TIME SCALES IN MAGNETISM

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Abstract. *In this lecture, an overview will be given of the different dynamic phenomena taking place in magnetism, from time scales of femtoseconds or less up to several years. The links between space- and time scales of the dynamics will be treated, as well as the influence of temperature. The importance of dynamic phenomena for applications of magnetic materials will be discussed, as well as future challenges for the study and use of magnetic devices.*

1. INTRODUCTION

Magnetic materials and magnetic devices play an important role in a great number of applications. For some of these applications, like electrical motors, permanent magnets with a strong magnetization that is very stable in time are necessary. For magnetic data storage, the magnetization direction has to be stable as well in order to guarantee that the information is preserved, but on the other hand a very fast reversal of the magnetization is necessary when new information has to be written. Read- and write times in magnetic storage devices nowadays are well below the nanosecond, and since about twenty years the fundamental limits of this reversal time are actively searched for.

At the longest time scales, thermal activation and thus influence of temperature plays an important role in the magnetization dynamics. In macroscopic magnetic materials, several stable or metastable states of the magnetization are usually available, separated by energy barriers. The system can transit between the (meta)stable states by thermal activation over the energy barrier separating the states, and the macroscopic magnetization can thus change even in the absence of a driving field. The time scales for this magnetization relaxation depend thus both on the barrier height and the temperature. In materials like spin glasses, where a great number of (meta)stable states with equivalent energies are existing, but also in hard magnetic materials or magnetic hard disks, at room temperature this relaxation can take place over time scales from seconds to many years. In magnetic hard disks, the guaranteed data stability for the moment is 10 years, but this stability strongly depends on the size of the magnetic grains used in the media, and a trade-off exists between data stability and storage density, as will be shown in this lecture.

The speed of magnetization reversal can be strongly influenced by the application of a magnetic field. In a macroscopic magnetic material or thin film, reversal of the magnetization starting from an initially saturated state takes place through the initial nucleation of some reversed domains and the subsequent propagation of domain walls [1]. Nucleation of reversed domains can be take place in times less than a nanosecond, while propagation speeds of domain walls are typically ranging from some mm/s to some hundreds of m/s. For both processes, thermal activation over energy barriers is still important, and we will show that as a consequence both the magnetic coercivity and the relative importance in the reversal of domain nucleation and domain wall propagation strongly depend on the magnetic field strength or the magnetic field sweep rate [2,3].

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Several groups have shown at the beginning of the 2000's that subnanosecond reversal of magnetic micro- and nanostructures was possible using magnetic field pulses with well-defined amplitude and direction [4,5]. In that case, use is made of the precessional motion of the magnetization vector around the effective field, governed by the Landau Lifshitz Gilbert equation of magnetization precession and damping. The frequency of this precession depends on the strength of the effective magnetic field.. This effective field includes contributions of the magnetic anisotropy and demagnetizing fields, and it was shown that by choosing the right parameters switching times of less than 100 picoseconds could be obtained. In addition to fast magnetization reversal, smaller angle precessional motion of the magnetization can also lead to other interesting phenomena, like ferromagnetic resonance and spin-waves [6]. These phenomena can be used to obtain accurate information on material parameters like exchange interaction, magnetic moment and anisotropy, but can also be used in applications like magnetically tunable filters and oscillators for microwave frequencies (up to frequencies of several GHz).
Even faster magnetization dynamics, in the femtosecond time scale, can be obtained using ultrashort, high intensity laser pulses, as was first shown about 15 years ago [7]. In that case, a very fast heating of the electron bath takes place, followed by a thermalization with the spin bath and the lattice. The initial heating leads to a very fast partial or complete demagnetization of the system, in some tens of femtoseconds, followed by a slower remagnetization. More recently it was shown that magnetization dynamics can also be induced directly, without heat transfer, by transfer of the photon angular momentum through the inverse Faraday effect [8,9]. This all-optical magnetization reversal can take place in the femtosecond time scale. Fundamental questions concerning the influence of the electronic structure, the energy transfer between the different baths and the conservation of angular momentum in laser-induced switching are still strongly debated on the basis of new experimental results and theoretical models, which will be partly treated in this school.
These recent developments in ultrafast magnetization switching but also in magnetization dynamics induced by spin-polarized currents are extremely interesting from a fundamental point of view, revealing several new physical phenomena. In order to be interesting for applications, like ultrafast and high density data storage, they have to be competitive with other techniques like all-electrical storage and phase-change memories, concerning speed, stability, cost and energy consumption. These aspects of magnetic devices, and the corresponding challenges, will also be discussed in this lecture.

REFERENCES

[1] Ferré, J., in *Spin Dynamics in Confined Magnetic Structures I,* Springer, New York, p. 127, 2002.
[2] Victora, R.H., *Phys. Rev. Lett.* **63**, 457, 1989.
[3] Raquet, B., Mamy, R., Ousset, J.C., Phys. Rev. B **54,** 4128, 1996.
[4] Schumacher, H.W. et al., *Phys.Rev.Lett.* **90**, 017201, 2003 ; *Phys.Rev.Lett.* **90**, 017204, 2003.
[5] Gerrits, T., et al., *Nature* **418**, 509, 2002.
[6] See Abstract of the lecture of S. Petit, and references therein.
[7] Beaurepaire, E., et al., *Phys. Rev. Lett.* **76**, 4250, 1996.
[8] Kimel, A.V., et al., *Nature* **435**, 655, 2005.
[9] Kirilyuk, A., Kimel, A.V., Rasing, T., *Rev. Modern Phys.* **82,** 2731, 2010.