Electron Spin for Modern and Future Microelectronics

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Continuous miniaturization of semiconductor devices' feature size remains the key driving force ensuring outstanding increase of performance of modern integrated circuits. While chips based on 5nm technology are already nearing production [1], the semiconductor industry is now focusing on a 3nm technology node. Although setting limits for scaling has proven to be a mere meaningless task in the past, it is obvious that the conventional transistor scaling is showing signs of saturation. To sustain the growing demand for high performance small area CPUs and high-capacity memory needed to handle an increasing information flow, an introduction of a disruptive technology employing new computing principles is anticipated. Most importantly, any emerging technology must be energy efficient, as a harmful active power penalty already prevents the clock frequency from being increased in CMOS circuits, while rapidly increasing leakages result in alarmingly growing stand-by power.

In contrast to charge, the electron spin has received less attention in microelectronics. The most significant employment of the spin degree in known devices is the magnetization direction of ferromagnetic media used to store the information in magnetic hard drives. The useful property of the magnetization to preserve its direction without energy source results in a non-volatile data storage. Introducing non-volatility is a promising way to reduce the stand-by power. Emerging spin-transfer torque (STT) magnetoresistive random access memory (MRAM) [2] is an electrically addressable non-volatile memory combining high speed, high endurance and long retention, and is suitable for replacing flash. The broad versatility of STT-MRAM with respect to the operation speed makes it a suitable candidate for embedded DRAM and low-level caches. In fact, all major foundries have announced the start of STT-MRAM production in 2018.

To further reduce the energy consumption, it is essential to replace high-level caches in modern hierarchical multi-level processor memory structures with a non-volatile memory. The development of an electrically addressable non-volatile memory combining sub-ns operation, high endurance, and long retention is thus essential for replacing SRAM. Among the newly discovered physical phenomena suitable for future MRAM generations is spin-orbit torque (SOT) assisted switching [3]. In these memory cells the free magnetic layer is grown on a material with a large spin Hall angle. By passing the current through the material, the SOT acting on the free layer is generated. As the switching current is injected in-plane along the heavy metal line, it results in a three-terminal configuration with the read and write paths separated.

SOT-MRAM is thus suitable for applications in caches. Recently, IMEC presented a technology to integrate SOT-MRAM on a 300mm CMOS wafer using CMOS compatible processes [4]. However, although the high switching current is not flowing through the tunnel barrier, the current and the current density are still high, and their reduction is the pressing issue in the field of SOT-MRAM development. In addition, inventing a switching scheme [5], which allows for deterministic switching of a perpendicularly magnetized structure without an external magnetic field, is urgently needed.

Regarding active power reduction, the availability of high-capacity non-volatile memory close to high-performance CMOS circuits allows exploring conceptually new logic-in-memory architectures. Employing the same non-volatile elements to store and to process the information paves the way for new low power and high-performance computing-in-memory paradigms [6]. Spin-based qubits also serve as building blocks for quantum logic gates to realize quantum algorithms [7] conceptually different from those based on the Boolean logic. Although it is not clear at the moment, which way microelectronics will develop, many challenges are lying ahead on the exciting journey to develop the computer architecture of the future.

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