are expected to be negligible \[27\], they will not be discussed in the
Two effects due to extrinsic SO coupling are the **Skew Scattering** and the **Side Jump** mechanism. Basically, by Skew Scattering carriers with opposite spins are deflected asymmetrically, while the Side Jump mechanism leads to transverse translation, a “jump”, in opposing directions without any deflection (cf. Fig. 2.2). Outstanding debates are held, to what extent which mechanism contributes in a particular case [29]. Both are explained briefly in the following.

### Skew Scattering

For scattering of a carrier with spin in a potential, the scattering cross sections depend on the spin state of the carriers due to the SO coupling, which is described generally by Eq. (2.8). The effect is well known as **Mott scattering** and was originally discussed for high-energy electrons scattered by an atom in vacuum [30]. The theoretical framework holds true in a solid if impurities are present (cf. Eq. (2.9)). The Skew Scattering was originally considered as origin for the AHE in ferromagnetic materials [31, 32]. Later its relevance for non-magnetic materials was suggested [5, 6, 33].

In a semiclassical approach (compare, e.g., [17] for complete calculations) the SO Hamiltonian, Eq. (2.9), will introduce an asymmetry into the collision term of Eq. (2.5). To calculate the collision term and subsequently the distribution function, one has to know the scattering probability $P_{\sigma,\sigma'}^{k,k'}$ from state $|k\sigma\rangle$ to state $|k'\sigma'\rangle$. Here $\sigma = \uparrow / \downarrow$ denotes the spin state. It can be calculated by the use of Fermi’s Golden Rule under the knowledge of the Hamiltonian. For SO coupled systems the scattering probability $P_{\sigma,\sigma'}^{k,k'}$ will not only comprise the symmetric Coulomb scattering, but also the asymmetric scattering due to the SO coupling:

$$P_{\sigma,\sigma'}^{k,k'} = P_{\text{sym}} + P_{\text{SS}} + ...$$

The Skew Scattering contribution $P_{\text{SS}}$ is spin dependent and proportional to $V_{\text{imp}}\eta_{\text{SO}}$:

$$P_{\text{SS}} \propto V_{\text{imp}}\eta_{\text{SO}}s(k \times k')$$

(2.10)

It was assumed a weak $\delta$-function potential of $V_{\text{imp}}(r) \approx V_{\text{imp}} \sum_i \delta(r - r_i)$. For a repulsive impurity potential $V_{\text{imp}} > 0$ the total probability will be maximal for $k \times k'$ parallel to $s$ and minimal for the antiparallel case. This means, that a spin-up electron will always scatter with higher probability to the left. Why this is the case can be understood easily, if one examines the Hamiltonian (cf. Eq. (2.9)). The energy contribution of $\hat{H}_{\text{SO}}$ will be positive for $s$ parallel to $(\nabla V_{\text{imp}} \times k)$ and negative for the antiparallel configuration. Thus the configuration where $(\nabla V_{\text{imp}} \times k)$ is antiparallel to the spin, which can be seen in Fig. 2.3, will be energetically favored for a repulsive potential and spin-up.

---

3There is ongoing discussion about whether intrinsic effects can contribute, or even dominate in metals, e.g. in Pt [28].
In a rather lengthy calculation (cf. e.g. [17]) one can determine the spin current density by the use of Eq. (2.7) and Eq. (2.10) to
\[
\mathbf{j}_s = \mathbf{j}_s^{eq} + \frac{\alpha_{SS}}{q} (\mathbf{e}_s \times \mathbf{j}_c).
\] (2.11)

Here \(\mathbf{e}_s\) denotes the quantization direction, which is generally chosen to coincide with the z-axis. The first term on the right arises for spin accumulation and is proportional to the gradient of the spin density\(^4\), \(\mathbf{j}_s^{eq} = -D_s \nabla S_z\), trying to return the system to equilibrium by diffusion. \(D_s\) is the spin diffusion constant. The second term is the influence of the Skew Scattering and leads to a transverse spin current for the presence of SO coupling. Here \(\alpha_{SS} = \frac{1}{3} \pi k_F^2 \eta_{SO} N(E_F) V_{imp}\) is the dimensionless SO coupling parameter with \(N(E_F)\) as the density of states at Fermi energy.

**Side Jump Mechanism**

The Side Jump model was first proposed in relation with the AHE [35, 36]. If a particle, represented by a wave packet, is scattered in presence of SO interaction, the average electron trajectory after scattering will not only form an angle with the former one, but also include a small lateral displacement \(\delta r_{SJ}\), a “side jump”. For scattering with momentum transfer \(\delta \mathbf{k}\) the side jump can be calculated to \(\delta r_{SJ} = (\mathbf{s} \times \delta \mathbf{k})\). This will lead to the so called *anomalous velocity* [17]
\[
\mathbf{v}_k^\sigma = \mathbf{v}_k + \alpha_{SJ} (\mathbf{e}_s \times \mathbf{v}_k),
\] (2.12)

which reflects a transverse movement by the side-jumps at repeated scattering events (cf. Fig. 2.4). \(\alpha_{SJ} = k_F^2 \eta_{SO} / l_e\) is the dimensionless SO coupling parameter for the Side Jump mechanism and scales reciprocally with the electron mean free path \(l_e\). With Eq. (2.3) follows
\[
\mathbf{j}_s = \frac{2\alpha_{SJ}}{q} (\mathbf{e}_s \times \mathbf{j}_c).
\] (2.13)

The result is very similar to the one before for Skew Scattering, but its sign is independent of \(V_{imp}\) [27]. If the carrier concentration is higher than the one of the impurities, which is the case in ordinary non-magnetic metals, the Skew Scattering dominates over the Side Jump contribution [17, 27].

\(^4\)In fact, this holds only true in non-magnetic materials, where no equilibrium spin density exists. Otherwise one must introduce the spin dependent chemical potential [17, 34].
2.3 Macroscopic Effects

All the microscopic mechanisms described in the previous section lead to two macroscopic effects: the Spin Hall Effect and its inverse, the Inverse Spin Hall Effect. This will be described in the following two subsections. In 2.3.3 the macroscopic diffusion equation will be introduced.

2.3.1 Spin Hall Effect

No matter which of the microscopic effects mentioned before dominates, the result will be a spatial separation of the two spin species in a conductive medium. In a pure charge current the number of carriers with spin up and with spin down are equal. By this, equal numbers of carriers with opposite spin will be deflected in opposing directions and thus lead to a pure spin current. This conversion between charge and spin current is called the Spin Hall Effect (SHE) (cf. Fig. 2.5a).

The complete spin current can be obtained by adding the contributions of Skew Scattering and Side Jump

\[ j_s = -D_s \nabla S_z + \frac{\alpha_{SHE}}{q} (e_s \times j_c) + \frac{2\alpha_{SJ}}{q} (e_s \times j_c) \]

In the case of vanishing spin accumulation, an applied electric field \( E \) will lead to

\[ j_s = q^{-1}\alpha_{SHE} \sigma (e_s \times E), \]

where \( \sigma \) denotes the charge conductivity. At this point, it is useful to define the Spin Hall Conductivity \( \sigma_{SHE} = \alpha_{SHE} \sigma \) to yield the dependence of the spin current on the electric field\(^5\):

\[ j_s = j_{s,eq} + \frac{\sigma_{SHE}}{q} (e_s \times E) \]  

(2.14)

The ratio of spin hall to charge conductivity, \( \alpha_{SHE} = \sigma_{SHE}/\sigma \), is sometimes called the Spin Hall Angle \([17]\).

\(^5\)Note that, according to the definition by Eq. 2.3, the factor \( q^{-1} \) is needed. Otherwise \( \alpha_{SHE} \) would not be dimensionless and would differ from values in parts of the literature.
2.3.2 Inverse Spin Hall Effect

For Skew Scattering and Side Jump one can calculate in a similar manner the charge current. If one takes the sum of \( j_\uparrow \) and \( j_\downarrow \) (or respectively Eq. (2.6)) instead of the difference, one obtains for the total charge current

\[
j_c = j_{c,\text{ohm}} + q\alpha_{\text{SHE}} (e_s \times j_s).
\]

(2.15)

While \( j_{c,\text{ohm}} = \sigma E \) is the contribution of symmetric scattering at the impurities, the second term rises by the asymmetric scattering due to SO coupling. As a result, a pure spin current will generate a transverse, pure charge current. As this behavior is complementary to the SHE (cf. Fig. 2.5b), it is called the **Inverse Spin Hall Effect** (ISHE). For an isolated sample the current will lead to a charge accumulation and thus to an electric field. The charge current \( j_{c,\text{ohm}} \) driven by this field will eventually balance the one generated by the ISHE. The electric field which will build up to reach a stationary state will be:

\[
E = -\frac{q\alpha_{\text{SHE}}}{\sigma} (e_s \times j_s)
\]

(2.16)

2.3.3 Equation of Continuity

Up to this point, the difficulty of \( j_s \) not being conserved was not of any importance. But for the following discussion of the spatial evolution of \( j_s \), one can not neglect the influence of spin-flip scattering anymore. By spin-flip scattering, the two spin species will equilibrate and thus the spin density will tend towards zero. This phenomenological *spin relaxation* approach can be implemented by an additional source term in the continuity equation, which describes how a spin current evolves over time [37]:

\[
\frac{\partial S_z}{\partial t} + \nabla \cdot j_s = -\frac{S_z}{\tau_s} + [\omega_B \times S]_z.
\]

(2.17)

Here \( \tau_s \) is the spin relaxation time, \( \omega_B = g\mu_B B \) the Larmor precession frequency. The quantization was chosen parallel to the z-axis and thus \( e_s = e_z \). For this reason only the z-component of the spin density, \( S_z \) is of interest. The second term on the right includes field-generated spin torque and must be added artificially (as the relaxation term) and vanishes for zero field. Under assumption of quasi-stationarity and use of Eq. (2.14), one obtains the diffusion equation of the spin density:

\[
D_s \Delta S_z - q\sigma_{\text{SHE}} [\nabla \times E]_z - \frac{S_z}{\tau_s} + [\omega_B \times S]_z = 0
\]

(2.18)

\[\text{Recently proposals for another definition of } j_s, \text{ which include nonconservation, were made [16, 38].} \]
2.4 Non-local Effects

The spin accumulation created solely by the SHE is not electrically detectable, as no charge accumulation is connected with it. In contrast, the combination of SHE and ISHE leads to interesting non-local charge transport, which is mediated by diffusive spin transport. Its observation can be made fully electrically without the need for sources of spin-polarized current as ferromagnetic injectors. First proposals for GaAs were made by Hankiewicz et al. [12] and recently applied to the diffusive regime in media with extrinsic SHE by Abanin et al. [13]. Although again GaAs is proposed as preferable material, the recently observed giant spin hall effect [11], favors also the same configuration in gold.

The idea is to fabricate metallic H-structures (cf. Fig. 2.6) and to send a charge current through one of the wires. By the SHE a pure spin current will be created in the transverse connection, which in turn, will invoke a electrically measurable charge separation in the other wire due to the ISHE. As can be seen in Fig. 2.6, independently of the microscopic mechanism at work, the carriers will be deflected twice in the same direction. The potential difference which builds up opposes the current flow and gives a positive resistance measurement. Or put differently, a current flow parallel to \( x \), from \( x_1 \) to \( x_2 < x_1 \) leads to the positive voltage \( V(x_1) - V(x_2) \) in the remote, parallel wire. There are several advantages over the previously applied configurations using spin injection via a ferromagnetic contact (cf. Ref. [8][11]). First of all, one avoids interfaces, whose influence is generally difficult to determine. Fur-
thermore, using only one material, no conductance mismatch is introduced. Another problem often discussed with magnetic probes is, whether the signal is sensitive to the stray field generated by the magnetic probes. And finally, one reduces the risk of introducing impurities, which can be responsible for an alteration of the non-local signal due to the Kondo effect. This was especially discussed \cite{39} for Fe impurities in the Au/FePt system used by Seki \textit{et al.} \cite{11}.

### 2.4.1 Spin Mediated Resistance

![Fig. 2.7: Schematic of the used geometry to calculate $R^{\text{SHE}}_{\text{nonlocal}}$](image)

Using the diffusion equation, Eq. (2.18), and the formulas for the SHE and the ISHE (Eq. (2.14) & (2.15)) one can determine the expected voltage of purely spin mediated charge transport. For the assumption of a narrow strip ($w \ll L$, cf. Fig. 2.7) the spin current $I_s = j_s w t$ generated by a charge current $I_c$ was calculated by Abanin \textit{et al.} \cite{13} to

$$I_s(y) = I_c \frac{\alpha_{\text{SHE}} w}{l_s} \exp\left(-\frac{|y|}{l_s}\right).$$

The spin current decays exponentially on a length-scale of the diffusion length $l_s$. The proportionality $I_s \propto l_s^{-1} \exp\left(-|y|/l_s\right)$ can be seen easily if one calculates the spin density $s_z$ in bulk with vanishing electric field. Thus the diffusion equation reduces to a homogeneous second order differential equation $\partial^2 y/s_z (y) - l_s^2 s_z (y) = 0$, where only the solution $\propto \exp\left(-|y|/l_s\right)$ is physically meaningful. For $E = 0$ the spin current density is proportional to $-\partial y/s_z (y)$ (cf. Eq. (2.14)), yielding the same proportionality as the calculation above.

According to Eq. (2.16), the spin current $I_s$ will generate a voltage $V^{\text{SHE}}_{\text{nonlocal}} (y) = -w E = t^{-1} q^{-1} \alpha_{\text{SHE}} I_s$ across the second wire. Therefore the measured resistance will be

$$R^{\text{SHE}}_{\text{nonlocal}} = \frac{1}{2} \alpha_{\text{SHE}}^2 \rho l \cdot w \exp\left(-\frac{L}{l_s}\right). \tag{2.19}$$

As one can see, the expected value is positive, depends quadratically on $\alpha_{\text{SHE}}$ and decays exponentially with the distance $L$. The characteristic length is the spin diffusion length $l_s$. Obviously a material is prefered, for which $\alpha_{\text{SHE}}$ and $l_s$ take maximal values.
2.4.2 Current Spreading

Also the spreading of the charge current gives rise to a positive contribution to the measured non-local voltage. If one assumes a sample (cf. Fig 2.8) with width $w$ and point like current injection probes, which are remote ($L \gg w$) from the voltage probes, one can calculate the expected non-local resistance $R^{\text{nonlocal}}$ by use of the van-der-Pauw theorem (vdP). The vdP theorem says that in a sample with arbitrary shape, free of holes and with homogeneous thickness $t$ the relation

$$\exp \left( -\frac{\pi t}{\rho} R_{AB,CD} \right) + \exp \left( -\frac{\pi t}{\rho} R_{BC,DA} \right) = 1$$

holds true. The resistance $R_{AB,CD}$ is defined as the voltage difference $V_D - V_C$ between point D and C per current $I_{A\rightarrow B}$ from contact A to B and $R_{BC,DA}$ as the corresponding permutation. The theorem can be proven by means of conformal mapping and using Ohm’s law \[40, 41\]. Usually it is used for the determination of resistivity and Hall coefficient. Here it will be used the other way round.

With a known resistivity $\rho$ one can determine the contribution of current spreading $R^{\text{cs}}_{\text{nonlocal}} = R_{AB,CD}$ to the non-local resistance. For remote contacting, one expects the non-local resistance to be small compared to the sheet resistance: $R_{AB,CD} \ll \rho/t$. Thus the first term on the left can be approximated by $1 - \pi t \rho^{-1} R_{AB,CD}$. As $L \gg w$ the local longitudinal resistance $R_{\text{local}},yy = \rho L / wt$ will be equal to $R_{BC,DA} = (V_A - V_D) / I_{B\rightarrow C}$. Therefore one obtains

$$R^{\text{cs}}_{\text{nonlocal}} = \frac{\rho}{\pi t} \exp \left( -\frac{\pi L}{w} \right)$$

(2.20)

for the expected signal. It decays exponentially with $w / \pi$ as characteristic decay length and should thus only depend on the resistivity and the geometry.

2.4.3 Estimation of Magnitudes

The contributions of the SHE and the current spreading decay on a different length scale. The characteristic length of $R^{\text{cs}}_{\text{nonlocal}}$ is $w / \pi$. It is determined only by geometry. The non-local signal due to Spin Hall on the other hand decays with the spin diffusion length $l_s$. For this reason, one expects the SHE to dominate for narrow wires. If the spin diffusion length is larger than the bar width the SHE should also be the major contribution at long distances. While the width of the bars is technically limited, it is possible (even easier) to fabricate samples with long distances. But then always the signal magnitude decays exponentially and thus will be too low to be detected with conventional methods at larger $L$.

In order to estimate the required dimensions and resolutions, solutions of Eq. (2.20)
and Eq. (2.19) are plotted in Fig. 2.9 against the width for gold (a), aluminum (b) and platinum (c). The signal due to the SHE is depicted in redish colors, while the contribution of current spreading is given in blueish ones. The intensity of the color reflects the three plotted lengths of 150 nm (darkred, darkblue), 225 nm (red, midblue) and 300 nm (orange, cyan). The intersections of the curves for both contributions are given by black circles. The green, slashed line shows the intersection for arbitrary $L$.

The used values for gold at $T = 300 \text{ K}$ are $\alpha_{\text{SHE}} = 0.113$, which has been recently measured and published as giant SHE [11], a diffusion length of $l_s = 168 \text{ nm}$ [42] and $\rho = 2.271 \mu\Omega\text{cm}$ [43]. For aluminum the values were $\alpha_{\text{SHE}} = 1 \times 10^{-4}$ [44], $l_s = 0.7 \mu\text{m}$ [8, 44] and $\rho = 2.733 \mu\Omega\text{cm}$ [43], while in Pt $\alpha_{\text{SHE}} = 3.7 \times 10^{-3}$ [9], $l_s = 14 \text{ nm}$ [45] and $\rho = 10.8 \mu\Omega\text{cm}$ [43] are used.

Although $R_{\text{SHE\ nonlocal}}^\text{SHE}$ increases with $w$, the total signal will be dominated by the contribution of the current spreading if $L$ is not large enough and if the width is not small enough. If one intends to determine the maximal width at which the two contributions are equal, one has to find the intersection of the corresponding curves for the two contributions. For example, at 150 nm in gold, the dark blue curve and thus the current spreading is dominant over the SHE (dark red) for all widths larger than roughly 85 nm. Thus, for smaller structures, the signal should be mainly due to the SHE. Comparing the other pairs of curves, it is clear, that break even will be at larger widths for larger distances. With this in mind, the most important curve is the one of the smallest $L$. As one wants the SHE not only to be equal, but to dominate the signal for all lengths, it is favorable to produce the samples as narrow as possible.

As one should keep in mind the needed resolution, one should not only compare the two contributions, but look at the absolute value. For gold the absolute magnitude is below 1 mΩ and thus small, but measurable. For a current of 100 µA the needed voltage resolution is 100 nV and therefore manageable.

In aluminum and platinum the picture is quite different. The needed widths are smaller by a factor four to five, which is not possible to fabricate with the means that are available for this thesis. Furthermore the resistance is lower than 50 pΩ in Al and below 1 pΩ in Pt and therefore not detectable with standard electrical measures. One can conclude, that, assuming the values for $\alpha_{\text{SHE}}$, $l_s$ and $\rho$ quoted in the literature being correct, only in gold a measurable SHE signal should exist at reasonable sample sizes.

This comparison also shows that by the method presented here the SHE can only be detected if the fairly high value for $\alpha_{\text{SHE}}$ reported by Seki et al. [11] holds true. Considering the atomic configuration, one would expect SHE values for gold and platinum which are of the same order of magnitude and thus a non-local resistance $R_{\text{SHE\ nonlocal}}^\text{SHE}$ whose detection will be extremely difficult.
2.4 Non-local Effects

Figure 2.9: Estimation of the expected magnitudes for the non-local resistance caused by the SHE (red) and the current spreading (blue) for $T = 300 \text{ K}$. In $a$) calculations for gold are presented, while $b$) depicts the situation in aluminum and $c$) in platinum. The metal thickness was always 50 nm. The solutions for gold ($a$), aluminum ($b$) and platinum ($c$) are shown. The saturation of the line color gives the distance $L$: darkest color means $L = 150 \text{ nm}$, medium 225 nm and the light color 300 nm.

In gold, the SHE should dominate for widths $w$ below about 90 nm and $L > 150 \text{ nm}$. The absolute value is roughly $0.55 - 1 \text{ mΩ}$. In aluminum and platinum the widths required for SHE to dominate are smaller by a factor 4 to 5 and the needed resolution must be below $50 \text{ pΩ}$ or $1 \text{ pΩ}$, respectively, making the detection of SHE extremely difficult.
2.4.4 Influence of an in-plane Magnetic Field

The non-local resistance will be modified in the presence of a magnetic field $B$. One can not neglect the spin torque term $[\mathbf{\omega}_B \times \mathbf{B}]_z$ in the diffusion equation anymore. For a field parallel to the $y$-axis and quantization in $z$, as in our geometry, the diffusion equation takes the form

\[
\begin{bmatrix}
D_s \Delta - \tau_s^{-1} & 0 & 0 \\
0 & D_s \Delta - \tau_s^{-1} & -\omega_B \\
0 & \omega_B & D_s \Delta - \tau_s^{-1}
\end{bmatrix} S = q\sigma_{\text{SHE}} [\nabla \times \mathbf{E}]_z \mathbf{e}_z.
\]

The term on the right is the creation of spin imbalance and thus spin density by the SHE. In the geometry here, only the $z$-component should be nonzero. This means, if one looks at $y$-component, that $D_s \Delta S_y - \tau_s^{-1} S_y = \omega_B S_z$. The $z$ component of the complete diffusion equation will thus be

\[
(D_s \Delta - \tau_s^{-1})^2 S_z + \omega_B^2 S_z = q\sigma_{\text{SHE}} (D_s \Delta - \tau_s^{-1}) [\nabla \times \mathbf{E}]_z
\]

The modified differential equation can be solved \cite{13}, leading to a non-local resistance of

\[
R_{\text{nonlocal}}^{\text{SHE}} (y, B) = R_{\text{nonlocal}}^{\text{SHE}} (0, 0) \cdot \Re \left[ \sqrt{1 + i \omega_B \tau_s} \exp \left( -\sqrt{1 + i \omega_B \tau_s} \frac{|y|}{l_s} \right) \right], \quad (2.21)
\]

which can be simplified to

\[
R_{\text{nonlocal}}^{\text{SHE}} (y, B) = R_{\text{nonlocal}}^{\text{SHE}} (0, 0) \cdot \sqrt{2} \eta \sin \left( \frac{\eta |y|}{l_s} + \frac{\pi}{4} \right) \exp \left( -\frac{\eta |y|}{l_s} \right),
\]
in the case of $\omega_B \tau_s \gg 1$. Here $\Re$ denotes the real part, $\eta = \sqrt{\omega_B \tau_s/2}$ and $R^\text{SHE}_{\text{non-local}}(0,0) = \frac{1}{2} \alpha_{\text{SHE}}^2 \frac{\rho}{l_s} \cdot \frac{\omega}{\tau_s}$ the non-local resistance in zero field for $|y| = 0$ (cf. Eq. (2.19)). The formula shows that the non-local signal is amplified by a factor $\sqrt{2} \eta$ and decays on a reduced length scale of $l_s/\eta$. For increasing magnetic field the signal is, after an initial enhancement, oscillating and finally suppressed at $\omega_B \tau_s \approx 1$.

In Fig. 2.10 the full solution, Eq. (2.21), is plotted. A very interesting effect can be seen. After an initial increase in magnitude, the signal decreases, changes sign and finally is suppressed while oscillating. The increase can be found for values of the magnetic field $\omega_B \tau_s < l_s/|y|$. The sign change is located at $\omega_B \tau_s \approx l_s/|y|$, while the suppression and oscillation occurs at higher fields.

Taking values for bulk gold found in literature, $g = 2.11$ and $\tau_s = 5 \times 10^{-10}$ s [46], one can estimate the field, which is necessary to observe a sign change, to $B_\ast = \frac{\hbar}{g \mu_B \tau_s} \approx 11$ mT. As this field is easily obtained in most measurement setups, the signature can be useful to prove whether the SHE is the origin for the non-local signal.

2.5 Summary

In this chapter a connection was drawn between the well-known and fundamental effect of the spin orbit coupling and the “new” Spin Hall Effect, which recently receives a lot of interest. The spin current was introduced and the microscopical mechanisms, which lead to a spin separation of moving carriers, were depicted. This was used to derive formulas for the Spin Hall Effect (SHE), its inverse, the Inverse Spin Hall Effect (ISHE), and the macroscopic diffusion equation for spin accumulation.

Finally, a new approach to measure the SHE fully electrically without magnetic contacts was explained and quantitative estimations of its magnitude given. Those were compared to a competing mechanism leading to a non-local signal, the current spreading. Its magnitude was deduced intuitively by the use of the van-der-Pauw theorem.

As a result, only in gold a measurable value of up to $1$ m$\Omega$ for the non-local resistance is expected, using literature values for $\alpha_{\text{SHE}}$, $l_s$ and $\rho$. Furthermore a different exponential decay for both contributions is predicted, giving a possibility to distinguish between those two. Another way to check, whether the measured signal originates from the SHE, is by an in-plane magnetic field. The SHE signal should show oscillations and suppression at fields of roughly $11$ mT.
Chapter 3
Experimental Methods

This chapter's aim is to describe all steps and devices being involved in the fabrication and measurement of our samples. The first section will explain the sample preparation, while the second part deals with the measurement setup. To ease reading, the recipes and program codes can be looked up separately in appendix A & C.

3.1 Sample Fabrication

As depicted in chapter 2, the lateral dimensions of our structure need to be in the range below $\lesssim 100$ nm. This requires the use of electron beam lithography (EBL) for patterning. Additionally, for being able to contact the structure with bond wires, one has to have reasonable sized contact pads. The long time needed to write such extensive areas via an e-beam impose the employment of a two step process including conventional optical lithography.

3.1.1 Outer Contact Structures

Optical Lithography

Prior to the main device, outer contact structures were fabricated with optical lithography, which is much less time consuming than EBL. The complete lithography was carried out in the clean room at the WMI, using the installed spin-coater, two hotplates and a MJB-HP/350 UHV 400 mask aligner from Karl Süss, now Süss Microtech AG. The lithographic mask involved was designed using a CAD system (Layouteditor) and manufactured by Masken Lithographie & Consulting GmbH (ML&C) in the forefront of this work. The mask is made out of a quartz glass substrate with a reflective chromium coating and contains 36 structures with the possibility to use up to 24 contacts and alignment markers, see also Fig. 3.1.

As substrate a 1-inch (25.4 mm), (100) orientated, oxidized silicon wafer was used, with an oxide thickness of 50 nm and an overall thickness of 525 µm. After cleaning, spin coating the AZ® 5214E reversal photo-resist at 4000 rpm gave a 1.4 µm thick resist layer, which was baked at 110°C for 70 s. A flood exposure of 0.3 s and a second baking step for 120 s at 130°C was applied to activate a cross-linking agent in the reversal resist. The resist is less light sensitive towards the surface, which results in an undercut after the actual exposure of 4.5 s and the subsequent development with AZ® Developer. The optimal development time was determined to 3 min and
purified water was used as stopper. Whether or not the development was successful can be easily checked with an optical microscope.

**DC Sputter Process**

The material for the contact structures can be deposited via a sputtering process in the BAL-TEC MED 020 HR modular sputtering device. After evacuating the vessel to at least $3 \times 10^{-5}$ mbar, it has to be flooded with argon to a pressure of $5 \times 10^{-2}$ mbar to enable ignition of a plasma next to the target containing the desired metal. The ions are accelerated towards the target by a voltage and erode the material, which then deposits onto the substrate. To achieve films of higher quality, a pre-sputtering step was used, which means sputtering with closed shutter in order to clean the target.

For this work, a 25 nm thick gold layer was deposited. As gold generally does not stick well to silicon oxide surfaces, often a chromium layer of roughly 3 nm is used as adhesion promoter. In the beginning, this was done for a number of samples, but left out soon because it proved unnecessary with the actual fabrication recipe.

To lift-off the spare gold ontop of the unexposed resist, the wafer was left in acetone for half an hour or longer with no ultrasonic cleaning step. The cautious lift-off procedure could be the reason why no adhesive layer was needed.

### 3.1.2 Inner Structures

**Electron Beam Lithography**

After succeeding with the lift-off of the contact structures, the wafers were spin-coated again. This time a bi-layer system of PMMA resist, manufactured by MicroChem Corp., was used. PMMA is an acronym for polymethylmethacrylate, which can be used as a positive resist. The exposure to an electron beam creates chain scission within the polymer, allowing to remove the pattern with a chemical de-
3.1 Sample Fabrication

Developer. Resolution can be as good as \( \approx 20 \text{ nm} \) [47]. Two layers were applied to obtain an undercut aiding the release in the final lift-off step. For the lower one a PMMA 495K A6 was spun onto the wafer at 8000 rpm and baked for 10 min at 175°C, resulting in a thickness of approximately 300 nm. After a quick check for bubbles or dust particles in the resist with the optical microscope, a second layer of PMMA 950K A4 was deployed and baked with the same parameters. This will lead to a layer of around 100 nm thickness, which is less sensitive to exposure, giving the desired undercut.

A focused electron beam was used to expose and pattern the bi-layer resist system. For this purpose, the WMI disposes of a Scanning Electron Microscope (SEM), a Philips XL30 SFEG, which is equipped with the ELPHY Plus lithographic system from Raith. In this system, the sample can be positioned by the use of a 3D laser interferometric stage. Electron beams with energies up to 30 keV can be delivered and a focus better than 2 nm achieved. The software is able, under the premise of a well focused beam and accurate adjustment of the coordinate system, to find the markers and make an alignment of the write-field automatically.

![Fig. 3.2: Schematic of the PMMA layer system, with undercut](image)

**Figure 3.3:** The first layouts, comprising structures with 55 nm widths. Shown is the complete write-field in a), the actual structure in b) and a magnification of the part with the smallest dimensions in c)

The layout was continuously improved during this work. In Fig. 3.3 the first working design is depicted. It is a filled 2D-structure, which will be scanned by the beam during the exposure. As can be seen in Fig. 3.3 c), for the smallest contact, with a nominal distance of 150 nm, the wires are led away in a 90° angle. This was done to prevent the building of too long, freestanding resist fingers due to the undercut, which will eventually break down in the deposition step (cf. Fig. 3.4). The problem becomes more difficult to prevent for structures with more wires being close together. After some evolution it was managed to get the combination of wires...
separated by 150, 200, 225, 250 & 300 nm with the layout shown in Fig. 3.5. After a successful run, the parts which were exposed to the beam are removed using the AR 600-56 developer from Allresist.

![Figure 3.4: Schematic of a freestanding resist finger](image)

**Figure 3.4:** Schematic of a freestanding resist finger

![Figure 3.5: The final layout for the structures](image)

**Figure 3.5:** The final layout for the structures

### Thin Film Deposition

The material for the inner structures was deposited using electron beam evaporation or an effusion cell. While the first is a well-established procedure at the WMI, enabling the use of gold, aluminum, platinum or nickel, the latter one was applied for the first time in the WMI in an apparatus set up by T. Brenninger and was only available for gold. Again all parameters can be found in appendix C.

Both methods use a beam of atoms in the gaseous phase which is aimed at the sample, where the atoms condense onto the surface, creating a thin film. High vacuum is necessary to maximize the mean free path of the atoms and minimize the implementation of other species. The equipment used during this work allowed base pressures of below $1 \times 10^{-8}$ mbar. The growth rates and the actual film thickness can be controlled via the change in resonance frequency of a quartz crystal due to the mass change during deposition.

### Notes

1. All separations quoted in this work are distances from center to center. This means, that, for example, a wire separation of 150 nm and a wire width of 70 nm leads to a gap between the wires of 80 nm.
2. Often referred to as EBPVD for electron beam physical vapor deposition.
3. Best value in the Effusion Cell setup: $3 \times 10^{-9}$ mbar.
3.2 Measurement Setup

**Electron Beam Evaporation** uses an electron beam, created by a tungsten filament, to heat a target, from which atoms transform into the gaseous phase. Depending on the material, different growth rates were used: 4.5/s for gold, 1.5/s for nickel and 12/s for aluminum.

**Effusion Cell** is another thermal evaporation method, which is widely used in the semiconductor research and industry for the epitaxial growth of thin films. At the WMI a high temperature effusion cell for gold evaporation is installed. Radiation heating is used to achieve temperatures high enough to evaporate the gold at a steady rate. Here, a temperature of 1530 °C was used to yield a rate of 0.2/s.

After deposition, the residual gold was lift-off in acetone. To avoid destruction of the fine structures, no ultrasound was used. Being unable to see the real structure under the optical microscope, the results were checked using the electron microscope. Pictures made with the SEM can be seen in Fig. 3.6 The smallest feature sizes that could be obtained were about 50 nm between a pair of short wires, while the smallest width for conducting wires was about 60 nm. Samples having such narrow wires could not be used as desired because the wires have proven unstable after some arbitrary time. The reason is the so-called electromigration, which is the movement of the ions in a conductor due to momentum transfer between conducting electrons and diffusing metal atoms [50, 51].

3.2 Measurement Setup

All measurements were done in liquid helium cooled cryostats. For most of the measurements, an Oxford Spectromag cryostat system was used. The system, as installed in the WMI, provides the possibility to apply a magnetic field with up to 7 T. The field direction with respect to the sample can be rotated for more than 360° via a stepper motor. The temperature of the cryostat VTI could be adjusted to a range from ≈ 2 K up to 300 K by the use of a helium gas flow and resistive heating. A second cryostat allowed fields as high as 17 T and temperatures from ≈ 1.4 K to ≈ 400 K. The temperature of the dipstick, onto which the sample was mounted, was controlled with a Lakeshore, Model 340, temperature controller.

For data acquisition a Microsoft Windows® based workstation was available and all routines were programmed in National Instruments’ Labview. 4 The samples are mounted to a 20-pin sample holder 5 as depicted in Fig. 3.7 The gold pads of the samples were connected (bonded) to the copper pads of the holder with a 30 μm thick aluminum wire. The contacts are led out of the cryostat with pair-twisted copper wires. Connection can be made at a matrix module, where each contact can be grounded, disconnected or connected to a MXC-connector. Using nanostructures, this is necessary due to the devices’ sensitivity to electrostatic discharges (ESDs).

4During this work a great amount of additional programs were developed, e.g. a remote interface to the SRS SR-830, programs related to Keithley devices and a program controlling and logging all cryostat related parameters (cf. Appendix B). All are integrated in the WMI’s labview file structure.

5During this work a new, 24-contact sample holder was designed and tested, but sockets for all cryostats were not available in time.
Figure 3.6: Top view SEM pictures of typical gold samples with the first (a) and the second layout (b). In c) pictures taken under tilted condition.
3.3 Electrical Measurements

When measuring in the nanovolt regime one has to overcome certain difficulties. Major issues are the low signal to noise ratio (S/N-ratio) and high thermoelectric voltages. For this work two different, supplementary methods were used to minimize the measurement’s error; namely AC measurements using a lock-in amplifier and DC using hardware synchronized current reversal. A brief overview over noise, thermoelectric voltages and both measurement techniques is given below.

Although the necessary devices for hardware synchronized DC current reversal were available at the WMI, it had never been implemented before. Therefore, a corresponding setup was assembled. More details on this configuration is given in appendix A.

3.3.1 Noise

There are different intrinsic noise sources present in every electronic signal. All noise sources are incoherent, giving the total random noise as the square root of the sum of the squared single sources.

**Johnson Noise** \[52, 53, 54\] is a noise source existing in all circuits and is created across the terminals of every resistor. The open-circuit noise voltage generated by a resistance \(R\) at a certain temperature \(T\) is given by

\[
V_{\text{noise}} \text{(rms)} = \sqrt{4kTR\Delta f}, \tag{3.1}
\]

where \(k\) is the Boltzmann constant \((1.38 \times 10^{-23} \text{ J/K})\) and \(\Delta f\) the equivalent noise bandwidth. Its origin is the thermal fluctuations in the electron density within the resistor. Even in equilibrium, that is without any applied voltage, Johnson noise exists. Its spectral power density is approximately equal throughout the whole frequency spectrum up to about 80 GHz, explaining why it is also often called white noise.

**Flicker Noise** \[54, 55\] is another very prominent source, often also called pink noise or \(1/f\)-noise. As indicated by the names, its spectral power density is not con-
stant, but falls off for higher frequencies. The possible physical causes are manifold, e.g. impurities in a conductive channel or generation or recombination noise in a transistor. It often affects signal quality in the input amplifier stages of measurement devices. In contrast to the Johnson noise, increasing the driving current does not improve, but can even worsen the S/N-ratio due to its direct dependence on the current.

**Shot Noise** owes to the finite nature of the carriers. Random fluctuations in the electrical current $I$ can occur and give rise to a noise current

$$I_{\text{noise}} \text{(rms)} = \sqrt{2eI\Delta f}$$

with $e$ being the electron charge. It is frequency independent, but scales with the signal current as $\sqrt{I}$ and therefore is more pronounced in low current measurements.

### 3.3.2 Thermoelectric Voltages

Thermoelectric voltages occur between points of different temperature in a conductor. This is often also referred to as the Seebeck effect. The physics behind can be explained as follows: higher temperature means that the charge carriers have higher kinetic energies. Therefore more carriers will diffuse from the hot point to the cold and will lead to an imbalance of charge and with this to an electric field $E_{\text{thermo}} = S \cdot \nabla T$, where $S$ is the Seebeck coefficient.

As depicted in Fig. 3.8a, having the same material all over the circuit, a measurement will not be influenced by thermoelectric voltages. For constant $S$ the voltage is $V_{43} = \int E \cdot \mathbf{d}r = S \int \nabla T \mathbf{d}r = 0$.

Connecting two materials A & B with different Seebeck coefficients $S_A$ & $S_B$, one gets a so-called thermocouple, as shown in Fig. 3.8b. For temperatures $T_1 \neq T_2$ there exists a potential difference of

$$V_{\text{Seebeck}} = \int_{T_1}^{T_2} (S_A(T) - S_B(T)) \cdot dT \quad (3.2)$$

between the two contacts. Its magnitude is in the order of some $\mu$V/K.

The origin for the temperature gradient could be extrinsic or intrinsic. The later refers to the existence of a temperature gradient between different points on the sample due to Joule heating by a current flow: $P = IR^2$. In contrast the extrinsic
3.3 Electrical Measurements

Gradient is not created by the used current but by coupling to different temperature baths. Obviously, for both origins, one expects no dependence on the sign of the current.

3.3.3 Common Mode Offsets and Noise

Another, more technical issue, can be the common mode rejection ratio (CMRR) of the different input amplifiers itself. CMRR specifies how well variations in the amplifier’s low potential can be rejected and is defined as $\text{CMRR} = \frac{A_{\text{NM}}}{A_{\text{CM}}}$ with $A_{\text{NM}}$ & $A_{\text{CM}}$ as the normal mode or respectively the common mode gain of the amplifier. After amplification, the output voltage has to be scaled, generally in the digital interface, to obtain the original value. The measured voltage, as detected by the device, will be thus $V_{\text{meas}} = (A_{\text{NM}}V_{\text{sample}} + A_{\text{CM}}V_{\text{error}}) A_{\text{NM}}^{-1} = V_{\text{NM}} + \frac{V_{\text{CM}}}{\text{CMRR}}$.

As depicted in Fig. 3.9, the four-wire configuration should enable one to measure the resistance of the sample without influence of the wires: $V_{\text{NM}} = R_{\text{sample}} \cdot I$. Taking into account the finite CMRR, the common mode voltage $V_{\text{CM}} = R_{\text{lead}} \cdot I$ leads to an offset error of

$$\frac{V_{\text{error}}}{V_{\text{sample}}} = \frac{R_{\text{lead}}}{R_{\text{sample}}} \cdot \text{CMRR}^{-1}$$

and with the same factor common mode noise is injected into the signal.

In most applications the error will be negligible, but if low resistances of, e.g., 1 mΩ are connected via a contact structure with resistance of 100 Ω, the percentual error $\frac{V_{\text{error}}}{V_{\text{sample}}}$ will be 100% for a device with a CMRR of 100 dB.

In the same manner any common mode noise present in $V_{\text{CM}}$ will be introduced partially into the measured voltage.

3.3.4 Low Level Measurement Techniques

To extract the original signal from the background noise, one often uses lock-in amplifiers or a combination of a nanovoltmeter and a current source with current reversal.

**Lock-in amplifiers** use the phase-sensitive detection (PSD) to single out the component of the signal at a specific reference frequency and phase [57]. A schematic overview can be found in Fig. 3.10. The lock-in generates a sinusoidal reference signal with given frequency and phase $V_{\text{ref}} = V_r \sin (\omega_r t + \theta_r)$ and multiplies it with the input signal. If this is also a sinusoidal $V_{\text{input}} = V_s \sin (\omega_s t + \theta_s)$, the resulting

---

6 generally the CMRR is quoted in dB: $\text{CMRR (dB)} = 20 \log_{10} (\text{CMRR})$
output $V_{\text{mult}}$ contains two AC signals\footnote{This can be easily proven by the use of the trigonometric identity $\sin \theta \sin \vartheta = \frac{1}{2} \left( \cos (\theta - \vartheta) - \cos (\theta + \vartheta) \right)$} one with the difference $(\omega_r - \omega_s)$ and the other with the sum frequency $(\omega_r + \omega_s)$.

For $\omega_s = \omega_r$, the difference frequency component will be a DC voltage, and can be separated by a low pass filter with cut-off frequency $\omega_{\text{cut}} = 1/\tau_{\text{RC}}$. $\tau_{\text{RC}}$ is the time constant, or often called integration time because the low pass is nothing else than an integrator:

$$V_{\text{out}} = \frac{1}{\tau_{\text{RC}}} \int_t^{t+\gamma_{\text{RC}}} V_{\text{mult}}(t') \, dt'.$$

The final output will be proportional to the signal amplitude and the phase difference

$$V_{\text{out}} = \frac{1}{2} V_s V_r \cos (\theta_s - \theta_r).$$

For a known phase shift one can determine the signal’s magnitude. To detect simultaneously magnitude and phase, dual-phase lock-in amplifiers use a second PSD stage with a signal shifted by 90°. The output of this will be proportional to $\sin (\theta_s - \theta_r)$.

Knowing the reference signal and defining $\theta_r \rightarrow 0$, the two outputs will be $X = V_s \cos \theta_s$, the 'in-phase' component, and $Y = V_s \sin \theta_s$, the 'quadrature'. The complete signal can be restored via

$$V_s = \sqrt{X^2 + Y^2}, \quad \theta_s = \tan^{-1} \left( \frac{Y}{X} \right).$$

The whole setup works like a very narrow, variable band-pass filter, the quality of which is defined by the equivalent bandwidth, which should not be confused with $\omega_{\text{cut}}$ and depends also on the filter’s order, the so-called roll-off\footnote{for more details see the Stanford Research System Manuals \cite{57}}.

The measured signal can be modulated in a variety of ways. In resistance measurements this is done by using an AC current source controlled by the output of the lock-in, which reproduces the reference signal.

\textbf{Current reversal with Nanovoltmeter} is another commonly applied way to measure low voltages. Here one takes a voltage $V_1$ with a certain response time $\tau_{\text{resp}} \propto 1/\Delta f$, then inverts the signal and measures again, yielding $V_2$. The mean $V_{\text{mean}} = 1/2 (V_1 - V_2)$ is the measurement value. All offsets and noise having lower frequencies than the one of the switching cancel out \cite{59}.

To achieve a high accuracy for the single DC measurements $V_1$ & $V_2$, commercially available nanovoltmeters chop the input signal with a certain frequency, above the
3.3 Electrical Measurements

Figure 3.11: Schematic diagram of a chopper type, dc nanovoltmeter, taken from [58]. CH1 and CH2 denotes the choppers for modulation and demodulation, respectively. The signal is fed at $V_S$ and the output at $V_4$ put into a low pass filter, amplification occurs at $A_1$, feedback via the IOA.

$1/f$- portion of the amplifier’s input noise. As can be seen in Fig. 3.11, the signal is amplified in the next stage, afterwards demodulated leading to a DC component, which is finally sent through a low pass filter [58].

Hence one can measure DC-signals while avoiding the flicker noise of the amplifier input. Depending on the total setup and its time constants the ratio between $\Delta f$ and the switching frequency is crucial. Higher switching frequency cancels out low frequency noise and thermal fluctuations, but on the other hand lowers $\Delta f$, leading to higher white noise components.

**Comparing lock-in and current reversal** one finds, that the same mechanisms are used to reduce errors and noise. By applying a current with alternating sign, constant or slowly varying offsets are canceled, no matter whether using AC current or reversing a DC current. Thermoelectric voltages should cancel because they do not depend on the current direction. Furthermore the S/N-ratio is improved by narrowing the equivalent noise bandwidth $\Delta f$.

Although the signal is modulated in both systems to avoid flicker noise, where the modulation takes part is quite different. In lock-in measurements the signal sent across the sample itself is modulated, while for the DC measurement this is done only in the input stage of the measurement amplifier. Depending on the setup, this can be advantageous or not. If one can choose high enough frequencies, it is useful to modulate the original signal, suppressing low frequency parts introduced by the sample or the leads. Unfortunately, for setups or samples with high reactances one is forced to use low frequencies, favoring modulation in the input stage only.

For the non-local measurements done here, also the voltage created by the mutual inductance can limit the range to lower frequencies. To estimate the expected
magnitude, one can apply the simplified picture of two long, parallel wires. Using well known formulas, e.g. in [60] on page 31, one yields a value of $4.2 \mu H$ for wires with length 1 mm, which are separated by a distance of 100 \( \mu \)m. This is more or less the case in the contact structures. If one uses values for the innerstructure, distance of 200 nm and lengths of roughly 10 \( \mu \)m, the mutual inductance is only $\approx 70 \, nH$.

Another example for the dependence of the quadrature’s signal \( Y \) on \( f \) in a lock-in measurement is shown in Fig. 3.12. One can see, that depending on the actual contact configuration, a positive or negative voltage is generated. Linear fitting yields a value for the mutual inductance of a few \( \mu \)H. This indicates, that the voltage is created by the mutual inductance of the contact structure.

Another reason promoting DC measurement is their typically higher CMRR. The lock-in used in this work is a Stanford Research Systems SR-830 with a CMRR of 100 dB at frequencies up to 10 kHz, while the nanovoltmeter’s reference sheet, which was the model 2182A from Keithley Instruments, quotes a CMRR of 140 dB, improving the S/N-ratio and offset errors in common mode by a factor of 100.

The connection scheme was a bit different depending on which method used. The lock-in amplifier was connected to the so-called Delft-Box, an analog measurement rack manufactured by the technicians of the Quantum Transport Group at the Technical University Delft, The Netherlands. It comprises a voltage driven current source, which has galvanically isolated input and a differential amplifier with again isolated output. To reduce noise pick-up, the source can be driven in differential mode. For the DC-measurements, the source, a 2400 SourceMeter from Keithley, and the nanovoltmeter where connected without any intermediate amplifiers and isolation. Although the electrical isolation is very handy, intermediate stages can enlarge response times and add additional noise, which was seen in first experiments.

With measurements performed at a short circuited sample carrier, noise levels and errors were compared for the different setups. In order to see the quality of the entire setup, the carrier was installed in the cryostat. The results for the optimized settings and a current of 100 \( \mu \)A are shown in Fig. 3.13. In Fig. 3.13a the measurement for 3 K (upper half) and 300 K with the lock-in amplifier at a refer-
ence frequency of 17.371 Hz, is shown. The integration time of 300 ms and a filter slope of 24 \text{db/oct}. results in a settling time of 3 s \[^{57}\]. In Fig. 3.13b one can find the same measurement using DC current reversal with an integration time of one power line cycle, which equals 20 ms, and digital filtering of 15 subsequent voltage samples. The total settling time for one current reversal was determined to 130 ms by measuring the trigger output signal with an oscilloscope. The total settling time is thus 1.95 s.

While the lock-in shows a peak-to-peak noise level of roughly 120 \text{nV}, the DC current reversal exhibits only about 12 \text{nV} noise. The difference can be explained by the better CMRR of the Keithley and the limitation to low frequencies for the lock-in in our case \[^{59, 61}\]. For further improvements, one can choose an integration time of 1 s for the lock-in or average over \(N\) samples, which decreases the noise by the factor \(1/\sqrt{N}\).

A second detail one can notice is, that at 3 K both measurements show a value of nearly zero. The reason is, that the short-circuit was soldered using a solder which becomes superconducting at this temperature\[^9\]. The offset from zero is introduced by the common mode voltage \(V_{CM}\). If one assumes a lead resistance of 20 \Omega, the expected offset for the lock-in is 20 \text{nV} and for the nanovoltmeter 0.2 \text{nV}, in good agreement with the actual measurement.

For the obvious reason of highly improved measurements, mainly the nanovoltmeters were used after all necessary routines were implemented in \textit{Labview}.

\[^9\]The critical temperatures for Pb and Sn are 7.2 and 3.7 K \[^{43}\].
3.3.5 Differential Resistance Measurement

A very important measurement to characterize nanostructures is the differential resistance measurement, in which the slope \( R(I) = \frac{dV}{dI} \) of the \( V-I \)-characteristic is determined. If the mathematical derivative is calculated out of a simple voltage-current sweep, the S/N ratio is very low. An improvement is the use of a mixed signal, including the bias current \( I_{bias} \), which is swept through the desired current range, and a considerably smaller, superimposed measurement current \( I_{meas} \). Thus, the signal alternates with an amplitude of \( I_{meas} = \Delta I/2 \) around the actual bias current \( I_{bias} \). In Fig. 3.14a the response of an ohmic sample on such a signal is depicted. The modulation in the current will be reflected in the voltage. If \( \Delta I \) is smaller than the feature size of the \( V-I \)-characteristic, one can apply \( \Delta V \approx R|I_{bias} \cdot \Delta I| \). The use of either AC or quasi DC modulation is possible, resulting in the stimuli shown in Fig. 3.14b.

The most common way to measure \( \frac{dV}{dI} \) in experiment is the use of a lock-in amplifier, whose voltage output is summed with a variable bias, generated by a digital-to-analog converter, in a voltage adder and afterwards fed to a current source (cf. Fig. 3.14c). If applied to a sample, the AC signal can be extracted by the lock-in amplifier.

Alternatively, the DC current method described above can be implemented \[62, 63\]. This comprises less hardware complexity (cf. Fig. 3.14d), but the necessity...
of tight synchronization between the source, the meter and the acquiring personal computer needs an extra effort in software development.

Concerning noise and offset errors, the DC current reversal exhibits again a higher performance for our samples, which can be explained along the same lines as in Sec. 3.3.4.

### 3.4 Summary

During this thesis a procedure for the fabrication of metallic nanostructures, with the smallest feature sizes being as small as 50 nm, was developed. A two step process, including photo- and electron beam lithography, was applied to prepare wire structures made of either nickel, gold or aluminum. Two complementary measurement setups for low level signals were implemented and compared: a AC configuration using a lock in amplifier and a DC setup with hardware triggered current reversal. Both configurations can be used for differential resistance measurements, magnetic field and temperature sweeps. For the objective of measuring very low signals with a highly resistive and inductive contact layout, the comparison of actual measurement data and theory favor the use of the DC option, whose S/N ratio is roughly one order of magnitude better. The resolution limit of the DC current reversal setup established in this work is of the order of 1 nV.
Chapter 4

Results

This chapter aims to give an overview of the data acquired during this work. The results are surprising and up to now not fully understood. Therefore a separate chapter is dedicated to the discussion of possible explanations (cf. Chapt. 5). After an introduction to the used nomenclature and sample configuration, the data of the original experiment with gold multi-H structures is presented. Subsequently, experiments with the same sample layout, but two other materials, aluminum and nickel are addressed. Finally a short conclusion summarizes the most important results, which are essential for the discussion in Chapt. 5.

4.1 Introduction

The measurements, which will be presented in the following sections, have been performed using two different contact configurations. For the determination of the local quantities, which are the longitudinal resistances $R_{\text{local}}$ and the deduced resistivity $\rho$, a conventional four point measurement configuration is used. The current is sent through the vertical wire, while the voltage probes are attached to two horizontal wires (cf. Fig. 4.1). To avoid Joule heating, the current should not exceed 100 $\mu$A (cf. Sec. 4.2.3). The high and low voltage inputs and current outputs, symbolized by + and -, are located on the same side, so that a positive voltage sign is detected for a positive current flow. Throughout this work, the length $L$ is measured from center to center of the wires. Due to the fabrication procedure the width of the vertical wire, $w_\uparrow$, can deviate slightly from the horizontal wire width $w_\leftrightarrow$, which should be taken into account when calculating the resistivity.

Figure 4.2 illustrates the configuration, which is used for the detection of the non-local voltage signal. The current, which again was usually chosen to 100 $\mu$A, is passed through one of the horizontal wires. The voltage probes are situated on the ends of another, parallel wire, which is not directly exposed to the current flow. As voltages generated by the Spin Hall Effect or current spreading scale linearly with the applied current, it is reasonable to introduce the non-local resistance $R_{\text{nonlocal}} = \frac{V_{\text{nonlocal}}}{I_{\text{local}}}$. One should keep in mind that, in contrast to the local resistance $R_{\text{local}}$, it is not
a true resistance, but a normalized voltage signal and therefore can take negative values.

All presented data is obtained with the current reversal method, as in the present scenario its performance is higher than the setup including the lock in amplifier (cf. Sec. 3.3.4). For a measurement current of 100 µA the noise level is about 0.1 mΩ, which can be further decreased to \(0.1/\sqrt{N}\) mΩ by averaging over \(N\) acquisitions. The maximum resolution is defined by the CMRR and takes a value of about 50 to 100 µΩ for the typical lead resistances found here. It was checked that there were no influences when connecting up to three nanovoltmeters simultaneously (cf. Fig. 4.2). As this was not the case, time intensive experiments, like temperature or magnetic field sweeps were performed using multiple nanovoltmeters.

### 4.2 Gold Structures

As described in chapter 2, due to the combination of a giant Spin Hall angle of 0.113 and the relatively large spin diffusion length \(l_s\) of 168 nm, gold should be the ideal metal to detect the SHE in a multi-H structure.

A variety of gold samples was made, including two different deposition processes, via effusion cell or electron beam evaporation (cf. Sec. 3.1) and two thicknesses, 50 & 26 nm. Furthermore, the exposure method in the electron beam lithography (EBL) step was varied for some samples. Instead of scanning an area, which has approximately the desired dimensions, with a low dose, one can scan single lines once, but with a higher dose. This leads to even smaller structures, while compromising reproducibility and quality due to higher vulnerability on slightest irregularities in beam intensity (cf. Fig. 4.3).

In the following, four samples are selected to be described in more detail. The first is made via an area scanned pattern and consists of 50 nm thick gold, which was deposited with the effusion cell (Sample A). Furthermore a structure, fabricated with a pattern, which was defined by line scans, is shown (Sample B). It was fabricated
on the same wafer and in the same run as the first sample, wherefore the gold has
the same thickness and similar quality as Sample A. The other two samples were
prepared by the use of the electron beam evaporation method. They differ in their
thicknesses of 50 and 26 nm (Samples C & D, respectively), while the pattern of both
was defined by scanning an area with the electron beam in the EBL step, as for the
Sample A. Furthermore the actual structure of those are not necessarily equal, as
they were made in different runs.

The pattern and the dose were chosen in a way, that according to preliminary tests,
a width of 75 nm was expected. Nevertheless slight variations can not be excluded in
such small nanostructures. Therefore the widths for the horizontal \( w_{\rightarrow} \) and vertical
\( w_{\updownarrow} \) wires was measured with the SEM with an accuracy of roughly 5 nm. Samples
A & D show a correct width for both directions, while Sample C has an enhanced
width for the vertical bar \( w_{\updownarrow} \approx 110 \text{ nm} \). A possible explanation is an astigmatism
correction which is not perfectly adjusted or a slightly misaligned write field. As
expected, Sample B shows a smaller but irregular width which was estimated to
\( \approx 65 \text{ nm} \) (cf. Fig. 4.3b).

The smaller thickness for Sample D was chosen to have a structure, in which the
electron mean free path \( l_e \) is shorter. It is smaller, because a thinner film in general
leads to a smaller grain size and, hence, to a reduction of \( l_e \).

### 4.2.1 Electrical Characterization

The distinct preparation methods should lead to a different layer composition and
therefore different electrical properties. Furthermore, it is not guaranteed that every
wire in a sample is conductive or has a well defined geometry. Free standing resist
fingers or a partly failed lift-off can alter the actual form and therefore the current
path.

For this reason, the samples were first characterized by four point measurements
for different sections of the vertical wire, which have distinct lengths \( L \). If the
longitudinal resistance \( R_{\text{local}} \) is plotted versus the probed length \( L \), one can separate
ill-behaved sections and see in a linear regression fit, \( R_{\text{local}} (L) = \rho / A \cdot [L + L_{\text{offset}},] \).
Figure 4.4: Local resistance, $R_{\text{local}}$, measured with different contact configurations, plotted against the length $L$ for different samples.

by a nonvanishing offset $L_{\text{offset}}$, whether a spreading of the current density into the voltage leads occurs. In Fig. 4.4 one can see the measurement for the Samples A to D. The measured data is shown as circles, while the fits are plotted with solid lines.

As one can see in the graphs, the accessible contacts show very little deviations from the fit for all the presented samples. The data, which could be extracted from the fits is given in table 4.1. The quoted error is not the total uncertainty, but the error margin of the linear fit. The total uncertainty is dominated by the low accuracy of the width determination via SEM of $\approx 5 \text{ nm}$, which corresponds to a percentual error of $5 - 8\%$. The higher variance seen for Sample B corresponds to the width variations found for samples, which were patterned with line scans.

The resistivities at 300 K are roughly a factor three higher than the bulk values of gold, $\rho_{\text{bulk,300K}} = 2.271 \mu\Omega\text{cm}$ [43]. This comes along with low values for the residual resistance ratio $\text{RRR} = \rho_{300K}/\rho_{3K}$ of 1.6 to 1.7 compared to the significantly higher value of $\approx 100$ in bulk [43]. If reducing the lateral dimensions, the resistivity increases, while RRR decreases. This can be seen for smaller width (Sample B) as well as for a thinner film (Sample D).

The decrease of conductivity in thin films is well-known and can be described in the Fuchs-Sondheimer (F-S) theory [64]. Fuchs [65] was the first to suggest the
4.2 Gold Structures

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\rho_{300,\text{K}}$ ($\mu\Omega\text{cm}$)</th>
<th>$\rho_{3,\text{K}}$ ($\mu\Omega\text{cm}$)</th>
<th>RRR</th>
<th>$L_{\text{offset,300,K}}$ (nm)</th>
<th>$L_{\text{offset,3,K}}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$5.74 \pm 0.08$</td>
<td>$3.35 \pm 0.02$</td>
<td>1.72</td>
<td>$3.4 \pm 6.8$</td>
<td>$-1.3 \pm 2.8$</td>
</tr>
<tr>
<td>B</td>
<td>$6.55 \pm 0.13$</td>
<td>$3.96 \pm 0.13$</td>
<td>1.65</td>
<td>$1.6 \pm 9.2$</td>
<td>$-1.6 \pm 15.8$</td>
</tr>
<tr>
<td>C</td>
<td>$6.55 \pm 0.04$</td>
<td>$3.79 \pm 0.03$</td>
<td>1.73</td>
<td>$15.6 \pm 7.1$</td>
<td>$10.8 \pm 8.6$</td>
</tr>
<tr>
<td>D</td>
<td>$7.25 \pm 0.06$</td>
<td>$4.60 \pm 0.05$</td>
<td>1.57</td>
<td>$9.93 \pm 9.63$</td>
<td>$10.7 \pm 11.2$</td>
</tr>
</tbody>
</table>

Table 4.1: Electrical properties, extracted by fits $R_{\text{local}}(L) = \frac{\rho}{A} \cdot (L + L_{\text{offset}})$

- Sample A: 50 nm, Area scanned & effusion cell
- Sample B: 50 nm, Line scanned & effusion cell
- Sample C: 50 nm, Area scanned & e-beam evaporation
- Sample D: 26 nm, Area scanned & e-beam evaporation

Inclusion of diffuse electron scattering at the surfaces and interfaces. Later the theory was extended to thin wires [66, 67] and to incorporate surface roughness [68]. In films and wires, where the mean free path and the grain size become comparable, grain boundary scattering significantly contributes to the resistivity [69]. This also leads to a RRR, which will approach 1 for even thinner samples [70], as the surface and boundary contribution, which are essentially independent of temperature, will become dominant. The actually measured values in this samples correspond to the ones found in literature [71, 72, 73, 74, 75]. Overall, Sample A, which was prepared with the effusion cell, shows the lowest resistivity. This seems reasonable, as one expects larger grain size due to the slower deposition rate (cf Sec. 3.1).

The calculated offset lengths $L_{\text{offset}}$ for the two samples, which were prepared by the use of the effusion cell, are negligible small. They are an indicator for possible current spreading into the voltage leads occurs. Although the fits for the two other samples show a slight offset, it is still in the order of the fit error and the accuracy of the SEM. For this reason, $L_{\text{offset}}$ will be assumed zero for all calculations in the following.

The resistivity $\rho = R_{\text{local}}w_1tL^{-1}$ was also measured as a function of $T$. In these measurements, the temperature was swept while the local resistance was acquired for the largest accessible length $L$. The results for the four different samples are shown in Fig. 4.5. It can be seen that the resistivity saturates for temperatures below 30 K. Above this temperature scales linear with temperature, as expected from electron-phonon scattering [76].

Overall the electrical characterization seems consistent within the measured samples and literature. This demonstrates the high structural quality which was achieved.

Fig. 4.5: Resistivities $\rho$ as a function of temperature $T$
Figure 4.6: Dependence of the non-local resistance $R_{\text{nonlocal}}$ on the temperature $T$. For comparison, the insets show $\rho(T)$. The signal changes sign for low temperatures and shows a saturation for $T \lesssim 30$ K.

4.2.2 Non-local Signal

With the electrical properties showing consistent results, one can go one step further and look at the non-local properties. Measurements on the temperature dependence of the non-local signal $R_{\text{nonlocal}}$ were performed for the different samples. The graphs (cf. Fig. 4.6) show the non-local resistance $R_{\text{nonlocal}}$ measured in the configuration of Fig. 4.2 for varying temperature $T$. The signal was recorded during a down- as well as up sweep, i.e. that the temperature was varied from the maximum to the minimum value and back. No difference depending on the sweep direction could be found. Therefore only one sweep direction is plotted. For comparison the corresponding local resistivity is shown in the insets.

While at room temperature the obtained signal is positive, as expected, at 3 K all presented samples show a negative resistance. Furthermore, the curvature of the $R_{\text{nonlocal}}(T)$ curves differs from the one of the local resistance $R_{\text{local}}(T)$ curves. Whereas the resistivity $\rho(T)$ is about linear for a temperature of $T \gtrsim 30$ K, the non-local signal shows a convex curvature. To highlight this, the ratio $R_{\text{nonlocal}}/\rho t^{-1}$

\[^1\]The results discussed here were also found for all of the approximately 10 other samples.
4.2 Gold Structures

Figure 4.7: Dependence of the ratio of the non-local to the sheet resistance \( R_{\text{nonlocal}}/ρt^{-1} \) on temperature \( T \) for distances of 150 nm (a) and 200 nm (b).

The dependence of the ratio of the non-local to the sheet resistance \( ρt^{-1} \) is shown in Fig. 4.7 as function of \( T \). As described in Sec. 2.6, the non-local signal is expected to be proportional to \( ρt^{-1} \), leading to a constant value in the graph. This is definitely not the case. Furthermore, no obvious dependencies of the signal on the method of sample preparation can be seen. For example, the zero crossing occurs at different temperatures for every sample and distance. However, some similarities can be found for all curves. The temperature of the zero crossing for a particular sample seems to depend on the grade of non-locality (i.e., different values of \( L \)). It occurs at higher temperatures for \( L = 200 \text{ nm} \) than for 150 nm. Another feature is, that the ratio saturates below approximately 30 K, as does \( ρ \).

Generally, non-local signals are expected to decay exponentially with increasing distance. To investigate this, measurements of \( R_{\text{nonlocal}} \) for different distance \( L \) were performed (cf. Fig. 4.8). To improve the S/N ratio a number of measurements at a stabilized temperature were taken and averaged. The noise could be suppressed below the resolution limit of roughly 40 to 70 µΩ (\( ≈ 4 – 7 \text{ nV} \)), which is defined by the CMRR ratio and the lead resistance including the contact structure of roughly 400 – 700 Ω (cf. Sec. 3.3.3) and marked as a green, hatched region in the plots. The data points are depicted as circles for 300 K (red) and 3 K (blue). In some plots two datapoints are shown for the same distance \( L \). This is because the same distance could be found two times on the same structure. To obtain information about the decay length \( λ \), exponential fits \( R_{\text{nonlocal}} = R_0 \exp \left( -L/λ \right) \) were made (solid lines) for all the values, which lie without the error bounds.

Obviously, the signal magnitude decays exponentially with increasing distance for both temperatures and is always positive for 300 K and always negative for 3 K. As an exception the values at 300 K for the Sample A and \( L = 225 \text{ nm} \) & 250 nm show a small, but negative resistance. As the magnitude is smaller than the error margin, the measured value is probably just an offset from zero by the common mode voltage. It can be found, that all samples show comparable results, with exception
of the Sample D. This sample, which has a thickness of 26 nm and therefore a smaller expected \( l_s \), shows values at 300 K, that are an order of magnitude higher than the absolute values at 3 K.

Comparing the fit result, one should be aware of that only few points can be used (for Sample B for example only two) and that the inevitable uncertainty in the widths of the wires would demand for more statistics. But still some observations can be made: the decay length at low temperatures is always a bit higher than at room temperature and in the range of roughly 18 to 31 nm.

The negative voltage and the sign reversal from 300 K to 3 K is surprising, as it is not predicted by either the Spin Hall Effect, nor by current spreading (cf. Sec. 2.6 & 2.4.2) in absence of a magnetic field. Both would lead to a positive sign for all temperatures. The spin current should decay exponentially, with \( \lambda = l_s \), the spin diffusion length. The decay length found here is far below the values found in literature of 86 [11] to 168 nm [42].

**Figure 4.8**: Dependence of the non-local resistance \( R_{\text{nonlocal}} \) on the nominal distance \( L \). The solid lines show exponential fits \( R_{\text{nonlocal}} = R_0 \exp \left( -L/\lambda \right) \), which reveal a comparable characteristic decay length \( \lambda \) for Samples A-D.
4.2 Gold Structures

4.2.3 Control Measurements

As a reversal of the sign of the voltage and a negative sign are predicted neither by the theories of the SHE nor by current spreading effects (cf. Sec. 2.4.2), additional control measurements were made to ensure consistency and to exclude the influence of thermal caloric effects.

The measurement setup was designed in such a way that it should not be influenced by voltages due to thermopowers (cf. Sec. 3.3). Thermal effects typically do not depend on the sign of the current, but rather scale with the power. Thus, using current reversal or sinusoidal AC current, these thermoelectric voltages should cancel. Nevertheless one could imagine configurations, in which a thermoelectric voltage could influence our measurement. Take for example two contacts with diode characteristics. Depending on the current direction one or the other contact will be reverse-biased and dissipate heat (cf. Fig. 4.9). Thus the temperature gradient $\nabla T$ and, in turn, the thermovoltage, can point in different directions.

The relatively high currents which are necessary to measure resistances as low as the non-local ones, combined with the extremely small sample dimensions, will lead to huge values for the dissipated power per unit area $P/A$ of up to 1 kW/cm$^2$. This way temperature gradients of several Kelvin could be built up easily. Hence, it is inevitable to check, whether the measured signal is influenced by the chosen measurement current.

Differential Resistance Measurement

One way to prove whether the measurement is influenced by Joule heating is to determine the differential resistance $dV/dI$ for varying bias current $I_{bias}$, as described in section 3.3.5. Ideally, in absence of heating, the resistance should not depend on the bias current.

The characterization was accomplished with each sample. As always similar results were obtained, only an exemplaric measurement, made at 3 K with Sample A, is discussed here (cf. Fig. 4.10). The graph shows the local (red) and the non-local (blue) resistance for a varying bias current $I_{bias}$. The measurement exhibits a change in $R_{local}$ and $R_{nonlocal}$ for $|I_{bias}| \gtrsim 0.3$ mA. While the local signal increases for higher currents, the absolute magnitude of $R_{nonlocal}$ decreases.

The change in the local resistance is related to a local heating of the sample due to the power dissipated by the current, $P = IR^2$. This will lead to an enhanced temperature for the region, which is exposed to the current flow. If the temperature is so high that the resistivity is changed (cf. Fig. 4.5), the measured local resistance will increase. The decrease of the maximal magnitude of the non-local signal excludes an influence of thermoelectric voltages, as the temperature gradients increase with
Figure 4.10: Measurement of the differential resistance $\frac{dV}{dI}(I_{\text{bias}})$ at $T = 3$ K in non-local (blue, left scale) and local (red, right scale) configuration with $I_{\text{meas}} = 10 \mu$A using DC current reversal. Dark and light colors indicate the up and down sweep, while the green marked region denotes the maximal currents used in this work.

the measurement current. The magnitude depends only on the absolute value of $T$ and not on its gradient.

The green marked region in the graph shows the maximum measurement current which has been used, never exceeding $100 \mu$A. No significant changes of the signal can be found in this region, and one can assume to not influence the measured quantity by the select current.

**Variation in Contact Scheme**

Another way to exclude thermoelectric effects, especially those originating from non-ohmic contacts, is to compare different connection schemes. For this purpose the layout of the inner structure was changed in such a way, that it is possible to contact the same wire by completely different connections (cf. Fig. 4.11). The number of joined H-structures was reduced to allow additional connections to one wire end. This way the single-H structure with nominal distance 150 nm can be accessed via different paths, including various bond contacts. If the signal were caused by temperature gradients, it should change dramatically by using another, spatially remote contact.

First, the wires carrying current and the voltage leads were interchanged. The current path was once through the upper wire (green) and once though the lower (orange) (cf. Fig. 4.12b). In Fig. 4.12a), where the non-local signal is plotted versus the temperature, one can see, that the two measurements are perfectly identical.

Additionally, measurements with different voltage configurations have been made. Three nanovoltmeters were connected in different ways to measure the same wire via distinct contacts. This was made for all possible permutations. One example
is shown in Fig. 4.12. Figure 4.12d shows the used contact configuration. The colors in the schematic correspond to the ones in the graph, in which \( R_{\text{nonlocal}} \) is plotted as a function of the temperature \( T \). Although spatially separated bond pads and different contact for the low input of the measurement amplifier were used, no change in the signal can be found.

Thus caloric effects have negligible influence on \( R_{\text{nonlocal}} \).

Figure 4.11: Layout with variable contacting possibilities for two single H-structures and nominal distance of 150 nm

Figure 4.12: Non-local resistance \( R_{\text{nonlocal}} \) versus temperature \( T \) for different contacting schemes with \( L = 150 \) nm and \( I = 100 \mu\text{A} \). It can be seen, that the signal is independent of the actual configuration.
4.2.4 Influence of a Magnetic Field

The theory presented by Abanin et al. [13] (cf. Sec. 2.4.4) predicts oscillations and suppression of the non-local signal for an applied in-plane magnetic field. Furthermore, a sign change should occur for $\omega_B \tau_s \geq 1$, where $\omega_B = g\mu_B |B|$ is the Larmor precession frequency and $\tau_s$ the spin relaxation time, with $g$ the g-factor and $\mu_B \approx 9.27 \times 10^{-24}$ J/T the Bohr magneton. Measurements showed, that $g = 2.11$ and $\tau_s = 5 \times 10^{-10}$ s in bulk gold [10]. With this information one can estimate the necessary field to observe oscillation and suppression to $B_\ast = \frac{\hbar}{g\mu_B \tau_s} \approx 11$ mT. The value can further decrease for low temperatures, as the spin relaxation time should increase at lower temperatures [77]. In principle, this could be an explanation for the negative signal, if one measures in a cryostat with superconducting coils. Within those a magnetic flux can be trapped and thus a small field could be present, if the coils were not warmed up before the measurements. On the other hand, due to the small field needed to suppress the non-local signal, it should be very sensitive to an externally applied magnetic field.

Measurements with in-plane fields of up to $\pm 7$ T and out-of-plane orientation with field strengths as high as $\pm 14$ T were made and are presented in Fig. 4.13. The graphs show always a sweep from low to high field (blue) and back (red). Figures 4.13 a & b show $R_{\text{nonlocal}}$ for an in-plane magnetic field, oriented perpendicular and parallel to the electrical current (cf. insets). In Fig. 4.13: the result of the out-of-plane configuration is presented. Every data point is averaged over 10 subsequent acquisitions for the in-plane and the out-of-plane configuration. Thus the expected noise (cf. Sec. 3.3.4) is as low as $100 \mu\Omega/\sqrt{10} \approx 30 \mu\Omega (\neq 3$ nV).

For the whole accessible field range, the signal does vary only slightly, a suppression or a change in sign is not observed anywhere. In the out-of-plane configuration a change in resistance of about $-0.1/1.85 \approx -5\%$ can be seen for high field values of 14 T, i.e. the absolute value of the negative resistance decreases. This can be probably attributed to the ordinary magneto resistance effect.

As the field range is quite high, a zoom-in of an arbitrary chosen part is depicted in Fig. 4.13 d, where the measurements seem quite noisy at a first glance. But the values for $R_{\text{nonlocal}}$ which were achieved in the up and down sweep are identical within the predicted noise margin for every single field point[2]. This way, one can not talk about noise, but of reproducible fluctuations. The most probable cause for those are the so called universal conductance fluctuations (UCFs) (cf Sec. 5.4).

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[2] Once again, the result highlights the exquisite resolution of the new measurement setup, keeping in mind the possibility to contact 20-pins in a cryogenic environment without any further pre-amplification and the little overall hardware expenses. With the initially used lock-in configuration, none of this details could be detected.
4.3 Aluminum

To investigate whether the presence of negative resistance is only observable in gold, aluminum sample were prepared. Although aluminum has a long spin diffusion length\(^3\) of 0.5 to 0.7 µm \([8, 44]\), the spin hall ratio \(\sigma_s/\sigma_c\) is small, with a value of \(1 \times 10^{-4}\) \([44]\). Therefore the Spin Hall Effect should be negligible (cf. Sec. 2.4.3).

A series of samples with an aluminum film of 50 nm thickness was prepared by electron beam evaporation. The geometric pattern was left unchanged and the outer contact structure consisted still of a 25 nm thick gold structure. It turned out that without further treatment the measurement on the aluminum samples is difficult, as after a short time (some days) the samples became non-conductive. One plausible reason is that by the handling in normal atmosphere the thin aluminum film oxidized. For this reason, the number of measurements on aluminum samples is lim-

\(^3\)For Comparison: in Au \(\alpha_{SHE} = 0.113\) & \(l_s = 168\) nm
Nevertheless, temperature sweeps on one sample are shown in Fig. 4.14a. The non-local resistance is plotted versus the temperature for the distances 200 nm (red) and 225 nm (green). The non-local signal is of order 100 µΩ and thus a bit smaller than in gold, the difference is, however, not significant. As in gold the deviation between the measurements of different samples is substantial, the difference could also result from a variance in the structure geometry.

Figure 4.14b depicts the dependence of $R_{\text{nonlocal}}$ on the distance $L$ for 3 K (blue) and 300 K (red). The datapoints (symbols) are extracted from the temperature sweep. Exponential fits are performed to extract the decay length (solid lines). The obtained decay lengths of roughly 24 nm at room temperature and 34 nm at 3 K have the same order of magnitude as the ones found previously in gold.

Both results, the presence of a negative resistance as well as a characteristic decay length akin to the one in gold is surprising. If the signal were related to the spin orbit coupling, one would expect aluminum to differ significantly from gold, as the strength of the coupling should be extremely different. Thus, not only the negative sign of the signal, but also its presence in Al exclude the Spin Hall Effect as a dominant origin for the detected non-local resistance.

![Figure 4.14: Non-local signal $R_{\text{nonlocal}}$ versus temperature $T$ (a) and distance $L$ (b) in an Al-H-sample. The values of b) are extracted from a). The solid lines show exponential fits $R_{\text{nonlocal}} = R_0 \exp(-L/\lambda)$. It can be seen that the signal magnitude is smaller than in gold, but not significantly. The characteristic decay length is about the same size as in gold.](image-url)
4.4 Nickel

As a ferromagnetic material, nickel was used for a series of multi-H structures. The samples were prepared by electron beam evaporation as described in chapter 3. The pattern width and the electron beam dose was selected such, that, considering the prior experiences, a width of 75 nm was expected. The thickness of the film was 50 nm. Because the nickel did not stick directly to the silicon oxide, 3 nm of gold were deposited as an adhesive layer first. The ratio between the two bulk resistivities, $\rho_{\text{Ni}}/\rho_{\text{Au}}$, is roughly 3, while the ratio between the layer thicknesses is about 17. Additionally, as seen before (cf. Sec. 4.2.1), both surfaces may enhance significantly the specific resistance of the very thin gold layer. To conclude, it seems reasonable to presume, that the current mainly flows in the Ni film. For this reasons, the adhesive layer is neglected and a nickel layer of 53 nm thickness is assumed.

Images made with the scanning electron microscope show that the horizontal wires have the desired dimensions. However, a slightly enhanced width ($\approx 80$ nm) for the most adjacent ones, with distances 150 and 200 nm, is found. For the vertical bar an even more pronounced widening to $\approx 110$ nm occurred. Those values are similar to the ones of the thin gold sample (cf. Sec. 4.2), what is not surprising because the wafer and thus the pattern written by EBL is the same for both.

To avoid unpredictable alterations of the sample’s surface, the images were made subsequent to the measurements. Several samples were measured and as similar results obtained, all data presented in the following (with exception of data in Fig. 4.16), is of one single sample. In this way consistency of the values is ensured.

4.4.1 Magnetic Structure

Nickel has a Curie temperature of 631 K [43] and therefore orders in a ferromagnetic state at room temperature and below. Generally, due to shape anisotropy the wire axis is also the easy axis of the magnetization in ferromagnetic nanowires [78, 79]. Therefore the easy axis of vertical and horizontal wires should be perpendicular, leading to rich physics at the crossing points, like a diversity of domain configurations. Furthermore the anisotropy can change with temperature due to a change in strain anisotropy caused by a tensile stress from a thermal expansion mismatch between nanowire and substrate [78, 80, 81]. In this work only the situation where the direction of the magnetization is well defined will be considered.

To find out which fields are needed to saturate the nickel nanostructures, magneto transport measurements for various in-plane magnetic fields $\mathbf{H}$ were accomplished. The sample was rotated in a constant magnetic field $\mathbf{H}$ to obtain different angles between field and current $\mathbf{I}$, at which the local resistance $R_{\text{local}}$ was determined with an applied current of 100 $\mu$A (cf. Fig. 4.15). The rotation was done for both senses of rotation successively and the current applied along the $y$-direction, as depicted in the inset of Fig. 4.15.

---

4 The outer contact structure was still made of gold
5 7.12 $\mu\Omega$cm for nickel and 2.255 $\mu\Omega$cm for gold at room temperature [43]
Figure 4.15: Dependence of the magneto resistivity on the angle \(\theta = \angle (\mathbf{H}, \mathbf{I})\) for a length of 2.25 \(\mu\)m. At low fields switching and hysteresis is present, at high fields of 2 T a \(\cos^2(\theta)\) behavior free of anisotropy.

In a ferromagnet, like nickel, the measured resistivity depends on the angle between magnetization and current flow due to the influence of the spin-orbit interaction on scattering. The effect is called anisotropic magneto resistance (AMR). In nickel the resistance for parallel orientation of \(\mathbf{H}\) and \(\mathbf{j}\) is higher than for \(\mathbf{H}\) perpendicular \(\mathbf{j}\). According to the Stoner-Wohlfahrt model (cf. [22]), one expects a perfect \(\cos^2(\theta)\) behavior of the magnetization, and thus of the resistance, if the Zeeman term dominates in a single domain ferromagnet. The angle \(\theta\) is defined as the angle between the current \(\mathbf{I}\) and the magnetic field \(\mathbf{H}\). Thus in the local geometry \(\theta = 0^\circ\) corresponds to \(\mathbf{H}\) parallel to the \(y\)-axis (cf. insets of Fig. 4.15).

The measurements exhibit a hysteretic behavior and sudden switching for lower fields, e.g. for 40 mT (red). For fields of 100 mT (blue) a deviation from the \(\cos^2(\theta)\) behavior can still be found, which vanishes for high fields, like at 2 T (green). The ratio \(\frac{R_\parallel - R_\perp}{R_\perp} = \frac{R_\parallel}{R_\perp} - 1\), which will be called the AMR value in this work, is 1.64\%. This is comparable to the value of AMR = 1.8\% found in literature [82].

Additionally, measurements of the local resistance in which the magnetic field strength was varied for parallel and perpendicular orientation of current were performed (cf. Fig. 4.16, note that data is taken from a different sample as those preliminary studies were not performed at every sample). The measurements show that the magneto resistance for parallel configuration increases, while for perpendicular field it stays nearly zero. Small features can be found around 15 mT. One can draw the conclusion that the magnetization in the vertical bar, where the current flows, is mainly transversely oriented and becomes only parallel for fields of more than 0.5 T.

This orientation of the easy axis originates probably from the influencing, horizontal wires (cf. inset in Fig. 4.15). The overall magnetization direction in the vertical bar will thus not change much by a field applied in \(x\)-direction and therefore stay in
the configuration of minimal resistance. For parallel aligned field, the magnetization will be forced out of the easy axis, towards a parallel alignment to current and with this towards a higher resistance.

As one can see, the influence of the shape anisotropy exists up to relatively high fields of 0.5 T. Considering the observations, a magnetic field of $\mu_0 H = 2$ T was chosen in subsequent measurements to ensure a well defined magnetization.

### 4.4.2 Electrical Characterization

As for gold, a characterization of the local signal should be done prior to any non-local detection. In Fig. 4.17, the local resistance $R_{\text{local}}$ is plotted (symbols) for distinct contact configurations and therefore for different lengths $L$. A field of 2 T was applied parallel to the current in order to saturate the magnetization and define its direction. Linear regression fits, $R_{\text{local}}(L) = \rho/2 \cdot (L + L_{\text{offset}})$ (solid lines), were performed to see whether a spreading of the current density into the voltage leads occurs and whether all contacts show a reasonable resistance. The fit results are listed in Tab. 4.2. As one can see in the graphs, the accessible contacts show little deviations from the respective fit for all contacts. Calculations of the resistivity\(^6\) give a value of 17$\mu\Omega$cm for 300 K, which is about a factor 2.5 higher than the bulk value of 7.12$\mu\Omega$cm\(^7\). As for the gold samples (cf. Sec. 4.2.1), this can be explained by a higher influence of surface and grain boundary scattering.

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\(^6\)for which, as explained before, a thickness of 53 nm was assumed
Figure 4.17: Local resistance $R_{\text{local}}$ for varying distance $L$ (a) and resistivity $\rho_{\parallel}$ in dependence of the temperature $T$ (b), both measured for magnetic fields applied parallel to current and $H = 2$ T. Linear fits show little deviation for the different contacts and an overall well defined pattern.

<table>
<thead>
<tr>
<th>$\rho_{300,\text{K}}$ ($\mu\Omega\text{cm}$)</th>
<th>$\rho_{3,\text{K}}$ ($\mu\Omega\text{cm}$)</th>
<th>RRR</th>
<th>$L_{\text{offset,300,\text{K}}}$ (nm)</th>
<th>$L_{\text{offset,3,\text{K}}}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17.0 ± 0.08</td>
<td>7.4 ± 0.02</td>
<td>2.31</td>
<td>12.7 ± 18.0</td>
<td>13.4 ± 18.0</td>
</tr>
</tbody>
</table>

Table 4.2: Electrical properties, extracted by fits $R_{\text{local}}(L) = \frac{\rho}{A} \cdot (L + L_{\text{offset}})$

The offset length $L_{\text{offset}}$, which could indicate a current spreading into the voltage leads, is small and within the fit error margins. As previously for the gold sample, a negligible offset length was assumed for the following. Also the dependence of the resistivity on temperature seems reasonable, as Fig. 4.17 depicts. The slope is linear for $T \gtrsim 30$ K, as expected for dominating electron-phonon scattering. Below this temperature $\rho$ saturates at a residual value whose origin is scattering at impurities and boundaries.

### 4.4.3 Non-local Magneto Resistance

If in-plane rotations of the magnetic field are made for the non-local geometry an interesting result is obtained. Figure 4.18 shows the dependence of the non-local magneto resistance $R_{\text{nonlocal}}$ on the angle $\theta$ between field and current $I$. One should notice that this time the current is parallel to the $x$-direction (cf. Fig. 4.2) and thus $\theta = 0^\circ$ means $H$ parallel to the $x$-axis. The magnitude of the field is chosen to $\mu_0H = 2$ T to avoid shape anisotropy. As before in the local geometry, the signal magnitude is proportional to $\cos^2(\theta)$ and higher for $H$ parallel to $I$. The sweeps were performed in both senses of rotation resulting in no difference at all. As expected, the magnitudes of $R_{\text{nonlocal}}$ at a given field orientation are substantially smaller than in the local case. The absolute magnitude is $111$ m$\Omega$ $\leq R_{\text{nonlocal}} \leq 117$ m$\Omega$ for $150$ nm and $1.5$ m$\Omega$ $\leq R_{\text{nonlocal}} \leq 1.75$ m$\Omega$ for $250$ nm.
Figure 4.18: Non-local magneto resistance versus angle $\theta$ between magnetic field and current. The shape resembles the local measurement, following $\cos(\theta)$. Although the absolute value is small, the AMR value is increasing with the non-locality, i.e. the separation $L$. (cf. 4.2).

Surprisingly, the anisotropic magneto resistance value AMR in the non-local geometry is significantly larger than in the local case. Furthermore it increases with higher distances $L$ between the wires, as it is evident from Fig. 4.18. It rises from $\frac{\rho_\parallel - \rho_\perp}{\rho_\parallel} = 6.0\%$ for 150 nm (blue), over 9.8 \% for 200 nm (red), to a value as high as 14.5 \% for $L = 250$ nm (green). For the longest distance available, 300 nm (magenta), an extremely high value of approximately 40 \% can be found. In this case, however, the magnitude is on the edge of the resolution limit of 100 $\mu\Omega$ (\approx 10 nV).
Figure 4.19: Dependence of the non-local signal $R_{\text{nonlocal}}$ on the temperature $T$ with applied field of $\mu_0 H = 2$ T in linear (a) and logarithmic representation (b). As comparison $\rho(T)$ is plotted in the inset of a). It can be seen, that the signal stays positive for all accessible temperatures and saturates below $\approx 30$ K.

4.4.4 Dependence of $R_{\text{nonlocal}}$ on $T$ and $L$

One interesting question with the nickel nanostructures is, how they compare to the gold structures at low temperatures. To find this out $R(T)$ sweeps were performed as before. Here a magnetic field of 2 T was applied in the $y$-direction, and thus perpendicular to the current, to measure with defined magnetization. In Fig. 4.19 the results are presented: in panel a) $R_{\text{nonlocal}}$ is plotted versus the temperature $T$ for different distances $L$ on a linear scale, while b) shows the same data on a semilogarithmic scale for easier comparison between different contact configurations. Furthermore, the inset of Fig. 4.19a shows the resistivity for comparison. The green region in Fig. 4.19b gives the maximum resolution due to CMRR offset errors (cf. Sec. 3.3.3).

The most obvious result is that the voltage stays positive over the whole temperature range, which is a completely different behavior as compared to gold and aluminum (cf. Sec. 4.2.2). Like the resistivity, $R_{\text{nonlocal}}$ saturates for temperatures of roughly below 30 K. If one assumes that the signal is not generated by the Spin Hall Effect due to short spin diffusion length, the positive signal is an indication for the presence of current spreading. But then the signal should be directly proportional to $R_{\text{nonlocal}}$ and the sheet resistance $\rho t^{-1}$. To check this, the signal was divided numerically by the sheet resistance $\rho t$ and plotted versus the temperature (cf. Fig. 4.20). As one can see, the ratio is not constant, and thus the signal is not directly proportional to $\rho t^{-1}$. Nevertheless the changes are small, when compared to the ones in gold (cf. Fig. 4.17). The slope varies slightly, giving the curve a little “bump”. The temperature dependence shows, with exception of the missing sign change, a certain similarity to the ones in gold.

Measurements on the decay length for increasing distance were made and are shown in Fig. 4.21 for $T = 3$ K (blue) and 300 K (red). An exponential decay can be found, as expected and seen prior in gold. If one fits an exponential function to the
measured data, a similar decay length of \( \approx 23 \text{ nm} \) is found for both temperatures. This is different to gold, where the decay length was higher at low temperatures. This suggests that the changes in sign and in the value of the decay length are somehow connected.

![Graph](image)

**Figure 4.20:** Ratio of non-local resistance to sheet resistance, \( \frac{R_{\text{nonlocal}}}{\rho t} \), multiplied by thousand. The dashed line is a guide to the eye.

![Graph](image)

**Figure 4.21:** Dependence of the non-local resistance \( R_{\text{nonlocal}} \) on the nominal distance \( L \). The solid lines show exponential fits \( R_{\text{nonlocal}} = R_0 \exp \left( -L/\lambda \right) \), revealing similar \( \lambda \) as for gold.
4.5 Summary

Extensive studies of non-local effects in nanostructures fabricated with three different metals, Au, Al and Ni, were performed by measurements of the non-local resistance $R_{\text{nonlocal}}$, i.e. the voltage response obtained in a wire when feeding a current to a remote one.

The measurements on gold include the dependence on temperature, distance and an external magnetic field and were accomplished for samples prepared under different conditions. By local resistance measurements the samples were characterized and checked for integrity of the pattern. Due to the small lateral dimensions, the obtained resistivities of $\approx 6 - 7 \mu\Omega\text{cm}$ are roughly a factor 3 higher than the bulk values. The resistivities were consistent not only between themselves, but also with literature.

The non-local signal in gold exhibits a surprising temperature dependence for all measured samples. While for high temperature a positive value is obtained, its sign reverses for low temperatures. For comparison, additional temperature sweeps were made on aluminum and nickel samples. While the gold structures and the aluminum sample showed qualitatively the same results, nickel has a positive non-local resistance over the whole accessible temperature range.

In all three metals, the signal decays at high, as well as at low $T$, over the distance on a characteristic lengthscale of 20 to 30 nm. At 3 K the decay length was a bit longer for all non-ferromagnetic samples. In contrast, the nickel sample showed a similar decay length of $\approx 23$ nm for both temperatures.

Control measurements were made to exclude thermal voltages by a different contact layout and by differential resistance measurements. The latter showed as a remarkable result that in the region of Joule heating the magnitude of the negative, non-local signal decreases with increasing heating and thus can not be attributed to thermal voltages. Furthermore, the signal is independent of the actual contacting scheme.

A magnetic field oriented out-of-plane gave a slight decrease in the negative value for high fields which is probably attributed to the ordinary magneto resistance. Furthermore, reproducible conductance fluctuations were found. Those features could only be resolved because of the exquisite sensitivity of the measurement setup established during this thesis.

The behavior of the nickel nanostructures in a magnetic field is highly interesting. The anisotropic magneto resistance, which can be found in the local signal to be around 1.6 %, not only translates into the non-local resistance, but is even enhanced. Furthermore the enhancement increases with the grade of non-locality, i.e. the distance between current and voltage probes, from 6 % at a distance of 150 nm, to nearly 40 % at $L = 300$ nm.

All findings are discussed in the next chapter.
Chapter 5
Discussion

The measured data (cf. Chapt. 4) is discussed in the following. The chapter is divided into sections about different transport mechanisms. Section 5.1 is devoted to the influence of a spreading of the charge current, while we will discuss in Sec. 5.2 the presence of the Spin Hall Effect. Section 5.3 deals with the influence of ballistic transport, followed by a brief discussion whether the fluctuations described in Sec. 4.2.4 can be attributed to Universal Conductance Fluctuations (UCFs). Finally a short summary is given.

5.1 Current Spreading

In Sec. 2.4.2 the expected non-local signal due to a spreading of the charge current into the vertical bar was calculated and an estimation of the magnitude was made (cf. Sec. 2.4.3). For further improvement of the theoretical prediction, simulations using the finite element method (FEM) were performed for the gold samples. They are presented in Sec. 5.1.1. In the following, the theory and the simulation are extended to describe the non-local AMR effects in nickel. Finally, the results for the discussion of current spreading are summarized in Sec. 5.1.3.

5.1.1 FEM Simulations for Gold

Although the analytical approach can give a qualitative picture, it is not useful for the calculation of absolute values, because the underlying assumptions of contact with negligible spatial extent and a high aspect ratio $L/w$ are not fulfilled in the actual geometry. To achieve higher accuracy in the theoretical determination of the signal, one can use a simulation based on the finite-element-method (FEM). This was done for a geometry resembling the structures as closely as possible, while minimizing computing time (cf. Fig. 5.1a). The used software package is COMSOL Multiphysics 3.2.

To keep simplicity, a two dimensional model including only Ohm’s Law, $j = \sigma E$, and the equation of continuity, $\nabla \cdot j = -\nabla \cdot (\sigma \nabla V) = 0$ was chosen. It can be found within COMSOL under the name conductive media DC application mode. The resistivity $\sigma$ was chosen isotropic and its value determined by local resistance measurements (cf. Sec. 4.2.1).
All boundaries but the ends of the wire, through which the current is driven, are electrically isolated: \( \mathbf{n} \cdot \mathbf{j} = 0 \). Here, \( \mathbf{n} \) is the normal vector of the boundary. One end of the current carrying bar is grounded, \( V = 0 \), while through the other an inward current flow \( -\mathbf{n} \cdot \mathbf{j} = j_n \), is defined. The simulation yields the distribution of the electric field \( E \) all over the sample. The non-local voltage is then determined by the difference between two nodes: \( V_+ - V_- \) (black dots).

In Fig. 5.1a) the simulated potential distribution can be seen for a configuration including \( L = 150 \text{ nm} \) and \( 200 \text{ nm} \). For better visibility, the region of the connected wire is greyed out and not included in the scale, as the magnitude varies strongly. One can see nicely, that a potential difference can be found in the parallel wires, although it decays very fast for larger separations.

The FEM simulations were made for the four samples which were analyzed in Sec. 4.2. The results for a sample with thickness of \( t = 50 \text{ nm} \) (Sample A) and the one with \( t = 26 \text{ nm} \) are presented in Fig. 5.2a and 5.2b, respectively. The non-local resistance \( R_{\text{nonlocal}} \) as measured (symbols) and as simulated (dashed lines) is plotted versus the distance \( L \) between the wires for 300 K (red) and 3 K (blue). Furthermore the simulation data at 3 K multiplied with -1 is denoted as a dotted blue line. The simulation does not contain free parameters: the used variables, which are the \( \rho \) and the dimensions, are completely determined by the samples.
5.1 Current Spreading

Figure 5.2: Comparison of the non-local resistance calculated by FEM simulations (dashed lines) with the measured data (symbols) for a sample with $t = 50\,\text{nm}$ (a) and one with $t = 26\,\text{nm}$ (b) at $T = 300\,\text{K}$ (red) and $T = 3\,\text{K}$ (blue). The dotted line shows the simulation results times minus one for 3 K. The simulation predicts very well the values for 300 K for Sample D and distances of 150 nm and 200 nm and approximately for Sample A and $L = 150\,\text{nm}$. For larger distances the actual signal decays faster than calculated at high temperatures.

At 300 K very good agreement between the predicted magnitude and the experiment can be found for short distances 150 and 200 nm and a thickness of 26 nm. For longer distances and $t = 50\,\text{nm}$ the measured signal decays faster than expected. At low temperatures, the measured signal decay is similar to the simulated one. Furthermore, the magnitude is in the same order for experiment and simulation but with a reversed sign.

5.1.2 Non-local AMR in Nickel

To describe the non-local resistance in nickel correctly, one has to consider the anisotropy in the resistivity due to an external magnetic field. Calculating the non-local signal due to the current spreading including the influence of the AMR effect one can explain the interesting result of an increase in the AMR value with distance (cf. Sec. 4.18). As the directions of low and high resistance change with the orientation of the magnetic field, also the current paths will spread differently (cf. Fig. 5.3a). In nickel the conductance is higher for current perpendicular to the magnetic field. Thus, for field in $x$-direction (red), the current can spread “easier” in vertical direction and will lead this way to a higher voltage difference at the voltage probes than for the field parallel to the $y$-direction (green).

In the following paragraph, this effect is described analytically for the assumption of one dimensional contacts and a structure of large aspect ratio $L/w$. To overcome those restrictions, FEM simulations are presented and compared to the experiment in the second paragraph.
**Analytical Description**  In a very simple approach, one can consider the problem as two dimensional and include into the resistivity only the anisotropy due to the AMR effect. In the system defined by \( e_\parallel \) and \( e_\perp \), the unit vectors parallel and perpendicular to the magnetic field \( H \), the resistivity tensor takes the form

\[
\hat{\rho}' = \begin{pmatrix} \rho_\parallel & 0 \\ 0 & \rho_\perp \end{pmatrix}
\]

with \( \rho_\parallel \) and \( \rho_\perp \) being the resistivities for current parallel and perpendicular to the field. By the use of the rotation matrix \( \hat{T} \), one can transform to the coordinate system of the sample (cf. Fig. 5.3b), defined by \( e_x \) and \( e_y \), which yields:

\[
\hat{\rho} = \begin{pmatrix} \rho_{xx} & \rho_{xy} \\ \rho_{yx} & \rho_{yy} \end{pmatrix} = \hat{T} \hat{\rho}' \hat{T}^T = \begin{pmatrix} \rho_\perp + \Delta \rho \cos^2 (\theta) & \Delta \rho \sin \theta \cos \theta \\ \Delta \rho \sin \theta \cos \theta & \rho_\parallel - \Delta \rho \cos^2 (\theta) \end{pmatrix},
\]

(5.1)

where \( \Delta \rho = (\rho_\parallel - \rho_\perp) \).

To calculate the current spreading, one has to generalize the *van-der-Pauw* theorem (cf. Sec. 2.4.2), which is only defined in isotropic media, to the anisotropic case [83, 84]. The resulting formula has the same general shape as before, but with the inverse of the resistivity \( \rho^{-1} \) being exchanged by \( s = \sqrt{|\hat{\sigma}|} \), where \( \hat{\sigma} = \hat{\rho}^{-1} \) is the conductance tensor. Then the anisotropic *van-der-Pauw* theorem takes the form:

\[
\exp (-\pi tsR_{AB,CD}) + \exp (-\pi tsR_{BC,DA}) = 1
\]

(5.2)

\( R_{AB,CD} \) is defined as the voltage difference between point D and C for a current from A to B. The actual non-local resistance \( R_{\text{nonlocal}} = R_{AB,CD} \) can be calculated with
the assumption $R_{AB,CD} \ll R_{BC,DA} = R_{\text{local},yy}$ to
\[ R_{\text{nonlocal}} \approx \frac{1}{\pi t_s} \exp(-\pi ds R_{\text{local},yy}). \]

For our particular resistivity tensor, Eq. (5.1), $s$ takes the simple form of $s = \left(\frac{\rho_{\|}}{\rho_{\perp}}\right)^{-1/2}$. In the geometry of the multi-H structures, the local resistance in $e_y$-direction can be expressed as $R_{\text{local,yy}} = \rho_{yy} \cdot L \cdot (wd)^{-1}$. The non-local resistance thus takes the form
\[ R_{\text{nonlocal}}(L,\theta) = \sqrt{\frac{\rho_{\|}}{\rho_{\perp}}} \frac{\pi d}{\frac{\rho_{\|}}{\rho_{\perp}}} \exp\left(-\frac{\pi L}{w} \frac{1}{\sqrt{\rho_{\|}} \rho_{\perp}} \left[\rho_{\|} - (\rho_{\|} - \rho_{\perp}) \cos^2 \theta\right]\right) \]
(5.3)
\[ = \sqrt{\frac{\rho_{\|}}{\rho_{\perp}}} \frac{\pi d}{\frac{\rho_{\|}}{\rho_{\perp}}} \exp\left(-\frac{\pi L}{w} \left[\gamma - (\gamma - \gamma^{-1}) \cos^2 \theta\right]\right) \]
(5.4)

with $\gamma = \sqrt{\frac{\rho_{\|}}{\rho_{\perp}}}$ . The solution leads to a $\pi$-periodic oscillation, whose percentual amplitude will increase with $L$. To obtain the AMR value, one can just consider the cases for $\theta = 0^\circ$ and $\theta = 90^\circ$, $R_{\text{nonlocal,\|}}$ and $R_{\text{nonlocal,\perp}}$:
\[ \text{AMR}_{\text{nonlocal}}(L) = \frac{R_{\text{nonlocal,\|}}(L)}{R_{\text{nonlocal,\perp}}(L)} - 1 = \exp\left(\frac{\pi L}{w} \left[\gamma - (\gamma - \gamma^{-1})\right]\right) - 1 \]
(5.5)

The solutions of Eq. (5.4) and Eq. (5.5) are plotted in Fig. 5.4 for the typical values of the samples investigated here (cf. Sec. 4.4.3), $\frac{\rho_{\|}}{\rho_{\perp}} - 1 \approx 1.6\%$ and $\frac{L}{w} \approx 1 - 5$. In Fig. 5.4a the angle dependence can be seen for different ratios of $\frac{L}{w}$. Here the value of $\gamma$ is fixed to $\sqrt{1.016}$. It can be seen, that the curves do not deviate much from the $\cos^2$ form. If one looks at the AMR value (cf. Fig. 5.4b), the strictly monotonic increase with $\frac{L}{w}$ can be seen clearly. Already a change from 1 (blue) to 2 % (red) for $\frac{\rho_{\|}}{\rho_{\perp}} - 1$ can lead to a drastic change in the nonlocal AMR. For the measured $\gamma$ of $\sqrt{1.016}$ the curve has an approximately constant slope over the shown range for $\frac{L}{w}$.

This behavior can be seen if one approximates Eq. (5.4). The exponential function can be factorized into
\[ R_{\text{nonlocal}}(L,\theta) = \sqrt{\frac{\rho_{\|}}{\rho_{\perp}}} \frac{\pi d}{\frac{\rho_{\|}}{\rho_{\perp}}} \exp\left(-\frac{\pi L}{w} \gamma\right) \exp\left(\frac{\pi L}{w} (\gamma - \gamma^{-1}) \cos^2 \theta\right) \]
for $(\gamma - \gamma^{-1}) \ll \frac{\pi L}{w}$ the second factor can be approximated and one finds
\[ R_{\text{nonlocal}}(L,\theta) \approx R_{\text{nonlocal,\|}} + R_{\text{nonlocal,\|}} (\gamma - \gamma^{-1}) \frac{\pi L}{w} \cos^2 (\theta) \]
\[ = A + B \cdot \cos^2 (\theta) \]
Figure 5.4: Analytical solutions for the dependence of $R_{\text{nonlocal}}$ on $\theta$ in percent for different ratios $L/w$ and a fixed value of $\gamma = \sqrt{\rho_\parallel/\rho_\perp} = \sqrt{1.016}$ (a). In b) AMR$_{\text{nonlocal}}(L/w)$ at different values $\gamma$ is given.

The AMR (cf. Eq. (5.5)) value simplifies with the same approximation to

$$\text{AMR}_{\text{nonlocal}}(L) \approx \frac{\pi L}{w} (\gamma - \gamma^{-1}) \approx \text{const.} \cdot L$$

and therefore to a linear increase with $L$.

**FEM Simulations** The simulations are made with the model and geometry described in Sec. 5.1.1. To include the AMR, the used resistivity tensor is anisotropic (cf. Eq. (5.1)). Only the extremal cases of field parallel and antiparallel to the current were considered. The resistivities $\rho_\perp$ and $\rho_\parallel$ were determined by fitting the measurement data of the local resistance in the vertical bar for a length of $L = 2.25 \mu m$ with the formula $R_{\text{local}}(\theta) = \frac{L}{w_1 \cdot d} \cdot \left[\rho_\perp + (\rho_\parallel - \rho_\perp) \cos^2(\theta)\right]$. Here $w_1$ denotes the width of the vertical bar, which was measured to $w_1 = 110 \text{ nm}$ by use of the scanning electron microscope. As mentioned before (cf. Sec. 4.4), the influence of the adhesion layer was neglected and a total thickness $d$ of 53 nm assumed. The AMR value extracted by the fits is 1.64% at 300 K and 1.41% and 3 K.

How the current spreading is influenced by the applied field is shown in Fig. 5.5 for an exemplaric simulation. Contour lines of constant current density are plotted for magnetic field parallel (red) and perpendicular (blue) to the $x$-axis. On the right side zoom-ins for two regions are given. The current spreads further into the $y$-direction if the field is parallel to $x$. The difference in the current density increases with distance, leading to an increased AMR value for higher non-locality, i.e. longer distance.

To compare the quantitative predictions of the simulations to the experimental data, Fig. 5.6a shows the experimental data (symbols) and fits to $R_{\text{nonlocal}}(\theta) =$
\( R_{\perp} + (R_{\parallel} - R_{\perp}) \cos^2(\theta) \) \textit{(solid lines)}. The fits were made to determine the minimal and maximal values of the non-local signal. Different distances from \( L = 150 \text{ nm} \) to \( 250 \text{ nm} \) \textit{(color)} and, for comparison, the local signal \textit{(black, dashed line)} are shown. To be able to show all the data in one single graph and to compare the percentual change, the data points are normalized to the respective \( R_{\perp} \). It can be seen, that the fit reflects very well the data and shows that the assumption of \( \cos^2 \) behavior is correct.

Figures 5.6b-d compare the experimental data to the simulations as function of the distance \( L \). Here, the color distinguishes the two investigated temperatures: \textit{blue} for 3K and \textit{red} for 300K. The measurement results are given as \textit{symbols} and the simulated values are depicted as \textit{dashed lines}. The AMR value in percent is shown in Fig. 5.6b, while the values for parallel and perpendicular direction of the magnetic field with respect to the current, \( R_{\text{nonlocal,\parallel}} \) and \( R_{\text{nonlocal,\perp}} \), are given in panel Fig. 5.6c and 5.6d, respectively. The simulated \( R_{\parallel} \) and \( R_{\perp} \) show a very good agreement with the actual experimental data for the two most adjacent configurations (\( L = 150 - 200 \text{ nm} \)). For those distances the AMR value calculated from the measurements reflects perfectly the predictions. For larger \( L \) the measured data is lower than simulated. This leads automatically to an AMR value which is far higher than expected.
5.1.3 Summary of Results for Current Spreading

With the model of current spreading the measured non-local signal could be predicted well for distances \( L \leq 200 \text{ nm} \) in both, nickel and gold at \( T = 300 \text{ K} \). At 3 K the experimental decay results in nickel can be well explained. In gold one can explain the exponential decay, but not the sign for low temperatures. The simulated non-local signal has roughly the same order of magnitude as the measurement. However, this may be accidental, as this obviously can not hold for temperatures between 300 K and 3 K. Furthermore, current spreading also accounts for the enhanced magneto resistance in nickel can be simulated very well. For larger distances between injected current and voltage probes, a similar trend is found in gold and nickel. A change in the decay characteristic towards faster fading is found. The origin for this could be a additional negative contribution, which has a larger characteristic decay length.
than the current spreading signal. As it declines slower, its influence on the total signal will intensify, leading to increasing deviation from the simulation. Furthermore it has to depend strongly on temperature or any connected parameter, like e.g. the electron mean free path $l_e$, to explain the large negative values for gold. To achieve such high values, the signal has to dominate over the current spreading.
5.2 Spin Hall Effect

As already mentioned in the theoretical discussion (cf. Sec. 2.4) and during the presentation of the measurement results in chapter 4, the occurrence of a sign change for low temperature cannot be explained by the Spin Hall Effect. In the used geometry the conversion between charge and spin current occurs twice (cf. Fig. 2.6). Both, the SHE and the ISHE rely on the same mechanisms of spin dependent scattering. Therefore a single charge carrier with spin will be deflected twice in the same direction. The accumulation will always occur in direction of the carrier source. Thus, even if the spin current had opposite sign, this would not lead to a negative sign of the measured signal. On the other hand, a sign change could theoretically occur due to the spin precession in an external magnetic field (cf. Sec. 2.4.4). As the influence of a magnetic field is weak to negligible (cf. Sec. 4.2.4), a negative sign due to the SHE in a small magnetic field is not plausible.

For this reasons, the SHE can not be made responsible for the deviations of the signal from the values expected due to current spreading. Nevertheless, one can not exclude its presence in the signal, as up to now the composition of the signal is not fully understood. This also implies, that no estimate for the upper bound of the SHE key parameters, the spin diffusion length $l_s$ and the ratio between the spin hall and the charge conductivity $\frac{\sigma_{\text{SHE}}}{\sigma}$, can be given.

5.3 Quasi-Ballistic Transport

Comparison with the simulations for current spreading indicate an additional negative contribution. A possible candidate for this effect is ballistic transport, which describes carrier transport if scattering can be neglected. Thus the criteria for the ballistic regime is that the lateral dimensions are smaller than $l_e$. For certain geometric configurations one can imagine a negative resistance for ballistic transport (cf. Fig. 5.7). The ballistic electron just “shoots” with a certain probability into the voltage lead, which will lead eventually to a reversed voltage. Studies on parallel wires connected by a perpendicular window in GaAs have indeed shown a negative
resistance for certain ratios of $L$ and $w$ \[\text{[85]}\]. The sign oscillates with $L/w$, which can be easily understood thinking of a billiard model. The transmission probability to the remote bar can be determined by counting the number of classical trajectories which reach the lead. Depending on the number of the reflections inside the vertical bar, the carrier will be reflected into one or the other side (cf. Fig. 5.8).

However, this scenario seems not adaptable in the present case. As stated above, the electron mean free path has to be larger than the trajectory. If one calculates $l_e$ for gold according to the Drude formula $l_e = \frac{\hbar e^2}{\rho} \left( \frac{3\pi^2 n^{-2}}{2} \right)^{1/3}$ the maximal mean free path in the structures is about 25 nm, when using $n = 5.9 \times 10^{28} \text{m}^{-3} \text{[86]}$ for the electron density. As the distances $L$ are larger by around one order of magnitude, one does not expect to be in the ballistic regime.

An idea to address this problem stated by Mihajlović et al. \[1\] is to assume a combination of diffusive and ballistic transport and thus a quasi-ballistic picture. Mihajlović et al. claim “that the negative $R_{nl}$ comes from electrons that reach the region between the voltage probes diffusively and then ballistically scatter into the [..] [right] voltage lead”. With this model the important length scale is then the width of the vertical bar $w_\perp$, which is only larger than $l_e$ by a factor of three. The non-local signal is fitted to a phenomenological equation:

$$R_{\text{nonlocal}} = \rho t^{-1} a \left( 1 - b \exp \left( -\frac{w_\perp}{l_e} \right) \right)$$

(5.6)

where $a$ and $b$ are dimensionless fitting parameters. In Ref. \[1\] the magnitude of $a$ decays exponentially, $a = \exp (-\pi L/w)$, with the distance $L$, indicating diffusive transport.

Although a high consistency could be achieved by Mihajlović et al. \[1\] for their data, we could not reproduce this with our measurements. Figure 5.9 shows the measured non-local signal (blue), which was normalized to the sheet resistance $\rho t^{-1}$, as a function of the electron mean free path $l_e$ for a distance of 150 nm. $l_e$ was determined from the resistivity via the Drude formula. The red line gives the best possible solution of Eq. (5.6). In Fig. 5.9a, where the results of Sample A and thus for $t = 50 \text{nm}$ is presented, a certain agreement between the model and the experiment can be obtained. This does not hold true for Sample D and thus a thickness of $t = 26 \text{nm}$ (cf. Fig. 5.9b). Furthermore, a change in the characteristic decay length can not be explained in this model, as only one exponential dependence on distance $L$, namely the one of the diffusive current spreading in the parameter $a$ is present.
That the model works differently well for the sample in Ref. [1] and for our samples is not surprising as different structural characteristics are found. While the samples presented in this work do not show any anomalies in the local resistance, the dependance of $R_{\text{local}}$ on distance for the samples in Ref. [1] shows a very large offset length of 70 nm.

In conclusion, one can say that, up to now, the model presented by Mihajlović et al. [1] is the best proposal to describe rudimentarily the negative non-local signal. On the other hand, the data presented in this thesis can not be described satisfactorily on the same footing. Nevertheless we think, that some kind of quasi-ballistic contribution might be a good candidate to explain the observations made during this thesis.

### 5.4 Universal Conductance Fluctuations

The fluctuations found in the non-local signal (cf. Sec. 4.2.4) for varying magnetic field, which are perfectly reproducible, remind one of Universal Conductance Fluctuations (UCFs) [87]. UCF is a quantum interference effect, which can be found if the relevant lateral dimensions of the sample are smaller than the phase coherence length $L_\phi$ of the charge carriers but larger than the electron mean free path $l_e$. In this regime the transport is diffusive, but different paths of the carriers are still correlated, so that interference is possible.

With the features of our sample being below 100 nm and thus smaller than the phase coherence length $L_\phi$, which is roughly 1 μm at 3 K in Au [88], it can be possible, that quantum interference effects have an influence on our non-local signal and that the observed fluctuations originate from UCFs.
If the fluctuations of the non-local signal are a result of UCFs, one expects, according to the Onsager relations, the signal to be symmetric in the magnetic field, \( R_{\text{nonlocal}}(H) = R_{\text{nonlocal}}(-H) \) [89]. This holds true in a two but not in a multi terminal configuration [90]. Another important value connected with UCFs is the universal amplitude of the fluctuation in the conductance \( G \), which lies in the order of \( e^2/h \), independent of the actual conductance \( G \) and the geometry [91]. However, in what way both predictions can be adapted to a non-local geometry is up to now not completely clear.

To get more insight into the fluctuations, Fig. 5.10 shows the fluctuations \( \Delta R_{\text{nonlocal}} \) as a function of the applied magnetic field \( \mu_0 H \). Here a background, containing a constant and a parabolic part, was subtracted from the original signal. The field was oriented out-of-plane and the temperature stabilized to 3 K (cf. Fig. 4.13 c&d). A certain symmetry in the signal can be found. On the other hand, asymmetric features, like e.g. the high peak at about \(-1.7 \, T\), are present. For a further in-depth analysis, smaller magnetic field step size is needed.

The fluctuation of the non-local resistance in our measurement is roughly 100\( \mu \Omega \), which corresponds to a voltage fluctuation of 10 nV. To get an idea of the value’s size, one can make a rough estimate of the expected fluctuation in the local resistance for a wire section with dimensions \( w \times L \times t = 75 \, \text{nm} \times 75 \, \text{nm} \times 50 \, \text{nm} \). Those values correspond to the intersection area of the vertical and the horizontal wires. The local resistance of this section is thus \( \rho L / A \approx 4 \, \mu \Omega \, \text{cm} \times 75 \, \text{nm} / (50 \times 75) \, \text{nm}^2 \approx 1 \, \Omega \). Using a simplified picture of the UCFs shown in Fig. 5.11, one can estimate the expected amplitude. The total resistance can be modeled as the shunt circuit of numerous conductance channels, where each one has the conductivity of one conductance quantum \( 2e^2/h \) [92]. This corresponds to a resistance of 12.9 k\( \Omega \). Therefore one needs 12900 channels to yield the above calculated value of 1 \( \Omega \). The fluctuation can now be calculated as the difference of this resistance to the one with a missing
\[ R' = 12.9 \text{k}\Omega /12899 \]

\[ \Delta R_{\text{local}} = R_{\text{local}} - R'_{\text{local}} \]
\[ = \frac{12.9 \text{k}\Omega}{12899} - \frac{12.9 \text{k}\Omega}{12900} \]
\[ \approx 80 \mu\Omega \]

This value agrees surprisingly well with the experimental data. That is very unexpected, as the measurement is made in non-local geometry. Intuitively, one would expect the fluctuation in the local conductance to be transmitted as a voltage fluctuation into the non-local measurement. The voltage, however, decays exponentially. Thus the expected non-local fluctuation should be smaller by about a factor of thousand, which is roughly the ratio between local and non-local resistance in the actual measurement.

This potential finding of giant non-local UCF needs further theoretical and experimental investigations. As those observations were only possible due to the enhanced resolution of the measurement setup developed during this work, they were made at the very end of this thesis. Due to the limited amount of time no further investigation could be conducted yet. The next step must be more focussed measurements with higher magnetic field resolution, which will enable more in-depth analysis of the effect.

Finally it should be noted, that even if UCF were present, they are not expected to lead to the observed negative signal. Nevertheless, without further theoretical groundwork of non-local conductance fluctuations we can not exclude this. Anyway, a better understanding of the origins of the fluctuations should give important insight into the transport effects which cause the negative non-local resistance.

### 5.5 Summary

In this chapter, a comparison between the experimental results (cf. chapter 4) and four possible transport mechanisms were made: current spreading in the diffusive regime, the Spin Hall Effect, quasi-ballistic contributions and quantum interference in the form of Universal Conductance Fluctuations (UCFs). The influence of current spreading was analyzed both, analytically and by the means of a finite element method (FEM) simulation. For high temperatures and short separation between current and voltage probes a very good agreement between measurements and simulation could be found for the gold samples. As expected, neither the faster decay at larger distances and \( T = 300 \text{K} \) nor the negative signal at lower temperatures (cf. Sec. 4.2.2) could be explained in this simple model. It seems, that two main contributions to the non-local signal exist: the current spreading and an additional effect with negative sign for the voltage, which decays also exponentially but with a larger characteristic decay length. It has to depend strongly on a temperature dependent parameter like, e.g., the mean free path.

Moreover the enhanced non-local magneto resistance found in nickel can be described perfectly by the model of current spreading (cf. Sec. 4.4.3). For this purpose,
the conventional model based on the \textit{van-der-Pauw} theorem was extended to include the anisotropic magneto resistance (AMR) found in ferromagnetic materials. In analytical calculations, this approach correctly describes the qualitative behavior and furthermore yields a reasonable estimate of the non-local AMR value. By additional application of FEM simulations, a perfect agreement between the experiment and the prediction could be found for separations of the wires $\lesssim 225 \text{ nm}$. For longer distances the same phenomenon of faster decay, as also found in gold, is observed. It can also not be explained by our simulations. Instead, it seems, that the presence of a second effect can not only be found in the non-magnetic gold, but also in the ferromagnetic nickel. As the temperature dependence of the Al resistivity could not be measured (cf. Sec. 4.3), no additional simulations for aluminum were made. On the other hand, as the experimental results for the non-local signal in aluminum were quite similar to the ones for gold, the qualitative observations made above should be applicable also to aluminum.

The presence of the Spin Hall Effect could neither be confirmed nor excluded, as the behavior, including at least one other effect, is far too complex to give reliable estimations of the key parameters of the SHE: the ratio of the conductivities $\alpha_{\text{SHE}}$ and the spin diffusion length $l_e$.

A possible candidate for the origin of a negative voltage is quasi-ballistic transport, where the carriers scatter ballistically into the voltage leads. This model is problematic, as the electron mean free path is roughly one order of magnitude below the typical separation distance between the wires. A phenomenological model, deduced by Mihajlović \textit{et al.} [1], in which a combination of diffusive and ballistic transport is assumed could describe the signal for their sample. However, their model does not satisfactorily describe our measurements. Nevertheless the qualitative picture is up to now the most promising.

Finally the reproducible fluctuations, found in the negative non-local signal at $3 \text{ K}$ (cf. Sec. 4.2.4), and their connection to Universal Conductance Fluctuations (UCFs) were briefly discussed. In principle, the non-local fluctuations can be caused by UCFs. However, for firm predictions more in-depth experiments are needed, as the measurements seem to indicate giant non-local UCFs. The amplitude of the oscillations are roughly $100 \mu \text{\Omega}$ for a non-local signal of $-1.9 \text{ m\Omega}$. This is surprisingly high, as the fluctuation amplitude in a local measurement with a resistance of $1 \Omega$ is in the same order of magnitude. One would expect the fluctuations to decay in a similar manner as the total signal, i.e. exponentially, and therefore to be smaller by a factor of approximately thousand. The findings are highly interesting not only because further understanding of the fluctuations could give insight into the mechanism behind the negative signal, but because up to now few experiments on non-local UCFs have been conducted.

In summary one can say, that although much progress was made during this thesis to understand the non-local signal, further experiments and especially theoretical groundwork are still required.
Chapter 6

Summary & Outlook

In the following section a summary of this thesis is given. It is held brief, as more detailed summaries can be found at the end of each of the previous chapters. Subsequent to the summary, an outlook to further experiments is given in Sec. 6.2.

6.1 Summary

The generation of pure spin currents is rapidly gaining importance for the development of new spintronic devices. Up to now the generation and detection of pure spin current always relied on magnetic contacts [8, 9, 11]. This not only increases fabrication complexity but also can add further problems due to the additional interface, impurity contamination and stray fields. A promising approach to circumvent magnetic materials is the successive use of the Spin Hall Effect and the Inverse Spin Hall Effect in H-shaped nanostructures. This way a pure spin current can be generated and detected fully electrically [12, 13]. A current sent through one wire should lead to a non-local voltage in the parallel wire due to transverse, diffusive spin transport in the perpendicular connection of the “H”.

During this thesis extensive studies on the design without any magnetic contacts were conducted. Regarding the theoretical estimations (cf. Sec. 2.4.3), in gold a measurable value of 1 mΩ is expected if recently published values for spin hall angle and the diffusion length are correct [11] and bar widths of approximately 75 nm are used. One way to critically test whether the measured signal can be attributed to the Spin Hall Effect is to apply a magnetic field in the plane of the metallic thin film. This should result in oscillations and suppression of the signal for field strengths of roughly 11 mT (cf. Sec. 2.4.4 [13]). Another characteristic of the signal is its exponential decay with the separation between the wires. Here the characteristic decay length is the spin diffusion length $l_s$.

To be able to probe different distances, multi-H structures were prepared with smallest feature sizes of 50 nm (cf. Sec. 3.1). Therefore a two-step process, including photo- and electron beam lithography and subsequent thin-film deposition, was established for gold, aluminum and nickel. To measure the expected low level signals, two complementary setups were implemented for use in differential resistance measurements, magnetic field and temperature sweeps (cf. Sec. 3.3.4). The AC setup using a lock in amplifier was replaced by a DC current reversal configuration, developed during this thesis, as the signal to noise ratio is better by at least one order of
magnitude for the parameter range of the samples. The final resolution limit is in the order of 1 nV under optimal condition, e.g. low lead resistance.

Local resistance measurements revealed a consistent picture for all samples, proving their high quality (cf. Sec. 4.2.1). In contrast, the non-local signal shows an unexpected behavior for the non-magnetic materials, gold and aluminum: while at room temperature a positive signal is measured, the sign changes towards lower temperatures (cf. Sec. 4.2.2). The negative signal can neither be explained by the Spin Hall Effect nor by a diffusive spreading of the current into the voltage leads. It was checked carefully, that thermopowers are not responsible for the non-local signal. The signal magnitude decays exponentially with the separation distance, although a change in the decay characteristic can be found for larger separation. In contrast to the negative signal in gold, nickel structures showed a positive signal over the whole accessible temperature range (cf. Sec. 4.4). Another interesting finding in nickel is an enhanced magneto resistance effect for non-local measurements. The enhancement further increases with the distance between current and voltage probes. We would like to note that the experimental data confirm the only measurement on SHE and ISHE in non-magnetic gold samples by Mihajlović et al. [1], however going substantially beyond the data in this group.

Four different transport mechanisms which could possibly contribute to the signal were discussed (cf. Chapt. 5). The Spin Hall Effect can be excluded from being the origin of the negative signal (cf. Sec. 5.2). But whether it is present or not could not be said with certainty as some other effect dominates. Therefore no estimations of the ratio of the Spin Hall and electrical conductivity and the spin diffusion length, which are the key parameters of the Spin Hall Effect, can be given.

Extensive studies including analytical calculations as well as simulations showed that current spreading plays an important role in the measured signal (cf. Sec. 5.1). For not too large separation in gold and at room temperature, the simulations predict very accurately the measured signal. In nickel not only the signal for short distances could be explained in the whole temperature range, but also the enhanced non-local magneto resistance effect. The origin of the deviations for larger distances and low temperatures is not yet clear. It can be assumed that an additional negative contribution is present, decaying slower than the signal due to current spreading. Furthermore it has to be highly sensitive on temperature or any connected parameter.

A possible candidate is quasi-ballistic transport (cf. Sec. 5.3). As the lateral dimensions of the sample are too large for direct ballistic transmission of carriers from one to another lead, a combination of diffusive and ballistic transport was suggested by Mihajlović et al. [1]. Although up to now this model is the only known giving a more or less complete picture, the results found during this thesis are not consistent with this theory.

Moreover reproducible fluctuations were observed in the negative non-local signal during magnetic field sweeps (cf. Sec. 4.2.4). Those fluctuations could possibly originate from Universal Conductance Fluctuations (UCFs) (cf. Sec. 5.4). Nevertheless, the most simple picture, where UCFs in the local Resistance lead to a fluctuation of the non-local voltage, is not applicable because of the amplitude of the non-local fluc-
6.2 Outlook

The goal of this thesis was to detect the Spin Hall Effect fully electrically without the need of magnetic contacts. This could not be achieved, as another effect dominates. As the effect is not yet well understood, more detailed experimental and theoretical analysis is needed. Very helpful would be to increase the statistics and thus the number of samples to overcome the variance in structure geometry. This should be accompanied by an extension of the range of lateral dimensions: a finer grid of distinct length can be advantageous, as the change in the decay of the non-local signal seems to be a key characteristic of the observed phenomena. On the other hand the type of decay of the signal is expected to differ strongly for distinct effects. Therefore a reliable study with varying widths can be fruitful.

Because a difference between nickel and gold or aluminum is found, the extension to more non- or ferromagnetic materials is of interest. Furthermore, it is still unclear whether impurities are somehow responsible for the signal. Recently influence of impurities was proposed as a reason for high non-local signals [93, 39]. Experiments with systematic doping can give further insight.

The non-local fluctuations, which were found, could indicate very interesting physics. It still has to be proven whether the fluctuations are a real effect and whether they can be attributed to the Universal Conductance Fluctuations. If true, this would be one of the first observations of UCFs in a non-local geometry, which even could be called giant non-local UCFs due to their high amplitude compared to the overall non-local signal. Obviously a better understanding of the fluctuations goes along with a better knowledge of the negative sign. Thus the next step should be to conduct further measurements in varying magnetic field but with much smaller step size and additional measurements at room temperature, where one does not expect any influence of UCFs.

Notwithstanding, that the observations made during this thesis are highly interesting from a physical point of view, the original goal for this thesis was not achieved. A promising way might be to extend the layout to use non-magnetic heterostructures. By this one sacrifices the appealing simplicity of the design on the one hand, but gains independent control of the spin orbit coupling strength and the spin diffusion length $l_e$ on the other hand. We propose to use a material with high spin orbit coupling and thus $\alpha_{\text{SHE}}$, e.g. platinum or gold, for the horizontal wires for large spin accumulation and sensitive detection. For minimal spin-flip scattering a material with large spin diffusion lengths, e.g. copper or aluminum, could be used for the vertical bar.

The results of this thesis underline the fact that the charge and spin transport in nanostructures is still not sufficiently understood. As in this thesis, surprises can be found and hinder the straightforward development of new devices. Therefore further experimental and theoretical insight in this relatively new field is of urgent need.
Appendix A

Setup for Fast Current Reversal Measurements

Faster switching of the current in current reversal measurements can decrease the amount of noise substantially. For fast switching, all noise with a time constant higher than the time needed to do a measurement with two current states should be canceled out [59, 62].

The devices used here were the Keithley K2400 SourceMeter and K2182 NanoVoltmeter. To achieve high speed tight synchronization of the source and the nanovoltmeter is essential. This can be ensured by using the TriggerLink of the Keithleys. When connecting multiple K2182s to one source be sure to disable the automatic range adjustment.

There are two modes of operation: the continuous switching, and semi-continuous switching. Both are described below. The basic difference is, that, while continuously switching, the SourceMeter can not be address unless to abort it’s action. This implies, that changing of the current driven and reading of the values measured by the SourceMeter is not possible. Still, for the majority of measurements this is a useful and easy mode.

In the following the code to program the Keithleys is given and explained. The routines were implemented in LabView, using the VISA interface. Here the code is given in a general form, where \( s \) (\ldots) means sending to the device, and \( r \) (\ldots) correspond to receive a message from the device.

A.1 Continuous Operation

The NanoVoltmeter has to be configure first:

\[
\begin{align*}
  s(:syst:pres) & \quad \# \text{ resets the device} \\
  s(:sens:volt:delt on) & \quad \# \text{ activate delta-(current reversal) mode} \\
  s(:sens:volt:nplc $n) & \quad \# \text{ select measurement time in power line cycles (1 NPLC = 20ms)} \ (n = 0.1...10) \\
  s(:sens:trig:del $n) & \quad \# \text{ delay after trigger detection in seconds (with only 1 K2182 can & should be set small or 0)}
\end{align*}
\]

\footnote{for connection and connector pin-layout refer to the manuals}
s(:sens:trig:sour ext)  # selects the TriggerLink as input for trigger signals
s(:sens:voltdfil $n)   # enables the digital filter, $n = 0 or 1
s(:sens:voltdfil:coun $n)  # sets the number of values used by the digital filter ($n = 1...100$)

s(:sens:voltlpas $n)  # enables the analog low pass filter ($n = 0$ or $1$), not recommended
s(:sens:voltrang:auto 0)  # disables the automatic range adjustment
s(:sens:voltrang $n)  # selects the measurement range ($n = 0.01,0.1,1,10,100$ [V])

Afterwards the SourceMeter can be configured and initialized:

s(*rst)  # resets the device
s(:arm:dir sour)  # don’t wait on the first trigger in the arm layer
s(:arm:coun inf)  # infinite number of cycles in the arm layer
s(:arm:sour tlin)  # selects the TriggerLink as input for trigger signals

s(:arm:outp none)  # no trigger emitted after every arm cycle
s(:trig:dir sour)  # don’t wait on the first trigger in the trigger layer
s(:trig:del $n)  # delay after trigger detection in seconds (with only 1 K2182 can & should be set 0)

s(:trig:outp sour)  # trigger signal emitted after every trigger cycle
s(:trig:coun 2)  # 2 trigger cycles before leaving trigger layer (+/- current)

s(:syst:azer:stat off)  # deactivate auto-zero (better performance)
s(:sour:func curr)  # select current source mode
s(:volt:prot $n)  # give voltage protection/compliance limit in Volts ($n$)

s(:sens:func 'volt')  # sense voltage (necessary for compliance)
s(:sour:curr:mode list)  # current value determined by list of values
s(:sour:list:curr $n,-$n)  # current values for list ($n=|current|$)

- wait some time to give the device time to process the commands (def: 1s)

s(:OUTP ON)  # turn source output on
- wait some time to give the device time to process the command (def: 1s)

s(:INIT)  # initialize the measurement loop
Now the K2182 can be read out continuously via:

\[
\begin{align*}
s(:fetch?) & \quad \# \text{ send request for data} \\
r(string) & \quad \# \text{ receive string containing the calculated voltage value}
\end{align*}
\]

- In order to receive independent values wait at least

\[
t_{\text{wait}} = (\text{NPLC} \times 20 \text{ ms}) \times 2 \times \#\text{FilterPoints}
\]

To stop the current reversal measurement

send the following message to the SourceMeter (it can not communicate while being in the arms layer)

\[
\begin{align*}
s(:abort) & \quad \# \text{ exit the measurement loop (exit arm layer)} \\
s(:outp off) & \quad \# \text{ deactivate current output}
\end{align*}
\]

If it doesn’t react, (probably due to buffer problems when having received other commands while in arms layer), press the ON/Off button on the device front panel.

### A.2 Semi-continuous Switching

In the semi-continuous implementation of current switching developed during this thesis one has the choice between six different ways to determine a single datapoint and can vary in which step how much averaging does take place (cf. Fig. A.1). The easiest is the repetitive two point measurement (cf. Fig. A.1 a) and will thus be explained as an example. In this case every acquisition contains one high current and one low current (e.g. +I and -I) measurement, which can be acquired using various Samples. Various acquisitions are averaged to yield the final data point. The number of acquisitions is called Counts. Thus the total number of set and measure cycles is

\[
N = \text{Counts} \times 2 \times \text{Samples}
\]

The final data point is calculated by

\[
V = \frac{1}{\text{Counts}} \sum_{i} \left( \frac{1}{\text{Samples}} \sum_{j} \frac{V(I_{+}) - V(I_{-})}{2} \right).
\]

An improvement can be made if one uses a three point measurement because thermal drifts are eliminated better (cf. Fig. A.1 b). Both methods can be implemented also using moving averages (cf. Fig. A.1 c-e).

A complete implementation of a IV-measurement can be found under \texttt{.\labview.lib\keithley\Delta\Differential\_Resistance.vi}. All necessary sub-vis, which could also be implemented in other applications, can be found in the library file Delta\_subs.llb in the same folder. The setup and
acquisition of the Keithley Nanovoltmeter and Sourcemeter is the same for all variations of the current reversal, with exception of the programmed current steps. The needed commands for programming and reading of the Keithleys is given below.

**Figure A.1:** Different current reversal methods: 
- **a)** repetitive 2Pt,
- **b)** repetitive 3Pt,
- **c)** moving average 2Pt,
- **d)** moving average 3Pt, with two points moving and 
- **e)** moving average 3Pt, with one point moving. The schematics are drawn for three samples and three counts.

The NanoVoltmeter has to be configured first:

```plaintext
s(:ABOR)  # abort any running processes
s(:SYST:PRES)  # reset settings
s(:STAT:PRES)  # reset status
s(*CLS)  # clear status
s(:TRAC:CLE)  # clear data buffer
s(:SENS:VOLT:NPLC $n)  # select measurement time in power line cycles (1 NPLC = 20ms) ($n = 0.1...10)
s(:SENS:VOLT:DFIL:COUN 1)  # internal digital filtering set to 1 (step not necessary)
s(:SENS:VOLT:DFIL OFF)  # no internal digital filtering
s(:SENS:VOLT:LPAS $n)  # enables the analog low pass filter ($n = 0 or 1), not recommended
s(:SENS:VOLT:RANG $n)  # selects the measurement range ($n = 0.01,0.1,1,10,100 [V])
s(:SENS:VOLT:RANG:AUTO $n)  # enables autorange ($n = 0 or 1), not recommended
s(:TIG:DEL $n)  # selects trigger delay ($n in seconds), def: 0.001
```
A.2 Semi-continuous Switching

\[
s(:\text{INIT:CONT OFF:})
\]
\[
s(:\text{TRIG:COUN } \text{n})
\]
\[
s(:\text{TRIG:SOUR } \text{EXT})
\]
\[
s(:\text{FORM SRE})
\]
\[
s(:\text{TRAC:FEED SENSE})
\]
\[
s(:\text{TRAC:POIN } \text{n})
\]
\[
s(:\text{TRAC:FEED:CONT NEXT})
\]
\[
s(:\text{STAT:MEAS:ENAB } 512)
\]
\[
s(*\text{SRE } 1)
\]
\[
s(:\text{INIT})
\]
\[
s(:\text{STAT:OPER?})
\]
\[
r(\text{decimal})
\]

Afterwards the SourceMeter can be configured and initialized

\[
s(:\text{ABOR})
\]
\[
s(:\text{SYST:PRES})
\]
\[
s(:\text{STAT:PRES})
\]
\[
s(*\text{CLS})
\]
\[
s(:\text{TRAC:FEED:CONT NEV})
\]
\[
s(:\text{ARM:DIR ACC})
\]
\[
s(:\text{ARM:COUN } 1)
\]
\[
s(:\text{ARM:OUTP NONE})
\]
\[
s(:\text{TRIG:DIR SOUR})
\]
\[
s(:\text{TRIG:OUTP SOUR})
\]
\[
s(:\text{TRIG:DEL } \text{n})
\]
\[
s(:\text{TRIG:COUN } \text{n})
\]
\[
s(:\text{SENS:FUNC } \text{volt'},'\text{curr'})
\]
\[
s(:\text{VOLT:PROT } \text{n})
\]
\[
s(:\text{SOUR:FUNC CURR})
\]
\[
s(:\text{SOUR:CURR:MODE LIST})
\]
\[
s(:\text{SENS:VOLT:RANG } \text{n})
\]
\[
s(:\text{SENS:VOLT:RANG:AUTO } \text{n})
\]
s(:SOUR:CURR:RANG $n)  # selects the measurement range for I source ($n = 0.01,0.1,1,10,100 [V])

s(:SOUR:CURR:RANG:AUTO $n)  # enables autorange for I source ($n = 0 or 1), not recommended

s(:SENS:CURR:RANG:AUTO $n)  # enables autorange for I measurement ($n = 0 or 1), not recommended

s(:SOUR:SWEEP:RANG $n)  # set sweep range ($n = FIX or BEST), FIX recommended

s(:SOUR:LIST:CURR $n)  # List of current steps ($n = I1, I2, I3,...)

s(:TRAC:FEED:CONT NEXT)  # enable buffer recording

s(:STAT:MEAS:ENAB 512)  # program measurement event register (512 = B9 = Buffer Full)

s(:STAT:OPER:ENAB 1024)  # program measurement event register (1024 = B10 = Idle)

- wait some time to give the device time to process the command (def: 1s)

s(:OUTP ON)  # turn source output on

- wait some time to give the device time to process the command (def: 1s)

s(:INIT)  # init source and therefore a set and measure cycle

To check when the cycle finishes one can poll the status byte (STB):

If B0 = request service byte is set, the buffer is full and the set and measure cycle completed. One can read out the data and initialize the next cycle.

Read out and re-initialize Nanovoltmeter:

s(:TRAC:DATA?)  # query buffer entries
r(binary data)  # reads buffer in binary form, first 2 bytes can be ignored

s(:TRAC:CLE)  # clear buffer
s(:STAT:MEAS?)  # query measurement status byte
r(string)  # read measurement status byte, clears the byte
s(:TRAC:FEED:CONT NEXT)  # enable storing to buffer again

Read out and re-initialize Sourcemeter:

s(:STAT:MEAS?)  # query measurement status byte
r(byte)  # read measurement status byte, B9 = Buffer Full must be set

s(:STAT:OPER?)  # query operation status byte
A.2 Semi-continuous Switching

\[ r(\text{byte}) \]  # read operation status byte, B10 = Idle must be set
\[ s(:\text{TRAC:DATA?}) \]  # query buffer entries
\[ r(\text{binary data}) \]  # reads buffer in binary form, first 2 bytes can be ignored, rest is \( N \) 3-tuples: 2pt voltage, current and status
\[ s(:\text{TRAC:CLE}) \]  # clear buffer
\[ s(:\text{TRAC:FEED:CONT NEXT}) \]  # enable storing to buffer again
\[ s(:\text{TRIG:CLE}) \]  # clear pending triggers

- if a new current list is desired (else skip this step for faster operation):

\[ s(:\text{SOUR:LIST:CURR } \$n) \]  # List of current steps (\$n = I1, I2, I3,...)

- initialize next set and measure cycle

\[ s(:\text{INIT}) \]  # init source and therefore the next set and measure cycle

**To stop the current reversal measurement**

send the following message to the SourceMeter (it can not communicate while being in the arms layer)

\[ s(:\text{abort}) \]  # exit the measurement loop (exit arm layer)
\[ s(:\text{outp off}) \]  # deactivate current output
Appendix B

Cryostat Control Program

During this thesis a Labview program was developed, facilitating the usage and control of the cryostats in the magnetism group at the WMI. A screenshot can be found in figure B.1. This new program logs and allows access to all important parameters like temperatures, needle valve settings, field, etc. and can be found under ..\labview.lib\allgemeine files\kryolog\kryolog.vi. The devices being supported actually are listed in tabular B.1.

At startup the oxford setup file is scanned for address information, which is checked and extended by an automatic scan. The oxford file must be set up once, which can be done manually, or through the setup vi’s supplied by the oxford

<table>
<thead>
<tr>
<th>$T$ Dipstick</th>
<th>Lakeshore 340, Oxford ITC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ VTI</td>
<td>Lakeshore 340, Oxford ITC</td>
</tr>
<tr>
<td>He(/N) level(s)</td>
<td>Oxford ILM</td>
</tr>
<tr>
<td>$p$ VTI</td>
<td>Oxford LC, Vacuubrand DVR5</td>
</tr>
<tr>
<td>Needle valve</td>
<td>Oxford ITC</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>Oxford IPS</td>
</tr>
</tbody>
</table>

Table B.1: Supported devices for cryostat control program
drivers, which can be found in ..\labview.lib\oxford\<devicename>\-<devicename>apps.llb. The scanning is done by sending a *IDN request to all GPIB devices. This should not interfere with any device operation, as long as the device can answer. Some devices, like the Keithley 2400 in a trigger cycle, will not respond until having finished a certain operation, which will eventually lead to a violation of the response time. The shown error can be neglected and the process continued, but if this occurs too often, the device buffer can be filled, making it impossible to communicate by means of normal GPIB communication. Settings for all devices can be changed manually by the menu, which can be access via the settings button. A second fact one should notice is, that while changing the magnetic field or the switch heater settings, no other commands can be given until the operation is completed, although monitoring and logging work properly. This was implemented to take care of magnet and supply settling times, but can lead to problems if the magnet is not working properly. For this reason, one should not use this option in remote mode if a proper operation cannot be ensured.

The log can be access by the button logview and is stored to the file ..\users\-kryolog.dat. With time the files can become quite huge, slowing the viewing process. To avoid this one should rename the file with the program being closed. A new file with correct header will be created upon the next startup.

If setting the read-out rate for the helium via the fast button of the program, the rate will be reset automatically to slow after half an hour to avoid unnecessary high consumption of helium.

The program has the advantage of reducing the amount of open windows to control all generally used devices down to one. Furthermore, logging all parameters eases the cryostat handling, e.g. one can easily check the helium consumption or track down anomalies.
Appendix C

Recipes for sample preparation

As substrate a 1-inch (25.4 mm), (100) orientated, oxidized silicon wafer was used, with an oxide thickness of 50 nm and an overall thickness of 525 µm. First a cleaning procedure was applied:

1. 2 min in acetone with ultrasound at level 2
2. second acetone bath, 2 min at level 2
3. 2 min in isopropyl alcohol with ultrasound at level 2
4. drying with nitrogen gas flow

C.1 Outer Contact Structure

After cleaning, the resist was spin-coated and exposed with MJB- HP/350 UHV 400

1. spin-coat AZ® 5214E at 4000 rpm (Pr.2)
2. back at 110 °C for 70 s
3. flood exposure (no mask) for 0.3 s
4. back at 130 °C for 120 s
5. expose (with mask cf. Fig. 3.1) for 4.5 s
6. develop in AZ® Developer for 3 min (process can be controlled by the eye, color changes)
7. stop develop process by two subsequent H₂O baths of 30 s
8. check with optical microscope: if not completely developed, repeat steps 6-7 for several seconds

Gold is then deposited via the BAL-TEC MED 020 HR modular sputtering device:

1. Process pressure of 5 × 10⁻² mbar (Argon)
2. current: 45 mA
3. pre-sputter 60 s (shutter closed)
4. deposition of 25 nm within 52 s

The **lift-off** process did not include any supersonic cleaning step:

1. 15 min in acetone bath at 70°C
2. rinse with acetone
3. 30 min in acetone bath at 70°C
4. short isopropyl alcohol bath and rinsing
5. dry with nitrogen gas flow

**C.2 Inner Structure**

On the wafer with contact structure a two-layer PMMA resist system from MicroChem Corp. was **spin-coated**:

1. spin coat PMMA 495K A6 at 8000 rpm (Pr.9)
2. back at 175°C for 10 min
3. spin coat PMMA 950K A4 at 8000 rpm (Pr.9)
4. back at 175°C for 10 min

For the **exposure via electron beam lithography** the mask seen in Fig. 3.3 & 3.5 were used. The final dose can be deduced by the area (or line) dose times the dose factor. The latter can vary depending on the actual state of the system (can be different after the recent maintenance). A test for different doses should be conducted to find the correct value. Following parameters were used:

- acceleration voltage: 30 kV
- spot size 1
- area dose: 200μAs/cm², area step size: 5.5 nm for area scans
- line dose: 600 pAs/cm², line step size: 3.7 nm for line scans
- write field size: 120μm × 120μm
- dose factor: 2.4 to 2.6 for area scans and 4.0 to 4.5 for line scans

Afterwards **develop** the resist:

1. develop exactly 2 min in AR 600-56 developer from Allresist.
2. stop develop process by two subsequent isopropyl alcohol baths of 30 s
3. dry with nitrogen gas flow

**Deposit** 50 nm of the desired material:

- Gold in effusion cell at 0.2/s, which corresponds to 1530 °C
- Electron beam evaporation:
  - Gold at 4.5/s
  - Nickel at 1.4/s
  - Aluminum at 12/s

The **lift-off** process did not include any supersonic cleaning step:

1. 15 min in acetone bath at 70 °C
2. rinse with acetone
3. 30 min in acetone bath at 70 °C
4. short isopropyl alcohol bath and rinsing
5. dry with nitrogen gas flow
Nomenclature

$\alpha_{\text{SHE}}$  Spin Hall Angle, $\alpha_{\text{SHE}} = \sigma_{\text{SHE}}/\sigma$

$B$  Magnetic Field

$c$  Velocity of Light, $c = 2.99792458 \times 10^8 \text{ m/s}$ [94]

CMRR  Common Mode Rejection Ratio

$D_s$  Spin Diffusion Constant, $D_s = l_s^2/\tau_s$

$E$  Electric Field

$e$  Elementary Charge, $e = 1.60217733 \times 10^{-19} \text{ C}$

$\eta_{\text{SO}}$  Spin Orbit Coupling Parameter

$\Delta f$  Equivalent Noise Bandwidth

$f_{k\sigma}$  Distribution Function

$g$  G-Factor

$h$  Planck Constant, $h = 6.6260755 \times 10^{-34} \text{ Js}$ [94]

$\hbar$  $h/2\pi = 1.05457266 \times 10^{-34} \text{ Js}$ [94]

$I = I_c$  Charge Current

$I_s$  Spin Current

$j_c$  Charge Current Density

$j_s$  Spin Current Density

$j_{\text{eq}}$  Spin Current Density due to Spin Accumulation

$k$  Boltzmann Constant, $k = 1.380658 \times 10^{-23} \text{ J/K}$

$k$  Momentum

$k_F$  Fermi Wave Vector

$l_s$  Spin Diffusion Length

$m$  Effective Mass
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$</td>
<td>Magnetic Moment</td>
</tr>
<tr>
<td>$\mu_B$</td>
<td>Bohr Magneton, $\mu_B = 9.2740154 \times 10^{-24} \text{ J/T}$</td>
</tr>
<tr>
<td>$n$</td>
<td>Carrier Density</td>
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<tr>
<td>$n$</td>
<td>Surface Normal</td>
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<tr>
<td>$n_{\uparrow/\downarrow}$</td>
<td>Carrier Density for Spin Up/Down</td>
</tr>
<tr>
<td>$\omega_B$</td>
<td>Larmor Precession Frequency</td>
</tr>
<tr>
<td>$q$</td>
<td>Electric Charge</td>
</tr>
<tr>
<td>$R = R_{\text{local}}$</td>
<td>Local Resistance</td>
</tr>
<tr>
<td>$R_{\text{nonlocal}}$</td>
<td>Non-local Resistance (= normalized voltage signal)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Resistivity</td>
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<tr>
<td>$S$</td>
<td>Seebeck Coefficient</td>
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<tr>
<td>$s$</td>
<td>Pauli Spin Operator</td>
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<tr>
<td>$\sigma_{\text{SHE}}$</td>
<td>Spin Hall Conductivity</td>
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<tr>
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<tr>
<td>$S_z$</td>
<td>Spin Density</td>
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<tr>
<td>$s_z$</td>
<td>$z$-component of the Spin Operator</td>
</tr>
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<td>Temperature</td>
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<tr>
<td>$\tau_s$</td>
<td>Spin Relaxation Time</td>
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<tr>
<td>$V_{\text{imp}}$</td>
<td>Impurity Scattering Potential</td>
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</tbody>
</table>
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