HIGHLY RELIABLE MEMS RELAY WITH TWO-STEP SPRING SYSTEM AND HEAT SINK INSULATOR FOR POWER APPLICATIONS

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ABSTRACT

This paper reports remarkably reliable MEMS relays having a unique two-step spring system and a heat sink insulator. The two-step spring system is designed to reduce Joule-heating by lowering contact resistance. The heat sink insulator is proposed for efficiently removing heat generated in the contact area. These two features are firstly adopted in the MEMS relay for minimizing thermal damage in high current level, thus enhancing reliability significantly. The fabricated relay demonstrated contact resistance of 2 mΩ, which is the lowest value compared to the state-of-the-art [11]. In addition, the relay was operated up to $5.3x10^6$ cycles at 1 V/200 mA in an air and hot switching condition with negligible contact resistance variation. The resulting lifetime is 500 times longer than that of the commercial MEMS relay measured in the same test setup.

INTRODUCTION

The electrostatically actuated MEMS relays for power applications have drawn considerable attention as a promising alternative to electromagnetic relays (EMRs) and solid state relays (SSRs) due to their effective power efficiency at on state, quasi-zero leakage current at off state and relatively small footprint [1], [2]. Various reports have been successfully published on this study with positive prospect [3-5].

In spite of the attractive performance and possibility for power application, the electrostatically actuated MEMS relays are still facing considerable difficulty for the commercialization. This is mainly due to poor reliability of the MEMS relays in high current level [6]. It is well known that the electrostatic force for operating the MEMS relays is relatively weak, which inevitably causes high contact resistance. The high contact resistance considerably increases Joule-heating, which results in thermal damage and in hence poor reliability of the MEMS relays. Furthermore, the high contact resistance affects badly to the reliability at high current level than low current level.

In order to overcome the critical reliability issue, new relay designs [7], [8] and new materials [9], [10] have been proposed. Among them, the relays with low contact resistance for minimizing Joule-heating have achieved remarkable improvement in the reliability [11], [12]. For example, Y. H. Song and et al. successfully demonstrated the reliable MEMS relays with world smallest contact resistance thanks to the stacked-electrode structure for achieving high contact force and low effective hardness of the contact material [11]. However, the removal of the generated heat has not been considered to the MEMS relays despite its positive effect speculated by simulation [13].

In this paper, we propose a new and efficient method to reduce the contact resistance and to remove the generated heat simultaneously. In order to meet this purpose, the two-step spring system and the heat sink insulator have been employed in the MEMS relays for the first time.

CONCEPT

Fig. 1 is the conceptual illustration of the proposed MEMS relays. In this structure, four crab legs which act as first spring support the source plate. The second spring is formed inside the source plate. Under the plate, meshed drain electrode is placed. The heat sink insulator is inserted under the drain to isolate drain and gate electrodes. The gate electrode is buried to attract the source plate.

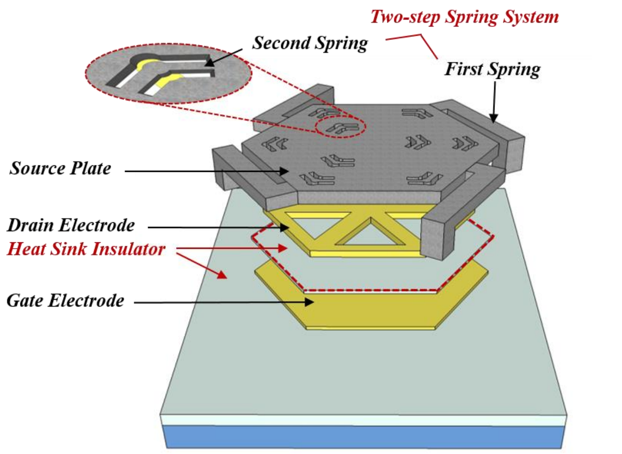

Fig.1 Conceptual illustration of the proposed MEMS relay with the two-step spring system (first spring and second spring) and the heat sink insulator.

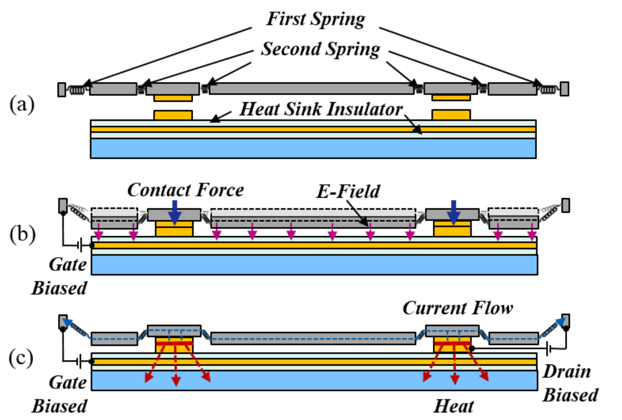

Fig.2 Actuation mechanism of the MEMS relay. (a) Initial state. (b) Contact state with increased contact force by the two-step spring system when the gate electrode is biased (c) Current flow state where the generated heat is effectively dissipated by the heat sink insulator.

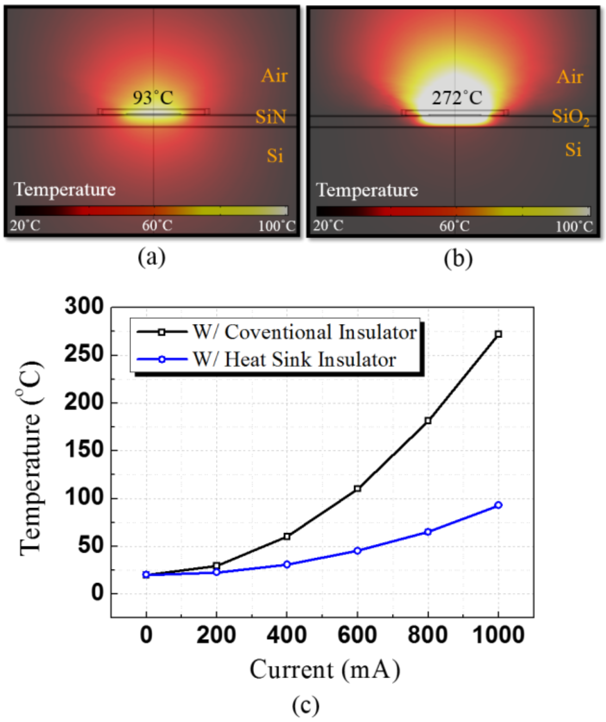

Fig.3 Finite element method (FEM) simulation results for thermal analysis. (a) Thermal profile with the heat sink insulator (SiN). (b) Thermal profile with the conventional insulator (SiO_2). (c) Temperature comparison as a function of the Joule-heating current.

Fig. 2(a) describes the cross sectional view of the proposed relays at initial state. As shown in Fig. 2(b), the grounded source plate moves down as a bias in the gate electrode increases until the plate contacts to the drain electrode (dot line). Conventional relay with a single spring system is stopped at this moment. Contrarily, the proposed relay's source plate additionally moves down by the second spring (solid line), which maximizes electrostatic force due to reduced air gap. As a result, the contact resistance is lowered, which induces the minimized Joule-heating at contact.

Fig. 2(c) shows that heat generated in the contact area by the drain-to-source current is efficiently dissipated to the substrate through a heat sink insulator. The heat sink insulator is realized by choosing a proper material of SiN having high thermal conductivity of 30.1 W/m·K which is 30 times higher than that of the generally used SiO_2 (1.04 W/m·K)

Fig. 3 represents finite element method simulation result for thermal analysis. Fig. 3(a) shows the uniform and lower temperature profile than Fig. 3(b) because the large amount of heat is dissipated down to the substrate via heat sink insulator (SiN). As a result, under the same Joule-heating condition, the temperature with the heat sink insulator (SiN) is considerably lower than their counter part (Fig. 3(c)). This simulation results can successfully anticipate that the heat sink insulator properly removes the generated heat in the contact area.

The two-step spring system and the heat sink insulator are proposed to relieve the thermal damage by minimizing the Joule-heating and removing the generated heat simultaneously.

FABRICATION

The proposed MEMS relays were fabricated with a six-mask process on the silicon substrate. First, the 1st SiN (0.3 μm) was deposited by low pressure chemical vapor deposition (LPCVD) for device isolation. Then, thermally evaporated Cr (1000 Å) was used as the gate electrode, where the Cr was selected for adhesion layer with SiN layer. Next, the 2nd SiN (1 μm) was deposited by plasma enhanced chemical vapor deposition (PECVD) for isolation between the gate and drain electrodes. A total of 5000-Å-thick Cr/Au layers were then deposited by evaporation and patterned by wet etching process to form the drain electrode.

In order to define initial air gap between the source plate and the drain electrode, the Ti/Cu/Ti sacrificial layers (totally 1.3 μm) were deposited. First, Ti (2000 Å) was deposited by sputter, which used as a diffusion barrier between Au and Cu. Subsequently, Cu (9000 Å) and Ti (2000 Å) were deposited as a sacrificial layer by sputter and thermal evaporator, respectively. Next, the sacrificial layers were patterned to form dimple and anchor as depicted in Fig. 4(d). A 1000-Å-thick Au was thermally evaporated as a contact material of the proposed MEMS relays. Next, thick photoresist (PR) was coated and patterned as a mold for electroplating. The PR mold was used to form an electroplated nickel film (10 μm) for the source plate. In the last step, the unnecessary PR mold, seed layer (Au) and, sacrificial layer (Ti/Cu/Ti) were removed. Then, critical point dryer was used for preventing initial stiction.

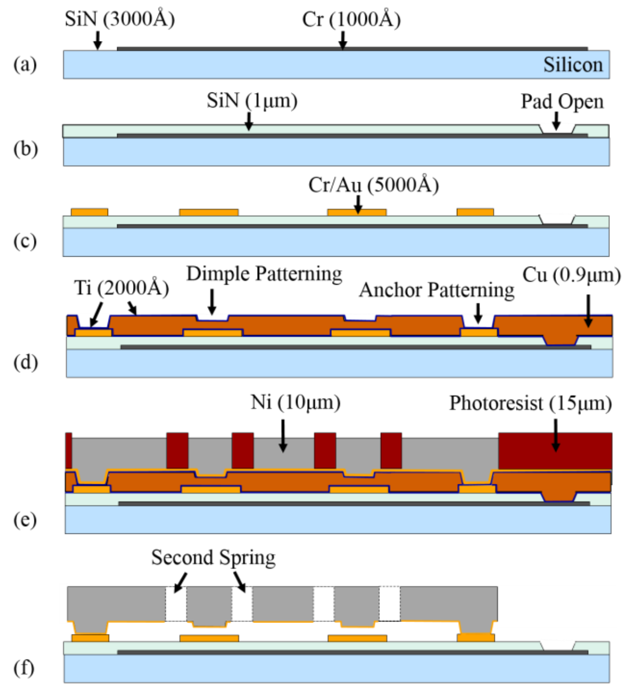

Fig.4 Overall fabrication process. (a) 1st SiN deposition and Gate electrode formation. (b) 2nd SiN deposition and pad open process for probing. (c) Drain electrode formation. (d) Sacrificial layer deposition with dimple and anchor patterning. (e) Seed layer deposition and nickel electroplating with a photoresist mold. (f) Releasing process by wet etching of the sacrificial layers.

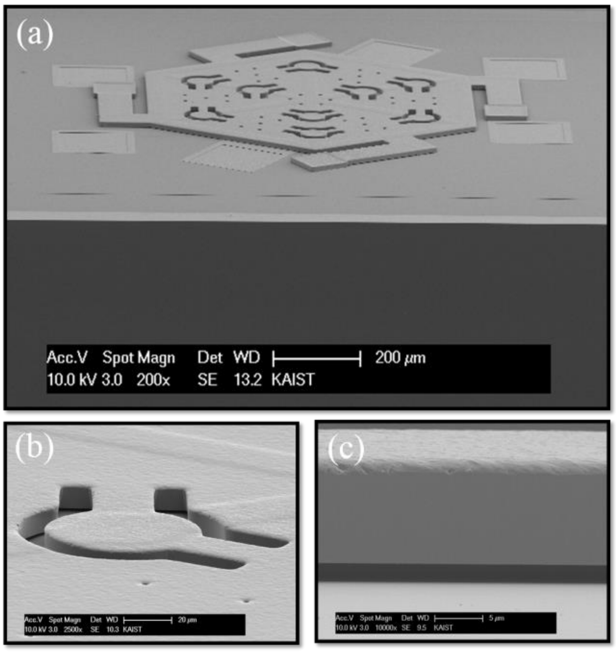

Fig.5 SEM photographs of the proposed MEMS relays. (a) Perspective overview. (b) Magnified view of the second spring. (c) Magnified view of the air gap.

Fig. 5(a) shows the scanning electron microscope image of the proposed MEMS relays with a source plate size of 600 μm x 600 μm. Fig. 5(b) and 5(c) represent the second spring and air gap respectively, which reveals that the proposed MEMS relays were successfully released.

RESULTS AND DISCUSSIONS

The measured actuation voltage (pull-in voltage) of the proposed MEMS relays was about 33 V ~ 42 V. The variation in pull-in voltage is originated from variation of plate's thickness during Ni electroplating. The calculated pull-in voltage was 35 V, which is comparable with the measured results. As shown in Fig. 6, the off current level was 10^{-12} A~10^{-11} A, which means that the proposed MEMS relays successfully disconnect a signal at off state.

Next, the contact resistance, the critical factor for the reliability, was measured. The Agilent 4156C parameter analyzer was used for precise measurement (the device can detect in the microvolt range) with a four-point probe method. A total of five devices were measured, and the testing current was 4 mA.

Fig. 7 represents the measured contact resistance with the aforementioned test setup. When the 40 V was biased to the gate electrode, the contact resistance of the MEMS relays with the two-step spring system exhibited about 50% lower value than their counterpart. This result implies that the contact force is successfully increased by the proposed two-step spring system. Furthermore, the contact resistance decreased further as the gate voltage was increased. The minimum value of the contact resistance was 2 mΩ at an applied voltage of 45 V, which breaks the previous world record to our best knowledge [11].

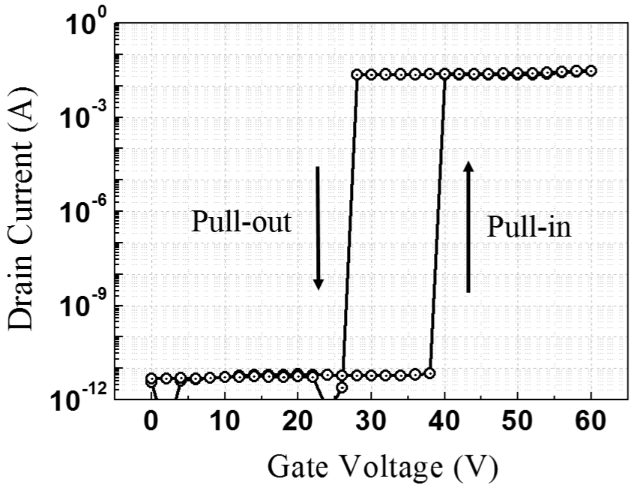

Fig.6 Measured drain current characteristic as a function of the gate voltage. Pull-in voltage was near 38V and pull-out voltage was near 25V

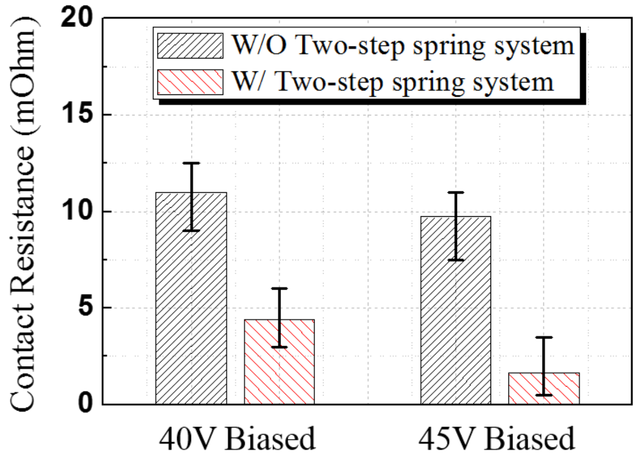

Fig.7 Measured contact resistance of the proposed MEMS relays with and without the two-step spring system. Minimum contact resistance was 2mΩ at 45V. The error bar means standard deviation of the five measured data.

The reliability test in high current level was also conducted. The Tabor-electronics function generator was used for deliberately making cyclic actuation signal, which has duty ratio of 20 %, frequency of 500 Hz, and the amplitude of 50 V. Then, the output signal was precisely detected by Keithley 2638B parameter analyzer. The testing was implemented in an air ambient (temperature: 23 ˚C, humidity: 35 %) and hot-switching condition.

Fig. 8 shows the reliability of the fabricated MEMS relays with the aforementioned test setup. The testing current of 200 mA was selected to validate the reliability at a high current level. As a result, The measured lifetime was 5.3×10^6 cycles, which is 500 times higher than that of the commercial MEMS Relay targeted for high power switching (RMSW 100HP from Radant Co.) in the same test setup. The failure mode of the both devices was due to the sudden increasing in the contact resistance.

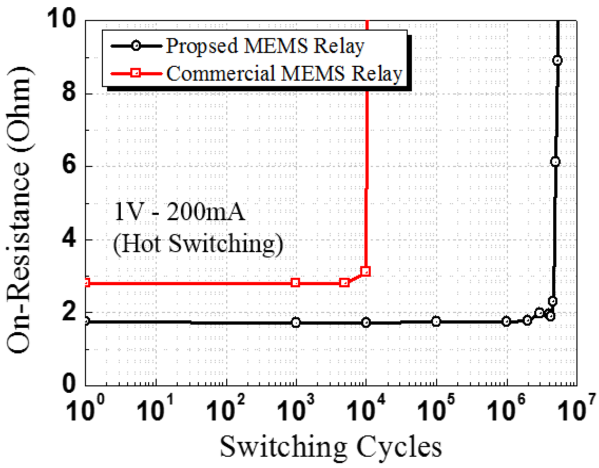

Fig.8 Measured lifetime of the proposed and commercial MEMS relays. The result was tested in an air and hot-switching condition.

CONCLUSION

An electrostatically actuated MEMS relays with the two-step spring system and the proper heat sink were suggested, fabricated and evaluated for the power applications. The proposed MEMS relays provided extremely low contact resistance of 2 mΩ, which is the smallest value among previously reported MEMS relays for power switching [11]. Also, they were able to operate up to 5.3x10^6 cycles at 200 mA current, which is 500 times higher than that of the commercial MEMS relays. The proposed MEMS relays with high reliability are expected to be considered as a promising device candidate for the power applications.

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