

A Laterally-Driven Bistable Electromagnetic Microrelay

Jong Soo Ko, Min Gon Lee, Jeong Sam Han, Jeung Sang Go, Bosung Shin, and Dae-Sik Lee

ABSTRACT—In this letter, a laterally-driven bistable electromagnetic microrelay is designed, fabricated, and tested. The proposed microrelay consists of a pair of arch-shaped leaf springs, a shuttle, and a contact bar made from silicon, low temperature oxide (LTO), and gold composite materials. Silicon-on-insulator wafers are used for electrical isolation and releasing of the moving microstructures. The high-aspect-ratio microstructures are fabricated using a deep reactive ion etching (DRIE) process. The tandem-typed leaf springs with a silicon/gold composite layer enhance the mechanical performances while reducing the electrical resistance. A permanent magnet is attached at the bottom of the silicon substrate, resulting in the generation of an external magnetic field in the direction vertical to the surface of the silicon substrate. The leaf springs show bistable characteristics. The resistance of the pair of leaf springs was $7.5\ \Omega$ and the contact resistance was $7.7\ \Omega$. The relay was operated at $\pm 0.12\text{ V}$.

Keywords—Microrelay, electromagnetic, Lorenz force, bistable.

I. Introduction

Microelectromechanical system (MEMS) constitutes one of the most promising technologies for miniaturized sensors and actuators from the viewpoint of production. Because of growing commercial applications, interest in MEMS has increased significantly in recent years [1]. In particular, engineers have shown great interest in applying microrelays based on MEMS technology for various applications such as information

processing, telecommunications, automotives, and so on. To date, various microactuators for microrelay applications including electromagnetic [2], electrostatic [3], thermal [4], and fluid flow [5] actuation have been developed. In general, microrelays require low on-resistance, high off-resistance, high speed, adequate displacement, low power consumption, and moderate fabrication cost. Among the reported microactuators, electromagnetic actuation has been widely researched because it shows promise in satisfying these characteristics. However, previous electromagnetic actuators have been equipped with micro-fabricated planar coils [6]–[8], which make the fabrication and generation of an adequate electromagnetic field difficult. Furthermore, the actuating mobility of electromagnetic microactuators with planar coils is limited to motion perpendicular to the silicon substrate (out-of-plane mode).

In this letter, we present a novel bistable microrelay based on the concept of a laterally-driven electromagnetic microactuator [9], [10] that allows movement parallel to the silicon substrate surface (in-plane mode).

II. Concept

As shown in Fig. 1(a), a microrelay comprising a pair of arch-shaped leaf springs, a shuttle, and a contact head, which are made from Si, LTO, and Au composite materials, is placed on a silicon substrate. The arch-shaped leaf springs with tandem layout are suspended on the silicon substrate [11]. Figure 1(b) illustrates the signal paths between two contact ports depending on whether there is contact with the contact head. In order to prevent signal leakage flowing through the neck and leaf springs, an electrical isolation component is equipped so that the contact head and leaf springs are electrically isolated.

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A permanent magnet is attached at the bottom of the silicon substrate, resulting in the generation of an external magnetic field in the vertical direction to the surface of the silicon substrate. Without a current flow, the leaf springs are not affected by the external magnetic field. With a current flow, however, a distributed Lorentz force, $f_L = i \times B$, is induced along the leaf springs, and the springs then begin to deflect toward the contact ports, as illustrated by the dotted line in Fig. 1. In the above equation, f_L , i , and B denote the induced Lorentz force per unit

length, the applied current, and the magnetic flux density, respectively. The direction of the deflection depends on that of the current flow. Even when the applied current is switched off, the deflected leaf springs maintain the deflected position, as illustrated by the dotted line in Fig. 1. The initial curvature of the leaf springs has a cosine function. Figure 2 shows the designed values of the microrelay. The initial height and straight length of the leaf spring are 6 and 800 μm , respectively. The gap between the contact head and contact ports is 9 μm .

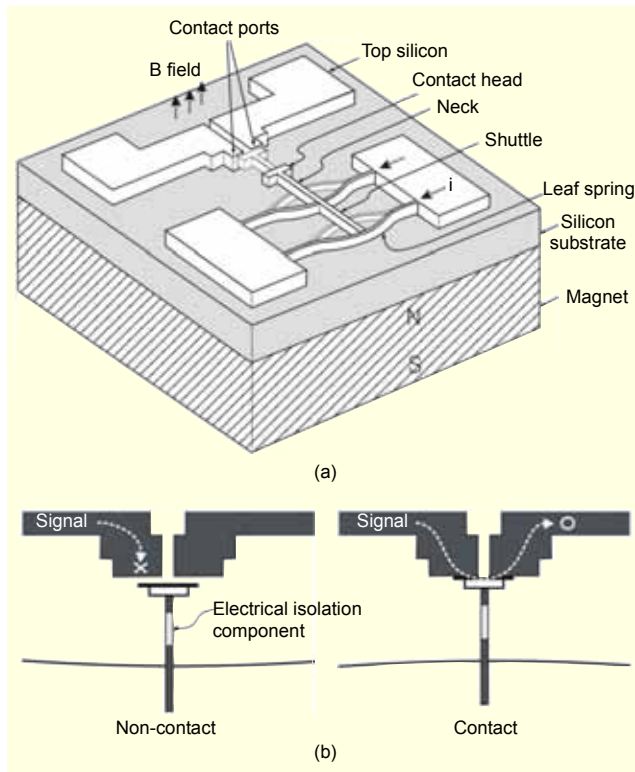


Fig. 1. Working principle of the proposed microrelay: (a) perspective view and (b) switching signal flows depending on contact (right) or non-contact (left).

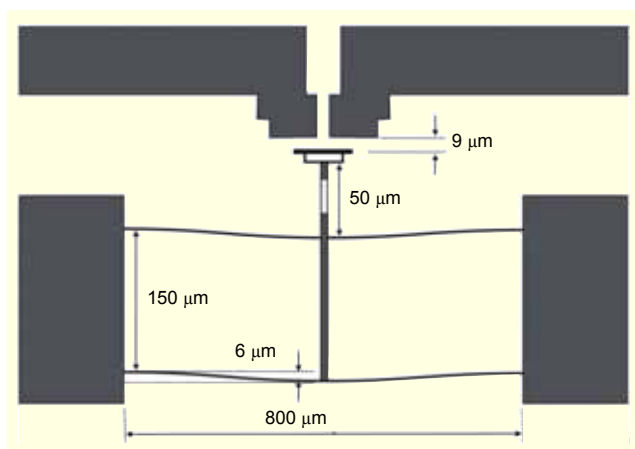


Fig. 2. Designed values of the microrelay.

III. Experiments and Results

The microrelay was fabricated in a silicon-on-insulator wafer, which consists of silicon (20 μm), oxide (3 μm), and silicon substrate (655 μm). The 3 μm thick oxide layer functions as an electrical isolation layer and also as a sacrificial layer. The 20 μm thick top silicon layer is utilized to form released microstructures including leaf springs, a shuttle, a neck, and a contact head. Figure 3 shows the main fabrication process steps at the neck of the microrelay. First, a photoresist is patterned, as shown in Fig. 3(a). Second, the DRIE process vertically etches the top silicon layer, producing high-aspect-ratio microstructures, as shown in Fig. 3(b). Third, a 3 μm thick oxide layer is then wet-etched with a buffered oxide etching solution, as shown in Fig. 3(c). Through this process, the leaf springs, shuttle, neck, and contact head are released from the silicon substrate. In this process, to prevent stiction of the suspended microstructures to the silicon substrate caused by surface tension of de-ionized water, a sublimation drying method was used in the drying step after de-ionized water rinsing. Dichlorobenzene (p-DCB) was adopted as a sublimation drying material. The processing wafers were immersed in a p-DCB solution at 50°C for 10 min. They were very carefully taken out from the p-DCB solution and immediately put onto a heated hotplate with 50°C. After the hotplate was turned off, the p-DCB solution started to solidify. The solidified p-DCB was very slowly sublimated. Full sublimation in air required 1 hour. Using this sublimation drying method, microstructures of around 90% were suspended from the silicon substrate surface. Fourth, a 300 nm thick low temperature oxide (LTO) for an electrical isolation between the top silicon and Cr/Au layer was deposited on the top surfaces of the processing wafer, as shown in Fig. 3(d). Fifth, Cr of 20 nm and Au of 300 nm were sequentially sputtered on the top and side faces of the microstructures, as shown in Fig. 3(e). The evenly coated Cr/Au layer on the side faces of the high-aspect-ratio silicon microstructures greatly enhanced the electrical conductivity along the leaf springs. Sixth, a thick photoresist (AZ5214, Clariant) was manually coated and patterned to open a Au area, which was to be etched

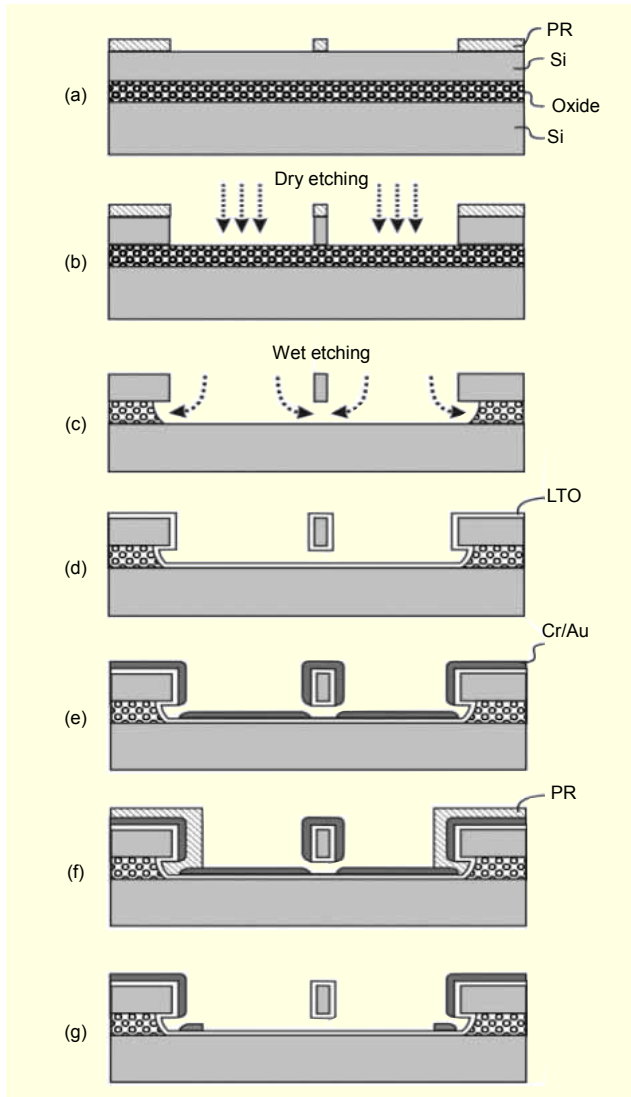


Fig. 3. Fabrication process of the microrelay: (a) photolithography, (b) top silicon etching by DRIE, (c) buried oxide etching, (d) low temperature oxide (LTO) deposition, (e) Cr/Au deposition, (f) thick PR photolithography, and (g) Cr/Au etching. The figures show the cross sectional views at the neck according to the fabrication sequence.

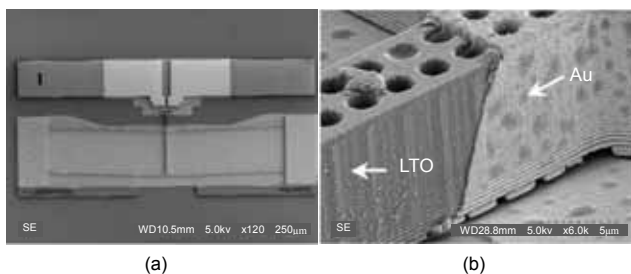


Fig. 4. Scanning electron micrographs of the fabricated microrelay: (a) whole device with a size of $1000\ \mu\text{m} \times 450\ \mu\text{m}$ and (b) electrical isolation component in the neck.

in the subsequent process, between the contact head and leaf springs, as shown in Fig. 3(f). Finally, by etching the opened Au and Cr, the electrical isolation part in the neck was defined, as shown in Figs. 3(g) and Fig. 4(b). Figure 4 shows scanning electron micrographs of the fabricated microrelay. The width of the fabricated leaf springs is $1.6\ \mu\text{m}$, and the total dimension of the fabricated relay is $1000\ \mu\text{m} \times 450\ \mu\text{m}$. After dicing, each microrelay was attached on a neodymium-iron-boron (NdFeB) permanent magnet with a magnetic flux density of 3000 G.

The fabricated leaf springs showed bistable characteristics. Because no further power consumption is required to maintain the deflected state, the bistable characteristic is very important from the point of view of low power consumption. The resistance of the pair of leaf springs was $7.5\ \Omega$. Figure 5 shows actuating images, captured through a microscopic system, at on and off states of the microrelay. When the relay is at the off position, contact resistance is infinite, while at the on position contact resistance between two contact ports is $7.7\ \Omega$. It is assumed that the high contact resistance was caused by the imperfect lateral contact between the contact head and contact ports. The imperfect lateral contact can be originated from the DRIE process. The DRIE process makes nanoscallopes with several tens of nanometers, as shown in Fig. 4(b), and a sometimes imperfect vertical etching profile. Nanoscallopes can be removed by the sequential process of thermal oxidation

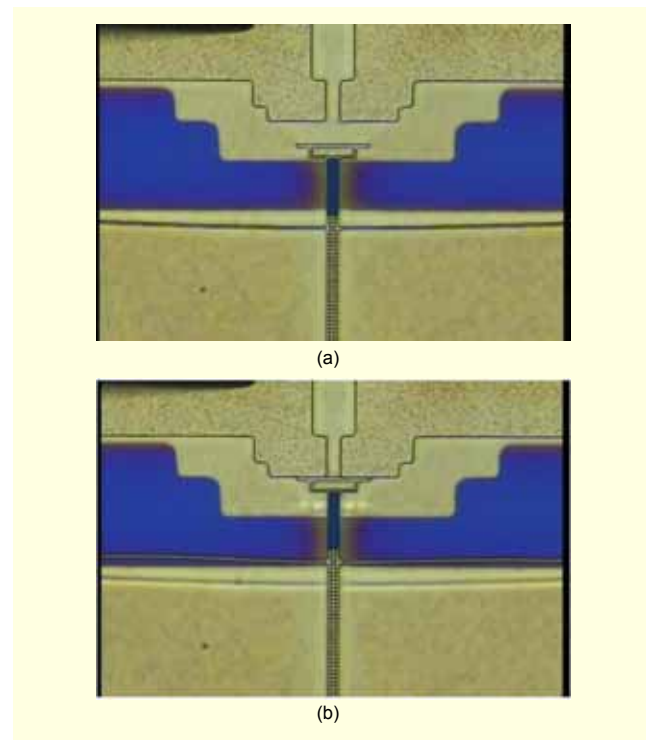


Fig. 5. Captured images of actuating sequence of the microrelay: (a) off-position and (b) on-position.

and etching of the thermally grown oxide.

The electrical switching characteristic is shown in Fig. 6. A waveform generator produced driving signals of square waves with a driving frequency of 5 Hz with 0.24 V_{p-p}. The driving signals were applied across the leaf springs. A dc voltage of 1 V was applied to the contact ports with a load resistor of 1 k Ω in series. Both the driving signals (V_d) and the switching signals (V_s) were recorded simultaneously on a digital oscilloscope. Figure 6 shows that the switching signal follows the driving signal correctly. Whereas metal microstructures are generally prone to fatigue, silicon microstructures are not resilient to shock. Compared with conventional microstructures made of only metal or silicon, the fabricated Si/Au composite microstructures minimize the inherent weak points of the respective composite materials.

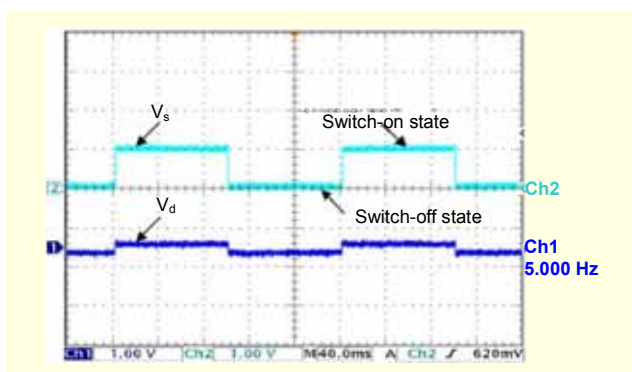


Fig. 6. Measured electrical switching characteristics of the microrelay.

IV. Conclusion

A laterally driven bistable electromagnetic microrelay has been realized. The microrelay shows bistable characteristics. Bistability is very important in relay applications, as it offers low average power consumption. The resistance of a pair of leaf springs was 7.5 Ω . The applied voltage to actuate a pair of leaf springs was ± 0.12 V. In order to further reduce the driving voltage for actuation, redesign of the spring shape, sandwich-typed multi-stacking of the magnet/microrelay/magnet, and adoption of a much stronger permanent magnet may be considered. Evaluations of the performances of the fabricated device confirm its viability as an alternative microrelay.

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