Superconducting Electronics and Spintronics for Energy-Efficient Computing

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According to the International Energy Agency (IEA), electricity consumption from data centers, artificial intelligence and the cryptocurrency sector could double by 2026 and exceed 1,000 TWh [1]. Reducing the power dissipation at the highest processing speed is the central objective for any information processing circuit technology.

Superconducting Single Flux Quantum (SFQ) digital electronics based on Josephson junction circuits with its unparallel clock speed at tens to even hundreds of GHz at very low-power dissipation [2,3] has been long considered as the most promising technology for variety of high-end applications including high-performance computing and quantum computing. However, the low integration density and the lack of high capacity, high operational margin superconducting memory technology compatible with digital superconducting circuits has been a major limiting factor in utilizing superconducting electronics for many decades.

Superconductor/ferromagnet heterostructures including Josephson junctions with ferromagnetic materials are capable of addressing these challenges and even potentially enable new applications in neuromorphic, reservoir, and quantum computing. In superconductor-ferromagnet Josephson junctions, the spin-singlet Cooper pairs perform phase oscillations as they go through a ferromagnetic material in the presence of the exchange field. As a result, the phase difference across such Josephson junctions oscillates between 0 and π as with the thickness of the ferromagnetic material [4]. This phenomenon is used to build the static phase shifters and switchable junctions in superconducting digital circuits to increase their operational tolerances, reduce total bias current, and enable new functionalities.

In particular, half-flux-quantum (HFQ) circuits are based on 0–π superconducting quantum interference devices (SQUIDs). Comparing the HFQ toggle flip-flop (TFF) with its rapid single-flux quantum (RSFQ) counterpart under the same fabrication process, it is anticipated that the HFQ TFF can achieve ~70% reduction in both static and dynamic power dissipation [5].

Another area where superconductor/ferromagnet heterostructures can make an impact is the development of non-reciprocal devices – superconducting diodes. This can be used in dc-biased SFQ circuits to avoid the rise of total bias current with the number of cells limiting the circuit scalability. This is also important for SFQ circuits used for qubit control and readout while minimizing thermal load and electromagnetic noise [6]. The recently developed superconducting diodes demonstrated high efficiency and tunability [7]. This enabled the construction of the first superconducting rectifiers with superconducting diodes made of thin-film bilayers of V/EuS. The rectifier operated with frequencies up to 40 kHz and efficiencies up to 43%. The efficiency of the individual diodes reaches up to ±50% by combining the effect of edge asymmetry in the superconducting vanadium (V) and stray fields from a ferromagnetic insulator (EuS) in the V/EuS bilayers [7].

The most significant impact is expected in using superconductor/ferromagnet elements for memory applications. If a junction contains multiple ferromagnetic layers whose relative magnetization directions can be controlled by application of a relatively small magnetic field (e.g., using current lines) or by spin torque, then this device can serve as a memory element. There are several challenges in ferromagnetic material choices to ensure a success [4]. Multiple memory cell designs were proposed and implemented. The key is to design a memory element which can be integrated to form a high density, highly energy efficient, fully addressable memory array compatible with SFQ digital technology.

A hybrid vertically integrated superconducting-ferromagnetic device can also serve as an addressable memory cell, in which the ferromagnetic junction stores the information, while superconducting Josephson junction acts as a readout device [8]. Electric current applied along the superconducting electrode can change the magnetization of the ferromagnetic layer in such a way that, for one current direction, a magnetic flux penetrates the junction perpendicular to the layers, whereas for the opposite direction, the perpendicular magnetic flux can be removed. In the former state, the modulation pattern of the Josephson critical current in the magnetic field may acquire minimum near zero field and restores its usual shape with maximum in the second state. This possibility of electric control, and a large discrimination between the Josephson critical current levels for the two states which will be preserved upon reduction of the device dimensions, is important for integration of memory arrays with high parameter margins.

For quantum computing, π junctions have been proposed as circuit elements qubit designs. The characteristic hysteretic behavior of the ferromagnetic barrier provides an alternative and intrinsically digital tuning of the qubit frequency by means of magnetic field pulses [9]. The functionalities and limitations of this device were tested by coupling to a readout resonator. The possibility to use the qubit as a noise detector and its relevance to investigate the subtle interplay of magnetism and superconductivity is envisaged. To make a real impact in superconducting qubit technology, ferromagnetic Josephson junction have to be transferred to aluminum technology – the dominant material for fabrication of Josephson junctions for all superconducting qubits. The recent results demonstrated that the ferromagnetic layer does not affect the quality of the junction in qubits.

In summary, we believe that cryogenic spintronic elements integrated with superconducting electronics can play an important enabling role in many new functionalities, performance capabilities, and practical working characteristics not attained with other technologies.

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