Fabrication and Simulation of an Electromagnetic Microrelay*

Zhang Yufeng[1] and Li Desheng[2]

(1 *Department of Automation Measurement and Control Engineering, Harbin Institute of Technology, Harbin* 150001, *China*)
(2 *College of Mechanical Engineering & Applied Electronics Technology, Beijing University of Technology, Beijing* 100022, *China*)

Abstract: The fabrication and simulation of an electromagnetic microrelay are presented based on micro electromechanical systems (MEMS) technique. The microrelay dimensions of about 4mm×4mm×0.5mm are fabricated with the common technique of micromachining. Compared with the traditional relays, a planar coil is substituted for a solenoid coil to favor the MEMS fabrication. Moreover, a bi-supporter cantilever beam with high sensitivity is fabricated to act as the movable electrode of the microrelay. Theoretical calculations and simulations are also carried out with respect to the electromagnetic force yielded by the exciting electromagnetic coil. The structure and parameters concerning the electromagnetic microrelay can be optimized using the results.

Key words: electromagnetic microrelay; MEMS; micromachining; planar coil; cantilever beam
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1 Introduction

It is a great topic of interest and growth that micro electromechanical systems (MEMS) technique has been applied to miniaturization of relays for a variety of applications in the telecommunications, automatic test equipment (ATE), industrial control and automotive fields. Recently, several types of microrelays based on MEMS have been presented. The microrelays are generally divided into electrostatic, thermalmechanical, and electromagnetic according to their actuation principles. The characteristics of the different actuation methods can be found in References[1, 2].

From the pros and cons of the electromagnetic type of actuation discussed, we wish to intergrate a planar electromagnetic actuator into the microrelays. In terms of the idea, a novel electromagnetic microrelay is presented in this paper. The proposed microrelay exhibits a few special features besides the common characteristics of electromagnetic ones. Compared with the traditional solenoid coil, a square planar coil is used to overcome the complex fabrication of the spirality. The simple semiconductor techniques are needed only for the great increase in the number of turns of the electromagnetic coil. Furthermore, the magnetic core is ignored because the FeSi is used for the substrate. In order to understand the characteristics of the electromagnetic microrelay well, theoretical results obtained from finite element (FE) simulations are also given in this paper.

2 Fabrication process

Fabrication process of a planar coil and a pair of contacts positioned above the coil is shown in Fig. 1. The fabrication of the electromagnetic coil was realized on a FeSi substrate with an insulated

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Zhang Yufeng　male, was born in 1976, PhD candidate. His current research interest focus on MEMS.
Li Desheng　male, was born in 1961, professor. His current research is in sensors and MEMS.

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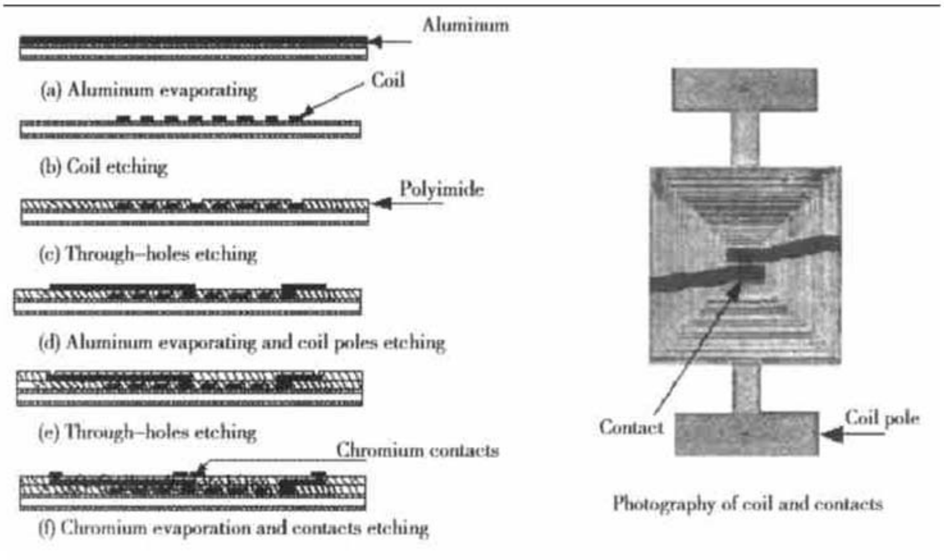

Fig. 1 Fabricating process of a planar coil and a pair of contacts

layer. On the substrate, an aluminum of 5μm thick was deposited by physical vapor deposition (PVD). The coil structure in this layer was defined by standard photolithography, followed by wet etching in the BHF solution. The resulting coil with 5μm thick consisted of 39 turns with a linewidth and space of 20μm. The inner and outer side lengths of the coil were 0.2mm and 3.2mm, respectively. The resistance of the coil was about 32Ω. In order to fetch out the two poles of the coil, a polyimide layer was coated on the coil and the two through-holes were patterned so that the coil was isolated and leveled off. A second aluminum layer of 2μm was deposited on the polyimide and the two poles of coil were obtained outside the coil by the same method. A second polyimide was coated and developed to obtain another two through-holes, and subsequently the chromium layer of 1μm was deposited on the second polyimide layer by PVD. Then, a pair of contacts and two coil poles were patterned by lithography, followed by wet etching in the glycerin solution (50%) and the hydrochloric acid solution (36%).

After completing the coil and the two contacts, the movable electrode suspended by thin beams was fabricated on another silicon substrate, which was approximately 300μm thick and has a thermally grown SiO_2 of 0.5μm. The fabrication steps are schematically shown in Fig. 2. Firstly, a copper seed of 1μm was deposited on the substrate by copper evaporation. The copper seed acts as both the electroplating seed and the sacrificial layer. Secondly, a photoresist layer was spun and patterned serving as a mold for electroplating of the movable electrode. Thirdly, a nickel of 10μm was directly electroplated above the mold of the mov-

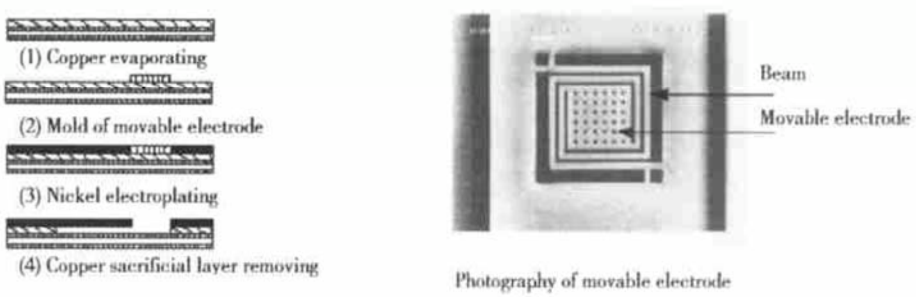

Fig. 2 Fabrication process of the movable electrode

able electrode. After the electroplating step, the photoresist mold was removed. Finally, the movable electrode was released by removing the copper sacrificial layer using the thick HNO_3. The movable electrode frame with the size of 0.5mm × 0.5mm was used to obtain higher sensitivity and better stability[3].

Both the microactuator and the movable electrode were conglutinated to compose the whole basic structure of the fabricated electromagnetic microrelay, as shown in Fig. 3. The microrelay was actuated by passing a current through the coil and generated a magnetic flux that mainly concentrated on the center of the planar coil. When the upper nickel movable electrode was magnetized and deflexed down toward the coil, it encountered the two contacts and stopped its motion. Since the upper electrode was conductive, a current flowed from one contact (through the upper electrode) into the other. The microrelay was normally in "ON" state. When the current in the coil was cut off, the mechnical restoring force of the upper movable electrode suspended by two beams was sufficient to pull the movable electrode off the contacts, and then the microrelay was in "OFF" state.

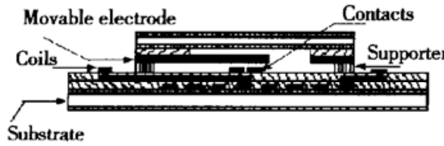

Fig. 3 Model of the proposed electromagnetic microrelay

3 Theoretical analysis

The goal of design is to realize a microrelay with the behaviors of "ON" and "OFF". Driven by the Lorentz force, the movable electrode moves in the magnetic field created by the electromagnetic coil. However, in order to produce large deflections, the square planar coil produces the magnetic gradient which is necessary for the actuation of the microrelay. The vertical electromagnetic force $\boldsymbol{F}_z$ acting on the nickel movable electrode with the isotropic magnetic medium is given by[4]:

$$\boldsymbol{F}_z = \int_V \boldsymbol{M}_z \frac{\mathrm{d}\boldsymbol{B}_z}{\mathrm{d}z} \mathrm{d}V \quad (1)$$

where $\boldsymbol{B}_z$ is the vertical component of the magnetic flux density produced by the planar coil, $\boldsymbol{M}_z$ is the vertical component of the nickel magnetization intensity, and V is the volume of the movable electrode. Consequently the volume density of the electromagnetic force f can be gained:

$$f = \boldsymbol{M}_z \frac{\mathrm{d}\boldsymbol{B}_z}{\mathrm{d}z} \quad (2)$$

Using the magnetic susceptibility χ_m or the vacuum permeability μ_0, and relative permeability μ_r, the magnetization $\boldsymbol{M}_z$ is expressed as:

$$\boldsymbol{M}_z = \chi_m \boldsymbol{H}_z = \frac{\mu_r - 1}{\mu_0 \mu_r} \boldsymbol{B}_z \quad (3)$$

where $\boldsymbol{H}_z$ is the vertical component of the magnetic field density produced by the planar coil, so f can be also expressed as:

$$f = \frac{\mu_r - 1}{\mu_0 \mu_r} \boldsymbol{B}_z \frac{\mathrm{d}\boldsymbol{B}_z}{\mathrm{d}z} = \frac{\mu_r - 1}{2\mu_0 \mu_r} \times \frac{\mathrm{d}\boldsymbol{B}^2}{\mathrm{d}z} \quad (4)$$

The expression of $\boldsymbol{B}_z$ produced by a rectangular current loop can be obtained from the Biot-Savat law. Using proposed equations above, the magnetic flux density of the planar coil for a current of 200mA is calculated as shown in Fig. 4.

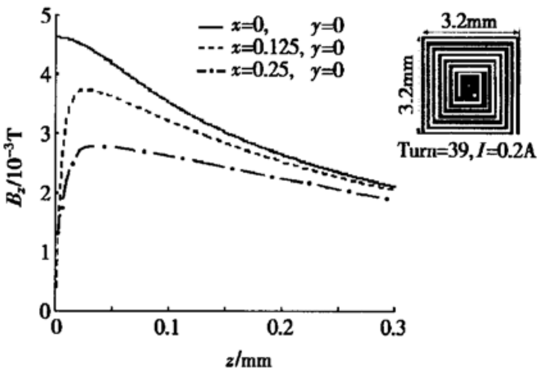

Fig. 4 Magnetic flux density $\boldsymbol{B}_z$ of a square planar coil

In addition, the static deflection Δz and resonant frequency f of the microrelay are given by the basic expressions of an undamped spring-mass system:

$$\Delta z = F_z/k$$

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{M}} \qquad (5)$$

where M is the sum of the masses of the movable electrode and the silicon substrate. For a two beam suspension as shown in Fig. 2, the spring constant can be approximated by follows:

$$k = \frac{2Ebd^3}{l^3} \qquad (6)$$

where d, b and l represent the thickness, width and mean length of the beam, E is the Young's modulus of nickel.

4 Simulation results

The basic structure of the electromagnetic microrelay has been simulated with the finite element software ANSYS, and two-dimensional (2D) magnetic analysis has been performed to obtain the electromagnetic force acting on the movable electrode of the microrelay. The finite element model for the magnetic analysis consists of a movable electrode, a planar coil and the surrounding air. Figure 5 shows the magnetic flux distributions of the 2D electromagnetic microrelay static analysis in which the current through the coil is 200mA.

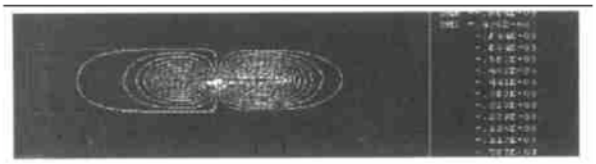

Fig. 5 Magnetic flux distributions of 2D electromagnetic microrelay static analysis

The electromagnetic force acting on a movable electrode with dimensions of 0.5mm × 0.5mm × 0.01mm is calculated within the magnetic analysis using the magnetic virtual displacement (MVDI) loading available in the ANSYS program. Figure 7 shows the F_z as a function of the distance z between coil and movable electrode for the theoretical data and simulational data, respectively. As expected, it is believed that the finite element model is suitable for the actual microrelay because the results obtained from the ANSYS simulation are approaching to those calculated by the theory of electromagnetic field. In order to keep the stability of the electromagnetic force on the movable electrode, it is found in the figure that the distance over 15μm can be selected as the movement space between the coil and the movable electrode.

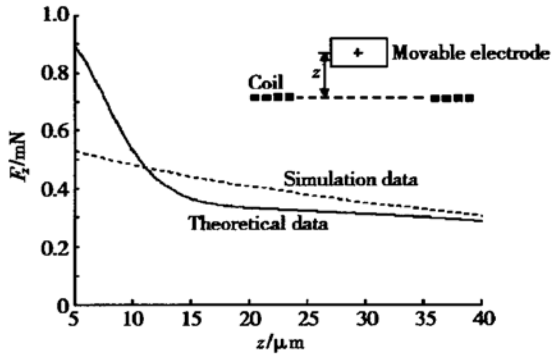

Fig. 6 Comparison of electromagnetic force on movable electrode

The substrate material can have great effects on the electromagnetic force acting on the movable electrode. Figure 7 shows the electromagnetic force F_z as a function of the distance z between coil and movable electrode when FeSi are chosen as the substrate. Obviously, the substrate of FeSi is used to create a closed magnetic flux path and reduce the leakage of flux and the coercive force so that the magnetic properties of the electromagnetic coil can be improved. Thus the electromagnetic force acting on the upper movable electrode can be increased greatly, then the movable electrode is easily deflexed to the contacts.

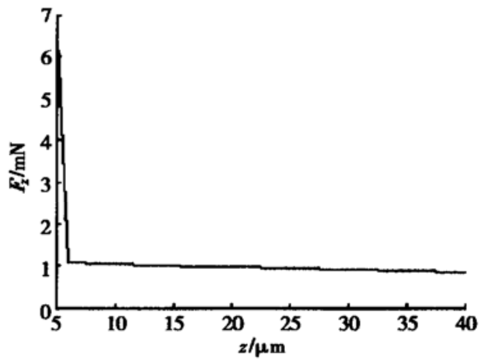

Fig. 7 Electromagnetic force on the movable electrode when the substrate of FeSi being used

5 Conclusion

Electromagnetic actuation has been applied to MEMS relays with the microelectronics fabrication methods. Application of MEMS technigue to relays should enable drastic reductions in costs of fabrication, physical size, and design complexity. A main advantage of the electromagnetic microrelay which can be realized with common micromachining techniques is the use of a square planar coil as an actuator. However, the planar electromagnetic coil has relatively poor efficiency, i.e., the resulting in electromagnetic force acting on the movable electrode is small comparing with the electric power consumption. To find some logical physical parameters of the microrelay, calculations and simulations of the electromagnetic force on the movable electrode are carried out with finite element analysis. This allows for the future optimization of the electromagnetic coil and the development of this new type of the electromagnetic microrelay.

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微型电磁继电器的制作和仿真分析*

张宇峰[1] 李德胜[2]

(1 哈尔滨工业大学自动化测试与控制系, 哈尔滨 150001)

(2 北京工业大学机电工程学院, 北京 100022)

摘要: 介绍了一种基于MEMS技术的微型电磁继电器的制作过程和仿真分析. 这种微继电器的大小约是4mm×4mm×0.5mm, 主要采用普通的微加工技术来完成全部制作工艺. 与传统继电器相比, 这种继电器采用平面线圈来代替螺线管线圈, 有利于MEMS工艺, 并且提出了一种双支撑的悬臂梁结构做为活动电极, 具有较高的灵敏性和稳定性. 另外, 还进行了一些有关线圈通过激励电流后对活动电极产生电磁力的理论计算和仿真分析, 利用这些结果可以对这种电磁继电器的结构和参数进一步优化.

关键词: 微型电磁继电器; MEMS; 微加工技术; 平面线圈; 双支撑悬臂梁

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张宇峰 男, 1976年出生, 博士研究生, 主要研究兴趣为微电子机械系统.

李德胜 男, 1961年出生, 教授, 博士生导师, 主要从事传感器和微电子机械系统方面的研究工作.

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