Magnetism and magnetization dynamics in thin film ferromagnets

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Summary

During the last 30 years, the number of both fundamental and applied studies of heterostructures of ferromagnets and normal metals has grown impressively. The attraction of studying these heterostructures lies in the fact that already at room temperature their charge transport properties can be strongly influenced by even small magnetic fields. This is nowadays applied in different integrated circuits like magnetic read heads for hard disks, magnetic memory and sensors.

Since the 1960s, studies in the field of semiconductor heterostructures showed that it is possible to fabricate light emitting devices (more specifically light emitting diodes, or LED's), which can emit visible, infrared and ultraviolet light. A LED consists of a semiconductor with an excess of electrons combined with a semiconductor with an excess of holes. When flowing a current through the semiconductor heterostructure, a non-equilibrium distribution of electrons and holes is created. Relaxation of this non-equilibrium state occurs by the recombination of an electron and a hole, whereby a photon is emitted.

Recently, it was proposed by Kadigrobov to combine both approaches and build a ferromagnetic LED, which has the special property that it can emit radiation within the so-called terahertz gap. The terahertz gap is the part of the electromagnetic spectrum between roughly 300 gigahertz and 30 terahertz, where it is very hard to generate radiation with conventional sources. In this PhD thesis we investigated the feasibility to build such a device.

In the ferromagnetic LED, it is not a non-equilibrium distribution of electrons and holes, but a non-equilibrium distribution of electrons with spin-up and spin-down which needs to be created. This distribution can relax by a spin-flip process and the emission of a photon. As we use a spin-flip process, the device can be called a spin-flip LED or laser. In **Chapter 1** and **Chapter 2**, the theory and recent developments in this field are described.

One way to create such a spin-flip laser is to inject a very high current density of electrons from a ferromagnet into a normal metal leading to a local excess of spin-up or spin-down electrons. When at the same time an external magnetic field is applied, with the field direction opposite to the magnetization of the ferromagnet, the injected spins are now in a non-equilibrium distribution. There is a finite probability that such spins relax by a spin-flip process where also a photon is emitted. In **Chapter 3** we describe point contact spectroscopy experiments which were meant as a first step to the final observation of radiation coming from the point contact. It did not prove possible, however, to observe signatures of the desired spin accumulation in the point contact.

The ferromagnet used in our spin-flip laser is $SmCo_5$, a hard ferromagnet with a very large coercive field. This is needed in order to allow the magnetic field to be opposite to the magnetization direction of the external magnetic field. In **Chapter 4**, we describe the sputter growth of thin films of Sm-Co. The thin films grown have a coercive field of approximately 3 T, although not all of them reach such large values. One of the main problems of growing Sm-Co films is the complexity of the phase diagram, which results in a large amount of different Sm-Co phases on the Co-rich side. Small variations in the Sm concentration results in a significant change of magnetic properties of the films.

One of the main problems of building a spin-flip laser is the issue of spin current injection and the relaxation of the spin current in an adjacent layer. In **Chapter 5** and **Chapter 6**, we use the ferromagnetic resonance technique (FMR) to study how the spin currents behave at the interface of a ferromagnet and a normal metal with large spin-orbit coupling, such as Pt or Pd. When spins are injected in such a metal, they are efficiently removed, which leads to a net spin current and is visible in the FMR spectrum as a broadening of the line. However, if a normal metal with a small spin-orbit coupling is used, as Cu or Al, the spins are removed less efficiently and almost no increase of the linewidth can be observed.

In **Chapter 5** we use FMR and electrical measurements to study spin current injection from thin Co films into a Pt capping layer. When varying the thickness of the Co layer and the angular dependence of the external magnetic field with respect to the normal of the thin film, we show that a spin current is indeed present. Next, we study the temperature dependence of the injection of this spin current. Going down in temperature we find that the basic injection efficiency does not change. The observed variation in FMR linewidth is due to changes in the intrinsic scattering mechanism in the ferromagnetic layer.

While studying the spin injection in Co/Pt sandwiches, also Co/Cu sandwiches were investigated for reference purposes. It was found that for very thin Co layers, the line broadening in Co/Cu is larger than could be expected, as Cu is a normal metal with weak spin-orbit coupling. In **Chapter 6** this system is studied in more detail. It is shown that measurements done on trilayers, where the ferromagetic layer is covered on both sides with the normal metal, does not show this large broadening. The large difference between bilayers and trilayers shows that the extra broadening is a property of the bilayer, which we tentatively attribute to a Rashba spin-orbit torque, provided not by the interface between the ferromagnet and the normal metal, but by the interface between the ferromagnet and the substrate.