

## SPECIAL ISSUE

### SPINTRONICS

Edited by H. Ohno, M. D. Stiles, and B. Dieny

- 1787 Spintronics, Magnetoresistive Heads, and the Emergence of the Digital World**  
By E. E. Fullerton and J. R. Childress

**INVITED PAPER** Two breeds of spintronics sensors based on giant magnetoresistance and tunnel magnetoresistance 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.

- 1796 Magnetoresistive Random Access Memory**

By D. Apalkov, B. Dieny, and J. M. Slaughter

**INVITED PAPER** Magnetoresistive random access memory (MRAM) and particularly spin-transfer-torque MRAM is a nonvolatile memory with very high endurance and scalability. It is based on an array of magnetic tunnel junctions with magnetoresistive readout of the state of device and uses spin-transfer torque to efficiently rewrite the memory.

- 1831 Emerging Three-Terminal Magnetic Memory Devices**

By S.-W. Lee and K.-J. Lee

**INVITED PAPER** 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.

- 1844 Standby-Power-Free Integrated Circuits Using MTJ-Based VLSI Computing**

By T. Hanyu, T. Endoh, D. Suzuki, H. Koike, Y. Ma, N. Onizawa, M. Natsui, S. Ikeda, and H. Ohno

**INVITED PAPER** Nonvolatile embedded working memory used in conjunction with complementary metal-oxide-semiconductor (CMOS)-based logic applications is a crucial first step toward standby-power-free logic circuits. MRAM-based logic-in-memory reduces the overhead of having memory and logic in close proximity and gives both minimized interconnection delay and nonvolatility.

- 1864 Spintronics and Security: Prospects, Vulnerabilities, Attack Models, and Preventions**

By S. Ghosh

**CONTRIBUTED PAPER** Spintronic devices gather a number of entropy sources which can be advantageously used for hardware security. The spatial and temporal randomness in the magnetic systems can complement the existing CMOS-based security and trust infrastructures to realize novel hardware security primitives such as physical unclonable functions, encryption engines, and true random number generators.

- 1894 Spintronic Sensors**

By P. P. Freitas, R. Ferreira, and S. Cardoso

**INVITED PAPER** Spintronic sensors start from a variety of fundamental physical principles: anisotropic magnetoresistance, giant magnetoresistance, and tunneling magnetoresistance, and have a wide variety of device geometries, sensitivities, intrinsic noise mechanisms, biasing, and interconnection schemes, depending on the specific application. Applications span from industrial applications to biosensor and biomedical applications.

[Continued on page 1778 ►]

## DEPARTMENTS

- 1779 POINT OF VIEW**

Ethics and Autonomous Systems: Perils and Promises  
By R. C. Arkin

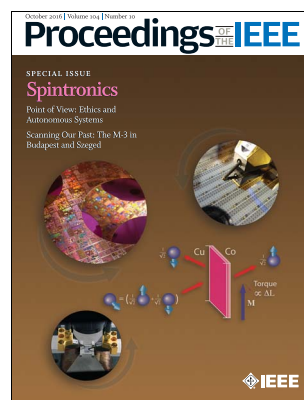
- 1782 SCANNING THE ISSUE**

Spintronics  
By H. Ohno, M. D. Stiles, and B. Dieny

- 2062 SCANNING OUR PAST**

The M-3 in Budapest and Szeged  
By M. Szabó

- 2070 FUTURE SPECIAL ISSUES/SPECIAL SECTIONS**



**On the Cover:** This month's cover integrates an image of the theoretical and conceptual aspects along with images of wafers, electronic characterization, and electromagnets to illustrate the wide range of topics associated with spintronics.

## SPECIAL ISSUE: Spintronics

### 1919 Spin-Torque and Spin-Hall Nano-Oscillators

By T. Chen, R. K. Dumas, A. Eklund, P. K. Muduli, A. Houshang, A. A. Awad, P. Dürrenfeld, B. G. Malm, A. Rusu, and J. Åkerman

**[INVITED PAPER]** Spin-torque nano-oscillators and spin-Hall effect nano-oscillators are in a class of miniaturized and ultrabroadband microwave signal generators, based on magnetic resonances in single or coupled magnetic thin films. These devices are auto-oscillators and so do not require any active feedback circuitry with positive gain for their operation and are highly nonlinear leading to frequency tunability, phase noise, modulation, injection locking, and mutual synchronization.

### 1946 Thermoelectric Generation Based on Spin Seebeck Effects

By K. Uchida, H. Adachi, T. Kikkawa, A. Kirihaara, M. Ishida, S. Yorozu, S. Maekawa, and E. Saitoh

**[INVITED PAPER]** The study of combined heat and spin flow, called spin caloritronics, may be used to develop more efficient thermoelectric conversion. Device structures using the most widely considered effect, the longitudinal spin Seebeck effect, differ significantly from conventional devices due to the orthogonality of the thermal gradient and resulting charge current, giving different strategies for applications.

### 1974 Electric-Field Control of Spin-Orbit Interaction for Low-Power Spintronics

By K. L. Wang, X. Kou, P. Upadhyaya, Y. Fan, Q. Shao, G. Yu, and P. K. Amiri

**[INVITED PAPER]** Control of magnetic properties through electric fields rather than currents raises the possibility of low energy magnetization reversal, providing a path toward low-power electronics and spintronics. Such control can be accomplished by modifying the spin-orbit interactions through applied voltages, in turn changing the anisotropy such that the magnetization rotates into a new direction.

### 2009 Control of Spin Defects in Wide-Bandgap Semiconductors for Quantum Technologies

By F. J. Heremans, C. G. Yale, and D. D. Awschalom

**[INVITED PAPER]** Deep level defects found in diamond (nitrogen-vacancy center) and in silicon carbide (divacancy) have a quantum nature for the spins 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.

### 2024 Spintronic Nanodevices for Bioinspired Computing

By J. Grollier, D. Querlioz, and M. D. Stiles

**[INVITED PAPER]** Bioinspired computing promises low-power, high-performance computing but will likely depend on devices beyond CMOS. Spin-torque-driven magnetic tunnel junctions, with their multiple, tunable functionalities and CMOS compatibility, are very well adapted for various roles in a variety of bioinspired architectures.

### 2040 Skyrmion-Electronics: An Overview and Outlook

By W. Kang, Y. Huang, X. Zhang, Y. Zhou, and W. Zhao

**[CONTRIBUTED PAPER]** Skyrmions 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 encode information. Ideas have been developed for creating, transporting, and manipulating skyrmions and suggest several possible advantages for skyrmion devices as compared to other related devices, such as bubble memory or racetrack memory.

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