PEEM Studies of Coupled-Nanomagnet Systems

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It has been demonstrated that linear chains of closely spaced, single domain, bar-shaped nanomagnets can propagate a binary signal over a useful distance [1, 2]. In these architectures, the nanomagnets are first driven ("clocked") into a high energy (hard-axis) alignment through the application of an external magnetic field. As the field is reduced, the magnetization of each nanomagnet will relax into one of two easy-axis directions (up or down), with dipole-field coupling between neighboring magnets causing the ensemble to relax into its global energy minimum configuration. The magnetic state of a nanomagnet at the end of the chain is therefore a function of the magnetic state of the nanomagnet at the front of the chain, and the chain thus acts as a magnetic wire for transmitting digital signals. Other configurations of nanomagnets also interacting through nearest neighbor dipole fields have been shown experimentally to operate as a universal logic gate [1]. Arbitrarily complex combinatorial logic is possible if the nanomagnets can be made to act reliably. The operation of such 'magnetic wires' and logic gates utilize electron spin rather than charge as the binary state variable, and signal propagation and logic functions do not involve the flow of electric current. This nanomagnetic logic technology is a potential successor to CMOS for ultra low power applications.

Currently, one goal for nanomagnetic logic is to engineer circuits that are reliable enough for practical applications. Using Magnetic Force Microscopy (MFM) and Photo Emission Electron Microscopy (PEEM) with circularly polarized X-rays, we studied error rates in large ensembles of nanomagnet chains to experimentally determine how various parameters affect reliability. Our results indicate that important parameters include nanomagnet aspect ratio, inter-nanomagnet spacing, and clocking magnetic field misalignment. We quantify statistically how reliability is affected by these parameters and discuss how this new knowledge can be incorporated into signal propagation models in nanomagnetic logic architectures.

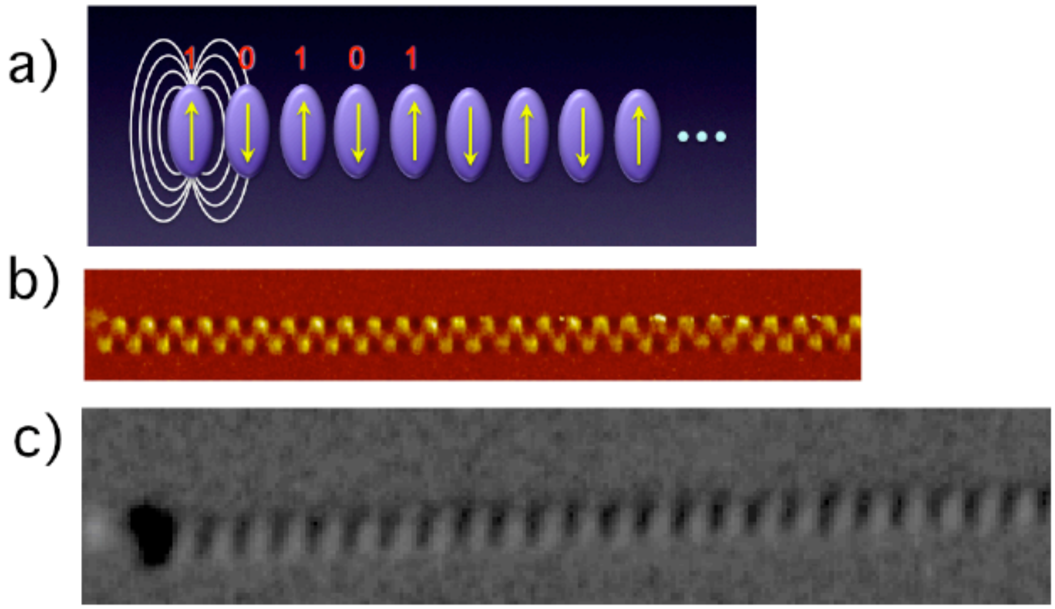

Figure 1. a) Schematic representation of a nanomagnet chain showing expected final magnetic state. The nanomagnets fall into an antiferrogmagnetic alignment. b, c) MFM and PEEM contrast images showing antiferrogmagnetic alignment in a lithographically patterned chain of permalloy nanomagnets.

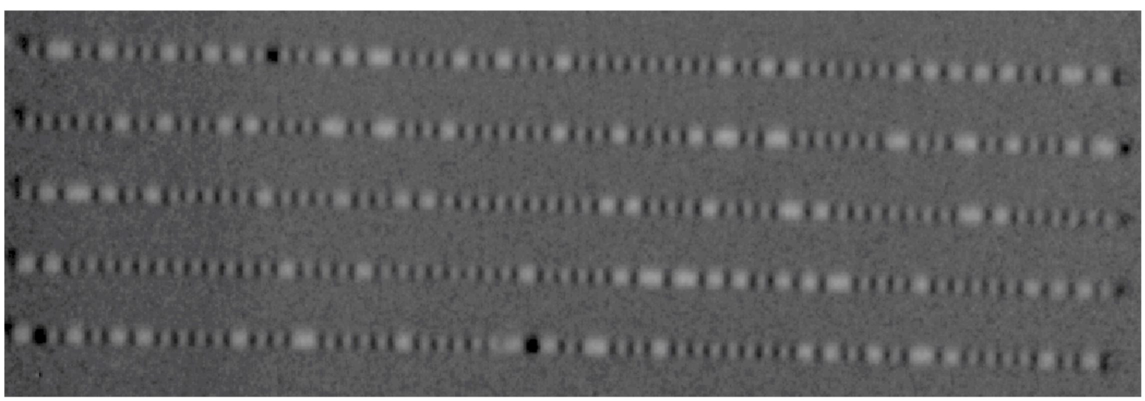

Figure 2. PEEM image showing magnetic contrast in long nanomagnet chains. Errors occur when two or more consecutive nanomagnets align in the same direction, appearing as elongated bright or dark spots in the figure above.

[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.

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