SPIN
Vol. 2, No. 3 (2012) 1202001 (3 pages)

DOI: 10.1142/S2010324712020018

# GUEST EDITORIAL — RECENT PROGRESS IN SPINTRONIC DEVICES

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Published 9 November 2012



The past three decades have witnessed an explosive growth of research activities and discoveries in the area of spintronics. At their heart, spintronic device technologies are based on physical phenomena that allow electrical signals (currents and voltages) to interact directly with spins in nanomagnetic structures, i.e., where magnetic and transport properties are directly coupled. Spintronics as a field of science has exhibited a remarkable rate of new fundamental discoveries, which in turn have been translated into industrial applications at a very rapid pace. The most prominent initial examples were the discoveries of the giant magnetoresistance (GMR) (by Albert Fert and Peter Grünberg, who won the Nobel Prize for Physics in 2007) and tunneling magnetoresistance (TMR) effects, which established a technologically significant (i.e., large) relationship between electrical resistance and magnetization states of nanostructures. These fundamental discoveries were adopted very quickly into hard disk drive read heads, revolutionizing the data storage industry. They also set the stage for the emergence of magnetic-field-switched (toggle) magnetoresistive random access memory (MRAM), which has been in production for several years at the time of this writing. The subsequent discovery of the spin-transfer torque (STT) effect greatly expanded the range of applications of — as well as fundamental phenomena of interest in — spintronic devices, with the most notable example being the emergence of STT-MRAM technology.

With the recent industrial adoption and emergent prospects of commercial STT-MRAM products to be introduced in the market, fundamental studies into novel phenomena for future generations of spintronic devices continue at a very fast pace. A common challenge is enhancing the energy efficiency of spintronic devices beyond that delivered by the STT effect, e.g., through the use of new physical mechanisms such as electric-field-control of magnetism, the use of nontraditional spin injection methods such as the spin Hall effect, and utilization of the newly discovered spin-momentum locking of topological insulators for efficient spin current injection. Another set of recent discoveries of interest are in the area of spin caloritronics and the spin Seebeck effect, i.e., investigating the interaction of thermal effects (phonons) with magnetic phenomena and transport in nanostructures. Overall, it is no exaggeration to state that the field of spintronics — in terms of both its industrial relevance and its rate of fundamental discoveries — is at an inflection point, with exciting new results not only hinting at the significant future possibilities for fundamental study, but also showing a roadmap towards emerging industrial applications that lie ahead.

This special issue aims to provide an overview of some of the most interesting recent discoveries in spintronic devices. By necessity, the scope of the papers included in this issue only partially captures the fast-growing body of work in this area, and is meant to provide a snapshot and to stimulate interest in selected areas, rather than to provide a comprehensive review.

In the first paper, the issue directly delves into the technological applications of spin-transfer devices, starting with a work on "Write Error Rate in Spin Transfer Torque Magnetic Random Access Memory" by Wang *et al.* The paper deals with the subject of write error rates (WER) in STT-MRAM, which is a highly important topic for the realization of practical memory products with reliable write operation. The authors review the existing body of work in this area, covering both in-plane and perpendicular magnetic tunnel junctions, and present their recent progress and physical insights into the development of devices with sufficient write margin.

Realization of devices with low WER is a key requirement for the technological adoption of STT-MRAM. While earlier work has pointed to the improved WER performance of fully perpendicular STT-MRAM cells, the work by Wang *et al.* points out the possibility of realizing sufficiently low WER as well as high speed in scaled in-plane STT-MRAM cells at the 65 nm technology node and below, due to the reduced role of sub-volume excitations and texture effects in the magnetic bit switching. While this may result in early market applications of in-plane STT-MRAM, especially in embedded memories and DRAM replacement in low-density applications, scaling beyond the 45 nm node will require the transitioning to fully perpendicular STT-MRAM due to the need for thermal stability. In-plane STT-MRAM cells rely on shape anisotropy to maintain their thermal stability, which fails to provide sufficient stability for the small bit areas below the 45 nm node. This is compounded by the fact that, as STT-MRAM array sizes grow, higher bit-level thermal stability factors are needed to maintain array-level stability and error-free data retention, as well as the fact that STT-MRAM chips are designed for reliable functioning in a temperature range including elevated temperatures such as 85°C−125°C.

Magnetic tunnel junctions with fully perpendicular free and fixed layers are thus of great importance for high-density STT-MRAM applications at scaled technology nodes, especially below 45 nm, due to their improved tradeoff between thermal stability and switching current compared to their in-plane counterparts, and are hence an important area of current research. In "Recent Progress of Perpendicular Anisotropy Magnetic Tunnel Junctions for Nonvolatile VLSI", Ikeda *et al.* review the most recent results in the development of these critically important devices for scaled STT-MRAM.

The topic of magnetic memory (and other spintronic devices) beyond STT is addressed in "Voltage-Controlled Magnetic Anisotropy in Spintronic Devices" by Khalili and Wang. STT-based devices utilize the interaction of spin-polarized currents with the magnetization of nanostructures to perform writing (i.e., switching) operations. Since the flow of charge currents in this type of devices leads to Ohmic loss and power dissipation, the ultimate energy-efficiency of STT devices is limited. As an alternative, electric-field-controlled devices which can efficiently manipulate magnetic moments show the potential of markedly improving energy-efficiency by several orders of magnitude. The recent results and future prospects of such voltage-controlled devices are discussed in this paper, along with their potential implications for the future of MRAM technology.

The use of electric-field-control can offer at least three distinct advantages in MRAM: First, it reduces the switching energy of magnetic bits to levels that are comparable to scaled CMOS transistors (i.e., $<1$ fJ, as opposed to $>100$ fJ for STT-based devices). This improved efficiency can potentially allow for a finer integration of CMOS and magnetic nonvolatile memory, down to the gate level, to allow for nonvolatile logic with instant on/off capability. It is known that the scaling of CMOS transistor technology will reach its scaling limit soon due to leakage currents, as a result of quantum mechanical tunneling. Thus, if the switching energy of magnetic memory devices can be further reduced to below that of CMOS, they can be integrated together and will enable a new paradigm of nonvolatile electronics. Second, electric-field-controlled writing does not require large currents to drive the switching of magnetic memory cells, and hence, unlike purely STT-based writing, does not require the use of large transistors. This results in major advantages in terms of density and scalability of memory arrays, especially for advanced technology nodes beyond

32 nm and for high-speed memories (<10 ns), where purely STT-based writing typically requires switching current densities larger than $2\,\mathrm{MA/cm^2}$, resulting in a large memory cell size. Finally, electric-field-controlled magnetic tunnel junctions can utilize larger tunnel barrier thickness and higher resistance-area products, which can lead to higher reliability and endurance.

In the fourth paper, "Voltage Control of Magnetism in Multiferroic Heterostructures and Devices" by Sun and Srinivasan, the special issue continues on the topic of electric-field-controlled devices, emphasizing different magnetoelectric coupling phenomena and different types of device applications. The paper provides a detailed review of multiferroic heterostructures with large converse magnetoelectric coupling, and their utilization in a wide range of voltage-tunable magnetic devices, such as microwave phase shifters and filters.

The paper by Zeng and Fang, "Progress on Maximizing Output Power in Spin Torque Nano-Oscillators", reviews recent results in the area of microwave oscillators based on the STT effect. While much of the attention to STT in recent years has been attributed to its significant applications for memory, STT oscillators are devices of great fundamental as well as potential technological interest. They represent some of the smallest auto-oscillators occurring in nature, while exhibiting rich nonlinear dynamics. From an applications point of view, oscillation frequency, bandwidth, and output power are the main features characterizing an STT oscillator. The paper reviews and presents recent progress with an eye on all of these performance parameters, and in particular on output power.

Beyond memory, spintronics offers possibilities for the realization of novel computing architectures beyond scaled CMOS technology. A discussion of one particular example of these possibilities is offered in the paper by Shabadi *et al.*, "Design of Spin Wave Functions Based Logic Circuits", which discusses the design of spin wave based logic circuits with potential orders of magnitude improvements in energy and density compared to conventional CMOS architectures.

With increasing interest in and approaching commercialization of STT-MRAM, the design of CMOS circuits combining STT elements with CMOS transistors is a highly relevant and timely topic. Two examples are presented in the next two articles. STT-based switching using CMOS architectures is the topic of "STT-RAM Cell Design Considering MTJ Asymmetric Switching" by Chen *et al.*, while reliable reading of information stored in STT-MRAM cells is the subject of "Voltage Driven Nondestructive Self-Reference Sensing for STT-RAM Yield Enhancement" by Li and Sun.

The last paper in this special issue, "Radio Frequency Magnetization Nonvolatility" by Wang, addresses and theoretically studies the important topic of the stability of magnetic memory bits, in particular under non-steady-state conditions where they are excited by high-frequency signals.

Overall, it is our hope that this selection of articles will serve as a valuable resource for researchers in academia and industry alike, both for reviewing the recent progress of spintronic device physics and technology in the areas covered by these papers, as well as to stimulate interest and to point to potential directions for future study. It is also our hope that, through the publication of this and future special issues focusing on research areas of high fundamental as well as practical relevance, SPIN will be a leading venue for the presentation of new ideas and results, and an important forum for the exchange of scholarly debates in spintronics and magnetism. In future special issues, we will be looking at additional frontier and emergent areas of the exciting field of spintronics.