State of Flux Quantum and Superconductor Processors for Energy-Efficient Computing

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Energy efficiency has firmly become a key metric in high-performance computing, reflecting the huge impact of power consumption on modern computer system design. Superconductor technology with its extremely low energy consumption at frequencies of 50–100 GHz is one of the candidates for use in future energy-efficient systems for critical mission applications.

Recent developments in the field of superconductor computer design have created a solid foundation on which the design of complex systems can be based. First, two new superconductor zero-static-energy logics, called reciprocal quantum logic (RQL) and energy-efficient rapid single-flux quantum (ERSFQ), have been developed, and several relatively complex RQL and ERSFQ circuits have been designed and demonstrated. In other US projects, the Stony Brook University (SBU) team has developed viable design techniques, including asynchronous wave pipelining, and set of design tools and cell libraries for VLSI-scale superconductor design. In 2011 and 2012, several RSFQ chips with the complexity of up to 10K Josephson junctions (JJs) have been designed using those techniques, fabricated by the US and Japanese foundries, and successfully demonstrated operation at 20 GHz. Finally, new memory design concepts called JJ-MRAM have been proposed and are under development.

In contrast to the past obsession with demonstrating ultra-high-clock frequencies for RSFQ circuits with relatively small complexity, the current work in the field has shifted its focus on practical VLSI-level superconductor computer design for extremely-low-power computing.

A recent design study at SBU has analyzed the energy efficiency of the RQL and ERSFQ superconductor logics for general-purpose computing, showing the energy consumption of less than 1 femtojoule per 32-bit operation in processor units operating at 9–10 GHz frequencies at 4.2 K.

However, in order to make the fair and meaningful comparison of superconductor and CMOS technologies, it is imperative to analyze advantages and disadvantages of SFQ technology in the context of a complete computer design that includes processing, control, and storage components. The ultimate goal of new superconductor computer design project (called Small Fish) started at SBU is to answer the question whether the superconductor technology in its latest form is capable of demonstrating significant advantages in terms of energy efficiency over future CMOS-based computer designs.