Editorial
A New Way of Teaching Micro Actuators
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We are pleased to present you our promised aim of the course “Micro Actuators” in the sommer term 2004 – A Class Book.
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Abstract—LIGA is a German acronym for lithography, electroplating and molding. Employing this technique it is possible to produce microstructures with a very high aspect ratio and with very smooth side walls. Structures with a wide range of materials can be produced, and with vertical dimensions ranging from micrometers to centimeters. The applications ...

Index Terms—LIGA, resist, aspect ratio.

I. INTRODUCTION

In the LIGA process, X-rays are used to carve out deep patterns in a resist. The created patterns are then electroplated to form a desired structure. Employing this technique, we can obtain microstructures with high aspect ratios, smooth side walls, and a high accuracy of 0.5 micrometers. The source of radiation used in the LIGA process comes from a synchrotron. To fabricate structures with a fine width, a synchrotron with a peak wavelength of 1 to 3Å is required to reduce the effects of diffraction. To obtain these parameters, a synchrotron of considerable dimensions (diameter between 50 and 100m) is required. Due to the limited number of such facilities and the high costs, a number of techniques have been developed to make this technology feasible for mass production. The common technique facilitating mass production is molding. A mold insert is created using SR lithography at a suitable synchrotron facility. Later, the microstructure is reproduced using a molding (abformung) process. The products of the process are polymer molds. Ceramic slurry can be used to create a ceramic structure from the molds. The problem with this process is that there is a limitation to the aspect ratio in the molding process, and the metal parts are difficult to produce using the polymer molds. There is increasing interest in finding a means of mass production by means of SR lithography and electroforming. The main idea is to use apply a more sensitive photo-resist that could be used with a SR source of weaker intensity, such as produced by more readily available synchrotrons with a diameter of less than 20m. In our following discussion, we shall present the state of the art in LIGA manufacturing, and discuss several challenges of the technique. Finally, some applications of the LIGA process will be illustrated.

II. LIGA FABRICATION

Fig. 1 Lithography and electroforming process

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A. **Liga Fabrication**

The stages of creating a microstructure are presented in Figure 2. In the initial stage of the LIGA fabrication process a silicon wafer covered with a sacrificial silicon oxide layer and a photoresist. A mask is then applied, and the photoresist is irradiated and developed. By doing so, a pattern is created on the sacrificial layer. By applying patterning, structures which are free or partly anchored to the substrate can be created. Whichever parts of the sacrificial layer are not covered by the photoresist after developing are removed in an etching process. After the etching process is complete, the wafer is covered with a thick layer of X-ray resist. Masking and irradiation of the X-ray resist with synchrotron radiation follow. After the X-ray resist is developed, metal is deposited in the cavities of the X-ray resist in the process of electrodeposition. Once this process is complete, the X-ray resist and the sacrificial layer are removed. Removing the sacrificial oxide layer from under the structure causes it to lose contact with the substrate, making it either movable or only partly anchored to the substrate. Examples of microstructures created in the process are shown in figure 2.

![Fig. 2 Motor stator (left) and microgear (right) manufactured in the LIGA process.](image)

B. **LIGA Molding Process**

As mentioned earlier, the most common way of mass production involving LIGA is by means of molding. This process is illustrated in figure 3. First, a metal mold insert is created in the process as described in the previous section. Next, plastic molds are created by means of precision plastic injection molding. These molds can then be used in as dies in an expended ceramic slurry casting process. Once the ceramic structure has been cast, the plastic is sintered away, leaving behind the ceramic microstructure.

![Fig. 3 LIGA manufacturing process](image)

C. **Developments in LIGA**

Inasmuch as molding is a cheap way of reproducing microstructures without the presence of a synchrotron, many applications require structures that can only be formed by SR lithography and electrodeposition. In order to make such microstructures commercially feasible, the cost of production must be lowered, which can be done by using a synchrotron of smaller diameter in the X-ray irradiation process. Since smaller synchrotrons produce radiation with intensity of about 10% of those used in the regular LIGA process, a method must be found to overcome this problem. The team of Yoshihiro Shirata of Harima R&D laboratories found that a lot of flexibility arises in the proper choice of the X-ray photoresist. PPMA, polymethyl methacrylate, the photoresist usually used in the LIGA process has very good accuracy, yet a low sensitivity. Generally, the sensitivity of a resin can be increased by increasing the X-ray absorbance or the chemical reaction yield by means of a chain reaction. This, however, leads to a deterioration of the precision. To avoid this problem, the sensitivity has to be enhanced by increasing the chemical reaction of the base resin. Shirata’s team developed a copolymer of methyl methacrylate (MMA) and methacrylic acid (MAA), which was considered to have higher yields. Consequently, with the choice of an appropriate developer, isobutyl ketone (MiBK), they were able to develop a resist with ten times higher sensitivity than PPMA.

The choice of the X-ray mask was also important to Shirata’s team. The typical X-ray mask consists of a silicon frame to which a 2µm thick membrane is mounted. A WN 5µm absorbing layer is deposited on the membrane. The WN, which is deposited by sputtering, usually has columnar structures with a width of 0.2µm. By adding nitrogen to the argon sputtering gas, Shirata’s team realized an edge roughness of 0.1µm. Furthermore, by cooling the substrate to -40°C during electron cyclotron resonance etching, they managed to side etching to less than 0.1µm. A result of these proceedings was a mask with smooth side walls (roughness: 30nm) and high accuracy.
III. LIGA APPLICATIONS

A. Micro Probe for IC Testing

IC technology is constantly moving towards larger integration, which implies that IC pad pitches become smaller. At present, pad pitches can be found in the range of 120-150 µm, and they are expected to reach 90 µm or less in the near future. To appropriately test this IC’s, a correspondingly smaller contact probe is needed (see figure 4). Contact probes work by sending and receiving electrical test signal through the pads. Through the use of SR lithography and electroforming instead of more conventional techniques, a contact probe with area of 30 µm square can be obtained.

B. Microconnectors

Current electronic applications require the use of heavily packed wiring and therefore the corresponding connectors must allow for a low insertion force in a reduced space. The terminals for such connectors can be fabricated using SR lithography and electroforming, which provide the required accuracy and high aspect ratio. Moreover, tests have shown that microconnectors produced in such a way can be used for up to 1000 times. An example is shown in figure 5.

C. The Development of a LIGA-Microfabricated Gripper for Micromanipulation Tasks

The importance of the development of an improved micromanipulation gripper results from the necessity of precise and secure handling, characteristics which are usually not satisfied completely by the tools available in the market. Moreover, for micromanipulation tools involving mechanical contact rather than non-contact forces (optical and electromagnetic), the difficulty in releasing components due to the effect of adhesion forces (surface tension, van der Waal’s and electrostatic) is a problem that requires especial attention. In this document, the design of a LIGA-fabricated gripper, which is a promising solution for tasks such as assembly of microelectronic components and microsurgery, is described.

The micro-gripper, described in detail shortly, is part of a micromanipulation systems comprised of a robot, for initial positioning of the gripper, plus a combination of sensors and actuators for the final and exact positioning. A schematic of the microgripper is shown in figure 6. As shown in the schematic, the microactuator is of the piezoelectric (PZT) type and produces the gripping action on the end-effector by acting on two pairs of beams. When voltage is applied to the PZT, it extends by about 10 µm, thus compressing the two pairs of beams (external beams: 50µm thick, 4 mm long; internal beams: 50µm thick, 2 mm long). The action on the two pairs of beams causes the two arms of the gripper to come closer, thus producing the desired effect (gripping action). The solution of the adhesion problem will be achieved through the implementation of a microfluidic system in the microgripper in conjunction with a saw-tooth design of the microgripper tip as shown in figure 7. The microfluidic system is based on a pneumatic microvalve, which can produce a vacuum in the interior of the end-effector for holding the microobject or pressure for releasing it.
IV. CONCLUSION

In this paper, we have presented a detailed description of the LIGA manufacturing process, focusing on the concepts necessary for an introduction into this machining technique. Moreover, we have illustrated some advantages and benefits of the implementation of LIGA through several application examples.

REFERENCES


Electrostatic Actuators I

Slawa Missal, Pablo Figueroa

Abstract—In this technical paper the electrostatic actuation principle based on electrostatic forces between two parallel plates is described. One application of this principle are the Micromachined Fabry-Perot switches. The emphasis of this paper is on the optical switching principle and physical characteristics of the switches. The design of the switches and their applications are introduced, as well.

Index Terms—Electrostatic actuator, constructive interference, Fabry-Perot Interferometer, Airy-function, micromachined optical switch.

I. INTRODUCTION

In this technical paper we describe the function and characteristics of micromechanical optical switches actuated by electrostatic forces. This technology can be adopted for producing compact displays similar to TFT displays. The principle of the optical switching is based on the Fabry-Perot interferometer. These switches can operate in reflection and transmission modes.

II. ELECTROSTATIC PRINCIPLE

The Actuation principle that electrostatic actuators use is based on the electrostatic force occurring between two isolated electrolates, when a voltage is applied between them. One of the plates is suspended in a way that enables its movement. There is a distance d between them. The material between them could be air or any other gas or fluid that allow the movement (fig. 1). The general formula describing the electrostatic force is:

\[ F_e = e_0 e_0 \frac{A U^2}{2d} \]  

(1)

Where \( e_0 \) is the relative permittivity, \( e_0 \) the vacuum permittivity, \( U \) the applied voltage, \( A \) the area of the plates and \( d \) is the distance between the plates.

The spring force of the system is:

\[ F_s = K \times x \]  

(2)

In order to analyse the spring’s force and electrostatic force, we should put the variable \( d \) (used in equation 1) in terms of \( x \) (spring’s displacement). So, equation for the electrostatic force is:

\[ F_{elect} = \frac{E A U^2}{2(d - x)^3} \]  

(3)

Where \( E \) is the electric field.

For finding the optimal parameters, we need to make these forces (electrostatic force and spring force) equal.

This equation results into a total force:

\[ F_{total} = -Kx + \frac{E A U^2}{2(d - x)^3} \]  

(4)

We can see from this equation the different behaviour between the Electrostatic force and the spring’s force. It is not difficult to realise that if we let the variable X be bigger and fix the voltage’s value, the behaviour of this system will be led for the electrostatic force (see fig. 2).
Solving this equation with respect to the voltage:

\[ U = (d - x) \sqrt{2 \frac{Kx}{EA}} \]  

After that, we should derive this equation with respect to \( x \), and see when we do have a maximum voltage value. This is:

\[ \frac{dU}{dx} = (d - x) \sqrt{2 \frac{Kx}{EA}} + \frac{d}{EA} \sqrt{\frac{Kx}{EA}} \]

After making this equation equal to zero, we can obtain the cric value of the distance where the value of voltage is maximum. We can observe that we should work always between 1/3 of the initial distance between the two plates (see figure 3). This is:

\[ x_{\text{crit}} = \frac{1}{3} d \]

The graph of the voltage versus \( X \) is:

In this graph we can observe that after reaching 0.33 of the initial distance, our system will be lead for the electrostatic force[8]. So, it is convenient to drive it, between this value. Now, we are going to give a description of how these principle is applied in optical switches.

III. OPTICAL PRINCIPLE

The optical switching principle is based on occurring of standing waves between two or more semi permeable mirrors when a certain distance \( d \) between them is achieved [1]. The condition for occurring of standing waves is met when \( d \) is a multiple of 1/4 of the wavelength. There are three cases (see fig. 4):

- reflection of a wave at a transition surface to a material with lower refractive index \( n \), so called “reflection at loose ends”: no phase shift of the reflected wave
- reflection of a wave at a transition surface to a material with higher \( n \), so called “reflection at fixed ends”: a phase shift of \( p \) is introduced to the reflected wave
- reflection of a wave at a “loose end” and at a “fixed end”

The condition for the first and second case is:

\[ d = 2m \times \frac{l}{4} = m \times \frac{l}{2} \]  

For the third case:

\[ d = (2m + 1) \times \frac{l}{4} \]

where \( d \) is the distance between the mirrors, \( l \) is the wavelength of light, \( n \) is the refraction index of the medium through which the light is propagating in and \( m \) is a natural number (0,1, 2, ...). However, these conditions have to be modified if the gap between the mirrors is not air or vacuum. The reason is the dependence of the wavelength of light on the refraction index of the material:

\[ l_{\text{material}} = \frac{l_{\text{vacuum}}}{n} \]

Thus, “fixed” or “loose” ends:

\[ d = m \times \frac{l_{\text{vacuum}}}{2n} \]
“fixed” and “loose” ends:

\[ d = (2m + 1) \frac{l_{\text{max}}}{4n} \]  

(12)

Now, the desired equations for the description of standing waves in a Fabry-Perot Interferometer are obtained.

IV. FABRY-PEROT INTERFEROMETER

A Fabry-Perot Interferometer consists of two plane and parallel semi permeable mirrors with the same optical characteristics. Within the gap the incident light is partially transmitted and reflected by both mirrors several times.

![Schematic illustration of a two mirror setup](image)

When the condition for the constructive interference is met then the intensity of light within the gap is much higher than the intensity of the incident light. As a result the intensity of the transmitted light is as high as the intensity of the incident light. In that case the intensity of the reflected light is zero because of the energy conservation law. This behaviour is described by the Airy-functions [3, 4]:

\[ R = \frac{I_r}{I_i} = F \sin^2 \left( \frac{2pd}{l} \right) \]

(14)

with coefficient of finesse

\[ F = \frac{2r}{1 - \frac{r}{2}} \]  

(15)

where \( r \) is the coefficient of reflectivity of each mirror. The coefficient of finesse has a decisive effect on the contrast between the “on” and “off” state of the interferometer: the higher \( F \) the higher the contrast (fig. 6).

V. MICROMACHINED FABRY-PEROT SWITCHES

Fabry-Perot switches have been fabricated at IMSAS [3]. In these optical switches, several transitions between different dielectric layers take over the part of mirrors. Switches working in reflection mode are fabricated on silicon/silicon oxide (silicon oxide is an insulation layer); those working in transmission mode are fabricated on quartz (fig. 7). A tungsten-titanium layer (WTi) represents the lower contact which is covered by an insulating silicon-nitride layer (Si\(_n\)N\(_x\)). An air-gap is located between the deflectable membrane (Si\(_n\)N\(_x\)) and the lower silicon-nitride layer. The membrane is covered with a gold electrode. Both, upper and lower electrodes are located on the margin of the switch leaving space for the optical active area. Bumps are created underside the membrane to prevent it from sticking [5] and to get a fixed switching position (fig. 8b).

![Schematic 3-D view of the functional layers in a Fabry-Perot switch](image)

All layers, except of the air-gap, have non-variable thicknesses suitable for generating constructive interference at certain wavelengths. Thus, each of them is working as a Fabry-Perot Interferometer. By applying a voltage between the electrodes the air-gap can be varied and in that way light switching is accomplished (fig. 8b). To improve the switching behaviour, the number of layers with alternating refractive indices has to be increased. In that case the total coefficient of reflectivity will rise and the contrast between the “on” and “off” states will be higher (fig. 7).
VI. PHYSICAL CHARACTERISTICS

The switches and their optical active areas have diameters of 130 µm and 60 µm respectively. Both types are designed for maximum transmission as well as reflection in deflected state. The density of the obtained optical switches reach a value of 80 pixels/mm². Light switching is accomplished at frequencies up to 2 kHz without lowering contrast. If required, the switches are able to hold the switching status for 1-10s due to their capacitive structure.

VII. APPLICATIONS

Thus their high density of pixels and the ability to hold the switching status, these type of optical-switches find their application in passive matrix displays [3]. This type of displays can be found in mobile phones, calculators or in car-radios.

Another application area for these optical-switches is the 3-dimensional shape measurement [6] (fig. 12).
In these measurement systems, a pattern (here stripes) is projected on an object and one or more cameras take a picture of this projection. Because the angle and distance between the camera and pattern source are known, the 3D-data of the object’s surface can be calculated by the triangulation method. These data can be used for engineering purposes, 3D-visualization (e.g. perfectly fitting Formula 1 helmet; fig. 13), quality control (comparison: designed vs. built object) and measurement of deformation (e.g. car crash test).

Due to the high miniaturisation degree of the switches a pattern source can be created and used in a 3D-endoscope. With such an endoscope, a 3D-visualization of inner organs can be accomplished to improve the capability of visual clinical diagnostics and surgery [7].

VIII. CONCLUSION

In this paper, electrostatically actuated micromachined optical Fabry-Perot switches are presented. Their physical characteristics show on the one hand high working frequency, high pixel density, low power consumption and a high miniaturization degree. On the other hand, they are still being developed and have some disadvantages, like small optical active area and a low contrast, compared to commercial available displays and projecting systems. To increase the optical active area, doped polycrystalline silicon can be chosen as a material for the membrane and bottom electrode [2]. It is an electrical conductor and it is transparent in visible spectrum of light. To increase the contrast between the “on” and “off” switching status, it is necessary to improve the fabrication processes in order to obtain the desired thicknesses of layers. Raising the number of layers with alternating refractive indices leads to higher contrast as well [3]. The electrostatic actuation principle is very advantageous in the case of these switches because of the super-proportional relationship between the electrostatic force and the voltage/distance between membranes. Therefore, the switches are low voltage capable, which is important for integration into CMOS circuits.

REFERENCES

I. INTRODUCTION

MICROACTUATORS are used in many different areas, e.g., for force rebalance and resonant sensors, micropositioners like the read/write actuation mechanism for magnetic disk drive heads, micromotors, switches and in adaptive optics systems.

For these applications normally “Parallel Plate” electrodes where used, which have several disadvantages. The nonlinear relationship between drive force and deflection is the biggest problem that we have with actuators using this technology.

In addition to this reduced physical range of motion is a problem as well as the reduced frequency response because of the rigid and solid materials.

Advantages of varying electrode overlap area motion are the linear force to displacement relationship due to a constant electrode gap, large actuation range and a higher stability.

But thus far the applications of this mode of operation were limited to lateral actuation, so there has to be developed a new generation of micro actuators which makes it possible to do movements in a vertical direction. This is what the Vertical Comb Array Microactuator can do.

II. DESIGN

The whole microactuator consists of a set of moving mechanical polysilicon (MP), that can move in deep trenches of the wafer surface (Fig 1). The upper innerwall is shaped by a p++ chassis, which serve as electrodes. A Control silicon separates the chassis and the MP layer. If a voltage is applied between the MP-beam and the p++ chassis, an electrostatic force is produced, which makes the whole MP-layer move upwards. The downward actuation is obtained by the force of some springs, on which the hole MP-layer is suspended. So you can control the MP position by changing the voltage. A whole VCAM consists of about 20 single beams. It is placed over an etch pit, which makes it move freely.

A VCAM is fabrication by using the trench-refilled-with-polysilicon (Trips) process technology. On a standard silicon wafer a p++ layer (10–μm) is created by using deep boron diffusion. Afterwards a thin control silicon layer is placed on it. The next step is the etching of the trenches. To achieve a high aspect ratio (1:20), the trenches are realized by several steps of dry etching and passivation of the trenches. The next step is the deposition of a sacrificial layer (~1μm). It determines the gap distance between the two electrodes. Now the trenches are refilled with an polysilicon (MP layer). To create an offset inside the trenches, the MP layer is selectively removed in the beam regions. The MP layer is now enclosed by a thin oxide layer to protect it from the final etch step. The sacrificial layer is removed from the strucure and the whole microactuator is undercut to ensure the mobility.

III. DEVELOPMENT

The behaviour of the VCAMs can be simulated with the capacitance extraction tool FastCap. In a FastCap simulation you can see, that in the region of zero to 80 % of overlapping, the proportion is linear.

The range of motion depends on different things, which are the height of the chassis, the depth of the trench, the various tether dimensions, square of the Voltage, and is limited by the offset and the overlap as already mentioned in the design part.

The drive strength of a VCAM is nearly the same as the strength of Parallel Plate electrodes and it is much more than in Lateral Comb Drives.

The actuation force is proportional to the perimeter of the electrode beam. So the force can be increased by increasing the perimeter which means using different beam surface structures. But using a different surface also means to increase the width between the beams.
Introduction of U-Shaped electrothermal microactuator

Zhang Zhihua, Yang Miao

Abstract—Thermal microactuator, which can generate relatively large force and displacement at low actuating voltage, has been extensively employed in MEMS. U-shaped actuator is a typical thermal actuator. Its model and characteristics are discussed in this article.

Index Terms—Electrothermal microactuator, U-shaped.

I. INTRODUCTION [1]

In micromechanical structures, electrothermal actuators are known to be capable of providing larger force and reasonable tip deflection compared to electrostatic ones. The output force and tip deflection are the major concerns on actuator design and applications. Many studies have been devoted to the analysis of the flexure actuators.

One of the most popular electrothermal actuators is called “U-shaped” actuator, whose typical layout is shown in figure 1. The device is composed of two suspended beams with variable cross sections joined at the free end, which constrains the tip to move in an arcing motion while current is passed through the actuator. The hot/cold arm thermal actuators consist of two asymmetric parallel arms connected at one end. One arm (hot arm) is long and thin and the other arm consists of a wide section (cold arm) and a shorter thin flexure section as shown schematically in figure 1. The hot arm and flexure, being thinner, have higher electrical resistance than the wider cold arm. When a current passes through the hot arm – cold arm–flexure loop, the hot arm and flexure have higher current densities than the cold arm; and thus will heat more than the cold arm. The net expansion creates a moment that bends the entire structure. Among those researches, Comtois [2] developed micro-polysilicon electro-thermal actuators using a commercial foundry process (MCNC, MUMPs). The relationship between input power and output force was analyzed, and the dynamic response of the actuator was investigated. Comtois [3] further proposed a design that layed out various microthermal actuators in array to gain larger output force. Similarly, Reid [4] designed various revisions of the microthermal actuators, which were applicable to various microdevices such as micromirrors, micromotors, microcrawls and microautomatic packing facilities. Recently, Huang [5] analyzed the effects of the beam length and gap width on the displacement of the actuators. They claimed that larger tip displacement was obtained as the gap between the two beams became smaller.

Details including modeling will be discussed in the following sections.

II. THEORETICAL MODEL

A. One-dimensional model [6]

A simple model of the heat transfer is used to determine the temperature of the actuator. Since the thermal actuator is much longer than it is thick or wide, a one-dimensional analysis of the heat flow along the actuator length will be performed. The one-dimensional analysis assumes that along the actuator the cross-section temperature is uniform.

A thermal actuator has three modes of heat transfer: conduction, convection and radiation.

The vertical spacing $\Delta z$ between the hot arm and the substrate is $2 \mu m$ and the vertical temperature gradients are very large. In this case, the conduction heat transfer coefficient $U$ to the substrate can be approximated by

$$U = \frac{k_{air}}{\Delta z}$$

Where $k_{air}$ is the air thermal conductivity.

The dimensionless Rayleigh number $Ra$ describes the relative importance of natural convection. In the macro world, $Ra$ is $10^5$ to $10^9$ when convection is important.
The hot arm reaches high temperatures and radiation effects may become important. The radiation heat transfer coefficient $U_r$ is given by

$$U_r = \varepsilon \sigma (T + T_w)(T^4 + T_w^4)$$

Where $\varepsilon$ is the emissivity of polysilicon, $\sigma$ is the Stefan–Boltzmann constant, $T$ is the element temperature (K) and $T_w$ is the ambient temperature (K).

The temperature distribution along the length of the actuator can be found by numerical integration over the arms. Figure 2 shows the resultant steady state temperature profile along an U-shaped arm thermal actuator subjected to 4 V dc.

![Figure 2. Simulated steady state temperature profile T(x) along the unfold U-shaped thermal actuator at 4 V dc.](image)

Electrical current passes through the actuator from anchor to anchor, and the higher current density in the hot beam causes the actuator to heat and expand more than in the cold beam, thus produced lateral arcing motion toward the cold beam side. For one-dimensional structural element, the net thermal expansion is

$$\Delta_{net} \approx \alpha_f [L_h T_{h_{avg}} - L_c T_{c_{avg}} - L_f T_{f_{avg}}]$$

Where $L_h$, $L_c$, $L_f$, $T_{h_{avg}}$, $T_{c_{avg}}$, and $T_{f_{avg}}$ are the length and the average arm temperatures of the hot, cold, and flex arms respectively; $\alpha_f$ is the thermal expansion coefficient of polysilicon.

**B. Deflection analysis [1]**

In figure 3, deflection of the actuator as a function of scaling factors for different driving currents is presented. It can be clearly seen that at a certain current a peak deflection is obtained. The peak deflection occurs at a scaling factor of around 1. The reasons are twofold. Firstly, it is found that the total beam length, $L$, contributes the most to the deflection, thus the shorter the total beam length, the smaller the deflection. Secondly, however, as the total beam length becomes larger, the thermal loss due to larger surface area decreases the temperature field. Thus a peak-shaped curve of the deflection versus scaling factor is obtained.

![Figure 3. Deflections versus scaling factors at different driving](image)

The deflection as a function of the length ratio of the cold beam to the hot one is presented in figure 4, where $L$ is the total beam length, and $L_c$ is cold beam length. The driving current for both cases is 1.0 mA. The dimensions of the actuators are corresponding to the scale factor of 1. It can be seen that the length ratio has a significant influence on the actuator deflection. A peak deflection is obtained as the ratio reaches about 86%. As the length of the cold beam becomes larger, the actuator becomes more flexible, resulting in a bigger deflection. However, as $L_c/L \to 1.0$, the actuator becomes too stiff to deflect. On the other hand, it is obvious that no deflection occurs when $L_c = 0$ since there is no cold beam anymore.

![Figure 4. The influence of beam ratio $L_c/L$ on tip deflection.](image)

**C. An effective 3-D FEA modeling [7]**

Considering the material properties of the polysilicon as follows: Young’s modulus of 160 GPa, as well as a Poisson’s ratio of 0.22 and a density of 2330 kg/m$^3$. Then an effective 3-dimensional FEA (Finite Element Analysis) modeling technique that considers convection and conduction is now used. Because the material properties are restricted to a 300 to 800 K temperature range, radiation heat transfer is not considered; however, the convective and conductive cooling effects from air are significant. The Grashoff number is considered.
\[ G_{\mu L} = \frac{g \beta (T_1 - T_\infty) L^3}{v^2} \]

Where \( g \) is gravitational acceleration, \( \beta \) is the volumetric expansion coefficient, \( L \) is the characteristic length, \( v \) is the viscosity, \( T_1 \) and \( T_\infty \) are the temperature on the surface and ambient, respectively. This nondimensional number provides a measure of the ratio of the buoyancy to viscous forces acting on a fluid.

D. New developments

1. Electrothermal microactuator with additional gold-layer deposition [1]

From the research of [1], it is found that a greater deflection can be obtained for gold-plated actuators. The results are presented in figure 5. It can be concluded that additional gold-layer deposition helps the actuator deflect more. As a gold layer is deposited on the cold beam, the resistance of the cold beam becomes smaller. Hence the temperature in the cold beam decreases, resulting in a more prominent effect on tip deflection. It was found that addition of this layer of gold could generate bigger displacement.

![Non-gold-plated vs gold-plated deflections](image)

**Figure 5.** Deflections versus driving currents for non-gold-plated actuator and gold-plated actuators (scaling factor = 1).

2. Two-hot-Arm electrothermal microactuator [8]

The two-hot arm thermal actuator is shown in Figure 6. In this new thermal actuator, the electric current only passes through the outer and inner hot arms. This avoids the cold arm and flexure to being part of the electric circuit. It dramatically increases the efficiency since all the power consumed in the actuator contributes to the deflection of the thermal actuator tip. The flexure can also be thinner than the hot arm because no current passes through the flexure.

Obviously, the new two-hot arm thermal actuator has improved the limitations of the traditional one. Thermal actuators have been widely used in many MEMS applications, in order to reduce the design circle and simplify MEMS design work.

![Two-hot-arm thermal actuator diagram](image)

**Figure 6.** Schematic diagram of two-hot-arm thermal actuator

III. Conclusion

We have introduced a description on electrothermal actuator and particularly introduced and analyzed the characters and modeling of U-shaped thermal actuators. Besides, we also induct some new develop on two arms actuator.

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[8] Dong Yan Mechanical Design and Modeling of MEMS Thermal Actuators for RF Applications
Zusammenfassung—Im Vortrag Thermische Aktoren II wird ein Ein Ventil beschrieben, welches von Lin Gui und Jing Liu entwickelt wurde. Das Eisventil getriert die durchfließende Flüssigkeit, wodurch der Fluss zum erliegen kommt und das Ventil schließt. Der Durchfluss wird wiederhergestellt, indem die Flüssigkeit wieder aufgetaut wird. Das Ventil ist damit wieder geöffnet. Vorteile sind hierbei, dass es keine beweglichen Elemente am Ventil gibt und eine 100%ige Verschlussqualität.

I. DAS EISVENTIL


II. DAS PRINZIP DES EISVENTILS

liegt an der Energiefreigabe beim Wechsel des Aggregatzustands von flüssig auf fest. Anschließend fällt die Temperatur auch am Einlass ab und nähert sich zusammen mit der Temperatur am Ausgang dem Gefrierpunkt. Die Temperatur in der Mitte sinkt weiter.

Abbildung 5. Beispiel passives Membranventil

III. FAZIT

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Overview on Magnetic Microactuators

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Abstract—This paper presents an overview on magnetic microactuators and their applications. It shows and explains when and how those microactuators are miniaturization friendly and presents in details the design and fabrication of one possible application: a bistable electromagnetically actuated microvalve.

Index Terms—Bistable, Electromagnetic forces, microactuators, microvalve, miniaturization.

I. INTRODUCTION

Magnetic micro-actuators belong to the family of Micro-Electro-Mechanical Systems (MEMS). MEMS owe their existence to the microelectronics industry that developed and is continuously developing smaller and smaller systems that consequently need ‘small’ sensors and actuators i.e. Nowadays, in the μm range. Due to their compatibility and close connection to the microelectronics environment (fabrication and technology), actuators based on electrostatic interactions were the first candidate of MEMS actuators. Few years later, actuators based on thermal effects started to be adopted and were mainly based on the bimorph effect from the dilatation of a heated conductor deposited on a thin silicon beam. However, actuators based on other operating principles like electromagnetism, piezoelectricity, shape memory alloy, and hydraulics, were slower to be adopted and thus developed mainly because they involve components and materials that were quite ‘far’ from the microelectronics technology.

Mid of 80’s, the question of the possibility of adopting electromagnetic interactions as operating principle in MEMS actuators was raised and was subject of many papers that didn’t draw any clear conclusions until the beginning of the 90’s when the first prototypes of magnetic micro-actuators started to appear [1].

This paper will present the equations governing magnetic and electromagnetic interactions in section 2, study the effect of miniaturization on these interactions in section 3, study and compare micromagnets and microcoils properties, a collection of applications related to magnetic microactuators in section 5 then will present a detailed study of a bistable electromagnetically actuated microvalve in section 6, and finally will list advantages and disadvantages of magnetic microactuators.

II. MAGNETIC INTERACTIONS

In this section and throughout this paper, the two possible sources of magnetic field considered and discussed are a permanent magnet and current conductor (coil).

First, let us consider a permanent magnet with volume \( v \) and polarization \( J \).

The scalar potential \( V \) created by the magnet at a point \( P \) is defined as follows [1]:

\[
V(P) = \frac{v}{4\pi \mu_0} \frac{J_r}{r^3}
\]  

(1)

Where \( \mu_0 \) and \( r \) are the magnetic permeability in vacuum and the distance from the magnet to the point \( P \) respectively.

Consequently, the magnetic field at the point \( P \) will be derived as follows [1]:

\[
\overrightarrow{H} = \text{grad}(V)
\]  

(2)

Now, let us consider a current conductor of length \( l \), cross-section \( S \) and carrying a current density \( \delta \).

The Biot-Savart law states that the magnetic field created by this current conductor on a point \( P \) is defined as follows [1]:

\[
\overrightarrow{H}(P) = \frac{1}{4\pi} \frac{\delta S dl \times \vec{r}}{r^3}
\]  

(3)

The force of a current conductor on a permanent magnet can be derived as follows [1]:

\[
\vec{W} = -J \times \overrightarrow{H} \\
\vec{F} = -\text{grad}(\vec{W})
\]  

(4)

Where \( W \) is the magnetic interaction energy.
III. MINIATURIZATION

To study the effect of miniaturization on magnetic interactions, let us consider a factor $k > 1$ that scales down the dimensions of the magnetic system without affecting the intrinsic physical properties of materials.

Considering the reduced permanent magnet as ‘center’ of the magnetic system, it can be remarked, simply by looking to equation (1), that the potential $V(P)$ will be divided by the scaling factor $k$ because the numerator will be reduced by a factor of $k^4$ ($k^3$ for $v$ and $k$ for $r$ ) and the denominator by $k^2$. As the magnetic field $H$ is related to the potential $V$ by the gradient operator (differentiation on distances), it will remain unchanged because all dimensions were reduced by the same factor. However, as all the distances were reduced by $k$ and the field remain unchanged, the field gradients will be multiplied by the factor $k$. Consequently, if the element interacting with the magnet is a current conductor, the volumic force on the conductor will remain unchanged because the acting Laplace-Lorenz force is proportional to the fields.

However, if the reduced magnet is interacting with another magnet or with a ferro-magnetic material, the volumic force, proportional to the field gradients, will be multiplied by $k$.

Considering now the current conductor as ‘center’ of the magnetic system, it can be proved by using equation (3) that the magnetic field created at a random point $P$ will be divided by $k$ because the numerator will be reduced by a factor of $k^4$ ($k^2$ for $S$ and $k$ for $dl$ and $r$ ) and the denominator by $k^3$. Also, field gradients will be divided by $k$ simply because distances and fields are divided by $k$. Consequently, if the element interacting with the magnet is a current conductor, and as the force defined in equation (4) is the negative gradient of the magnetic interaction energy $W$, it will remain unchanged. However, if the current conductor is interacting with another current conductor or with a ferro-magnetic material, the volumic force, directly proportional to the field gradients, will be divided by $k$.

Presenting the effect of a scaling down factor $k$ on magnetic interactions, it can be concluded that miniaturization of magnetic elements is possible even though some of the interactions are not miniaturization friendly, and that the most beneficial systems for scaling down are those involving permanent magnets.

IV. MICROMAGNETS AND MICROCOILS

Unfortunately, until now permanent micromagnets’ fabrication is still not well mastered. In order to obtain a micromagnet with relatively good magnetic property, the fabrication processes involved, like sputtering or pulsed laser deposition, are most of the time not easy and incompatible with the ‘classical’ microtechnologies and batch production. On the other hand, all the well mastered microtechnologies like wire electro-discharge machining or electroplating which also offer possibility of batch production, produce most of the time permanent micromagnets with relatively poor magnetic properties [1].

On the contrary, microcoils fabrication with different shapes and sizes is well mastered. Also, in this process, miniaturization plays a positive role in terms of heat losses and make microcoils withstand very high current densities (several kA/mm$^2$) compared to macrocoils. This advantage is achieved because the Joule losses that heat the coil and increase the risk of burning it are proportional to its volume and the heat flows that cool it are proportional to its surface. Consequently, after a scaling down by a factor $k$, volume will be decreased by a factor $k^3$ and the surface by $k^2$ and thus losses will be better evacuated, specifically, by a factor of $k$.

Briefly, micromagnets, after miniaturization, offer the best magnetic interactions whereas the microcoils are easier to fabricate. Therefore, is it possible to find a connection or an equivalence between those two sources of magnetic field?

Mathematically, the magnetization of a micromagnet is proportional to its polarization and to its volume ($k^3$) and that of a microcoil is proportional to the current density in it and to its squared surface ($k^2$). Thus, to make the magnetization of a microcoil equivalent to that of a permanent magnet, its current density should be increased by a factor $k$. This increase directly affects the Joule losses and thus poses limitations on the current density (currently around 10kA/mm$^2$).

Finally, it can be concluded that each of the two sources has its advantages and disadvantages depending on the application in question and that neither of them can replace the other but together they can form a powerful hybrid configuration for an efficient magnetic microactuator.

V. APPLICATIONS

Unlike the magnetic sensors which are well established in commercial products, magnetic actuators are still in the phase of laboratory prototyping, and only few reached the phase of commercial and batch fabrication. Laboratory-developed, read/write heads and micropositioners, matrixes of optical microcommutators for fiber optic networks, micromotors for noninvasive surgery and microrobotics, micropumps and microvalves for lab-on-chip and micro-fluidic devices, electrical microgenerators for autonomous power supplies, micromirrors for adaptive optics, magnetic suspensions for hard disk drives, etc.

In this section a short overview on the operating principles and realization of few types of magnetic micro-actuators will be presented

A. Deformable mirrors for adaptive optics

A number of micro permanent magnets is fixed on a flexible membrane coated by a reflective surface. The contactless magnetic interaction between the permanent magnets and the micro coils on the rigid layer under the membrane allows to achieve a controlled deformation of the
membrane, which is normally used in Astronomy and Ophthalmology to get a better image quality.

B. Magnetic printing heads:

For this application, two different approaches for the design of the magnetic circuit are presented. The first design consists of a single layer Au coil, fabricated around a NiFe pole on a silicon substrate.

The second design approach consists of a multi layer Cu coil, fabricated on a ferromagnetic substrate with a NiFe magnetic pole.

Experiment results showed that the second design approach is superior in the sense of generating a magnetic force at coil lower input power.

C. Micro relays:

Due to the advantage presented above, the multi layer coil design approach was used in the fabrication of magnetic micro-relays.

VI. BISTABLE MICRO VALVE

The low actuation voltage and the low operating temperature associated with the magnetic actuation principle gave it an advantage over the electrostatic, piezoelectric, and thermal ones in the design of the magnetic micro valve under consideration. A drawback of magnetic actuators is the continuous power supply needed to keep a normally closed valve in the opening position, this problem can be solved using a bistable valve that latches in the open position and requires power only to switch between the two stable positions.

A. Operating principle:

The valve consists of two main parts, the coil part and the cantilever part. The rigid part of the cantilever controls the flow of the fluid through the orifice. If no power is supplied to the coil, the valve is kept in the closed position due to the elastic energy in the cantilever beam and to the attraction between the magnet and the NiFe Alloy surrounding the magnet. Supplying a current to the coil causes the cantilever to bend and rotates around the edge of the cavity, thus opening the valve gradually. The magnet induces a flux in the NiFe alloy under the coil, this latches the valve in the opening position, and thus bistability is achieved.
**B. MICROABRICATION:**

1) Microfabrication of the coil:

The coil part is fabricated using a P type 100 Si Wafer with 1 μm oxide on both sides. The subsequent steps are as follows:

1) Cr layer is evaporated (Physical Vapour Deposition) on one side of the substrate and patterned by lithography.
2) Resist is spun and patterned on the other side of the substrate using IR alignment with respect to Cr.
3) SiO2 is patterned using BOE.
4) Resist and Cr are removed.
5) Silicon is etched anisotropically in CsOH.
6) The bottom lead of the coil is made by electroplating Au in a mold of a positive resist on a seed layer of TiAu, the seed layer is essential to provide a conducting surface during the subsequent electroplating process.
7) The bottom lead is electrically isolated by a layer of Parylene deposited by PVD and patterned as follows:
8) Cr, resist, patterning Cr.
9) Removing Parylene (RIE), resist, and Cr.
10) A seed layer of CrAu is evaporated.
11) A polyimide mold is spun and patterned using UV light.
12) Au is electroplated in the mold.
13) Polyimide mold is removed (RIE).
14) Seed layer is removed.
15) The whole structure is coated by Parylene (PVD).
16) A seed layer of CrAu is deposited by evaporation on both sides.
17) A resist mask is patterned on the back side.
18) NiFe layer is electroplated on both sides.
19) The resist is removed from the back side.

2) Microfabrication of the cantilever:

The substrate of the cantilever part is a Silicon wafer with 1 μm oxide layer on both sides. The subsequent steps are as follows:

1) Cr layer is evaporated and patterned on one side of the substrate using resist and Cr enchant.
2) A resist layer is spun and patterned on the other side using IR alignment.
3) SiO2 is etched (BOE), then the resist and Cr are removed.
4) The backside of the Si substrate is etched anisotropically (CsOH).
5) SiO2 is etched in both sides (BOE).
6) A seed layer of Cr Au is evaporated.
7) Thin NiFe layer is electroplated on both sides using a resist patterning mold.
8) The rigid part is electroplated with a thick NiFe layer in a resist mask.
9) The resist is removed.
10) The whole structure is covered by CrAu layer as protection against corrosion.
11) A piece of magnetic foil is was magnetized by inserting into a special magnetizer tool, subsequently it is coated by a thin layer of Parylene and bonded on the rigid part of the cantilever.

3) Finalizing the microfabrication:

In the last phase of the fabrication, the coil part and the cantilever part are bonded together using epoxy glue.

**VII. ADVANTAGES AND DISADVANTAGES**

Magnetic actuators offer permanent forces when permanent magnets are involved and thus can keep a system in a certain configuration without the need for energy. Also, these forces can offer more security in case of power failure in radio frequency or fiber optics actuators. In addition, these forces can be used in the development of magnetic suspensions and thus solve the problem of friction in MEMS.

Compared to other actuation principles, electromagnetism
offers a long range actuation i.e. long throws and wide angles can be achieved.

Moreover, magnetic actuation is possible through sealed surfaces. Therefore, magnetic microactuators can be packed in a way to resist harsh environments or to work in special conditions (vacuum).

However, magnetic microactuators have some disadvantages and are still facing development problems. Compared to other microactuators, they are not considered to be miniaturization friendly and are still large in size. Also, permanent magnets fabrication is still not well mastered and needs to be more compatible with microtechnologies. Finally, magnetic microactuators require power supplies different than those used in MEMS mainly because they need low voltage and moderate current with faster pulse patterns than the available ones.

VIII. CONCLUSION

Magnetic microactuators were proven to be promising for the future and to have advantages over many other actuation principles. They are still prototypes and not widely spread and because they are facing mainly fabrication compatibility problems that, after continuous researches, seem to be reduced day after day. In conclusion, and in order to really experience the benefits of magnetic actuators, let us just give them a little bit more attention and time so that they can reach a ‘mature’ stage of development!

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