Design and Fabrication of Integrated Magnetic Elastomer-Based Soft Actuator

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Primary CNF Tools Used: Heidelberg Mask Writer - DWL2000, ABM Contact Aligner, Hamatech Hot Pirana/Wafer Processor Develop, PT 72, C&D SmartProP9000, DISCO Dicing Saw, AFM - Veeco Icon, P7 Profilometer, RC2 Woollam Ellipsometer

Abstract:

Technological advancements to date have primarily focused on stimulating only two of the five human senses: sight and hearing. Touch-based interactive technologies can still be considered to be in their infancy. Haptic devices allow tactile interactions between humans and digital interfaces in many different arenas such as user interfaces for assisted and autonomous driving [1] and teleoperation [2]. Magnetorheological elastomers (MREs) based on nanoparticles constitute a promising candidate material for creating tactile interfaces capable of creating high-resolution features on the micron scale [3,4]. These magneto-responsive elastomers must be integrated with magnetic controls to create the local magnetic fields necessary to actuate deformations. Such a system composed of a magneto-responsive soft material and integrated magnetic controls has not been developed to date.

In order to highlight the potential for these devices, a process was developed to create a system of micromagnetic controls integrated into free-standing microscale cantilevers and beams. First, magnetic microscale circular and elliptical pillars were developed via sputtering and photolithography utilizing a lift-off process. These structures were utilized to create magnets with magnetic moments pointing respectively in the direction perpendicular and parallel to their surface. The magnetic properties of the deposited magnets were studied via vibrating sample magnetometry and the optimal dimensions for both geometries were identified. Based of simulation results, the optimally fabricated circles and ellipses were then deposited in pairs at different distances from each other. These systems of magnets were ultimately designed to be integrated into cantilevers and beams made of a micrometer thin nanoparticle-based MRE to create a magnetic soft actuator.

Summary of Research:

First, sets of micromagnets were fabricated with two geometries in order to preferentially set the anisotropy (direction of the magnetic moments) along two specific directions. Contact photolithography, sputtering, lift-off and argon ion milling (see Figures 1 and 2) were used to fabricate the magnets. Pillars with a circular base were developed to create magnets with perpendicular magnetic anisotropy (PMA), so with magnetic moments pointing in the thickness direction of the pillars. Pillars with an elliptical base were instead developed to create magnets with in-plane magnetic anisotropy (IMA), so with magnetic moments pointing in a direction lying on the base of the pillars. The effect of the size of the magnets on their magnetic properties was investigated by depositing sets of magnets of different sizes on a wafer and then cutting the wafer into dies, with each die having a set of magnets with specific geometry and dimensions. These dies were then tested in a vibrating sample magnetometer to record magnetic hysteresis loops (magnetization vs. magnetic field). For the PMA magnets, pillars having a circular base with 5 µm diameter were determined to be optimal, since they yield a remanent to saturation magnetization almost equal to 1 and a large coercivity of about 1000 Oe.

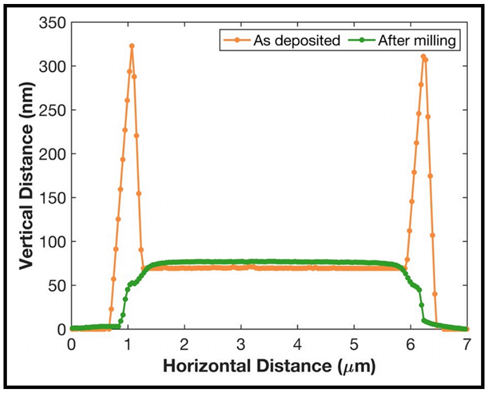

Figure 1: 2D AFM profile of 5 µm diameter circular pillar as deposited and after argon ion milling of the "rabbit ears".

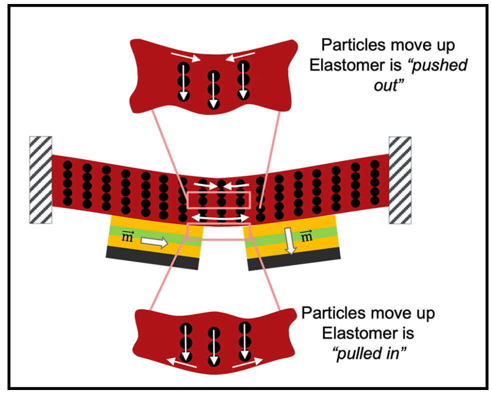

Figure 3: A magnetic soft actuator in the form of a simply supported beam. The two micromagnets generate the local fields that cause the deflection of the magnetic elastomer.

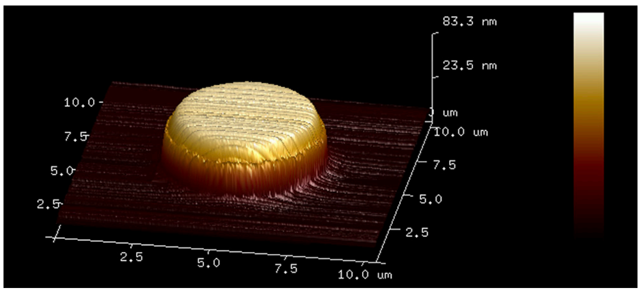

Figure 2: 3D AFM image of 5 µm diameter circular pillar after argon ion milling, showing smooth edges and absence of "rabbit ears" characteristic of lift-off process using deposition via sputtering.

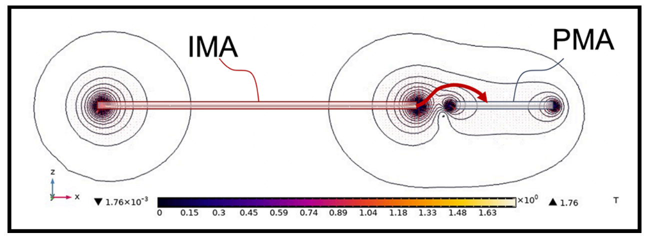

Figure 4: Magnetic simulation of IMA and PMA magnets spaced 1.5 µm away from each other. The contour lines show the change in magnitude of the magnetic flux density. The red arrow emphasizes the direction of magnetic flux closure from the IMA to the PMA magnet.

For the IMA magnets, elliptical pillars with long and short axes dimensions of 3 and 15 µm were chosen as the optimal ones. This size allows to better tune the magnetic anisotropy in the direction of the long axis of the pillar (with larger sizes the difference between the loops recorded along the short and long axes of the pillars becomes less pronounced).

In order to obtain a soft magnetic elastomer with magnetic controls able to actuate deflections, we designed a system composed of a magnetorheological elastomer and the two optimally fabricated micromagnets described above (Figure 3 illustrates the device in the case of a simply supported beam). By having a PMA and an IMA magnet on the surface on a magnetoresponsive material, the two magnets can couple with each other with magnetic flux lines penetrating into the material. Based on magnetic simulations performed in COMSOL Multiphysics, the two magnets were spaced 1, 1.5 and 2 µm away from each other (Figure 4 shows the 1.5 µm spacing case). These spacings guarantee strong coupling between IMA and PMA magnets so that the flux generated by the IMA magnet closes into the PMA one, creating a strong field extending into the elastomer. This magnetic flux closure generates a magnetic field gradient in proximity of the gap between the two magnets, which in turn causes the magnetic particles embedded into the elastomer to move towards where the flux is stronger, forcing the magnetic elastomer to deform.

Conclusions and Future Steps:

We have successfully fabricated micro-sized magnets with perpendicular (PMA) and in-plane (IMA) magnetic anisotropy. In the case of PMA magnets, circular pillars were selected as the geometry of choice and an optimal diameter of 5 µm was determined. On the other hand, in the case of IMA magnets, elliptical pillars were selected as the geometry of choice and optimal long and short axes dimensions of 3 and 15 µm were selected.

PMA and IMA magnets were then fabricated on a wafer with spacings of 1, 1.5 and 2 µm between them. Simulations results indicated that such spacings allow the magnetic flux from the IMA magnet to couple with the PMA one. The next steps will require embedding these sets of micromagnets into a thin (2 µm thick) magnetic elastomer and shape this into beams to test their actuation performance.

References:

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