ALS SCIENCE HIGHLIGHT

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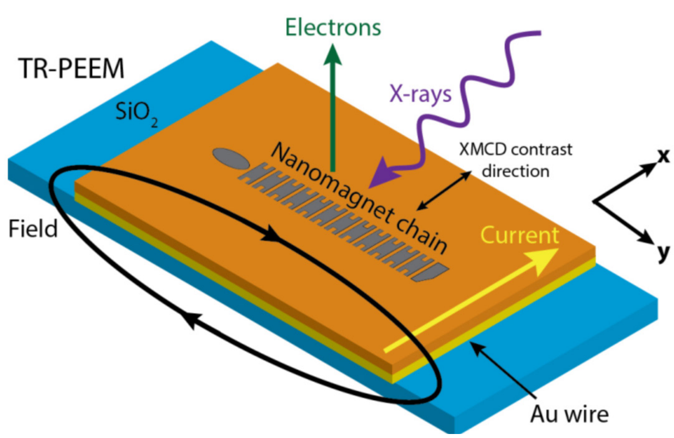
Signal Speed in Nanomagnetic Logic Chains

The miniaturization of computing architectures has paved the way for personal hand-held electronic devices (smartphones, tablets, etc.) that feature extraordinary computing power. For such battery-operated devices, keeping the power consumption low while continuing to add features is a major challenge. To address this issue, there is a worldwide research effort dedicated to minimizing the energy required to perform computational operations and to find a successor to silicon integrated circuit (IC) technology, which is approaching fundamental limits. One such architecture, called nanomagnetic logic (NML), employs chains of nanosized magnets instead of transistors. At the ALS, researchers have used a time-resolved x-ray imaging technique with 100-picosecond resolution to directly observe the signal propagation dynamics in these nanomagnetic chains. The technique can assess NML reliability on fast time scales and help determine optimal nanomagnet geometry, spacing, and material.



Schematic of time-resolved photoemission electron microscopy (TR-PEEM) experiment. Nanomagnet chains were fabricated on gold (Au) wires. The orientations of the nanomagnets were repeatedly reset by current pulses that generated on-chip magnetic "clock fields." Upon removal of the clock field, each magnet becomes coupled to a nearest-neighbor magnet by dipolar fields. X-ray magnetic circular dichroism (XMCD) contrast was measured in the nanomagnets along the x-axis.

The energy required to flip a magnet's orientation (performing a logic function) can be orders of magnitude lower than the operational energy of a single transistor. In NML, the magnetization of single-domain ferromagnetic thin-film islands are coupled by magnetic fields generated from adjacent islands, which impart a preference for neighboring islands to align in antiparallel directions. A chain of these closely spaced nanomagnets propagates binary information from one end to the other sequentially through a series of inversions, performing a function similar to a conventional IC connection but with a potentially lower dissipation energy per switching event.

Signal propagation in nanomagnet chains had previously been characterized by static magnetic imaging experiments; however, the mechanisms that determine the final state and their reproducibility over millions of cycles of high-speed operation had yet to be experimentally investigated. Characterizing the time scale of magnetic interactions in this energy-efficient computing architecture provides a critical benchmark comparison to other competing technologies.

In this study, researchers characterized NML operation on picosecond time scales and observed, for the first time, the magnetic dynamics within this high-speed regime. They directly imaged digital-signal propagation in permalloy nanomagnet chains using full-field magnetic x-ray transmission microscopy (MTXM) and time-resolved photoemission electron

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microscopy (TR-PEEM) at the ALS after applying short magnetic-field pulses. These experiments, and accompanying macrospin and micromagnetic simulations, revealed the underlying physics of NML architectures that are repetitively operated at picosecond time scales and identified relevant engineering parameters for optimizing performance and reliability.

Previous studies of NML have used static magnetic imaging (e.g., magnetic force microscopy) to assess the magnetic signal propagation based on the final observed output state. For example, in cases where magnets were perfectly anti-aligned throughout the chain, researchers assumed that perfect dipolar signal propagation occurred.

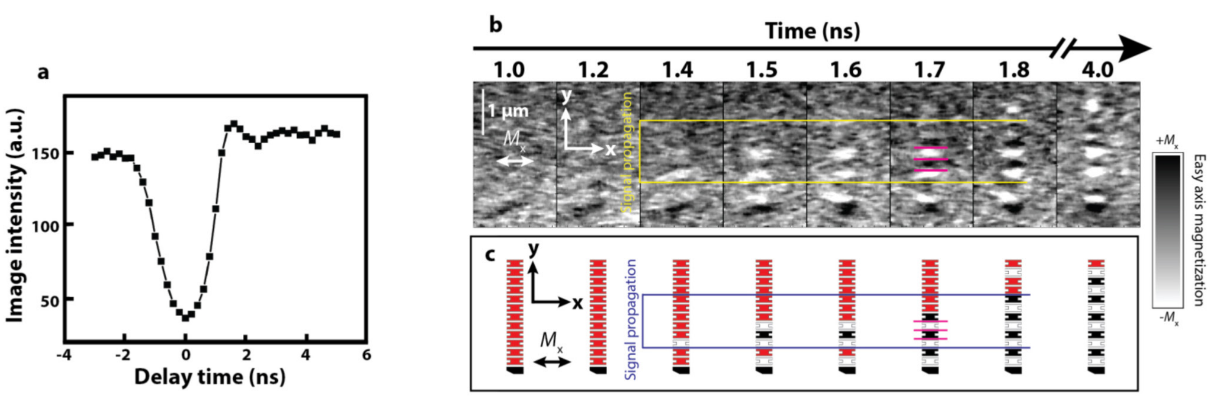
In this work, the researchers tested those assumptions by directly observing the magnetic signal propagation using an x-ray based imaging technique with 100-ps resolution. First, using MTXM at Beamline 6.1.2, the researchers statistically analyzed the static signal-propagation reliability of nanomagnet chains reset by nanosecond magnetic-field pulses. This identified geometries that optimize signal propagation and verified that short pulses could be reliably employed to perform a time-resolved measurement. After confirming that nanosecond pulses are suitable, the researchers then used TR-PEEM at Beamline 11.0.1 to directly image the magnetic signal-propagation dynamics in chains by synchronizing the magnetic-field pulses with pulsed x-rays from the ALS.

The TR-PEEM data confirms that signal propagation proceeds at a rate of approximately 100 ps per switching event, as predicted previously through computational studies. This time-resolved NML assessment technique introduces the ability to examine the performance of individual nanomagnets during signal propagation, a feature not present in existing quasi-static imaging measurements. Experimentally evaluating the performance of NML chains complements existing time-resolved micromagnetic simulations, offers realistic assessments of nanomagnet designs, and identifies systematic errors and architectural weaknesses.

Transitioning from the Transistor

In 1965, Gordon Moore, a founder of Intel, observed that the number of components on integrated circuits—microchips—doubled approximately every two years. "Moore's Law," as it came to be known, has held now for decades, morphing from observation to prediction to benchmark, driving the semiconductor industry to keep up the exponential growth or fall behind competitors. Now, after 50 years, Moore himself has said that, despite the creativity of engineers in finding ways around some pretty hard stops, "We won't have the rate of progress that we've had over the last few decades. I think that's inevitable with any technology; it eventually saturates out. I guess I see Moore's Law dying here in the next decade or so, but that's not surprising." The question then arises: What's next?

One novel idea is to replace conventional transistors, which operate based on electronic charge, with nanomagnetic logic chains, which operate based on electronic spin (in other words, magnetism). The nanosized magnetic structures that constitute a nanomagnetic logic device would "compute" with very little electric current, maintain their (up or down) states even without power, and be very dense without the problem of current leakage when in standby mode—a vexing problem for portable electronics that run on batteries. Since a major roadblock limiting the density of integrated circuits is the issue of power dissipation, nanomagnetic logic is a very promising computational architecture for ultralow-energy operation.



Observation of signal propagation by dipolar coupling. (a) Waveform corresponding to the magnetic clock field pulse, measured by detecting transient deflection of the emitted photoelectrons. (b) Averaged time-resolved XMCD-PEEM images of a nanomagnet chain at various time delays from 1 ns to 4 ns from the peak of the magnetic clock pulse shown in (a). The lateral scale in these images is indicated by the 1 µm scale bar. Signal propagation from the third nanomagnet to the eighth nanomagnet driven by dipolar coupling (emphasized in the yellow region) is observed between 1.4 and 1.8 ns. Pink lines distinguish individual nanomagnets in the chain. (c) An interpretation of the switching events observed in part (b). Black and white indicate magnets that have oriented along the easy (x) axis in opposite directions, respectively.