Time-Lapse Imaging of Thermally-Driven Signal Propagation in Nanomagnetic Logic

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In nanomagnetic logic [1], dipole-coupled chains of ferromagnetic islands propagate and process bits of information without displacing electronic charge, i.e., without resistive heat losses. This feature makes it an attractive alternative to conventional information processing technologies for ultra-low power computer applications. To better understand the nature of information propagation in nanomagnetic logic, we have carried out a series of experiments in which we directly observe the propagation of a binary signal in a nanomagnet chain. We fabricated chains of permalloy nanomagnets on a silicon substrate using a standard e-beam liftoff process and obtained magnetic contrast images of the sample using the x-ray photoelectron emission microscope (X-PEEM) at the Advanced Light Source, Lawrence Berkeley National Laboratory. At room temperature, we captured a time-lapse series of magnetic contrast images of the nanomagnet chain over a span of several hours at approximately one minute intervals. No external perturbations were applied to the sample for the duration of the experiment and the temperature was held fixed. The resulting series of images reveals the thermally-driven random walk of a binary signal along the chain, with the signal shifting one island to the right or left several times per hour due to thermal magnetization flipping. The observed behavior is consistent with micromagnetic simulations and mathematical models of random walk dynamics. Follow-up experiments demonstrate additional behavior associated with thermally-driven signal propagation, including the collision of multiple signals on a nanomagnet chain and the operation of magnetic logic gates. Our experiments and the underlying model of information propagation they demonstrate have important implications for the performance and reliability of nanomagnetic logic [2], which we discuss.

References:

[1] A. Imre, G. Csaba, L. Ji, A. Orlov, G. H. Bernstein, and W. Porod, “Majority logic gate for Magnetic Quantum-Dot Cellular Automata”. *Science* vol. 311, pp. 205 (2006).

[2] D. Carlton, N. Emley, E. Tuchfeld, and J. Bokor, “Simulation studies of a nanomagnet-based logic architecture”. *NanoLetters*, vol. 8, no. 12, pp. 4173-4178, 2008.

Figures

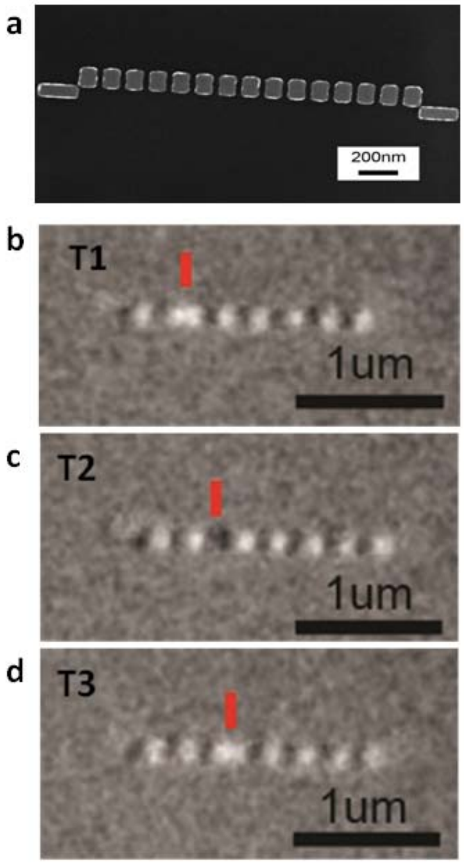

Figure 1: (a) Scanning electron microscope image of a chain of permalloy nanomagnets fabricated by electron beam lithography. (**b-d)** Time-resolved magnetic contrast images (Light – magnetized up along vertical axis, dark – magnetized down) of a nanomagnet chain taken by X-PEEM microscopy. Thermal magnetization switching moves the signal front (red pointer) along the chain by a random walk as time progresses.