METAL FOIL RF MICRO-RELAY WITH INTEGRATED HEAT SINK FOR HIGH POWER APPLICATIONS

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ABSTRACT

This paper reports an electrostatically actuated ohmic contact micro-relay for high power RF applications. Stainless steel cantilevered micro-relays with platinum-rhodium contacts are micromachined from bulk foils and assembled on the printed circuit boards. Micromachined aluminum heat sinks are integrated on the cantilevers above the point of contact. The devices have a footprint of 2x3.2 mm^2. Fabricated relays with 90 V turn-on voltage accommodate 10 W of incident RF power at 1 GHz with -0.25 dB of down-state insertion loss and -37 dB of up-state isolation.

INTRODUCTION

Micro-relays are widely used in signal switching, RF communications and radar applications. As a consequence of the recent developments in microelectromechanical systems (MEMS), the miniaturization and integration of micro-relays for such applications has been the topic of extensive research [1-2]. When compared to solid-state counterparts, micromechanical RF switches exhibit high linearity, low loss and low power consumption [3]. While considerable attention has been directed to the longevity of relays and switches, most of the effort has been directed at devices handling relatively low levels of power, i.e. below 100 mW [4]. High RF power handling in MEMS switches is sought for applications such as in satellite transmitters and/or earth-based communications stations [5]. The design of high-power (>1 W) metal-contact RF micro-relays is of particular concern. Challenges include not only self-actuation but also failure mechanisms such as metal alloying, softening and microwelding directly relate to contact behavior [6]. Past improvements have focused on thin film contact materials [7] and hybrid actuation principles that attempt to reduce the deterioration of contact surfaces by increasing contact force [8]. The former rely primarily on sputtered thin films and limits bulk foil alloy patterning whereas latter introduces large footprints. Platinum-rhodium (Pt-Rh) is both chemically inert and mechanically robust, hence alleviates packaging demands. These properties also make Pt-Rh well suited for high power relays and RF switches. A micromachined all-metal micro-relay directly assembled on printed circuit board (PCB) was reported earlier [9]. This paper presents a micro-relay, utilizing a stacked structure with platinum-rhodium (Pt-Rh) contacts and integrated aluminum (Al) heat sinks for high RF power handling capability.

DESIGN

The device is a 3-terminal switch; it employs a vertically stacked cantilever structure on a 50 Ω microstrip transmission line with RF ground underneath the PCB. A cantilever (2000x3200 μm^2) is placed orthogonally with respect to the transmission line and suspended above a break (Figure 1). It is elevated above the pull-down electrode on the PCB by a cantilever spacer and anchored through alignment posts that perforate it. These posts fit tightly into the vias located on the PCB. Plated vias on the PCB shunt DC and RF grounds for reduced interference and fringing effects. Two ground spacers (each 50μm-thick) are placed on the common DC-RF ground electrode to define cantilever-ground gap for electrostatic actuation. At the distal end of the cantilever is a multi-level structure. A contact bridge (600x1000 μm^2) provides an ohmic contact between two open ends of the microstrip underneath. A thermally conductive sapphire micro-rod (700 μm height, 250 μm diameter, Meller Optics Inc.) is used to couple the contact bridge to the cantilever. It acts as a dielectric which isolates RF signal from the DC bias. It also performs as a thermal conductor to take heat away from the contact bridge. A micromachined heat sink with 4 fins (each 150x150 μm^2 and 1 mm tall) is used to dissipate local contact heating when combined with a commercially available fan (Sunon-UF3A3).

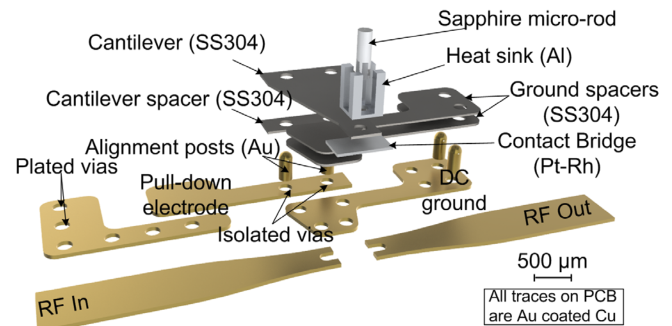

Figure 1: Expanded view of stacked structure assembly. Cantilever and ground spacers are placed to elevate cantilever from the signal line for electrostatic actuation. Cantilever pushes the contact bridge via thermally conductive micro-rod. A heat sink is integrated atop the point of contact, which is a Pt-Rh element.

FABRICATION/ASSEMBLY

Fabrication and assembly of the RF micro-relay is detailed for several components.

Contact Bridge, Heat Sink and Cantilever Spacer

The contact bridges were micro-electrodischarge machined (μEDM) down to 30 μm final thickness of 50 μm thick Pt-Rh (80:20) foil. The heat sinks were μEDM'ed from 1 mm-thick Al (3003) foil whereas cantilever spacer was μEDM'ed down to 110 μm thickness from 125 μm-thick stainless-steel (SS304) stock foil. For each relay, two

perforations of 300 µm diameter were positioned on the cantilever spacers for attachment to the PCB and cantilever. A through hole of 250 µm diameter was machined at the base of the heat sink for the subsequent assembly of the micro-rod and the contact bridge.

Cantilever and Ground Spacers
Cantilever and ground spacers were photochemically etched from 50µm-thick SS304 foils (Kemac Technology Inc., CA). Perforations were located both on the cantilever and the spacers for alignment, PCB attachment, contact bridge, micro-rod and heat sink assembly.

Printed Circuit Board
A 500 µm-thick Rogers 4003 is used as the substrate for the RF line (Advanced Circuits Inc., CO). Metal interconnect traces of 70 µm-thick Cu provided bias electrodes and surface microstrip. In such PCBs, 4 µm thick Ni was used as an adhesion layer on the Cu base, and 0.25 µm thick outer gold layer provided a low resistivity electrical contact. Two types of vias were located on the PCB: isolated vias to anchor the cantilever and the spacers; and plated vias to short DC and RF grounds for reduced interference and fringing.

Assembly
Alignment posts (400 µm-height; 300 µm-diameter), were µEDM'ed from gold wire, and tightly fitted into the isolated-vias on the PCB (Figure 2a). Conical wire tips facilitated the insertion of components. Cantilever and ground spacers were assembled over the posts (Figure 2b) and fixed by applying conductive epoxy (Creative Materials, volume resistivity: 300 µΩ-cm). This was followed by the cantilever and the heat sink assembly (Figure 2c). The heat sink was attached onto the cantilever by aligning the perforation at its base to the one on the cantilever tip, and securing with high temperature epoxy (Cotronics Duralco 4703, 645 K maximum temperature). The flatness of the cantilever as well as the electrode gap of 10 µm was maintained during the assembly process with the help of a high resolution laser displacement sensor (Keyence LK-G32). The contact bridge was aligned on the transmission line. The sapphire micro-rod was then tightly fitted into the overlapping perforations on the heat sink and the cantilever making contact with the bridge underneath. High temperature epoxy was applied to fix the parts (Figure 2d).

DEVICE PERFORMANCE

Small Signal Characterization
Device testing circuitry included a 1 pF DC-block capacitor and a 1 MΩ resistor, R_{ISO}, to monitor cantilever isolation and current leakage (Figure 3a). The turn-on voltage for the device was 90 V, whereas the actuation times were approximately 10 ms. The on-state resistance of the micro-relay, R_{ON}, was characterized in DC by an I-V measurement of the signal line at 1.8 Ω for a gate voltage of 130 V. The components of R_{ON} included contact resistance, contact bridge resistance and parasitics. All tests were conducted in air ambient. To characterize S-parameters, a small-signal full-wave analysis was conducted from near DC to 10 GHz. Experimental results were compared with HFSS modeling results.

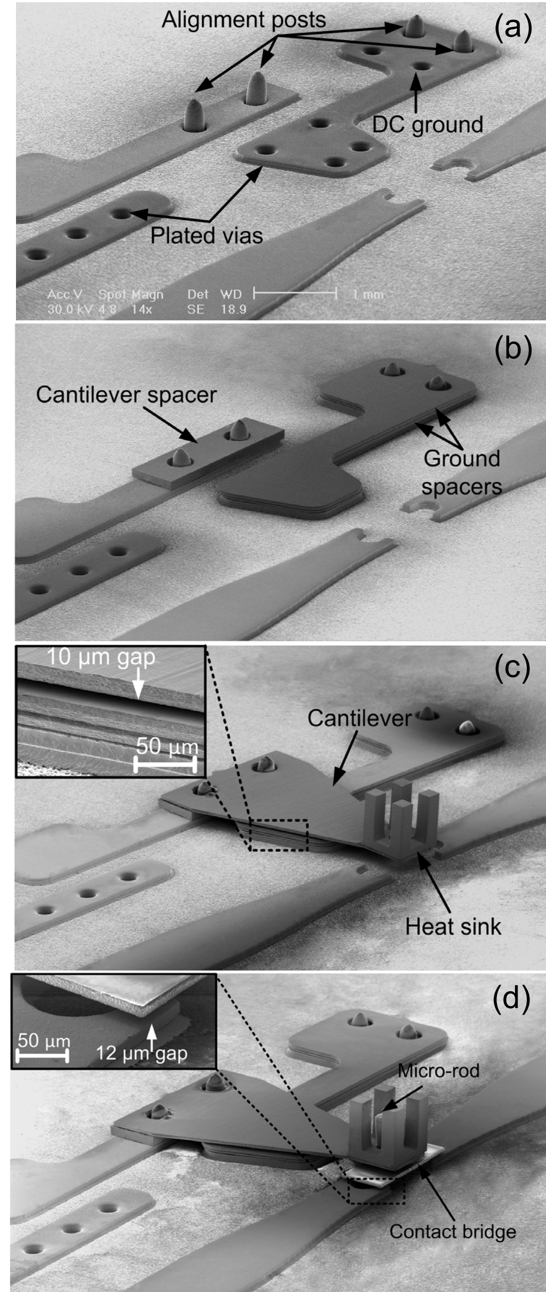

Figure 2: Assembly sequence for RF micro-relay showing: (a) alignment posts inserted. (b) Cantilever and ground spacers (SS304) aligned on top of the posts through perforations and anchored with electrically conductive epoxy. (c) Cantilever and heat sink placed on top. Interelectrode gap of 10 µm and stacked PCB-spacer-cantilever structure is shown in the inset. (d) Contact bridge placed on the signal line and coupled with cantilever through an embedded micro-rod fixed with epoxy in the mid section of heat sink, ensuring uniform contact when actuated. Contact gap is shown in the inset.

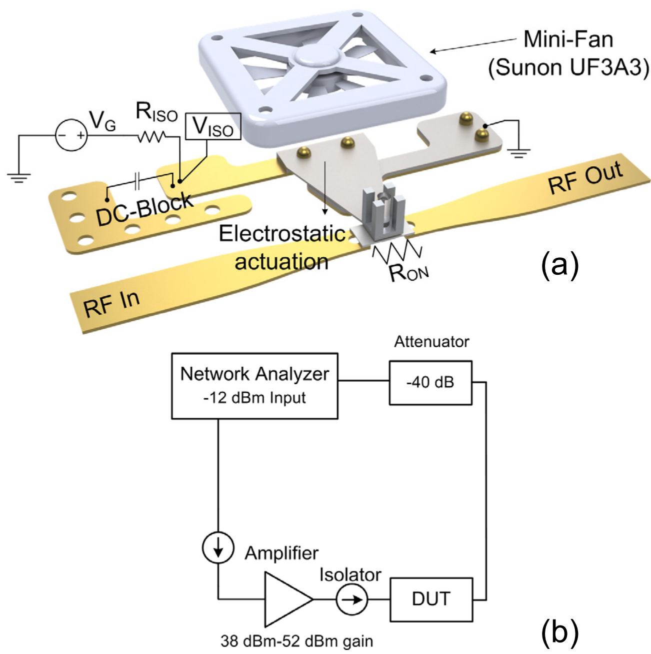

Figure 3: (a) Device circuitry; V_{ISO} is for contact isolation monitoring, R_{ON} is on-state resistance. Surface mount capacitor is used for DC-blocking. (b) High power RF test setup (limited to 10 W of maximum RF power at 1 GHz).

The micro-relay exhibited adequate performance in the down-state. The typical insertion loss was better than -0.2 dB up to 7.5 GHz and better than -0.4 dB at 10 GHz (Figure 4). The corresponding return loss was approximately -20 dB highest in the bandwidth.

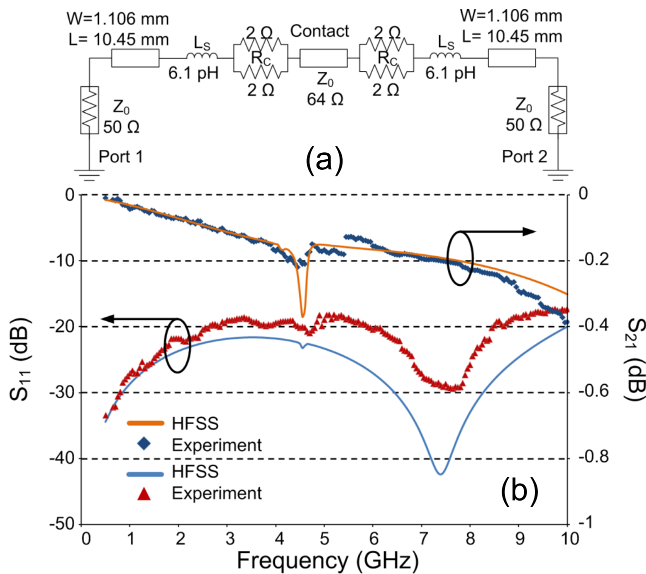

Figure 4: (a) Equivalent circuit for the switch in down-state. Contact bridge characteristic impedance was 64 Ω whereas contact resistance was modeled 2 Ω. 110 fF of up-state capacitance was extracted from the full wave simulations. (b) Down-state 500 MHz-10 GHz small-signal analysis. Experimental data compared with simulation. Down-state insertion loss was below -0.2 dB for up to 5 GHz.

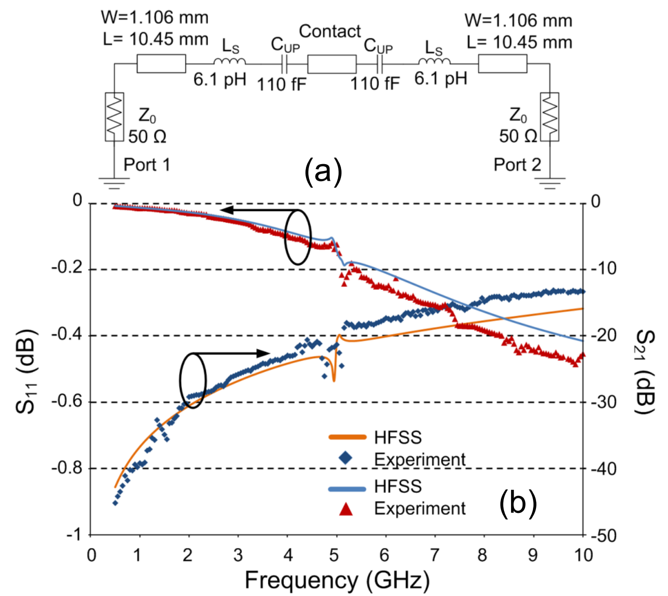

Figure 5: (a) Equivalent circuit for the switch in up-state. Capacitance of 110 fF was extracted from the full wave simulations. (b) Small-signal analysis for up-state up to 10 GHz. Experimental data compared with simulation. The isolation was better than -20 dB up to 5 GHz. Up-state capacitance was experimentally extracted from full-wave analysis and was in good agreement with simulation.

Up-state small signal analysis is shown in Figure 5. The isolation was better than -20 dB up to 5 GHz and around -15 dB at 10 GHz. Extracted up-state capacitance was 116 fF. Overall, HFSS and experimental results were in good accord.

High Power Testing and Thermal Performance

High power testing consisted of discrete power sweep through 11 gain levels up to 10 W of incident power at 1 GHz (testing setup limit) (Figure 3b). Changes in S_{21} were observed under hot-switching conditions.

The typical down-state insertion loss was consistent up to 3.5 W and slightly increased beyond this point. However, no failures were observed during tests up to 10 W RF power (Figure 6a). The up-state isolation was steady near -37 dB for the duration of the test. No self-actuation was observed (Figure 6b).

Figure 7 shows multiphysics electrothermal simulation to estimate contact area temperatures. The electric field distribution under high power (10 W) handling conditions was modeled in HFSS. This solution was imported to ANSYS multiphysics solver to serve as the boundary condition. Contact temperature modeling for a simulation of joule heating considered 1-s of continuous actuation. The FEA showed a temperature increase of approximately 100 K on contacts for 10 W of RF power that was continuously transmitted. Experimentally, contact area temperatures were measured in the down-state using an infrared thermometer. Overall, these were in good agreement with the simulations (Figure 7a).

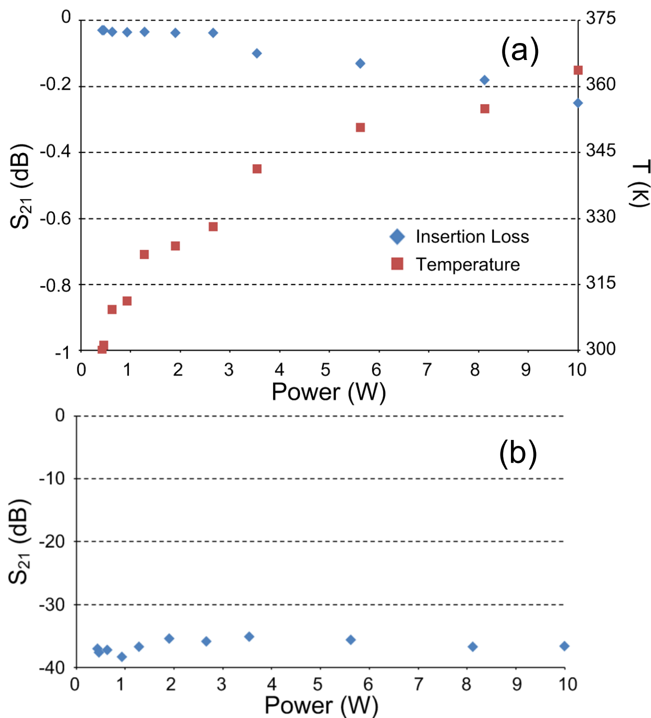

Figure 6: High power testing for RF micro-relay. (a) Insertion loss at down-state was below -0.25 dB at 1 GHz for up to 10 W (test setup limit) and the device failure did not occur. Mini-fan was on during testing and contact temperatures were measured using an infrared thermometer (following 1-s on-state time). (b) Isolation was around -37 dB at up-state and self-actuation did not occur.

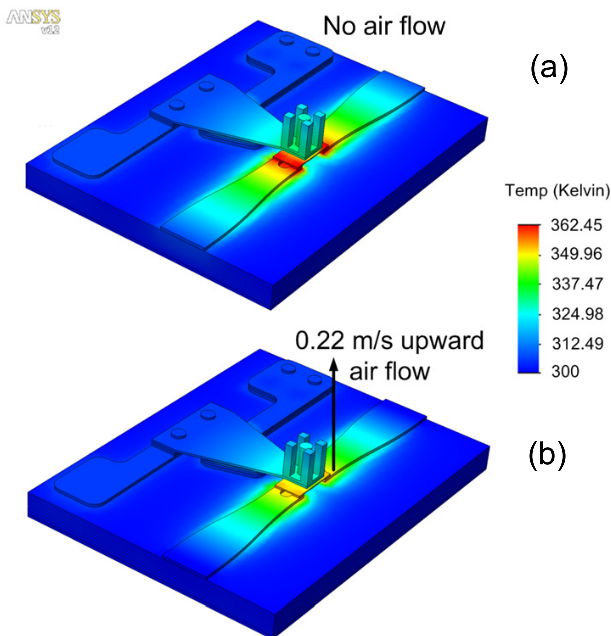

Figure 7: Multiphysics FEA results for 1-s on-state time. HFSS high power electric field distribution was imported to ANSYS as the boundary condition for joule heating simulations. Contact area temperature distribution for (a) unforced (b) forced cooling (1 GHz, 10 W of incident RF Power, 2 Ω modeled R_{ON}, 300 K ambient, 0.22m/s upward flow, Sunon UF3A3 mini-fan).

CONCLUSIONS

Based on the performance of the RF micro-relay described in this work, Pt-Rh foil appears promising for high power applications. It also appears that the use of this chemically inert and mechanically robust bulk foil alloy may alleviate packaging demands. The work also shows how a micro-machined heat sink can be directly assembled on-device for cooling. Fabricated micro-relays are tested in air ambient up to 10 W incident RF power without any failure.

ACKNOWLEDGEMENT

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