Micromachined Magnetic Actuators Using Electroplated Permalloy

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Abstract—Results on design, fabrication, and testing of silicon micromachined magnetic actuators are presented. Electroplated, low-stress permalloy (Ni$_{80}$Fe$_{20}$) material is the medium for magnetic interaction and force generation. The permalloy piece is supported by a structural plate, which consists of polycrystalline silicon thin film prepared by low-pressure chemical vapor deposition (LPCVD). Magnetic actuators supported both by cantilever beams and by torsional beams can provide large force (on the order of 100 $\mu$N) and large displacement (on the order of 100 $\mu$m). The vertical loading force of magnetic actuators under external bias have been experimentally determined. Applications of such actuators in magnetically assisted levitation and parallel assembly of three-dimensional structures are demonstrated.

Index Terms—Magnetic actuators, permalloy.

I. INTRODUCTION

MICROMACHINING technology and microelectromechanical systems (MEMS) have been undergoing dynamic development in the past 15 years [1], [2]. The characteristic length scale of micromachined devices ranges from micrometer to millimeter. MEMS offers unique advantages including miniaturization, mass fabrication, and monolithic integration with microelectronics. It has enabled successful demonstration of novel sensors, actuators, and systems in many diverse application areas such as optics [3], fluid mechanics [4], biological and medical science [5], communication [6], information storage [7], and more.

Force, torque, displacement, or strain can be generated using a variety of energy-transduction mechanisms. Among them, the electrostatic interaction, magnetostatic interaction, bimetallic thermal expansion, and piezoelectric effects are the most widely used. The relative merits of these mechanisms are summarized in the following. Electrostatic interaction is the most prevalent technology; it has been used in micromachined sensors and actuators, including accelerometers [8] and microoptical components [3]. Although the implementation of electrostatic mechanisms is generally simple and compatible with integrated circuit processes, the magnitude of electrostatic force decreases rapidly as the spacing between electrodes increases. Electrostatic actuation therefore cannot generally provide large force (approximately 100 $\mu$N) over a long range of displacement (>10 $\mu$m). This can be illustrated with the example of a parallel-plate capacitor, a fundamental configuration for electrostatic sensors and actuators. Assume such a capacitor with an overlapping area of $A$ and an electrode spacing of $d$, the magnitude of the attractive electrostatic force is linearly proportional to $A$ and inversely proportional to $d^2$. Other configurations of electrostatic actuation (e.g., interdigitated comb fingers) suffer from similar limitations. The magnitude of voltage applied to electrostatic actuators is also restricted in order to avoid electric breakdown under high electric field or to comply with integrated-circuits conventions. Actuation based on bimetallic thermal expansion, on the other hand, typically exhibits high level of energy consumption (e.g., more than 50 mW per device) and a slow time response. With regard to piezoelectric actuation, the energy-coupling coefficient and the maximum strain of existing materials are still small. The compatibility of existing high-performance piezoelectric films with conventional IC and MEMS processes remains an active and challenging research topic. More detailed discussions of various microactuation methods can be found in [9].

Compared with aforementioned methods, magnetic actuation is uniquely capable of realizing large force along with large displacement. Many materials typically encountered in MEMS (e.g., silicon and silicon dioxide) have low magnetic susceptibility and do not develop appreciable internal magnetization. As these materials are transparent to magnetostatic field, magnetic components can be activated using a globally applied, external magnetic field. In contrast, the electrical susceptibility ($\chi_e$) of most materials are greater than zero (e.g., $\chi_e$ of silicon is 10.7); therefore, electric field lines usually cannot penetrate material layers without significant shielding. In addition, high magnetic field (0.01 to 1 Tesla) is not associated with material damages whereas high electric field is likely to introduce dielectric breakdown.

Several groups have published results on micromachined magnetic actuators in the past. Wagner et al. [10] manually attached precision-machined permanent magnet pieces on suspended plates. Integrated in-plane coils on the same chip generate an external magnetic field. However, such a permanent-magnet piece can only be achieved through discrete assembly and is not suited for integrated fabrication and packaging. Liu et al. developed an integrated coil-type magnetic actuator capable of achieving large out-of-plane vertical displacement (on the order of several hundred micrometers) [11], [12]. A torque is generated via the interaction between an external magnetic field and the magnetic moment produced by the planar electric coil. Unfortunately, coil-type actuators typically require large biasing electric current (>50

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A high level of current, coupled with great wire length and, hence, electric resistance (typically >20 Ω), can cause significant ohmic heating and power loss. Judy et al. demonstrated in-plane motion of a suspended polycrystalline silicon structure with an electroplated magnetic piece [13]. The actuator achieved large deflection angle (over 180°) under a torque of approximately 0.185 Nm. An out-of-plane microactuator based on a similar principle has also been realized [14] by the same group. Recently, Miller et al. [15] and Judy et al. [16] have demonstrated permalloy magnetic actuators capable of individual addressing. In addition to unit actuators, complex electromagnetic subsystems, including planar electromagnets [17] and magnetic micromotors [18], have also been developed.

In this paper, results on the design, fabrication, and testing of surface micromachined magnetic actuators are presented. The actuators are supported both by cantilever beams and by torsion beams. The latter is similar to actuators discussed in [14]. Applications of magnetic actuation in levitation and assembly are discussed.

II. THEORIES OF OPERATION

Schematic diagrams of two types of developed actuators are shown in Fig. 1. A common component of these actuators is a thin-film structure plate that supports an electroplated permalloy piece, which generates mechanical force and torque when it is placed within a magnetic field. These actuators are distinguished by the nature of their mechanical supports, which are based on cantilever beams [Type-1 actuator, Fig. 1(a)] and torsion beams [Type-2 actuator, Fig. 1(b)]. Both the structure plates and support beams are made of polycrystalline silicon thin films.

The mechanism of actuation is illustrated using the example of a Type-1 actuator [Fig 1(a)] with key physical dimensions identified in Fig. 2. Three terms, \( L \), \( W \), and \( T \), represent the length, width, and thickness of the magnetic piece, respectively. The cantilever beam is \( l \) long, \( w \) wide, and \( t \) in thickness. When the external magnetic field is zero, the structural plate is parallel to the substrate plane [Fig. 3(a)]. When an external magnetic field \( H_{\text{ext}} \) is applied normal to the plane of the structure plate, a magnetization vector \( M \) develops within the permalloy piece and subsequently interacts with \( H_{\text{ext}} \) [Fig. 3(b)]. The interaction creates a torque (\( M_{\text{mag}} \)) and a small force (\( F \)), acting at the free ends of the cantilever beams and causing these to bend [Fig. 3(c)].

An analysis of the quasi-static characteristics of these actuators is provided in the following two sections. The torque \( M_{\text{mag}} \) and force \( F \) due to magnetic interaction will first be analyzed. The overall displacement of the actuator is then derived.

A. Torques and Forces Due to Magnetic Interaction

The easy axis is predominantly determined by the geometric shape of the permalloy piece [14]. For the actuator shown in Fig. 2, the lateral dimension of the permalloy piece is much greater compared with its thickness; the easy axis is parallel with the plane and perpendicular to the direction of the thickness. The magnitude of \( M \) depends on the externally applied magnetic field (according to B–H curve) and on the angular position of the magnetic piece. Since the remnant magnetization of the electroplated permalloy material is low, the permalloy piece is considered nonmagnetized when \( H_{\text{ext}} \) equals zero. As \( H_{\text{ext}} \) increases, the magnitude of \( M \) increases until it reaches the value of the saturation magnetization \( M_s \).

Since the permeability of the material is high (\( \mu_r \approx 4500 \)), saturation of magnetization occurs at a relatively low \( H_{\text{ext}} \), which is denoted as \( H_k \).

Current actuator designs focus on the large-displacement regime and do not involve comprehensive modeling of actuator behavior at low field levels (below saturation). When an external bias is applied, the permalloy material is treated as having a fixed in-plane magnetization with its magnitude being equal to the saturation magnetization \( M_s \). Two force components are generated when the external magnetic field is applied. The magnitude of these two forces, \( F_1 \) (acting at the upper edge) and \( F_2 \) (acting at the lower edge) [Fig. 3(b)], are given by

\[
F_1 = M_s \cdot W \cdot T \cdot H_1 \\
F_2 = M_s \cdot W \cdot T \cdot H_2
\]

where \( H_1 \) and \( H_2 \) are the magnetic field strengths at the top and bottom edges of the plate (\( H_2 > H_1 \) in the current configuration). The magnitudes of \( H_1 \) and \( H_2 \) are linearly dependent on the respective distance to the surface of the electromagnet core.

The structure plate, along with the permalloy piece, has a thickness of \( t + T \). Its moment of inertia \( I \) is proportional to \((t + T)^3\) and is much greater compared with that of the cantilever beam, which has a thickness of \( t \). The structure plate, combined with the permalloy piece, is thus considered as a rigid body. Based on this assumption, the force system is simplified by translating \( F_1 \) to coincide with \( F_2 \). The result is a counterclockwise torque \( M_{\text{mag}} \) and a point force \( F \) (diagramed in Fig. 3) acting on the bottom edge of the structural plate. These are expressed as

\[
M_{\text{mag}} = F_1 L \cos \theta \\
F = F_2 - F_1
\]
The torque always tends to minimize the overall energy in an actuator system by aligning the magnetization with the field lines of the external magnetic field.

B. Displacement of Actuators

The displacement of the actuator at equilibrium is derived by coupling the magnetic torque and force to the support structures. The analysis for both types of actuators is presented in the following.

Type-1 Actuator with Cantilever-Beam Supports: The angular as well as vertical deflections due to $M_{\text{mag}}$ and $F$ are solved independently and the results are linearly superimposed. This simplification is justified because the magnitude of deflection due to $F$ is estimated to be at least one order of magnitude smaller compared with the deflection caused by $M_{\text{mag}}$.

Beam displacement under the $M_{\text{mag}}$ is solved first. The magnitude of the vertical displacement at the free end of the beam is much greater compared with the thickness of the beam; linearized, small-displacement assumptions are no longer valid. The deflection of the cantilever beam is determined by a universal equation [19] that relates the radius
of curvature of the bent beam with the magnitude of $M_{\text{mag}}$ (Fig. 4)

$$\frac{1}{r} = \frac{y''}{(1 + (y')^2)^{3/2}} = \frac{M_{\text{mag}}}{EI}. \quad (3)$$

Here, $x$ and $y$ are the horizontal and vertical coordinates of a point along the cantilever beam at an arc length of $s$, $E$, and $I$ which are the Young’s modulus and the moment of inertia of the cantilever beam, respectively.

The cantilever beam assumes the shape of an arc with a constant radius of curvature $r$. The maximum angular deflection occurs at the free end of the cantilever beam ($s = l$)

$$\theta_{\text{force}} = \frac{l}{r}. \quad (4)$$

The $x$ and $y$ coordinates at $s = l$ are

$$x(s = l) = r \sin \left( \frac{l}{r} \right)$$

$$y(s = l) = r \left[ 1 - \cos \left( \frac{l}{r} \right) \right]. \quad (5)$$

Beam bending due to the force is solved by applying $F$ at the free end of a precurved beam under the influence of $M_{\text{mag}}$. The maximum angular displacement ($\theta_{\text{force}}$) and vertical deflection ($y_{\text{force}}$), both occurring at the free end of cantilever beams, are expressed as

$$\theta_{\text{force}} = \frac{(\pi/2 - 1)FR^2}{EI} \quad (6)$$

$$y_{\text{force}} = \frac{(3\pi/4 - 2)FR^2}{EI}. \quad (7)$$

The overall angular deflection of the beam (at $s = l$) is found by combining (4) and (6)

$$\theta(s = l) = \theta_{\text{force}} - \theta_{\text{force}}. \quad (8)$$

The maximum vertical deflection at the end of the rigid structural plate is

$$y_{\text{max}} = y(s = l) - y_{\text{force}} + L \cdot \sin \theta(s = l). \quad (9)$$

Type-2 Actuators with Torsion-Beam Supports: The above analysis for a Type-1 actuator considers only the pure bending mode under ideal loading conditions. In the pure bending mode, cantilever beams can withstand 180° bending without fracture. However, nonideal external loading conditions occur frequently in many applications such as fluid-dynamical control [4]. Experiments have shown that undesirable displacement modes, such as the twisting of cantilever beams, are dominant in causing structural failures in Type-1 actuators.

Type-2 actuators with torsion-beam supports successfully reduce damages generated by twisting motion. These are more robust compared with Type-1 actuators. For a Type-2 actuator, the angular displacement is related to the torque by the following expression

$$M_{\text{mag}} = \frac{2\theta}{l} KG$$

where $\theta$ is the angular displacement experienced by each torsion beam, $l$ is the length of each torsion beam, and $G$ is the torsion modulus of elasticity of the material. $K$ is a constant determined by the specific cross-sectional geometry of the beams; for a torsion beam with a rectangular cross section and an area of $w \times t$

$$k = ab^3 \left[ \frac{16}{3} - 3.36 \frac{a}{b} \left( 1 - \frac{b^4}{12a^4} \right) \right] \quad (11)$$

where $a = w/2$ and $b = t/2$. The force $F$ also creates bending within the support beams that contribute to an out-of-plane translation. However, this displacement is small (due to the fixed-fixed beam boundary conditions) and is typically ignored in our analysis.

C. Summary of Actuator Design

A number of geometric parameters are fixed within our design. The rigid structure plate has a fixed area of $1 \times 1$ mm$^2$. The thickness of the magnetic material is $5 \mu$m. For Type-1 actuators, the typical length and width of the cantilever beam are 400 and 100 μm, respectively. For Type-2 actuators, the width and length of the torsion beam are 2 and 50 μm, respectively.

III. FABRICATION

The fabrication process for a typical magnetic actuator is summarized in Fig. 5. The entire process is divided into five steps and discussed accordingly.

Step 1—Fig. 5(a): A 3-μm-thick phosphosilicate glass (PSG) thin film is first deposited on top of a silicon substrate at 450°C. The thin film functions as a sacrificial material. The PSG layer is patterned using photolithography and then etched using buffered hydrofluoric acid (BHF) to form separated mesas on top of which individual actuators will be located. These mesas isolate individual actuators and limit the total amount of lateral dimension expansion that will result from undercut during the sacrificial-layer etching processing. This feature therefore provides robust process control and results in high structural yield even when overtime sacrificial etch is applied. It also increases the potential area density of actuators by allowing actuators to be placed closer to one another.
After removal of the photoresist layer, the wafer is annealed in a nitrogen ambient at 1000°C for one hour. This step serves two purposes. First, it activates the phosphorus dopant (6 wt.% within the PSG layer and increases its etch rate in BHF. Second, the PSG material reflows slightly at the temperature of the oxidation, creating rounded, smooth profile along the perimeter of PSG mesas. The wafer is then covered by a highly conformal deposition of thin LPCVD polycrystalline silicon. The reflowed profile of the mesas translates directly into rounded corners in structural layers. The rounding alleviates stress concentration and enhances the reliability of actuators.

A 0.5-μm-thick PSG layer is then deposited on top of the polysilicon. It serves as a complimentary doping source. During a 1 h, 950°C stress-relief anneal in nitrogen ambient, the polysilicon is doped symmetrically from both sides by diffusion from the solid source. The symmetric doping reduces the intrinsic-stress gradient across the thickness of the polysilicon and minimizes residue beam bending. The top PSG layer is later removed by using BHF.

Step 2—Fig. 5(b): Before performing the electroplating, an electrically conductive seedlayer must be applied to the front surface of the wafer. The seedlayer contains 200 Å-thick Cr and 1800 Å-thick Cu thin films. Experiments have proven that such thickness is adequate to produce electrical continuity across the entire wafer. The Cr layer enhances adhesion between the Cu and the polysilicon layers.

Step 3—Fig. 5(c): During the plating process, the wafer is affixed to the cathode and the pure Ni piece serves as the anode. An external-biasing magnet (450 Oe) is applied with the field lines being parallel to the wafer substrate. This bias establishes directions of preferred magnetization (easy axis) within the permalloy piece. Electroplating takes place at a rate of 5 μm/h under a bias-current density of 8 to 12 mA/cm². Two different plating techniques are available: mold plating and frame plating. In the mode-plating technique, photoresist covers all area of the wafer except where permalloy is intended. In the frame-plating technique, which is applied in this study, plating occurs only where a majority portion of the wafer area, including regions where the magnetic material is not intended. Narrow photoresist frames separate these regions. Unintended electroplated material is later selectively removed. The frame-plating technique allows more robust, uniform, and controllable plating over the entire area of the silicon substrate.

Step 4—Fig. 5(d): After electroplating, the wafer is flood-exposed with ultraviolet radiation and the photoresist is removed with a standard photoresist developer. The wafer is further cleaned using acetone and then isopropanal alcohol solutions.

Step 5—Fig. 5(e): The seedlayer that is unmasked by the permalloy is removed by using Cu etchant (100:5:5 wt. water:acetic acid:hydrogen peroxide) and then a Cr-mask etchant. The Cr-layer removal can be accomplished using either a commercial etchant or diluted HCl (Cr etchant:10 water:1 HCl). Actuators are then released by 49% HF within 20 min. To facilitate the sacrificial release process, etch holes (30 μm × 30 μm in area and 250 mm apart) are opened on the plate. The permalloy material sustains HF etching without any structural or chemical damage. It should be noted that the total area occupied by etch holes is small compared with the area of the permalloy plate, therefore the effect of etch holes on the actuation characteristics is ignored.

Since the structure plates have large surface areas and the supporting beams are soft (spring constant ~100 μN/1 mm = 0.1 N/m for cantilever beams), these can be easily pulled down by surface tension to the substrate and form permanent bonds if conventional drying techniques are used. To ensure high yield, the structural plate is levitated away from the substrate surface through magnetic interactions. This method effectively prevents the actuators from coming into contact with the substrate, therefore guaranteeing that 100% yield is routinely achieved. More details of the release technique will be reviewed in Section V-A.

1 Cr mask etchant, Transene Co., USA.
Magnetic Properties of the Permalloy Material: The electroplated permalloy has a composition of 80% Ni and 20% Ir. It exhibits low residue mechanical stress, which is crucial for large-area flaps to remain flat. The low-stress permalloy material has a polycrystalline structure and contains a large number of magnetic domains. Each magnetic domain has \(10^{10} - 10^{15}\) atoms and is spontaneously magnetized in one direction at room temperature. The directions of magnetization of different domains are randomly organized. Despite this, there are directions of easy and hard magnetization, a phenomena called crystalline anisotropy. \(H_k\) is defined as the magnetic field intensity needed to saturate a soft magnetic material in a specific direction (Fig. 7). In the direction of easy magnetization, the easy axis \(H_{k_{\text{easy}}}\) of the hysteresis is smaller than the \(H_k\) along the hard axis (\(H_{k_{\text{hard}}}\)). Experimental B–H hysteresis curves along the easy axis and the hard axis are shown in Fig. 7. The material exhibits a somewhat small difference between the magnitudes of \(H_k\) in the easy and hard axes. During the NiFe electroplating, the direction of the biasing magnetic field dictates the orientation of the easy axis [23], [24]; domain walls move in such a manner that domains favorably oriented with the magnetic field grow at the expense of unfavorably oriented domains. Therefore, the direction parallel with the external magnetic field during the plating process is the easy axis while the orthogonal in-plane direction is the hard axis. This phenomenon has been studied by Takahashi [23]; it has been found that an external field of \(H \geq 30\) Oe is sufficient to induce the direction order. In addition, shape anisotropy plays a dominant role in determining the properties of the magnetic material and actuation. Measured properties of the electroplated magnetic material are summarized in Table I.

IV. TESTING

Actuation is quantitatively characterized by using a microscope-monitoring system (Fig. 8). A magnetic field is provided by an electromagnet which has a cross-sectional core area of \(3 \times 3\) cm\(^2\). The variation of \(H\) with respect to the vertical spacing (\(d\)) to the surface of the magnetic core is calibrated experimentally. Near the surface of the core (\(d < 2.5\) mm), the magnitude of \(H\) is nearly linear with respect to the spacing \(d\)

\[
H = 14 \times 10^4 - 28 \times 10^4 d. \tag{12}
\]

The units of \(d\) and \(H\) are mm and A/m, respectively. In their resting positions, actuators are separated from the electromagnet by a distance of 0.5 mm, which is the thickness of the silicon substrate.

Fig. 9 contains a sequence of video images showing the side profile of a Type-1 actuator at the resting and activated positions. The angular and vertical displacement of the actuator is measured directly from the side profile of the actuator. Fig. 10 shows the measured deflection magnitude, together with theoretical predictions obtained using (8) and (9). Results from theory and experiments match well in the regime of large displacement (beyond magnetic saturation).

The behavior of magnetic actuators in low field situations is also experimentally characterized (Fig. 11). An actuator is first activated with the magnetic field increasing in one polarity. The polarity is then reversed and the magnitude of the magnetic bias is increased again. The angular-deflection curves for both cases highlight a peculiar bend at the low field level (\(H\) below \(12 \times 10^3\) A/m). This lowered angular displacement is contributed by the switching of the magnetic domain.

The maximum response speed of a magnetic actuator is studied. The time constant is currently not limited by the domain switching process, which dominate the establishment of magnetization and has a typically time constant on the order of one picosecond. Rather, the maximum response speed is limited by the electromagnet that is modulated using mechanical switches. The relatively large size and inductance of the electromagnet increases the time constant, which has been measured to be between 1–10 ms. The time-constant measurement was conducted by using a miniature secondary
coil placed on the front surface of the core. If higher response speed is intended, magnets with smaller inductance must be developed.

To measure the vertical force-loading capacity of actuators under the current experimental conditions, a 5 × 5 array of actuators is used to hold controlled weights, in the form of precision cut silicon chips. A magnetic field [following (12)] is applied to activate the entire array. Silicon chips of known weights are sequentially stacked on top of raised actuators, until the actuator array can no longer hold against the stack weight and drops to the substrate plane. The amount of weight that can be held by an array of actuators in their fully raised position is defined as the maximum vertical loading capacity (MVLC). The measured MVLC weighs 222 mg, or 2.18 mN. This translates into roughly a maximum loading force of 87 μN (or 8.88 mg) for each actuator, which has a mass of only 44.5 μg itself. It should be noted that the loading capacity is a function of the angular position. At lower displacement angles, the MVLC would produce more torque and therefore cannot lift by the actuators from their rest positions.
Fig. 10. Angular and vertical displacement of the structure plate with respect to the biasing magnetic field intensity \( H \). (a) Theoretical and experimental rotation angle \( \theta \) and (b) vertical deflection \( y_{\text{max}} \). The size of the plate is 1 \( \times \) 1 mm, the beam length and width are 400 and 100 \( \mu \text{m} \), respectively. The beam thickness is 1 \( \mu \text{m} \).

Fig. 11. Hysteresis behavior of a Type-1 actuator under forward and reverse biasing conditions.

In pure bending modes, actuators with cantilever beam and torsion beam supports can achieve more than 180\(^\circ\) displacement without fracture. Fracture strain equals to 0.93\% according to an early report by Tai et al. [25]. This unique characteristic is due to the reduced thickness of the cantilever beam.


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V. APPLICATIONS

Developed magnetic actuators have been used in magnetic-assisted levitation (for surface structure release), massively parallel assembly of array MEMS, fluid dynamic control [4], and active robotics surfaces. The first two applications are outlined in Sections V-A and V-B.

A. Magnetic Assisted Levitation

Successful use of array MEMS devices demands a robust, efficient, and high-yield fabrication process. Surface micromachined devices are typically developed using sacrificial-layer-etching techniques. Devices are freed by removing the underlying sacrificial layer in a wet chemical ambient (e.g.,
concentrated HF solution for removing PSG). Following the wet etching, a drying process must be performed. This step has the potential of causing significant yield losses due to stiction (sticking and friction). The mechanism for stiction is the following: during the drying process, the liquid on top of a free-standing structure will evaporate first; liquid that is trapped underneath structures remains temporarily and exerts a full-down force due to surface tension. Because surface microstructures are located close to the substrate (with spacing of only several \( \mu m \)) and are typically compliant (with spring constant \(<1 N/m\)), the pull-down force is capable of drawing the structure into intimate contact with the substrate. In many cases, this contact produces permanent bonding and irreversible sticking. The probability of stiction damage increases with decreasing structural stiffness and increasing surface-contact area.

Previously published results on antistiction techniques focus on the following methodologies. First, certain post-release chemicals modify the surface-layer composition [26] and prevent sticking by chemical bonds. Second, the liquid-vapor phase transformation, which is the cause of the surface-tension force, can be replaced by a freeze-sublimation procedure [27]. Third, microstructures can be kept away from the substrate during release/drying by solid organic polymer columns, which are then removed by plasma dry etching [28]. Other novel techniques include using special antistiction geometry [29], applying pulsed magnetic forces to relieve stuck structures [30], and using gas phase etchant for sacrificial-layer removal [31].

In practice, many microstructures have relatively large surface areas (e.g., \( >1 \times 1 \text{ mm}^2 \)). The probability of stiction-induced damages is higher, as demonstrated by an initial low yield (<10%) for Type-1 actuators when no specific drying technique was applied. To achieve high-yield drying for large-area structures, a novel drying process has been developed. During the liquid-removal step, freestanding structures are actively levitated out-of-plane; the liquid is removed, after which suspended structures are returned to the substrate plane. This method prevents stiction because levitation force counteracts the surface tension force so microstructures and the substrate will never come into contact. This process requires that an additional patch of permalloy material be integrated with individual microdevices.

Effectiveness of this method is demonstrated using developed Type-1 magnetic actuators. Fabricated test structures (so called dies) were first immersed in HF solution (40%) for 10 min to remove the sacrificial layer. These wet dies are then transferred directly to deionized (DI) water and then immersed in a final rinse solution, which is one of the following chemicals: isopropyl alcohol, methyl alcohol, acetone, or water. Wet dies are placed within the magnetic field of an electromagnet and air-dried. The result shows that 100% yield is routinely achieved.

B. Parallel Assembly of MEMS

MEMS technology is inherently characterized by efficient mass production and three-dimensional (3-D) structures. Arrayed MEMS devices will offer unique advantages that are unavailable in macroscopic, conventional systems, and singular microdevices. Very-large-scale-integrated circuits (VLSI) exemplifies the tremendous benefits offered by array operation
of modular components (e.g., transistors). Nowadays, many MEMS devices are developed based on fundamentally two-dimensional (2-D) fabrication techniques. In order to realize true 3-D structures, a fabrication process for developing 3-D devices from as-fabricated, 2-D layers is required. Such a process must offer a global (instead of local) addressability. Because the magnetic field can penetrate the substrate layer with little loss, it is uniquely suited for this application. We have developed a new process in which microstructures can be deployed by magnetic actuation to form complex 3-D structures (Fig. 12).

VI. CONCLUSIONS

Design, fabrication, and testing results of surface micromachined magnetic actuator has been presented. Electroplated permalloy material is used to provide magnetic interaction and generate force/torque. The magnetic actuators are mechanically supported by flexural cantilever beams and torsion beams. The advantage of magnetic actuators is to satisfy requirements for large force and large displacement simultaneously. Experiments have demonstrated vertical loading capacity on the order of 87 μN per device and large displacements. These unique actuation characteristics have enabled high-yield release/drying of surface microstructures and parallel assembly of 3-D structures.

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