Harnessing Magnetic-Field Driven Actuation for Microscale Motion in MEMS-Inspired Device

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Primary CNF Tools Used: Heidelberg Mask Writer – DWL2000, SUSS MicroTec Gamma Cluster Tool, ASML PAS 5500/300C DUV Wafer Stepper, Oxford ALD FlexAL, Plasma-Therm Takachi HDP-CVD, Oxford 81/82/100 ICP and PT770 Etchers, Xactix XeF_2 Isotropic Silicon Etch System, DISCO Dicing Saw, Zeiss Ultra SEM, AFM – Veeco Icon, P7 Profilometer

Abstract:

Accurate small-scale control of magnetic actuation necessitates exact tuning of the magnetic fields and gradients that drive movement. In this study, two control magnets create the local magnetic fields needed to induce microscale deflections of a shuttle (in a micromechanical system) equipped with a soft magnetic element. The magnetization orientation and anisotropy of the magnetic element are optimized to maximize deflection in the ON state and its contrast with the OFF state. To demonstrate the effectiveness of the actuation force, a double-folded beam MEMS structure integrated with the control magnets is designed and fabricated.

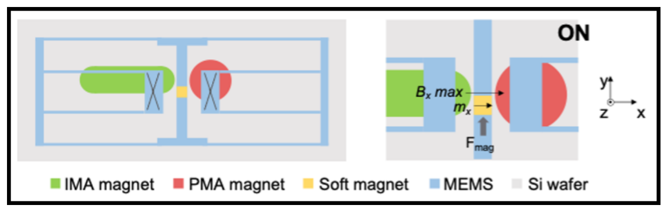

Figure 1: Integrated MEMS featuring a system of beams and magnetic controls.

Summary of Research:

Magnetic actuation stands out in mechanical systems as it allows the generation of large forces in a contactless manner. Various forms of magnetic actuators exist, including magnetic elastomers for millimeter-scale actuation [1-3] and programmable actuators with nanoscale magnets for creating microscale robots [4]. These studies typically use large NdFeB permanent magnets or electromagnetic coils to generate the necessary magnetic fields. However, integrated solutions are needed where both the actuation driver (generating the magnetic field) and actuated mechanism (moving in response to the field) exist within the same micrometer-scale device. Challenges include miniaturizing the switchable magnetic controls and fabricating microscale devices that respond mechanically to magnetic fields. Thin-film magnets produce fields that extend only short distances, requiring precise design of the geometry of the actuating mechanism to meet structural constraints. Despite these challenges, magnetic actuation offers a compact, low-power solution for micro-actuators.

This research tackles these issues and presents a tenable design for high-resolution, programmable MEMS micro-actuator. Our novel device uses micro-magnetic controls interacting with a soft magnetic element on a flexible beam system to induce deflection. By programming the magnetization of the control magnets and the soft magnetic element, the system can switch between ON and OFF states. The proposed design features a pair of IMA (in-plane magnetic anisotropy) and PMA (perpendicular magnetic anisotropy) control magnets, as shown in Figure 1.

A double folded beam MEMS is elevated over the magnets, anchored to them by the two supports, each denoted with a cross. The MEMS center shuttle is equipped with a soft magnetic element. This magnet, in response to the field exerted by the two control magnets, imparts a force to the shuttle, causing motion along the y-direction. In the current setup, the presence of a magnetic field coupling between the control magnets above (or below) their surface corresponds to the ON (and OFF) states.

The control magnets were engineered to obtain the desired anisotropies. The IMA magnet is deposited as a single layer of pure Co in the shape of an elongated ellipse, forcing magnetization along its long dimension purely through shape anisotropy. The PMA magnet, instead, is grown as a Co/Pt heterostructure with 20 repeating layers of nanometer-thick Co and patterned to a circular shape. In the ON state, the IMA and PMA magnets are magnetized in the +x and -z directions, respectively, to concentrate the magnetic flux between them just above their surface. This strong magnetic flux density localization between the two magnets (separated by 1 μm) creates a significant Bxy ($\partial B/\partial y$) flux density gradient component, inducing a powerful actuation force on the soft magnet (an analytical model was developed to guide the device design). In the complete MEMS actuator, the beams can deflect if the magnetic force overcomes the mechanical restoring force. The mechanical restoring force from the MEMS is calculated by treating it as a system of fixed-guided beams [5]. By fabricating beams with a width (y-direction) of 30 nm and a thickness of 300 nm, and by depositing a soft magnet being 125 nm thick, large deflections up to 1 μm can be achieved.

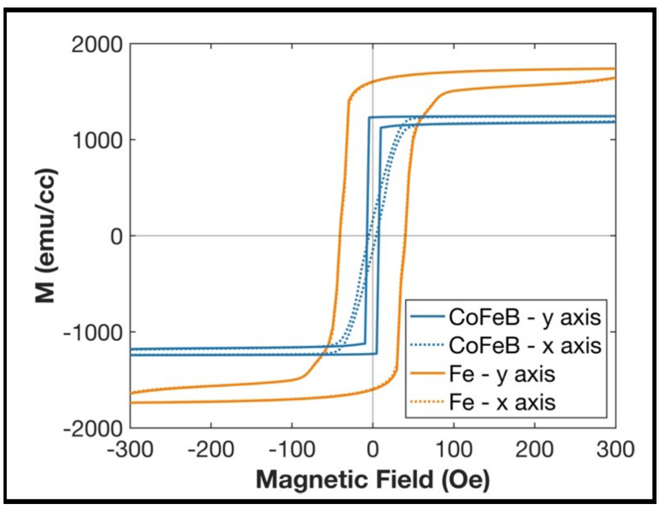

Figure 2: M vs H hysteresis loops along the x and y axes for Fe and CoFeB magnets deposited in the presence of an in-plane magnetic field.

The soft magnetic element was engineered to orient its easy axis along the y-direction in the OFF state, while allowing magnetization in the x-direction when exposed to small fields in the ON state. By depositing a square magnet using $Co_{43}Fe_{43}B_{14}$ in an in-plane field of 200 Oe along the y-direction, the desired behavior with a switching field (Hk) of 40 Oe was achieved, as shown in Figure 2 (this switching can be obtained with the system of IMA/PMA magnets). This switching behavior cannot be replicated with pure Fe, where magnetocrystalline anisotropy is not induced with the application of a field during deposition. As a result, Fe shows identical behavior along the x and y axes due to the absence of shape anisotropy in the square pattern.

Conclusions and Future Steps:

This research paves the way for high-resolution micrometer-scale magnetic actuators. By integrating the magnetic controls (actuating driver) with the MEMS featuring an embedded magnet (actuated mechanism), we are pioneering the development of the first fully-integrated magnetic actuator. Our innovative magnetic design maximizes the contrast in actuation between ON and OFF states. The resulting device, comprising control magnets, a soft magnetic element, and a folded beam MEMS structure, will be the first example of a fully-integrated magnetic actuation system.

References:

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