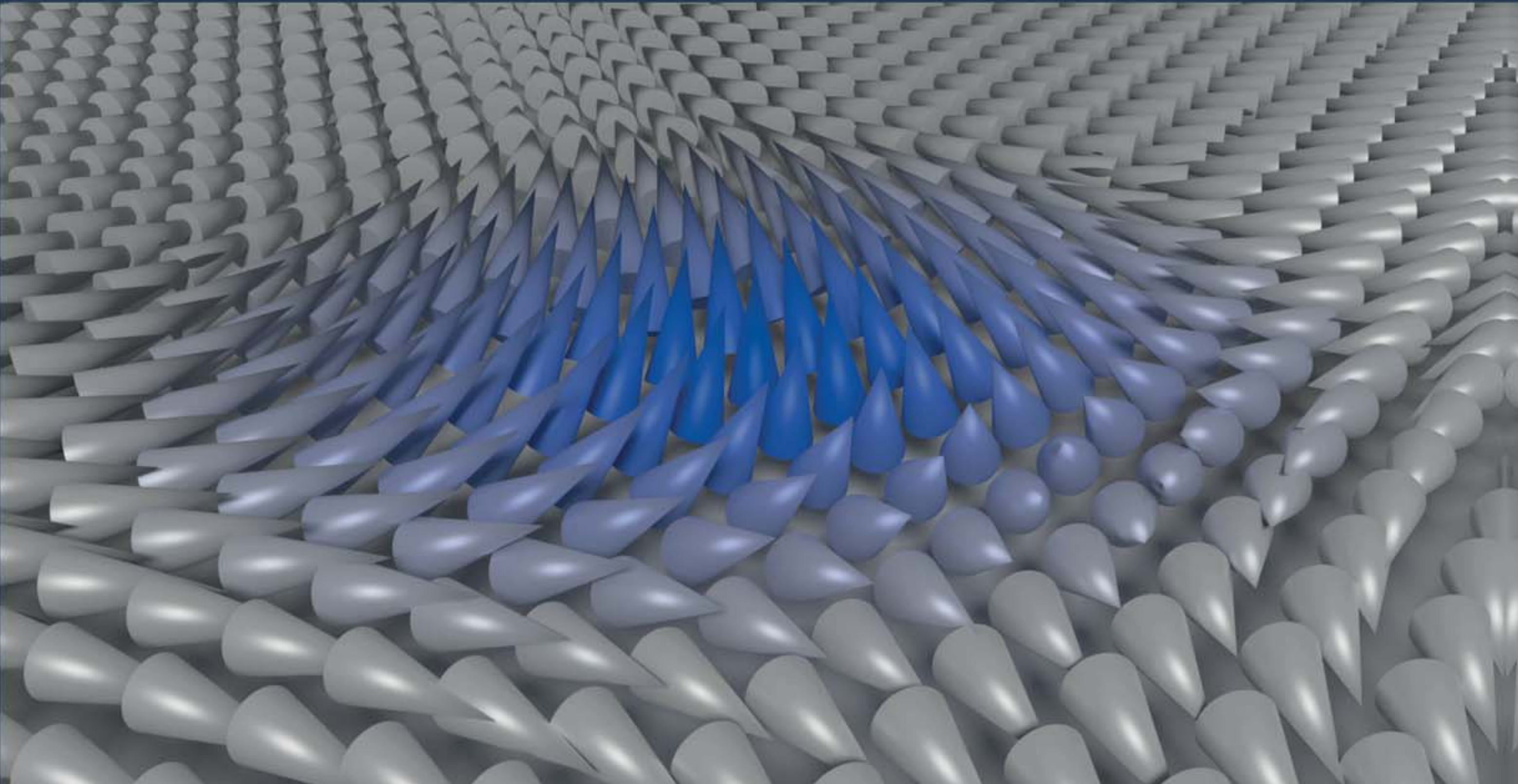
Michael Martens

Dynamics of magnetic vortices and antivortices studied by ferromagnetic absorption spectroscopy and transmission x-ray microscopy



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Abstract

Magnetic singularities in micron-sized ferromagnetic elements have been proposed for new concepts of magnetic data storage and are an ideal model system for the investigation of magnetization dynamics. In this thesis we deal with the dynamics of magnetic vortices as well as antivortices at picosecond and nanosecond timescales. High frequency alternating fields and spin-polarized currents are used for the manipulation of the vortices' magnetic states. The special case of rotational excitation is investigated by time-resolved magnetic transmission x-ray microscopy, micromagnetic simulations, and analytical calculations. For magnetic antivortices we find an asymmetric response to field and current excitation that we can explain with the negative winding number of the domains. In addition, we study the dynamics of magnetic vortices in the frequency domain by means of ferromagnetic absorption spectroscopy. We find deviations from the linear dynamics that we assumed previously. These deviations are explained in the context of a nonparabolic confining potential and a critical maximum velocity of vortex motion. Absorption spectra are found to be crucially influenced by the continuous reversal of the vortex-core polarization for high amplitudes of excitation. The measurement of the reversal threshold and its prediction within our analytical model is one prerequisite for technological applications. We verify our findings by direct imaging using magnetic transmission x-ray microscopy. For the interpretation of the data a detailed understanding of the underlying processes is developed based on micromagnetic simulations. We demonstrate that the eigenfrequency of magnetic vortex motion is also influenced by static magnetic fields. This is modeled analytically by anisotropic extensions that represent the shape of the microstructure. The insight into vortex dynamics gained in this work is crucial for a successful application of vortices for data storage devices.

Zusammenfassung

Magnetische Singularitäten in mikroskopisch kleinen, ferromagnetischen Dünnfilmelementen könnten in der Zukunft in magnetischen Speichermedien Verwendung finden. Des Weiteren stellen sie ein ideales Modellsystem für die Untersuchung der Magnetisierungsdynamik dar. In dieser Arbeit betrachten wir die Dynamik magnetischer Wirbel, der sogenannten Vortizes und Antivortizes, auf Zeitskalen von wenigen Pikosekunden bis zu mehreren Nanosekunden. Hochfrequente magnetische Wechselfelder und spin-polarisierte Ströme werden genutzt um die magnetischen Zustände dieser Strukturen gezielt zu verändern. Mittels zeitaufgelöster Röntgenmikroskopie, mikromagnetischer Simulationen und analytischer Berechnungen untersuchen wir den speziellen Fall einer rotierenden Anregung. Für magnetische Antivortizes erhalten wir ein asymmetrisches Verhalten bezüglich der Feld- und Stromanregung, welche auf die besondere, negative Windungszahl der Domänenstruktur zurückzuführen ist. Zusätzlich erforschen wir die Dynamik magnetischer Vortizes im Frequenzraum mittels ferromagnetischer Absorptionsspektroskopie. Hierbei finden wir Abweichungen von den zuvor entwickelten linearen Bewegungsgleichungen. Diese Abweichungen lassen sich jedoch durch die Annahme nicht-parabolischer Einschluss-Potentiale und einer kritischen maximalen Geschwindigkeit der Vortexbewegung erklären. Es stellt sich heraus, dass die gemessenen Absorptionsspektren ab einer gewissen Anregungsamplitude grundlegend durch das kontinuierliche Schalten der Vortex-Polarisation beeinflusst werden. Die genaue Messung und Vorhersage dieser Schaltschwellen ist eine Voraussetzung dafür, dass Vortizes technologische Verwendung finden können. Wir verifizieren unsere Ergebnisse zusätzlich durch die direkte Abbildung der Vortexbewegung mittels Röntgenmikroskopie. Für die Interpretation dieser Daten wird ein fundamentales Verständnis der zugrunde liegenden Prozesse benötigt. Dieses erhalten wir durch ergänzende Simulationen. Wir zeigen außerdem, dass sich die Eigenfrequenz der Vortexbewegung durch statische Magnetfelder beeinflussen lässt. Dieses Verhalten kann durch anisotrope Erweiterungen unseres Modells verstanden werden, die die Form der Mikrostruktur widerspiegeln. Der Einblick, der durch die vorliegende Arbeit in die Dynamik magnetischer Wirbel gewonnen wird, ist Grundlage für eine erfolgreiche Anwendung magnetischer Vortizes als Speichermedium.

Contents

1. Introduction

Since the beginning of the information age in the 1960s, the development of magnetic storage devices played the decisive role for the advancements in computer technology. The importance of this core technology for the digital revolution is equivalent with that of the silicon transistor, firstly developed by Morris Tanenbaum in 1954 [Tan55]. Only an ongoing miniaturization and increase in storage density was capable to keep up with the needs of digitalization in all areas of life [Plu12]. It was only in the last several years that the solid-state drive (SSD), which is based on integrated circuits and semiconductor technology, gained importance as a mass storage medium because of its speed advantage. In terms of storage size, reliability, and price per data volume, however, the SSD cannot compete with a magnetic hard disk drive (HDD). In these respects the HDD is still the first choice.

The basic function principle of a HDD has not been changed over decades. A circular disk coated with a ferromagnetic material rotates beneath a coil which serves as a switchable electromagnet. The magnetic field of this coil aligns the magnetization of microscopic areas, the so-called domains, along one of two opposite directions. These domains represent the bits as the smallest units of digital information. Nevertheless, during the process of miniaturization many issues had to be solved. The most noteworthy discovery is for sure the giant magnetoresistance (GMR) [Bai88, Bin89] which resulted in a dramatical increase of the sensitivity of the reading sensors and allows for much smaller domains. This importance was eventually honored with the Nobel Prize in Physics for Albert Fert and Peter Grünberg in 2007. It also demonstrates that new surprising discoveries are still possible in the field of magnetism and may have a huge impact on technology. Today the use of perpendicular magnetic recording makes it possible to realize even higher densities of the data.

Although the hard disk drive concept has proven itself over half a century, the two major problems, namely liability of the mechanical parts and non-addressability of individual bits, are still an issue. The information has to be read sequentially from large blocks limiting the speed of data access. This is in contrast to random-access memory where in principle every data cell can be accessed directly. Originally this range of application was covered by transistor-based devices which store the information in form of electrical charges. Today magnetoresistive random-access memory (MRAM), which again uses the magnetization for storage, is believed to combine the speed advantage of direct access with the nonvolatility of conventional magnetic recording. The spin-transfer induced switching of magnetic cells is the latest advancement currently in development. Instead of using the magnetic field accompanying high electrical currents for the switching of data bits, the torque of a much smaller spin-polarized current is used for the writing process. This reduces not only the power consumption but also allows for

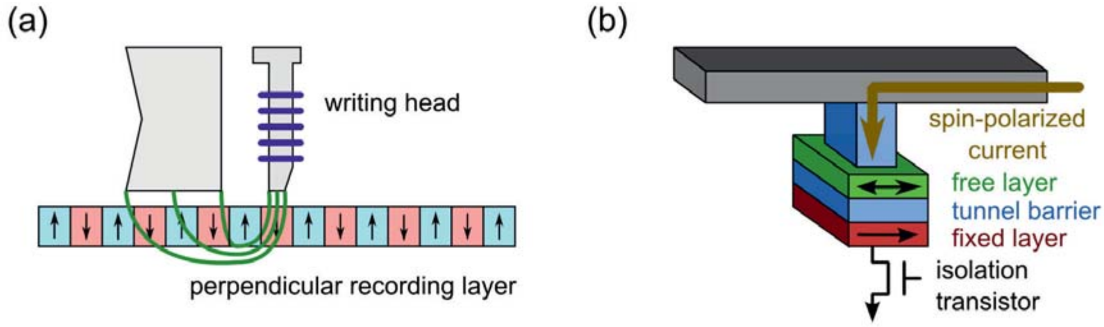

Figure 1.1.: Illustration of state-of-the-art magnetic recording and storage media. (a) Hard disk drive using perpendicular recording. The perpendicularly magnetized media allows for a much higher data density than the conventional in-plane type. The disk rotates beneath the writing head which focuses the magnetic field lines in order to switch single domains. (b) Single data cell of a spin-torque magnetoresistive random-access memory (ST-MRAM). A spin-polarized electrical current exerts a torque on the the free layer and switches its magnetization. For the reading process the cell serves as a magnetic tunnel junction. The illustration is modified from Ref. [Eve14].

much higher element density because of lower crosstalk. At the same time the cell serves as a magnetic tunnel junction that makes use of the tunnel magnetoresistance (TMR) effect [Jul75, Miy95] for the purpose of reading and the identification of the magnetic state. Figure 1.1 illustrates two different state-of-the-art concepts for magnetic data storage.

Another recently proposed concept for an MRAM is the vortex random access memory (VRAM) [Boh08]. It uses a combination of alternating magnetic fields and spin-polarized currents to switch the state of a special magnetic domain pattern [Wae06], the so-called magnetic vortex. These vortices occur in ferromagnetic microstructures resembling a disk, and are characterized by a curling of the magnetization around a core. The direction of this vortex core and the sense of curling can be controlled independently. By that one single disk can represent even four different states which is equivalent to two bits of information. Furthermore, the magnetic vortex shows unique high-frequency dynamics [Cho04] studied intensely. Several concepts for the selective manipulation of the vortex state, including rotational excitation [Kra07, Kim08], picosecond excitation by spin-waves [Kam11, Kam12], or out-of-plane currents [Cho10] have been presented.

All these concepts motivate a detailed investigation of magnetic vortices under the influence of magnetic fields and spin currents, which is the main topic of this thesis. In addition we study the topological counterpart, the magnetic antivortex, that has not attracted much attention to date but shows a similar dynamic behavior [Wan07] and could also be used for data-storage devices [Dre09]. Many publications are limited to one single method of investigation. Here we present a comprehensive study that includes the combination of different experiments, theoretical descriptions, as well as micromagnetic simulations. As one experimental method we use the time-resolved x-ray microscopy available at synchrotron-light sources, such as the Advanced Light Source in Berkeley, CA, USA and BESSY II, Berlin, Germany. It offers a unique possibility to directly image the vortex dynamics at its genuine time and length scales.

We develop a profound understanding which is supported by broadband ferromagnetic absorption spectroscopy that gives the response in the frequency domain.

This work is structured as follows: in chapter 2 we recapitulate the theoretical background that is necessary for the understanding of vortex dynamics as well as the experimental techniques. The latter are presented in chapter 3. Furthermore, we give an overview on the computational methods, with a focus on the numerical solution of the micromagnetic equations. Although these are known for many decades [Lan35], only the advancement of computational power in the last twenty years enabled an accurate simulation of the micron-sized structures investigated in this work. This is followed by a detailed description of the experimental setups used for x-ray microscopy and ferromagnetic absorption spectroscopy. Our results are presented in chapter 4. We begin with a comprehensive analytical model in Sec. 4.1, that describes the excitation of magnetic vortices and antivortices by two-dimensional fields and spin-currents. The model is applied to the special case of rotational excitation. For antivortices this calculation results in a surprising asymmetric coupling to the two driving forces. We use micromagnetic simulations and time-resolved x-ray microscopy for the verification of these main findings. In a second part, Sec. 4.2, we present experimental results that clearly show deviations from the model derived in the first part. This motivates us to introduce additional nonlinear extensions. A detailed understanding of these aspects is the key for a successful application of vortices for data storage, as presented above. The extensions include nonparabolic and anisotropic confining potentials as well as a critical limit for the vortex velocity. Finally, the presentation of our results closes with a conclusion in chapter 5. Most of the work presented is published in articles of peer-reviewed journals. We concentrate on the results of four publications. A full list of publications is found in appendix D.