Cooperative Research on the Metal Oxide Magnetic Nanoparticles

Xiaowei Teng[§], Meigan Aronson[£]

[§] Department of Chemical Engineering, University of New Hampshire
[£]Condensed Matter Physics and Materials Science Department,
Brookhaven National Laboratory,
[£]Department of Physics and Astronomy, State University of New York, Stony Brook

Abstract: The purpose of this white paper is to give an overview of metal oxide magnetic nanoparticles, including the current progress that has been made, the transformative potential that they may have for enabling high density data storage, and the roadblocks that still lie in the way of this emerging technology. The paper will also elucidate how the development of research on metal oxide magnetic nanoparticles will fulfill a critical national need, and why adequate funding to support this research should be a high priority.

1. Statement of Proposed Research

1.1 Introduction

In 1965, Gordon E. Moore wrote an article for Electronics Magazine, in which he stated the number of transistors on an integrated circuit will grow exponentially, more or less doubling every eighteen months. This empirical observation has withstood the test of time, and is referred as “Moore’s Law”. However, as miniaturization of components and devices continues, the quantum effect of the wave-like behavior of the electrons begins to perturb the designed functionality of the device. Many experts predict that silicon technology is approaching its fundamental limits. For example, Intel has reached 45nm metal gate silicon technology in its next-generation Intel® Core™ microarchitecture. Miniaturizing the design unit obviously will or has placed severe demands on the materials and manufacturing techniques. Therefore, this approaching crisis requires extensive research which seeks new materials and new ways to compress storage into even smaller spaces, while keeping the energy demand low, especially in the field of data storage.

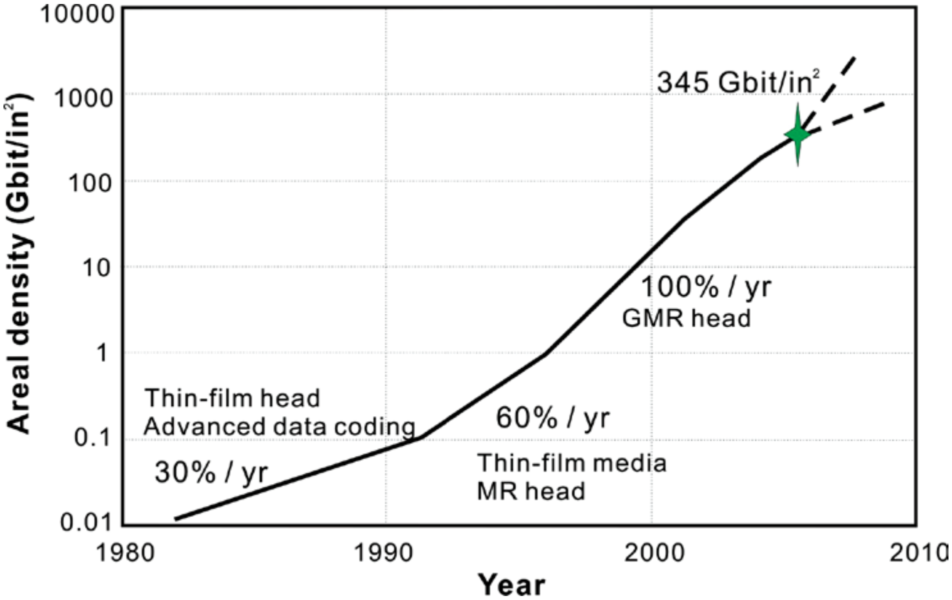

Figure 1 Data storage density for magnetic data recording

In accordance with the current growth of information technology, the need for fast, high density and reliable storage medium is paramount. Magnetic recording, as one of the most important technologies in data storage, has received enormous attention. Figure 1 shows the trend in areal density of magnetic data storage during the past 30 years. Before 1990, the data storage capacity increased at about 30% per year, which arose from the introduction of the thin-film head and advanced data coding. Then a 60% growth rate began in 1991, which was caused by the applications of the magnetoresistive head (MR) and thin-film recording media. In the late 1990s, the storage density of the hard disk increased by over 100% through the introduction of a giant magnetoresistive (GMR) reading sensor.[1] In September 2006, a storage density (density per unit area) of 345 Gbits/in^2 in perpendicular recording was demonstrated in laboratory by Hitachi Global Storage Technologies. Nonetheless, the accelerating need for more information capacity ensures that there is still great demand for improvements in ultrahigh density data. In this context, nanotechnology focuses on the design, construction, and use of structures and devices measured on the nanometer scale (between 1 and 100 nanometers). A nanometer is 1/1,000,000,000 of a meter, or one-billionth of a meter. Data storage indeed focuses on the effects of matter at the nano-microscopic level.

1.2 Data Storage, Exchange Bias and Metal Oxide Particles

The ever-increasing need for storage capacity has driven the storage density ever-higher, especially in hard disk design. Such rapid improvements in the future are however likely to be much more problematic. This is primarily due to the now well-known superparamagnetic limit (where ambient thermal energy is sufficient to reverse the recorded magnetization). Overcoming the superparamagnetic limit is currently a prime concern for the hard disk industry, and many novel approaches are being considered. In particular, development of exchange bias magnetic materials has drawn great attention. Since the most advanced disk media are antiferromagnetically coupled, magnetic material with exchange bias properties will effectively increase the stability of small magnetic particles whose behavior would otherwise be superparamagnetic. Exchange bias was initially used to stabilize the magnetization of soft ferromagnetic layers in readback heads of hard disc based on the anisotropic magnetoresistance (AMR) effect. Without the stabilization, the magnetic domain state of the head could be unpredictable, leading to reliability problems in hard disk design.

Desirable properties for an exchange bias material include a high Néel temperature (the temperature at which the thermal energy becomes large enough to destroy the macroscopic magnetic ordering within the material), a large magnetocrystalline anisotropy and good chemical and structural compatibility with ferromagnetic films (the materials record data directionally to represent either a 0 or a 1 binary digit). The most technologically significant exchange bias materials have been the antiferromagnetic oxides like NiO, CoO. Although exchange bias materials play important roles in current and future data storage device, for many years the exchange bias effect, discovered in 1956 by Meiklejohn and Bean,[2] has been optimized through materials engineering and employed in devices without a good scientific understanding, especially for the nanosized exchange bias materials (e.g. NiO, CoO). It is partially due to the difficulties poised by the material preparation, structural characterization and function measurement. However, recent advances in metal oxide (CoO, NiO in particular) have stimulated the research on exchange bias nanomaterials, as well as their implication for the next generation data storage device.

1.3 Advances in the Synthesis of Metal Oxide Nanoparticles

Nanoparticles have been obtained by two different approaches, which are called "top–down" (from large to small dimensions) and "bottom–up" (from molecular scale to nanoscale) methods. A common "top–down" approach involves breaking bulk materials to nanometer-sized particles. This process is generally associated with the use of mechanical force, such as grinding and ball milling. Though this approach is easy for large scale production, the size distribution of particles obtained is broad and degrades the magnitude of the exchange bias field, which is largest in nanoparticles where the dimensions of the ferromagnetic and antiferromagnetic components are similar, and where their interface has a high degree of crystalline perfection. A large variety of metal oxide nanoparticles can be synthesized via the "bottom–up" approach, which relies on chemical methods held in an aqueous or organic liquid phase. Parameters, which are important in controlling the size and shape of metal oxide nanoparticles, include reaction time, temperature and concentration of the reagents. It has already been demonstrated that suitably prepared nanoparticle systems show a significantly enhanced exchange bias effect, approaching the theoretical limit.[3] The biggest concern encountered in the synthesis process is the aggregation of nanoparticles, caused by van der Waals force of attraction and/or magnetic interactions between magnetic nanoparticles existing in the nanoparticle system. In order to avoid this problem, a repulsive or stabilizing force is needed. Organic ligands bearing long chain hydrocarbons chains (surfactants) provide a steric repulsion to increase the stability of nanoparticles.[4]

1.4 Advances in Instrumentation and Metrology

For the past half century, research on the exchange bias effect has been fueled by the search for structures with much larger bias field; however, the real mechanism of the exchange bias phenomenon remains obscure. Historically, the main problem in establishing a realistic model of exchange bias is attributed to the lack of information on the spin structure at the ferromagnetic – antiferromagnetic interface, an inherently nanoscaled problem. Structural characterization of nanomaterials has been slow to develop, given that their scale presents new challenges to traditional approaches, and since they are generally available only in small quantities which rules out many bulk characterization techniques. While even today new aspects of this phenomenon are still being discovered, neutron scattering and electronic microscopy measurements have made key contributions in the past few years to the solution of the long-standing puzzle by providing direct information on the magnetic structure at the interface.

Transmission Electronic microscope (TEM) is a powerful and unique technique for the characterization of individual nanostructures, which can not only provide real space imaging at a resolution of a few angstrom (Å), but also an analytical tool for quantitative structure and chemical analysis. At present, scanning TEM (STEM) equipped with spherical aberration correctors has been revolutionizing their performance, by dramatically improving spatial resolution and the beam current at a given resolution by a few more orders magnifications.[5] In this context, an aberration–corrected STEM could claim to be the most precise instrument ever constructed, exhibiting a strong ability to analyze the materials with a resolution of the single atom, which provides great opportunities to interpret the real heterogeneous structure of individual nanomaterial.

Neutron scattering is a unique technique to characterize magnetic structures. Unlike an x-ray photon, the neutrons, interacting with neutrons themselves, exhibit pronounced interference and energy transfer effects in scattering experiments. Neutrons are deeply penetrating due to their electric neutrality, suitable for a wide range of materials which are difficult to use with X-ray sources. In particular, in the study of condensed matter, neutrons can also readily interact with internal magnetic fields in the sample, allowing the simultaneous exploration of both nuclear and magnetic structure. Therefore, both the structural and magnetic properties as measured by neutrons can be compared quantitatively with the results of other characterization techniques.

1.5 Advances in Patterning Magnetic Nanoparticles

Patterned media present a potential application for ultrahigh density magnetic storage. One of the challenges for patterned media is whether economical methods exist to prepare nanoscale patterned particles, especially the fabrication of ultrafine, uniformly ordered nanoparticles. To obtain a theoretical data storage density as large as 1 T bit/in^2 (1 Terabit = 1000 Gigabit), a spacing of 25 nm between particles is required. For 10 T bit/in^2, this spacing is reduced to 8 nm. It will be difficult to realize such small spacing periods by the nanofabrication methods. Therefore, low-cost, reliable patterning magnetic nanomaterials are also very important in the next generation data storage device. In this context, self-assembly and template-directed assembly of magnetic nanoparticles is inexpensive with a rapid process. Theoretically, by controlling the conditions of deposition, these monodisperse magnetic nanoparticles can be organized onto the surface of substrates with two-dimensional (2D) or three-dimensional (3D) superlattice structures, patterned in such a way as to allow high frequency and highly parallel readout of the matrix of magnetic particles.

The forces involved in self-assembly include generally weak interactions, such as hydrogen bonding and hydrophobic interaction, steric repulsion, magnetostatic interaction, van der Waals interaction and Coulombic interaction and so on. Which of these dominates the behavior of self-assembly depends on the size, size distribution, shape of nanoparticles, and also the properties of solvents. Actually, the packing and perfection of self-assembled arrays can be fine-tuned. Using the same nanoparticles, different packing styles from hexagonal close packing, square packing, to linear chains were achieved by selecting appropriate conditions.

Template-assisted assembly was used to assemble the nanoparticles in a controlled manner with robust mechanical properties, in which the substrates are functionalized by special molecules or pretreated to get particular surface structure. For example, a DNA molecule can be used as a template for the growth and assembly of various nanostructures.[6]

2. How Proposed Research Meets the Selection Criteria of TIP

2.1 Maps to Administration Guidance

Popularity and market growth of personal computer has affected many everyday environments, and given rise to new applications, including e-mail, internet access, computer games, home-computing, and mobile devices. According to the Gartner Group, worldwide some 257.1 million PCs shipped in 2007. In particular, the portability revolution is already underway with mini laptops, palmtops, tablet PCs and touch screen laptops. Combining extreme portability, WiFi and tactical screens, these mini laptops will replace gradually paper, order sheets, notebooks and others. Enabling these applications in portable devices requires that they host a substantial amount of data, thus increasing the pressure to develop fast, reliable storage in a small space. Small businesses, hospitals, large corporations, and governments worldwide have all increased their demand for storage space by exponential amounts. These developments have required both Research and Development (R&D) to develop mass-storage technologies that use less energy and less space per bit stored.

2.2 Justification for Government Attention

US's global leadership in technology innovation has led to a string of transformative research breakthroughs in Information Technology, from transistors, mobile phones, personal computing to the Internet. Over the past decade, many of our competitors—from Great Britain, Japan, South Korea, to India, China and Brazil —have created national innovation strategies designed specifically to link science, technology, and innovation with economic growth. In February, 2009, the Information Technology and Innovation Foundation's (ITIF) Atlantic Century report ranked the United States sixth out of 40 leading industrialized nations in innovation competitiveness. A March 2009 Boston Consulting Group study ranked the United States eighth out of 110 countries. Of course, we need to do better and to regain our former world-leading position.

Technology innovation on data storage, combined with advances in nanotechnology, plays a critical role in addressing the needs of information technology in general. Even many developing countries have revealed a surprising amount of nanotechnology R&D activities. For example, Indian nanotechnology efforts cover a wide spectrum of areas, including microelectromechanical systems (MEMS), nanostructure synthesis and characterization, quantum computing electronics, nanoparticles, nanocomposites, and biomedical applications of nanotechnology.

2.3 Essentials for TIP Funding

There are several funding categories under the National Science Foundation devoted to the nanomagnetism , including “Condensed Matter Physics”, “Metals and Metallic Nanostructures” , and “Technological Challenges in Organic Electronics, Photonics and Magnetics”. Although research on magnetic nanomaterials might be funded under those programs, none of the programs are targeted specifically at the research on metal oxide based exchange bias magnetic nanomaterials. A further complication for traditional funding sources is the inherently interdisciplinary nature of nanoscience research, and particularly a lack of focus on transitioning laboratory breakthroughs to devices which can be manufactured. A new type of funding mechanism is required to realize the full transformative impact of exchange bias nanomaterials for high density data storage applications.

3. Summary

Research on metal oxide based exchange bias nanomaterials offers great possibilities for future improvements in data storage, transfer, and retrieval. In order to meet the needs of increasingly demanding IT markets and industries, it will be necessary to understand the exchange bias mechanism, and to design new exchange bias materials for next generation data storage technologies which can move beyond Moore’s Law. Someday, the combination of magnetism and nanotechnology may make it possible to store a bit of data on a single atom.[7] The implications, in terms of data retrieval speed, energy savings, and storage capacity, are astonishing. The possibilities of magnetic materials, coupled with other developments in nanotechnology, are endless.

4. References

1. Thompson, D. A.; Best, J. S., *The future of magnetic data storage technology*. ***IBM J. Res. Dev***., **44**, 311, 2000

2. Meiklejohn, W. H.; Bean, C. P., *New Magnetic Anisotropy*. ***Physical Review*** **102**, 1413, 1956

3. Inderhees, S. E.; Borchers, J. A.; Green, K. S.; Kim, M. S.; Sun, K.; Strycker, G. L.; Aronson, M. C., *Manipulating the magnetic structure of Co Core/CoO shell nanoparticles: Implications for controlling the exchange bias*. ***Physical Review Letters***, **101**, 2008

4. Teng, X. W.; Yang, H., *Effects of surfactants and synthetic conditions on the sizes and self-assembly of monodisperse iron oxide nanoparticles*. ***Journal of Materials Chemistry***, **14**, 774, 2004

5. Zhu, Y.; Inada, H.; Nakamura, K.; Wall, J., *Imaging single atoms using secondary electrons with an aberration-corrected electron microscope*. ***Nature Materials***, **8**, 808, 2009

6. Nykypanchuk, D.; Maye, M. M.; van der Lelie, D.; Gang, O., *DNA-guided crystallization of colloidal nanoparticles*. ***Nature***, **451**, 549, 2008

7. Feynman, R. *There's Plenty of Room at the Bottom*, 1959