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Planar-type micro-electromagnetic actuators using patterned thin film permanent magnets and mesh type coils

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ABSTRACT

In this paper, we propose several types of planar micro-electromagnetic actuator that can be applied in micro-pumps and micro-valves. The various types each consist of a thin film permanent magnet (TFPM), a micro-coil and, in some cases, a ferromagnetic layer. The magnetic properties of a TFPM with a multilayered structure, comprising 300 nm thick NdFeB and 10 nm thick Ta layers deposited sequentially, are as high as bulk NdFeB magnets. Conventional micro-electromagnetic actuators consist of a bulk permanent magnet and a spiral micro-coil, whereas the actuators proposed in this paper consist of segmented patterns of TFPM, such as line/space and chessboard patterns, and mesh coils surrounding the segmented patterns. The TFPMs are segmented in order to reduce the demagnetization effect and to generate a large flux density. The proposed micro-coils possess a 2D structure and are easy to fabricate compared with spiral type micro-coils. The results of simulation show that the electromagnetic forces generated by actuators with segmented TFPMs are several times higher than one without segmentation. Furthermore, the actuation force performance is enhanced by covering the TFPM pattern with a ferromagnetic layer of $Ni_{55}Fe_{45}$ permalloy. The electromagnetic actuators are fabricated by a fully integrated MEMS process. The measured magnetic flux densities generated by the patterned TFPMs agree with the simulated results. The electromagnetic force between the patterned TFPM and the micro-coil is measured by an electronic force balance. Due to alignment errors between the micro-magnet and micro-coil, the experimentally measured forces are from 70% to 90% of the simulated ones.

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1. Introduction

Electromagnetic actuators are used extensively in many areas such as the automobile and robotics industries, and in other types of machinery. In recent years, microelectromechanical system (MEMS) technologies have come to the fore and MEMS components are now being widely produced. Compared with other kinds of MEMS actuation mechanisms, such as electrostatic, piezoelectric, thermopneumatic, and using shape memory alloy (SMA) [1–4], electromagnetic actuation has the advantage of a relatively large force, large displacement and low actuation voltage. A growing number of MEMS devices utilizing electromagnetic actuators are under development such as micro-motors in non-invasive surgery; micro-pumps and micro-valves for micro-fluidic systems; micro-generators for independent power supplies and micro-mirrors for adaptive optics [5].

Many devices, such as micro-pumps and micro-valves, utilize bulk magnets and solenoids consisting of wound coils to generate sufficient force [6–10]. In these cases, the size of the magnet is usually on the millimeter scale. Furthermore, the processing conditions for fabricating these bulk electromagnetic actuators are incompatible with MEMS fabrication processes.

Some researchers have developed planar electromagnetic actuators integrated with MEMS fabrication processes. A common configuration for an electromagnetic actuator is a planar micro-magnet driven by a planar micro-coil. Conventional wafer level deposition processes for magnets include electroplating, sputtering and pulsed-laser deposition (PLD) [11]. Planar spiral micro-coils are fabricated through deposition combined with a lift-off process.

The performance of such actuators, however, is fairly poor. Su and Chen [12] developed an actuator comprising an electroplated

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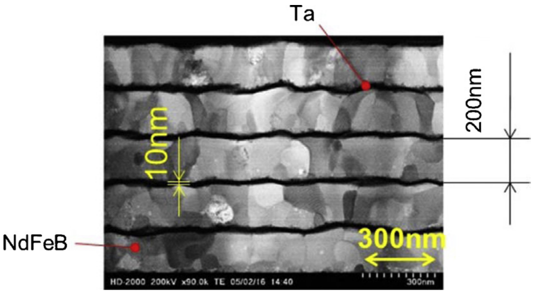

Fig. 1. Cross-section of the TFPM multilayer structure.

CoNiMnP magnet array (0.35 mm × 0.35 mm × 0.02 mm) and a micro-coil (7 turns). Simulation showed that a force of 36 μN/A could be generated by this. Lee and Chen [13] realized an integrated micro-actuator consisting of an electroplated magnet (3 mm in diameter, around 100 μm thick) and a micro-coil (20 turns, 19 mm in diameter). The force generated by this actuator in simulation was around 20 μN/A. Integrated micro-electromagnetic actuators are rarely used in cases requiring forces of the order of mN.

In addition to the effect of scaling which means that the electromagnetic interaction is reduced as the actuator size is scaled down [5], there are other reasons that impede the performance of micro-electromagnetic actuators and limit their application. Firstly, permanent magnets fabricated using electroplating are usually based on CoPt, FePt or CoNiMnP. The coercivities of electroplated magnets are usually in the range of 30–200 kA/m, and the magnetic remanences are usually less than 0.5 T [14,15], which is much less than that of high performance bulk NdFeB magnets (magnetic remanence Br 1.24 T, coercivity Hc 923 kA/m). Secondly, the planar micro-magnets are several micrometers thick and several square millimeters in area. Due to the large self-demagnetization factor [16], the magnetic flux density distribution is very different from that of common bulk magnets, which is illustrated in detail in Section 2.2. Thus spiral micro-coils and planar micro-magnets are not efficiently designed. Furthermore, spiral coils require connection to a central electrode, for which electroplating through holes [7] or resist insulation [9] complicates the fabrication process.

In this paper we aim to enhance the performance of planar-type micro-electromagnetic actuators and to simplify the micro-coil fabrication by the following method. Firstly, a thin film permanent magnet (TFPM) [17] with a magnetic performance (Br 1.3 T, Hc 927 kA/m) as good as bulk NdFeB magnets is utilized. The TFPM is fabricated using a sputtering process that is compatible with MEMS processes, the cross-section view of the NdFeB multilayer is shown in Fig. 1 [18]. Secondly, the magnetic resistance is reduced by segmenting the TFPM in specially designed line/space and chessboard patterns. Two dimensional (2D) mesh-type micro-coils which are easy to fabricate using a MEMS process are also optimized along with the magnet patterns. The actuator performance is further enhanced by covering the TFPM with a ferromagnetic layer. The actuators proposed in this paper are simulated, fabricated and experimentally evaluated.

2. Design of the electromagnetic actuator

Planar electromagnetic actuators usually comprise a micro-magnet and a planar micro-coil. The permanent magnet as well as the micro-coil is several micrometers thick and several square millimeters in area. In order to compare several actuator designs, we set the size of the TFPM to be 5 mm × 5 mm × 20 μm, with the size of the coil the same as the TFPM. The magnetic properties of the TFPM are the same as a conventional bulk NdFeB magnet. The current input into the coil is set to be 1 A.

A geometrical view of the actuator is shown in Fig. 2. The default unit in this paper is the millimeter. The actuator illustrated in Fig. 2 consists of mainly three parts, a micro-coil, a TFPM, and a back yoke on the TFPM. The gap between the TFPM and micro-coil is set to between 0 and 200 μm. In Fig. 2, Plane 1 is located 100 μm beneath the TFPM surface; Plane A is the cross-section of TFPM and back yoke.

Permalloy is specially chosen as the back yoke's material for the following two reasons. Firstly, it has high magnetic permeability and saturation. Secondly, it can be deposited by sputtering or electroplating process, which are both compatible with MEMS processes. In this paper, the permalloy material is designed to be Ni_{48}, which is a very common industrial permalloy with a high magnetic saturation around 1.2 T.

2.1. Proposed actuators

Fig. 3 shows the proposed designs for the electromagnetic actuators. There are three main types.

Type 1 is a conventional configuration with a non-segmented micro-magnet and a spiral micro-coil, which is a similar configuration to that in [12,13].

In Type 2, the TFPM is formed into a line/space configuration. The unit size of the magnet is 0.5 mm × 5 mm × 20 μm. For this type of actuator, a micro-coil with a meandering shape has been designed. Type 2(1) has no back yoke, whereas Type 2(2) has a back yoke.

In Type 3, the magnet has a chessboard pattern. The mesh shape micro-coil has also been specially designed. Type 3 is also divided into Type 3(1) without a back yoke and Type 3(2) with a back yoke. Compared with the line/space pattern in Type 2(1), the chessboard pattern has a smaller unit size of 0.5 mm × 0.5 mm × 20 μm.

2.2. Magnetic flux density analysis

The simulated magnetic flux density distributions in the Z direction (B_z) generated by the TFPMs on Plane 1 and Plane A (defined in Fig. 2) are shown in Fig. 4. The white line represents TFPM's

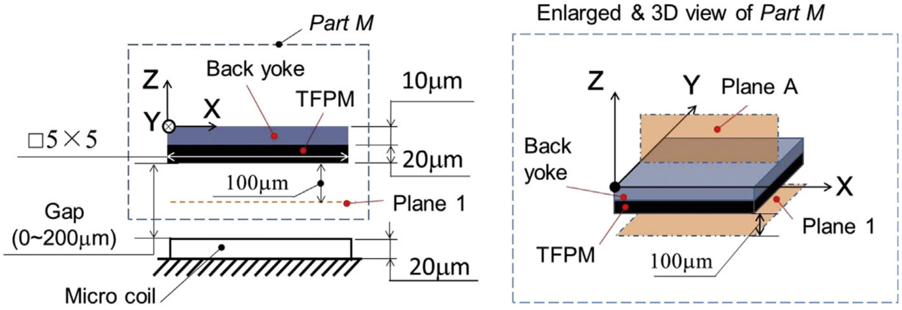

Fig. 2. Micro electromagnetic actuator configuration.

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