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Nanoelectronics—Beyond CMOS Computing

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THE SIX ARTICLES IN THIS SPECIAL issue of *IEEE Nanotechnology Magazine* provide a broad perspective on future computing paradigms based on nanoelectronic technology. Nanoelectronics, as the word implies, is literally electronics at the nanoscale, i.e., with characteristic feature sizes less than 50 nm. By most measures, the semiconductor microelectronics industry today is the largest and most successful example of nanoelectronics and nanotechnology in general, where current transistor technology is below 3-nm gate lengths for the most advanced technologies, and the volume of semiconductor industry revenue exceeds US$450 billion. Semiconductor sales, in turn, power portable electronics, personal computers, mainframes, and multiple other industries.

One of the main drivers of the information revolution fueled by nanoelectronics has been Moore's law, an empirical relation representing the doubling of the number of CMOS transistors per integrated circuit every two years. Moore's law is responsible for the exponential increase in the computational capabilities of information technology, together with architectural advancements in the design of information systems. The limits of Moore's law are clearly being reached, in terms of issues such as limits to the physical gate length and power dissipation as density increases, although predictions of the end of Moore's law have been surpassed on many occasions through continued manufacturing innovation. Nonetheless, there is currently a great deal of focus on "beyond CMOS" technologies, which will allow for a continuation of Moore's law in terms of computational speed and complexity. These include new approaches to information processing based on using spin rather than charge in terms of nanomagnetic and spintronic devices and architectures, biologically inspired or "neuromorphic" systems for massively parallel processing, and ultimately, quantum information processing, that is, encoding processing information into the wave function of individual atoms. In this issue we explore beyond CMOS, focusing on these nanoelectronic realizations, their modeling, and simulation.

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In the first article, Nikandish et al. start our journey with innovative CMOS technologies for implementing large-array quantum computing circuits. CMOS technology is very promising as it can enable implementing, on a single chip, large arrays of qubits together with their readout and control circuits. The article presents the current developments and future perspectives on CMOS quantum computing. Semiconductor qubit structures and candidates for CMOS implementations are presented, focusing on the interface between qubits and classical electronics where the control and readout of their states is of critical importance. A comparison between charge and spin qubits for large-scale integration shows spin qubits—as standalone elements—provide superior performance, while charge qubits integrate more efficiently with control and readout circuitry. Possible hybrid systems are suggested.

Next, Krylov et al. focus on very important issues of design methods for modern superconductive electronics based on Josephson junctions, such as rapid single-flux quantum, adiabatic quantum-flux parametron, and reciprocal quantum logic. These systems promise at least two orders of magnitude improvement in energy efficiency as compared to conventional semiconductor-based supercomputers. The article reviews modern electronic design automation methodologies, techniques, and algorithms for these superconductive digital systems. The differences in design flows as compared to CMOS are highlighted in three areas: simulation/modeling, synthesis/place and route, and verification.

The third article, by Yu et al., addresses annealing-based high-performance computing as a promising advance that enables hard combinatorial problems to be solved. The methods are inspired by simulated annealing, originally developed for metallurgy. The authors discuss the evolution to quantum-based annealers and how they can be used with Ising machines to address computationally hard problems. They outline the software and hardware requirements for annealing-based methods and provide a partial list of Ising machine developers. Topical examples of optimization connected to the COVID-19 pandemic are presented, including hospital staff scheduling, medical resource allocation, and food delivery; and improvements to the technology considered. Finally, the authors present the research landscape for this technology in Taiwan and look to its promise as an important component for high-performance computing.

In the fourth article, Bindal et al. provide an accessible overview of magnetic skyrmions and possible applications. The authors review the opportunities and challenges of magnetic skyrmions as a natively nanoscale technology for high-density memory, transistors, circuits, and neuromorphic computing applications. They give a comprehensive introduction to the background and fundamental physics of magnetic skyrmions, which are topological spin structures that can be considered as localized quasi-particles. They describe features that are of importance for applications and discuss the bulk and multilayered materials needed to host these quasi-particles. They summarize their discussion with a helpful table showing material, transition temperature, and skyrmion type. Many novel applications are considered, suggesting the potential wide applicability of magnetic skyrmions for nanoscale circuits, logic gates, memory devices, spin-transfer devices, and qubits. The article also addresses some of the challenges, such as controlling skyrmion motion, and suggests possible solutions.

The fifth article, by William Vandenberghe, presents a first-principles theoretical framework for the modeling and simulation of new emerging materials relevant to beyond CMOS nanoelectronic technologies. In particular, 2D materials such as transition-metal dichalcogenide materials are of current interest for highly scaled transistor technologies due to their ultrathin structures. A comprehensive automated approach starting from ab initio density functional theory methods through the calculation of the relevant dielectric, magnetic, and electronic transport properties is described to provide a road map for prospective materials driving Moore's law in the future.

The final article complements and expands the focus of this special issue by providing a review of analog electronic systems whose operation is based on biological cell function—cytomorphic electronic systems. Beahm et al. review the mapping of biological systems to subthreshold transistor circuits and discuss their applications and scalability. They show that simulations using cytomorphic chips can be considerably faster than those achieved using digital computation, arguing that more than a million-fold increase in speed is feasible. The authors consider cytomorphic supercomputers for drug discovery and summarize the workflows needed to produce cytomorphic-based simulations. As a specific example, the authors discuss how these systems might help in the search for drug combinations to address the early-stage COVID-19 infections. N