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Fabrication of micro electromagnetic actuator of high energy density

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Abstract

This paper introduced a new technology to fabricate electromagnetic actuator of high energy density without enclosed magnetic circuit. This technology includes fabricating multi-turns planar microcoils and the thick magnetic (NiFe) core on the silicon wafer. The multi-turns planar microcoils were fabricated by the electroplating method from surface to along the line and dynamically controlling the current density of the copper electrolytes. In order to fabricate thick magnetic plating, the adhesion properties between the NiFe plating and the silicon substrates were improved by changing the surface roughness of silicon substrates and increasing the thickness of seed layer. Lastly, the micro electromagnetic actuator was tested and the energy density of actuator was evaluated by the force of testing. Experiment shows this microactuator is efficient in producing magnetic energy density, magnetic force and has flexibility in application.

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Keywords: Micro electromagnetic actuator; High energy density; Multi-turns planar microcoils; Permalloy core

1. Introduction

For application to microsystem, such as microvalve, micropump, micro relays and micromotor [1–6], the high energy density actuators are needed. The electromagnetic actuator is one of the good candidates for its large force output and low voltage driving. It is well known that the magnetic energy density is proportional to the square of the magnetomotive force ($N \times I$) and relate to the leakage of the magnetic flux produced by the coil. But the current of it is limited by the heat produced in coils. To increase the number of coil-turns per unit area and decrease the magnetic leakage by inlaiding thick magnetic materials are two ways often used to improve the energy density.

Recently, there have been lots of designs for it. Yao et al. proposed an electromagnetic actuator by a photolithography process using the negative photoresist SU-8 in a single layer [7], in which the thickness of the copper wire (x_t) is about 20 μm, aspect ratio (r) is 0.8, the turns (n) is 12 per unit area, and the thickness of magnetic core is 50 μm. Ko and Yang [8] designed an efficient spiral-type micro magnetic actuator on permalloy substrates, in which x_t is about 12 μm, $r = 0.5$, $n = 17$, and the thickness of magnetic core is 10 μm. Sutanto et al. [9] fabricated the microactuator on the soft magnetic base (NiFe) by Co–Pt electrodepositing and fabricated supported legs (NiFe) to form closed magnetic circuit, which x_t is 8 μm, r is 0.8, n is 11. Guo et al. [5] and Yang et al. [6] improved the magnetic energy density by fabricating the double coils on the pros and cons of the silicon wafer to get more turns, in which the number of coil-turn is 8 and 10 per unit area, respectively, but there is no magnetic core in the coils.

Two difficulties are as follows:

> Firstly, the challenge for multi-turns coils is the resistance increased with the number of coil-turns, and hard to grow in the plate bath. As the electrical path to inside turns must trace through all the coil lines, and there is an electrical potential drop between the two coil ends arising from the resistance of the seed layer (a few thousand ohms). Secondly, magnetic plating layer (thickness less than 50 μm) was presented by Zhang et al. [4,6,9,10–12], the challenge is magnetic core shedding from the silicon wafer easily when its thickness increasing.

In this paper, a new technology to fabricate electromagnetic actuator of high energy density without enclosed magnetic circuit was introduced. This technology includes fabricating

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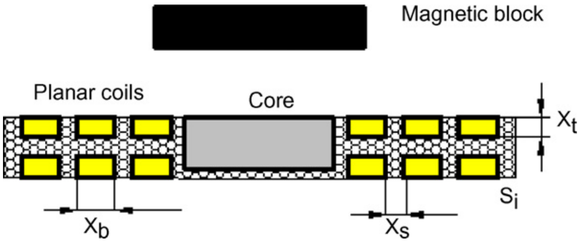

Fig. 1. The schematic of electromagnetic microactuator.

multi-turns planar microcoils and fabricating the thick magnetic (NiFe) core on the silicon wafer. The micro electromagnetic actuator with 20 × 2 turns coils per unit area and thick permalloy core (thickness is 200 μm) on silicon wafer was fabricated. At last, the magnetic force of actuator was tested in order to compare the energy density with others.

2. Design and theory

Fig. 1 shows the model of the micro electromagnetic actuator without enclosed magnetic circuit. The planar coil is fabricated on the pros and cons of the silicon substrates through deep silicon etching. The silicon hole is used to connect the upper and lower levels coil. The groove is etched into silicon wafer in the central coil before electroplating thick magnetic core. The operation of the actuator is given as follows: when the electrical current is applied to the coils, a magnetic field is generated around the coils perpendicular to the plane of the coils. When we apply the magnetic field on the magnetic films attached on the deformable membrane, a large magnetic force is generated.

From the formula (1)–(3), we can obtain the magnetic force F_m, it shows clearly that F_m is proportional to the square of the magnetomotive force ($N \times I$) from the formula.

$$\omega_m = \frac{1}{2}BH \tag{1}$$

$$W_m = \int_v \omega_m \, dV = \frac{1}{2}\frac{(NI)^2}{\Re} \tag{2}$$

$$F_m = \frac{dW_m}{dz} = -\frac{1}{2}\left(\frac{NI}{\Re}\right)^2 \frac{d\Re}{dz} \tag{3}$$

where ω_m is the magnetic energy density, W_m is the magnetic energy, $\Re$ is total magnetic reluctance, $\boldsymbol{\mu} = \mu_1\mu_0$ is magnetic permeability.

In Fig. 1, x_b is the width of copper wire, x_t is the thickness of the copper wire, x_s is the space between the coil-turns, $A = x_b x_t$, L is the total length of the coil, n is the number of coil-turns per unit area.

$$R = \rho_r \frac{L}{A} \tag{4}$$

$$I^2 R = Km\Delta k \tag{5}$$

During the copper electroplating, because there exists surface tension of liquid and edge effect of plating [13]. So, the experiment value of copper coil, $x_t < 100$ μm and the aspect ratio less than 5, was chose. From the formula (4) and (5), we can find the relationship between the maximum turns of planar coil per unit area and the temperature between the coil and the ambient temperature, as shown in Fig. 2.

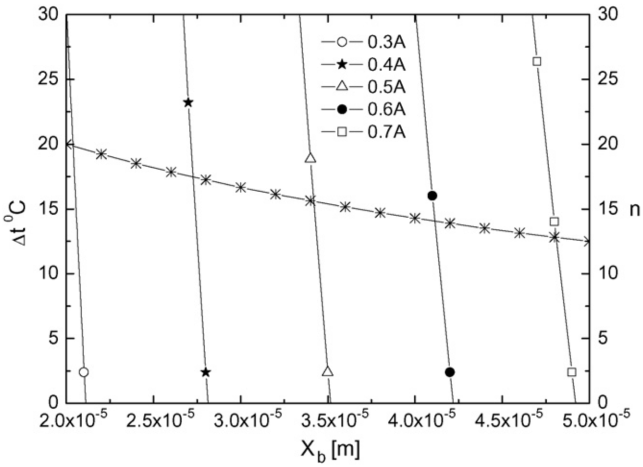

Fig. 2. The number of coil-turns (n) per unit area versus the temperature between the coil and the ambient temperature (Δt).

3. Fabrication

3.1. Fabrication process

There are two electroplating ways of microcoil: the first one is surface electroplating, as shown in Fig. 3(a), in which the current in the groove come from silicon surface; the second method is along the Cu wire line electroplating, as shown in Fig. 3(b), in which the current come from coil entrance. In this paper, when only the second method is used, the middle part of coil was fallen in liquid immersion before it is growing even with high current, because the coil length is too long and the resistance is too large. When only the fist method is used, the mouth of coil groove will be closed before the coil groove was filled with copper, which led to holes inside the copper wire as a result of the edge effect with the increase of the electroplating time. So, it is necessary to combine these two kinds of electroplating process, which not only make the seed layer full growth but also reduce empty in the coil wire. The main fabrication steps are as follows:

Firstly, as shown in Fig. 4(a), coil-shaped and core-shaped trenches were etched into silicon wafers as electroplating molds through lithography, radiography, corrosion process and deep reactive ion etching.

Secondly, as shown in Fig. 4(b), a seed layer of copper is deposited on the wafer molds by ion beam assistant deposi-

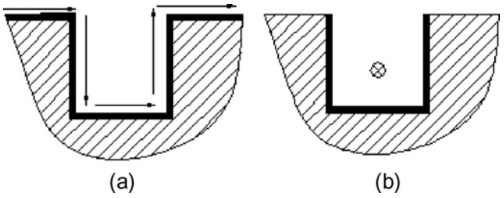

Fig. 3. The method of electroplated.

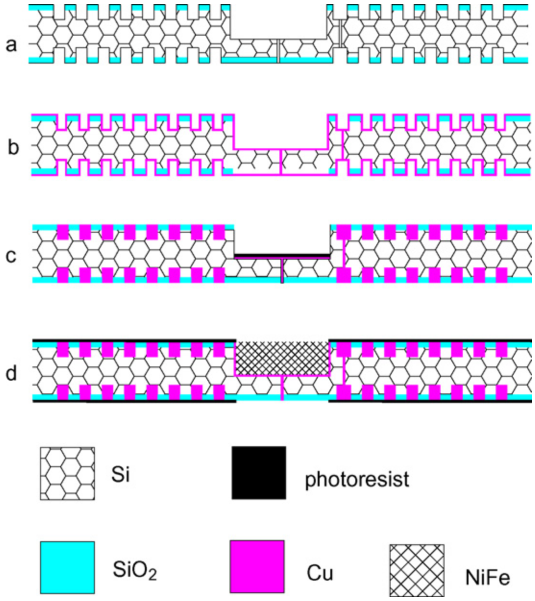

Fig. 4. The main fabrication processes of micro electromagnetic actuator chip.

tion. Then the whole seed layer is electrodeposited by surface electroforming method until the thick of plating reach to about 20 μm in the Cu electrolytes.

Thirdly, corresponding to Fig. 4(c), peeling the surface plating on the wafer surface and persevering the plating in the groove, then coating the core surface by photoresist, electroplating the coil in the groove until the whole groove full along the line in the Cu electrolytes.

Lastly, when the coil groove was filled with copper, the coil is coated by photoresist and permally core is electroplated in NiFe electrolytes, as shown in Fig. 4(d).

The technology adopt electroplating overall the copper coil seed layer directly replacing secondary lithography and corrosion process before electroplating process, which reduce processing cycle and decrease cost compared to the technology in the reported [6]. The seed layer in the core groove reach to about 20 μm by electroforming copper before electroplating magnetic core. The method overcomes the difficult of plating thick magnetic material on the silicon wafer.

3.2. *Dynamic controlling current density*

In electroplating process of copper, because the position and shape of cathode (silicon mold) is different, current density distribution is uneven. In the part of large resistance because of the weaker current, the positive ions in the solution cannot be attracted to the substrates cathode. If seed layer have not been plated in the aqueous metal solution for long time, as a result of liquid immersion, the seed layer is easier to shed, as shown in Fig. 5. Therefore the seed layer must be growing rapidly before falling from the silicon wafers. Because the metal ion deposition rate increases with the current density (as shown in Fig. 6), the large current density should be adopted at the beginning of electroplating process.

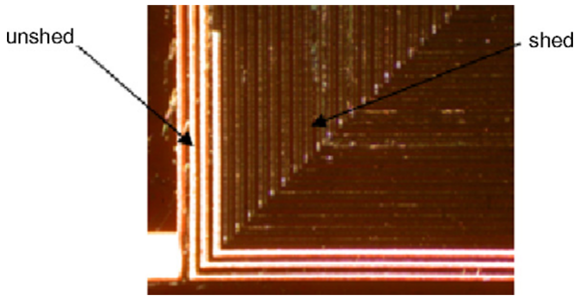

Fig. 5. The photo of coil.

On the ordinary electroplating condition, the current density is about 20 mA cm^{-2} when the plating is glazed, the upper limit current density is 90 mA cm^{-2}, when the plating is semi-glazed [14], However current density do not exceed the permitted limit (different current density threshold exists in the different electrolytes). If current density is over upper limit, due to serious lack of metal ions in the around cathode, irregular meta plating like the branches or spongy meta plating are formed at the cathode tip or convex part. With the growth of plating inlaid the silicon wafer, binding force between the plating and substrate has been strengthened [15], at the same time, coil resistance will be gradually lowered. When the seed layer growth to certain thickness, the electroplating process method along copper lines can be used. In order to gain uniformity copper plating, electroplating with low current density should be selected in the lines plating process [16].

So, during electroplating the process of the multi-turns micro planar coil, the current density should be controlled dynamically. Fig. 7 shows the dynamic control curves of the current density: when $x_b = 50\,\mu$m, the current density is 80–100 mA cm^{-2} in the surface electroforming method. When the current density is over 100 mA cm^{-2}, “char” phenomenon is formed at the sharp corners and edges. After 5–6 h (about 20 μm thick), the coating out of the groove is peeled, then the 30–50 mA cm^{-2} current density is used to electroplate the plating stay in groove bed until the entire

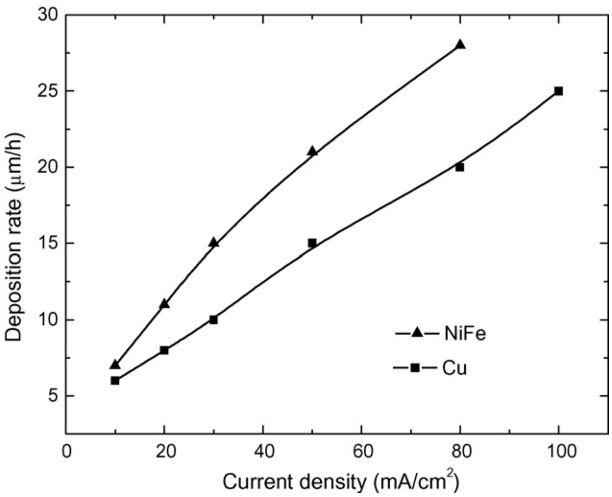

Fig. 6. The relationship between deposition rate and current density.

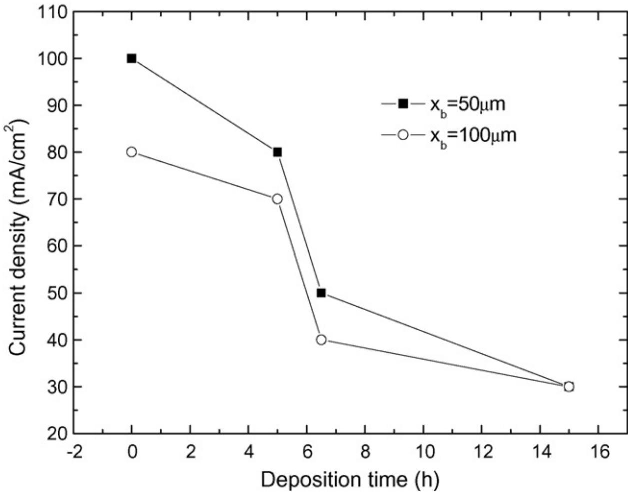

Fig. 7. The dynamic control of the current density.

silicon groove filled with copper by electroplating along the line.

3.3. Electroforming magnetic core

3.3.1. Soft material choice

NiFe alloy is the most commonly magnetic materials used in MEMS, which have a relatively high magnetic saturation, low coercivity, good corrosion resistance, and near zero magnetostriction and the simple deposition method, compared to other soft materials, such as CoFeCu. During the processing of NiFe alloy, the residual stress and deformation of plating can be reduced with sulfamate-chloride electrolytes used as the main salt [17].

3.3.2. Fe content controlling

During the NiFe alloy electroplating, the plating have a good magnetic properties only when the Ni and Fe composition of plating and permalloy is very close. When the Fe content is 19–24% in the coating, the plating show better magnetic properties [18], accordingly the Fe composition is usually limited to 20 ± 1%, in which the major factors affecting the Fe composition of the plating are the content of Fe^{2+} ions and current density in the electrolytes.

Because the NiFe alloy plating is untraditional deposition process, the Fe^{2+} ions have the strong priority deposition tendency compared to Ni^{2+}. Thus the composition of Ni^{2+}/Fe^{2+} in the electroplating solution is different from the composition rate of Ni/Fe. When the composition of Ni^{2+}/Fe^{2+} is higher than 70:1, the plating Ni/Fe ratio can reach to 80:20. Thus the concentration of Fe^{2+} in the electroplating bath is low even so small changes will also make significant changes in plating composition. The Fe^{2+} ingredients should be selected suitably to reduce the impact on the ratio of components. Fig. 8 is the relationship between the iron content of alloy plating and ferrous sulfate content of electroplating solution. In the experiment, when the content of $FeSO_4 \cdot 7H_2O$ is about 4 g L^{-1}, the composition of Fe in the NiFe alloys can reach to 20%.

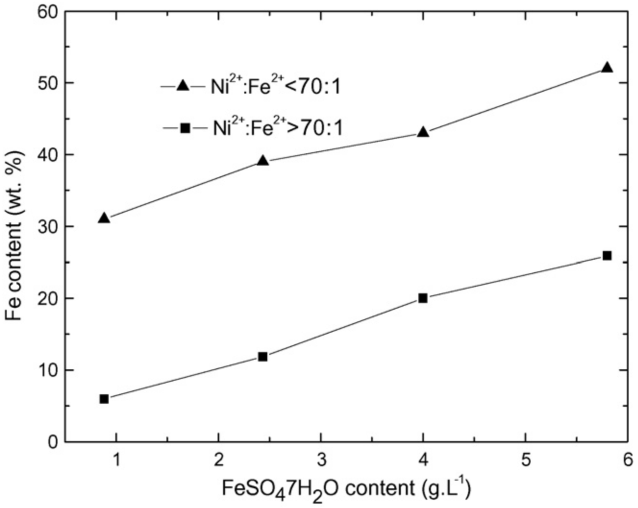

Fig. 8. The relationship between Fe content in alloy and $FeSO_4 \cdot 7H_2O$ content in bath.

Some people think that a large current density means high plating speed and does not have a large impact on the composition of alloy [19]. But during the process of selective electroplating in the fabricating micro structure, there are inevitable differences in current density. When the current density affects the plating composition of alloy seriously, the plating composition will be inconsistent and the coating performance becomes bad. Therefore, it is important to choose suitable current density during the electroforming process. Fig. 9 shows the relationship curve between the current density and the Fe and Ni content in the plating.

As can be seen from Fig. 9, when the current density is below 30 mA cm^{-2}, current density have a small impact on the Fe content of plating. So even if there is a little difference on current density selected below 30 mA cm^{-2} during the plating, uniform magnetic plating can be produced. Fig. 10 shows the array of planar coil with magnetic core in the silicon substrates.

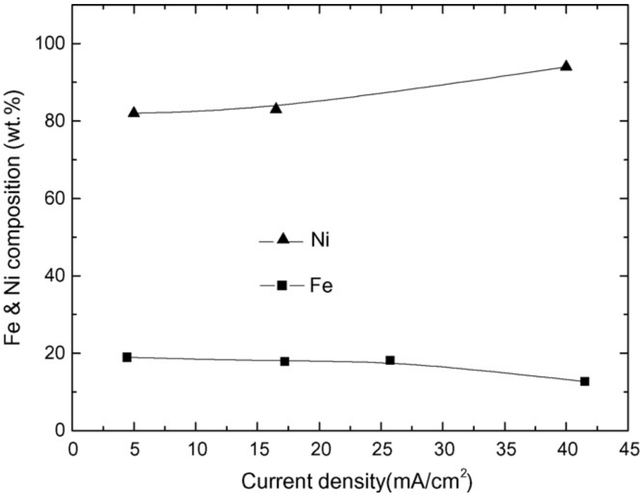

Fig. 9. The relationship between Fe and Ni content in alloy and current density.

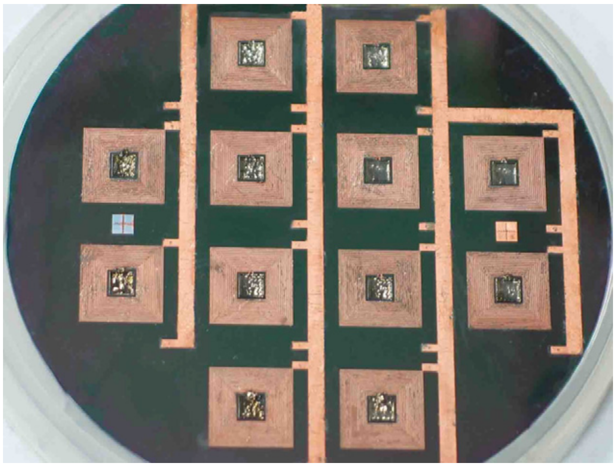

Fig. 10. The array of planar coil with magnetic core.

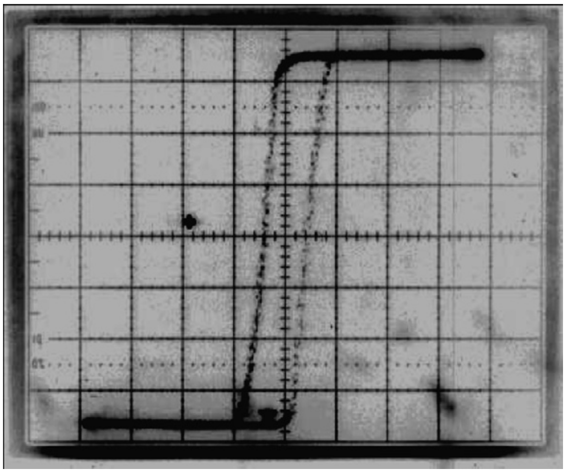

Fig. 12. The *BH*-loop of electroplated sample.

4. Result and discussion

In the same aspect ratio of coil, the resistance difference of coil between theory and measurement decreases with x_b, and this resistance difference increases with aspect ratio in the same x_b, as shown in Fig. 11. It also means that quality of coil becomes better when the aspect ratio gets lower and the width of copper wire gets larger.

In this paper, the 20 × 2 turn double planar microcoil per unit area, in which the thickness is 90 μm and the aspect ratio is 3, is fabricated by this technology. The practical resistance of double planar coils is about 6.8 Ω, while the theoretical value of multi-coils is 7.5 Ω. The difference between the experiment and the theory is caused by the uneven depth of the coil while electroplating. However the experimental value is very close to the theoretical value, so the technology succeeds in producing multi-turns planar microcoils.

The NiFe alloy plating with its thickness more than 200 μm was fabricated on the silicon wafer by increasing the thickness of the Cu seed layer. Furthermore, the thickness of the seed layer does not affect the performance of NiFe alloy plating. As can be seen from the *B–H* curve of the magnetic coating in Fig. 12, it illustrates the magnetic properties of the plating sample. Specifically, the coercivity H_c is about 70 A m^{-1}.

The micro electromagnetic actuator is tested, in which sinusoidal driver current density is 2.5×10^7 A m^{-2} (equivalent to 0.3 A). The energy density of actuator was evaluated by the force of testing.

Fig. 13 shows the electromagnetic force of our actuator along the symmetry line (*z* axis). Solid square (■) is testing value, solid circle (●) is theoretical value, solid triangle (▲) is number value reported in the reference [8]. We clearly observe the entire trend of force is in good agreement with result from other works, and the maximum estimated force produced by the integrated electromagnetic microactuator is around 45 mN at a sinusoidal current of 0.3 A amplitude, the maximum value is higher than the result of reference [8]. At the same time, we also observe that in the range of 0–3 mm area, the energy density is higher than other range and not obvious changes, which shows the magnetic field concentrate near the center of the electromagnetic force because the soft magnetic iron core. However, when the gap $\Delta z > 3$ mm, the magnetic induction of

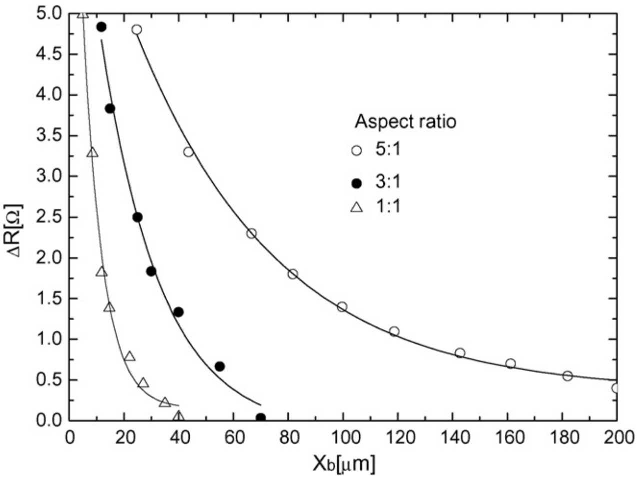

Fig. 11. The resistance difference of coil between theory and measurement versus x_b with the different aspect ratio.

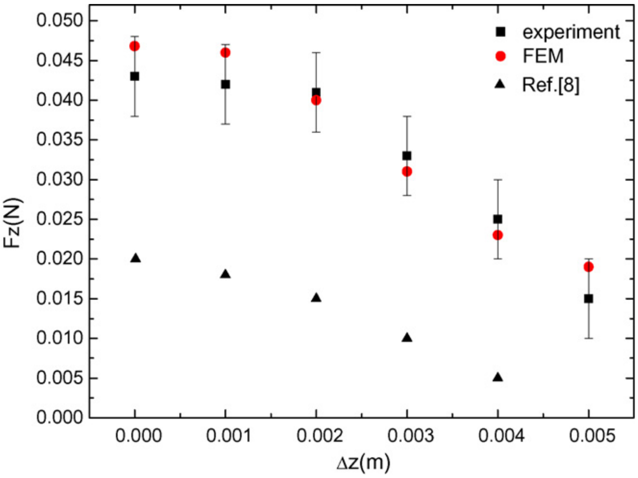

Fig. 13. The magnetic force along the symmetry line (*z* axis).

the actuator decrease markedly because of large magnetic flux leak.

This electromagnetic microactuator has higher energy density, as compared to which developed by C.H. Ko et al. in Section 1.

5. Conclusions and outlook

In this paper, a new technology is developed to form high energy density micro electromagnetic actuator on the silicon wafer, which solves the process difficult of electroplating multi-turns double planar microcoils and growing thick magnetic material on the silicon wafer.

During the process of the multi-turn coils, the double multi-coils was fabricated by surface electroplating, along the copper wire electroplating and controlling the current density dynamically process. We observe the around 20 μm thick copper as critical value from surface electroforming to along the copper wire line electroforming. In the process of thick NiFe alloy plating, when the $FeSO_4 \cdot 7H_2O$ content is about $4\,g\,L^{-1}$ and current density is about $30\,mA\,cm^{-2}$, the NiFe alloys plating with Fe content 20% can be acquired. The experiment provides a good basis for fabricating of multi-turns planar microcoils and the thick magnetic core on the silicon wafer.

At last, the micro electromagnetic actuator was tested and the energy density of actuator was evaluated by the force of testing. The experimental results show that the micro electromagnetic actuator has higher electromagnetic energy density than others by compare the electromagnetic force.

Future developments include the higher energy density electromagnetic actuator by increasing the turns of coil, by increasing the thickness of magnetic core and by enclosed magnetic circuit. In particular, we anticipate that the technology presented above can be advantageously applied for lab-on-a-chip applications where low cost.

Acknowledgements

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