Plastic Deformation Magnetic Assembly (PDMA) of Out-of-Plane Microstructures: Technology and Application

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Abstract—This paper presents results on the development and application of a three-dimensional (3-D) microstructure assembly technique—Plastic deformation magnetic assembly (PDMA). In PDMA, certain part of the microstructure to be assembled is plastically deformed by the magnetic force generated from the interaction between a magnetic material piece deposited on the microstructure and an external magnetic field. As a result, the entire microstructure can remain at a rest angle with respect to the substrate surface due to the plastic deformation. The amount of plastic deformation and the rest angle are found to be strongly dependent on the properties and the geometric parameters of the deformation region of the microstructure and also the magnetic material piece. A general design rule for PDMA has been given. PDMA is capable of batch-scale assembly. It has been successfully applied to fabricate novel micromachined devices with high yield and good controllability. As an example, the results of a novel vertical planar spiral inductor realized by the application of PDMA have also been presented in the paper.

Index Terms—Magnetic actuation, plastic deformation, three-dimensional (3-D) assembly, vertical inductor.

I. INTRODUCTION

In the past few years, three-dimensional (3-D) microdevices have been achieved through the assembly of two-dimensional (2-D) surface micromachined planar structures. Applications include free-space beam steering reflectors [1], tunable Fabry–Pérot etalons [2], and corner cube reflectors [3], etc. The most commonly used technique is micromachined hinges [4]. To achieve stable 3-D assemblies, multiple hinged flaps are rotated off the substrate surface simultaneously. With special latching components, these flaps will be able to contact and support each other to form the required 3-D structure. Different actuation schemes, such as turbulent fluid flow and dedicated on-chip microactuators (e.g., thermal [5] and electrostatic actuator [6]) have been devised to render the assembly process. However, dedicated microactuators have relatively large footprints. Incorporating microactuators will sacrifice the time. In a more recent work, photoresist was used to reduce the temperature required by the assembly process [15].

In this paper, the results of the development and application of a new alternative assembly process—plastic deformation magnetic assembly (PDMA) are presented. PDMA has several unique advantages: 1) it only requires one structural and one sacrificial layer; 2) good electrical connection between the out-of-plane structures and the substrate can be built if metal is chosen as the plastic deformation material [16]; 3) it is a room temperature process without mechanical slacks. Experiments show that an efficient batch-scale assembly of novel microdevices can be achieved with a high yield and good controllability by using PDMA.

II. THE PDMA PROCESS

The basic PDMA process is illustrated in Fig. 1. A surface micromachined planar flap with a flexible region is used as an example to describe the essential steps. The planar flap with a piece of magnetic material is fabricated and released from the substrate surface in a predetermined sequence, so that the assembly of complicated 3-D structures is possible. Since the Permalloy piece is directly attached onto each flap, the additional substrate space for the actuator is then not required. This actuation method is space-efficient and capable of addressing a batch-scale assembly in parallel.

The hinged structure assembly process has several inherent disadvantages. First, it requires multiple structural and sacrificial layers to fabricate the microhinged flaps. Second, there is mechanical slack in the hinges after the flaps are released, which may incur unwanted movement of the flaps after the assembly. Finally, it is difficult to create a good electrical connection between the assembled out-of-plane flaps and the substrate.

Recently, 3-D structure assembly processes using surface tension as the actuation force have also been reported. The surface tension force is provided by the phase change of low melting point materials, such as solder and organic polymers (e.g., photoresist). Surface micromachined flaps with or without hinges were rotated off the substrate surface and then fixed at a certain angle by the melting and then freezing of solder pads [12], [13] or solder ball bumps [14]. The rotation angle of the assembled flaps was reported to be affected by many factors, including the shape, volume and composition of the solder piece, the reflow temperature and time. In a more recent work, photoresist was used to reduce the temperature required by the assembly process [15].

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When an external magnetic field \( \mathbf{H}_{\text{ext}} \) is applied, the magnetic material piece will bend the planar flap off the substrate due to the magnetic field acting on the magnetic material piece, as well as the applied external field \( \mathbf{H}_{\text{ext}} \). We have conducted experiments to establish a design rule for the plastic deformation by fabricating and testing a series of gold cantilever beams with electroplated Permalloy (Ni\(_80\)Fe\(_{20}\)) pieces.

### A. Fabrication of the Testing Structures

The fabrication of the gold cantilever beams begins with a silicon nitride coated silicon substrate. First, a 0.5-\(\mu\)m-thick silicon oxide is deposited by using PECVD (plasma enhanced chemical vapor deposition) and patterned, which serves as the sacrificial layer. Second, a 200-Å-thick chromium film followed by a 0.5-\(\mu\)m-thick gold film are deposited by using thermal evaporation and then patterned to make the cantilever beam. Third, a piece of Permalloy is electroplated onto the gold cantilever beam. Finally, the oxide sacrificial layer is etched completely in HF (hydrofluoric acid, 49%) solution to free the gold cantilever beam. The entire substrate with the fabricated cantilever beams is dried in a super critical carbon dioxide dryer. In this case, the magnetic actuation for the gold cantilever beams can be conducted in the air. However, this drying step is not necessary in a standard PDMA process. The scanning electron micrographs of a few fabricated gold cantilever beams (before and after assembly) are shown in Fig. 2. A large plastic deformation has been created in the bending region (10 \(\mu\)m long) of these cantilever beams during the magnetic actuation so that they can stand almost vertically above the substrate (corresponding to a rest angle value \(\phi\) of nearly 90\(^\circ\)).

### B. Test Setup

A schematic diagram of the test setup for the characterization of PDMA is shown in Fig. 3. The geometric parameters of the tested gold cantilever beams with the attached Permalloy pieces are listed in Table I. An industrial strength electromagnet is used to provide the necessary external magnet field \( \mathbf{H}_{\text{ext}} \). In the center of the magnetic core, the magnetic field is uniform and perpendicular to the upper surface of the electromagnet. The projection height \( h \) of the bended gold cantilever beam is measured using a Mitutoyo digital indicator attached to the objective lens stage of a microscope. The indicator has a displacement resolution of 1 \(\mu\)m. The projection height is measured by using the following method. The microscope is first focused on the substrate surface to establish the measurement reference. Next, it is focused at the free end of the bended cantilever beam. The projection height value is obtained from the reading of the indicator. The bending angle can be estimated as

\[
\theta = \sin^{-1}\left(\frac{h}{l_{g} + l_{p}}\right),
\]

where \( l_{g} \) and \( l_{p} \) are the length of the gold bending region and the Permalloy piece, respectively.
Fig. 2. Scanning electron micrographs of gold cantilever beams with electroplate Permalloy pieces used in the characterization of PDMA. (a) Unreleased cantilevers lying in the substrate plane before magnetic actuation. (b) The same structures after the application of PDMA.

IV. ANALYSIS AND EXPERIMENTAL VALIDATION

During the testing, the magnitude of the magnetic field is increased slowly by manually adjusting the input current of the electromagnet, so that the loading is applied in a quasistatic state. The gravitational force is negligible when compared with the magnetic force.

The torque $T_m$ generated on the Permalloy piece by the applied external magnetic field $H_{ext}$ can be estimated by

$$T_m = Mw_p t_p H_{ext} \cos \theta,$$  \hfill (2)

where $M$ is the magnetization of the Permalloy piece, and $w_p$, $t_p$ are the width and thickness of the Permalloy piece, respectively [7]. The value of $M$ increases with $\theta$ until it reaches its saturation value $M_s$ [11]. The value of $M_s$ for the Permalloy we used is 1 Tesla [17].

A. First-Order Estimation of the Bending Angle $\theta$ as a Function of $H_{ext}$

Since the Permalloy piece is 4–7 $\mu$m thick and the thickness of the gold beam is only 0.5 $\mu$m, the Permalloy piece is considered being rigid. Thus, the bending only occurs in the flexible region, which has no Permalloy coverage. The mechanical analysis can be simplified to the deformation of a gold cantilever beam with a torque $T_m$ (determined by (2)) applied at its free end, shown in Fig. 4. The width and thickness of the simplified gold beams are denoted as $w_g$ and $t_g$, respectively. In the following analysis, we assume that this simplified gold cantilever beam has an ideal elastic–plastic deformation behavior. As $T_m$ increases, its bending first remain in the elastic regime and then changes into the plastic regime. The elastic-to-plastic transition occurs when the torque $T_m$ is equal to the yielding moment $M_y$ of the simplified gold cantilever beam [18], which is defined as

$$M_y = \frac{\sigma_y w_g t_g^2}{4},$$  \hfill (3)

where $\sigma_y$ is the yield stress of the gold cantilever beam.

In the elastic bending regime, the relationship between the bending angle $\theta$ and the torque $T_m$ is determined by [19]

$$T_m = \frac{E_g I_g}{I_g} \theta$$  \hfill (4)

where $E_g$ and $I_g$ are the Young’s modulus and the moment of inertia of the simplified gold cantilever beam.
Equating (2) and (4) yields the relationship between $\theta$ and $a$ given $H_{\text{ext}}$ in the elastic bending regime, namely

$$H_{\text{ext}} = \frac{E_g L_g}{L_g M_{\text{u}} V_p} \frac{\theta}{\cos \theta}$$

where $V_p$ is the volume of the Permalloy piece.

When the bending enters the plastic regime, the torque $T_m$ will be equal to the yielding moment ($M_y$) of the simplified gold cantilever beam. Equating (2), (3) yields the relationship between $\theta$ and a given $H_{\text{ext}}$ in the plastic bending regime, namely

$$H_{\text{ext}} = \frac{\sigma_y M_{\text{u}} L_g^2 }{4 M_{\text{u}} V_p} \frac{1}{\cos \theta}$$

where $\sigma_y$ is the yield stress of gold.

For a given structure, the $\theta$–$H_{\text{ext}}$ curves governing the elastic bending regime can be obtained from (5), whereas the $\theta$–$H_{\text{ext}}$ curve governing the plastic bending regime can be obtained from (6) (Fig. 5). The interception point (yielding point) of these two curves denotes the transition from elastic bending to plastic bending. When $\theta$ is small, the bending is in the elastic regime and $\theta$ increases with $H_{\text{ext}}$ along the elastic curve until it reaches the yielding point. As the bending changes into the plastic regime, $\theta$ increases with $H_{\text{ext}}$ along the plastic curve until it saturates because of the diminishing of the torque $T_m$ at large bending angles.

The Young’s modulus of gold ($E_g$) is found to be 79.4 GPa [20], [21]. However, the exact value of the yield stress of gold ($\sigma_y$) is difficult to obtain, especially for microstructures since they are closely related to the materials as well as the deposition condition. In our analysis, we use a value of 206 MPa obtained from [21] and assume that the stress in the bent gold cantilever beam will remain a constant value of $\sigma_y$ in the plastic regime.

The saturation magnetization ($M_s$) of the Permalloy is 1 Tesla in our experiment. The value of $M$ is smaller than that of $M_s$ at small bending angles because the Permalloy piece is not fully magnetized. A more detailed analysis of $M$ as a function of $\theta$ can be found in [11]. Although the assumption of constant $M$ value introduces a small overestimation of $\theta$ in the elastic regime when $\theta$ is small, we believe that this will not be a major concern for establishing the bending criteria since the analysis is focused in the plastic regime, which occurs at relatively large values of $\theta$.

The bending angle $\theta$ as a function of $H_{\text{ext}}$ is measured for various groups of cantilever beams with different geometries. Fig. 6(a)–(c) shows the measurement result for three groups of gold cantilever beams with different lengths of Permalloy piece ($L_p$): (a) $L_p = 550 \mu$m; (b) $L_p = 650 \mu$m; (c) $L_p = 750 \mu$m. The measured bending saturation angles of $\theta$ are 71.6°, 76.1° and 78.3°, respectively.
are summarized in Table II. The value of \( \theta \) increases with \( H_{\text{ext}} \) and starts to saturate at its maximum value because the \( \cos \theta \) term in the \( T_{\text{m}} \) formula [see (1)] dominates at larger values of \( \theta \). The average saturation angles are 71.6°, 76.1°, and 78.3°, respectively for the three gold cantilever beam groups. Experiments show that in the same magnetic field, larger Permalloy piece can generate a larger torque, resulting a larger saturation value of \( \theta \).

The two \( \theta-H_{\text{ext}} \) curves (elastic and plastic) generated by using (5) and (6) are also plotted in Fig. 6(a)–(c), respectively, to be compared with the corresponding measurement data. The agreement between the theoretical estimation and the measurement results shows that the above analysis is valid for a first-order estimation.

V. The Assembly of Vertical Planar Spiral Inductor by PDMA

The development of wireless communication systems requires high-performance and low-cost components. High-level system integration is necessary to meet this need. One component that is difficult to integrate up to now is the microspiral
Fig. 9. The application of PDMA to realize vertical planar spiral inductor. (a) Scanning electron micrograph of a planar spiral inductor fabricated on the substrate surface before the PDMA assembly; (b) Scanning electron micrograph of the same inductor after the PDMA assembly.

Fig. 10. The measured $S_{11}$ parameter (0–1.1 GHz) of a planar spiral inductor before and after the PDMA assembly: (a) magnitude and (b) phase.

inductor. Although planar spiral inductors can be integrated with other circuits using current standard integrated circuit (IC) fabrication process, their performance is still unsatisfactory. Oftentimes, planar spiral inductors are directly fabricated onto the dielectric layer on top of the conductive substrate, which lowers the quality factors and degrades the performance by introducing extra loss, noise and parasitic capacitance [22]. Another disadvantage of a planar spiral inductor lies in the fact that it has a large footprint to achieve the required inductance value [23]. As an example, Fig. 8 shows the microscopic picture of a voltage controlled oscillator circuit chip with two integrated planar spiral inductors. Each inductor has an inductance value of only 7 nH. However, the two inductors occupy most of the chip area.

In recent years, much effort has been made to reduce the adverse effects from the substrate so as to improve the performance of planar spiral inductors. The methods reported so far include using high resistive substrate [24], coating polyimide to increase thickness of the dielectric layer underneath the inductor [25], partially or completely removing the substrate material underneath the inductor [26]. More recently, surface micromachining technology has been applied in the fabrication of planar spiral inductors to create an air gap between the inductor and substrate [27]. These methods may involve certain materials or fabrication steps, which are not compatible with current standard IC fabrication process. Moreover, none of the methods mentioned above has solved the large footprint problem of planar spiral inductors.

We have successfully applied the PDMA to assemble vertical planar spiral inductors. The entire process is compatible with present standard IC fabrication. The inductor can be monolithically integrated with other circuits even after the IC components have been fabricated. First, the planar spiral inductors are fabricated by using a standard surface micromachining process [see Fig. 9(a)]. This process will be discussed in detail in future publications. Next, PDMA is implemented after all the fabrication steps are finished [see Fig. 9(b)]. The geometric parameters of the planar spiral inductor are specially designed so that the rest angle of the inductor after the assembly is almost 90°. However, the substrate loss and parasitics can still be reduced even if the inductor stays at an angle smaller than 90° off the substrate.

The vertical inductors offer two major advantages over the horizontal ones. First, the vertical inductors have almost zero footprints. This will help to increase the achievable device density and lower the fabrication cost of a radio frequency (RF) circuit chip. Second, the substrate effect is also greatly reduced. Fig. 10(a) and (b) shows the $S_{11}$ measurement results of one planar spiral inductor before and after the assembly. Although the design and fabrication of the planar spiral inductor is not optimized, our measurement result has clearly shown that the inductor has lower loss and better characteristic of inductance in the vertical position after the assembly. We believe that this ben-
Fig. 11. A schematic illustration of the creation of a vertical assembly by “overbending” the flexible region. (a) Microflap is bent to a certain angle $\theta$ larger than $90^\circ$ by using an oblique magnetic field $H_{\text{ext}}$. (b) Microflap stays at a rest angle of about $90^\circ$ after the relaxation.

Fig. 12. (a) Scanning electron micrograph of an assembled test structure by PDMA before parylene coating. (b) Scanning electron micrograph of the same structure after a 3-$\mu$m-thick Parylene coating.

efits from the reduced substrate loss and parasitics when the inductor is in the vertical position. Theoretical analysis and modeling are being performed to further improve the performance of the vertical planar spiral inductors.

VI. DISCUSSION AND CONCLUSION

A novel assembly process—PDMA has been demonstrated and characterized. PDMA is a simple batch-scale assembly process, which has already found its application in the fabrication of certain novel microdevices. Once the fabrication process is established, PDMA can be implemented with high yield, good controllability, and repeatability. However, there are still some aspects and issues, which require attention and further investigation.

1) The mechanical model we currently derive is a first order estimation. Model refinement can be made by including a number of factors, which are neglected in our model. In the plastic deformation regime of a material, the stress will slowly increase with the strain from $\sigma_y$ due to the strain hardening effect [18]. When a constant stress of $\sigma_y$ is assumed, the bending angle will also be slightly overestimated in the plastic bending regime. Meanwhile, it is a transition region instead of a transition point, which separates the elastic regime and plastic regime. An improved model will be presented in detail in future publications.

2) One important application of PDMA would be a “strictly” vertical assembly ($\phi \approx 90^\circ$). Since the magnetic torque ($T_m$) is always trying to align the Permalloy piece with the magnetic field, the maximum bending angle and the rest angle can be changed by adjusting the direction of the magnetic field with respect to the substrate. For example, by using a magnetic field at a suitable angle larger than $90^\circ$, a strictly vertical assembly can be realized by creating a proper “overbending” ($\theta > 90^\circ$) in the flexible region to compensate its relaxation (Fig. 11).

3) Parylene coating is found to be able to further strengthen the assembled structure and reduce the relaxation of its deformation. Parylene gas-phase coating has been widely used to protect circuit chips or boards from corrosion in harsh environments. The coating is conformal and with low stress. Fig. 12(a), (b) shows an assembled test structure before and after a 3-$\mu$m thick Parylene coating. The sample with a permanent magnet underneath is placed into the chamber of a Parylene coater. It is fixed at its maximum bending angle with little bending relaxation after the Parylene coating.

REFERENCES


