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High frequency spin dynamics in hybrid metallic devices

Costache, Marius Vasile

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Chapter 1

Introduction

1.1 Spintronics

The evolution of the microelectronics industry, where flow of electric charge is the driving force, is summarized in Moore's Law. This law implies that microprocessors will double in computing power every 18 months as electronic devices shrink. However, this will reach a limit as the size of the transistor approaches the dimension of atoms. Well before this limit there will already be severe problems with leakage and heat dissipation.

This is one of the reasons, in addition to the relevance for fundamental physics, why scientists have been eager to exploit another property of the electron, its intrinsic angular momentum known as **spin**. Spin is a purely quantum mechanical phenomenon, and is linked to the magnetic moment of the electron. The projection of the magnetic moment along a certain quantization axis can exhibit only two values $\pm\frac{1}{2}g\mu_B$, where g is the gyromagnetic ratio and $\mu_B = e\hbar/2m_e$ the Bohr magneton, the basic unit of the magnetic moment [1].

The motion of spins, like the flow of charge, can also carry information. A few of the advantages of spin over charge are: first, the spins can be easily manipulated by applied magnetic fields; second, the spins have a long coherence, or relaxation, time - once created it tends to stay that way for a long time, unlike charges states, which are destroyed by scattering with impurities or other charges.

These characteristics together with control over fabrication techniques which allowed access to the micro- and nano-scale regime (early 1980's) opened the possibility of developing a new research field called spintronics (spin-based electronics). Spintronics offers opportunities for a new generation of devices combining standard microelectronics with spin-dependent effects that arise from the interaction between spin of the carrier and the magnetic properties of the material [2, 3].

Basic research in spintronics is moving rapidly to smaller structures and novel materials, as well as focusing on new physical phenomena. This research has already led to the introduction of a variety of devices, from magnetic sensors for magnetic hard drives to a novel non-volatile magnetic random access memory (MRAM). For the continuing development of spintronics devices, however, we need a much better understanding of two fundamental issues: spin injection/detection (how spins are created and measured) and spin transport/dynamics (how spins move/act in metals and semiconductors).

The discovery of giant magnetoresistance (GMR) phenomenon in the late 1980's by Baibich et al. [4], was a stimulus for the field, in part because of its rapid incorporation into commercial devices, as the readhead in magnetic hard disc drives (IBM, 1997). The GMR sandwich structure consists of alternating ferromagnetic and non-magnetic (paramagnetic or normal-metal) metal multilayers. The electrical resistance of the multilayer structure changes (more than 50%) with the relative orientation of the magnetization direction of the ferromagnetic layers. A low resistance state occurs if the magnetization direction of the different layers are aligned parallel. The anti-parallel configuration has a higher resistance. The physical origin of GMR comes from the spin dependent scattering of electrons both at the ferromagnet/normal-metal interfaces and in the bulk of the ferromagnet layers.

Other important discovery in the field of spintronics which has application in MRAM devices is tunneling magnetoresistance (TMR). Where two ferromagnet layers are separated by a thin (about 1 nm) insulator layer. The TMR is the change of the tunneling current between the magnetic layers that depends on the relative magnetization directions of the two ferromagnetic layers [5, 6].

There is particular interest in spin based semiconductors devices because of the possibility of easier integration with traditional semiconductor technology. Although this can offer clear advantages and despite several years of effort, many basic question remain to be answered, see refs. [3, 7, 8].

Metallic spintronics. The subject of this thesis falls under the heading of metallic spintronics and, in particular, explores ferromagnetic magnetization and spin dynamics (in normal-metals) at frequencies in the GHz-range. In addition to understanding the basic physics of magnetization and spin dynamics at high frequencies, we were able to develop new microwave measurement techniques.

Twenty years ago, pioneering experiments on spin injection were performed by Johnson and Silsbee [9] on ferromagnet/normal-metal/ferromagnet lateral spin-valve structures to demonstrate spin transfer from a ferromagnet into a normal-metal. They used a four terminal spin valve (permalloy/aluminium/permalloy) device at temperatures below 77 K. By apply-

ing a bias voltage across a permalloy/aluminium junction a spin polarized current is injected into the aluminium. The injected spin current creates a spin accumulation close to the interface that decays spatially on the scale of the spin relaxation length. The second permalloy electrode placed within this distance is used to detect the spin imbalance in the aluminium.

Recently, Jedema et al. [10, 11] here in Groningen, clearly demonstrated the effect at room temperature in mesoscopic metallic spin-valve devices. The reduced size of the devices helped to increase the detected signal by six orders of magnitude as compared to the seminal experiment of Johnson and Silsbee. Similar results were obtained by Kimura et al. [12] and Valenzuela et al. [13]. For overall reviews that focus on spin-polarized transport, see refs. [3, 14–18].

In addition, in the last few years there has been a growing interest in spin dynamics at high frequencies induced by the spin transfer torque, a phenomenon predicted by the Slonczewski [19] and Berger [20]. In a spin valve structure (ferromagnet/normal-metal/ferromagnet') with the magnetization of the ferromagnets non-collinear (neither parallel nor antiparallel), the situation becomes more complicated. By sending a charge current through the structure, a non-collinear to the free layer (ferromagnet' is assumed to be soft with easily rotated magnetization) spin-current and spin imbalance can appear in the normal-metal. In this case an angular momentum is absorbed by the magnetization of the ferromagnets. Due to the angular momentum conservation, the macroscopic magnetization receives a torque equal to the absorbed angular momentum. This can have dramatic consequences for magnetization dynamics in nanostructures, leading to various instabilities and even reversal of the magnetization of the free layer [21–23].

This interest is motivated not only by the wish to understand the physics underlying the new phenomenon but also to its potential for device applications. An application is magnetization switching in magnetic memories (MRAM). In these devices, externally generated magnetic fields are used to reverse the magnetic moments. A current pulse through perpendicular ferromagnet/normal-metal/ferromagnet' spin valves can reverse the free layer magnetization more effectively in small structures since one does not waste energy on generation of a magnetic field outside of the sample, thus also improving possibilities for further miniaturization.

1.2 Motivation

The central subject of this thesis is to study the inverse effect of the spin transfer torque effect, called spin pumping. Spin pumping [24] is a mechanism where a pure spin current, which does not involve net charge currents,

is generated at the interface between a ferromagnet with a precessing magnetization and a normal-metal region. There are several motivations for the experiments presented in this thesis:

Study the inverse effect of the spin transfer torque. As shown above, a detailed understanding of the spin transfer effect is necessary not only from the point of view on fundamental physics, but also for the technological design of future devices. Therefore understanding the spin pumping effect would result in a better understanding also of the spin transfer torque.

Create a highly efficient spin source. The method developed by Johnson and Silsbee [9] for the injection of spins by charge transfer across a ferromagnet/ normal-metal interface is a very useful technique, however for technological applications it has limitations. The polarization of the spin current (defined by Eq. 2.7) is only a few percent (1-20%), which means that only a fraction of the total (charge) current is used in the process of spin injection. Spin injection by the precessing magnetization, i.e. spin pumping, can be used as an alternative source for spins into normal-metals (or semiconductors), the polarization of the spin current in this case is 100%.

Advances in understanding the basic physics are not possible without developing new measurements/analysis techniques. Research on magnetic/non-magnetic structures benefits enormously from the use of microwave measurement techniques. First, because the magnetization and spin dynamics are in this frequency range. Second, by probing the ac-properties of such systems, the measurement bandwidth is increased drastically, enabling experiments on shorter time scales with larger signal to noise ratios than in traditional dc- or low frequency transport measurements. In chapters 5 and 6 we discuss a new technique to control on-chip the magnetization of a individual submicron ferromagnetic element by inducing ferromagnetic resonance.

1.3 Outline

In the course of this thesis work, a number of different topics in mesoscopic spintronics and magnetization dynamics have been covered in a systematic approach to the goal of studying the spin pumping effect.

Chapter 2 covers some background information, with an introduction to the basics physics of spintronics. A general discussion of spin torque transfer and spin pumping effects is given. The chapter ends with discussion about magnetization dynamics of a ferromagnetic strip.

Chapter 3 is devoted to the device fabrication processes. Measurement techniques and on-chip ac generation of the magnetic fields are also discussed.

The remainder of the thesis describes the experimental results. This covers three different topics:

1. *Chapter 4* presents the measurement of **dc spin accumulation** in multiterminal mesoscopic lateral devices. This is an extension of the Jedema et al. [14] work.
2. Inducing and detecting **ferromagnetic resonance** of a single sub-micron permalloy strip. We discuss two detection methods, inductive detection of the oscillating magnetic flux due to the magnetization dynamics (*Chapter 5*) and dc anisotropic magnetoresistance measurement (*Chapter 6*). In addition, in *Chapter 8* we describe a detection method for microwave spectroscopy on magnetization reversal dynamics of a submicron cobalt strip. These techniques were an important precursor to the spin pumping work.
3. In *Chapter 7* we present direct electrical detection of **spin pumping**, using a lateral normal-metal/ferromagnet/normal-metal device, where a single ferromagnet in ferromagnetic resonance pumps spin polarized electrons into the normal-metal.

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