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Physical Concepts in Spintronics

SpinFETs and Spin-Valves

Introduction

Electronics work by applying electric fields that create forces on electrons or other charge carriers giving influence over their movement. Charge is an intrinsic property of the electron and is useful as a two-state system because a measurement can be made where there are either an excess or absence of electrons resulting in a negative or positive measurement. Charge is not the only intrinsic property of an electron however. Spin is also a property that could potentially be used for signaling. For electrons and other fermions spin is by nature a two-state system that could be used to represent information.

An advantage of a two state spin versus charge system is that while an electronic system typically requires a large number of charge carriers to move as electrical current to change a signal from negative to positive, but the spin of an electron or ensemble of electrons can change in place without heat generation from a charge current. A *spin current* can be created however without a net charge being transported. This means a majority spin polarization can be created in a localized area and the random motion of electrons will spread these spins throughout the system [1].

Spintronic devices can be classified into two main categories. The spin-valve is an example of a passive device that is used for sensing while a spinFET is considered an active device associated with signal gain. Electronics are categorized this way as well. Fully spintronic systems would be able to transmit information encoded in spin polarizations and have reliable ways to detect them. Devices of this type prove to be extremely difficult to make due to the sensitive nature of spin and the many random interactions that occur capable of inducing a spin flip. Spins will typically flip on the order of a nanosecond but new materials have showed times of up to 10ns [2].

Most of the spintronic devices that are being developed or already exist are hybrids of electronic and spintronic elements. The spinFET (spin field effect transistor) and spin-valve that are discussed in this paper fall into this category. Information is still encoded in the charges of the system and spin is used to influence their movement. This still leads to many possible benefits over traditional electronics such as increased data processing speeds, power efficiency, densities, and non-volatility of information in memory applications such as magnetoresistance random access memory (MRAM) which is a commercially available alternative to DRAM in embedded systems.

Research on how spin can be used to enhance information processing has been going on since the 1980's but has recently gained momentum with increased interest in spin-based quantum computing. Here qubits use the spin of single electrons to encode information offering many advantages to traditional computing in speed, efficiency, and the ability to solve complex problems not possible by classical computers. The benefits of achieving quantum computers are great enough that a lot of funding is being spent in fields that could benefit their development. Some of the challenges spintronic devices face will likely be solved along the way.

Physical Concepts in Spintronics

Spintronic devices all work based on the physics of spin. The idea that spin can affect the flow of charge carriers was first discovered in the 1980's by Peter Gruenberg and Albert Fert who observed large differences in the resistance of materials made up of thin layers of various magnetic elements when applying an external magnetic field. Figure 1 shows a change in resistance across an iron-chromium junction [3]. At an applied magnetic field of ± 20kGauss the resistance drops around 80%. This was much larger than any resistance change known due to a change in magnetism at the time and was given the name "giant magnetoresistance" (GMR). Conceptually this can be understood by realizing the conduction channel in metals is split between up-spin and down-spin electrons which have asymmetric density of states in ferromagnetic materials. Because there are more states for electrons aligned parallel to the magnetization, parallel aligned electrons experience less scattering while anti-parallel electrons experience strong scattering. The resistivity of the material reflects the channel of least resistance and is much lower when a magnetic field is applied.

A basic model of a spin valve is to have a paramagnetic layer between two ferromagnetic layers. One of the ferromagnetic layers is "pinned" having magnetization in one direction while the other is tunable by an external source. In equilibrium the paramagnetic layer has an equal amount of spin-up and spin-down electrons and is mainly used to decouple the two ferromagnetic layers so that one can remain tunable. By applying a small magnetic field that aligns the free ferromagnetic layer with the pinned layer the resistance of the tri-layer drops to a minimum. Ideally the ferromagnetic layer passing current to the paramagnetic layer would inject only electrons with spins parallel to the magnetization, and similarly the ferromagnetic layer being passed the current would accept only parallel aligned electrons. This leads to the concept of spin injection efficiency, spin detection efficiency, spin relaxation time, and spin diffusion length.

If we consider a simple electrical diffusion method of spin injection the spin current can be roughly estimated if the spin polarization of the ferromagnetic metal (F) and the current through the layer are known. In this case the spins in the ratio described by the spin polarization of F are entering the nonmagnetic layer (N). When this spin current enters N many different spin-randomizing events can happen that results the spin current diffusing over a distance. In one dimension we can model this with the diffusion equation

$$\frac{d^2 s(x)}{dx^2} = \frac{s(x)}{L_s^2} \tag{1}$$

where $s(x)$ is the spin density and L_s is the spin diffusion length

$$L_s = \sqrt{D\tau_s} \tag{2}$$

with D the experimental diffusivity and τ_s the spin relaxation time. This differential equation has the general form

$$s(x) = s_0 e^{-x/L_s} \tag{3}$$

showing the spin density decays exponentially over a characteristic length or time when substituting Equation 2. A spin current can then be defined

$$j_s = \frac{-eD}{L_s} s_0 e^{-x/L_s} \text{ [3].} \tag{4}$$

Now if we consider the full FNF junction we can calculate the resistance the electrons will encounter in the case that the F-metals are polarized parallel versus anti-parallel. Many derivations model the two conduction paths in the F-metals as resistors because the resistance equations turn out similar to a circuit with two parallel paths each with three resistors as shown in Figure 2. The conduction channel of the electrons aligned with their spin parallel to the magnetization are represented by small resisters and the anti-parallel aligned electrons large resistors. When the two F layers are polarized parallel to one another it's like having the two small resistors on one parallel branch of the circuit and the two large resistors on the other branch. The N material can be represented as a resistor of constant size on both sides of the circuit.

If the middle material is a Mott semiconductor with two channels like the F-metals then

$$2R_{SC} = R_{SC,\uparrow} = R_{SC,\downarrow}$$

where $R_{SC} = \frac{\rho_{sc} d}{A}$ with ρ_{sc} the resistivity of the semiconductor, d the width and A the area of the layer. If the F-metals are aligned anti-parallel we see the resistance of the trilayer is

$$R_{AP} = \frac{(R_{fm,\downarrow} + 2R_{SC} + R_{fm,\uparrow})}{2} \tag{5}$$

and for the parallel case

$$R_P = \frac{(2R_{fm,\uparrow} + 2R_{sc})(2R_{fm,\uparrow} + 2R_{sc})}{2R_{fm,\uparrow} + 2R_{fm,\downarrow} + 4R_{sc}} \tag{6}$$

Here Bandyopadhyay and Cahay (2008) define the polarization of the spin current as

$\alpha_p = \frac{R_\downarrow - R_\uparrow}{R_\downarrow + R_\uparrow}$ and the conductivity spin polarization $\beta_p = \frac{\sigma_\downarrow - \sigma_\uparrow}{\sigma_\downarrow + \sigma_\uparrow}$ to illustrate some important relations. An equation relating the two quantities can be written

$$\alpha_p = \beta_p \left(\frac{R_{fm}}{R_{sc}}\right) \frac{2}{\left[\frac{2R_{fm}}{R_{sc}} + (1 - \beta_p^2\right]}. \tag{7}$$

α_p vs β_p is shown in Figure 3 for different values of $\frac{R_{fm}}{R_{sc}}$ showing how the different values relate [4]. We see that even in the unlikely case that the resistance of the ferromagnet and semiconductor are roughly equal the spin efficiency still falls off superlinear with a change in spin polarization. Many devices like the spinFET require nearly 100% efficiency so for this simple direct contact diffusive method of injecting spin to work a ferromagnet with nearly perfect spin polarization would have to exist. When these experiments were getting started no such material existed. Today complicated This kind of experiment is what got the field of spintronics started, eventually leading to the discovery of the giant magnetoresistance which is used in many devices today, such as nearly all HDDs commercially sold. Magnetoresistance random access memory is another GMR device that is commercially available but hasn't been widely adapted yet. These devices are successful because they still use the charge as a signal for information processing.

Before exploring different methods of spin injection we will look at another early spintronic device that will introduce more physical principles. In 1990 Datta and Das proposed the spinFET which was the first device proposed to use solely the spin of the electron and not the charge. The spinFET shown in Figure 4 looks very similar to a traditional transistor [5]. The two contacts in the case are ferromagnets called the polarizer and analyzer. The medium between them, a two dimensional degenerate Fermi-gas in this case can be controlled by the gate contact and influence the net rotation of spin in the 2DEG. The device at first looks like it would work in a similar way to the spin-valve but the idea is much different. To understand it we must first derive the Rashba interaction.

The Rashba interaction is a spin-orbit interaction that arises from a particle generating a magnetic moment while rotating about its axis that interacts with its own orbital angular momentum. The Rashba interaction is interesting because it one of the phenomena that give rise to concepts like spin relaxation time. An electron orbiting around the nucleus sees an electric field from the positive charge of the nucleus. In the electron's rest frame a magnetic field then arises from the movement of a charged particle in an electric field. This magnetic field according to special relativity will be $\vec{B} = \frac{\vec{\varepsilon} \times \vec{v}}{c^2\sqrt{1-v^2/c^2}}$ where $\vec{\varepsilon}$ is the electric field, $\vec{v}$ is the electron's velocity, and c is the speed of light. Because the electron is constantly accelerating however this equation is not exactly right and the actual magnetic field has an extra factor of 2 in the denominator that was derived by L. H. Thomas in 1926, resulting in

$$\vec{B} = \frac{\vec{\varepsilon} \times \vec{v}}{2c^2\sqrt{1-v^2/c^2}}. \tag{8}$$

The interaction energy between the electron's magnetic moment $-\mu_e$ and this field is then $E = -\mu_e \cdot \vec{B}$ which introducing the ratio of the magnetic moment over the angular momentum $-g_0$ and making further substitutions can be written

$$E = \frac{g_0}{2}\frac{e\hbar}{2m}\frac{\vec{\varepsilon} \times \vec{v}}{2c^2\sqrt{1-v^2/c^2}} \cdot \vec{\sigma} \tag{9}$$

where $\vec{\sigma}$ is the spin of the electron. The Bio-Savart law for the magnetic flux density at the electron is $B_0 = \frac{\vec{\varepsilon} \times \vec{v}}{c^2}$. If we let $\vec{K}$=m$\vec{r} \times \vec{v}_{orbital} = \vec{l}\hbar$ with m the electron mass we get the final energy

$$E = g_0\mu_e\hbar\frac{Ze}{8\pi\epsilon_0 mc^2r^3}\vec{l} \cdot \vec{s} \tag{9}$$

which includes the extra factor of two from Equation 8. Here we $\vec{l} \cdot \vec{s}$ interaction affects the energy. The interaction is in the form of a Hamiltonian that by setting $g_0 = 2$ and dropping the Lorrentz factor since we will be working in a solid is

$$H_{SO} = \frac{ge\hbar}{8\left(m*(\vec{r})\right)^2 c^2} \vec{\nabla} V \cdot (\vec{\sigma} \times \vec{p}).$$

The Rashba interaction is then obtained by taking $\vec{\nabla} V = \vec{\varepsilon}$ and grouping the constants and electric field into variable $\vec{\eta}_R(\vec{r})$ to get

$$H_R = \vec{\eta}_R(\vec{r}) \cdot (\vec{\sigma} \times \vec{p}). \tag{10}$$

finally one last rearrangement of terms into another constant and changing $\vec{p}$ to $\vec{p} + e\vec{A}$ where $\vec{A}$ is the magnetic vector potential puts H_R in the form

$$H_R = \frac{a_{46}}{\hbar} \vec{\varepsilon}(\vec{r}) \cdot \left[\vec{\sigma} \times (\vec{p} + e\vec{A})\right] \tag{11}$$

where a_{46} is a material constant containing information about the bandgap E_g and the spin orbit splitting energy Δ_s [4].

$$a_{46} = \frac{\pi e\hbar^2}{m^*} \frac{\Delta_s(2E_g + \Delta_s)}{E_g(E_g + \Delta_s)(3E_g + 2\Delta_s)}. \tag{12}$$

Equation 11 shows that the Hamiltonian of the electron depends on the external electric field. This is a critical component to how the spinFET is proposed to work.

The polarizer and analyzer contacts are made of ferromagnets and aligned parallel. They are connected by a 2DEG that passes under the gate terminal. When no potential is applied to the gate and a potential is applied between the polarizer and analyzer (source and drain) the polarizer injects electrons with spins polarized parallel to the ferromagnets. The polarizer and analyzer ideally inject and detect only spins polarized this way. In this state there is only an electric field in the direction of current flow. Equation 8 shows that an electron with velocity parallel to the electric field will not feel a magnetic field that leads to the Rashba interaction. When a potential is applied to the gate an electric field will be created perpendicular to the velocity of the electrons and a strong Rashba interaction will occur resulting in a net magnetic field. If we call the direction of current flow between the ferromagnets $\hat{x}$ and the direction of the gate electric field $\hat{y}$ then the Rashba magnetic field vector will point in the $\hat{z}$ direction and is give by

$$B_{Rashba} = \left[\frac{2m*a_{46}}{g\mu_e\hbar}\,\varepsilon_y v_x\right]\hat{z}.$$

Now when an electron is injected into the 2DEG by the polarizer it experiences a magnetic field in the $\hat{z}$ and will precess about the x-y plane. The precession is spin independent and all particles will precess exactly the same way. The analyzer only accepts electrons with spin polarized along the $\hat{x}$ axis of which there are none now, so current stops flowing in the $\hat{x}$ and has been successfully shut off. When the potential is removed from the gate terminal the electrons align with the ferromagnetic terminals and current begins flowing again.

It is easy to see why spin injection and detection efficiencies have to be nearly 100%. If electrons with stray spin polarizations get into the 2DEG they will experience a Rashba interaction and start a chain reaction. This is why spinFETs have not yet been realized. There is a tradeoff between using a semiconductor channel with strong spin-orbit interactions capable of shutting the current completely off because this strong coupling leaving less room for error in the spin-injection [6]. Over the past few decades several different methods of spin injection have been developed. Tunnel injection adds a thin tunneling layer between F and N to solve the resistance mismatch problem. The resistance of the tunnel barrier should be equal to or greater than the spin diffusion length of F divided by the conductivity of F [9]. Electrons with spins in the direction of the magnetic field will see less resistance to tunnel through the barrier due the density of that spin state being higher. The tunnel barrier significantly increases spin efficiency but at the cost of reduced current flow.

Hot electron injection uses tunnel injection to send spin polarized electrons with energies much greater than the fermi energy into the ferromagnetic terminal. The spin-up and spin-down electrons will have much different mean free paths with the spin-up's being larger. This can cause a spin efficiency of up to 90%. These are just some of the different ways spin can be injected and different methods work better different materials and applications.

New 2D semiconductors like graphene and black phosphorous are leading to devices with better characteristics than ever before. The first spintronic devices showed spin lifetimes of around 0.1ns. Recent experiments using graphene show lifetimes of 10ns which researchers at the Centre for Advanced 2D Materials in Singapore say is suitable for spin communication channels. The lack of a band gap however does not allow charge and spin conductance to be suppressed, making it less suitable for some devices [8]. The same team says new 2D black phosphorous structures could be the best spintronic material yet due to its direct band-gap size and room temperature mobilities. They present results of spin relaxation times of 4ns at distances over 6μm.

Many of the experiments happening today are using non-local spin valves as a testing platform. The tri-layer structure discussed in this paper has current passing through all three layers which can bring along affects that make spin detection very difficult. In a non-local spin-valve the two F-metals never pass a charge current to one another but a channel still exists for a spin current to travel. Non-local spin valves are primarily used for taking measurements the following way. Referring to Figure 5 the left ferromagnetic contact carries a current I_c which results in spin accumulation in the channel below. On the left side of the current carrying contact the spin can be diffusive or drift. On the right hand side it can only be diffusive and the spin decays exponentially. The spin current eventually reaches the other side where spin-charge coupling induces measurable readings in the potential [10]. Figure 6 shows what these measurements look like for a measurement of the spin scattering of IrO_2.

Conclusion

Although only a few devices and the physics involved were discussed many of the central themes in spintronics were talked about. All spintronic devices will need efficient ways to inject or detect a spin current and many will need diffusion lengths long enough to transfer information to other parts of the circuit. Hybrid electronic and spintronic devices will likely start finding themselves in practical settings as the technology continues to improve. Classical transistors have just about reached the limit of how small they can get and quantum computers are still decades away. This leaves plenty of time for generations of spintronic devices to work their way in to our current information processing systems.

References

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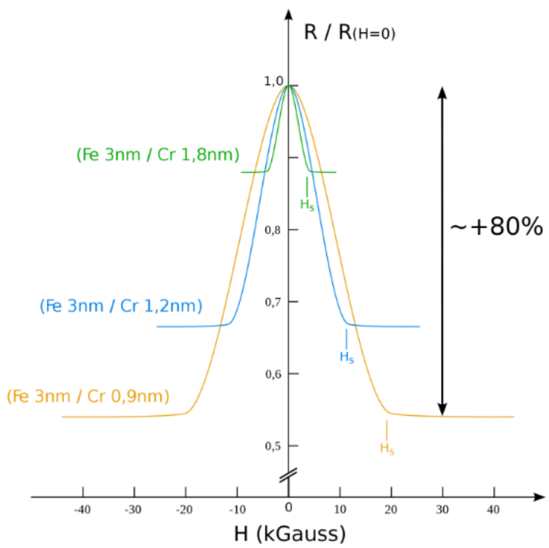


Figure 1 - GMR Experiment with Iron/Chromium junction

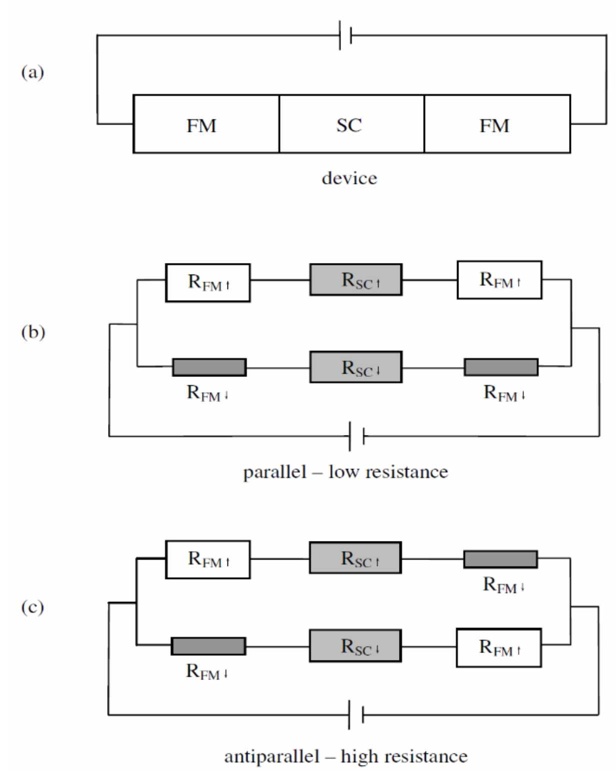


Figure 2 – Resistor model of spin-valve tri-layer [4]

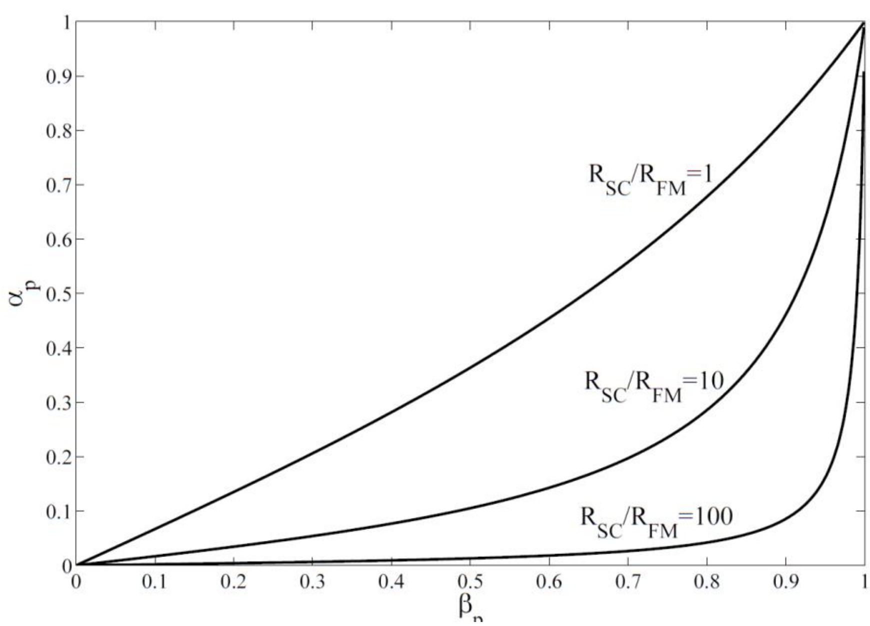


Figure 3 – Relation between spin current polarization and conductivity polarization [4]

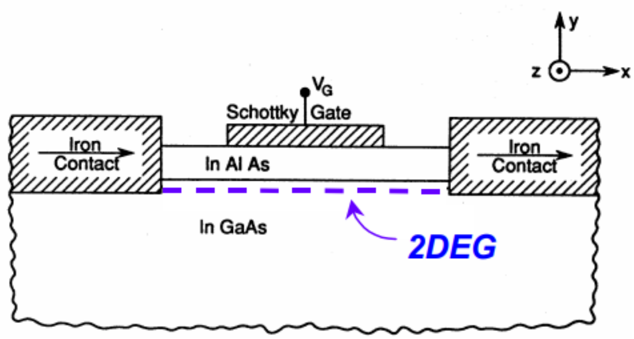


Figure 4 – SpinFET [3]

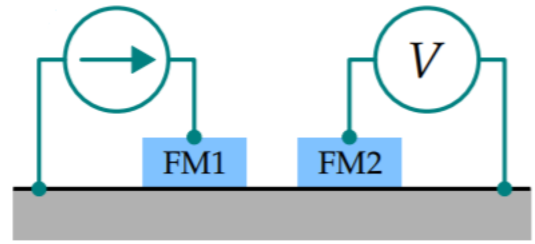
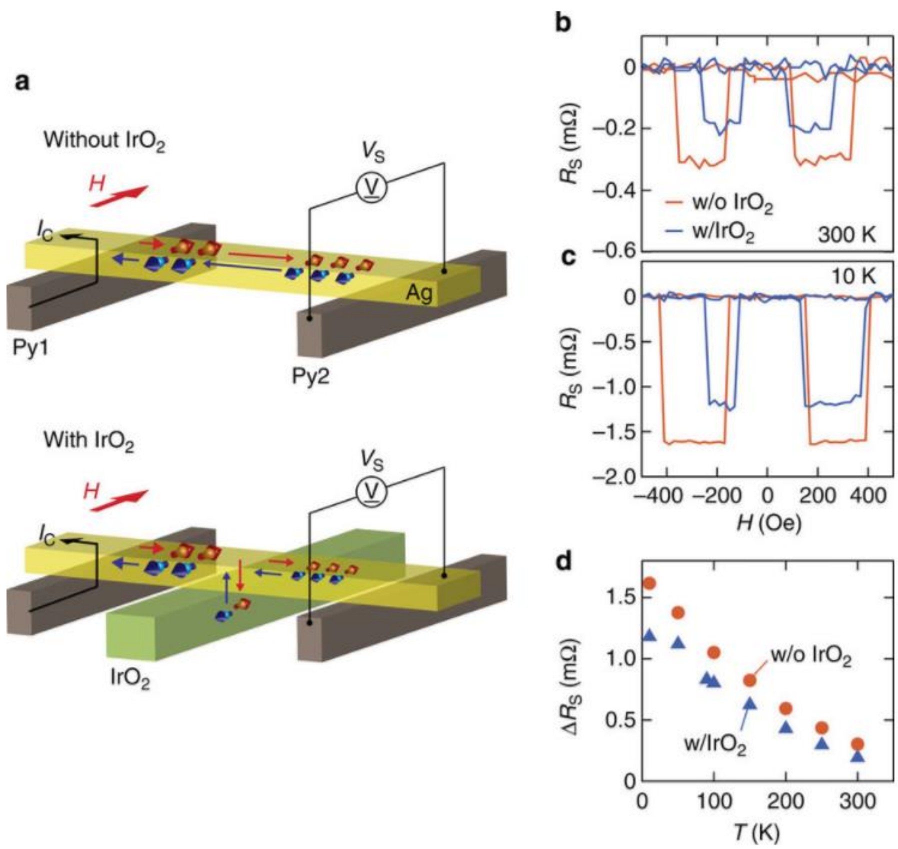


Figure 5 – Non-local Spin-Valve [10]



(**a**) The set-up of measurement is schematically depicted. The magnetic field H is applied along the easy axis of the Py electrodes. (**b**,**c**) NLSV signals measured at 300 K and 10 K for Py/Ag/Py LSVs without and with the polycrystalline IrO_2 middle wire. (**d**) Temperature dependences of the NLSV signals.

Figure 6 – A measurement of the spin scattering properties of $\mathrm{Ir}O_2$ [11]