

Magnetic memory accelerates combinatorial optimization

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An integrated array of magnetic tunnel junctions can be used to solve model-optimization problems based on the Ising model quickly and with low energy consumption.

Laying out computer chips, scheduling flights and delivering packages are optimization problems for which substantial financial benefits could be achieved by solving them as efficiently as possible. But such optimization calculations are notoriously difficult to solve because the number of options increases exponentially with system size¹. An important class of these optimization problems – known as non-deterministic polynomial-time (NP)-hard – cannot be solved exactly in polynomial time. This is especially concerning in modern chip design as there are millions to billions of objects to be optimized. Although deterministic and heuristic algorithms for partitioning circuit components to

minimize partition cost have been adopted in electronic design automation, they can easily get trapped in suboptimal solutions. Writing in *Nature Electronics*, Weisheng Zhao and colleagues now report a platform based on an integrated array of magnetic tunnel junctions that can be used to solve model-optimization problems, such as those in chip layout, quickly and with low energy consumption².

It is possible to create models, called Ising models, based on binary components such as spins that can be up and down (or +1 and –1) such that the minimum-energy configuration of a connected network of spins corresponds to the optimum solution³. A problem is then encoded in the coupling between the spins. For each spin configuration, the coupling determines the energy, which is minimized to find the solution. The advantage of formulating the problem this way is that tools developed to understand physical systems, such as spin glasses, can be used to efficiently find solutions. In general, these problems are difficult to solve because there are energy barriers between local minima. Finding the true minimum requires temporarily evolving the spin configuration through higher-energy states. Simulating the

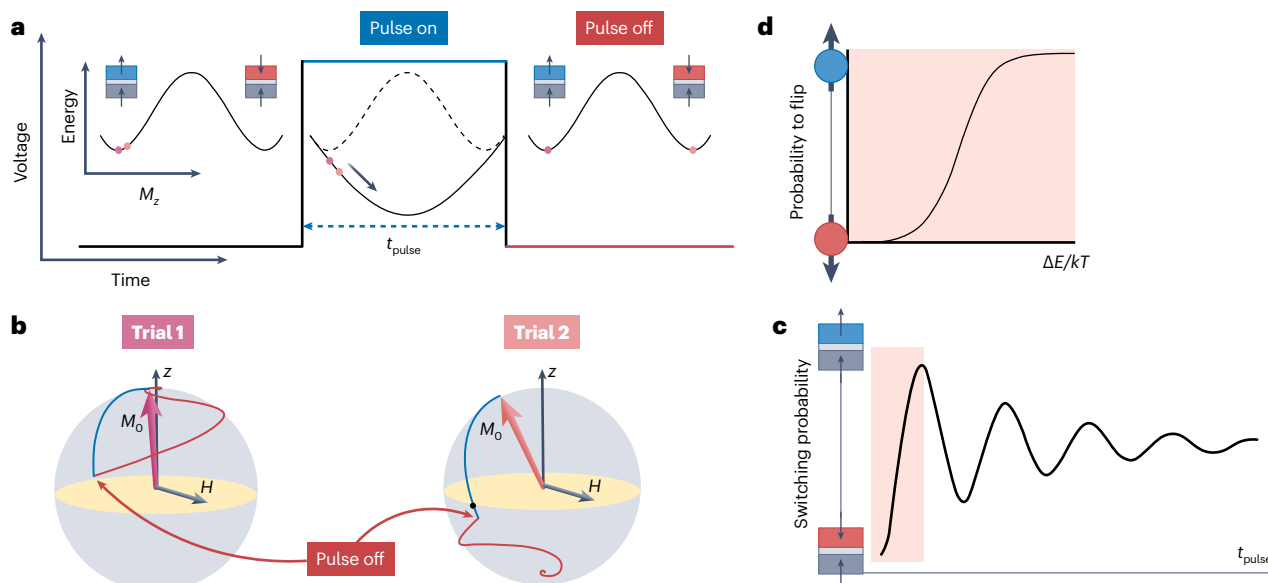


Fig. 1 | Switching magnetic tunnel junctions with voltage-controlled magnetic anisotropy. **a**, As a voltage pulse of duration t_{pulse} is applied to the magnetic tunnel junctions, the potential energy as a function of the z component of the magnetization M_z changes. When the voltage is off, there are two energy minima separated by a barrier (left inset). When the pulse is on, the uniaxial anisotropy of the magnetization reduces, causing the magnetization to precess around a bias field (H) (middle inset). After the pulse is switched off, the junction will be in one of the two energy minima states (right inset). Owing to thermal fluctuations before the pulse, the magnetization starts at different points in each trial (dark pink and light pink points in the left inset). **b**, Magnetization trajectories during

the applied pulse (blue) and afterwards (red), starting from different initial magnetization states M_0 . The two sample trajectories have different endpoints, and the magnetization switches directions or not, depending on the starting point. **c**, Probability of switching as a function of pulse width. The pink shaded region indicates the range of pulse widths used by Zhao and colleagues². The probability as a function of pulse width is very similar to the desired probability as a function of model energy difference ΔE divided by the thermal energy kT where k is the Boltzmann constant and T is the temperature. **d**, Encoding this energy difference in the pulse width yields a highly efficient means of determining whether to switch the tunnel junction.

dynamics at finite temperature, in which thermal noise causes stochastic transitions that can be uphill, can accomplish the required evolution.

But it is not only simulation tools that can be used to solve these models: it is also possible to design systems, called Ising machines, with physical implementations of these spins, which naturally evolve towards the ground state. These systems are currently being developed using a variety of platforms, including electronic⁴, optical⁵ and magnetic systems. The main requirement of such platforms is that its elements are capable of switching their state stochastically.

Magnetic tunnel junctions are a natural representation of Ising spins⁶. They exist in two magnetic configurations, each having a different resistance, and can be switched by magnetic fields, electric currents and voltages. Importantly for stochastic switching, thermal processes can have an important role in the switching dynamics. There have been various implementations of tunnel junctions as Ising spins. In some, the tunnel junctions are superparamagnetic, meaning that the spins flip back and forth due to thermal agitation, with mean occupation probabilities set by the instantaneous states of their neighbours⁷. In others, the tunnel junctions are pulsed to generate a fifty-fifty mixture of ones and zeros, which are then used to determine whether a spin flips or not⁸. Another development combines magnetic tunnel junctions for randomness with memristor crossbar arrays for analogue storage of coupling strengths⁹.

The researchers – who are based at Beihang University, Suzhou Inston Technology and Empryrean Technology – developed a way to update Ising spins using a particularly fast switching process that combines deterministic switching with stochastic thermal processes (Fig. 1). Their magnetic tunnel junctions contain thick tunnel barriers, resulting in a high resistance. This resistance means that a high voltage can be applied without drawing much current. Low current means that spin-transfer torques do not have a major role in the switching process, whereas high voltage means that voltage-controlled magnetic anisotropy¹⁰ has a key role, leading to low-energy switching.

With no applied voltage, the magnetic uniaxial anisotropy keeps the magnetization either up or down. When the voltage across the junction is pulsed, the uniaxial magnetic anisotropy vanishes, and the magnetization precesses around a perpendicular bias field. In the absence of thermal effects, the magnetization would predictably alternate between switching or not, depending on the pulse width. Thermal effects modify the switching process, giving a switching probability that varies smoothly with the voltage pulse width, mimicking the switching probability as a function of the modelled Ising spin's energy change.

Subnanosecond magnetization switching, material-stack integrated bias fields and the use of systems such as Ising spins have all previously been demonstrated independently. However, Zhao and colleagues combine the three into an integrated chip containing 96,000 magnetic tunnel junctions. Coupled to an on-chip pulse generator, the chip supports a fast, energy-efficient framework for updating Ising spins. The team then show that the platform can solve two integrated circuit design problems: global routing and layer assignment.

Much work remains to be done with hardware accelerators based on Ising models. Zhao and colleagues have provided an efficient and scalable method of deciding whether to flip an Ising spin once the energy change is known. The issue now is the effort it takes in terms of time and energy to compute the energy change. Progress could be made by developing a specialized chip for that task, rather than using the field-programmable gate array currently used in the system. But further progress will be needed as the Ising models scale to sizes relevant for problems of commercial interest and the number of connections increases rapidly. Finally, such accelerators will need to be integrated into existing solvers that partition problems into subproblems that are small enough to be addressed by Ising machines.

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Competing interests

The authors declare no competing interests.