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Composite ferromagnetic photoresist for the fabrication of microelectromechanical systems

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Abstract

This paper describes a simple method for the microfabrication of mechanically compliant, magnetically-responsive microstructures. These microstructures were fabricated in one step by using a ferromagnetic photoresist, which, in turn, was prepared by suspending nickel nanospheres in a negative photosensitive epoxy (SU8). The nominal diameter of the nickel nanospheres was 80–150 nm, that is, much smaller than the wavelength of the UV light (365 and 405 nm) used to expose the photoresist. Diffraction and scattering of light from the nanospheres allowed for full exposure of the photoresist, even after the incorporation of nanospheres at levels at which it became opaque. The ferromagnetic photoresist was cross-linked after exposure and development, and yielded a stable, compliant, ferromagnetic pattern. The paper characterizes the effect of the weight density of the nickel nanospheres on the transmittance of films made by this technique at wavelengths from 330 nm to 610 nm. It also describes a number of microstructures made with the photoresist: examples include lines, posts and meshes. As a demonstration, the procedure was applied to the microfabrication of a set of magnetically-actuated micromirrors. These micromirrors achieved large deflections: deflection at the tip of a 12 mm long, 250 μm wide and 70 μm thick cantilever of the ferromagnetic photoresist exceeded 1.4 mm, when actuated by a NbFeB permanent magnet with field strength $\sim$120 mT. The cantilever maintained its mechanical properties after cycling $\sim 10^6$ times.

S This article has online supplementary material

1. Introduction

The full integration of ferromagnetic materials with microelectromechanical systems (MEMS) would expand the capabilities of micro actuators and sensors. Current applications of ferromagnetic materials in MEMS range from micro relays [1] to integrated magnetic sensors [2] and micro actuators [3–5]. A number of methods of microfabricating patterned, magnetically-responsive materials (e.g., Ni, NiFe, etc) are available [6–11]. The most commonly explored approaches are: electroplating through a polymer or a photoresist mold [12], direct sputtering (patterned by lift-off or wet etching) [13–15], forming composites of polymer/magnetic material (patterned by dry etching or micro molding) [16] and micro electro discharge machining [17].

This paper reports a ferromagnetic photoresist made from a suspension of nickel nanospheres in a photosensitive epoxy.

The photoresist is magnetically active and can be used as the structural material for components of MEMS. This composite ferromagnetic photoresist (FPR) offers three advantages for fabricating magnetically-responsive microstructures. (i) The structure can be made in one step. There is no need to fabricate a mold, or to electroplate, or for subsequent lithography and etching steps. (ii) Unlike films made by sputtering or dry etching of polymer/magnetic material mixtures, the thickness of the structure can be adjusted over a wide range: from sub-micron to hundreds of microns. (iii) Flexible ferromagnetic microstructures and mechanisms can be fabricated from the FPR. Young's modulus of the SU8 (3×10^9 N m^{-2}) [18] is significantly smaller than that of other magnetic materials used for micromachining, such as nickel (207×10^9 N m^{-2}) or iron (208×10^9 N m^{-2}) [19]. Using the weighted average, we estimate Young's modulus of the FPR prepared by suspending nickel nanoparticles (5% by weight) in photosensitive epoxy SU8 (95%) to be $\sim 13 \times 10^9$ N m^{-2}. The small Young's modulus of FPR means that a suspended structure made of this material is compliant, and has a larger range of motion than one made from nickel or iron under the same actuation force.

Composites of magnetic materials and photosensitive epoxies have been explored previously [4, 5, 9]. Dutoit *et al* [20] used Sm_2Co_{17} powder with nominal grain size of 10 μm suspended in SU8 to make photo-definable magnets for a variable-reluctance position sensor. The mechanism responsible for forming the structure in that work was fundamentally different from that which we use. In the process developed by Dutoit, the magnetic particles shadowed the area immediately underneath them. Upon exposure with UV light, the particle-free areas cross-linked into a matrix that held the magnetic particles and the unexposed shadowed areas underneath them. Effectively, the unexposed parts were 'trapped' in the structure. This mechanism limits the usage of this fabrication method to large (significantly larger than the grain size of the Sm_2Co_{17} powder) and rough structures. Also, only negative-base photosensitive epoxies are compatible with this mechanism, since for a positive photoresist, shadowing prohibits the full exposure of the clear areas.

We report the development and characterization of an FPR that exploits reflection/scattering and diffraction of light around nanospheres for full exposure of the photoresist/nanosphere composite. We generated the FPR by suspending nickel nanospheres (80–150 nm in diameter; 1.33%–13.3% by weight) in a commercially-available photoresist (SU8-50). Three phenomena—reflection, scattering and diffraction of light from the nanospheres—assisted in the proper exposure of the photoresist, despite the fact that it contained an opaque additive. Since the wavelength of light used for exposure (365 or 405 nm) was larger than the size of the suspended nanospheres in the photoresist, diffraction and scattering of light allowed for exposure of the volume of photoresist immediately behind the nanospheres (figure 1). Multiple scattering of light from individual nanospheres, and reflections from aggregates, helped further penetration of the light into the FPR.

We have fabricated a number of magnetically-responsive structures—beams, posts and meshes—from the FPR. We discuss fabrication and characterization of a set of magnetically actuated micromirrors in detail as an application of this method.

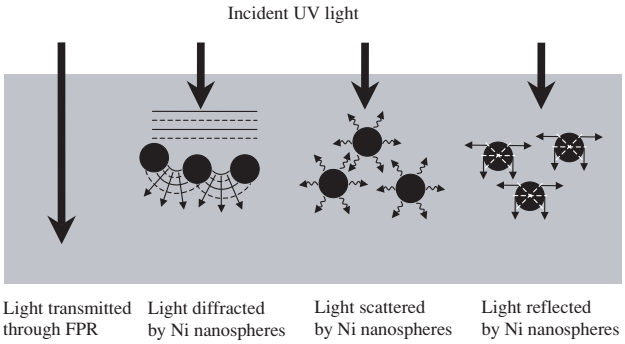

Figure 1. Exposure mechanisms of the FPR: transmission, diffraction, scattering and reflection by Ni nanospheres.

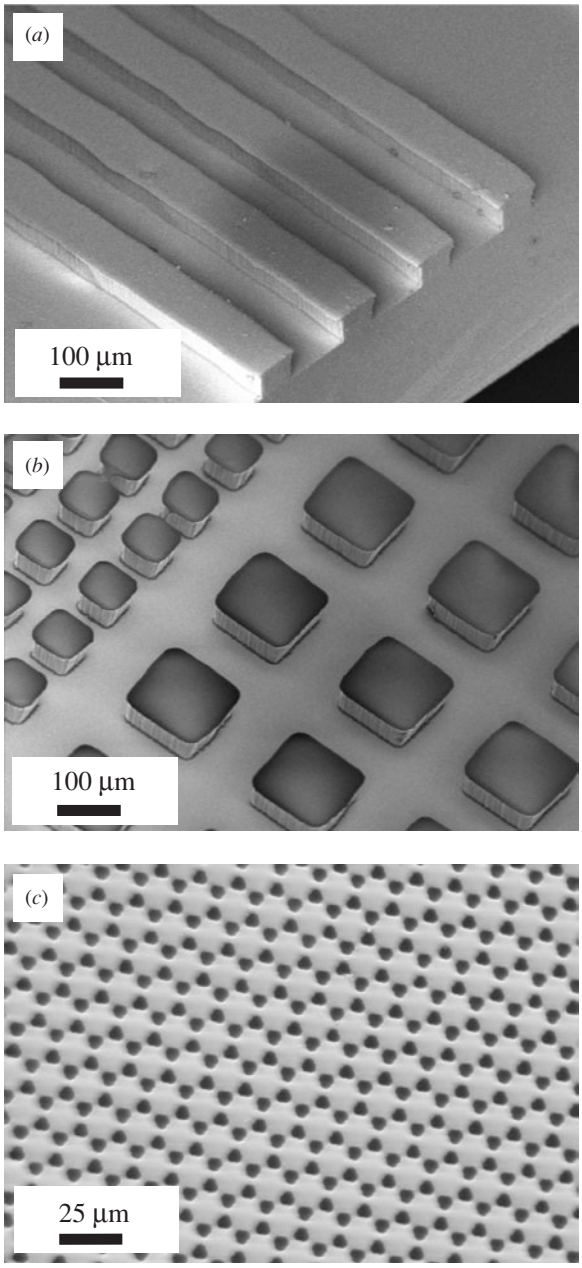

Figure 2. Scanning electron microscope images of structures made of FPR-1. (*a*) Lines. (*b*) Square posts of various sizes. (*c*) 15 μm thick filter mesh.

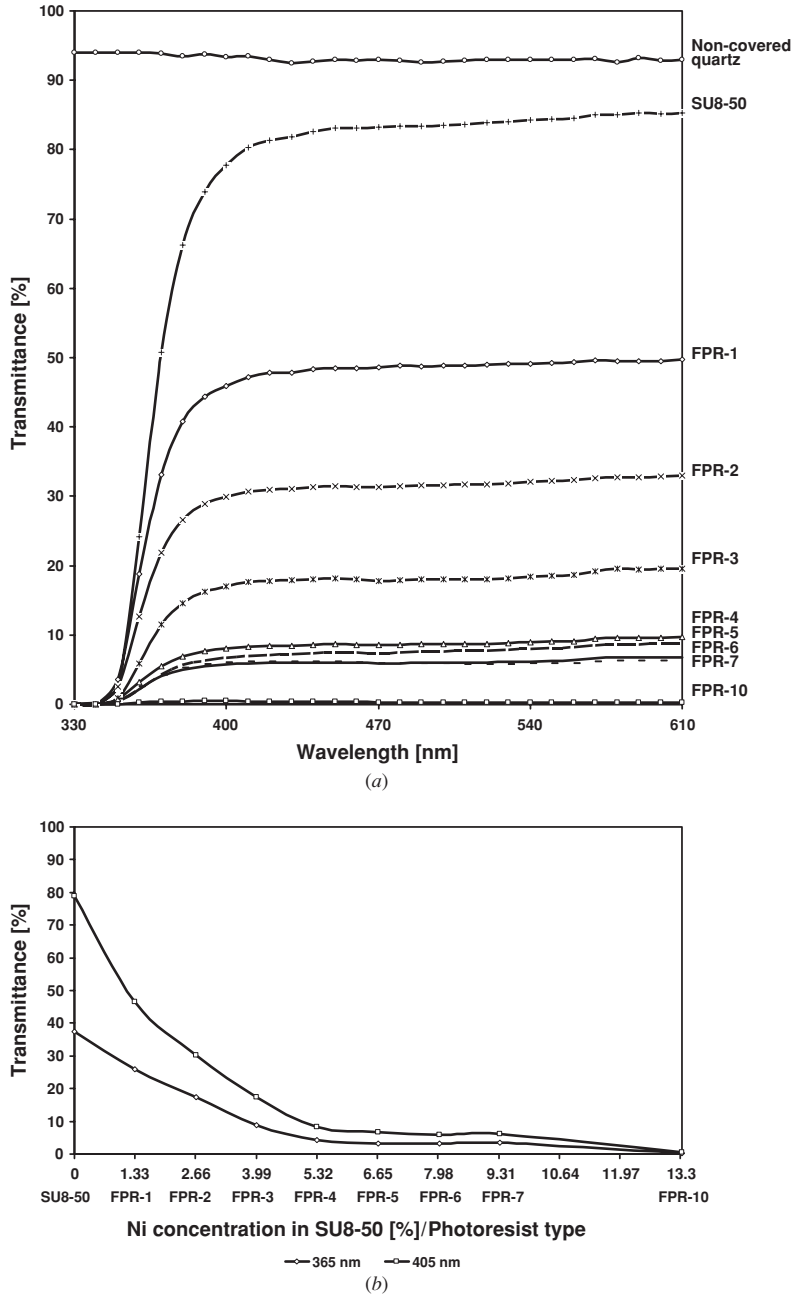

Figure 3. (*a*) Measured transmittance of 70 μm thick FPR-*n* ($n = 0, 1, \ldots, 7$, and 10) on quartz disks. Five points on each disk were measured; the deviation between these measurements was less than 2% for each wavelength (not shown in the figure). (*b*) Measured transmittance of processed FPR-*n* at wavelengths 365 nm (I-line) and 405 nm (H-line) as a function of the nickel concentration (data extracted from figure 4(*a*)).

2. Preparation and characterization of the FPR

We prepared the FPR by mixing (by hand) the two components: SU8-50 photoresist (MicroChem, MA, USA) and nickel powder (spherical, APS 80–150 nm, Alfa Aesar, IL, USA) in a glass vial for several minutes (until it yielded a homogeneous suspension). These components were used as received. After mixing, we left the closed vial containing the FPR suspension undisturbed for 12 h to allow bubbles of air to separate. The FPR should be used within 36 h after mixing to avoid settling of the nickel nanospheres. We varied the weight ratio of the SU8-50 and the nickel from (100:1.33) to (100:13.3), this translated to a variation of volume ratios from (100:0.18) to (100:0.018). We will refer to an FPR with the SU8-50/nickel weight ratio of (100: $n \times 1.33$) as FPR-*n*, where $n = 0, 1, 2, \ldots, 10$. Using this notation, FPR-0 refers to the unmodified SU8-50 photoresist.

We have fabricated a number of microstructures using the FPR (figure 2).

In order to measure the optical properties of the ferromagnetic photoresist, we spin-coated 70 μm of various FPR-*n* on 1 in quartz disks (Chemglass, Inc., NJ, USA), and followed the standard processing procedures for SU8-50 of this thickness. This standard process included pre-baking,

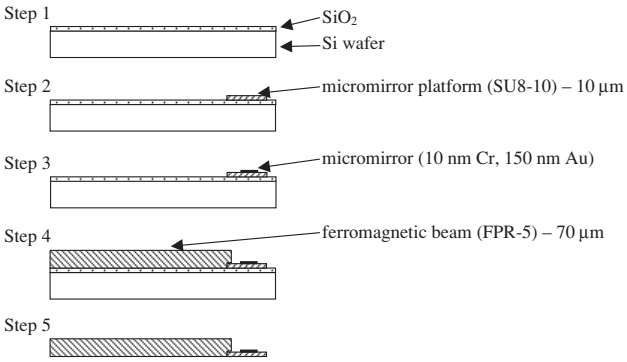

Figure 4. Cross-section of the fabrication process for the magnetically-actuated micromirror. Main steps include: (1) thermal growth of silicon dioxide; (2) patterning the micromirror platform; (3) forming the micromirror; (4) fabricating the beam from FPR and (5) releasing the cantilever.

exposure, post-baking, developing and hard-baking. We measured the transmittance spectra of the quartz disks coated with FPRs using an HP 8453 UV–visible spectrophotometer. Figure 3 shows the results of the measurements. As expected, increasing the Ni concentration led to a decrease in the transmittance across the entire spectrum. We used the information from figure 3 to optimize the exposure time of each FPR-*n*.

3. Fabrication and characterization of magnetically actuated micromirrors

In order to show the utility of the FPR for fabrication of magnetically-responsive microstructures, we designed and fabricated a set of micromirrors supported on cantilevers made of the FPR. We used an external magnetic field to actuate the cantilevers, and thus to change the position of the micromirrors. Figure 4 outlines the steps involved in the fabrication of the cantilevers. The process started on blank silicon wafers by a 10 h dry oxidation at 1000 °C to grow 0.2 μm of silicon dioxide. We used SU8-10 to pattern a 10 μm thick platform used to support the micromirrors. Then we made the micromirrors by patterning the wafer with a 20 μm layer of Shipley 5740 photoresist (MicroChem Co., MA, USA), thermally evaporating 10 nm of chromium (used as an adhesion promotor) followed by 150 nm of gold, and lifting-off in acetone. We used FPR-5 to make the 70 μm thick ferromagnetic cantilever. In order to release the structure

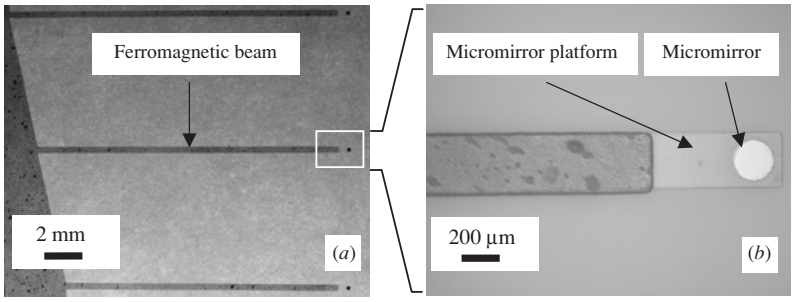

Figure 5. (Top view) Optical microscope images of the magnetically actuated micromirrors after release. (*a*) A set of three cantilevers, 10 mm, 11 mm and 12 mm long. The micromirrors are at the end of each cantilever. (*b*) Close-up image of the end of a cantilever, showing the circular micromirror and the supporting platform.

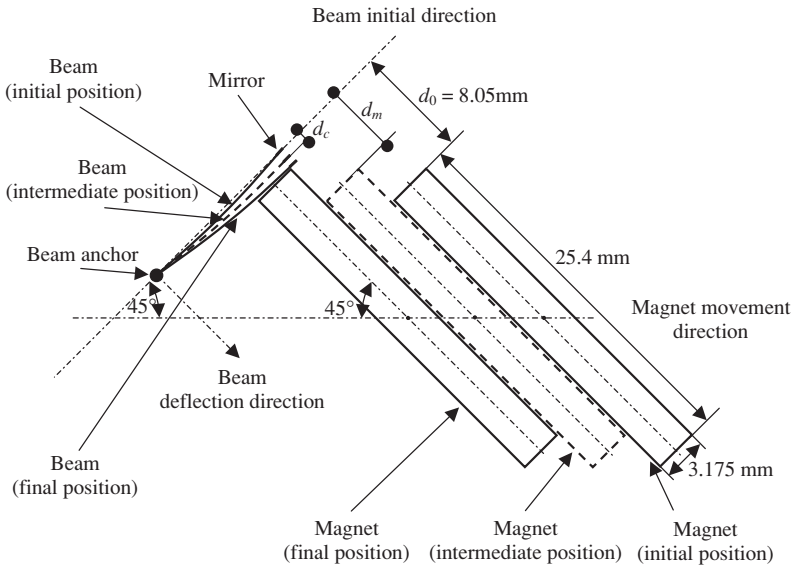

Figure 6. Sketch of the experimental set-up for the determination of the deflection of the cantilever versus displacement of the permanent magnet. In the final position of the magnet, the magnet is in physical contact with the cantilever.

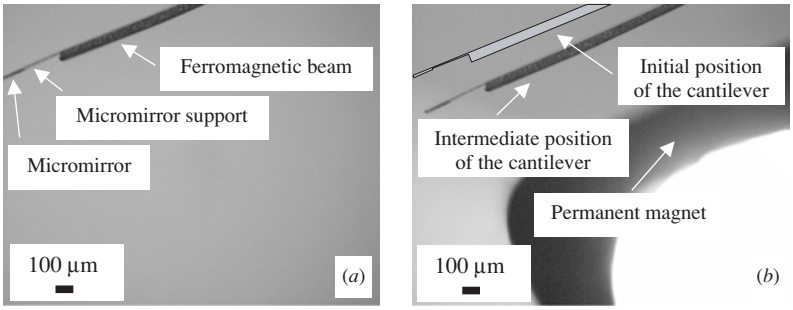

Figure 7. (Side view) Deflection of the tip of the cantilever as the permanent magnet approached. The micromirror was positioned at the tip of the cantilever on the supporting platform. The other end of the cantilever was anchored (not shown in the figures). (*a*) Initial position of the cantilever. (*b*) Intermediate position of the cantilever and of the permanent magnet.

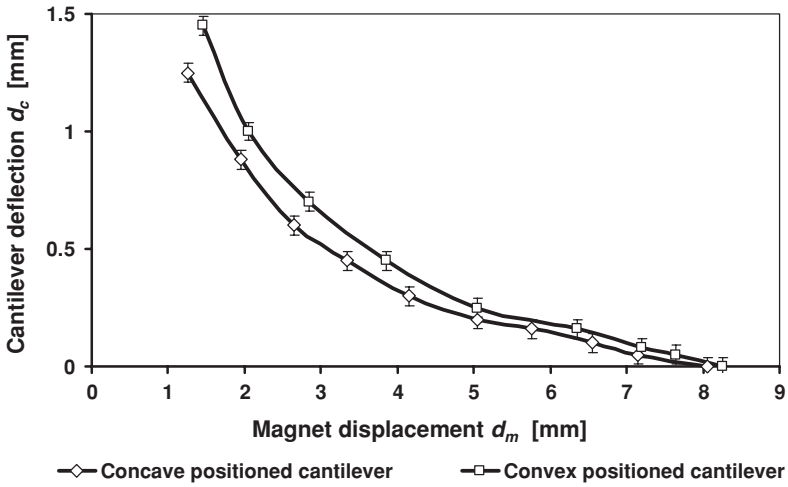

Figure 8. Deflection of the cantilever (d_c) versus distance between the permanent magnet and the initial position of the cantilever (d_m). The initial value of d_m was $d_0 = 8.05$ mm when the magnet was facing the concave side of the cantilever and $d_0 = 8.25$ mm when the magnet was facing the convex side of the cantilever. For both situations we moved the permanent magnet back and forth, the deviation between these pairs of deflection measurements was less than 40 μm for each position of the permanent magnet.

from the surface of the wafer, we immersed the wafer in a 48% HF solution for 2 h. The exposure to HF completely removed the sacrificial silicon dioxide layer and released the structure. We completed the fabrication process by a final rinse with de-ionized water. Figure 5 shows the results of the fabrication.

Due to the residual intrinsic stress, the cantilevers had a finite radius of curvature after the release. For cantilevers 70 μm thick and 12 mm long, this radius was 559 mm $\pm$ 10 mm. The initial curvature made the stiffness of the cantilevers anisotropic.

In order to actuate the micromirrors magnetically, we anchored the cantilevers at one end with a pair of tweezers, and brought the permanent magnet (NbFeB 36, 1 in $\times$ 0.5 in $\times$ 0.125 in, Edmund Scientific's, Tonawonda, NY, USA) close to the other end (figure 6). We measured the distance between the magnet and the micromirror, and also the deflection of the cantilever under an optical microscope. We held the magnet at a 45° angle with respect to the cantilever to maximize the field gradient (see supplemental material for characterization of the magnetic field). Figure 7 shows two optical images depicting this experiment. In the final position, the cantilever touched the magnet. Figure 8 presents the measured deflection of the cantilever as a function of the distance between the cantilever and the permanent magnet. The magnitude of the deflection was dependent on the direction from which the magnet approached the cantilever. We observed large deflections (more than 1.4 mm at the end of a 12 mm long cantilever) for the field strength of $\sim$120 mT. This observation confirms that by using the FPR, one can successfully fabricate compliant, magnetically-responsive microstructures.

We also tested the behavior of the cantilever during and after its deflection over many cycles. The cantilever was cycled $\sim 10^6$ times with an electromagnet. We did not observe any changes in the mechanical properties of the cantilever after this cycling (see supplemental material for details of this experiment).

4. Conclusions

We have demonstrated a simple method for making a ferromagnetic photoresist that can be used as a structural material in MEMS. We prepared this photoresist by mixing a photosensitive epoxy (SU-8) with nickel nanospheres. Using nanospheres with nominal diameters (80–150 nm) smaller than the wavelength of light employed for photopatterning (365 nm or 405 nm), and relying on diffraction, scattering and reflection of light from the nanospheres, we were able to expose the composite material fully. This photoresist is particularly useful

for one-step fabrication of flexible microstructures, and for rapid prototyping of micromagnetic systems. The photoresist allows us to control all three dimensions of the fabricated ferromagnetic microstructures with the precision allowed by the lithographic procedure.

After cross-linking, the photoresist can be used as a stable structural material. We have made various compliant magnetically-responsive microstructures in the ferromagnetic material. The effective Young's modulus of these structures is more than one order of magnitude smaller than similar structures made with nickel or iron. This photoresist combines magnetic responsivity and mechanical compliance in a single structure. A potential drawback of using the photoresist is the reduced magnetic response. A low nickel concentration photoresist may not generate sufficient force for deflection in a small magnetic field gradient. On the other hand, a high nickel concentration photoresist may not be compliant enough to achieve large deflections. The trade off between the compliance of the structure and the magnetic response can be tuned by changing the volume ratio of polymer to nickel in the photoresist composite depending on the application. The structures made with the photoresist were also resilient to degradation due to cycling. We were able to cycle (deflect and release) cantilevers carrying micromirrors $\sim 10^6$ times with an electromagnet without observing any change in the mechanical properties of the structures. We believe that this method for one-step fabrication of highly compliant, magnetically-responsive microstructures can find applications in various devices ranging from optical MEMS to reconfigurable filters in microfluidic channels.

Acknowledgments

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Supplementary material. Experimental details are available from stacks.iop.org/JMM/15/29.

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