Magnetic-Field Driven By-Stable Switching of Magnetic Cantilevers/Beams via Microscale Magnetic Controls

CNF Project Number: 2866-20
Principal Investigator(s): Amal El-Ghazaly
User(s): Ludovico Cestarollo, Karthik Srinivasan, Zexi Liang, Melody Xuan Lim

Affiliation(s): Electrical and Computer Engineering, Materials Science and Engineering; Cornell University

Primary Source(s) of Research Funding: National Science Foundation

Contact: ase63@cornell.edu, lc942@cornell.edu, ks934@cornell.edu, zl467@cornell.edu, mxl3@cornell.edu
Website(s): https://vesl.ece.cornell.edu

Primary CNF Tools Used: Heidelberg Mask Writer - DWL2000, SÜSS MicroTec Gamma Cluster Tool, ASML PAS 5500/300C DUV Wafer Stepper, Oxford 81 Etcher, Xactix XeF_2 Isotropic Silicon etch system, C&D SmartProP9000, DISCO Dicing Saw, Zeiss Ultra SEM, AFM - Veeco Icon, P7 Profilometer

Abstract:

The primary objective of this research is to establish large-deformation tactile displays using magnetic elastomer actuators. Magnetic actuators require reproducible, small-scale approaches for controlling the magnetic field gradient and direction used to drive the actuation. Over the past year our research group has been investigating the design and fabrication of micro-magnetic controls capable of generating localized magnetic fields and gradients necessary to actuate deformations in these magnetic elastomers. We have fabricated and optimized control micromagnets with different magnetic states and properties. The efforts have then been focused on experimentally demonstrating the ability of these control magnets to cause actuation via a system composed of a magnetic cantilever/beam.

Summary of Research:

One of the favored modes of actuation in large-scale mechanical systems (motors, relays, etc.) is magnetic because of its ability to generate large forces from relatively compact form-factors. However, the scaling down of magnetic actuation controls has posed numerous challenges. In the case of magnetic materials used for control, thin-film processing and smaller dimensions cause reduced flux density and demagnetization of the films. In the case of electromagnetic coils, the smaller size increases resistance and leads to unreasonably high-power consumption and heating. On the other hand, if successfully scaled down and integrated with Oersted-field or spintronic switching, magnetic actuation can potentially offer a low-power and compact solution to micro-actuators, including MEMS relays, microfluidic pumps, and novel haptic interfaces with the desired micrometer-scale resolution of magnetic fields and gradients [1-4].

This research project focuses on enabling the development of high-resolution, programmable haptic interfaces by developing a system of control magnets able to control the deflection of microscale beams/cantilevers.

A system of control magnets is designed to generate the local magnetic fields that would cause actuation. Two control magnets are engineered to have magnetizations preferentially pointing along two orthogonal axes, leading to the coupling of the magnetic flux densities between them and the generation of a field (and gradient) localized with micrometer resolution. These two control magnets are referred to as PMA (perpendicular magnetic anisotropy) and IMA (in-plane magnetic anisotropy) magnets. To investigate the ability of this system of magnets to generate useful forces for haptic applications, the team has designed a system composed of the two controls and an ALD (atomic layer deposition) beam/cantilever, which is made magnetic by embedding very thin soft magnets on its surface. The proposed design allows localization of a strong magnetic flux density and its gradient to a confined region of space between the two control magnets, enabling the magnetic actuation of the beam/cantilever with micro-scale resolution (Figure 1).

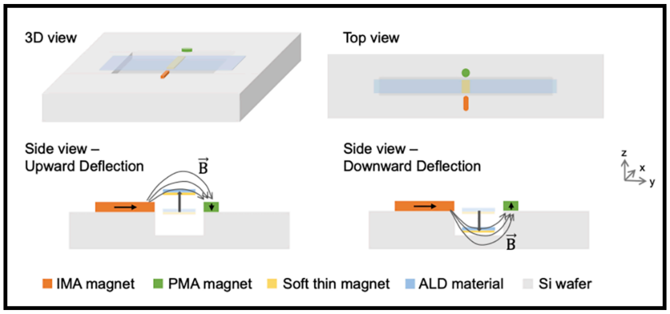

Figure 1: Magnetic actuation of a magnetic ALD beam via system of control PMA/IMA magnets.

Simulations have been designed and run to show that at these small microscales the generated magnetic flux density gradients between the two magnets are on the order of 10^4 T/m at vertical distances of hundreds of nanometers above (below) the magnets. These field gradients would act of the beam/cantilever by deflecting it to where the magnetic field is the strongest. This is at roughly 100 nm above the control magnets in the case of the PMA magnet being downward magnetized, and 100 nm below the magnets when the PMA magnet is upward magnetized.

The magnetic pull force exerted on the cantilever/beam, expressed as $F_z = m_x B_{xz} + m_y B_{yz}$ (where m=magnetic moment, and B=magnetic flux density), is computed. Simulations show that the B_{xz} component of the field gradient (rate of change of B_x as a function of z) is order of magnitudes larger than B_{yz}. This indicates that the soft thin magnets on the cantilever/beam should be designed with an elongated shape in the x-direction to promote magnetic anisotropy along this axis and maximize the magnetic force F_z. Furthermore, this magnetic force is shown to be greater than the mechanical force from the beam/cantilever, proving that the control magnets exert a magnetic field and gradient that are sufficient to mechanically deflect the beam/cantilever (Figure 2).

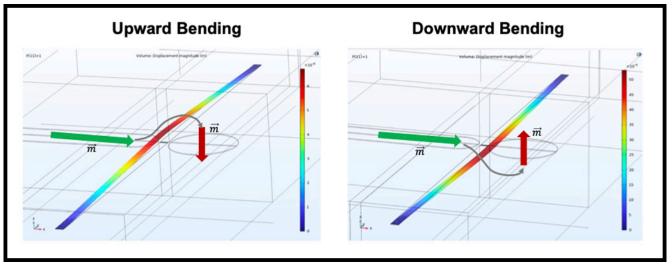

Figure 2: Magneto-mechanical simulation showing bipolar switching of a magnetic ALD beam via system of control PMA/IMA magnets.

The team is currently working on fabricating the system presented above. Deposition and patterning steps have been optimized to obtain the designed structures.

Conclusions and Future Steps:

This research shows that IMA and PMA magnets can be engineered and combined to generate magnetic flux density coupling useful for high-resolution magnetic actuation. Localization of a magnetic field (and a gradient) is achieved in a very narrow region of space with micrometer resolution. This system of magnets is integrated into a device with a narrow cantilever/beam, which is made responsive to applied magnetic fields by adding small magnets to it. In conclusion, this work will enable the realization of high-resolution, micrometer-scale magnetic actuators for haptics and numerous other mechanical applications.

References:

[1] L. Cestarollo, S. Smolenski, and A. El-Ghazaly, "Nanoparticle-based magnetorheological elastomers with enhanced mechanical deflection for haptic displays," ACS Applied Materials & Interfaces, vol. 14, no. 16, pp. 19002-19011, 2022.

[2] S. Marchi, et al., "Highly magneto-responsive elastomeric films created by a two-step fabrication process", ACS Applied Materials & Interfaces, vol. 7, no. 34, pp. 19112.19118, 2015.

[3] K. J. Dorsey, et al., "Atomic layer deposition for membranes, metamate-rials, and mechanisms," Advanced Materials, vol. 31, no. 29, 1901944, 2019.

[4] J. Streque, et al., "New magnetic microactuator design based on PDMS elastomer and MEMS technologies for tactile display," IEEE Trans. Hap-tics, vol. 3, no. 2, pp. 88-97, 2010.