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High frequency spin dynamics in hybrid metallic devices

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Summary

This thesis describes a series of experiments aimed at the understanding of the physics of magnetization and spin dynamics in the GHz frequencies range (1 - 40 GHz) in hybrid submicron ferromagnet/normal-metal devices. Understanding and control of the interplay between charge, spin and magnetization dynamics in ferromagnet/normal-metal structure is required for further development of nanoscale spintronic devices. In addition to understanding the basic physics of magnetization and spin dynamics at high frequencies, we were able to develop two new microwave measurement techniques.

The major results of this thesis are as follows:

1. The influence of multiple electrode magnetic configurations on the spin valve signal in a four ferromagnetic terminal spin valve device is observed (chapter 4).
2. New methods to induce and detect on-chip ferromagnetic resonance in an individual, submicron permalloy strip are developed (chapter 5 and 6).
3. Anisotropic magnetoresistance detection of resonantly enhanced magnetization reversal by microwave magnetic fields in a single cobalt strip (chapter 8).
4. Dc electrical detection of the spin pumping effect due to the precessing magnetization of a single ferromagnet (chapter 7).

We started with an extension of work done here in Groningen by Jedema, *et al.* and Zaffalon, *et al.*. In general, in a four-terminal measurement on a lateral spin valve device, at least two electrodes should be ferromagnetic, one for spin injection and the second for detection. For practical reasons, it is easier to fabricate devices with all four electrodes ferromagnetic. In chapter 4, we studied dc spin accumulation in an Al island, connected by four Co

electrodes. Due to the small differences produced during the fabrication and to magnetic interactions between the Co electrodes, the switching fields for identically designed Co electrodes may not be the same. However, from the measurements we can identify the sequence of the magnetization switching of the ferromagnetic contacts.

Next we focused on high frequency experiments. Advances in understanding of the high frequency physics of ferromagnet/normal-metal structures are not possible without developing new microwave measurement techniques. In chapter 5 and 6 we describe two experiments in which we induce and detect on-chip ferromagnetic resonance (FMR) in an individual, sub-micron ferromagnetic element, and measured its precession cone angle with the dc anisotropic magnetoresistance (AMR) effect.

In these experiments, a ferromagnetic permalloy strip is embedded in an on-chip, lateral microwave transmission line device. Strong on-chip resonant driving of large cone angle magnetization precession of the element is achieved by locating the element in close proximity to the shorted end of a coplanar strip waveguide which generates an intense, local microwave magnetic field. In the first method, the FMR uniform precession mode is measured by inductive detection of the oscillating magnetic flux due to the magnetization dynamics (chapter 5). In the second method, by applying a dc current across the stripe and measuring its AMR, we determine the cone angle of the precessing magnetization with high precision. The perfect fit of the experimental data with the Kittel equation for the uniform precession mode demonstrates the viability of both methods.

In an early attempt to detect FMR in a submicron cobalt strip (chapter 8), we developed a new detection method for microwave spectroscopy on magnetization reversal dynamics of the strip. We used AMR measurements to probe how magnetization reversal of a Co strip is enhanced by resonant microwave magnetic fields.

All these techniques were an important precursor to the spin pumping work, which is the main result of this thesis. In chapter 7, we demonstrate that simply the motion of the magnetization of a ferromagnet can generate a voltage. This is due to the spin pumping effect, where the motion of the magnetization pumps a pure spin current (without a charge current) into an adjacent normal-metal region, resulting in a spin accumulation. The spin accumulation induces a backflow of spin current into the ferromagnet which generates a dc voltage due to the spin dependent conductivities of the ferromagnet. By comparing different contact materials (Al and/or Pt) and different contact geometries, we find, in agreement with theory, that the spin-related properties of the normal metal dictate the magnitude of the dc voltage. Therefore, an important characteristic is that the same ferromagnet acts as both the source as well as the detector of the spin pumped current. This offers a very sensitive method for electrical detection of magnetization

dynamics.

This thesis presents a systematic study on mesoscopic physics in particular on metallic spintronics. Starting with a lateral spin valve device which was a simple extension of the previous work done here in Groningen, we have successfully introduced high frequency measurement techniques by the incorporation of on-chip waveguides. The main focus was the precise fabrication and layout of submicron metallic structures for different functionalities: delivery of high-intense and localized microwave magnetic fields, ferromagnetic stripes for electrical spin injection and detection, and various paramagnetic metals as spin transport channels.

The detection of spin pumping offers novel insight into the fundamental physics of spintronics and could lead to new technological applications.

