CONTROLLING MAGNETIC HYSTERESIS BY NANO-SCALE MATERIALS DESIGN

A. Berger
CIC nanoGUNE Consolider, E-20009 Donostia – San Sebastián, Spain
a.berger@nanogune.eu

Magnetic hysteresis, i.e. the multi-valued magnetization vs. applied magnetic field dependence, is one of the core properties of ferromagnetic materials, both in terms of their fundamental properties as well as their technological relevance. Hereby, the needs of specific applications reach from complete suppression of magnetic hysteresis, such as in transformer magnets to avoid energy losses or in field sensors to achieve signal linearity, to hard magnets with maximized hysteresis for the stable generation of high magnetic fields without the need for an external current source or energy supply. To allow for the whole bandwidth of these requirements, magnetic materials are designed specifically by means of their shape, their micro- and nanostructure, and the materials used.

Besides local magnetic properties, in particular the magneto-crystalline anisotropy, it is the ferromagnetic exchange interaction and the dipole-dipole coupling of the elementary magnets that determines macroscopic hysteresis loop characteristics. Hereby, the ferromagnetic exchange favors parallel alignment of all spins even during the magnetization reversal process, which generally results in very rectangular hysteresis loops. On the other hand, the dipole-dipole interaction generally favors the creation of non-uniform intermediate magnetization states that result in very sheared hysteresis loops. It is for this reason that magnetic thin films are particularly well suited to study certain fundamental properties of magnetic hysteresis and ferromagnetism in general, because the influence of dipole-dipole interactions is strongly suppressed. This allowed, for instance, the first experimental observations of hysteresis loop criticality [1] and the dynamic phase transition [2]. Hereby, it is interesting to observe that even in perpendicularly magnetized magnetic films, the influence of the dipole-dipole interaction is suppressed, i.e. allowing for very rectangular hysteresis loops, because a domain formation does not allow for any substantial reduction of the dipolar energy, even though this energy is actually rather large [2,3]. The hysteresis loop criticality itself describes the phenomenon that in films without (or with strongly suppressed) dipolar interaction, there is a critical level of local disorder such as anisotropy or grain orientation, at which the system transitions to a fully correlated magnetic reversal despite the fact that local properties are not uniform [1]. The behavior shows all the characteristics of a (non-equilibrium) phase transition. The dynamic phase transition on the other hand shows that even a system with perfectly uniform magnetic properties can undergo a transition into non-uniform magnetization states if it is cycled at high enough frequencies [2].

For an observation of these fundamental aspects of magnetic hysteresis, it is generally very important to produce macroscopically extended materials with extremely uniform magnetic properties, which is a very substantial materials fabrication challenge. The same is true for the exact opposite of the spectrum, in which one tries to limit the local correlation of magnetic reversal to the smallest possible length scale, namely individual nano-magnets with less then 10 nm diameter. This is of crucial significance for magnetic recording, because one tries to write extremely small magnetic pattern with highly localized magnetic fields [4]. Thus, it is important that these highly localized fields only produce a very localized response. Such a behavior is accomplished by growing granular materials with highly oriented nano-scale grains that are separated from each other by non-magnetic grain boundaries formed by means of alloy segregation. In the most modern designs though, the optimized materials do not just have a distinct lateral grain structure, but also consist of a vertical layer sequence to optimize their hysteresis properties. For instance, the recently introduces exchange spring media consist of three separate functional layers in about 15 nm thickness: main recording layer, coupling layer, and soft-magnetic exchange spring layer [5]. This specific design enables a non-uniform magnetization reversal at high magnetic fields, i.e. in the magnetic write process, that is not accessible in the low field case under normal storage conditions. Correspondingly, the highly problematic correlation of magnetic writability and stability is broken, which would otherwise limit magnetic recording technology [6].

Another nano-scale design tool that allows for the tuning of hysteresis properties of magnetic materials is the so-called exchange bias effect. Here, the coupling of ferromagnets to adjacent antiferromagnets is utilized to shift and/or broaden magnetic hysteresis loops [7]. This effect however relies heavily on the quality of the interface and basically requires almost atomic control over it. An alternative approach was recently introduced by using a very hard magnetic material as a replacement for the antiferromagnet, which allows for easier processing and better interface coupling control [8]. Subsequently, these all-ferromagnetic exchange bias systems have been successfully used to study the fundamentals of the exchange bias phenomenon [9,10].

[1] A. Berger, A. Inomata, J. S. Jiang, J. E. Pearson, and S. D. Bader, Phys. Rev. Lett. **85**, 4176 (2000)
[2] D. T. Robb, Y. H. Xu, O. Hellwig, A. Berger, M. A. Novotny, and P. A. Rikvold, Phys. Rev. **B 78**, 134422 (2008)
[3] Y. Yafet and E. M. Gyorgy, Phys. Rev. B **38**, 9145 (1988)
[4] Eric E. Fullerton, D. T. Margulies, N. Supper, H. Do, M. Schabes, A. Berger, and A. Moser, IEEE Trans. MAG **39**, 639 (2003)
[5] A. Berger, N. Supper, Y. Ikeda, B. Lengsfield, A. Moser and E. E. Fullerton, Appl. Phys. Lett. **93**, 122502 (2008)
[6] S. H. Charap, P. L. Lu, and Y. He, IEEE Trans. Magn. **33**, 978 (1997)
[7] J. Nogués and I. K. Schuller, J. Magn. Magn. Mater. **192**, 203 (1999)
[8] A. Berger, D. T. Margulies, and H. Do, Appl. Phys. Lett. **85**, 1571 (2004)
[9] Ch. Binek, S. Polisetty, Xi He, and A. Berger, Phys. Rev. Lett. **96**, 067201 (2006)
[10] A. Berger, O. Hovorka, G. Friedman, and E. E. Fullerton, Phys. Rev. **B 78**, 224407 (2008)