# Programmable Magnetic Microsystems

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**Principal Investigator(s): Paul L. McEuen[1,2], Itai Cohen[1,2], Michael Brenner[3]**

**User(s): Tanner Pearson[4], Conrad Smart[5], Chrisy Xiyu Du[3], Hanyu Alice Zhang[4]**

*Affiliation(s): 1. Laboratory of Atomic and Solid State Physics, Cornell University; 2. Kavli Institute for Nanoscale Science, Cornell University; 3. School of Engineering and Applied Sciences, Harvard University; 4. School of Applied and Engineering Physics, Cornell University; 5. Department of Physics, Cornell University*

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*Contact(s): plm23@cornell.edu, itai.cohen@cornell.edu, brenner@seas.harvard.edu, tgp34@cornell.edu, cs2239@cornell.edu, xiyudu@seas.harvard.edu, hz496@cornell.edu*

*Primary CNF Tools Used: Oxford FlexAL ALD, ASML DUV stepper, JEOL 6300, CVC e-beam evaporators, Oxford 81/82/100 etchers, PT770 and PT740 etchers, Anatech asher, Zeiss SEMs, Veeco atomic force microscope, Tencor P7 profilometer, Filmetrics UV, DISCO dicing saw, Heidelberg mask writer - DWL2000, AJA sputter deposition*

## *Abstract:*

**We develop programmable microscopic systems based on nanomagnetic information. By taking advantage of magnetic shape anisotropy, we sequentially program the orientation of magnetic dipole moments on rigid panels. We can connect these panels with flexible glass hinges to develop actuatable structures capable of locomotion. Additionally, we can leave panels detached from each other and agitate them to demonstrate smart handshake self-assembly based on dipole-dipole interactions. These programmable systems have a diverse range of applications ranging from microrobotics to synthetic DNA assembly and replication.**

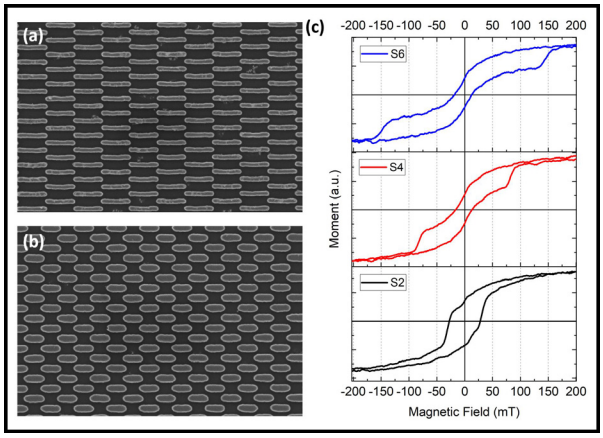


*Figure 1: (a) SEM image of high AR nanomagnets. (b) SEM of low AR nanomagnets. (c) Magnetic hysteresis loops for different AR nanomagnets (S2 AR = 3, S4 AR = 5, S6 AR = 9). Width of hysteresis, and therefore coercive field, increases with increasing AR.*

## *Summary of Research:*

We create systems embedded with complex magnetic information by utilizing electron beam lithography (EBL) to fabricate single domain cobalt nanomagnets with varying aspect ratios (Figure 1a-b) [1]. The coercive fields of these nanomagnets and the orientations of their moments are intrinsically tied to shape anisotropy. Since magnetic moments prefer to be oriented along the long axis of a magnet, high aspect ratio (AR) magnets will exhibit higher coercive fields along their long axes than those with smaller aspect ratios. We tune the nanomagnet dimensions to achieve magnetic dipoles with coercive fields ranging from 30 mT to 140 mT (Figure 1c).

We sequentially program multiple magnetization directions by using two species of nanomagnets with disparate coercive fields [1]. With the long axis of the two species oriented along the same global axis, we apply a magnetic field greater than the coercivity of the high aspect ratio magnets to program all the magnets in one direction. We then use an opposing field with a magnitude between the coercivities of the two magnet species to reverse the orientation of the lower aspect ratio magnets. With an orthogonal pair of magnet species, we can achieve up to four discrete moment orientations ($\pm x$, $\pm y$). Superpositions of these moments provide additional orientations. We confirm dipole moment orientations with magnetic force microscopy (MFM) (Figure 2b).

We have previously shown that nanometer-thick glass deposited by atomic layer deposition (ALD) is an ideal material for flexible microsystems due to its incredibly low

bending stiffness [2]. By combining EBL and deep ultraviolet (DUV) lithography, we can integrate programmable nanomagnets onto rigid panels connected by flexible glass hinges to create a variety of actuatable devices. Here we show a device consisting of two panels, comprised of arrays of 800 nanomagnets with opposing moments, connected by two 5 nm thick glass hinges (Figure 2a-b). We can apply a uniform external field in $z$ to torque both panels up or down, demonstrating the basic mountain-valley fold essential for microscopic origami and origami-inspired metamaterials.

Moreover, we can apply a combination of sinusoidal in-plane and out-of-plane fields to achieve a crawling motion akin to that of an inchworm (Figure 2c). Starting with both legs on the substrate, these fields continuously cycle through the following sequence of motions: the device tilts to its back leg, stretches the front leg forward, tilts to its front leg, pulls the back leg forward, and returns to its start position. In this way the device achieves net forward motion (Figure 2d). We can increase the frequency of this cyclic motion to achieve impressive crawling speeds of over a body length per second. Additionally, the phase and amplitudes of the in-plane field components can be modulated to achieve direction reversal and turning, respectively. This deceptively simple device illustrates how even a small amount of magnetic information can enable complex actuation dynamics necessary for robotic microsystems.

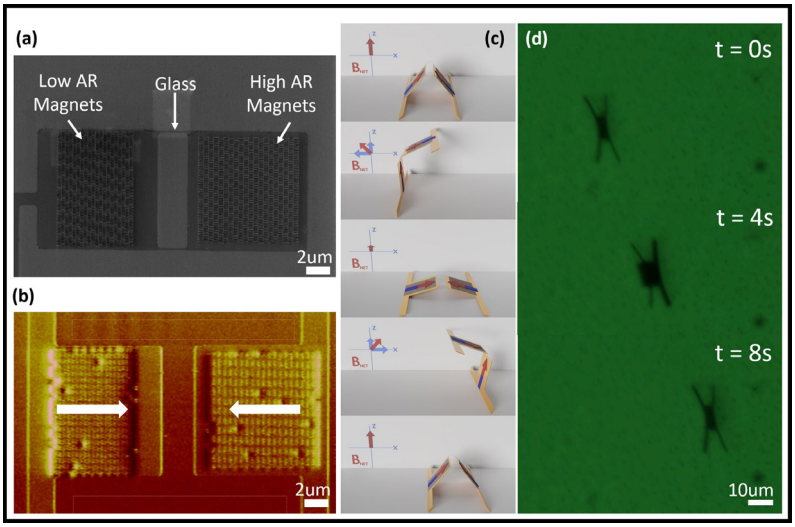


*Figure 2: (a) SEM image of inchworm device. Glass hinges (dark grey) are each 250 nm × 2.5 µm. Panels are (10 µm)² and each consist of 800 magnets. (b) MFM image confirming the opposing net magnetic moments of each panel. (c) Cartoon illustrating stepping sequence of device. (d) Position over time of device cycled at 1 Hz, demonstrating net forward motion.*

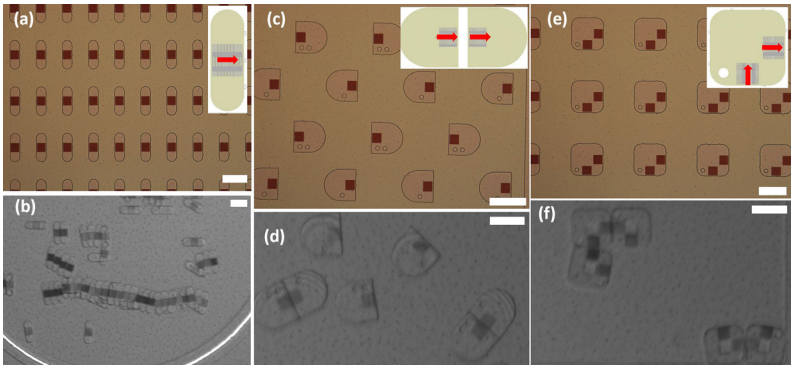


*Figure 3: (a-b) Panels assembling into simple polymer chains. (c-d) Panels assembling into dimers. (e-f) Assembly of square panels with two dipole moments. Full assembly would yield 2 × 2 panel arrays. Insets show cartoons of panel magnetizations. Scale bars 30 µm.*

We also use programmable nanomagnets to develop microscopic handshake systems capable of smart self-assembly (Figure 3) [3]. The fabrication process consists of embedding one or more nanomagnetic dipoles into thick, disconnected glass panels. When released from the substrate, panels are sonicated to facilitate lock-key binding of dipoles at the sides of complementary panels. With careful design of the panel geometry and magnetic dipole-dipole interactions, we can enable a wide range of well-defined assemblies. As the number of dipoles per panel increases, the lock-key binding becomes more specified, and more complex assemblies are possible. Moreover, these systems can be influenced by external magnetic fields at any point during or after the assembly process, providing a unique mechanism to manipulate assembled structures.

The possible applications for programmable nanomagnetic microsystems are immense. Magnetic panels connected by flexible glass hinges can be used to create mechanical and optical metamaterials and explore magnetically induced defects in those metamaterials. They can also be integrated into locomotive microrobots.

By eliminating the connective membranes between panels, we can further develop intelligent handshake systems governed by lock-key dipole-dipole interactions. These can be used to create assemblies that behave analogous to polymers and DNA.

## References:


[1] J. Cui, T. Huang, Z. Luo, P. Testa, H. Gu, X. Chen, B. J. Nelson, L. J. Heyderman, Nature 2019, 575, 164.

[2] K. J. Dorsey, T. G. Pearson, E. Esposito, S. Russell, B. Bircan, Y. Han, M. Z. Miskin, D. A. Muller, I. Cohen, P. L. McEuen, Adv. Mater. 2019, 31, 1901944.

[3] R. Niu, C. X. Du, E. Esposito, J. Ng, M. P. Brenner, P. L. McEuen, I. Cohen, PNAS 2019, 116 (49), 24402.