Low-voltage small-size double-arm MEMS actuator

N. Biyikli, Y. Damgaci and B.A. Cetiner

The fabrication and characterisation of a double-arm cantilever-type metallic DC-contact MEMS actuator with low pull-down voltage are reported. Bi-layer TiW cantilevers with an internal stress gradient were fabricated using a microwave-compatible fabrication process. Owing to its small size, cantilever length ($L = 5$–50 μm) and width ($W = 2$–40 μm), i.e. ~10–100 times smaller in lateral dimensions than a standard MEMS actuator, this actuator showed actuation voltages lower than 10 V. RF measurements of the 10 μm-wide actuators yielded an average insertion loss less than 1 dB and isolation higher than 40 dB up to 25 GHz. The developed actuator is well suited for integration in reconfigurable microwave circuits and systems such as reconfigurable antennas and arrays.

Introduction: MEMS-based switches/actuators with low loss, high linearity and low DC-power consumption properties have proven to be well suited for various microwave applications such as reconfigurable cognitive wireless communication systems, adaptive matching networks, etc. [1–3]. However, the long term reliability of MEMS actuators, in particular during hot switching events, has been a major concern. The two primary failure mechanisms for DC-contact MEMS actuators are stiction (stuck closed) and increased contact resistance [4]. In addition to reliability issues, high actuation voltages (30–80 V) and low switching speeds (10–20 μs) may not be appropriate for next generation cognitive wireless communication applications. In these systems, the reconfigurability must be fast enough (~less than 1 μs) in order to respond to short-term channel statistics and to support most dynamic adaptation schemes such as opportunistic beamforming schemes [5].

A high-reliability miniature RF-MEMS switched capacitor, similar to the standard capacitive membrane-type switch, has recently been reported [6]. The reported device with typical lateral dimensions of beamwidth = 10 μm and beam length = 20 μm, achieves a pull-down voltage of 27 V. In this Letter, we report a double-arm DC-contact small-size MEMS switch, where each cantilever length and width is as small as 10 and 2 μm, respectively. Fig. 1 shows the schematic and SEM picture of a typical actuator along with typical dimensions. The measured actuation voltages were consistently less than 10 V. DC-contact MEMS actuators were chosen over their capacitive contact counterparts owing to their wide frequency range of operation. Also, a cantilever structure is used as opposed to a beam-membrane structure in order to precisely control the internal stress gradient, which in turn provides control on actuation voltage and isolation performance. It is also worth noting that the small size of MEMS actuators combined with cantilever design results in excellent mechanical properties such as increased spring constant and restoring force per contact area, which makes them less sensitive to residual stress or temperature variations compared to standard MEMS devices [6]. These are critically important features for reliable packaging processes.

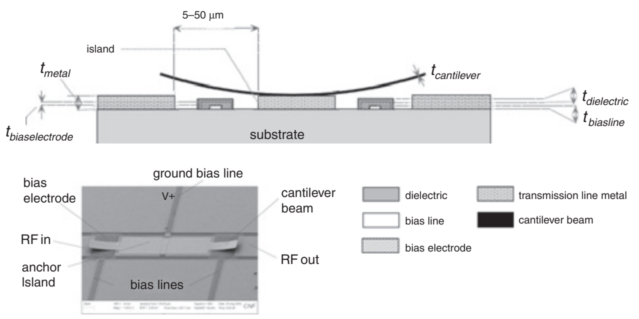

Fig. 1 *Schematic and SEM picture of DC-contact double-arm cantilever-type MEMS actuator*

a Schematic
b SEM picture of DC-contact double-arm cantilever-type MEMS actuator
Dimensions: cantilever width = 2–40 μm, $t_{metal} = 1.0$ μm, $t_{cantilever} = 0.2$–0.4 μm, $t_{biaselectrode} \sim 0.2$ μm, $t_{biasline} = 0.1$–0.2 μm, $t_{dielectric} \sim 0.2$ μm

Design and microfabrication: The double-arm MEMS actuators were realised on a microwave coplanar waveguide (CPW) transmission line and fabricated on a synthetic quartz substrate using a six-layer microwave-compatible fabrication process. The relative dielectric constant and loss tangent of the quartz substrate for the frequency range 0.1–30 GHz are 3.9 and ~0.0002, respectively. Fig. 2 shows the step-by-step fabrication procedure. First, the bias lines were formed by a ~150 nm-thick Ti/Cr layer deposited by DC-sputtering. Bias electrode pads were formed with an e-beam evaporated ~200 nm-thick Ti/Cu layer. Afterwards, bias lines and bias electrodes were passivated with a 250 nm-thick SiO_2 dielectric layer deposited at 275°C with a plasma-enhanced chemical vapour-deposition (PECVD) system. In the fourth step, using the e-beam evaporation system, a 1.0 μm-thick Ti/Cu metal layer was deposited as a microwave CPW transmission line. A thick (~2 μm) amorphous Si (a:Si) sacrificial layer was deposited in the PECVD system at 200°C. Our process optimisation efforts showed that the planarisation of the sacrificial layer was of critical importance for the successful release and mechanical integrity of subsequently deposited cantilevers. A chemical-mechanical polishing (CMP) technique was used to planarise the a:Si sacrificial layer. The polishing process was stopped when ~ 0.1 μm a:Si layer was left on top of Ti/Cu CPW. In the final step, a ~0.4 μm-thick TiW layer was DC-sputtered using 25 sccm Ar and a TiW (90/10 % wt) target. The TiW cantilevers were patterned using a CF_4-based reactive ion etch (RIE). The release of the cantilevers was completed in a XeF_2-etcher system where the underlying a:Si sacrificial layer was effectively etched at lateral etch rates more than 10 μm/min.

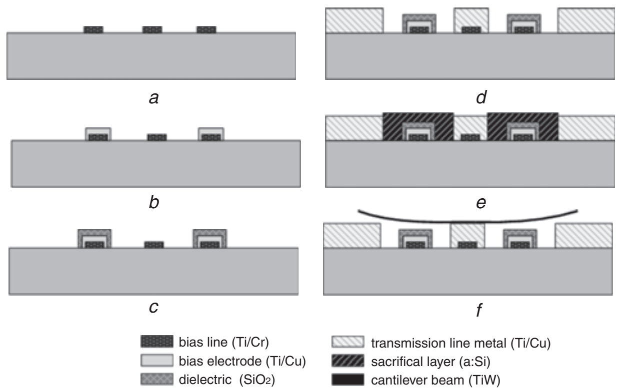

Fig. 2 *Fabrication process steps for double-arm DC-contact MEMS actuators*

a Deposition of Ti/Cr DC bias lines
b Ti/Cu bias electrode metal deposition
c SiO_2 dielectric layer deposition
d Ti/Cu transmission line (CPW) metal formation
e a:Si sacrificial layer deposition and planarisation
f TiW cantilever formation and release process

The cantilevers curled upwards as expected after the release process, owing to the internal stress gradient within the deposited TiW. The stress gradient was achieved by depositing the TiW under two different sputtering conditions: the bottom half was deposited under 16 mtorr chamber pressures, which resulted in a compressively stressed layer, whereas the top half was sputtered under 21 mtorr, resulting in a top layer with tensile stress. The corresponding internal stress gradient was about 1000 MP. By increasing/decreasing the pressure difference of the two TiW layers, it is possible to tune the internal stress gradient to achieve the desired amount of cantilever bending.

Results: MEMS actuators of various lateral cantilever sizes with length ($L = 5$–50 μm) and width ($W = 2$–40 μm) were fabricated. Fig. 3 shows pictures of different devices taken by a scanning electron microscope (SEM). The amount of curling increases with the length of cantilever. The actuation (pull-down) voltage of devices was measured on-wafer using a probe station and a DC bias source. All MEMS actuators exhibited actuation voltages below 20 V. For cantilever widths smaller than 20 μm, actuation voltages lower than 10 V were consistently measured.

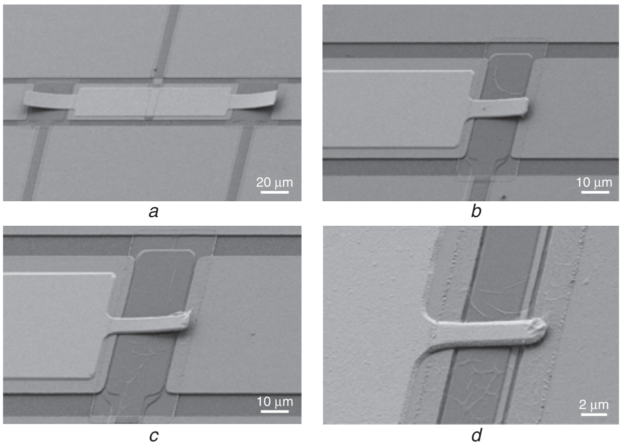

Fig. 3 *SEM pictures of DC-contact RF MEMS double-arm actuators*

a $L = 50$ µm, $W = 20$ µm (both arms shown)
b $L = 25$ µm, $W = 10$ µm
c $L = 20$ µm, $W = 5$ µm
d $L = 10$ µm, $W = 2$ µm

The RF performance of fabricated MEMS actuators has been characterised by measuring small-signal *S*-parameters using a probe station with 40 GHz RF probes and a 26 GHz network analyser. The actuators exhibited excellent isolation (an average of 50 dB) of the zero-bias open-state (OFF-state) for any of the cantilever dimensions as shown in Fig. 4*a*. Fig. 4*b* shows the measured insertion losses of the biased actuator (ON-state) for different cantilever dimensions as a function of frequency. As can be seen in Fig. 4b, insertion loss steadily increases for decreasing membrane dimensions, which is an indication that the contact resistance gets larger as the membrane width gets smaller. The insertion loss is relatively constant over the frequency range of 100 MHz–25 GHz, which is consistent with the constant loss prediction of real resistance, $S_{21} = 2Z_o/(2Z_o + R_c)$, where R_c is the contact resistance. The average insertion loss is at around 0.2 dB for 40 µm-wide actuators, while it degrades to around 2 dB for 2 µm-wide actuators.

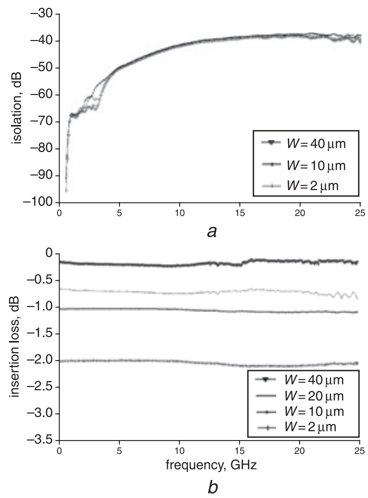

Fig. 4 *Measured isolation and insertion loss of fabricated DC-contact MEMS double-arm actuator for membrane widths, W= 40, 20, 10, and 2 µm*

Conclusions: Significant progress towards obtaining highly reliable small size MEMS actuators with low actuation voltage and fast switching speed is reported. We have fabricated and characterised the DC and RF performance of small-size double-arm DC-contact MEMS actuators of cantilever type with an internal stress gradient. The actuators showed promising performance results. To improve the insertion loss performance of the actuators with a small cantilever width, we are currently optimising mechanical switch design using novel contact architectures and investigating various alloy electric contact metallurgies with desired electrical and mechanical properties. We are also developing new nanofabrication processes as a way of reducing contact resistance and improving reliability.

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