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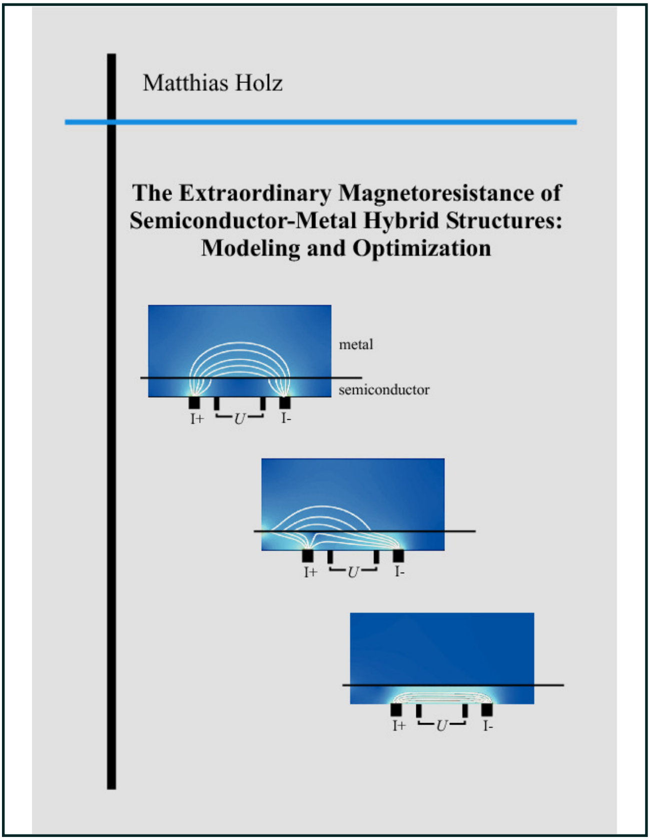
The Extraordinary Magnetoresistance of Semiconducter-Metal Hybrid Structures: Modeling and Optimization



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Chapter 1

Introduction

Magnetic–field sensors are used in a broad variety of applications. These include devices for storage technology, for medical applications, and for the characterization of materials [Men97, Her93]. Many applications also use magnetic–field sensors to measure other quantities like mechanical parameters, e.g., position or angle. Depending on the specific requirements of the application, different physical structures are used as sensor devices. These structures show either a geometrical magnetoresistance effect like, e.g., the Hall effect, or a spin–transport effect like, e.g., the giant magnetoresistance (GMR) effect. The electrical and material properties of these structures determine the application for which they are used: e.g., while the distance between a bulk magnet and a sensor on the cm scale can easily be detected by means of a Hall sensor, the stray field of a nanostructured magnetic bit is measured by means of a read head, which incorporates a stack of metal layers [Men97].

Recently, it was observed that non–magnetic semiconductor–metal hybrid structures can exhibit a very large geometrical magnetoresistance effect [STHH00], the so–called extraordinary magnetoresistance (EMR) effect. Relative enhancements of the resistance as large as 750 000 % have been observed in a magnetic field of

4 T [STHH00]. The EMR effect was found in hybrid structures involving either a bulk semiconductor [STHH00, ZHS01], or a modulation–doped semiconductor heterostructure incorporating a high–mobility two–dimensional electron system (2DES) [MKG+02, SHR+02]. Both types of structures do not involve magnetic materials and thus do not show magnetic noise or demagnetisation effects. The large EMR effect led to the prospect of using semiconductor–metal hybrid structures in magnetic–field sensors and, in particular, in read heads in magnetic storage technology [SHR+02, SHT+02, MRMRS03, HKG03b].

In this work, the EMR effect in semiconductor–metal hybrid structures is studied theoretically. It is organized as follows: After a short overview over geometrical and spin–transport magnetoresistance effects and a description of the physical origin of the EMR effect in Chapter 2, a model based on diffusive transport in hybrid structures is discussed in Chapter 3. This model is solved by means of the finite element method (FEM). The results are found to be in very good quantitative agreement with experimental data on the EMR effect. In addition, the model provides a deeper insight into the mechanisms leading to the EMR effect.

In Chapter 4, this model is used to analyze the dependence of the magnetoresistance on material parameters and geometry. In Chapter 5 it is discussed, how semiconductor–metal hybrid structures exhibiting the EMR effect can be optimized for high–sensitive magnetic–field sensors. In particular, the excellent performance of an EMR device in a read–head application is evaluated. This work closes in Chapter 6 with a conclusion and an outlook.

Chapter 2

Geometric and Spin–Transport Magnetoresistance Effects in Sensor Applications

2.1 Magnetic Field Sensors

Magnetic field sensors are used in a variety of applications. These reach from the detection of very small fields in the pT and nT range in the diagnosis of electrical currents in the brain or the heart, respectively, to applications in magnetic storage technology [Her93, Men97]. Figure 2.1 shows some areas of application and the magnetoresistance effects used in them. In Section 2.2, a short overview over these magnetoresistance effects will be given.
Depending on the application, for which the sensor is designed, one or more of the following quantities are important:

- **current sensitivity** dR/dB,

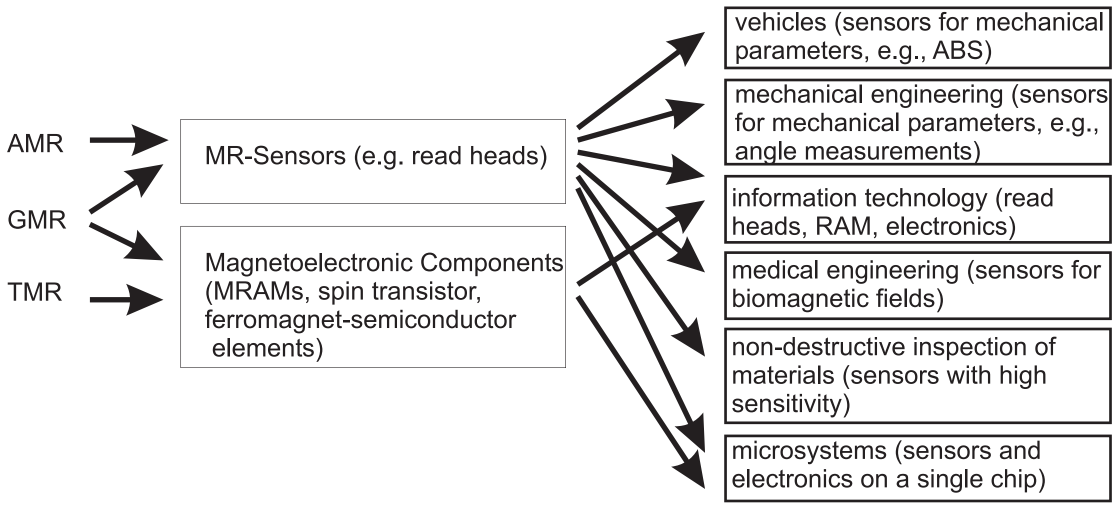

Fig. 2.1: Current and future applications of magnetoresistance effects. This scheme is extracted from [Men97].

- **voltage sensitivity** $1/R\, dR/dB$,
- **magnetoresistance effect** $\mathrm{MR(B, B_{ref})} = [R(B) - R(B_{\mathrm{ref}})]/R(B_{\mathrm{ref}})$.

Large current and voltage sensitivities around a magnetic field B are, e.g., important, if small deviations from a homogeneous background field B are to be detected. A large magnetoresistance effect $\mathrm{MR}(B, B_{\mathrm{ref}})$, on the other hand, is useful for measuring the deviation of the magnetic field B from a reference field B_{ref}, or for detecting a binary field code. The latter case is given, e.g., for a read head in magnetic storage technology. Here, a binary stray field is detected, which at the position of an EMR read head is about $B = \pm 50$ mT [STHH00]. Hence, $\mathrm{MR}(+50\ \mathrm{mT}, -50\ \mathrm{mT})$ is an interesting figure–of–merit for such an application.

In the following, some magnetoresistance effects used in magnetic–field sensors are discussed. Here, the figure–of–merit often used to parametrize the relative magnetoresistance change is

$$\mathrm{MR}^{\max} = \max_{B, B_{\mathrm{ref}}} \{\mathrm{MR}(B, B_{\mathrm{ref}})\} = \frac{R^{\max} - R^{\min}}{R^{\min}}, \tag{2.1}$$

i.e., the maximum relative enhancement of the resistance R for a field B with respect to a reference field B_{ref}. $\mathrm{MR}^{\max}$ will be given in each case.

2.2 Magnetoresistance Effects: An Overview

2.2.1 Anisotropic Magnetoresistance Effect

Generally, the resistance of a ferromagnetic conductor depends on the orientation of the current flow relative to the magnetization. This is the origin of the so-called anisotropic magnetoresistance (AMR) effect, which was discovered in 1857 by W. Thomson [Tum01]. The magnetoresistance follows the magnetization curve of the material and saturates when the material is fully polarized. The value of $\mathrm{MR}^{\max}$ is typically of the order of 2 % to 4 % [Tum01, Men97]. AMR sensors mostly consist of a homogeneous material system of Fe, Ni, or a Co alloy [Men97].
Sensors based on the AMR effect are used in a broad range of applications in the fields of, e.g., mechanical engineering, vehicle engineering, and material characterization. In the 1990's, AMR sensors were applied in read heads for magnetic storage technology. This led to an increase in the growth rate of storage density in hard disks by a factor of two [Men97].

2.2.2 Giant Magnetoresistance Effect

M. N. Baibich *et al.* [BBF$^+$88] and G. Binasch *et al.* [BGSZ89] discovered a large magnetoresistance effect in Fe/Cr layer systems, the so–called giant magnetoresistance (GMR) effect. This effect was found in, both, sandwich structures ABA, and

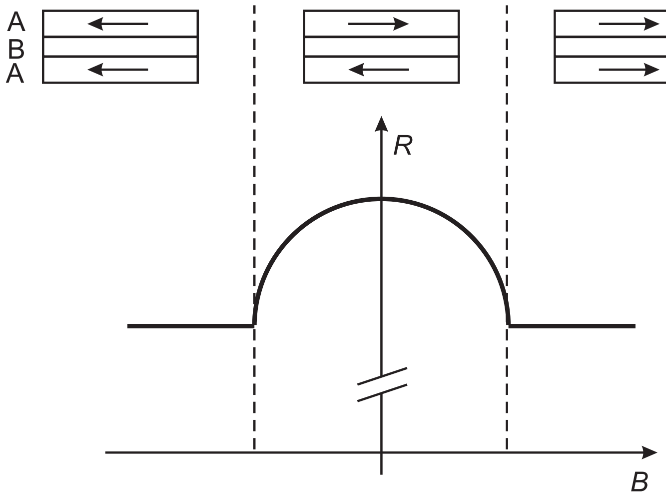

Fig. 2.2: Schematic drawing of a layered structure showing the GMR effect [BBF+88, BGSZ89] and the typical magnetoresistance behavior depicted as resistance R vs. magnetic field B. The upper and lower layer consist of a magnetic material A like, e.g., Fe, and the intermediate layer consists of a conducting, non–magnetic material B like, e.g., Cr.

multilayer systems. The principle is shown in Fig. 2.2: a layer of a conducting, non–magnetic material B is sandwiched between two layers of a ferromagnetic material A. The resistance of this structure depends on the relative magnetic polarization of the two magnetic layers: for a parallel orientation of the polarizations, the resistance is smaller than for an antiparallel orientation. This is due to the spin dependence of the electron scattering at the AB interface [BGSZ89].

Depending on the orientation of the current injection relative to the layer plane, the GMR effect can be observed in current–in–plane (CIP) or current–perpendicular–to–plane (CPP) geometry. Usually, the CPP geometry provides the larger $\mathrm{MR}^{\max}$, but it is more difficult to be realized than the CIP geometry [Men97].

The maximum magnetoresistance $\mathrm{MR}^{\max}$ in a trilayered sandwich structure (Fig. 2.2) is about 6 % to 8 % [Tum01]. The GMR effect is extensively used in current read–head technology [Men97].

2.2.3 Tunneling Magnetoresistance Effect

Also observed in layered magnetic structures is the tunneling magnetoresistance (TMR) effect. In structures exhibiting the TMR effect the intermediate layer in Fig. 2.2 is replaced by an oxide, i.e., the two magnetic layers are separated by a thin non–conducting layer. Electronic transport from one magnetic layer to the other thus occurs via quantum mechanical tunneling. The tunneling current depends on the relative orientation of the polarizations of the magnetic layers [MKWM95], giving rise to the TMR effect. The spin–dependent density of states in the ferromagnetic layers is the important parameter for the magnetic–field dependent tunneling resistance.

TMR structures generally show a larger resistance change than GMR structures. The maximum values of $\mathrm{MR}^{\mathrm{max}}$ for the TMR effect in such trilayer sandwich structures are about 20 % [Men97]. This value of $\mathrm{MR}^{\mathrm{max}}$ is hence larger than the GMR effect in trilayer structures.

2.2.4 Hall Effect

In 1879, E.H. Hall found a pronounced magnetoresistance effect in a thin Au film [Hal79], the so–called Hall effect. Figure 2.3 shows a schematic setup for observing the Hall effect. Under the action of a magnetic field B applied perpendicular to the plane of the sample, a voltage is created perpendicular to, both, the magnetic field and the direction of the current flow. The voltage is

$$V = \frac{IB}{ntq}, \tag{2.2}$$

where n denotes the carrier concentration, t the thickness of the film, I the current, and q the carrier charge. Interestingly, the resistance $R(B) = V(B)/I$ depends