Charge and spin transport in Nb-doped SrTiO3 using Co/AlOx spin injection contacts
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Chapter 7

Inherent temperature driven inversion of spin accumulation in Nb: SrTiO$_3$

Abstract

In this chapter we explore the temperature dependence of the devices discussed in chapter 4 and 5 as well as spin injection contacts with a thinner AlO$_x$ tunnel barrier. A systematic sign inversion of the spin signal is observed below $\sim 150$ K for all devices studied. Below the temperature where inversion sets in the spin signal sign is bias dependent, recovering the conventional positive sign at large positive bias. Unlike the cases where sign inversion was observed for spin injection into Si, Ge or GaAs we do not employ epitaxial contacts. Unlike in conventional semiconductors Schottky barriers in Nb: SrTiO$_3$ are inherently temperature dependent since the electric field in the space-charge region leads to non-linearity of Nb: SrTiO$_3$’s permittivity. We propose that it is this inherent dependence of the Schottky barrier profile on temperature and bias that results in the bias dependent sign inversion at lower temperatures. Since the Schottky barrier profile change is fully determined by the non-linearity of the permittivity an universal, temperature driven, inversion of the spin signal is expected as long as spin are injected through a space-charge region with large enough electric field.

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7. Inherent temperature driven inversion of spin accumulation in Nb:SrTiO$_3$

7.1 Introduction

The last decade has shown huge progress in the realization of all-electrical creation and detection of a spin polarization inside non-magnetic semiconductors. It also revealed that the precise interface structure of the ferromagnet/semiconductor interface has profound influence on the details of the spin polarization. For instance, a (bias dependent) sign change of the polarization has been observed which has been explained by tunneling via resonance states at the interface [1–5]. The details of the sign change vary strongly from device to device or a change is altogether absent, which can be understood from the extremely sensitive nature of the interface electronic structure [6, 7]. Additionally, the inversion is only observed at low temperatures possibly because thermal smearing reduces the resonance feature.

Here we show that the spin accumulation inside Nb:SrTiO$_3$ shows a sign inversion around 150 K. Unlike previous works this inversion is systematically observed for many devices even when different spin injection contacts are used. We attribute the origin of the inversion to the non-linear permittivity $\epsilon_r(E, T)$ of Nb:SrTiO$_3$ which results in a temperature dependent Schottky barrier profile [8]. Such a sign change of the polarization due to the alteration of the potential barrier has been theoretically predicted [9]. The sign change is thus related to an intrinsic property of the Nb:SrTiO$_3$ bulk crystal, namely $\epsilon_r(E, T)$. As a consequence the inversion is not as strongly related to the exact interfacial electronic structure, which is complicated to reproducibly control. Moreover, the sign of the spin accumulation can be controlled via junction bias at the temperature where inversion sets in. This temperature is related to the non-linearity of $\epsilon_r$ and is around $\sim$150 K for the current devices. This temperature can in principle be raised to room temperature by proper engineering of the Schottky barrier width via doping density control. Narrowing the Schottky barrier leads to an increase of the electric field, which can in principle result in non-linear behavior of $\epsilon_r$ at room temperature. This would allow voltage bias control over the sign of the spin polarization inside the semiconductor at room temperature providing additional control over the spin state compared to conventional semiconductors.

In this chapter, I discuss the temperature dependent behavior of the spin injection devices in chapter [4]. The overall behavior of the spin signal at lower temperatures is similar to that at room temperature (see chapter [4] and chapter [5]: the in-plane spin lifetime $\tau_\parallel$ increases with positive bias while the anisotropy of the spin lifetime $\tau_\perp/\tau_\parallel$ decreases with positive bias [10]. This behavior was shown to be consistent with spin dephasing due to electric field tuning of the Rashba-like SOC strength. A slight increase of $\tau_\parallel$ is observed with reducing temperature up to 40 ± 5 ps at 4 K and at large positive bias. At lower temperatures TAMR appears which complicates the magnetic field response of the spin injection devices however, it will be shown that this is not an issue when investigating the sign inversion of the in-plane spin accumulation.
7.2 Results

SrTiO$_3$ has a perovskite crystal structure which becomes n-type conducting by doping Nb$^{5+}$ at the Ti$^{4+}$ site. The crystal has a very large permittivity $\epsilon_r$ of $\sim 300$ at room temperature and is a non-linear dielectric [11]. As semiconductor, commercially available 0.1 wt% Nb-doped SrTiO$_3$ (Nb-SrTiO$_3$) single crystal substrates from Crystec GmbH are used. Prior to deposition the crystal is subsequently immersed in methanol (10 min), DI water (30 min), BHF (30 s) and finally in DI water (10 min) all inside an ultrasonic bath. After a blow dry with N$_2$ it is inserted in an e-beam evaporator and in-situ O$_2$ plasma is used to clean the Nb-SrTiO$_3$ surface. The spin injection contacts are formed by $\sim 10$ Å Al, which is in-situ O$_2$ plasma oxidized followed by subsequent growth of 20 nm of Co and Au. The contact sizes range from 50×200 up to 200×200 µm$^2$ and are separated by at least 100 µm.

To measure the spin accumulation, temperature dependent Hanle precession experiments are performed in a three terminal spin injection/detection geometry which is shown at the top of Fig. 7.1. A constant bias current is sourced between contact 1 and 2 creating a spin accumulation of in-plane pointing spins. By applying an out-of-plane magnetic field ($B$) the spin accumulation is removed due to Lamor precession. This leads to a change in the potential of the central contact which is measured relative to a contact (nr. 3) outside the current path. Such measurement have been carried out for various temperatures from 300 K to 4 K and junction bias currents resulting in voltages between $-0.3$ V and $1.1$ V.

In Fig. 7.1 a selection of Hanle measurements is shown at 2.5 mA from 300 K to 100 K which captures all the essential features observed in the large range of Hanle measurements performed. The temperature and junction background voltage ($V_{bg}$) is mentioned next to each curve. At 250 K (black squares) the lineshape corresponds to that expected from spin dephasing by Lamor precession: a decreasing voltage with a Lorentzian lineshape at low fields, related to the dephasing of in-plane spins, and an increase of the voltage at larger fields ($B > 1$ T) due to the accumulation of out-of-plane pointing spins. The out-of-plane spin accumulation results from the rotation of cobalt’s magnetization, which defines the spin orientation axis, due to the applied magnetic field. Hence, when the magnetization points along the magnetic field the lineshape saturates. At high fields a background magnetoresistance (MR) effect is observed which behaves proportional to $|B|$ and has been subtracted. Such an MR effect has been reported before for ferromagnetic contacts on Nb:SrTiO$_3$ although its origin was not discussed [12]. For completeness sake two measurements where the field was applied both in- and out-of-plane are shown in the supplementary information, without removing the linear MR.

With reducing temperature the amplitude of the spin signal is observed to decrease considerably, especially in the regime from 300 K to 200 K. Below 175 K the lineshape can no longer be described by spin dephasing only and an additional MR
Figure 7.1: Hanle measurements at different temperatures at 2.5 mA bias. The data is given by the open symbols and the solid lines are fits using a superposition of a diffusive Hanle fit function and a TAMR fit function, $V_\perp$ is set to zero when no upturn is visible (e.g. for $T \leq 175$ K). The presence of TAMR at forward bias becomes clearly visible at 150 K and below. The inversion of the Hanle signal is visible at 100 K. Note that the linear MR has already been subtracted as discussed in the text.

Effect (proportional to $B^2$) is need to describe the lineshape. This MR effect also saturates when the magnetization has fully aligned with the magnetic field and can be attributed to tunneling anisotropic magnetoresistance (TAMR) (see chapter 6). At 130 K the lineshape can be described by only assuming a TAMR effect. Around this temperature the sign of the spin signal is strongly bias dependent and the absence of a spin signal is because the device is biased at the turning point where the spin signal changes sign. Finally at 100 K an inversion of the spin signal is observed as a small dip at low fields on top of the TAMR effect.

The observed field response can be well fitted with a diffusive three terminal Hanle equation and an additional term accounting for the TAMR and is given by:

$$\Delta V = (V_\perp + V_{TAMR}) \cos^2(\theta) + \frac{V_{\parallel} \sin^2(\theta)}{\sqrt{2}} \sqrt{\frac{1 + \sqrt{1 + (\omega L \tau_\parallel)^2}}{1 + (\omega L \tau_\parallel)^2}},$$

(7.1)
Figure 7.2: In-plane (black circles) and out-of-plane (red triangles) spin voltage as a function of temperature at (a) 5 mA bias (b) 2.5 mA bias (c) 1 mA. A clear reduction of in- and out-of-plane spin voltage with reducing temperature is observed. Except for the high bias data in (a) inversion of the spin signal is observed. (d) In-plane spin voltage as function of junction voltage at different temperatures (175 K (black squares), 150 K (red circles), 130 K (green upwards triangles), 100 K (blue downwards triangles) and 12 K (wine diamonds). Inversion of the spin signal occurs around 130 K and remains present all the way down to 12 K. At large junction voltage the spin signal returns to its normal sign.

with ωₗ = (egB/2m*), the Larmor precession term (g = 2, m* = mₑ), θ = θ(B) the angle between the surface normal and the magnetization vector of cobalt which is a function of the applied magnetic field (see top of Fig.7.1), τ∥ the in-plane spin lifetime, V⊥ and V∥ the spin voltage developed by the out- and in-plane spin accumulation, respectively and VTAMR the amplitude of the TAMR effect. Note that while the sign of VTAMR can in principle be positive or negative, it is observed to be negative for Co/NbSrTiO₃ based junctions (also see chapter 6). Therefore, the voltage generated by TAMR and out-of-plane spins is opposite however both effects have the same lineshape.

Due to the similar lineshape of V⊥ and VTAMR the extraction of V⊥ is no longer well defined as it can be suppressed by the TAMR effect without altering the Hanle
lineshape (see supplementary information). The analysis in this paper is limited to the behavior of the in-plane spin accumulation only and hence is not significantly affected by this complication. The obtained values for $V_\perp$ in Fig. 7.2(a)-(c) were obtained by setting $V_{TAMR} = 0$ as long as the lineshape could be described by pure spin dephasing and $V_\perp = 0$ as soon as TAMR was needed to fit the lineshape (i.e. the regime where $V_{TAMR} > V_\perp$). This is the reason $V_\perp$ goes to zero rather abruptly and stays zero below 130 K at all biases. Unfortunately, the actual temperature dependence of $V_\perp$ or $V_{TAMR}$ can not be obtained via Hanle measurements.

The extracted in- and out-of-plane spin voltages (black circles, red triangles respectively) from the Hanle measurements at different temperatures are shown Fig. 7.2 at a bias of 5 mA in (a), 2.5 mA in (b) and 1 mA in (c). A strong decrease of the amplitude for both out and in-plane spins is observed at all biases with reducing temperature. While the spin signal stays positive for the largest bias an inversion of the sign is observed for 2.5 mA below 100 K and below 130 K for 1 mA. The sign inversion is thus driven by temperature but can be tuned with junction bias. With reducing temperature increasingly larger positive junction voltage is needed to obtain the conventional positive sign. This can be clearly seen in Fig. 7.2(d) where $V_\parallel$ is plotted as function of junction voltage for different temperatures. An overview of all the fitted Hanle measurements can be found in the supplementary materials.

**MR lineshape at negative bias**  In Fig. 7.3 the numerical derivative of Hanle measurements at −10 mA in the temperature range 4 K - 300 K are shown. The derivative allows an easier observation of the lineshape compared to the Hanle data. In panel (a) the data is fit using only the derivative of the TAMR effect. This results in a linear dependence on field in the region where $|B| < 1.5$ T. The fits describes the data very accurately at $T \leq 130$ K but clearly deviates at higher temperatures. In panel (b) the same data is fitted using the derivative of Eq. 7.1 with $V_{TAMR} = 0$. In this case the data can be fitted over the full temperature range accurately. Above $T = 130$ K the data can not be described by only assuming a TAMR effect and hence at least a part of the response originates from spin accumulation. At lower temperatures it is no longer possible to determine whether out-of-plane spin accumulation is present as both the spin accumulation of spins with very low spin lifetimes or only TAMR produce the same line shape. However, since the spin voltage is expected to decrease when the spin lifetime becomes shorter it is likely that a significant part originates from TAMR. Additionally the presence of TAMR is observed at positive junction voltage and TAMR is expected to be larger at negative bias. Note that for the fits a small misalignment angle of the applied magnetic field of 1.3° away from the semiconductor surface normal was used to accurately describe the data at high fields. The magnetization angle as function of field has been calculated numerically within the framework of the Stoner-Wohlfarth model.
7.3. Discussion

Overall a significant reduction of the spin voltage is observed when reducing the measurement temperature. A junction voltage dependent sign inversion of the spin accumulation is observed at temperatures around 130 K.

Inversion of the spin signal in n-doped semiconductors has been reported before in optical or non-local (four terminal) measurements [1, 2, 13–18] and in rare cases in three terminal Hanle measurements [19, 21]. However, there are several important differences with the inversion observed for the devices discussed in this paper and those in the literature. Many of these devices use a thin, highly doped semiconductor layer at the interface to narrow the Schottky contact which can give rise to a quantum well close to the interface. It has been shown that tunneling from the bound states in

Figure 7.3: (a) Numerical derivative of Hanle measurements at ~10 mA for various temperatures (4 K to 300 K). The gray lines are fits to the data using the 1st order derivative of the TAMR fit function. Good agreement is observed below 150 K while at higher temperatures the data clear deviates from the lineshape described by TAMR. (b) The same data but now fitted using the diffusive Hanle fit function (Eq. 7.1 with $V_{TAMR} = 0$). Good agreement is observed over the full temperature range. Note that the lineshape described by the fit function approaches the TAMR lineshape when $\tau_\parallel \to 0$. 

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such a quantum well can lead to inversion of the polarization [22]. Additionally, the interfaces showing inversion are formed by epitaxial Fe Schottky interfaces or highly ordered CoFe/MgO tunnel interfaces. There is significant evidence that in these cases tunneling via resonance states can lead to polarization inversion [3–5]. Since the formation of resonance states is extremely sensitive to the electronic structure at the interface it is difficult to control their formation. Generally a large variation in the exact details of the inversion from device to device is observed [2, 17] or inversion is completely absent [6, 7, 23–26]. Especially in the case of three terminal measurements only very few reports show a (bias dependent) inversion of the Hanle effect and when observed no discussion is provided about the device to device variation or reproducibility [19, 20]. Importantly, no observation of a (bias dependent) sign inversion has to our knowledge been reported using non-epitaxial contacts, either in a three-terminal or non-local geometry.

The spin injection devices discussed in this paper have a single doping density and the inversion is observed over a wide temperature range ruling out inversion due to tunneling from a quantum well at the interface. The spin injection contacts (Co and AlOx layers) have not been grown epitaxial with the semiconductor, hence any inversion related to resonance states seems unlikely. We believe that the observed inversion originates from temperature and bias dependent driven modulation of the potential barrier shape.

Such an inversion was proposed by Smith and Ruden as an alternative explanation of the sign inversion observed in Fe/GaAs devices [9]. They showed that the spin dependent transmission coefficient depends on the potential barrier shape and alteration of the shape can lead to inversion of the spin current polarization. Hence when the barrier shape is changed, for instance due to a bias voltage or a change in temperature, the polarization could be altered or even inverted. Unlike Schottky barriers in conventional semiconductors the Schottky barrier in Nb: SrTiO3 is not only altered when applying a bias but is also strongly temperature dependent [8]. This is due to the non-linear relative permittivity \( \epsilon_r \) of Nb: SrTiO3 which depends on both electric field and temperature. Due to the Schottky barrier a non-uniform electric field is present at the interface and hence causes \( \epsilon_r \) to be non-uniform in the depletion region hence \( \epsilon_r = \epsilon_r(x) \). Since the shape of the Schottky barrier is dependent on the semiconductor permittivity it changes when \( \epsilon_r \) changes. This results in a drastic potential profile alteration which is much more complex compared to conventional semiconductors. Also note that when applying a bias to the junction the permittivity profile in the depletion region will change (since the local electric field distribution in the depletion region is altered) leading to a much more complex bias dependence of the Schottky barrier profile.

Additionally, the bias dependent inversion of the spin signal below 150 K in these devices is observed in many different junctions on the same chip as well as for devices with a thinner tunnel barrier thickness. This can be observed in Fig. 7.4 which shows
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Figure 7.4: (a) Temperature dependent Hanle measurements of a Co/AlOₓ(7 Å)/Nb: SrTiO₃(0.1 wt%) spin injection device at 400 µA. An inversion of the spin signal is observed around 130 K. (b) Bias dependent Hanle measurements of the same device at 130 K clearly showing the inversion can be controlled with junction bias.

Temperature dependent Hanle measurements for a device with a thinner 7 Å thick AlOₓ tunnel barrier. In these devices the Schottky barrier height and depletion width are significantly larger compared to the devices with an 11 Å thick AlOₓ tunnel barrier. The temperature and bias dependent change of the potential profile is however very similar to that of the devices with thicker AlOₓ. Indeed, qualitatively very similar behavior of the spin signal is observed: in panel (a) a temperature driven inversion occurs around 130 K which is shown to be bias dependent in panel (b). This much more systematic observation of sign inversion points towards a relation with a more fundamental property of Nb: SrTiO₃.

To substantiate the effective change in Schottky barrier, driven by temperature, we have calculated the temperature dependent change of the electro-static landscape at the interface at zero bias condition. A direct correlation with actual devices is complicated since the interface potentials are likely laterally inhomogeneous due to the presence of terrace steps and inhomogeneous Nb-doping. The model calculations use an AlOₓ thickness of 5 Å, a carrier density of 5 × 10⁻¹⁹ cm⁻³ and an intrinsic Schottky barrier height (φ_B) of 0.9 eV. This results in a potential landscape with a Schottky barrier height and width in between that expected for the devices with 7 Å and 11 Å AlOₓ.
Figure 7.5: Schottky barrier profiles of a Co/AlO\(_x\)(5 Å)/Nb:SiO\(_3\) interface normalized with respect to their heights at various temperatures. A clear change in the barrier profile with temperature is visible. The most pronounced alteration occurs in the regime below 100 K but close to the depletion edge significant changes occur from 300 K downwards. The inset shows the band profiles including the insulator at 25 K (black), 150 K (blue) and 300 K (wine). A significant reduction of the Schottky barrier height with reducing temperature is observed.

In Fig. 7.5 the normalized Schottky barrier potential profile at different temperatures is shown and were calculated as described in Ref. [8]. The Schottky barrier height is also temperature dependent, to emphasize the shape change the profiles are normalized by dividing them by \( \phi_B(T) \). The semiconductor is degenerate resulting in a Fermi level slightly above the conduction band at the depletion edge (~50 meV), as indicated by \( E_F \). A significant change in the barrier shape is apparent when the temperature decreases below 100 K. This is because the \( \epsilon_r \) of Nb:SiO\(_3\) varies much stronger with electric field at low temperatures. However, a significant change in the barrier profile close to the Fermi level is observed over the full temperature range. The inset shows the calculated band profile of the complete interface with a strongly trapezoidal tunnel barrier formed by the AlO\(_x\) at 25 K, 150 K and 300 K. This shows that apart from the shape change the Schottky barrier height reduces with decreasing temperature (due to the changing capacitance of the depletion region). Hence the non-linear \( \epsilon_r \) results in a temperature and bias dependent Schottky barrier shape and height (\( \phi_B = \phi_B(V, T) \)).

Additionally I would like to point out that the strong reduction of the spin signal amplitude and especially the bias dependent sign inversion are not consistent with the framework of impurity-assisted-Tunneling Magneto-Resistance (iaTMR), a mechanism which can give rise to an MR effect very similar to that expected for spin accumulation in a three-terminal geometry [12, 27–31]. This is of significant impor-
tance since there is currently an intense debate whether the observed Lorentzian magneto-resistance signals observed in such three-terminal devices originate from spin accumulation or another magneto-resistance effect. In the iaTMR framework a strong increase of the MR amplitude is expected when decreasing temperature opposite to the behavior for the devices in this work. Additionally, the inversion of the sign would only be possible within the iaTMR theory if the magnetization anisotropy of the cobalt layer is altered such that its easy axis is rotated to the out-of-plane direction. Electric field control of the surface magnetization is in principle possible and currently an actively pursued research direction \[32-35\]. Moreover, the effect can be expected to be rather large due to the large permittivity of Nb:SrTiO\(_3\) \[36\]. However, if such an electric-field induced anisotropy change is present it would reflect on the TAMR effect as well\[1\] which is not observed. As discussed, the observations can be explained within the framework of spin accumulation where polarization inversion is well know to occur.

7.4 Conclusions

In conclusion, we have measured the temperature dependent evolution of spin injection in the degenerate semiconductor Nb:SrTiO\(_3\). The bias dependence at lower temperatures are qualitatively similar to those observed at room temperature: in-plane spin lifetime increases with positive junction voltage while the spin voltage anisotropy decreases. With reducing temperature the spin signal amplitude is seen to decrease and below 150 K shows a bias dependent inversion of the spin polarization.

The temperature driven inversion as well as the control over the spin polarization sign below 150 K are attributed to the shape change of the potential barrier. This shape change is strongly temperature dependent unlike in conventional semiconductors. This is attributed to the interaction of the non-linear relative permittivity \(\epsilon_r(E, T)\) of Nb-SrTiO\(_3\) and the local electric field present at the interface due to the space-charge region (i.e. the depletion region). Additionally, an applied bias alters this local electric field effecting \(\epsilon_r(E, T)\) causing significant lineshape changes of the potential profile. Such a control over the spin polarization could in principle be achieved at room temperature by creating spin injection interface with a thin Schottky barrier width. Such a narrow depletion region would lead to significantly larger built-in electric fields causing non-linear effects in \(\epsilon_r(E, T)\) at room temperature.

\(^1\)Causing a sign change of the amplitude as well as dependent on in-plane magnetic field instead of out-of-plane.
7.5 Supplementary Information

Reduction of the $V_{\perp}/V_{\parallel}$ ratio due to TAMR

As long as $V_{TAMR} \leq V_{\perp}$ the measured lineshape can be fitted by only using the diffusive Hanle fit function (i.e. using Eq. 7.1 with $V_{TAMR} = 0$). When $V_{TAMR} > V_{\perp}$ the lineshape can no longer be fitted with the diffusive Hanle fit function (assuming $\text{sign}(V_{\perp}) = \text{sign}(V_{\parallel})$). This transition is graphically shown in Fig. 7.6 where a diffusive Hanle curve is simulated (using $V_{\perp} = 50 \mu V, V_{\parallel} = 100 \mu V$ and $\tau_{\parallel} = 50 \text{ ps}$) (black curve). A TAMR voltage is added to the Hanle curve with three different amplitudes $V_{TAMR} = -10, -50$ and $-150 \mu V$. As long as $V_{TAMR} \leq V_{\perp}$ the lineshape can be reproduced using the diffusive fit function and will simply result in lower values of $V_{\perp}$ (red and blue dashed curves). When $V_{TAMR} > V_{\perp}$ a parabolic MR can be seen on top of the Hanle curve. Only in this regime the lineshape deviates from the one expected for spin accumulation and can the presence of TAMR be verified.

Hence, since both $V_{\perp}$ and $V_{TAMR}$ depend on the angular rotation of the ferromagnet’s magnetization they can not be uniquely determined. The analysis in this paper is limited to the behavior of the in-plane spin accumulation only and hence is not significantly affected by this complication. To confirm this we have extracted the fit parameters using a fixed ratio of $V_{\perp}/V_{\parallel} = 0.5$ in the regime where the apparent ratio

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This is only the case when the out-of-plane spins accumulation has the same polarization sign as the in-plane spins.
Figure 7.7: Junction response as function of out-of-plane (black squares) and in-plane (red circles) magnetic field at (left) 10 mA current bias and 250 K and (right) 1 milliA bias current and 150 K. In both measurements the inverted Hanle effect is observed although significantly smaller than the Hanle effect. At 150 K the deformation of the Hanle lineshape shows the presence of a TAMR where $V_{TAMR} > V_\perp$. In both measurements a isotropic linear magnetoresistance (proportional to $|B|$) is observed although the sign of the slope reverses at low temperature.

is smaller than 0.5 and compared it to the results when other ratios where used. This shows that the extracted spin lifetime and spin voltage of the in-plane spin signal has a weak dependence on the value of the $V_\perp/V_\parallel$ ratio which does not influence the observed trends.

**V-H measurements for in and out-of-plane magnetic field**

In Fig. 7.7 the in- ($B_\parallel$) and out-of-plane ($B_\perp$) magnetic field response of a Co/AlO$_x$ (11 Å) spin injection device are shown. The left panel shows a measurement at a large positive bias current of 10 mA at 250 K. Only a background voltage related to the charge current is subtracted from the data. For $B_\perp$ a typical Hanle curve is observed while $B_\parallel$ reveals the presence of an inverted Hanle effect along with a small anomalous peak at zero bias. At large fields, where the magnetization is aligned with the applied magnetic field, an isotropic linear magnetoresistance effect is observed which is proportional to $|B|$.

The right panel shows similar measurements but now at a smaller bias current of 1 mA at 150 K. Here the out-of-plane field response can be fitted assuming the superposition of an out-of-plane TAMR effect and the presence of a spin accumulation. The in-plane field response shows the presence of a small inverted Hanle effect again with the anomalous peak at low fields. At high magnetic fields the isotropic linear magnetoresistance effect is again observed however it slope is opposite compared to that observed at 250K. This slope change happens gradually with reducing temperature. Although not shown here the inverted Hanle peak is observed to reverse sign when the Hanle peak reverses sign as well.
Evolution of in-plane spin lifetime and spin voltage anisotropy

In Fig. 7.8(a) the extracted in-plane spin lifetimes are shown as a function of temperature for three different current biases: 10 mA (black squares), 2.5 mA (red circles) and 1 mA (green triangles). Due to the presence of TAMR at lower temperatures the extracted spin lifetimes show large errors below 175 K. A least square fit to the data points suggest a slight bias dependent increase of the spin lifetime with reducing temperature. In panel (b) the anisotropy in the spin voltage is plotted, due to the presence of TAMR at lower temperatures the ratio decreases very fast. To extract the ratio’s the TAMR amplitude has been set to zero as long as a clear upturn of the voltage at high fields was visible. When this was no longer the case the ratio could not be defined any further (shaded regime). To extract in-plane spin parameters in this region fits to the data were made using $V_\perp = 0$. As mentioned before the extracted parameters did not differ significantly when performing the same fits with a forced ratio of $\Delta V_\perp / \Delta V_\parallel = 0$. An additional set of data points (marked dev2) is shown for another device at 200 K showing similar trends.
Figure 7.9: Temperature dependent Hanle measurements at 10 mA (left top), 1 mA (right top), 0.25 mA (left bottom) and −10 mA (right bottom) bias. The top most curve in each panel is at 100 K (purple triangles) than for each curve below the temperatures are 130 K (wine diamonds), 150 K (blue down-triangles), 175 K (green up-triangles), 200 K (red circles) and 250 K (black squares). The solid lines are fit using Eq. 7.1. The −10 mA data has been fit by forcing $V_{TAMR} = 0$ and $V_{\perp} = 0$. The Hanle measurement are offset for clarity.

Overview of temperature dependent Hanle data

In Fig. 7.9 an overview of the temperature dependent Hanle measurements is shown (open symbols) along with the fits (solid lines). Apart from the Hanle measurements used for Fig. 7.2(a)-(d) in the main paper we show the response at a low bias current of 0.25 mA and −10 mA.

References

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References


