Magneitcally-actuated bending-mode microactuators with excimer laser ablation

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Bending-mode polyimide-based (PI) electromagnetic microactuators with different geometries were fabricated and tested. Fabrication of the electromagnetic microactuator consists of electroplated 10 μm thick Ni/Fe (80:20) permalloy on a PI diaphragm, high aspect ratio electroplating of a copper planar micro-coil, bulk micromachining, low-temperature bonding, and 248 nm excimer laser selective ablation. They were fabricated by a novel concept avoiding the etching selectivity and residual stress problems which occur during wafer etching. The magnetic field generated by the planar micro-coil was used to provide an external magnetic field ($H_{\text{ext}}$) to interact with Ni/Fe on the PI diaphragm, by which a repulsive force can be induced to provide a large deflection angle. The deflection angle of the microactuator with different $H_{\text{ext}}$ values was measured. Preliminary results show that 82° can be obtained. In addition, to provide a high strength and low temperature bonding process for the microactuator system, a polymer-based photoresist with patternable characteristics was used as the adhesive bonding material. The bonding results for different photoresists are compared and discussed.

Keywords: PI, Permalloy, Electroplating, Microactuator, Excimer laser, Bonding

Introduction

With the microelectromechanical system (MEMS) technique, the size scale of microactuators can be decreased efficiently and the basic element of microactuators can be integrated with integrated circuits (IC).1,2 The microactuator is an important component in a variety of applications such as optical communications and biomedication. Magnetic microactuators have been applied as micromirrors, delta-wing controls3 and optical switches.4 The operational principle of permalloy magnetic microactuators has been demonstrated and explained.5,6

Polyimide (PI) is widely used in MEMS. The applications of PI are promising.7 The thickness of PI film is easily controlled by changing the speed of spin coating. After fully curing, PI shows excellent electrical, mechanical, chemical and thermal properties as well as a lower Young’s modulus.8 Therefore, the PI microactuator has a much better performance than conventional microactuators made of silicon layers or silicon oxide layers. This method will simplify the process and take less time to accomplish it.

Excimer laser ablation of polymer materials (PI, polycarbonate, polyester, etc.) has been successfully demonstrated and proved.9 It is useful in PCB drilling, laser-LIGA, rapid prototyping and manufacturing of various microstructures. Compared with other laser machining, cold ablation is a unique characteristic of excimer laser micromachining. When the excimer laser beam is impinged on the surface of the polymer, chemical bonds are broken by the absorption of laser pulse energy. Thus, precise removal of long chain molecular polymers is achieved with a small thermal effect.10

Use of the electromagnetic microactuator has found significant growth in the field of microsystems, however, there are still problems with high power consumption and low displacement. Hence, the present study discusses a highly efficient electromagnetic PI microactuator consisting of a planar micro-coil with a high aspect ratio, NiFe permalloy by microelectroplating, a low temperature bonding technique and excimer laser ablation. PI has excellent mechanic strength and low Young’s modulus. Under the same actuation force, it leads to a large deflection angle. The new process proves that a microactuator can be patterned after release. Moreover, the combination of thick photoresist lithography, electroplating, bulk micromachining, excimer laser ablation, and bonding process improves the flexibility of the process. The process has some characteristics and advantages. First, it demonstrates that a microactuator can be patterned after release, which avoids the protection and problems of residual stress which occur with wafer etching of bulk micromachining. Second, the thickness range of the PI diaphragm for the microactuator is wider than with...
conventional silicon, polysilicon or nitride thin film. Third, PI is easily micromachined by excimer laser ablation. With the alignment of substrate and 4:1 mask projection of the excimer laser, microbeams are ablated precisely. After laser ablation, the permalloy plate on the PI diaphragm remains of high flatness without anti-stiction bumps and etching holes, which may be used for micro-optical applications.

Finally, a new bonding method was developed using photosensitive material as the adhesive intermediate layer. Through the photolithography process, the bonding pad resolution can be increased significantly. The method can reduce the residual stress during packaging. In the following sections, the fabrication and results of testing are presented.

**PI microactuator fabrication**

**Excimer laser ablation**

An Exitech 8000 excimer laser workstation was used in the present study as illustrated in Fig. 1. The excimer laser was a Lambda Physik COMPex-110 industrial type with 248 nm wavelength, 400 mJ pulse energy, 25 ns pulse duration time, and 100 Hz peak pulse repetition rate. The approximate magnification from mask to workpiece is four times. Under the scanning and repeat of laser micromachining, one-quarter pattern in dimension is transferred on to the PI diaphragm.

Ablation parameters such as laser fluence, shot number and repetition rate were tested for different polymeric materials. Figure 2a shows the ablation rate (depth per pulse; μm/pulse) versus fluence, and Fig. 2b shows ablation depth (μm) versus laser shot number. The higher the laser energy absorbed by the material, the higher the higher ablation rate and ablation depth at a constant repetition rate. Figure 2c shows the effect of laser repetition rate. It shows a constant ablation rate per laser pulse at frequencies >10 Hz. It is worth noting that when frequencies >10 Hz are applied, a constant ablation rate per second is achieved.

A laser pulse energy higher than 200 mJ (per pulse) will destroy the Cr film on the conventional quartz mask during excimer laser projection ablation. Furthermore, a higher pulse energy and repetition rate (>60 Hz) can cause cumulative heat in PI and permalloy, which may tear off the permalloy plate as a result of the mismatch of thermal expansion coefficients between the two materials. Also, the cumulative heat during ablation significantly affects the quality of the adjacent PI. Therefore, based on the experimental results, parameters
for fluence and repetition rate of 0.445 J cm\(^{-2}\) and
40 Hz, respectively, were selected. For a 10 \(\mu\)m thick PI
diaphragm, at least 80 shots are needed. In practice, 100
shots are used in order to penetrate it thoroughly.

**Permalloy electroplating process**
The electroplating bath for Ni/Fe mainly consists of
Ni\(^{2+}\) (45–50 g L\(^{-1}\)) and Fe\(^{2+}\) (6–9 g L\(^{-1}\)). In order to
induce the initial magnetic dipole along the easy axis, a
strong external magnetic field is applied parallel to the
direction of the Ni/Fe plate during the electroplating
process. Later, the Ni/Fe electroplating technique will be
applied to fabricate the permalloy plate on the PI
diaphragm and permalloy circuit loop process.

**Fabrication of PI diaphragm**
First, 1600 nm of wet SiO\(_2\) is grown at 1100°C on a
double polished (100)-oriented silicon wafer. The bulk
etching area is patterned on the back side. SiO\(_2\) is used
as etching mask and etching stop film during KOH
anisotropic wet etching. Then PI film is spin-coated on
the front side of the silicon wafer. After fully curing in
an oven at 350°C, the thickness of PI is controlled at
10 \(\mu\)m. Subsequently, 100 nm of Ag seed layer is
deposited on the PI film by a sputtering process. A
15 \(\mu\)m thick electroplating photoresist template (AZ-
4620) is patterned by UV lithography for electroplating
Ni/Fe. Later, Ni/Fe permalloy 10 \(\mu\)m in thickness and
800 \(\mu\)m \(\times\) 800 \(\mu\)m in area is electroplated on the photo-
resist template. Finally, photoresist and seed layer are
stripped off. Under the protection of a Teflon chuck, the
whole wafer is immersed in 30% KOH solution at 70°C
to release the PI diaphragm. The final process is to
fabricate the PI plate and microbeams by excimer laser
ablation of the wafer. Under the 4:1 magnification from
mask to workpiece, the one-quarter mask pattern is
accurately transferred onto the PI film. The final
dimension of the PI plate is 10 \(\mu\)m in thickness,
1000 \(\mu\)m in length and 1000 \(\mu\)m in width.

**Fabrication of planar micro-coil**
As for the planar micro-coil, the electroplating bath
mainly consists of Cu\(_2\)P\(_2\)O\(_7\)\(\cdot\)3H\(_2\)O and K\(_2\)P\(_2\)O\(_7\). First, a
150 nm thick adhesive layer of Cr is deposited on the
silicon wafer, followed by 100 nm of Cu serving as a
seed layer. Then a 15 \(\mu\)m thick photoresist template
(AZ-4620) is defined by UV lithography for Cu planar
micro-coil electroplating. Later, a 10 \(\mu\)m thick layer of
Cu is electroplated on the photoresist template. Cu
electroplating parameters are listed in Table 1. By the
time the process of the planar micro-coil is finished, the
photoresist template is removed. The experimental result
is shown in Fig. 3.

| Table 1 Electroplating parameters for Cu planar micro-coil |
|-----------------|-------|
| pH of bath      | 8–9   |
| Applied voltage | 5–6 V |
| Electroplating temperature | 45–50°C |
| Current density | 3–4 ASD |
| Filter size     | 1 \(\mu\)m |
| Anodic material | Cu    |
| Electroplating deposition rate | 0.3–0.5 \(\mu\)m min\(^{-1}\) |

**Bonding process**
There are several important processes involved in the
bonding technique. First, the material layer was spin-
coated onto the silicon wafer and then the photolitho-
graphy process was used to pattern the bonding pad. After
the two silicon wafers were aligned, the wafers
were placed into a bonding chamber. The intermediate
layer material needs to have low glass transition
temperature \(T_g\), and high viscosity. In addition, after
bonding, excellent adhesion and low residual stress are
required.

Therefore, AZ-4620 (a positive photoresist from Shipley), JSR-137N (a negative photoresist from Japan
Synthesis Rubber Co.), SU-8 (a negative photoresist
from Microchem Co.), BCB (Dow Chemical), and SP341 (a positive photoresist from Toray Co.) with stable
characteristics were selected for the experiments.

The bonding process is shown in Fig. 4. The photo-
sensitive materials were spin-coated onto the surface of
the silicon wafer. To evaporate the solvent contained in
the photosensitive materials, the material was baked for
a period of time determined by the thickness of the material.
The sample was then exposed and developed to
define the bonding pad, as shown in Fig. 4a. Two wafers
were then aligned pad to pad (Fig. 4b) and placed in a
bonding machine under a certain bonding force and
temperature.

**Results and discussion**
Larger volumes of permalloy will enhance stronger
magnetic forces. However, a high aspect ratio of
permalloy will cause significant residual stress at the
interface between PI and permalloy. Therefore, the
aspect ratio of permalloy cannot be too high so as to
avoid peeling off from the PI diaphragm during
electroplating. To avoid the above problems, Ni/Fe
permalloy 10 \(\mu\)m in thickness and 200 \(\mu\)m \(\times\) 200 \(\mu\)m in area was fabricated and tested.

Micro actuators with smaller beam widths will pro-
duce larger displacements. However, a smaller beam
width is difficult to fabricate and does not have sufficient
stiffness to support the permalloy plate in practice.
Therefore, in the present study, beam widths around 100
and 200 \(\mu\)m were fabricated and tested.

The bonding temperatures of five kinds of photo-
sensitive material were tested. The curves for the
bonding strengths are shown in Fig. 5. Each data point
represents the average of three measurements. It shows
the tensile test curves as a function of bonding temperature under a constant bonding force (50 N).

From the results, it can be seen that when the bonding temperature for SU-8, JSR, AZ-4620, BCB and SP-341 was between 80 and 120 °C, the bond strength reached its maximum value. When the bonding temperatures were higher than 140 °C, AZ-4620 will be scorched. In addition, when the bonding temperature was higher than 200 °C, SU-8, JSR, BCB and SP-341 exhibited the same bonding strength as those values produced at around 100 °C.

It also shows that SU-8 serving as adhesive layer under a bonding temperature of 90 °C has a maximum bonding strength of about 213 kg cm⁻² (20.6 MPa). SU-8 has many attractive properties as an intermediate adhesive layer described as follows. SU-8 has an epoxy feature with very high bonding strength. It is a negative photoresist and is crosslinked after exposed to UV light. It exhibits excellent chemical resistance after UV exposure. In addition, it requires a very low bonding temperature of 90 °C to produce excellent bonding strength. Therefore, in the present study, SU-8 was used as the adhesive material to bond the microactuator system.

A simplified set-up of an IR bond imaging system was established. It consisted of an IR source and an IR-sensitive camera. The bonded wafer pair is located between the IR source and camera. Any defect in the bond shows up. Examples of the images obtained by the method for two bonded 4" silicon wafer pairs are shown in Fig. 6. Figure 6a shows a successful bonding result. On the other hand, as shown in Fig. 6b, if Newton’s Rings appears, a void or gap is present in the bonding area. This imaging method generally cannot image voids with a dimension less than one-quarter of the wavelength of the IR source. Figure 7 shows experimental photographs. In the study, two different PI beam widths (b=100 and 200 μm) are fabricated and tested. With two different geometries of PI beam, the relationship between the external magnetic field and deflection angle is shown in Fig. 8. When the PI beam width b is 100 μm, the deflection angles approach 60° and 82° at $H_{ext}=1220$ and 4840 A m⁻¹, respectively.

The deflection angle increases with increasing $H_{ext}$. However, the slope of the deflection angle curve decreases gradually when $H_{ext}$ is larger than 2000 A m⁻¹. This is the result of several factors which are not taken into account in the simulation, such as the neglected mass of the PI plate, and saturation of permalloy at high $H_{ext}$. In addition, the elastic effect of the permalloy on the PI plate was not taken into consideration. They all may be responsible for the phenomenon. In future research, the effect of PI mass and elastic permalloy will be studied.
Conclusions

A large deflection angle was successfully demonstrated for bending-mode PI microstructures. The research provides an innovative fabrication process for micro-actuators integrated with micro-electroplating, bulk micromachining, bonding and excimer laser ablation. The process avoids complex procedures, etching selectivity and residual stress problems compared with conventional wafer etching. Results reveal that a smaller beam width will cause a larger deflection angle. When the beam width is larger than 100 μm, the increment of induced maximum shear stress in the beam will become smaller. Therefore, in the present study, beam widths of b=100 and 200 μm were fabricated and tested. In addition, to avoid residual stress problems after permalloy electroplating, 10 μm thick permalloy was fabricated and tested. The magnetic field was generated by a planar micro-coil. Ni/Fe with 200 × 200 × 10 μm³ in volume was fabricated. SU-8 served as the adhesive layer and, under a bonding temperature of 90°C, has a maximum bonding strength of about 213 kg cm⁻² (20.6 MPa). The preliminary experimental result for the deflection angle is 82° at 4840 A m⁻¹.

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References

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