INTRODUCTION

Because they have higher isolation and lower insertion loss compared to semiconductor switches, the last decade has seen the development of several types of MEMS (Micro Electro Mechanical Systems) switch. Many of these are electrostatically actuated and so need high drive voltages, limiting the initial gap between the contact points to a few micrometers [1-3]. Such small gaps between the contact points limit the isolation properties of the switch.

Other MEMS switches are electromagnetically actuated at low voltages [4]. However, these usually require electrical power to maintain the switch in both the on and off positions. Y. Zhang et al. proposed an electromagnetically actuated MEMS switch using permanent magnets in order to save on the power consumption required to maintain the switch in the on and off positions [5]; however, the performance of permanent magnets used in MEMS switches is inferior to that of conventional sintered NdFeB magnets.

A high performance NdFeB/Ta thin film permanent magnet (TFPM), which not only has a high remnant flux density and a high coercive force similar to those of conventional sintered NdFeB magnets, but also has high heat tolerance, was developed [6]. A 4mm long cantilever type micro actuator using the TFPM and an air-core coil to generate bi-directional out-of-plane displacement up to 700µm was developed [7].

The purpose of this research is to apply a cantilever type micro actuator using the TFPM to a MEMS switch, which is expected to have good electrical isolation due to the gap of several hundreds of microns between the contact points, and thus significantly reduce the electrical power needed to maintain the switch in the on and off positions. This switch was fabricated and experimentally evaluated.

PROPOSED MEMS SWITCH

MEMS Switch Configuration

Fig. 1 shows the configuration of the proposed electromagnetically actuated MEMS switch. The switch consists of a paddle-shaped cantilever with a TFPM at the tip, an air-core coil, a ferromagnetic film and electrodes as contact points. The on/off switching motion is realized using the deformation induced in the cantilever by the resultant force from the Lorenz force between the coil and the TFPM, the reluctance force between the ferromagnetic film and the TFPM, and the restoring force of the cantilever.

Driving Principle

The principle of the on/off switching is shown in Fig. 2. Fig. 2(1) shows the initial position in which the switch is off without any current through the coil. On supplying a current to the coil, an attractive force acts on the TFPM and the cantilever bends downward as the current increases.
For any displacement, as shown in Fig 2(2), where the sum of the attractive forces between the coil and the TFPM and between the TFPM and the ferromagnetic film is greater than the restoring force of the cantilever, the TFPM is pulled in the direction of the ferromagnetic film.

The switch is maintained in the on position without any coil current since the attractive force between the TFPM and the ferromagnetic film is larger than the restoring force of the cantilever due to the nonlinear characteristics of the magnetic force, as shown in Fig. 2(3).

Fig. 2(4) shows the transition from the on to the off position. The contact points release when a reverse current is supplied to the coil. In this case the sum of the Lorentz force and the restoring force of the cantilever is greater than the attractive force between the TFPM and the ferromagnetic film. The cantilever returns to its initial position where the restoring force of the cantilever is greater than the attractive force acting on the TFPM and no further current is required to maintain the cantilever in this position.

**DESIGN**

**MEMS Switch Structure**

Fig. 3 shows the structure of the MEMS switch. A paddle-shaped cantilever type micro actuator is used to move the contact point of the MEMS switch. This actuator, which has a driving range of more than several hundreds of micrometers, is suitable for the MEMS switch because the large gap ensures high electrical isolation.

The main structural component of the actuator is a SiN paddle-shaped cantilever consisting of a 2mm×0.4mm×0.003mm cantilever combined with a 2mm×2mm×0.003mm plate. A 3µm thick TFPM is deposited on the plate. The ferromagnetic layer is a 2mm×2mm×0.005mm Ni thin film set beneath the TFPM plate of the actuator. A U-shaped coil made of 0.25mm diameter copper wire is placed under the Ni film. The distance between the coil and the Ni film is 380µm.

**Setup of the Initial Gap between the TFPM and the Ferromagnetic Film**

In order to realize the proposed switching method, the initial gap between the TFPM and the ferromagnetic film needs to be determined. The attractive force $F_F$ induced by the Ni film, the Lorentz force $F_C$ generated by the current in the coil and the restoring force of the cantilever $F_S$ act on the TFPM. $F_F$ and $F_C$ are simulated using three dimensional magnetic field analysis software (Ansoft, Maxwell 3D Ver.12.2), and $F_S$ is calculated using the differential equation of the deflection curve of the cantilever.

In order to maintain the switch in the on position, Eq. (1) should be satisfied for zero gap, where the TFPM touches the ferromagnetic film.
On the other hand, in order to maintain the switch in the off position, Eq. (2) should be satisfied at some point between zero gap and the initial gap.

\[ F_s > F_F \]  \hspace{1cm} (2)

\( F_s \) and \( F_F \) were simulated for various gaps between the TFPM and the Ni film, as shown in Fig. 4. The results of this analysis indicate that the above condition is satisfied for an initial gap of more than 600µm. In the prototype MEMS switch, the initial gap was set to 700µm.

At zero gap, the attractive force between the TFPM and the Ni film was much greater than the largest Lorentz force produced by the coil. Therefore, a 100µm thick isolation layer was placed on top of the Ni thin film. The simulated pull-in and pull-out currents for an initial gap of 700µm are about -0.5A and 0.35A, respectively.

![FIGURE 4. Comparison of simulated restoring and attractive forces](image)

**FABRICATION PROCESS**

**Fabrication of the Cantilever With a TFPM**

The cantilever was fabricated on a 500µm-thick Si substrate. A 3µm thick SiN film was deposited on both surfaces using low pressure chemical vapor deposition (LPCVD). Next, Cu was sputtered and patterned on both surfaces of the substrate. The exposed SiN was removed from both sides using reactive ion etching (RIE), and the exposed Si was removed in TMAH. Then, the 3µm thick TFPM was deposited on the plate at the end of the cantilever using a magnetron sputtering process at a temperature of 475 degree Celsius using a Ti hard mask to control the shape. After deposition of the TFPM, a 1µm thick Cr was deposited on the TFPM at room temperature using a sputtering process. The cantilever with the TFPM and the Cr thin film was annealed at 450 degree Celsius for one hour. The tensile stress generated in the Cr by annealing cancels the compressive stress in the TFPM. Finally, a current pulse was used to magnetize the TFPM vertically with respect to the plate. The Si substrate was sandwiched between glass substrates to restrict the deformation of the cantilever due to the magnetic force induced by eddy currents during pulse magnetization.

**Assembly**

The cantilever was deformed due to its weight and the residual stress in the TFPM. In order to set the initial gap between the Ni film and the tip of the cantilever to 700µm, 400µm thick Si rubber films were inserted between the upper Si substrate and the lower one, on which the coil and the multilayer film consisting of a polyimide film and a Ni film were attached, with Au coatings. Fig. 5 shows a photograph of the fabricated MEMS switch.

![FIGURE 5. Fabricated MEMS switch](image)

**EXPERIMENTS**

**Measurements of the Cantilever Displacement**

The displacement of the cantilever was measured with an optical fiber displacement sensor in order to ensure the MEMS switch makes contact.

The sinusoidal current was supplied to the coil, the cantilever displacement was measured. The pull-in/-out currents are -0.43A and 0.25A, respectively. These values are 14% and 29% smaller than the designed values.
Fig. 6 shows the measured cantilever displacement with a rectangular current supplied to the coil. Step 1 shows the switching on motion. Step 2 shows the switch in the on position without current. Step 3 shows the switching off motion. Finally, Step 4 shows the MEMS switch returned to the off position without any current.

**Switching Tests**

In this experiment, 0.1µm thick Au electrodes were deposited for the contact points. The continuity of the MEMS switch was measured with the contact points touching without any current supplied to the coil. Continuity was not realized because the area of contact was small due to the residual deformation of the TFPM, and also because of the lack of contact pressure.

In order to increase the contact area, the cantilever was reversed to take advantage of the residual deformation of the cantilever. Furthermore, in order to increase the contact pressure, a -1.6A current was supplied to the coil to drive the switch. Under these conditions continuity between the contact points was realized.

**CONCLUSION**

In this paper, a MEMS switch consisting of a TFPM, a paddle-shaped cantilever on to which the TFPM was deposited, an air-core coil and a ferromagnetic film, was proposed and fabricated. The switch had a gap of several hundreds of microns between the contact points, and no electrical power was needed to maintain it in either the on or off positions. Based on simple driving experiments, the proposed switching action was demonstrated. In these experiments, the pull-in current was -0.43A and the pull-out current was 0.25A. Although continuity between the switch contacts wasn't realized in the original MEMS switch, optimizing the shape of the contact and increasing the contact area and the contact pressure enabled continuity.

In future work, the continuity is to be improved, the electrical isolation properties evaluated and life time tests carried out.

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**REFERENCES**


