Honors Thesis Proposal

for

An Investigation of Superconducting Spin Dynamics by Dynamical Spin Injection in a Niobium Tri-Layer

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INTRODUCTION

Spintronics is an emerging multidisciplinary field defined by the manipulation of electron spin currents in solid state systems and devices. Spin-polarized transport through magnetic multilayers has gained attention through since the discovery of giant magnetoresistance [1]. Future applications of spin transport are magnetic random access memory (MRAM), spin-torque MRAM, spin-torque nano-oscillators, or racetrack memory [2], among others. Also, spin torque-transfer has generated great attention due to its application with spin valve devices. Spin valves based on spin-transfer torque are on the verge of commercialization as the basic units of ultra-fast, low-power consumption MRAM memories [3].

One of the major challenges within the general field of spintronics, is generating large spin currents to create an efficient net spin polarization [4] [5]. Several methods of spin injection are available, but dynamical spin pumping offers spin injection over large mesoscopic areas without the need of a charge current [6]. This is accomplished by generating a non-equilibrium spin population in the material. The rate of spin accumulation is dependent on the spin relaxation, which tries to return the spin population back to equilibrium [7], and since the spin currents are dissipative, the charge current to generate pure spin current results in heat dissipation with the devices [8] [9].

Finding ways to prolong spin lifetimes is high priority in spintronics, where the combination of superconductivity with spintronics may shed light into this issue [10]. Also, introducing superconductivity into spintronics may result in novel applications, such as improved Josephson junctions and quantum computing, of high interest within the study of superconductors

[8] [9]. Superconducting spin current has historically focused on the net spin polarization of quasi-particles formed in the superconducting state that may be used for spin logic operations. This coexistence may provide unique opportunities to spintronics which as of today is one of the most active areas of research [10].

Purpose and Motivation

Superconductivity at superconductor-ferromagnet (SC/FM) heterostructures has been proposed theoretically and its potential applications have attracted a great deal of attention [11]. Currently, there are intense investigations focused on identifying material combinations that may promote superconductivity in spintronic devices [10] as well as improving device structures to prevent suppression of the superconductivity [8]. The proximity effect has been found to have negative effects in these studies [12], and heating effects around the area of spin injection has also been determined as an issue [8].

Niobium (Nb) has been studied with different methods of spin injection [8, 9, 12]. Several functional superconducting spintronics devices have been theoretically proposed but super conductors have been left unstudied in terms of pure spin currents [9]. Therefore, spin pumping, which allows the injection of pure spin currents without the generation of a net charge current, may arise as an effective means to investigate spin dynamics in FM/SC systems. By studying spin pumping in Nb, it is possible to understand spin dynamics while preventing proximity effect issues in the corresponding devices. In addition, spin pumping may be an effective means of reducing heating effects associated to spin injection.

LITERATURE REVIEW

Superconductivity in Thin Films

Ferromagnetism and superconductivity are known as antagonistic phenomena and their coexistence in uniform materials is very difficult to achieve. Their competition for existence can be understood through BCS theory. As described by Izyumov et. al, in a superconducting state, attraction between electrons generate Cooper pairs which form a singlet state with net spin S = 0. However, ferromagnetism wishes to arrange the electron spins such that they are parallel to each other, hence $S \neq 0$. In the presence of magnetic field, the Zeeman energy of the electrons exceeds the coupling energy given by the superconducting gap Δ, thereby destroying the superconducting state [13].

But now, it is widely known that the interaction between conventional superconductivity and ferromagnetism in between FM/SC interfaces can lead to the formation of a triplet state for the Cooper pairs [11]. The two-fermion correlation function f describing Cooper pairs is subject to the Pauli-exclusion principle so f must be antisymmetric under an overall exchange of fermions, which includes both spin and space coordinates of the electron pair. So if the space coordinate is antisymmetric, then the Cooper pairs may reside in a spin triplet state of: $(\uparrow\downarrow + \downarrow\uparrow),\ \uparrow\uparrow, or\ \downarrow\downarrow$.This spin triplet state may coexist with the magnetic field as the Zeeman interaction may no longer break the Cooper pairs, as long as the orbital effect is suppressed [10].

If the superconductor is brought into contact with a non-superconducting material, the physical properties of both materials may change. If the non-superconductor is ferromagnetic, the most pronounced consequence of the interaction is the suppression of the superconductivity from the ferromagnetism. However, the reversal of suppression is also possible, known as the inverse proximity effect [14].

Several studies have been conducted to investigate spin injection into niobium (Nb) at the superconducting state [8, 9, 12, 15]. It was reported that by the use of a lateral based spin valve, spin current is reflected by the superconducting Nb using a copper spacer between Nb and the Py (ferromagnetic alloy) nano-pillar. This was carried out by means of non-local spin injection. However, the spin relaxation process in the Cu layer was not affected by the proximity effect from the superconductor [9]. Another experiment carried out utilized a Nb/Cu/Py multi-terminal lateral structure. This however, showed there was no observed change in spin current absorption whether the Nb was superconducting or normal-conducting [8]

An investigation of spin pumping Nb layer in contact with a permalloy layer (Py) experienced a suppression in the spin-sinking mechanism provided by the non-magnetic layer at the superconducting regime. This was attributed due to the proximity effect inducing a superconducting state within the (Py) [12]. This was carried out by FMR microwave measurements. The suppression in spin pumping was attributed to the decrease in the Gilbert damping of the curve.

FMR/Spin-Pumping

Of the current methods present for generating spin polarizations, spin pumping is advantageous since it does not require the employment of charge current for spin polarization. This reduces the spin dissipation across the interface as the impedance mismatch problem is avoided [16]. Spin pumping or dynamical spin injection is carried out by the exchange of spin-angular momentum between spin currents in the non-magnetic material and the precessing magnetization in the ferromagnet [4].

In an experiment where an extended FM/NM (ferromagnetic – normal metal) bilayer film is placed on the sensing area of a FMR spectrometer, the transfer of angular momentum from the FM into the NM layer results in an enhancement of the Gilbert damping in the ferromagnet [4, 17] and, hence, in a broadening of the FMR linewidth of the FM/NM system with respect to that of the FM alone. This process is carried out by driving the magnetization layer into ferromagnetic resonance (FMR). By applying an AC magnetic field perpendicular to the applied magnetic field, this shall maximize the effects of the precession. The FMR then provides an enhanced Gilbert damping constant due to the presence of spin pumping [18]. This can be understood in terms of the Landau-Lifshitz-Gilbert Equation:

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma \mathbf{m} \times \mathbf{H}_{eff} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}$$

where $\gamma$is the gyromagnetic ratio, $\mathbf{H}_{eff}$ is an effective magnetic field and α is the Gilbert constant, the primary parameter for the damping. This parameter can be expressed as $G = \alpha\gamma M_s$ where M_s is the saturation magnetization [12].

Consequently, FMR experiments on extended films can be used both to generate the dynamical spin pumping from the FM into the NM and to evaluate the spin current's magnitude from broadening of the FMR linewidth with respect to the FM. However, most studies of spin pumping concentrate on metals with large spin-orbit coupling which enables the conversion of the injected spin current into an electric voltage across the NM layer, a phenomenon known as inverse spin Hall Effect (ISHE) [5, 6]. This provides a much more quantitative assessment about the nature of the spin injection than that obtained from the broadening of the FMR linewidth.

Inverse-Spin Hall Effect

It is well known that spin current can be generated in a non- magnetic material through the Spin Hall Effect (SHE) [19]. If an electric current flows through a non-magnetic material with strong spin-orbit coupling, a pure spin current is generated traverse through the charge current. This is a consequence of the spin orbit coupling deflecting the electrons with different spin orientations

The SHE can generate pure spin currents that are strong enough to induce the reversal of the magnetization of a ferromagnetic film deposited directly on top of a nonmagnetic layer with strong spin-orbit coupling [20]. The inverse spin Hall Effect provides a means for quantifying spin current generated by spin Hall effect, a consequence of spin-orbit interaction, by converting it into a charge current [17]. Nb has a large spin-orbit coupling and the large spin orbit interaction is still effective for the spin absorption even below the transition temperature T_C [15]. Also the ISHE has already been demonstrated at room temperature for Nb [21].

RESEARCH QUESTION

This study will investigate spin pumping into a FM/NM/SC tri-layer of Py/Cu/Nb, to determine the effectiveness of a copper spacer as a means of inhibiting the proximity effect. This can be seen in Figure 1. Below the superconducting transition temperature, the effective spin diffusion length in the Nb decreases from 50 nm to about 20 nm close to the coherence length ξ_S [12]. With a copper spacer greater than the coherence length, the proximity effects may be prevented.

Spin pumping shall be the method of spin injection. The FMR signal will be measured to determine the spin pumping efficiency. The ISHE shall be measured to further quantify the spin dynamics of the tri-layer. Two devices have been fabricated for this project. Both devices are integrated coplanar waveguides (CPW) with the tri-layer integrated into the device. These devices have been fabricated at the UCF Material Sciences Department.

Figure 1: The tri-layer used within this study uses Permalloy as the ferromagnet as the source of spin pumping. The niobium is seperated from the permalloy by a copper spacer intended to disrupt any proximity effects.

Experimental Methods

Ferromagnetic Resonance Experiment

The first part of the project will consist of measuring the FMR of the sample. This shall consist of two measurements: one measurement will be carried out at room temperature and the other at low temperature, inducing the superconductivity of the Nb. The device used for this has the tri-layer evaporated underneath the central line of the CPW for the microwave transmission. This can be seen in Figure 2. The device will be characterized by a Portable Network Analyzer (PNA) to measure the transmission through the device.

The room temperature measurement shall consist of measuring the FMR at multiple frequencies since the transmission is frequency dependent. A suitable FMR signal shall consist of a symmetric curve with minimal noise. A housing box with coaxial transmission lines will contain

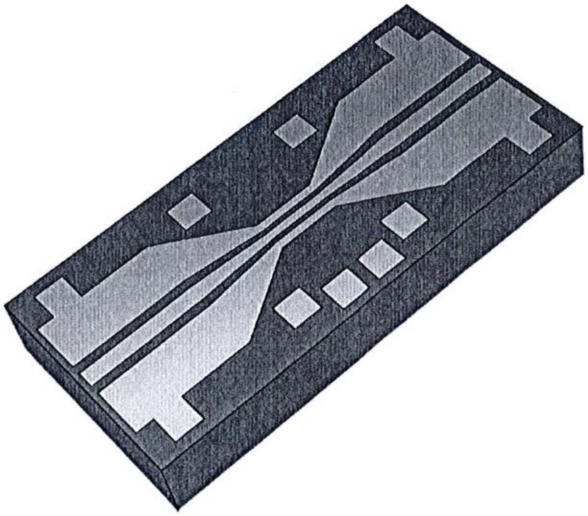

Figure 2: The integrated CPW with the Py/Cu/Nb stack underneath the central line used for the FMR measuremetns.

the device for FMR measurements. The device will require mounting onto a probe with coaxial connections for the microwave input. The PNA will provide the microwave input and will measure the amount of transmission at resonance. A sweeping magnetic field will be issued for a suitable range to produce a transmission curve. A Labview vi is written to control the sweeping magnetic field and the PNA will be connected to the computer with the program via GPIB. This will record the data.

Low temperature measurements will require the use of an Oxford Instruments ^{3}He Cryostat. The device will be transferred to a housing box that can be mounted to the cryostat. This cryostat has microwave connections accessible to the housing box necessary for the measurements. The cryostat will then be submerged into a dewar with liquid helium containing the magnet. The same FMR measurements shall be performed as for the room temperature measurements, however, the measurements will include a temperature sweep. The ^{3}He cryostat can reach a base temperature of 250 mK.

The FMR measurements will be carried out starting at base temperature, and in 250 mK increments will be increased in temperature so that the measurements will be carried out below and above T_c. The incremental measurements allow for an easy manipulation for the construction of a contour plot of the FMR signal. This will show a three parameter projection of the temperature dependence of the FMR. The derivative again can be taken for each data measurement and plotted three-dimensionally as well to give the nature of the change in the FWHM.

Inverse Spin Hall Effect Measurements

The second part of this experiment will consist of measuring the ISHE of the tri-layer. A second device is designed for the measurement of a potential difference across the sample. This will also be carried out a room temperature and low temperature. The room temperature measurements will use a Lock-In Amplifier for the measurements. The lock-in technique will allow the measurement of very small signals which is generated by the ISHE. To use the lock-in amplifier, a pulse must be sent to a microwave source to generate a frequency that the amplifier can measure at. Once a frequency is selected the measurements can be carried out.

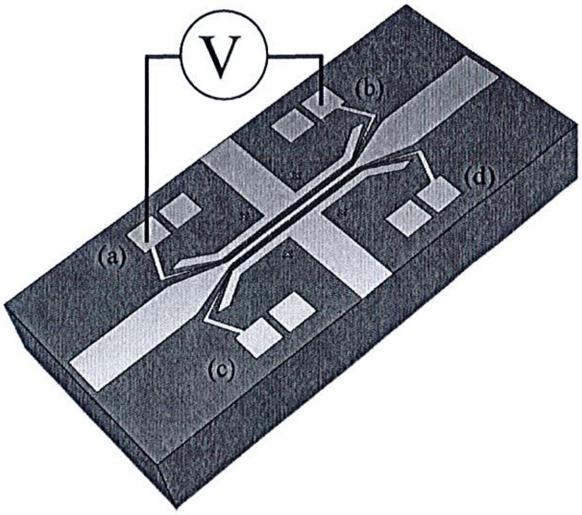

Figure 3: The integrated CPW used for the ISHE measurements. The material is layered in between electrical contacts made at (a) and (b) and also between (c) and (d). Electrical connections will need to be made to the contacts for measurement at the Lock – In Amplifier

Although the Nb becomes superconducting, the microwaves can still generate heat within the device itself, which can break the superconductivity of the sample. Reducing the power input into the sample is critical for this experiment. A series of measurements at room temperature will be carried out to minimize the power input into the sample. This will involve decreasing the duty cycle of the pulse as well as attenuating the power to the sample directly. A comparative analysis will show the consequences in the signal. The goal is to find the minimum power input to which the signal may be seen at low temperature.

Once a reliable power is found to generate the ISHE with minimal heat input, the experiment will then be carried out at low temperature. The device will also permit the measurement of resistance through the sample which will allow for precise determination of the transition temperature. This will aid in the interpretation of the FMR results. The ISHE will then be measured above and below the transition temperature of the Nb and a comparative analysis of the voltage signal will be carried out after the data acquisition.

Hypothesis

The strong spin-orbit coupling of the niobium as should provide as an effective sample to measure the ISHE at low-temperature. This study should provide an effective analysis of a Py/Cu/Nb tri-layer combination to prevent any proximity effects. Also, the technique for measuring the ISHE should provide an effective technique for reducing heating around the area of spin injection.

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