Active Opening Force and Passive Contact Force Electrostatic Switches for Soft Metal Contact Materials

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***Abstract*—This paper reports on a mechanically bi-stable, electrostatically actuated switch mechanism with a large active opening force and a small passive closing force, designed to fit the contact and opening force requirements of soft contact materials such as gold. So far, most microelectromechanical systems (MEMS) switch designs have been optimized for a large contact force without paying too much attention to the opening force. In the "conventional," most commonly used electrostatic microswitch concept, the force of the actuator is used to close the switch contacts, and the switch is opened by the passive restoring force of the deflected cantilever or membrane. This concept results in a large contact force, but the opening force is typically too small to overcome the contact adhesion force of soft metals, which makes this concept less suitable for contact materials such as gold with its low contact resistance at low contact forces. The switch concept presented in this paper is based on two cantilevers laterally moving by curved electrode actuators. The tips of the cantilevers are endowed with hooks which can be mechanically interlocked. In the latched state, the spring forces of the deflected cantilevers also act as the passive contact force between the switch contacts. The opening force is actively created by the curved-electrode actuators, which are utilized close to their best electromechanical operating point resulting in a maximum contact separation force. The theoretical discussion of the new concept as compared to conventional switch designs is supported by simulation results, measurements on fabricated devices, and by an analysis of exemplary switches published in the literature. [1735]**

***Index Terms*—Contact material, curved-electrode actuator, microelectromechanical systems (MEMS) switch, microswitch, RF MEMS.**

I. Introduction

A. Microswitch Contact and Adhesion Forces

ONE OF THE major issues in microelectromechanical systems (MEMS) metal-contact switch design is the choice of the contact material. In contrast to macroscopic relays with contact forces typically larger than 100 mN [1], MEMS switches are equipped with relatively weak actuators generating contact forces in the range of 10 μN to 5 mN only. The dependence of the contact resistance on the contact force has been thoroughly investigated for different contact materials, as summarized in Table I. It is difficult to compare the many studies [1]–[9] since the measurement results not only depend on the contact force, but also on the metal deposition process, the contact cleaning procedure, surface contamination, the atmospheric environment, the measurement current, and the switching history. Also, many investigations were carried out on test setups and not on fabricated MEMS switches. In general, the contact resistance is decreasing with increasing contact force. However, a "threshold level" of the force can be identified, which is the minimum contact force required for a getting a stable and reproducible contact resistance. Forces above this threshold level further decrease the contact resistance, but to a smaller extent only. As shown in Table I, both the contact resistance and the minimum contact force are smaller for soft materials than for hard contact materials. This relationship is explained by the contact surfaces adapting to each other due to elastoplastic deformation, finally resulting in a sufficiently large effective contact area and, thus, in a stable contact resistance [2], which occurs for softer materials at smaller forces than for harder materials. Therefore, for microrelay contacts, soft contact materials are generally preferred over hard materials. Especially, gold was found to be very suitable because of its low electrical resistivity, its low contact resistance at very low contact forces, its high thermal conductivity, its ease to deposit by a variety of fabrication processes, its high oxidation resistance, its relatively high melting temperature for being a soft metal [5], [10, Sec. 7], and its good resistance to absorption of surface contaminants, despite its tendency to absorb thin carbonaceous layers [11], [12]. However, due to its softness,

TABLE I
Minimum Contact Force to Achieve a Stable Microcontact Resistance for Different Metals, and Contact Resistance at the Minimum Contact Force

	material	minimum contact force μN	contact resistance mΩ
soft	gold (Au) [1]–[7]	50–100	70–200
	'fine-gold' (AuCuCd) [8]	200	50–80
↕	'hard-gold' (AuNi, 5%) [9]	300–450	<100
	gold-palladium (AuPd) [10]	200–2000	500–3000
	palladium (Pd) [3]	300	[a]
hard	silver (Ag) [3]	600	[a]
	rhodium (Rh) [4]	600–900	800

[a]The minimum stable contact resistance values published in [3], one of the very first studies on microcontact behavior, have not been taken over into the table, since the setup used in that study generally resulted in much higher contact resistance values for all materials investigated, as compared to the major part of the investigations carried out later [1], [2], [4]–[10].

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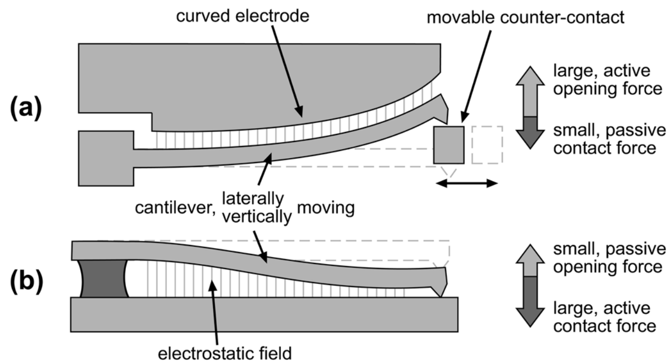

Fig. 1. Schematic drawings of (a) "active opening force/passive contact force" switch concept with the electrostatic force of a laterally moving curved-electrode actuator utilized to separate the switching contacts with a very large active opening force; and (b) conventional concept of a vertically moving cantilever beam switch featuring active closing by the electrostatic force.

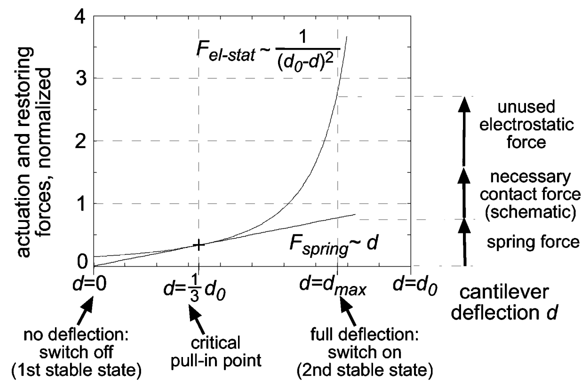

Fig. 2. Forces acting in a parallel-electrode model of a conventional cantilever-spring switch design, plotted for the critical case where the electrostatic force is just large enough for pull-in. In the contact position, the switch develops a very large electrostatic force, but only a relatively small restoring spring force (d_0 is the initial distance between the actuator electrodes).

gold typically develops much larger adhesion forces between the touching microcontacts. Typical release forces needed to separate microswitch contacts are 100–2700 μN for gold, as compared to about 300 μN for a hard-gold alloy with 5% nickel, and to less than 100 μN as reported for rhodium, one of the hardest contact materials investigated [9], [13]. The large adhesion forces of gold contacts increase the susceptibility for permanent contact stiction and thus decrease the lifetime of gold microswitches [12], [13]. A switch design equipped with gold contacts showed a cold-switching lifetime of about 10 million switching cycles before irreversable contact stiction occured, whereas the same design with harder, "a platinum group" metal contacts, exceeded 100 billion switching cycles [14]. The reduced lifetime of gold microcontacts can be explained by contact wear and material transfer between the contacts, which is reported for gold to occur earlier than for other materials [15]. Hardening the gold by alloying it with nickel, palladium, copper/cadmium, ruthenium, silver or platinum seems to be an acceptable compromise to achieve higher contact reliability but at the price of an increased contact resistance and requiring a larger minimum contact force [12].

In conclusion, (pure) gold contacts have superior electrical contact performance in microactuators as compared to harder materials, but are inferior in terms of their mechanical stability. Thus, a switch mechanism utilizing the advantages of gold microcontacts has to provide with a large opening force to achieve a sufficiently long contact lifetime.

B. Contact and Restoring Forces in "Conventional" Switch Designs

The most promising MEMS switch designs, in terms of reliability and suitability for high-volume wafer-scale manufacturing techniques, are based on electrostatic actuators [16]. This principle is of high interest for actuating moving parts in microsystems because of the high-energy densities and large forces due to the scaling laws in small dimensions, and because of relatively simple fabrication [17].

The conventional, most-commonly used and electrostatically actuated switch concept, based on a cantilever-spring or membrane-spring system, is shown in Fig. 1(b). The actuator mechanism features active closing of the switch contacts by the electrostatic force and passive opening by the spring energy stored in the deflected, pulled-in structure. Assuming a simplified model with parallel-plate electrodes, the electrostatic force is proportional to $(d_0 - d)^{-2}$ with d_0 the initial electrode distance and d the deflection of the cantilever. For a typical design, only 40%–90% of the total electrostatic force is used as the contact force, with the remainder part contributing to beam flexture or being lost at the anchor suspension [10, Sec. 2.9]. The counter-acting restoring spring force is directly proportional to the cantilever deflection d. To ensure the pull-in of the cantilever, which is necessary in a microswitch design to achieve sufficiently large contact separation in the off-state and a large contact force at an acceptable actuation voltage and actuator size, the electrostatic force has to be larger than the restoring spring force for all possible cantilever deflections. That results in the design criteria for a parallel-electrode model, that the electrostatic force has to be larger than the spring force at $2/3$ of the initial electrode distance, independent on any other geometrical parameter [10, Sec. 2.6]. This criteria in connection with the nonlinear growing electrostatic force results in a very large contact force in the final contact position $d_{\max}$, but only in a comparatively small restoring spring force. Fig. 2 shows a plot of the contact and restoring forces over the cantilever deflection, plotted for the critical pull-in condition of a parallel-electrode model. The contact force of switches of this conventional type is typically in the range of 100–500 μN, but the restoring force is usually much lower than 100 μN, which makes this concept very susceptible for contact stiction, especially when soft contact materials are used. Increasing the spring force for improving the contact separation force requires an even stronger, thus larger electrostatic actuator and/or higher actuation voltages. From a design-efficiency point of view such an actuator is "overkill," since its large active contact force as a result of the requirements on the restoring force is not utilized, especially for switching soft contact materials.

Thus, the conventional electrostatic switch concept based on an active contact and on a passive restoring force, definitively a good choice for medium-hard contact materials, is less suitable for exploiting the potential of soft contact materials.

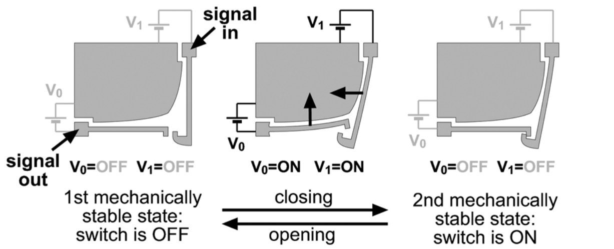

Fig. 3. Actuation phases of the mechanically bi-stable, "active opening force/ passive contact force" switch mechanism as proposed in this paper. The transition phase consists of sub-phases sequentially coordinating the movement of the independently controllable cantilevers, as described in Section II and illustrated in Table II.

TABLE II
SYNCHRONIZATION OF THE ACTUATION VOLTAGES FOR THE SWITCH TRANSITIONS BETWEEN THE ON-STATE AND THE OFF-STATE, REFERRING TO FIG. 3

phase	switch transition off→on		on→off	
	V_0	V_1	V_0	V_1
1	ON	OFF	ON	ON
2	ON	ON	ON	OFF
3	OFF	ON	OFF	OFF
4	OFF	OFF		

II. THE "ACTIVE OPENING FORCE/PASSIVE CONTACT FORCE" SWITCH CONCEPT

This paper presents and investigates a metal-contact switch concept whose actuator, in contrast to conventional switch designs, is utilized for active opening of the switch contacts as illustrated in Fig. 1(a). This concept provides with a large, externally controllable opening force and is therefore suitable to overcome large adhesion forces between the metal contacts. The switch mechanism consists of two cantilevers which are moved by curved-electrode electrostatic actuators. The cantilever tips are endowed with hooks which are mechanically interlocked in the on-state. Thus, the concept features mechanical bi-stability. Basically, all ON–OFF type microswitches are bi-stable, but typically only one of the two stable states is mechanically stable, i.e., stable without applying any external energy. For the presented switch as for any other mechanically bi-stable mechanisms, the energy source is only needed for triggering the transition between the two states.

Fig. 3 shows the mechanical configuration of the cantilevers in the two stable states and during the switching transition. For interlocking the hooks, the cantilevers have first to be moved to their maximum deflection and are then, one after the other, relaxed to their interlocked position, in the sequential order as described in Table II.

A curved-electrode actuator is an electrostatic actuator typically utilized for deflecting a cantilever laterally. The fixed electrode is curved which results in the electrode distance gradually increasing from the clamped end to the free end of the cantilever. Due to the narrow gap in the beginning, high forces initialize the bending of successive parts of the cantilever. Thus, the short electrode distance with the large actuation force is

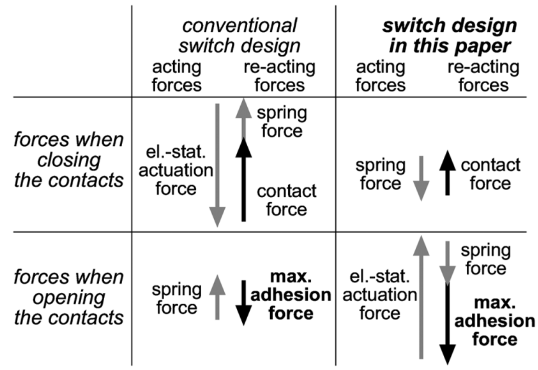

Fig. 4. Qualitative comparison of the forces acting in the conventional and in the new switch design. The "active opening force/passive contact force" switch is capable of overcoming much larger adhesion forces and is therefore more suitable for soft contact materials.

moving along the fixed electrode, similar to the closing of a zipper. Such actuators achieve large tip deflection at substantially lower actuation voltages as compared to parallel-electrode designs [17]–[20]. Another important feature of curved-electrode actuators is that they develop their maximum actuation force in the deflected end-position where the distance between the electrodes is very small along the whole actuator, as illustrated in Fig. 1(a), which results in a very large electrostatic force between the electrodes. For the presented switch concept, the working point of the curved-electrode actuators is the interlocked on-state of the switch, where the actuators are used to separate the switch contacts. The switch is designed in a way that the cantilevers in this state are deflected close to their maximum displacement. Thus, the design utilizes the actuators close to their best operating point to develop a maximum opening force.

The passive contact force in the interlocked state is created by the spring energy stored in the deflected cantilevers. The spring force of an electrostatically actuated cantilever-spring or membrane-spring system with or without pull-in capability is smaller than its actuation force in any state of deflection (see Fig. 2). That means for the presented switch design that the contact force is much smaller than the electrostatic opening force, and smaller as compared to the active contact force of a conventional switch design. For designing the contact force, the same rules apply as for designing the opening force in a conventional switch design: a cantilever with large spring constant increases the force, but also increases the switch actuation voltage or decreases the possible cantilever tip deflection, the latter being an important factor for the switch isolation in the off-state.

Fig. 4 shows a qualitative comparison of the forces in the new switch concept with the forces in the conventional switch design. The switches represented in the two drawings are assumed to have equal strong electrostatic actuators and cantilevers with equally stiff spring constants. The main difference is that the new concept is able to overcome much larger adhesion forces between the switch contacts, since it features active opening. Thus, almost the whole electrostatic actuation force, only reduced by the much smaller spring force, is contributed to separating the switching contacts. The figure also illustrates that the contact force is much smaller as compared to conventional

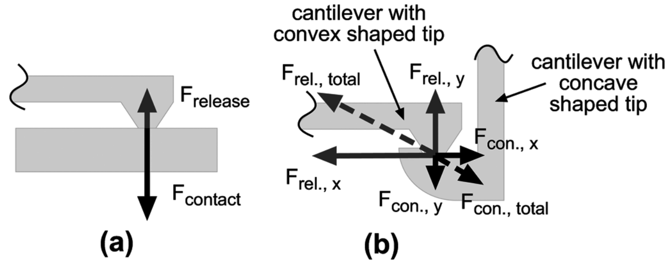

Fig. 5. Forces between the switch contacts to open and to close the switch: (a) conventional switch concept and (b) "active opening force/passive contact force" switch concept. As shown in the drawing, the forces in the x-direction are larger than the forces in the y-direction, since the vertical cantilever of the fabricated devices investigated in this paper was found to be more deflected than the horizontal cantilever in the interlocked position, which results in a smaller electrode distance and therefore larger actuation force acting on the vertical cantilever.

switch designs, which results in a larger contact resistance for hard contact materials. However, since the large opening force of this concept allows for using soft metals as contact material, the lower contact force is still large enough for achieving a low contact resistance.

It is also interesting to note that the actuation voltage to open the switch is applied simultaneously on both cantilevers, since the cantilevers are interlocked in the on-state and thus electrically connected. Therefore, the total opening force consists of two components perpendicular to each other, as shown in Fig. 5. Having both a horizontal and a vertical, even though not independently controllable, force component acting on the adhering contacts might also result in an improved condition for the contact separation physics, since the contact surfaces are not flat on a nano-scale but have a three-dimensional (3-D) topography due to their surface roughness. In the same way, also the contact force consists of two components, as illustrated in the figure.

The very large opening force and the small, but for soft-metal contacts sufficiently large contact force make this switch concept much more suitable for soft-metal contact materials than conventional switch designs. The main advantages and disadvantages of the new switch concept are summarized in Table III.

TABLE III
SUMMARY OF THE MAIN ADVANTAGES AND DISADVANTAGES OF THE NEW SWITCH CONCEPT AS COMPARED TO A CONVENTIONAL, ELECTROSTATICALLY ACTUATED SWITCH DESIGN

advantages	disadvantages
• large active opening force • suitable for soft contact materials • mechanically bi-stable • simple, low-cost, one-mask fabrication • all-metal design (no charging problems of isolation layers) • energy-efficient actuator (no actuator oversizing) • opening force with two perpendicular components	• large total resistance (insertion loss) due to the signal routed over the long cantilevers • low contact force less suitable for hard contact materials (larger contact resistance) • two independently controllable actuation voltages required • in-line switch concept[a]

[a]Signal and actuation paths electrically not separated. However, beside the frequency domain division in which conventional in-line switch designs are controlled, the signal/control potential sharing is also possible by time division, since the presented switch concept is mechanically bi-stable.

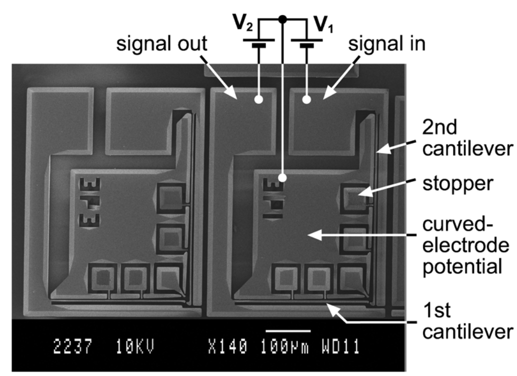

Fig. 6. SEM picture of two switches of the "active opening force/passive contact force" switch design, which is based on two perpendicularly arranged cantilevers with interlocking hooks deflected by curved-electrode actuators.

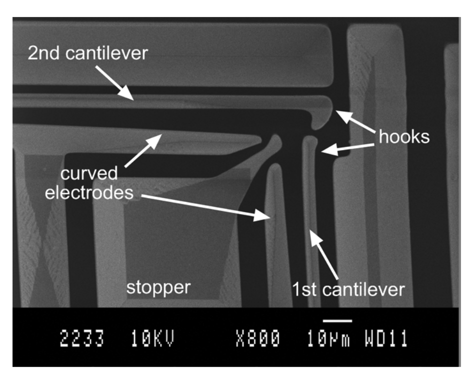

Fig. 7. Close-up view of the cantilever tips with the two interlocking hooks. The central stopper and parts of the curved electrode are visible as well.

III. DEVICE FABRICATION

The mechanically bi-stable switches have been fabricated in three different design variants with a total cantilever beam thickness of 3.6, 4.1, and 4.6 $\mu\mathrm{m}$ (designs I, II, and III, respectively). Each switch consists of two cantilevers. The cantilever with the convex-shaped hook-tip [see Fig. 5(b)] has a length of 300 $\mu\mathrm{m}$, and the cantilever with the concave-shaped tip has a length of 400 $\mu\mathrm{m}$. The devices have been fabricated by deep-reactive-ion-etching (DRIE) in a silicon-on-glass substrate with a 60 $\mu\mathrm{m}$ silicon device layer. The total cantilever thickness is composed by the silicon core plus a sputtered chromium/gold coating layer with a sidewall thickness of 450–500 nm measured at a sidewall distance of 17 $\mu\mathrm{m}$. The gold layer serves as the contact material and increases the electrical conductivity of the cantilevers. Since the electrodes are not covered by isolation layers, each actuator is endowed with three stoppers placed along the curved electrodes, which are electrically isolated posts keeping the distance between the cantilever and the curved electrode, and prevent both an electrical short-circuit and stiction between the electrodes. A SEM-picture of two switches is shown in Fig. 6, and a close-up view of the region around the cantilever tips is shown in Fig. 7. More detailed information on the device fabrication can be found in [21].

TABLE IV
MEASURED AND SIMULATED PULL-IN VOLTAGES OF THE THREE BASIC SWITCH DESIGN VARIANTS. THE CANTILEVER THICKNESS REFERS TO THE TOTAL THICKNESS MEASURED ON FABRICATED DEVICES, INCLUDING THE GOLD COATING LAYER

	actuation voltages in V measured (simulated)		
design	*I*	*II*	*III*
cantilever thickness	*3.6 μm*	*4.1 μm*	*4.6 μm*
400 μm cantilever	30.8 (33.1)	38.7 (41.1)	43.5 (49.5)
300 μm cantilever	45.2 (46.3)	56.4 (57.3)	63.1 (69.0)

IV. PERFORMANCE EVALUATION

The measured and simulated pull-in voltages of the three basic switch design variants are summarized in Table IV. The measured voltages are very well reproducible with a standard deviation of 0.62 and 1.93 V of ten subsequent measurements of the 300 $\mu\mathrm{m}$ and the 400 $\mu\mathrm{m}$ long cantilevers, respectively. As shown in the table, the measured values correspond to the simulated pull-in voltages with an accuracy of 10% or better. The simulations were performed with a numerical algorithm explicitly developed by the authors for simulating and designing curved-electrode actuators [22]. The measured actuation voltage to open the switches is not as well reproducible and varies for design I with 3.6-μm-thick cantilevers between 48 and 65 V, even for subsequent cycles of the same device. The large variation in the voltage required to open the switch indicates that the contact adhesion varies from cycle to cycle. This also implies that measuring the contact separation voltage of the proposed switch mechanism can be used to investigate the contact adhesion behavior varying over the lifetime of a metal-contact switch.

For evaluating the contact separation voltage, the devices were cold-switched, i.e., the signal current of 1 mA was applied in each closed state for at least 10 s, but removed during the switch transition. The contacts have been cleaned with isopropanol before carrying out the first switching cycle. For the different cantilever thicknesses of 3.6, 4.1, and 4.6 $\mu\mathrm{m}$ (designs I, II, and III), the average opening voltage was measured to 56.5, 60.6, and 85.0 V, respectively.

The opening force of the three novel switch designs was determined by simulating the equivalent cantilever tip force corresponding to the total torque created by the distributed electrostatic force, at the measured cantilever deflection in the interlocked state and for the measured switch opening voltage. The contact force was estimated by using the measured deflection of the cantilevers according to the formula

$$F_{\mathrm{cont.}} = 3EI\frac{d_{\mathrm{cont.}}}{L^3} \tag{1}$$

with E, I, and L the Young's modulus,[1] the moment of inertia and the length of the cantilever, and $d_{\mathrm{cont.}}$ the measured deflection in the interlocked position (SI units apply). Since both

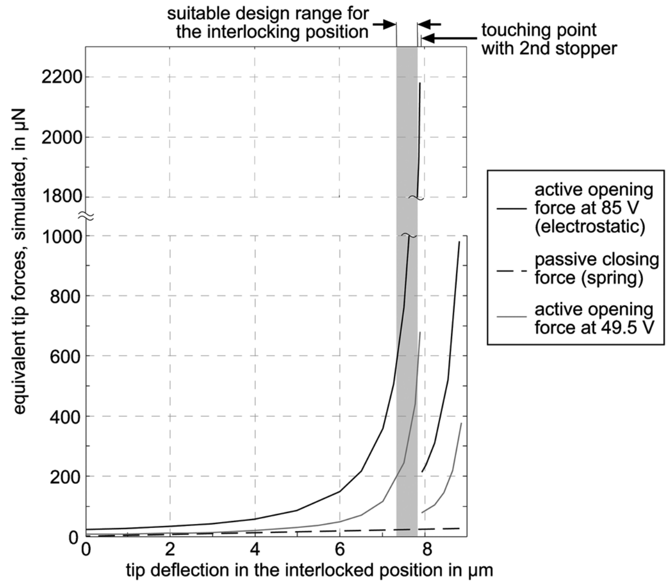

Fig. 8. Simulated equivalent tip forces for active opening and passive closing of the switch contacts, over the cantilever deflection in possible interlocked positions. The switch design achieves its maximum opening force when the cantilevers in the interlocked state are deflected to a position just before they touch a stopper. After the touching point, the counteracting force on the stopper substantially reduces the cantilever tip force. The opening force is shown both for the average measured opening voltage (85 V), and for the measured pull-in voltage from the noninterlocked, nondeflected position of the 400 $\mu\mathrm{m}$ long cantilever of design III (49.5 V).

cantilevers contribute to the contact and opening forces, as illustrated in Fig. 5, the resulting contact and opening forces are calculated by the geometrical addition of their two force components.

The interlocking position of the two cantilevers can be designed by geometrical parameters such as the hook shape and by the cantilever length. For achieving the largest opening force, the cantilever deflection in the interlocked state has to be chosen at the position where the actuator develops its maximum force. Fig. 8 shows a plot of the simulated contact and opening forces over the tip deflection in possible interlocked positions, for the 400 $\mu\mathrm{m}$ long cantilever of design III. Due to the decreasing electrode distance at larger deflection d and the $(d_0 - d)^{-2}$ correlation between the electrostatic force and the local cantilever deflection, the active opening force is growing much faster than its counteracting spring force, similar to the contact force in a conventional switch design as displayed in Fig. 2. The discontinuity of the simulated opening force at a tip deflection of about 7.9 $\mu\mathrm{m}$ stems from the cantilever touching the second stopper, which counteracts to a large amount of the electrostatic force. With further increasing tip deflection, the equivalent tip force is growing again, until the cantilever finally touches the third stopper.[2] Thus, the maximum opening force is achieved slightly before the cantilever touches the second stopper, which is therefore the best position for interlocking the cantilevers. The opening force of design III with the stiffest cantilevers is displayed for the average measured actuation voltage necessary to

[1]Equations (1)–(3) in this paper can only be applied to cantilever beams composed of a homogeneous material. Therefore, the effective Young's modulus of the multilayer cantilever structure has been determined by FEM simulations to 121, 125, and 129 GPa for designs I, II, and III, respectively, assuming $E = 169\ \mathrm{GPa}$ for monocrystalline silicon and 77 GPa for sputtered gold.

[2]For the present design, it was found during the evaluation that the first stopper is never touched during ordinary operation and is therefore redundant, but still contributing to the overall reliability of the actuator by preventing possible electrode stiction.

open the interlocked switching contacts in the deflected state (85.0 V, contact adhesion force has to be overcome), and for the simulated pull-in actuation voltage from a noninterlocked, non-deflected state (49.5 V, no contact adhesion force). The simulated opening force developed by the electrostatic actuator reaches a maximum of 686 μN at the actuation voltage of 49.5 V, and 2180 μN at 85.0 V, respectively, demonstrating the potential of the actuator to create very large opening forces and thus being able to overcome large contact adhesion forces, as long as the cantilever is not touching any of the stoppers along the curved electrode.

The total switch resistance measured between the input contact pad and the output contact pad was determined to 2.31 Ω (average of ten successive switching cycles with a measuremend current of 1 mA; standard deviation of the resistance 8.94 $\mathrm{m}\Omega$), which is rather large for a micromachined switch with gold contacts. Since the first design did not contain connected cantilevers for reference measurements of the total signal path resistance, the pure contact resistance could not be derived from the measurements. However, the main contribution of the resistance is assumed to stem from the two cantilevers with a total length of 700 $\mu\mathrm{m}$, consisting of high-resistive silicon ($> 4000\ \Omega\mathrm{cm}$) covered with a thin chromium/gold coating. The thickness of the chromium/gold layer varies substantially over the height of the sidewalls and with the distance between the sidewalls of the curved-electrode actuators. The total resistance of the two cantilevers was estimated by calculations to be between 1.2 and 2.5 Ω, corresponding to an assumed averaged coating thickness of 400 to 200 nm. Furthermore, the reproducibility of the total switch resistance with less than 20 $\mathrm{m}\Omega$ is an indicator that the contact resistance is less than 200 mOhm [2], [9].

V. Force Comparison to Conventional Switch Designs

Table V summarizes the contact and opening forces of the three switch designs and compares these data to three conventional switch designs: a switch by Radant MEMS, MA, USA (former Northeastern University/Analog Devices design) [10, Sec. 5.11], [23], a switch by HRL Laboratories, CA, USA [24], and a switch design by OMRON, Japan [25]. The restoring spring forces of the conventional switch designs are between 2 and 9 times smaller than their active contact forces. In contrast to this, the opening forces of the switch designs presented in this paper are larger than their contact forces, and even exceed them by a factor of 55 to 73. The opening forces of the new switch designs for the actuation voltages as stated above are between 1100 and 2180 μN. The contact forces are relatively small and between 15 and 31 μN. However, even the small contact force of 15 μN of the fabricated switch design I results in fully metallic contact behavior, which is indicated by the total switch resistance being stable within 20 $\mathrm{m}\Omega$ measured for successive switch cycles at a signal current of 1 mA.

Fig. 9, lower part, shows a double-logarithmic diagram plotting the area of possible microswitch designs spread out over the opening-force and the contact-force. Different design regions have been classified by the opening force according to the probability for contact stiction of gold contacts, and by the contact force according to the conductive behavior of pure gold contacts exposed to low contact forces [1], [2], [6], [9], [13], [26]. The

TABLE V

Contact Forces $F_{\mathrm{cont.}}$, Restoring Forces $F_{\mathrm{rest.}}$, Spring Constants k, Unpackaged Switch Sizes A and Actuation Voltages V of the Switch Designs Plotted in Fig. 9. "Conventional" Switch Designs: (a) Radant MEMS Switch [10, Sec. 5.11], [23]; (b) HRL Switch [24]; (c) OMRON Switch [25]; (d1)–(d3) Switch Designs as Proposed in This Paper

switch	$F_{cont.}$ μN	$F_{rest.}$ μN	$\frac{F_{cont.}}{F_{rest.}}$	k Nm^{-1}	A mm^2	V V
(a) Radant	100[a]	53[b]	2:1	100[c]	0.01[d]	60–80[c]
(b) HRL	400[a]	46[b]	9:1	4–8[c]	0.04[d]	40–60[c]
(c) OMRON	5000[a]	1000[c]	5:1	400[c]	1.80[d]	19[c]
(d1) design I	*15*[e]	*1100*[f]	*1:73*	*3*[g]	0.12[h]	30–65[i]
(d2) design II	*22*[e]	*1210*[f]	*1:55*	*5*[g]	0.12[h]	35–70[i]
(d3) design III	*31*[e]	*2180*[f]	*1:70*	*7*[g]	0.12[h]	40–90[i]

[a] published data, force per single contact

[b] estimated from published data by $F_{rest.} = k \times d_{max}$, with k the spring constant, and d_{max} the cantilever deflection in the on-state

[c] data as published in the literature

[d] size estimated by the authors by measuring published SEM-pictures or photographs

[e] superimposed simulated spring forces at the measured interlocked cantilever deflection

[f] simulated equivalent electrostatic tip force at the average measured opening voltage, deducted by the spring force, for the deflection in the optimal interlocking position

[g] derived from simulation results with FEM software

[h] total, rectangular switch area spread out between the two perpendicularly arranged cantilevers; the area effectively occupied by the two perpendicularly arranged curved-electrode actuators is with 0.012 mm^2 much smaller; vertical dimensions of the laterally moving actuators not taken into account

[i] range including the cantilever pull-in voltages and the active opening voltages, the latter much higher than the former

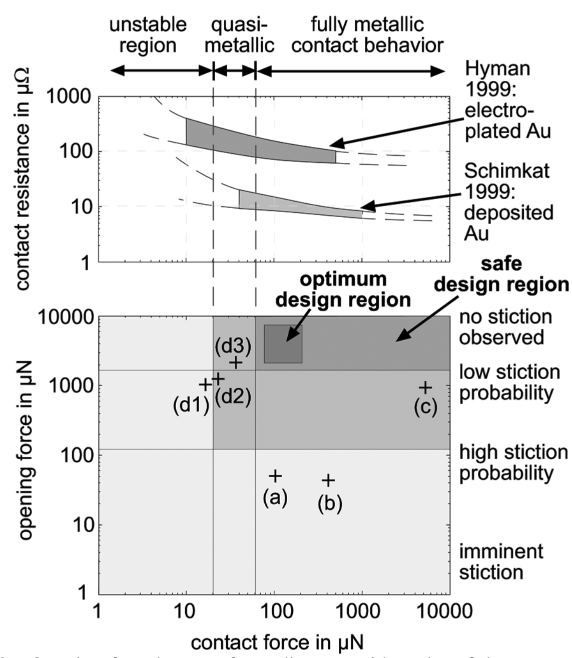

Fig. 9. Opening-force/contact-force diagram with a plot of the contact resistance over the contact force for gold switch contacts. The safe, critical and unsuitable design regions are estimated according to data from the literature [2], [9], [26]. Conventional switch designs, as shown for (a) switch by Radant MEMS [10, Sec. 5.11], [23], Inc., and (b) HRL switch [24], are not creating reliable opening forces for soft gold contacts, unless a very strong actuator such as the OMRON switch (c) is used [25]. The novel :active opening force/passive contact force" designs [(d1), (d2), (d3)] fit the contact/opening force requirements of gold much better.

"safe design region" is the region with the contact force larger than the minimum force required for fully metallic contact behavior, and the opening force larger than the typical adhesion forces occurring between gold contacts as reported in the literature. The area just to the right of the minimum contact force line and just above the minimum opening force line is classified by the authors as the "optimum design region," i.e., the forces are large enough for providing with sufficient contact reliability, but the actuator is definitively not yet "oversized," which is the case for switch designs more to the right in the safe design region. The resistance of gold microcontacts corresponding to the contact force is plotted above the diagram for two different studies as reported in the literature [2], [9].

The six switch designs which are discussed in this section and listed in Table V are also plotted in the opening-force/contact-force diagram of Fig. 9. The switch designs (a), Analog Devices/Radant MEMS, and (b), HRL, are less suitable for pure gold contacts but surely suitable for harder materials, since they develop relatively low opening forces. Out of the conventional switch designs, only (c), the OMRON switch, offers an opening force large enough for reliable separating pure gold contacts, achieved at the cost of an "oversized" actuator with a for a MEMS switch extremely large contact force. The table also contains information on the unpackaged area of the switches. The OMRON switch is by far the largest one, but achieves the largest contact and opening forces at a much lower actuation voltage as compared to the other designs. The novel microswitch designs presented in this paper, (d1)–(d3), come quite close to the optimum design region even though the contact force, found to be sufficiently large for metallic switching behavior, should have been designed in the range of 50–100 μN instead of 15–30 μN, for better resistance to surface contamination. Improvement is possible by increasing the cantilever stiffness, e.g., which does not substantially decrease the opening force, since the opening force is by far larger than its counteracting spring force.

VI. Unintentional Opening and Closing Due to External Mechanical Excitation

Due to the the relatively small spring constants of the long and thin cantilevers (see Table V), the presented switch design is potentially more susceptible to unintentional opening and closing due to external vibration induced forces, which is especially critical for excitation sources close to the mechanical resonance frequencies of the cantilevers.

A. Mechanical Stability in the On-State

For the interlocked state, the first mode resonance frequencies of the 400 $\mu\mathrm{m}$ long cantilevers were calculated to 71.1, 85.6, and 100.9 kHz for designs I, II, and III, with a total cantilever thickness of 3.6, 4.1, and 4.6 $\mu\mathrm{m}$, respectively [27, p. 108, one side clamped, one side pinned cantilever support]. [3]

To study the mechanical stability of the latched hooks, it has to be investigated whether it is possible for an external excitation to develop a separation force on the pinned suspension which is larger than the interlocking spring force of the cantilever.

The maximum deflection of a clamped-pinned supported cantilever when applying a single external force in the middle of the cantilever is calculated by

$$y_{\max} = \frac{1}{24\sqrt{2}\sqrt{5}}\frac{F_{\mathrm{ext}}L^3}{EI} \tag{2}$$

with E, I, and L the Young's modulus, moment of inertia, and length of the cantilever, and F_{ext} the external force (SI units apply) [28, Table 8.1, case 1c]. Furthermore, the force at the pinned anchor counteracting the external force imposed at the middle of the cantilever is given to $F_{\mathrm{pin}} = 5/16F_{\mathrm{ext}}$. Converting this equation and inserting it into (2), results in the following expression for the maximum cantilever deflection as a function of the reacting force on the pinned suspension as a result of the external force:

$$y_{\max} = \frac{\sqrt{2}}{15\sqrt{5}}\frac{F_{\mathrm{pin}}L^3}{EI}. \tag{3}$$

Using this formula it can be found that the force at the pinned anchor would exceed the switch latching force when the middle of the cantilever is deflected by 2.9, 2.8, and 2.7 $\mu\mathrm{m}$ for design I with a contact force of 15 μN, design II with 22 $\mu\mathrm{m}$, and design III with 31 μN, respectively (prestress of the predeflected cantilever not taken into account). Since the hook interlocking point of the prototype switches is designed to occur at a distance less than 0.5 $\mu\mathrm{m}$ from the position where the cantilever touches the first stopper (Fig. 8), such large additional deflections or vibration amplitudes and thus the separation of the latched hooks are prevented by the stoppers along the curved electrode.

B. Mechanical Stability in the Off-State

The first mode resonance frequencies of the 400 $\mu\mathrm{m}$ long, noninterlocked cantilevers are 16.2, 19.5, and 22.0 kHz for designs I, II, and III, respectively [27, p.108, clamped-free cantilever configuration].

Similar to the conventional switch concept, unintentional closing of the switch contacts due to external mechanical shock is not prevented by the switch geometry. However, the development of a large amplitude in the resonance case can be prohibited in the novel switch concept by placing stoppers on the opposite side of the curved electrode, with the distance between the cantilever and the stoppers being smaller than the distance between the two cantilever tips in the off-state.

Most conventional switch designs have spring constants of 15–40 Nm^{-1} and a contact separation of typically 3 $\mu\mathrm{m}$ in the off-state [10, Sec. 2.9]. The much smaller spring constants of 3–7 Nm^{-1} of the prototype designs are somehow compensated by the safety margin provided by the larger distance between the cantilever tips. Moreover, the design can be improved by increasing the cantilever stiffness, which also results in a larger contact force without substantially decreasing the large opening force, as mentioned in Section V.

VII. Conclusion

This paper reports on a novel metal-contact switch concept with a large active opening force and a passive contact force which makes this concept very suitable for soft-metal contact materials. Mechanically bi-stable switches based on

[3] Pinned means no displacement, but rotation allowed, with the boundary conditions $y = \partial^2 y/\partial x^2 \equiv 0$. These are the appropriate boundary conditions modeling the joint between the two hooks.

laterally moving, electrostatically actuated curved-electrode actuators have been fabricated by a silicon-on-glass process. The switches have been evaluated by simulations and measurements and were compared in their contact-force/opening-force performance to conventional, electrostatically actuated MEMS switch designs. The novel switches have been found to be very suitable for soft-metal contact materials because of their potentially very large opening force of up to 2.18 mN, which is large enough to break the adhesion force between gold contacts, and since their passive contact force of 15–31 μN is, though rather on the lower side, still large enough to establish a stable contact resistance between the sputtered gold contacts.

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