Stochastic Spintronic Devices and Oscillator Networks for Energy-Based Analog Computing

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Inspired by statistical physics, Ising machines promise to efficiently address complex optimization problems by leveraging topologies that enable local information processing. At the algorithmic level, they emulate Boltzmann probability laws to explore the state space and tend toward optimal configurations. Guided by thermodynamic principles, they minimize collective energy while preserving the entropy-driven ability to move to neighboring states at a given temperature. Among various approaches to implementing Ising machines, analog/mixed-signal accelerators built from networks of nanodevices or small circuits most closely resemble the microscopic model of directly interacting spins, operating with minimal update instructions or temporary storage of global cost functions and gradients.

The energy barrier separating the two resistive states of Magnetic Tunnel Junctions (MTJ) can be lowered by stack engineering, in order to obtain memory-less telegraphic signal generators. We extracted dwell times below 10 ns in STT-MTJs with perpendicular magnetic anisotropy [1]. We recently proposed a hybrid Ising machine combining an RRAM array storing multi-level couplings, and stochastic MTJs (SMTJ) acting as thermally-driven artificial spins [2]. Because the same read voltage that interrogates the crossbar also biases the SMTJ, increasing this voltage automatically lowers the effective temperature of the machine, providing an intrinsic, nearly circuit-free annealing technique. Operating at zero magnetic field, our prototype consistently reaches the global optimum of a 24-node weighted MAX-CUT problem (Fig. 1).

An alternative approach, known as Oscillator-based Ising Machines (OIM), leverages the collective phase dynamics of connected oscillators to rapidly converge towards Ising Hamiltonian minima [3]. This process requires binarizing the phases across the network, typically achieved via sub-harmonic injection locking at 2f. We developed a CMOS Ring Oscillator prototype chip (Fig. 2) solving various instances of optimization problems, including weighted MAX-CUT [4] and Boolean satisfiability [5]. Spin-Torque Oscillators (STOs) are nanoscale spintronic devices with rich nonlinear dynamics spanning MHz–GHz frequencies, and are thus considered as promising OIM building blocks. We investigated correlations between STOs under injection-locking conditions and variable passive coupling [6].

References

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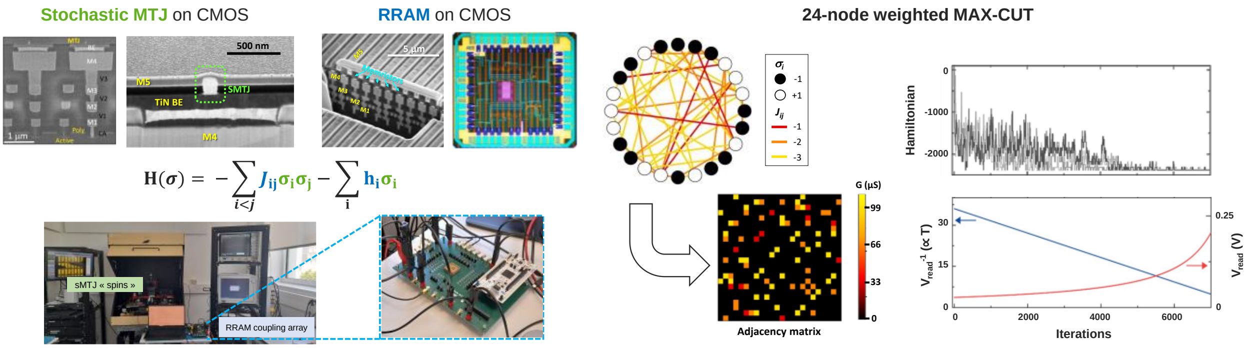

Fig. 1: (Left) Hybrid SMTJ-RRAM Ising-machine experiment. A hafnium-oxide RRAM crossbar computes the weighted sum of neighbouring spins (local field) as a multiply-accumulate current, while a stochastic magnetic tunnel junction (SMTJ) converts this current into a probabilistic spin update. (Right) Experimental resolution of a 24-node weighted MAX-CUT combinatorial optimization task. The weights encoding the problem are expressed as the conductance levels in the RRAM array. Intrinsic annealing is performed by increasing the RRAM array read voltage with number of iterations. The global optimum was reached consistently across multiple runs for this annealing schedule.

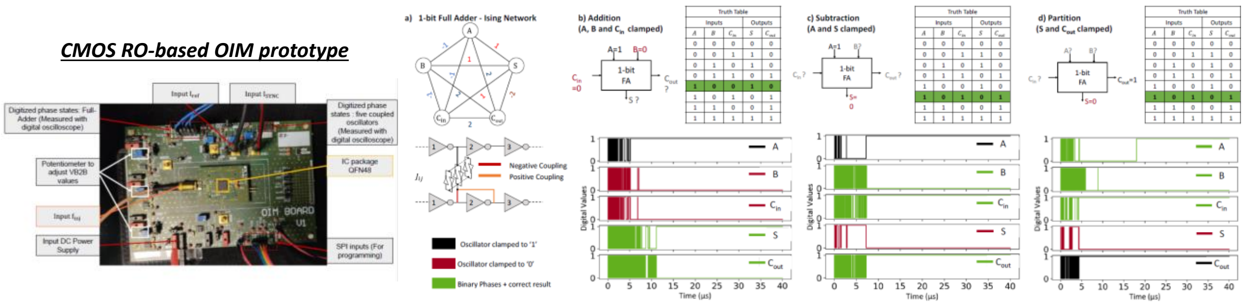

Fig. 2: Test board and chip fabricated in 22 nm FDSOI technology for Ising networks of CMOS Ring Oscillators (a) Ising representation of a 1-bit full adder with coupling adjusted by parallelizing back-to-back inverters. Experimental results for (b) addition, (c) subtraction, and (d) partitioning.