Non-Local Measurements on Lateral Spin Valves of Permalloy and Silver

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Abstract

Lateral spin valve structures were fabricated from permalloy and silver, where the permalloy functions as injector of spin polarization to induce a pure spin current in the silver. A second permalloy wire was used to measure a non local signal that is the result of this spin current.

Contents

Chapter 1

Introduction

Computers are deeply engrained in modern society. As more data can be stored, computers can be allocated more and more tasks. Likewise, as technology finds more applications, the demand for data storage increases. In the past decades technology has rapidly getting more compact. In 1975 it was predicted that the amount of transistors that can be crammed on a chip would double every two years. So far this empirical statement, known as Moore's law, has held true quite well. Transistors have been getting very small. As they are getting smaller, they are also approaching the limits of how electron charge behaves in a solid. Additionally, placing electrical component closer together introduces heat due to a lot of current flowing through wires with any kind of resistance. Another problem is parasitic capacitance between components placed closely together. As the clock speed of computers increases, the alternating current combined with unwanted capacitance can cause short circuits. Also heating gets significant when electronic components are being placed closer together. A way that these problem might be dealt with is by not only using the charge of electrons, but also their spin. The field of science which seeks to incorporate spin into electronics is called spintronics. Though quite novel, incorporating spin in data storage technologies seems promising. Controlling a spin state should not cost a lot of energy, which could allow for devices that produce little heat and are very fast. [1]

1.1 Spintronics

So what is spintronics? In typical electronics the transport of electron charge is studied. In spintronics one seeks to manipulate spin in solid state systems. That could either be just a few electron spins or the population of spin states for many electrons. Ways to induce and detect spin polarization are being researched, as well as how long this spin state can be maintained. The latter question is what this thesis is about. We have done non-local measurements on lateral spin valves of permalloy and silver. This was done before by T. Kimura and Y. Otani [2] where they employed this method to determine the spin accumulation length in silver.

Chapter 2

Theory

2.1 Magnetism

Electrons, as well as protons, neutrons and other particles have an intrinsic angular momentum called spin. [3] For electrons the magnitude of the spin is a set quantity and occurs in two configurations: spin up and spin down down. [3] Spin up and spin down are expressions of the direction of the spin, or more specifically the projection of the spin on a certain axis. It is common to pick this axis to be in the direction of magnetization. For charged particles, this intrinsic angular momentum is related to a magnetic moment, which scales with angular momentum as $1/\mathrm{m}$. [4] Since the mass of electrons is a lot less than that of protons, the magnetic moment is mostly due to electrons. The total magnetic moment of one atom is caused by the spin of the electrons and their orbital momentum, which is their precesion around the nucleus. When those atoms align their magnetic moment we speak of magnetism.

A special case of magnetism is ferromagnetism, which is when the magnetic moments of atoms remain aligned after a magnetic field is removed. Examples of ferromagnetic materials include iron, cobalt, nickel and most of their alloys. In this project permalloy, an alloy of iron and nickle, is used as the ferromagnet for our experiments. The response of a ferromagnets magnetization M to an applied magnetic field H is expressed as hysteresis. Before ever applying a magnetic field, the magnetization of the material is zero. There is magnetic ordering happening at submicrometer scale, in small regions called domains, but the magnenization direction is random. When a magnetic field is imposed, the domains will tend to align with the field. At high enough field the magnet will be saturated. Its magnetization at that point is called the saturation magnetization M_s. When after that the field is removed, there is a remaining magnetization M_r. The point at which the magnetization changes sign is the coercive field H_c. All of this can be seen in a hysteresis loop, which displays the magnetization as a function of an imposed field H.

2.1.1 Band structure

A useful tool to understand magnetism is band structure. An electron can be in different states that are associated with different energies. The amount of states associated with a certain energy is given by the density of states. The energy range for which there are allowed energy states is referred to as a band. [5] The electrons fill up the lowest energy levels whilst obeying Pauli's exclusion principle. That is, each state can be occupied only once, with the two spin states counting as different states. When the energy levels are filled up like this, so filling all the lowest energy states, the energy of the highest occupied state is called the Fermi energy E_F. The energy associated with a certain state is affected by the states of other electrons through something called exchange interaction. This causes a lower energy state when electrons align their spins. This energy competes with the filling of the lowest energy single electron states. When aligning spins results in a lower energy, ferromagnetism occurs. In the band structure this can be visualized as one of the bands shifting up due to the exchange interaction. [6] [5] So when all states up to the Fermi level are occupied, there will be a net spin and thus a net magnetization.

2.2 Spin polarization

In a ferromagnet the spin up and the spin down states are not equally occupied. A means of expressing the difference in a certain quantity between the spin up state and the spin down state is polarization. Polarization for some property x is defined as [7]

$$P_x = \frac{x_\uparrow - x_\downarrow}{x_\uparrow + x_\downarrow}.$$

Typically, spin polarization indicates the polarization of the density of states at the Fermi level E_F. Electrons in these states can easilly go into slightly higher energy states. This means these electrons can acquire momentum, and therefore "flow". This polarization is therefore related to the polarization of the current density j, though it is not necessarily equal.

2.2.1 Spin current

Electric current in metals can be explained with the free electron model. Here electrons scatter with a mean free path length λ and a momentum relaxation time τ, which are characteristic to the material. These parameters can be different for spin up and spin down [4]. Then when a voltage, so a potential gradient is applied, the electrons obtain a net momentum in the opposite direction. Here's an expression for current density in direction x [8]:

$$j_x = \frac{\sigma}{e}\frac{\partial \mu}{\partial x}$$

Here σ is the conductivity and μ is the electrochemical potential. In a ferromagnet σ (and with that j) differs for spin up and down as it is related to the density of states at the Fermi level. This difference results in a transport of spin, called the spin polarized current or spin current.

$$P_j = \frac{j_\uparrow - j_\downarrow}{j_\uparrow + j_\downarrow}.$$

An important difference between spin current and electric current is that while charge is conserved, spin is not. As electrons scatter, it will undergo mostly elastic collisions and occasionally inelastic collisions. In elastic collisions there is only momentum transfer between the two colliding electrons. In an inelastic collision on the other hand, there is an energy exchange with the surroundings, which can cause the angular momentum of the electron to change. After this inelastic collision the spin will be random. [4] Causes for spin relaxation are spin-spin interaction, spin-orbit coupling and exchange interaction. [8] The typical length over which the spin is conserved is called the spin diffusion length. The spin diffusion length is a material property and is independent of current. A way to determine spin diffusion length is by non-local spin valve measurement[4], as was first described/done in 1985 by Johnson and Silsbee [9]. In this experiment we've attempted this method in spin valves of permalloy and silver, after the example of Kimura and Otani [2].

2.3 Spin valve measurement

The device used in this experiment is a lateral spin valve of the ferromagnet permalloy and the normal metal silver. There are two parallel permalloy wires and one silver wire connecting the two. The first permalloy wire, F1, is used to inject polarized spins into the silver wire, N. There the spin diffuses. The second permalloy wire is used to detect how spin polarized the electrons are at a certain distance. At the interfaces between the metals there will be a so called "giant magnetoresistance", abbreviated to GMR, which depends on the relative magnetization of the two materials. The GMR will be different for a parallel or an antiparallel orientation of the magnetization of the ferromagnets. In order to determine the spin diffusion length, a non-local measurement set up is used. This means that the voltage is measured outside the applied current loop.

2.3.1 Spin injection

When current is flowing through the material, in general the electrochemical potential $\mu_{\uparrow,\downarrow}$ for spin up and spin down respectively are equal. This is the energy level up to which the states are filled, and in the lowest energy state this coincides with the Fermi energy. The conductivities for spin up, $\sigma_\uparrow$, and for spin down, $\sigma_\downarrow$ in the ferromagnet are different which means the current is polarized. (This is in part related to the density of states, which also differ, but also to other factors [8]) The conductivities $\sigma_\uparrow$ and $\sigma_\downarrow$ in the normal metal however are equal. At the interface σ suddenly changes, but the current has to stay continuous. To accomodate for that difference, the gradient in chemical potential on either side of the interface also changes, resulting in a difference in $\mu_\uparrow$ and $\mu_\downarrow$. [6] This difference is defined as the spin accumulation $\Delta\mu$. There's an unequal supply of up and down electrons from the ferromagnet. The normal metal wants to transport them at the same rate though, causing an obstruction for the majority spin while the minority spin can pass through very easily. When electrons come from the ferromagnet to the normal metal, the surplus of majority spin electrons forces them to occupy a higher energy state, while the minority spin electrons are able to occupy a lower energy state than the equilibrium energy, causing a difference in electrochemical potential between up and down spins. The accumulation in the normal metal is also felt on the ferromagnet side of the interface. The electron with majority spin have a hard time passing and some of them will scatter back instead, whereas the minority spin electrons will flow even better. The accumulation is eventually resolved as the electrons flip their spin to obtain the equilibrium polarization. The distance over which this diffusion happens is characterized by [4]

$$(\mu_\uparrow - \mu_\downarrow)_x = (\mu_\uparrow - \mu_\downarrow)_0 e^{-x/\lambda}$$

where $(\mu_\uparrow - \mu_\downarrow)_x$ is the spin accumulation at discance x in a material with spin diffusion length λ. In the non-local setup, there is a current flowing through the ferromagnet and through the interface, but not through the normal metal part in between the two ferromagnets. In that part there is no net flow of electrons, only spin diffusion. Detection, the FNF structure In order to characterize the spin diffusion, a second ferromagnet F2 is used to measure the spin accumulation at different distances from the first ferromagnet F1. The spin current at the second interface goes into F2 [10] where it affects the chemical potential in F2. How the chemical potential is affected differs depending on whether the magnetization of F2 is parallel or antiparallel to that in F1. F2 will be more sensitive to one of the two spin currents, and the electrochemical potential for that current will influence the electrochemical potential in F2. The difference between the electrochemical potential in N (the average between the up and down electrochemical potential) and in F2 is measured as a voltage. This results in a non-local resistance which differs for parallel and antiparallel orientation of F1 and F2. This resistance difference is given by: Resistance difference measured: [11]

$$R_s = \frac{4{p_F}^2}{(1-{p_F}^2)^2} R_N (\frac{R_F}{R_N})^2 \frac{e^{-x/\lambda_N}}{1-e^{-x/\lambda_N}}$$

Here $R_{F,N}$ are the resistances of the Py and Ag resp., p_F is the polarization of the current and λ_N is the spin diffusion length in Ag. The dependence on the distance and spin diffusion length is only in the last term, so the spin diffusion length can be found by fitting the measured resistance difference to this equation.

Chapter 3

Fabrication and Measurement Setup

In this chapter, fabrication of the lateral spin valves is discussed in detail. The last section describes the measurement setup and the techniques we used to study the physics of our device. We've made spin valves from permalloy and silver, as well as some single nanowires in order to test the fabrication methods. Measurements were done in the Physical Properties Measurement System (PPMS). This is a cryogenic chamber that can reach temperatures down to 2 K, in which a magnetic field can be applied upto 9 T. Keithley 6221 current source is used to apply AC current to our devices. The voltage is measured with an SR830 DSP lock-in amplifier for AC measurements and a Keithley 2182A nanovoltmeter for DC measurements.

3.1 Fabrication

The permalloy nanowires were fabricated on a silicon wafer with 300 nm thermalized silicon oxide (resistivity $\sim$ .001-.005 Ωcm). The nanowires are patterned using electron beam lithography (EBL). Then Py is deposited by ultra high vacuum (UHV) sputtering technique which is then lifted-off to get the desired nanowires. Ag contacts on top of the Py nanowire are then added by means of EBL, RF diode sputtering and lift-off.

3.1.1 E-beam

In electron beam lithography, or EBL, a focused beam of electrons is used to draw a design on a thin layer of electronsensitive resist. This changes the solubility of the resist. After lithography the sample is developed to remove the part of the resist where it has been exposed by the electron beam. What remains is a mask. Material can then be deposited over this mask, after which the mask is lifted off, leaving only the desired material.

3.1.2 Spin Coating

Resist needed for EBL is put on the substrate by means of vacuum spin coating. The substrate with a drop of liquid resist is rotated at a high speed, spreading the liquid homogeneously and removing the excess.

When depositing via sputtering, material comes at the substrate in an isotropic manner, which makes it to accumulate not only at the substrate but also at the sides of the mask. In order to minimize this effect, two resists of different electronsensitivty (and viscosity) are used. The lower layer is more electronsensitive, which creates an undercut. This can help in preventing the "ear formation" which is a common problem in the sputtering and lift-off process.

3.1.3 Sputtering

For sputtering two machines are utilised, the UHV magnetron sputtering system for permalloy and the z407 RF diode sputtering system for silver. In both systems particles are removed from a target by argon plasma and are then deposited on the substrate. The (positive) argon ions hit the target with a high energy, transferring some of that energy to the target atoms which are then removed from the target. [12] The UHV sputtering system uses a magnetron to keep the plasma at the surface of the target. The low pressure in the chamber ensures a large mean free path for the electrons. As the target is placed at a large distance, this long mean free path allows for a rather uniform direction of deposition. The z407 sputtering system works with an alternating voltage behind the target. The sample is placed on a grounded plate.

3.1.4 Etching

The Py wires oxidize in the atmosphere which forms an insulating layer at the top that needs to be removed before depositing Ag to get a transparent Ohmic interface contacts. This is done by etching, for which the z407 is used. To etch, plasma is directed towards the sample rather than the target.

This is done by applying the alternating potential to the plate holding the sample and using the target holder as ground.

3.2 Designs

We've made single nanowires and spin valves.

3.2.1 Nanowires

We've made two types of devices consisting of a single nanowire and contacts in a configuration for performing four point measurements. One type consists of a permalloy wire and silver contacts and measurement probes. This design is shown in figure **??**. The other type, shown in figure **??**, has a permalloy wire with a permalloy contact pad at one end, as well as a notch between the two measurement probes. The other contact pads as well as the measurement probes are again silver. The permalloy wire in all cases has a width of 200 nm and a length varying between 60 μm and 90 μm including interfaces. The silver measurement probes all have a width of 400 nm and were spaced either 15 μm or 24 μm apart. The measurements performed on these devices include 2 probe IV over te interfaces, as well as a 4 point MR measurement. Here an AC current was applied between 1 and 3, and a signal was measured between 2 and 4. A field was applied in the horizontal direction.

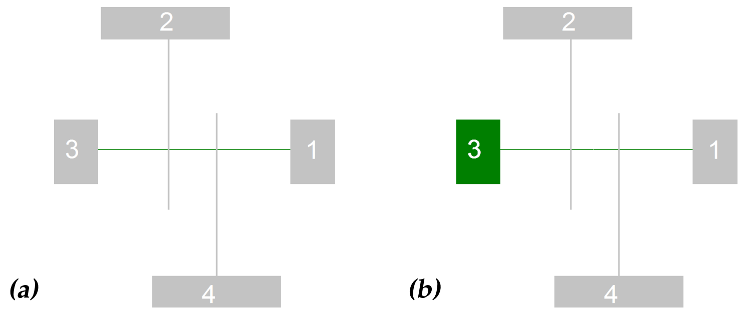


*Figure 3.1: Py nanowires **(a)** with all Ag contact pad **(b)** with Py contact pad and notch*

3.2.2 Spin valves

The spin valve devices consist of two parallel permalloy wires with a silver wire on top connecting the two. The dimensions of the upper wire are 60

μm $\times$ 200 nm. The lower wire has dimensions 13μm $\times$ 1μm. The width of the silver wire is 400 nm. The distance between the two permalloy wires is varied between 400 nm and 600 nm. In the first designs all contact pads were silver. Later contact pad 1 was changed out for a permalloy contact pad. In figure 3.2 the design is shown with the non local measurement setup. An alternating current of 100 μA with a frequency of 77.4 Hz is applied between 4 and 5, and a voltage is measured over 2 and 3.

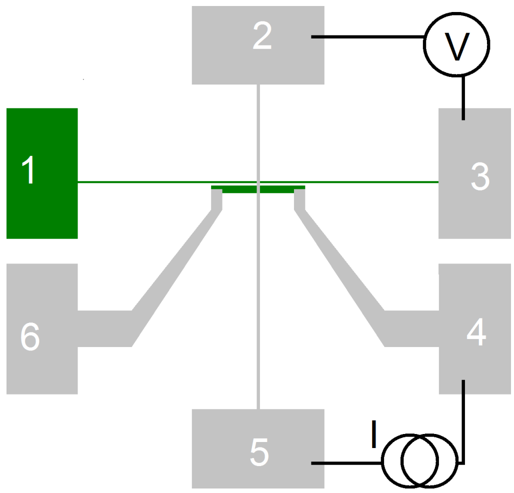


Figure 3.2: *Spin valve with Py contact pad in non-local measurement setup*

Chapter 4

Results

This chapter will contain results of the measurements for both the spin valves and the test devices.

4.1 Interfaces

Before doing measurements on spin valves in the non-local setup, we tried to get ohmic and with that hopefully transparent interfaces in order to minimize the noise of the measurements and to have it be in accordance with the theoretical model. An Ohmic interface is characterized by a linear relation between the current and the voltage. The measured voltage and resistance were plotted against the applied current. The voltage should form a straight line and the resistance should approach a constant value for non-zero current.

We've tried two methods of silver deposition: resistance evaporation and sputtering. Resistance evaporation has the advantage over sputtering that it results in wires of rather uniform thickness. The sputtering on the other hand can be preceded by argon etching in the same machine. To find the ideal amount of etching, the duration of the etching is varied. In figure 4.3 and figure 4.4, found ant the end of this chapter, a comparison is shown of the interface resistance for devices with evaporated silver and sputtered silver with different etching times.

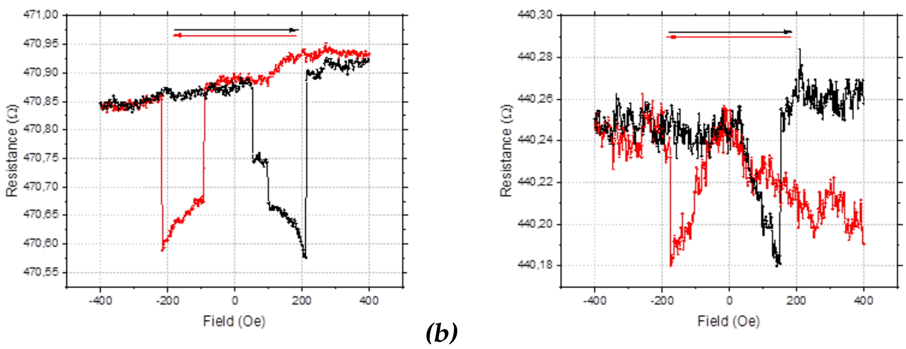
There's three things to notice about the results: the shape of the curves around zero, the asymptotic behaviour at the sides and the overall value of the resistance. The shape around zero looks quite irregular in figures. That's because it is difficult to accurately measure voltage (resistance) at very low current.

The resistance seems to be decreasing as the etching time is decreased. However the measured interface resistances differed by a few hundreds ohms within one device, so this alone is not a reliable measure for the quality of the interface.

The behaviour at the sides of the graph gives further information. For the lower etching times the sides seem to approximate a horizontal line, though there is still a difference in the resistance value for the positive current and negative current. For the higher etching times a parabolic behaviour seems to be approached. This behaviour is typical to Joule heating and indicative of a high resistance at the interface. It seems like the ideal amount of etching is around 30 to 40 seconds.

4.2 Domain Walls

In order to see if we could measure a change in magnetoresistance we made test devices that could have a pinned domain wall in the wire. This is done by making a constriction in the wire and attaching a permalloy contact pad on one side. A domain wall can be pinned at the constriction as the wire changes its direction of magnetization. Then, for as long as the domain wall is present, the measured resistance will have a different value. This effect can be seen in figure 4.1.



(a) *(b)*

Figure 4.1: *MR measurement of Py wires with contact pad and constriction. Results for **(a)** interfaces with 80 seconds of etching and narrow constriction and **(b)** 120 seconds of etching and a wider constriction.*

There is a visible difference in resistance on either side of the graph which means we are indeed measuring a change in resistance due to domain walls being present. The drop in resistance is different for the two measurements. The major differences between these two devices are the width of the constriction and the quality of the interfaces. The 60 μm wire has a deeper constriction than the 50 μm one. Additionally, the 60 μm one had been etched for 80 seconds, whereas the 50 μm one was etched for 120 seconds.

4.3 Spin valves

For most of the spin valves we've only measured noise. Additionally, the phase difference between the applied current and the measured voltage was around 90 degrees. This could be due to capacitive coupling in the device which may come from the bad interfaces.

Eventually we were able to measure one device where we found the behaviour we were looking for. Here one of the two permalloy wires is connected to a permalloy contact pad in order to facilitate the switching of magnetization. The non local signal can clearly be seen in figure 4.2.

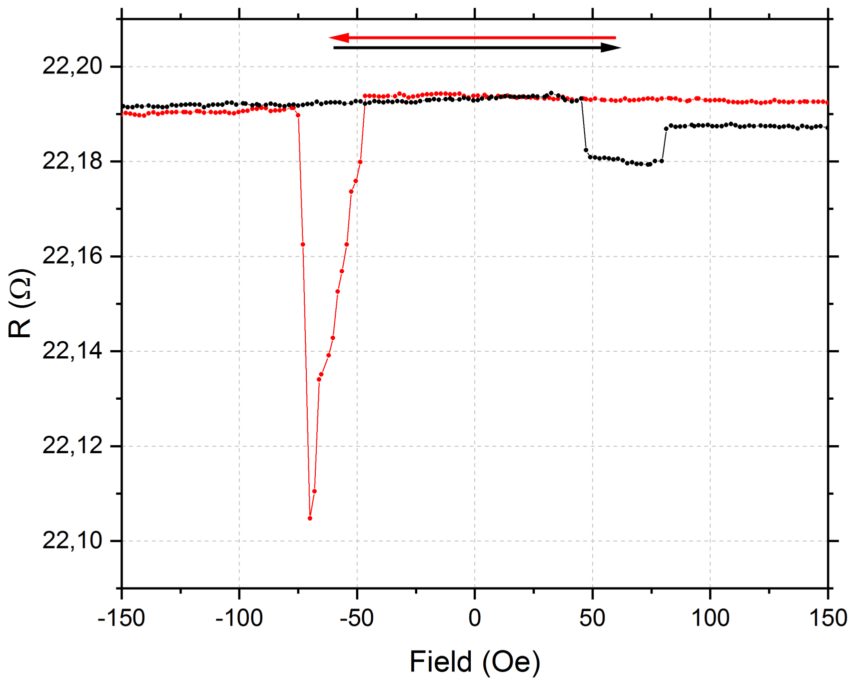


Figure 4.2: *Non local signal for spin valve with permalloy contact pad*

In this measurement there is a clear drop in the resistance on either side after the magnetization has switched, which can be attributed to the non-local spin valve effect. However, the resistance on the left side drops far more than on the right side. The non-local signal measured by Kimura and Otani was approximately 10 mΩ both at 77K and at room temperature [2]. This is similar to the drop in resistance on the right side of the graph. It is not clear what causes the drop in resistance on the left side of the graph.

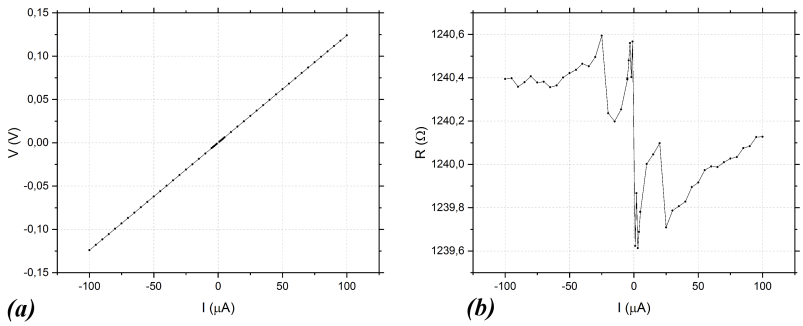


Figure 4.3: *Interface IV measurements on devices with evaporated silver. On horizontal axis the applied current is shown and on the vertical axis **(a)** measured voltage and **(b)** resistance*

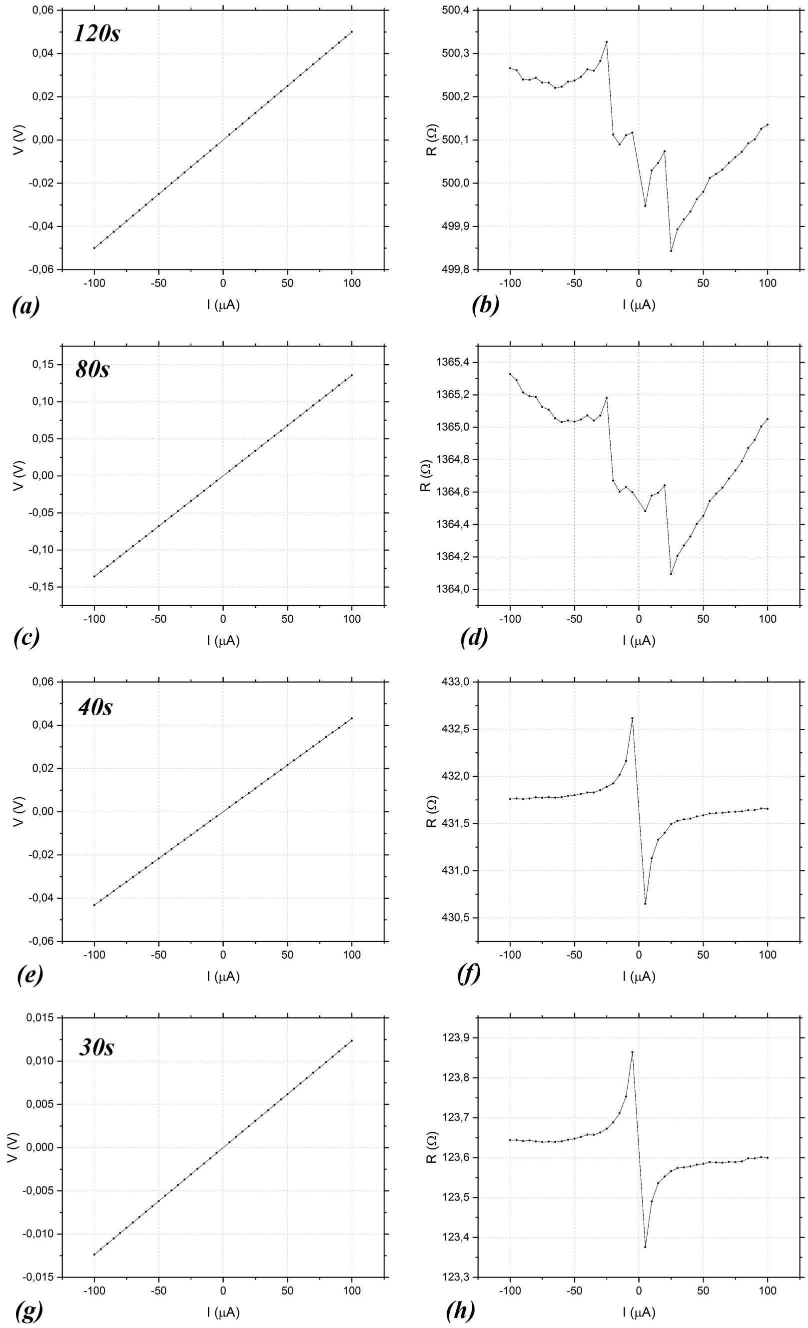


Figure 4.4: *Interface IV measurements on devices sputtered silver. The etching times are given on the left side of the figures. On the horizontal axis the applied current is shown and on the vertical axis* ***(a, c, d, g)*** *measured voltage and* ***(b, d, f, h)*** *resistance*

Chapter 5

conclusion

In this project we have optimized the creation of structures containing permalloy and silver nanowires with regards to the quality of the interfaces. A transparent interface was consistently created between permalloy and silver wires. This was done in a two step process of electron beam lithography, material deposition and liftoff. Permalloy was deposited by means of UHV sputtering, after which the surface was etched with argon plasma, immediately followed by silver deposition through sputtering. The optimized fabrication process was then implemented in making spin valves. Two types of spin valves were fabricated, both with varying distances between the two permalloy wires. The difference between the two types of devices was the presence of a contact pad on one side of one of the permalloy wires, in order to facilitate switching of the direction of magnetization. Non-local measurements with a varying magnetic field along the direction of the wire were performed. A change in the resistance due to sin diffusion was found for one of the devices. This result was only found in one device that had a permalloy contact pad.

The non-local measurement displayed two behaviours that have yet to be explained. One is that there seems to be a background voltage that is measured, which can probably not be attributed to the spin diffusion. The offset in the signal is likely to be noise coming from the measurement setup itself.

The other behaviour that is not understood is the asymmetric drop in the signal. When the field is swept in one direction the non-local signal drops far more than when the field is swept back. The smaller drop in the signal is consistent with the literature. The deep drop might be a result of the addition of the contact pad. This design is quite unconventional, and it might cause interfering magnetic fields.

So far, we've only had one succesful non-local measurement. In order to find answers to explain this behaviour more non-local measurements would be needed. The contact pad in the design was used to ensure switching of the magnetization, but this switching could also be achieved by changing the shape of the wire in question.

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