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Fabricating a Micro Electromagnetic Actuator with High Energy Density*

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Abstract: This paper introduces a new technology to fabricate a micro electromagnetic actuator with high energy density without an enclosed magnetic circuit. This technology includes fabricating multi-turns planar micro coils and fabricating the thick magnetic (NiFe) core on the silicon wafer. The multi-turns planar micro coils are fabricated by the electroplating method from the surface along the line and by dynamically controlling the current density of the copper electrolytes. In order to fabricate thick NiFe plating, the adhesion properties between the NiFe plating and the silicon substrates are improved by changing the surface roughness of the silicon substrates and increasing the thickness of the seed layer. Furthermore, the micro electromagnetic actuator is tested and the energy density of the actuator is evaluated by force testing. The experiments show that the microactuator is efficient in producing high magnetic energy density and high magnetic force.

Key words: micro electromagnetic actuator; high energy density; multi-turns double planar microcoils; thick permalloy core
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1 Introduction

For application in microsystems such as microvalves, micropumps, micro relays, and micromotors[1~6], high energy density actuators are needed in order to obtain smaller volume, higher performance MEMS. The electromagnetic actuator is a good candidate due to its large force output and low voltage driving. The magnetic energy density is proportional to the square of the magnetomotive force (NI) and related to the leakage of the magnetic flux produced by the coil. But, its current is limited by the heat produced in the coils. To increase the number of coil-turns per unit area and decrease the magnetic leakage by inlaid thick magnetic materials are two methods often used to improve the energy density.

Recently, there have been many designs proposed. 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 copper wire thickness (z_t) is about 20μm, the aspect ratio (r) is 0.8, the turns (n) is 12 per unit area, and the thickness of magnetic core is 50μm. Ko *et al*.[8] designed an efficient spiral-type micro magnetic actuator on permalloy substrates, which is about 12μm, and $r = 0.5$, $n = 17$, and the thickness of magnetic core is 10μm. Sutanto *et al*.[9] fabricated the microactuator on a soft magnetic base (NiFe) by Co-Pt electrodepositing and fabricated supported legs (NiFe) to form a closed magnetic circuit, in which z_t is 8μm, r is 0.8, and n is 11. Guo[5] and Yang[6] improved the magnetic energy density by fabricating double coils on the front and rear sides of the silicon wafer to create more turns, in which the number of coil-turns is 8 and 10 per unit area respectively, but there is no magnetic core in the coils.

However, there remain two difficulties:

First, the challenge for multi-turn coils is that the resistance increases with the number of coil-turns, and they are hard to grow in an electroplating bath. Because the electrical path to the inside turns must trace through all the coil lines, and the resistance of the seed layer will be large (a few thousand ohms), there is an electrical potential drop between the coil ends. Second, a magnetic plating layer of thickness less than 50μm was presented by Zhang *et al*.[4,6,9~12]. The challenge is that the magnetic core sheds from the silicon wafer easily when its thickness increases.

In this paper, a new technology to fabricate an electromagnetic actuator of high energy density without an enclosed magnetic circuit is introduced. This technology includes fabricating multi-turn planar micro coils and fabricating the thick magnetic (NiFe)

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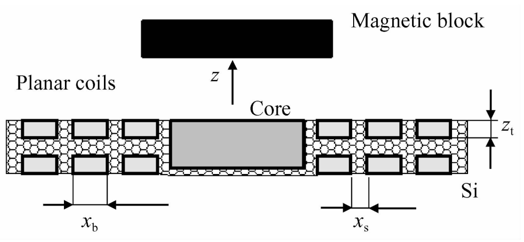

Fig.1 Schematic of electromagnetic microactuator

core on the silicon wafer. The micro electromagnetic actuator with 20×2 turns coils and a thick permalloy core (thickness is 200μm) in per unit area silicon wafer is fabricated. Finally, the magnetic force of the actuator is tested in order to compare the energy density with other designs.

2 Design and theory

The model of the micro electromagnetic actuator without an enclosed magnetic circuit is shown in Fig. 1. The planar coil is fabricated on the front and rear sides of the silicon substrates through deep silicon etching. The silicon hole connects the upper and lower coil levels. The trench is etched into the silicon wafer in the central coil before electroplating the 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 Eqs. (1)～(3), we can obtain the magnetic force F_m, which shows that F_m is proportional to the square of the magnetomotive force (NI).

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

$$W_m = \int_v \omega_m \mathrm{d}V = \frac{1}{2} \times \frac{(NI)^2}{\Re} \tag{2}$$

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

where ω_m is the magnetic energy density, W_m is the magnetic energy, and $\Re$ is the total magnetic reluctance.

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

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

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

where K is the specific heat, m is the mass of the coil, ρ_r is the resistivity of the copper, and Δt is the difference between the coil temperature and the ambient temperature.

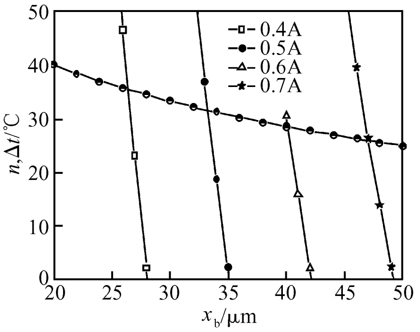

Fig.2 Number of coil-turns (n) per unit area versus the difference of temperature between the coil and the ambient temperature (Δt)

Because of the surface tension of the liquid and the edge effect of the plating[13] during the copper electroplating, the experimental value of copper coil is chosen to be $z_t < 100\mu$m and the aspect ratio to be less than 5. From Eqs. (4) and (5), we can find the relationship between the maximum number of coil-turns per unit area and the difference between the coil temperature and the ambient temperature. Figure 2 shows that when $x_b = 30\mu$m, $z_t = 90\mu$m, $\Delta t < 5$℃ and the maximum load current of coil is 0.4, 0.5, 0.6, and 0.7A, the maximum number of coil-turns per unit area is 34, 32, 28, and 25, respectively.

3 Fabrication

3.1 Fabrication process

There are two electroplating methods for micro coil. First is surface electroplating, shown in Fig. 3(a), in which the current in the trench comes from the silicon surface; the second method is along the Cu wire line electroplating, shown in Fig. 3(b), in which the current comes from the coil entrance. In this paper, when only the second method was used, the middle of the coil was striped in the liquid before it grew even with high current, because the coil length was too long and the resistance was too large.

When only the fist method was used, the mouth of the coil trench closed before the coil trench was

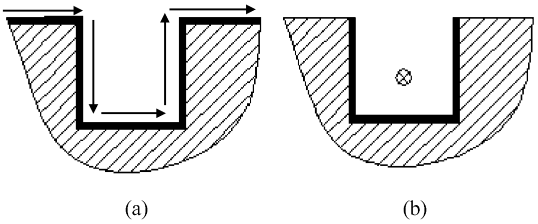
(a) (b)

Fig.3 Method of electroplating

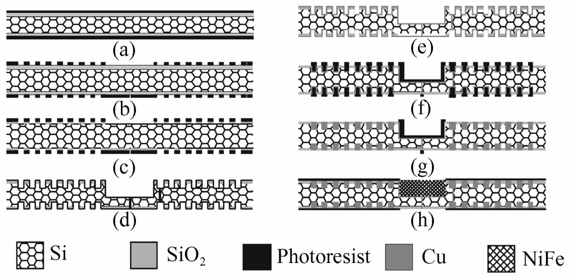

Fig.4 Fabrication processes of the double plane microcoil

filled with copper, which led to holes inside the copper wire. So, it is necessary to combine these two kinds of electroplating processes to make the seed layer fully grown but also to reduce the hollow in the coil wire. The main fabrication steps are as follows:

First, coil-shaped and core-shaped trenches were etched by lithography (Fig. 4(a)), radiography (Fig. 4 (b)), corrosion process (Fig. 4(c)), and deep reactive ion etching (Fig. 4(d)).

Second, as shown in Fig. 4(e), a seed layer of copper was deposited on the wafer mold by ion beam assistant deposition. Then, the whole seed layer was electrodeposited by the surface electroforming method until its Cu thickness reaches about 20μm.

Third, corresponding to Fig. 4(f), we corroded the surface plating on the wafer surface and persevered the plating in the trench, then coated the core surface by photoresist, electroplating the coil in the trench until the whole trench is full along the line in the Cu electrolytes in Fig. 4(g).

Lastly, when the coil trench was filled with copper, the coil was coated by photoresist before the permally core was electroplated in NiFe electrolytes, as shown in Fig. 4(h).

This technology adopts electroplating over the copper coil seed layer, directly replacing secondary lithography and the corrosion process before electroplating process, which reduces processing cycles and decreases cost compared to the technology reported in Ref. [6]. This method overcomes the difficulty of plating thick magnetic material on the silicon wafer.

3.2 Dynamically controlling current density

In the electroplating process of copper, because the position and shape of the cathode (silicon mold) is different, current density distribution is uneven. In the part with large resistance, the positive ions in the solution cannot be attracted to the substrates cathode due to the weaker current. If the seed layer was not 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 grow 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.

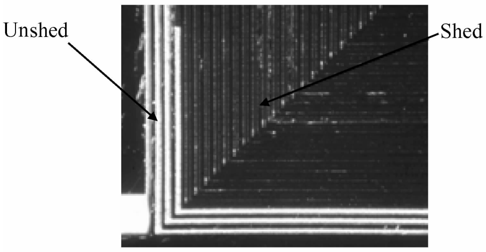

Fig.5 Photo of the coil

For ordinary electroplating conditions, the plating is glazed when the current density is about 20mA/cm^2, and the electroplating is semi-glazed when the upper limit current density is 90mA/cm^2[14]. However, current density cannot exceed the permitted limit (different current density threshold exists in the different electrolytes). If current density is over the upper limit, due to a lack of the metal ions around the cathode, irregular metal plating like branches or a spongy shape form at the cathode tip or convex part. With the growth of plating, the binding force between the plating and substrate strengthens[15] while the coil resistance gradually decreases. When the seed layer reaches a certain thickness, the electroplating process method along copper lines can be used. In order to gain uniform copper plating, electroplating with low current density should be selected in the lines plating process[16].

So, during electroplating of the multi-turn micro planar coil, the current density should be controlled dynamically. Figure 7 is the dynamic control curves when the current density is from 80 to 100mA/cm^2 in the surface electroforming method. When the current density is over 100mA/cm^2, a "char" phenomenon occurs at the sharp corners and edges. After 5 to 6 hours (about 20μm thick), the coating out of the trench is peeled, then 30～50mA/cm^2 current density

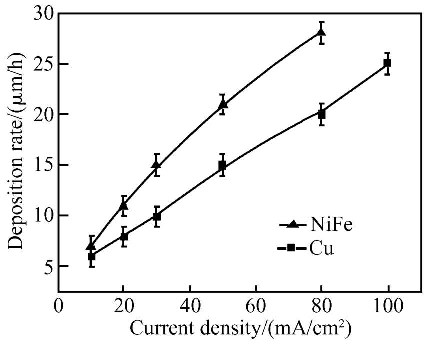

Fig. 6 Relationship between deposition rate and current density

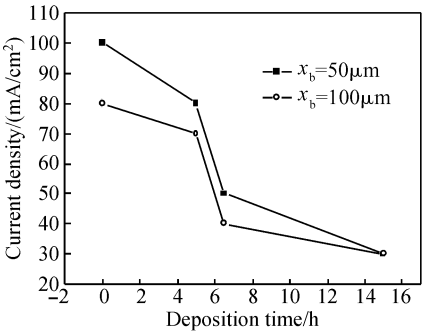

Fig.7 Dynamic control of the current density

is used to electroplate the plating in the trench bed until the entire silicon trench is filled with copper by electroplating along the line.

3.3 Electroforming magnetic core

3.3.1 Soft material choice

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

3.3.2 Fe content control

During the NiFe alloy electroplating, the plating has good magnetic properties only when the Ni&Fe composition of plating is closed to permalloy. When the Fe content is 19～24% in the plating, the plating shows better magnetic properties[18]. Accordingly, the Fe composition is usually limited to 20 ± 1% by controlling the content of Fe^{2+} ions and the current density in the electrolytes, which are the major factors affecting the Fe composition of the plating.

Because NiFe alloy electroplating is a non-traditional deposition process, the Fe^{2+} ions have a 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 80 : 20. Therefore, the concentration of Fe^{2+} in the electroplating bath is lower. Under such circumstances, small changes in the concentration will make significant changes in plating composition. The Fe^{2+} ingredients should be selected suitably to reduce the impact on the ratio of components. Figure 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 4g/L, the composition of Fe in the NiFe alloys can reach 20%.

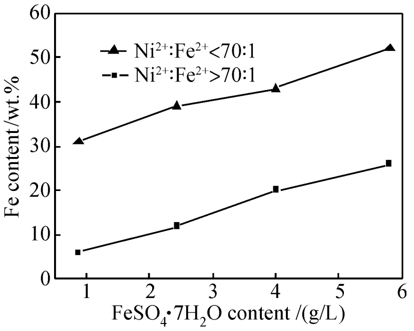

Fig.8 Relationship between Fe content in alloy and $FeSO_4 \cdot 7H_2O$ content in bath

In the past, researchers thought that the large current density meant high plating speed and did not consider the impact on the composition of alloy. But during the process of selective electroplating in fabricating micro structure, there are inevitable differences in current density[19]. When the current density affects the plating composition of alloy seriously, the plating composition will be inconsistent and the plating performance worsens. Therefore, it is important to choose suitable current density for the electroforming. Figure 9 is the relationship curves between the current density and the Fe & Ni content in the plating.

Figure 9 shows that when the current density is below 30mA/cm^2, current density has a smaller impact on the Fe content of the plating. So, even if there is little difference in current density selected below 30mA/cm^2, uniform magnetic plating can be produced.

4 Results and discussion

In this paper, a 20 × 2 turn double planar micro coil per unit area, in which the thickness is 90μm and the aspect ratio is 3, is fabricated. Figure 10 is the array of planar coil with magnetic core in the silicon

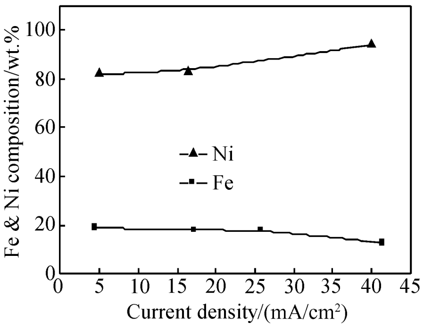

Fig.9 Relationship between Fe & Ni content in alloy and current density

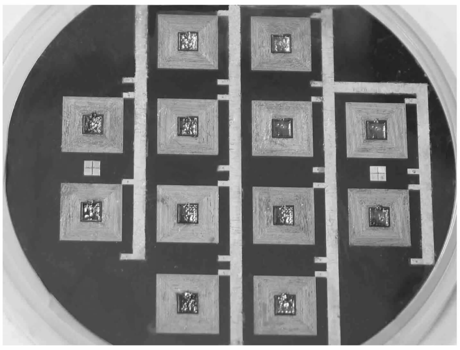

Fig.10 Array of planar coil with magnetic core

substrates.

In the same aspect ratio of coil, the resistance difference between theory and measurement value of coil decreases with x_b, and it increases with aspect ratio in the same x_b, as shown in Fig. 11. The quality of coil becomes better when the aspect ratio decreases and the width of the copper wire increases.

The practical resistance of the double planar coils of the actuator is about 6.8Ω, while the calculated value of this coil is 7.5Ω. The difference between the experimental and the theoretical value is caused by the uneven depth of the coil. However, they are very close.

The NiFe alloy plating with a thickness of more than 200μm 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. This can be seen from the *B-H* curve of the magnetic film in Fig. 12. Specifically, the coercivity H_c is about 70A/m.

The micro electromagnetic actuator is tested, in which the sinusoidal driver current density is $2.5\times10^7\mathrm{A/m^2}$ (equivalent to 0.3A). The energy density of the actuator can be evaluated by driving electromagnetic force testing. Figure 13 shows the electromagnetic force of the actuator along the symmetry line (z axis). The solid squares (■) are the testing values, the solid circles (●) are the theoretical values, and the solid triangles (▲) are the values reported in Ref.[8]. The maximum force produced by the integrated electromagnetic microactuator is about 45mN at a sinusoidal current of 0.3A amplitude and the maximum value is higher than the result in Ref.[8]. At the same time, the energy density is higher than other ranges and there are not obvious changes in the range of 0～3mm area, which shows the magnetic field concentrate near the center of the electromagnetic force because of the soft magnetic iron core.

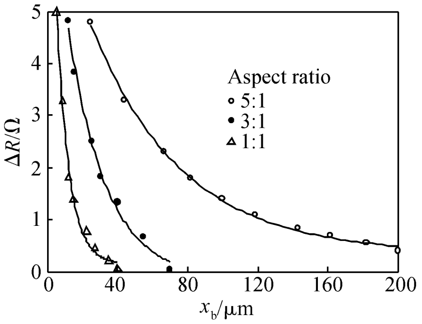

Fig.11 Resistance difference of coil between theory and measurement versus x_b with different aspect ratios

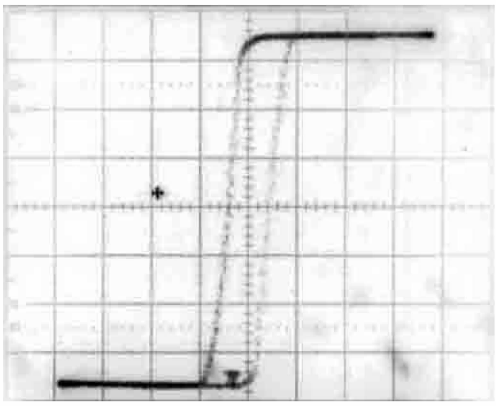

Fig.12 *BH*-loop of the electroplated sample

5 Conclusion

In this paper, a new technology is developed to form a high energy density micro electromagnetic actuator on a silicon wafer. The process difficulties, which are electroplating multi-turn double planar microcoils and growing thick magnetic material on the silicon wafer, are solved.

During the process of the multi-turn coils, the double multi-coils was fabricated by surface electroplating, along the copper wire electroplating and current density dynamic control process. 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 the seed layer.

When the $FeSO_4\cdot7H_2O$ content is about 4g/L

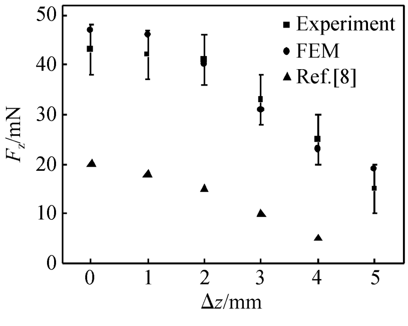

Fig.13 Magnetic force along the symmetry line (z axis)

and the current density is about 30mA/cm^2 during the process of thick NiFe alloy plating，NiFe alloys electroplating with Fe content 20% can be acquired.

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

References

[1] Meckes A，Behrens J，Benecke W. A microvalve with electromagnetic actuator. 6th International Conference on New Actuators，1998：17

[2] Behrens J，Mexkes A，Gebhard M，et al. Electromagnetic actuation for micropump and valves. 5th International Conference on New Actuators，1996：26

[3] William P T，Oliver B，Mark G A. Fully integrated magnetically actuated micromachined relays. J Microelectromechaml Syst，1998，40(2)：181

[4] Klopzig M. A novel linear micromachined electromagnetic actuator including magnetic suspension. 6th International Conference on New Actuators，1998：17

[5] Guo Z S，Wu Y H，Xuan M，et al. Electro-magnetic planar micromotor and its fabrication. Optics and Precision Engineering，2003，11(2)：120 (in Chinese)[郭占社，吴一辉，宣明，等．电磁型平面微电机及其制作工艺．光学精密工程，2003，11(2)：120]

[6] Yang J W，Wu Y H，Jia H G. Design method and magnetic field analysis of axial-magnetized permanent magnet micromotor. Optics and Precision Engineering，2006，14(1)：83 (in Chinese)[杨杰伟，吴一辉，贾宏光．轴向磁化永磁微电机磁场分析及设计方法研究．光学精密工程，2006，14(1)：83]

[7] Yao F，Erol C H，Muralidhar K. Fabrication of microstructures with different aspect rations in a single layer. Proc SPIE，2005，5650：156

[8] Ko C H，Yang J J. Efficient magnetic microactuator with an enclosed magnetic core. Microlith，Microfab，Microsyst，2002，1(2)：144

[9] Sutanto J，Papania A D，Berthelot Y H，et al. Dynamic characteristics of membrane displacrment of a bidirectional electromagnetic microactuator with microcoil fabricated on a single wafer. Microelectronic Engineering，2005，82：12

[10] Jack W J. Magnetic microactuators with polysilicon flexures. Univesity of Berkeley Doctor Dissertation，1994：66

[11] Hyouny J C，Chong H. A bidirectional magnetic microactuator using electroplated permanent magent arrays. Journal of Microelectro-Mechanical Systems，2002，11(1)：78

[12] Zhang Y H，Ding G F，Cai Y L，et al. Electroplating of low stress permalloy for MEMS. Materials Characterization，2006，1(6)：1

[13] Soifer Y M，Verdyan A，Kazakevich M，et al. Edge effect during nanoindentation of thin copper films. Mater Lett，2005，59：1434

[14] Wang B F，Huang Y H，Yu C Y. Experimental research on jet electroforming. Journal of Nanjing University of Aeronautics & Astronautics，2002，34(4)：328

[15] Zhang T，Wu Y H，Zhang P，et al. The growth and adhesion properties research of the Cu/NiFe films on the silicon substrates. Chinese Journal of Sensors and Actuators，2006，9(5)：1444 (in Chinese)[张涛，吴一辉，张平，等．Si 基 Cu/NiFe 薄膜的生长及其粘附特性研究．传感技术学报，2006，9(5)：1444]

[16] Yang J W，Wu Y H，Wang S R，et al. Study on fabrication process of planar stator coil of micromotor. Microfabrication Technology，2006，6(3)：27 (in Chinese)[杨杰伟，吴一辉，王淑荣，等．平面微电机定子线圈制作工艺研究．微细加工技术，2006，6(3)：27]

[17] Lan Y B，Yu J K. Experiment research of plating technique of NiFe alloy. Corrosion and Protection，1999，120(8)：355 (in Chinese)[兰英斌，于金库．电镀 NiFe 合金的实验研究．腐蚀与防护，1999，120(8)：355]

[18] Ding G F，Zhang S B，Li Y Q，et al. A study on plating soft magnetic underlayer for the rotor of micromotor. Microfabrication Technology，1996，3：71 (in Chinese)[丁桂甫，张寿柏，李依群，等．微马达转子电镀导磁的研究．微细加工技术，1996，3：71]

[19] Quemper J M，Nicolas S，Gilles J P，et al. Permalloy electroplating through photoresist molds. Sensors and Actuators，1999，74：1

高能量密度微电磁驱动器的制作方法*

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摘要： 提出了一种非闭合磁路型高能量密度微电磁驱动器的制作方法，即利用 MEMS 工艺在单位面积硅基体上制作多匝、高深宽比的平面线圈和高厚度的磁芯．通过先面电铸再线电铸的方式，以及动态控制电铸电流密度的方法进行平面线圈的制作；通过改变衬底表面粗糙度和种子层厚度的方法，改善合金镀层与衬底的粘附性能，可以在单位面积的硅片上，制作出厚度更大的磁性合金镀层．初步实验结果表明：该微型电磁驱动器在相同的输入功率下，比同类其他微电磁驱动器，能产生更大的电磁驱动力，具有更高的能量密度．

关键词： 微型电磁驱动器；高能量密度；多匝双层平面微线圈；厚 NiFe 合金镀层

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