Spintronics

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I. INTRODUCTION

This special issue covers recent developments in spintronics, where the spin degree of freedom of electrons is used to expand the capabilities of electronic devices. The papers that follow cover the progress over the last ten years. This progress has led to technologies ranging from some that are already commercially important, through promising ones currently in development, to very speculative possibilities. Today, the most commercially important class of devices consists of magnetic sensors, which play an important role in a wide variety of applications, a particularly prominent example of which is magnetic recording. Nonvolatile memories, in particular magnetic random access memories (MRAMs) based on magnetic tunnel junctions (MTJs), are commercial products and may develop into additional high impact applications either as standalone memories to replace other random access memories or embedded in complementary metal–oxide–semiconductor (CMOS) logic. A number of technologies have appealing capabilities that may improve sensors and magnetic memories or develop into other devices. These technologies include three-terminal devices based on different aspects of spin-transfer torques, spin-torque nano-oscillators, devices controlled by electric fields rather than currents, and devices based on magnetic skyrmions. Even further in the future are spintronics-based applications in energy harvesting, bioinspired computing, and quantum technologies.

This special issue highlights the developments in the area of spintronics by looking at technologies that are already commercially important or are currently in development, and those that offer possibilities for the future.

Spintronics utilizes the spin degree of freedom of electrons. The concept of using the spin degree of freedom to control electrical current dates back to the 1960s in an early study carried out in Leo Esaki's group at IBM showing that an antiferromagnetic barrier of EuSe sandwiched between metal electrodes exhibits a large magnetoresistance [1]. Subsequent advances of semiconductor thin film deposition techniques such as molecular beam epitaxy led to the development of semiconductor quantum structures, which prompted studies of magnetic multilayers [2]. Subsequent studies of magnetic multilayers resulted in the discovery of giant magnetoresistance (GMR) in 1988 [3]. This effect was used to make magnetic sensors, which boosted the areal density of hard disk drives and led to the 2007 Nobel Prize in Physics awarded to Albert Fert and Peter Grünberg [3]. The first Special Issue on Spintronics of the PROCEEDINGS OF THE IEEE was published in 2003 and covered developments prior to that year [4]. Since then rapid progress has continued to enhance both the role and the potential of spintronics. Applications now range from nanoscale spintronics sensors that further enhance the areal density of hard disk drives, through MRAMs that are seriously being considered to replace embedded flash, static random access memories (SRAM) and at a later stage dynamic random access memories (DRAM), to devices utilizing spin current and the resulting torque to make oscillators and to transmit information without current. The spin degree of freedom is also being used to convert heat to energy through the spin Seebeck effect, to manipulate quantum states in solids for information processing and communication, and to realize biologically inspired computing. These new developments in information storage, computing, communication, energy harvesting, and highly sensitive sensors have prompted this Special Issue on Spintronics.

II. OVERVIEW OF THE SPECIAL ISSUE

This issue contains 12 papers and covers the fields that have made remarkable progresses since the 2003 issue was published. When reading

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this special issue, it is useful to consider how well the field was able to envision the future in that earlier issue. In 2003, the field was in the middle of rapid development in the science of semiconductor-based spintronics with great optimism about potential for applications. The earlier special issue devoted several articles to that topic. While the scientific progress continued, the promise of applications has not yet been realized, although semiconductor-spintronic-based quantum computing is still being actively pursued. At the time, there was steady progress in metal-based spintronics and even then several applications, including sensors and MRAMs, were in development. This development continues to this day and is represented by several papers in the present collection. The metrology and physics at low temperatures covered in the previous issue continue to be of great importance for further advancing the field, but the emphasis of the field reflected in the present issue has shifted more to the applied aspects of spintronics.

The first paper, by Fullerton and Childress, describes modern digital data storage, particularly hard disk drives and the role played by two breeds of spintronics sensors that replaced conventional sensors utilizing anisotropic magnetoresistance (AMR); the first was based on GMR and the second on tunnel magnetoresistance (TMR). TMR is also currently being used as a building block of magnetoresistive random access memory covered by a subsequent paper in this issue. Spintronic sensors are part of the technology development that enabled the increase of storage density by several orders of magnitude reaching 10 TB per unit, laying the foundation of today's information age in the form of data centers installed by the cloud computing industry.

The second paper, by Apalkov *et al.*, deals with magnetoresistive random access memory (MRAM) and particularly spin-transfer-torque (STT-MRAM), a nonvolatile memory with very high endurance and scalability. The current STT-MRAM technology uses an array of MTJs with perpendicular easy axis of magnetization. These MTJs utilize interface perpendicular anisotropy at the CoFeB–MgO interface, along with the large TMR of the system, for reading the state of magnetization. Spin-transfer torque exerted by spin-polarized current is used to change the magnetization direction offering an efficient way of rewriting the memory. The CoFeB–MgO perpendicular-easy-axis MTJs present a high tunnel magnetoresistance ratio, high thermal stability, low-switching current, and high tolerance to annealing, all of which are critical for nonvolatile working memory applications of energy critical missions, such as in controllers for internet-of-things (IoT) applications, where reduction of standby power is of the highest priority. Thermally assisted MRAM is another MRAM technology in which the write step is assisted by the Joule heat produced by a pulse of current flowing through the MTJs. The paper also presents the technology's possible impacts on applications such as sensor networks/big data, smartphones, and high end computing.

The third paper, by S.-W. Lee and K.-J. Lee, describes emerging three-terminal spintronic memory devices. Three-terminal devices have an advantage over the standard two-terminal MTJs used in memory applications like MRAM in that separating the read and write functions potentially overcomes 1) the correlations between read, write, and breakdown voltages; 2) the correlation between the switching current and retention times; and 3) the rapid increase of critical switching currents for current pulses shorter than 10 ns. The paper describes two writing schemes: one is based on spin currents generated by an electrical current running through a heavy metal adjacent to the free layer of the MTJ. The current generates a spin current both in the bulk of the heavy metal and at the interface; this spin current then exerts a torque, called the spin-orbit torque, on the magnetization. In this scheme, the write current does not pass through the MTJ, separating the write and read functions. The other scheme uses current-induced domain-wall motion to move a domain wall in the free layer of the MTJ from one side of the fixed layer to the other. In this scheme, the current passes through the free layer, but not the tunnel barrier, again separating the read and write functions. On the other hand, three-terminal devices have a significant disadvantage compared to their two-terminal counterparts in that the area required for installing three-terminal devices is twice as large as for the corresponding two-terminal devices. The increase in area makes three-terminal devices unfavorable for high density applications. For applications in which the density is not the top priority, the separation of the read and write current paths in three-terminal MRAM devices is very attractive for high speed and reliable operation.

The fourth paper, by Hanyu *et al.*, discusses how spintronic-based nonvolatile memories can be used in conjunction with CMOS-based logic applications. Making embedded working memory nonvolatile is a crucial first step toward standby-power-free logic circuits that are much needed for IoT applications. Conventional two-terminal MTJs have a characteristic of requiring high current densities for switching times below 10 ns. This requirement can be masked by smart circuit design involving the separation of the CMOS and MTJ write processes, resulting in fast and nonvolatile memory operation with reduced power consumption. This approach combined with a nonvolatile flip-flop provides the basis for the design and demonstration of a spintronics-based microprocessor unit where fine-grained power gating is used to reduce the power consumption. Another application of embedded MRAM devices is an architecture called logic in memory where memories are embedded on the logic CMOS plane. This type of architecture, proposed in 1969 [5], minimizes the interconnection delay between memory and logic because of the much reduced physical length between the two. However, the overhead of having memory and logic in close proximity has been prohibitively high until now. MRAM-based logic in memory reduces this overhead allowing the design and demonstration of power-efficient field-programmable gate arrays (FPGAs), ternary content addressable memory (TCAM), as well as other variants. These circuits have the advantage of both the minimized interconnection delay and the nonvolatility of the memory.

The fifth paper, by Ghosh, deals with security issues in spintronic devices. These devices have shown great promise for logic and memory applications due to their energy efficiency, very high write endurance, and nonvolatility. Besides, these systems gather a number of entropy sources which can be advantageously used for hardware security. In particular, the spatial and temporal randomness in the magnetic system associated with complex micromagnetic configurations, nonlinearity of magnetization dynamics, cell-to-cell process variations, or thermally induced fluctuations of magnetization can be employed to realize novel hardware security primitives such as physical unclonable functions, encryption engines, and true random number generators. Due to their relative simplicity of integration, the spintronic circuits can complement the existing CMOS-based security and trust infrastructures. However, spintronics circuits have also their specific vulnerabilities. New forms of attacks could be launched using low-cost noninvasive techniques such as temperature rise or large magnetic field exposure with the intention to corrupt the data. Data privacy associated with the nonvolatility of the spintronics elements is also an addressed issue. Security vulnerabilities, security and privacy attack models, and possible countermeasures to enable safe computing environment using spintronics are thoroughly addressed and discussed in this review paper.

The sixth paper, by Freitas *et al.*, describes spintronic sensors starting from their fundamental physical principles: anisotropic magnetoresistance, giant magnetoresistance, and tunneling magnetoresistance. It then discusses typical device geometries, such planar-Hall structures and spin valves, sensitivities, intrinsic noise mechanisms, biasing, and interconnection schemes. These magnetoresistive integrated thin film devices can be fabricated with high yields, in 200-mm-diameter wafers, to detect fields ranging from a few tens of millitesla down to tens of picotesla, therefore spanning eight to nine orders of magnitude in field range. They are large bandwidth devices that can operate from direct current (dc) to the gigahertz range, with an adjustable impedance (from 1 Ω to 100 kΩ) and a magnetic sensitivity range (from 0.1 to 100 mT) that can be matched to specific application requirements. These devices can be used with a variety of systems including integration with CMOS and incorporation on flexible substrates. Magnetic flux guides provide field gain to access the picotesla range for frequencies below 100 Hz. The spatial resolution scales with the sensor dimensions (down to tens of nanometers), for applications requiring a small footprint, good field sensitivity, and good spatial resolution. In addition to the hard disk market (read heads are covered in the first paper in this series), the range of applications spans from industrial applications to biosensor and biomedical applications. The paper describes sensor layout and full system integration including signal conditioning electronics (discrete or ASIC) for some of these applications.

The seventh paper, by Chen *et al.*, deals with spin-torque nano-oscillators (STNOs) and spin-Hall-effect nano-oscillators (SHNOs), the two members of an emerging class of miniaturized and ultrabroadband microwave signal generators. Both types of devices are based on magnetic resonances in single or coupled magnetic thin films where magnetic torques, either spin-transfer torque due to spin-polarized current (STNOs) or spin Hall torque due to pure spin current (SHNOs), are used to both excite the resonances and subsequently tune them. These devices are auto-oscillators and so do not require any active feedback circuitry with positive gain for their operation. The auto-oscillatory state has strong nonlinearity causing phase–amplitude coupling, which governs a wide range of properties, including frequency tunability, phase noise, modulation, injection locking, and mutual synchronization. STNOs and SHNOs can, in principle, operate at any frequency supported by a magnetic mode, resulting in a potential frequency range of over six orders of magnitude, from below 100 MHz for magnetic vortex gyration modes to beyond 1 THz for exchange dominated modes. Since STNOs and SHNOs can also act as tunable detectors over this frequency range, there is significant potential for novel devices and applications. The primary hurdles to be overcome before such applications can become reality are the low output power and the large phase noise. Intense research is directed to achieve increasingly high output powers, primarily through the use of MTJs, and higher coherence, through the mutual synchronization of either individual oscillators, or concurrent modes in the same oscillator.

The eighth paper, by Uchida *et al.*, discusses one of the more recent developments in spintronics, spin caloritronics, and how it might be used to develop more efficient thermoelectrics. Much of the focus of research in spin caloritronics has been the longitudinal spin Seebeck effect, which refers to spin-current generation by temperature gradients across junctions between metallic layers and magnetic layers. The generated spin current in the metallic layer gets converted into a charge current by the inverse spin Hall effect, making a two-step conversion process from a thermal gradient perpendicular to the interface into a charge current in the plane of the interface. This process can be used for thermoelectric conversion. Device structures using the spin Seebeck effect differ significantly from those using conventional Seebeck effects due to the orthogonality of the thermal gradient and resulting charge current, giving different strategies for applications of the two effects. This paper reviews the physics background, typical experiments, mechanisms that determine the efficiency, and prospects for applications of spin Seebeck effects.

The ninth paper, by Wang *et al.*, deals with electric-field control of the spin-orbit interaction. Electric-field control of the carrier concentration in diluted magnetic semiconductors, as in ordinary semiconductor field-effect transistors, leads to manipulation of magnetization through properties like the transition temperature and anisotropy. This control of magnetic properties through electric fields rather than currents suggests paths toward low energy magnetization reversal, which is needed for low-power electronics and spintronics. One specific way to accomplish this low energy switching is through electric-field control of spin-orbit interactions that leads to modification of the magnetic anisotropy. By applying a voltage to a device, it is possible to change the anisotropy such that the magnetization rotates into a new direction. While such demonstrations of switching alone are not sufficient to make a viable device, voltage-controlled reversal is a promising pathway toward low-energy nonvolatile memory devices. The paper finally discusses new materials such as antiferromagnets and topological insulators for spintronics and their electric-field tunable properties.

The tenth paper, by Heremans *et al.*, goes over progress made in quantum technologies based on the quantum nature of spins in deep level defects found in diamond (nitrogen-vacancy center) and in silicon carbide (divacancy). The quantum nature of these spins manifests itself even at room temperature and can be used as extremely sensitive nanoscale temperature, and magnetic-field and electric-field sensors. The authors then discuss the development of quantum networks and quantum transducers that lead to quantum technology, by fully utilizing microwave, photonic, electrical, and mechanical control of these spins.

The eleventh paper, by Grollier *et al.*, discusses approaches to bioinspired computing based on spintronic devices. The hope for bioinspired computing is that it enables low-power, high-performance computing and the expectation is that spintronic devices could play an important role in this development. The paper describes some of the features of bioinspired computing and some of the properties of MTJs that may be useful in implementing some of these features. Low-power, high-performance bioinspired hardware relies on ultrahigh-density networks built out of complex processing units interlinked by tunable connections. The paper describes several ways in which spin-torque-driven MTJs, with their multiple, tunable functionalities and CMOS compatibility, are very well adapted for this purpose. A number of groups have recently proposed a variety of bioinspired architectures, including one or several types of spin-torque nanodevices. This paper discusses the different bioinspired concepts that can be implemented in spintronics (spiking neural networks, associative memories, and so on) and their application scope. It describes how they could be mapped in hardware by hybridizing spintronics on CMOS, and reviews the recent advances in this direction.

The last article, by Kang *et al.*, discusses the device prospects of one of the most recent topics to generate substantial excitement in spintronics—skyrmions. The concept of skyrmions derives from high energy physics. In magnetic systems, they are magnetic textures that can be viewed as topological objects. There are indications that they have properties that might make them useful objects in which to store and manipulate information. Many of the ideas are similar to ideas that were developed decades ago for bubble memory or, more recently, racetrack memory. There are several possible advantages for skyrmion devices as compared to other related devices. They are potentially higher density and lower energy, although the arguments for these remain to be experimentally verified. The authors describe ideas that have been developed for creating, transporting, and manipulating skyrmions. They then describe how the concepts can be combined to make logic devices.

III. THE FUTURE OF SPINTRONICS

How will these articles be viewed in another 13 years? Will the role of spintronics in technology increase or decrease? We are optimistic that it will continue to having increasing impact, but the future is uncertain. The importance of magnetic sensors is likely to remain important while the importance of the magnetic sensor in hard disk drives appears to depend on the economics of mass storage in the cloud. MRAM appears likely to play an increasing role both as standalone memory and embedded in CMOS. The degree of adoption still depends on a few technical and many economic considerations. The acceleration, over the past few months, of announcements and demonstrations related to STT-MRAM produced by major microelectronics companies seems to indicate that large volume production of STT-MRAM is getting quite close. If the adoption of this technology by microelectronics industry becomes a reality, the whole field will be strongly boosted. Spintronics can play in the future a very important role in areas such as IoT, ultralow-power electronics, high-performance computing (HPC). Besides, in 13 years, we are likely to see a much greater role played by alternative forms of computing. The role that spintronics plays in those technologies is likely to be strongly influenced by the success of MRAM. If MRAM is successful, we will have developed the ability to manufacture it making it easier to import into other technologies. Several of the papers in this special issues address recent technical developments that have significant virtues for applications. It is likely that some will play a role in technology 13 years from now but many will not. Research on many of these ideas will continue and will spawn related areas. Material research is key along this road. Innovative materials allowing efficient charge to spin and spin to charge current conversion, or good control of magnetic properties by voltage, or efficient injection/manipulation/detection of spins in semiconductors can play major roles. Along this idea, the use of oxide materials in spintronic devices can become quite important. Oxides share crystallinity with semiconductors in distinction to metallic magnetic devices. Will the greater control that comes with crystallinity give advantages to oxides in future devices? These are some of the many topics that are likely to be addressed in the next 13 years. ■

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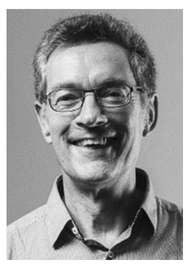

Bernard Dieny (Fellow, IEEE) has been conducting research in magnetism and spin electronics for 34 years. He played a key role in the pioneer work on giant magnetoresistance spin valves which were introduced in hard disk drives in 1998. In 2001, he co-founded “SPINTEC” (Spintronics and Technology of components) in Grenoble, France, a government laboratory devoted to spinelectronics. His team was awarded the European Descartes Price for Research for his work on thermally assisted magnetic random access memories (TA-MRAM) in 2006. This work yielded the creation of a startup company (Crocus Technology) in 2006. He received two Advanced Research grants from the European Research Council in 2009 and in 2014. In 2014, he became cofounder of another startup of design of hybrid CMOS/magnetic digital circuits (EVADERIS). He is currently chief scientist at SPINTEC.