

Superconducting Digital Electronics: Current Advances and the Beginning of a New Era

Nobuyuki Yoshikawa

Yokohama National University, Yokohama, Japan

E-mail: Yoshikawa-nobuyuki-gt@ynu.ac.jp

Abstract—Advances in the information society have relied on the miniaturization of CMOS ICs. However, in scientific computing and AI, exploding compute demand makes energy use a critical bottleneck. With CMOS scaling nearing its limits, breakthrough technologies are urgently needed to deliver far greater energy efficiency. Superconducting digital electronics (SDE) offers the potential for ultra-efficient computation as AI data-center demand accelerates. This talk surveys two leading paradigms: rapid single-flux-quantum (RSFQ) for ultrafast switching, and adiabatic quantum-flux-parametron (AQFP) for a near-Landauer switching energies. Process and design advances now enable ICs with tens of thousands Josephson junctions, supported by superconducting EDA flows. Representative demonstrations include a bit-serial 8-bit RSFQ microprocessor operating at 60 GHz and an AQFP 4-bit RISC achieving ~15 aJ/op.

For quantum control, MCM-integrated SFQ drivers deliver ~99.5% average single-qubit fidelities with nW-level dissipation, while AQFP multiplexers target ~81.8 pW per-qubit control. In neuromorphic directions, Josephson-based neurons and synapses promise 10–100 GHz spiking at attojoule energies, with magnetic-JJ elements emerging for nonvolatility. We also outline superconducting-optoelectronic schemes that integrate analog, digital, and photonic links for scalable communication.

Reversible AQFP approaches the $kBT \ln 2$ energy-consumption limit when erasure dominates, suggesting thermodynamically efficient logic. Remaining challenges include device scaling for density, robust high-density memories, and standardized PDK and EDA infrastructure.

Keywords (Index Terms)—Digital, Adiabatic Quantum-flux-parametron, Josephson devices, Quantum computing, Neuromorphic computing