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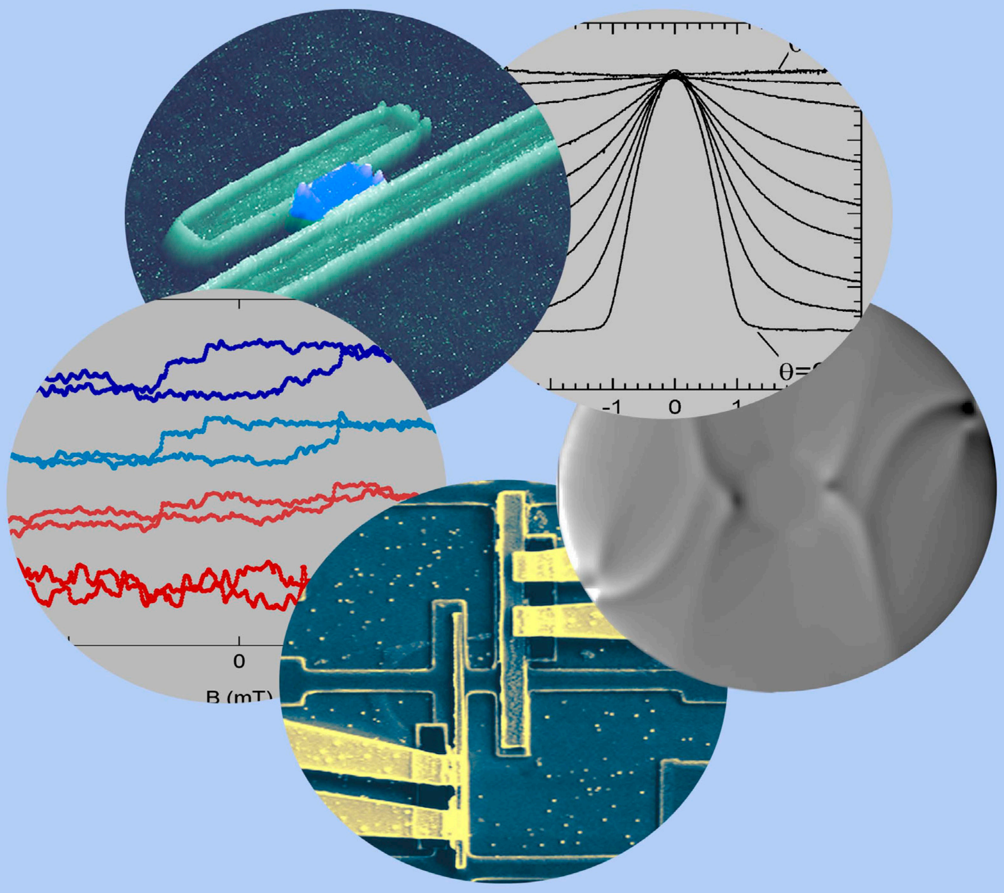

Micromagnetism and Electrical Resistance of Ferromagnetic Electrodes for Spin-Injection Devices

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Abstract

In the present work the characteristics of microstructured hybrid ferromagnet/semiconductor devices are presented. A Hall micromagnetometry study of permalloy rings reveals the "onion", the "vortex", and the "local vortex" state for different magnetic fields. These magnetic states are stable up to room temperature as proven by magnetic-force microscopy. The variation of the geometrical parameters of the rings offers the possibility to control the switching fields and the overall magnetic behavior. Micromagnetic simulations are used to investigate the rings numerically and are in very good accordance with the measurements.

Two different types of rectangular permalloy elements are investigated by transport measurements, namely single-domain and multi-domain samples. The anisotropic magnetoresistance is the governing resistance contribution. In the single-domain sample the classical anisotropic magnetoresistance is measured as well as additional resistance jumps. The angle dependence of the switching fields indicates the switching mode, which is identified as a curling-like magnetization reversal. In multi-domain samples the transport data become more difficult to interpret but it is shown by micromagnetic simulations that the main contribution to the resistance is generated by the anisotropic magnetoresistance. Domain-wall contributions to the resistance can be neglected in the present samples.

To inject spin-polarized electrons from a ferromagnet into a semiconductor, two approaches are followed. In the first, both materials are contacted directly. Small magnetoresistance changes are detected which are in accordance with model calculations. In a second approach, the spin-injection efficiency is enhanced by a tunnel barrier which is integrated between ferromagnet and semiconductor. The temperature dependence of the observed magnetoresistance jumps in both experiments resemble each other. This provides a hint for the successful injection of spin-polarized electrons into the semiconductor.

Inhaltsangabe

In der vorliegenden Arbeit werden die charakteristischen Eigenschaften von mikrostrukturierten, hybriden Ferromagnet/Halbleiter Bauelementen vorgestellt. Eine Untersuchung an Permalloyringen mittels Hall-Mikromagnetometrie zeigt eindeutig den “onion”, den “vortex” und den “local vortex” Zustand für verschiedene magnetische Felder. Diese magnetischen Zustände sind bis zu Raumtemperatur stabil wie duch Magnetkraftmikroskopieaufnahmen bestätigt wird. Durch die Variation der geometrischen Parameter der Ringe wird die Beeinflussung der Schaltfelder und das gesamte magnetische Verhalten der Ringe festgelegt. Mikromagnetische Simulationen der Magnetisierungszustände der Ringe stimmen mit den experimentellen Ergebnissen sehr gut überein.

Für Transportuntersuchungen wurden zwei verschiedene Arten länglicher Permalloyelemente verwendet. Der maßgebliche Widerstandsbeitrag in den Proben ist der anisotrope Magnetowiderstand. An eindomänigen Proben werden neben dem bekannten anisotropen Magnetowiderstand auch noch zusätzliche Widerstandssprünge gemessen. Die Winkelabhängigkeit der Sprünge gibt Aufschluss über den Ummagnetisierungsprozess. Es wird ein “curling”-artiges Umschalten beobachtet. Für mehrdomänige Proben stellt sich die Interpretation der Messdaten schwieriger dar, der hauptsächliche Widerstandsbeitrag kann jedoch ebenfalls auf den anisotropen Magnetowiderstandseffekt zurückgeführt werden. Widerstandsbeiträge der Domänenwände sind für die vorliegenden mikrostrukturierten Proben vernachlässigbar.

Die Injektion von spinpolarisierten Elektronen aus einem Ferromagneten in ein halbleitendes Material wird in zwei verschiedenen Ansätzen untersucht. Der erste Ansatz zeichnet sich durch den direkten Kontakt beider Materialien aus. Es werden kleine Magnetowiderstandsänderungen beobachtet, die in Übereinstimmung mit den Berechnungen sind. Um die Effizienz der Spininjektion zu erhöhen werden in einer zweiten Probengeometrie Tunnelbarrieren zwischen Ferromagnet und Halbleiter eingefügt. Die Temperaturabhängigkeit der beobachteten Sprünge in den Magnetowiderständen beider Proben ist sehr ähnlich und stellt einen starken Hinweis dafür dar, dass spinpolarisierte Elektronen in den Halbleiter injiziert werden.

Contents

1. Introduction

The phenomenon of magnetism was already discovered in the antique by the Greek and the Chinese. They knew that loadstone attracts iron but indications that magnets have two poles were found only in chinese scripts [1]. In the middle ages almost no deeper insight into the properties or the origin of magnetism was obtained. This changed in the Renaissance with the renunciation from alchemy and the development of the modern sciences. Systematical studies were performed and the knowledge increased but it lasted until the beginning of the 19^{th} century when M. Faraday and H.C. Oersted showed convincingly that magnetism is related directly to current flows and therefore to moving charges. A variety of discoveries followed and eventually Maxwell developed his unified field theory for the electromagnetism in 1864. The idea that the electron is an elementary particle developed in the outgoing 19^{th} century and was confirmed experimentally by J.J. Thompson in 1897. With the development of quantum mechanics it became apparent that quantization is a general phenomenon in physics. One experimental evidence was found in the quantization of the angular momentum in atoms by O. Stern and W. Gerlach in 1921. G.E. Uhlenbeck and S.A. Goudsmit found out in 1925 that electrons have an additional spin. This spin is related directly to the magnetic moment and W. Heisenberg could explain ferromagnetism in solid states as a collective coupling of the electron spins.

Even though the principle ideas of ferromagnetism are understood since the 1920s, there is still increasing interest in magnetic systems. The reason for this lies in the diversity of effects and material systems that show magnetic behavior. The advancements in experimental techniques, e.g. synchrotron-light sources, scanning-microscopy techniques, cryo techniques for temperatures down to the sub-milli Kelvin range, and many more, offer the possibility to investigate magnetic samples under various conditions. Thus, by using complementary techniques insight into the complex ferromagnetic systems can be gained from different perspectives.

For applications the possibility to exploit the non-volatility of the magnetization in small magnetic particles for information storage has been recognized early and magnetic core memories have been used in the 1950-1970s in the first computers. From these days the development of semiconductor-based processors and non-volatile storage units took place separately. The processor development was triggered by the invention of the transistor in 1947 by J. Bardeen, W. Schockley, W. Brattain [2, 3] and follows Moore's law, i.e., doubling the number of transistors of a processor approximately every 18 months. This could be realized by decreasing the lateral sizes and using improved materials and techniques. On the other hand, magnetic thin film techniques have been optimized for the application in hard disks. Storage densities of up to 100 $\mathrm{Gbit/in^2}$ are realized today in laboratory prototypes [4].

The integration of these two development directions to devices combining the advantages of both technologies is the next step. First applications are the Magnetic Random Access Memories (MRAM) [5]. Here, the non-volatility is combined with silicon processor technologies for fast storage cells. These devices are based on the giant magnetoresistance (GMR) [6, 7] or the tunnel magnetoresistance (TMR) effect [8].
In recent years, investigations of the resistance contributions in ferromagnets have attracted a lot of interest because new physical effects have been predicted. For very high current densities domains and domain walls can be influenced and moved. This effect may allow faster switching cycles compared to the switching fields that are generated by the traditional “bit-line” concept.
Further developments are still under consideration. The idea of a transistor that uses the electron spin [9] instead of its charge is widely discussed. Magnetic semiconductors [10] are a material class with promising properties for applications. Combining electron transport with optical data transmission in semiconductors illustrates a further development with a high potential for fast data processing and storage on a single chip. First approaches towards a quantum computer using the electron spin are also discussed and predicted to generate computational performances beyond traditional expectations. First experimental realizations of coupled “qubits” have already been demonstrated [11], but the large-scale integration of “qubits” is still a challenge.

The contribution of this experimental work to the rapid development in magnetism consists of three main topics. First, the study of the magnetization in magnetic rings is an example of the complexity of magnetic systems. By Hall micromagnetometry and magnetic-force microscopy (MFM) different magnetic configurations are observed and can be verified by numerical simulations. It is shown that the magnetic configurations and switching processes can be controlled by the geometry of the rings. All configurations survive up to room temperature and thus make them interesting for storage applications. Secondly, magnetoresistance experiments are performed on different microstructured magnets. The resistance contributions in micromagnets are investigated and from transport experiments conclusions concerning reversal mechanisms are drawn. At third, microstructured ferromagnets are combined with semiconducting heterostructures to so-called hybrid devices. This approach aims at the efficient injection of spin-polarized electrons into semiconductors.

This thesis is organized as follows: The second chapter gives an overview of the basic physical concepts which are necessary to understand the experiments. Starting from the fundamentals of ferromagnetism the resistance contributions arising in ferromagnetic samples are discussed. Finally, models for hybrid devices with semiconductors are presented in which spin-polarized electrons are injected. The third chapter introduces material systems, preparation techniques, and the most important measurement techniques. Chapter 4 and 5 summarize the results of the investigations on microstructured rings and ferromagnetic rectangles, respectively. In chapter 6 the experiments on hybrid devices are presented followed by a discussion of the difficulties and possible future approaches. Conclusions can be found in chapter 7.