4CF17-2017-000022

Abstract for an Invited Paper
for the 4CF17 Meeting of
the American Physical Society

High-Speed Low-Energy Superconducting/Magnetic Josephson Junction Neurons and Neural Nets

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Superconducting single flux quantum (SFQ) circuits form a natural neuromorphic technology with SFQ pulses and superconducting transmission lines simulating action potentials and axons, respectively. Here we present a new component, magnetic Josephson junctions, that have a tunablility and re-configurability that was lacking from previous SFQ neuromorphic circuits. Neuromorphic magnetic Josephson junctions differ from devices designed for digital memory applications, such as spin-valve Josephson junctions, in that they use magnetic nanoclusters as the tunable magnetic element. The nanoscale magnetic structure acts as a tunable synaptic constituent that modifies the junction critical current. High quality Josephson junctions and junction arrays have been fabricated using Mn-doped Si barriers. The magnetic structure can be tuned by rapid thermal annealing and shows superparamagnetic behavior in the zero-field-cooled field-cooled magnetization measurements. The junction critical currents can be modified by 200 ps current pulses and with training energies down to 3 aJ. These circuits can operate near the thermal limit where stochastic firing of the neurons is an essential component of the technology. Magnetic Josephson junction device models have been developed in Verilog A and used to model simple neural structures using SPICE with thermal noise terms. A simple multilayer perceptron neural net has been designed and modelled to demonstrate image processing at GHz rates. This technology can be extended to create complex neural systems with greater than 10^{18} neural firings per second with less than 1 W dissipation. For reference, the human brain has 10^{17} neural firings per second and dissipates 100 W.