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## **Advancements in spintronics**

*Applications now include 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).*

**By Hideo Ohno, Mark Stiles, and Bernard Dieny, IEEE**

Spintronics is the concept of using the spin degree of freedom to control electrical current to expand the capabilities of electronic devices. Over the last 10 years' considerable progress has been made. This progress has led to technologies ranging from some that are already commercially valuable, through promising ones currently in development, to very speculative possibilities.

Today, the most commercially important class of devices consists of magnetic sensors, which play a major role in a wide variety of applications, a particularly prominent example of which is magnetic recording. Nonvolatile memories called 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.

Some 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.

But before we get into detail about where Spintronics is today, we need to cover the history of Spintronics.

### **The history of spintronics**

Spintronics dates to the 1960s and was discovered by a group at IBM headed by Leo Esaki, a Japanese physicist who would later go on to win a share of the Nobel Prize in 1973 for discovering the phenomenon of electronic tunneling. Esaki and his team conducted a study which showed an antiferromagnetic barrier of EuSe sandwiched between metal electrodes exhibits a large magnetoresistance.

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. Ensuing studies of magnetic multilayers resulted in the

discovery of giant magnetoresistance (GMR) in 1988. This effect was used to make magnetic sensors, which boosted the areal density of information stored on hard disk drives and led to the 2007 Nobel Prize in Physics awarded to Albert Fert and Peter Grunberg.

Since then rapid progress has continued to enhance both the role and the potential of Spintronics. So, let's take a look at where we are now.

### **Where we are now**

Applications now include 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). Applications also include devices that utilize spin current and the resulting torque to make oscillators and to transmit information without current.

Now let's look at those applications and more in-depth.

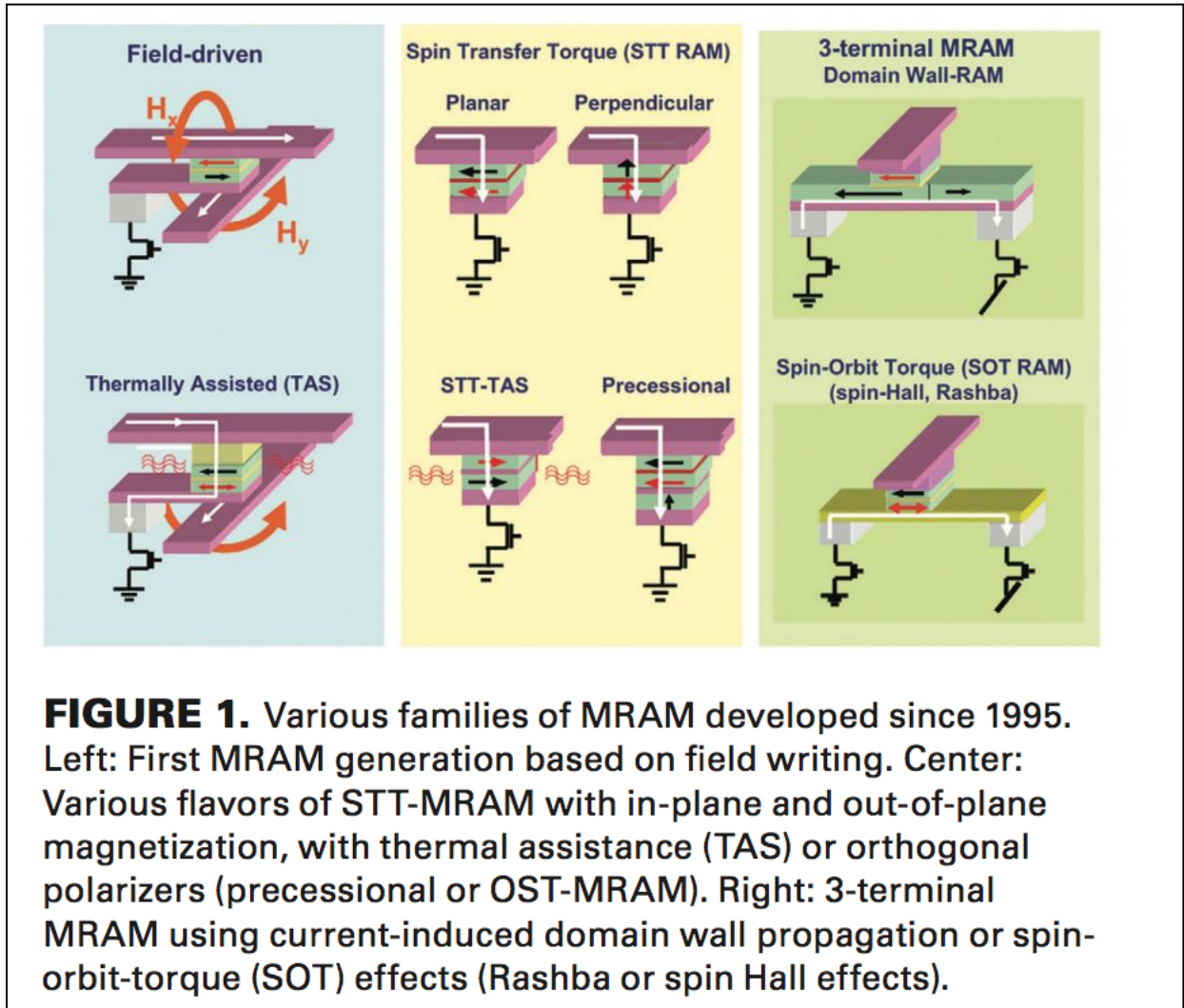
**Modern Hard Disk Drives:** Two breeds of Spintronics sensors have replaced traditional anisotropic magnetoresistance (AMR) sensors. Those sensors include giant magnetoresistance (GMR) sensors (used in hard disk drives between 1998 and 2004) and tunnel magnetoresistance (TMR) sensors (used since 2004).

Those sensors are part of the technology development that enabled the increase of storage density of hard disk drives by several orders of magnitude, laying the foundation of today's information age in the form of data centers installed by the cloud computing industry.

**Magnetoresistive Random Access Memory (MRAM):** MRAM and particularly spin-transfer-torque MRAM (STT-MRAM) is a nonvolatile memory with very high endurance and scalability. The current STT-MRAM technology uses an array of MTJs with an easy axis of magnetization oriented out of the plane of the layers. 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. The spin-transfer torque exerted by a spin polarized current is used to change the magnetization direction, offering an efficient way of rewriting the memory. **FIGURE 1** shows the main families of MRAM that have evolved since 1995.

**Three Terminal Magnetic Memory Devices:** Recent physics developments raise the prospect of three-terminal spintronic memory devices. These devices have an advantage over the standard two-terminal devices used in memory applications such as MRAM in that separating the read and write functions potentially overcomes several future roadblocks in the development of MRAM. There are 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 causes 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.



**Standby-Power-Free Integrated Circuits Using MTJ-Based VLSI Computing:** Spintronic-based nonvolatile embedded working memory used in conjunction with CMOS-based logic applications is a crucial first step toward standby-power-free logic circuits that are much needed for Internet of Things (IoT) applications. MRAM based logic-in-memory reduces the overhead of having memory and logic apart and gives both minimized interconnection delay and nonvolatility.

**Security:** 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 many entropy sources which can be advantageously used for hardware security. The spatial and

temporal randomness in the magnetic system associated with complex micromagnetic configurations, the 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.

**Spin-Torque and Spin-Hall Nano-Oscillators:** Spin-torque nano-oscillators (STNO) and spin-Hall effect nano-oscillators (SHNO) are in a class of miniaturized and ultra-broadband microwave signal generators that are based on magnetic resonances in single or coupled magnetic thin films. These oscillators are based on magnetic resonances in single or combined magnetic thin films where magnetic torques are used to both excite the resonances and subsequently tune them. The torques can be either spin-transfer torques due to spin-polarized currents (STNOs) or spin Hall torques due to pure spin currents (SHNOs). These devices are auto-oscillators and so do not require any active feedback circuitry with a positive gain for their operation. The auto-oscillatory state is strongly nonlinear, causing phase–amplitude coupling, which governs a wide range of properties, including frequency tunability, modulation, injection locking, mutual synchronization, but also causes significant phase noise. 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.

Beyond the applications listed, 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 may lead to new developments in information storage, computing, communication, energy harvesting, and highly sensitive sensors. Let's take a look at these new developments.

**Thermoelectric Generation Based on Spin Seebeck Effects:** The study of combined heat and spin flow, called spin caloritronics, may be used to develop more efficient thermoelectric conversion. 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.

**Electric-Field Control of Spin-Orbit Interaction for Low-Power Spintronics:** Control of magnetic properties through electric fields rather than currents raises the possibility of 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 electronic states leading 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.

**Control of Spin Defects in Wide-Bandgap Semiconductors for Quantum Technologies:** The spins in deep level defects found in diamond (nitrogen- vacancy center) and in silicon carbide (divacancy) have a quantum nature that manifests itself even at room temperature. These can be used as extremely sensitive nanoscale temperature, magnetic-field, and electric-field sensors. In the future, microwave, photonic, electrical, and mechanical control of these spins may lead to quantum networks and quantum transducers.

**Spintronic Nanodevices for Bioinspired Computing:** Bioinspired computing devices promises low-power, high-performance computing but will likely depend on devices beyond CMOS. Low-power, high performance bioinspired hardware relies on ultrahigh- density networks built out of complex processing units interlinked by tunable connections (synapses). There are several ways in which spin-torque-driven MTJs, with their multiple, tunable functionalities and CMOS compatibility, are very well adapted for this purpose. Some groups have recently proposed a variety of bioin- spired architectures that include one or several types of spin-torque nanodevices.

**Skyrmion-Electronics: An Overview and Outlook:** The concept of skyrmions derives from high energy physics. In magnetic systems, skyrmions are magnetic textures that can be viewed as topological objects. Theory suggests that they have properties that might make them useful objects in which to store and manip- ulate 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.

So, what does the future of spintronics have in store?

### **The future**

Spintronics will continue to have increasing impact, but the future is somewhat uncertain. The importance of magnetic sensors is likely to remain important while the importance of the magnetic sensors in hard disk drives appears to depend on the economics of mass storage in the cloud.

MRAM seems 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.

In the future, Spintronics can play a critical role in areas such as IoT, ultralow-power electronics, high-performance computing (HPC). Besides, in the next 10 to 15 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.

Some of the recent technical developments that have significant virtues for applications will likely play a role in technology 10 to 15 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 with 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 coming years.