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A resettable polysilicon MEMS-based circuit breaker

Abdurrashid Hassan Shuaibu^{*} , Almur A S Rabih, Yves Blaqui re and Frederic Nabki

Department of Electrical Engineering,  cole de Technologie Sup rieure, Universit  du Qu bec, Montr al, QC H3C 1K3, Canada

^{*} Author to whom any correspondence should be addressed.E-mail: abdurrashid-hassan.shuaibu.1@ens.etsmtl.ca**Keywords:** microelectromechanical systems (MEMS) switch, microbreaker, on–off actuator, electrostatic, thermal actuator

Abstract

This work presents a novel resettable microelectromechanical systems-based circuit breaker (MCB) that utilizes electrostatic actuation for switching and Joule heating for reset functionality. The device integrates a dual air gap and a straight beam suspension structure to enhance contact force, reduce resistance, and improve switching efficiency. Fabricated using the PolyMUMPs process, the MCB features a polysilicon microbridge that achieves stable contact at an electrostatic actuation voltage of approximately 75 V. The circuit-interruption threshold was experimentally determined to be 14–17 mA. Experimental results further validate that the device achieves an average single contact resistance of 162.5 Ω , and a total MCB resistance of 325 Ω , demonstrating its suitability for current-limiting and protection applications.

1. Introduction

While electronic systems continue to evolve toward greater integration, miniaturization, and complexity, conventional circuit protection technologies such as electromechanical relays (EMRs) and solid-state relays (SSRs) are increasingly unable to meet the requirements of next-generation applications [1, 2]. EMRs provide high current handling capability and robust galvanic isolation; however, they suffer from large form factors, mechanical wear, and slow switching speeds [3]. In contrast, SSRs offer fast response and long operational lifetimes due to the absence of moving parts, but they introduce continuous conduction losses, thermal management challenges, and limited electrical isolation arising from leakage currents and susceptibility to voltage transients [4, 5]. These limitations become particularly critical in compact, thermally constrained, and energy-sensitive systems.

To overcome these challenges, microelectromechanical systems (MEMS) switches have emerged as a promising alternative, offering a pathway to bridge the gap between EMRs and SSRs. MEMS switches employ micromachined contacts to physically interrupt the current path, thereby providing true galvanic isolation in the OFF-state while maintaining extremely low leakage currents. Their compact footprint and fast switching characteristics make them well suited for integration into space-constrained electronic systems [6–10]. By combining the speed and scalability of semiconductor devices with the air-gap isolation of mechanical systems, MEMS switches offer a compelling platform for next-generation switching applications [11–15].

Despite these advantages, achieving reliable MEMS switching remains challenging due to issues such as stiction, contact degradation, elevated contact resistance, and the difficulty of implementing repeatable reset mechanisms [16–19]. Among these, stiction—arising from surface forces, electrostatic effects, and interface roughness—remains a dominant reliability concern, often leading to contact welding, incomplete release, and performance degradation over repeated cycles. These challenges become even more critical when extending MEMS switching concepts toward circuit protection applications, where stable latching, controlled interruption, and reliable reset under electrical load are required.

Various approaches have been proposed to mitigate stiction in MEMS switches, including multi-contact geometries, dual-gate actuation schemes, and thermally assisted recovery mechanisms [16, 19–25]. For example, electrostatic recovery techniques using opposing gate electrodes have been shown to

improve release reliability, while micro-heater-based approaches enable localized thermal actuation to overcome adhesion forces [17, 26].

In this context, MEMS-based circuit breakers (MCBs) have been explored as an extension of MEMS switching technology for low-power protection systems. Unlike conventional MEMS switches, MCBs must not only establish reliable contact but also support controlled interruption and reset under electrical load conditions. Early work in [27] demonstrated a thermally actuated MEMS breaker capable of handling trip currents up to 300 mA. Subsequently, [28] proposed a compact MEMS circuit breaker combining electrostatic actuation with thermal reset, achieving fast switching and low static power consumption. However, these approaches remain limited by restricted current handling capability, sensitivity to fabrication-induced variability, and the need for precise thermal control to ensure consistent reset behavior.

While stiction is traditionally treated as a failure mechanism, recent perspectives suggest that it can be intentionally exploited as a functional feature in MEMS devices. In particular, adhesion can serve as a passive latching mechanism, enabling stable contact without continuous power consumption [29]. This concept opens new opportunities for developing energy-efficient MEMS-based circuit protection devices.

Motivated by these challenges and the limited number of reported MEMS circuit breakers, this work presents a resettable polysilicon MEMS circuit breaker fabricated using the commercial PolyMUMPs surface micromachining process. The proposed device combines electrostatic actuation for low-power contact closure with a Joule-heating-based thermal mechanism for controlled reset. A dual-gap contact configuration and straight-beam suspension are employed to improve alignment, enhance contact force, and mitigate stiction while reducing ON-state resistance.

The proposed device demonstrates a proof-of-concept resettable polysilicon microbreaker for low current microsystem protection. With further reduction of its ON-state resistance, it has potential to evolve into a general purpose low voltage DC power line breaker.

2. Design and simulation

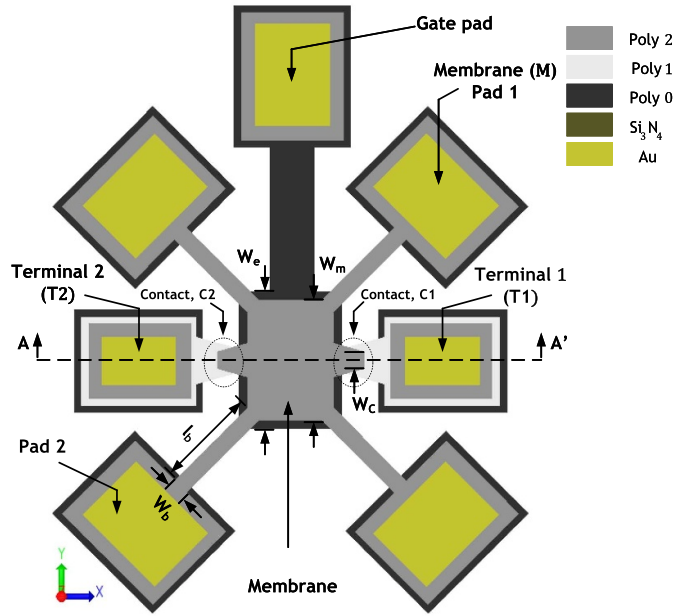
2.1. Design and operating principle

The MCB architecture follows a four-terminal (4-T) configuration, comprising terminal 1 (T1), terminal 2 (T2), membrane (M) and gate (G). Figure 1(a) presents a 2D schematic top-view of the MCB device. It consists of a rectangular membrane ($70\mu\text{m} \times 50\mu\text{m}$) supported at its corners by four beam springs, with dimensions of $50\mu\text{m} \times 10\mu\text{m}$. This membrane is made of $1.5\mu\text{m}$ -thick polysilicon (Poly2), and is positioned above the bottom gate. The gate is formed using the first $0.5\mu\text{m}$ -thick polysilicon layer (Poly0), and is directly anchored to the substrate through an insulating silicon nitride (Si_3N_4) layer. T1 and T2 are formed using the second $2\mu\text{m}$ -thick polysilicon layer (Poly1), and extended as a protruding cantilever beneath the suspended membrane to enable switching operations. To enable out-of-plane transduction, the actuation air gap (g_o) and the contact air gap (g_c) are designed to be $2.75\mu\text{m}$ and $0.75\mu\text{m}$ across, respectively. These vertical gap separations are defined by lithographically patterned phosphosilicate glass (PSG) sacrificial layers during fabrication.

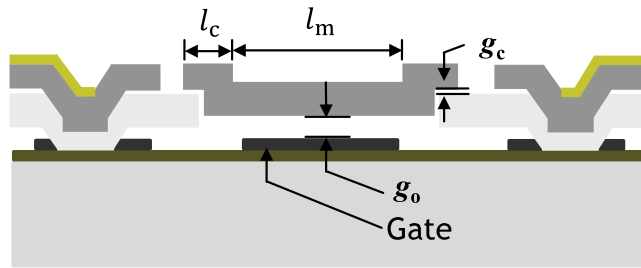
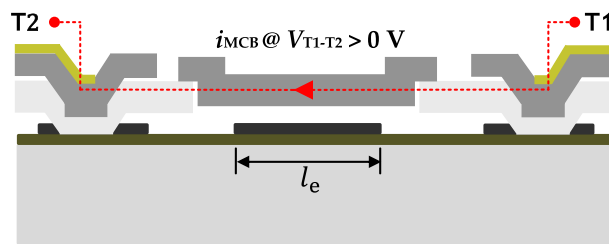
Figure 1(b) shows the schematic cross-sectional view of the MCB. The terminals are patterned and isolated by anchoring them on the Si_3N_4 insulating layer stacked onto the substrate. Accordingly, all of the anchored mechanical pads are electrically isolated from each other to avoid electrical interference. The gate and the suspended membrane structure form an electrostatic closing-gap actuator, which pulls the tip of the membrane into contact with T1 and T2 to provide a conducting path to the MCB current.

Upon application of a gate-to-membrane bias voltage (V_{GM}), an electrostatic force is generated between the gate and the membrane. This force pulls the membrane downward, closing gap g_c , and thereby establishing an ON-state (i.e. closed condition). Consequently, the MCB current (I_{MCB}) flows between T1 and T2, as illustrated in figure 1(c). The specific voltage at which this contact occurs is defined as the closing voltage (V_C). To turn off the MCB, V_{GM} is gradually reduced, weakening the electrostatic attraction. Once the mechanical restoring force of the membrane exceeds the diminishing electrostatic force, the membrane retracts and separates from both contact terminals. This restores the open gap and interrupts current flow, thereby returning the device to its OFF-state. The voltage at which this separation occurs is referred to as the opening voltage (V_O). In this state, the device maintains negligible leakage current due to true galvanic isolation between terminals T1 and T2.

To enhance the contact force, an overdrive voltage defined as the voltage beyond V_C can be applied, thereby resulting in reducing the C1 and C2 contact resistances, at the interface between the membrane



(a) Top view

(b) Cross-section A–A' in the open state with $V_{GM} = 0$ V (not to scale)(c) Cross-section A–A' in the ON-state with $V_{GM} \geq V_C$ (not to scale)**Figure 1.** Device structure, cross-sections, and operating mechanisms of the proposed MCB.

and T1 and T2, respectively. To achieve this, V_{GM} can be increased to values near that of the g_o gap pull-in voltage ($V_{pull-in}$), as defined by:

$$V_{pull-in} = \sqrt{\frac{8kg_0^3}{27\epsilon_0 A}}, \quad (1)$$

where k is the stiffness of the beams used to suspend the membrane, g_o is the initial gap between the membrane and the gate, ϵ_0 is the permittivity of the air and A is the overlap area between the membrane and gate. The design parameters of the MCB proposed in figure 1 are summarized in table 1.

Table 1. Geometry parameters of the switch.

Parameter	Symbol	Value (μm)
Membrane length	l_m	70
Membrane width	w_m	50
Beam length	l_b	50
Beam width	w_b	10
Gate length	l_e	80
Gate width	w_e	80
Contact width	w_c	10
Contact length	l_c	10
Membrane-to-gate separation gap	g_o	2.75
Membrane-to-terminal separation gap	g_c	0.75
Membrane thickness	t_{Poly2}	1.5
Gate thickness	t_{Poly0}	0.5

The stiffness of the four beams used to support the membrane can be estimated as

$$k_{\text{eff}} \approx \frac{4Et_{\text{Poly2}}^3 w_b}{l_b^3}, \quad (2)$$

where E is the Young's modulus of the structural material, t_{Poly2} is the beam thickness, and w_b and l_b are the width and length of the supporting beams, respectively.

The electrostatic force F_e required to overcome the mechanical restoring force F and close the contact is related to the driving voltage using [30]:

$$F_e = \frac{1}{2} \frac{\epsilon_0 A V_C^2}{(g_o - z)^2}, \quad (3)$$

where z is the downward displacement of the membrane toward the gate, due to voltage $V_{\text{GM}} = V_C$. The mechanical restoring force F depends only on z and k as shown in:

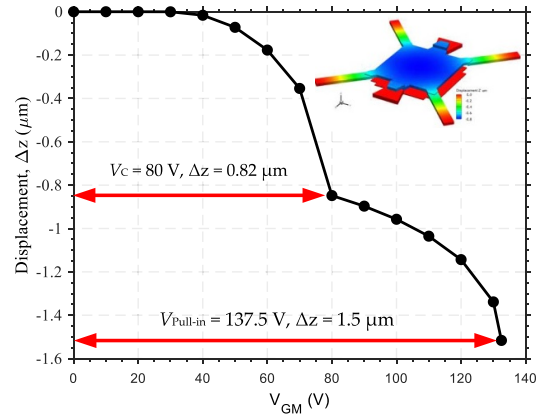
$$F = -kz. \quad (4)$$

When sufficient V_{GM} is applied between the membrane and the gate, the membrane is pulled into contact with the T1 and T2 terminals. Due to the designed geometry and material interfaces, the adhesion between the membrane and the terminals exceeds the restoring force of the bent suspension beams. This adhesion is primarily attributed to the inherent stiction characteristic of the PolyMUMPs fabrication process [31]. The resulting mechanical latching ensures that the contact remains closed even after the V_{GM} voltage source is disconnected, thereby enabling non-volatile switching without continuous power consumption, an essential feature for energy-efficient systems. The contacts remain closed until the operating current exceeds a certain threshold. Beyond that threshold, the current generates sufficient heat to release the membrane and open the switch.

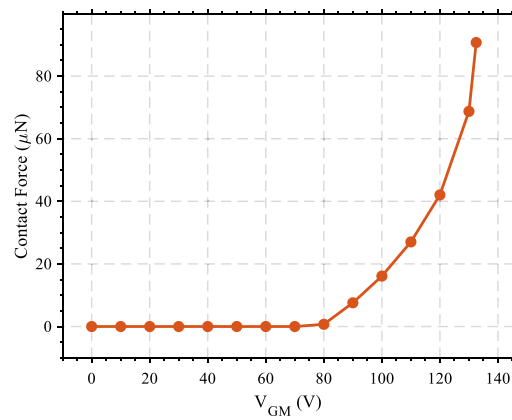
Although both T1 and T2 and all four anchors of the membrane are electrically shorted in the ON-state, the device operates as a normally open single-pole single-throw switch. The gate-membrane actuation path remains electrically isolated from the conduction path (T1–T2), allowing for a safe power transfer between T1 and T2. In this design, stiction is deliberately harnessed to achieve a stable and persistent ON-state, transforming a typical reliability concern into a functional advantage.

2.2. FEA simulation

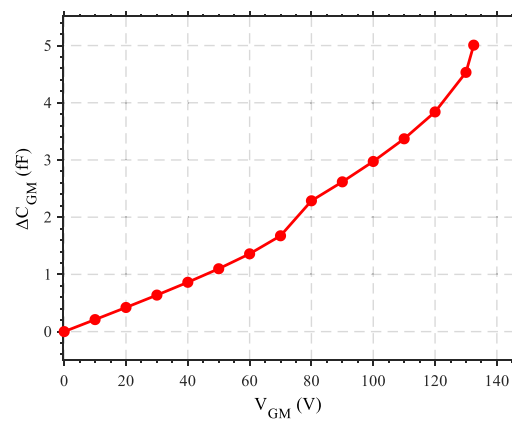
The electromechanical performance of the MCB was analyzed using CoventorWare 11.1 (Coventor, Raleigh, NC, USA), a finite element method simulation tool, utilizing the CoSolveEM and MemMech finite element analysis (FEA) suites. Figure 2(a) illustrates the displacement behavior of the device during actuation, showing both the V_{GM} required to close the contact gap and the pull-in state where the restoring force is insufficient to counteract the electrostatic attraction. V_{GM} was increased from 0 V to 140 V in 10 V steps, to find the voltage required to close the contact in addition to finding the $V_{\text{pull-in}}$. The simulated V_C , was found to be 80 V with the displacement equal to 0.82 μm . Beyond the contact closure, the displacement curve has changed due to the increase of the total membrane stiffness caused by the connected T1 and T2 terminals. As such, the $V_{\text{pull-in}}$ was extended to 137.5 V with a maximum traveled displacement of 1.5 μm , as confirmed by the figure 2(a). The simulated $V_{\text{pull-in}}$ voltage of



(a) Membrane displacement



(b) Contact force



(c) Gate-membrane capacitance change

Figure 2. Finite element modeling simulation of the microbreaker according to an increase of the bias voltage V_{GM} .

137.5 V provides an overdrive margin of 57.5 V relative to the initial contact closure voltage. As shown in figure 2(b), the electrostatic force at pull-in reaches approximately 90 μN .

Figure 2(c) shows the extracted gate-membrane capacitance change (ΔC_{GM}) of the MCB as a function of V_{GM} . The value of ΔC_{GM} in the closed state was determined to be low with a maximum value of 2.2 fF at V_C , whereas at the $V_{\text{pull-in}}$, ΔC_{GM} reached approximately 5 fF. This is recorded with regard to the initial static capacitance of ≈ 11 fF. The measured ΔC_{GM} could be used to track the displacement of

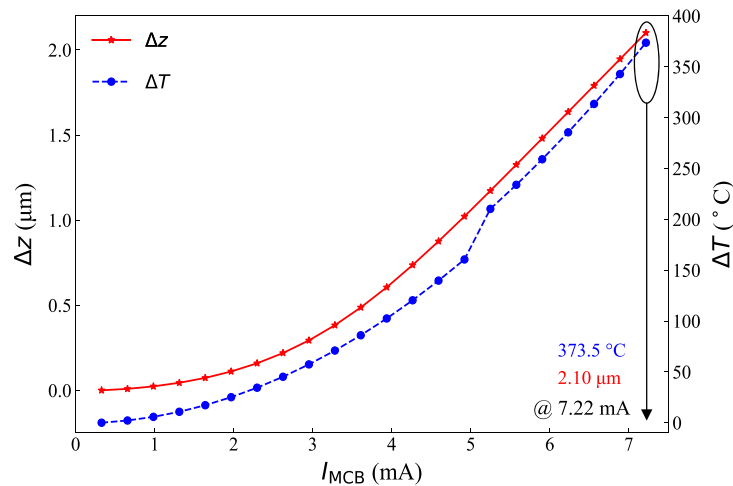


Figure 3. Simulated upward displacement (Δz) and corresponding temperature rise (ΔT) as functions of current flowing through Pad 1 and Pad 2 path shown in figure 1(a).

the membrane and therefore it could be used to calibrate the MCB. In addition, the capacitance variation could also serve as an indicator to measure the life-time of the device.

Additional electro-thermal simulations were performed using the Pad 1–Pad 2 current path shown in figure 1(a) to illustrate the underlying thermo-mechanical release mechanism in a simplified and well-controlled configuration. In this case, a current of approximately 7.22 mA produces a temperature rise of about 373.5 °C, corresponding to an upward displacement of 2.10 μm , as shown in figure 3. Although the heating distribution differs from the localized contact heating associated with T1–T2 excitation, both configurations rely on the same physical mechanism, namely thermally induced upward membrane deformation that weakens adhesion and promotes release. Accordingly, these simulations are intended to demonstrate the direction, magnitude, and thermal origin of the reset-driving deformation, rather than to reproduce the exact localized heating conditions at the contact interface.

3. Microfabrication

The MCB devices were fabricated using the Polysilicon based Multi-User MEMS process (PolyMUMPs) provided by Science Corp., Alameda, California, USA) [32]. This surface micromachining process includes three layers of polysilicon heavily doped with phosphorus in a standard diffusion furnace using a PSG sacrificial layer as a dopant source.

Figure 4(a) illustrates the isometric 3D view and figure 4(b) depicts the cross-sectional view of the fabrication process, highlighting the six key steps involved in the device fabrication process. The process begins with a 100 mm n-type (100) silicon wafer with a resistivity of 1–2 $\Omega\cdot\text{cm}$, covered with a blanket layer of 600 nm thick of Si_3N_4 , which serves as an electrical insulating layer between polysilicon layers and the substrate. The gate and the electrical routing signals are formed by lithographically patterning a 500 nm-thick polysilicon layer (Poly0) deposited by low pressure chemical vapor deposition (LPCVD) and patterned by reactive ion etching (RIE), as shown in figures 4(b) and (I). After the unwanted polysilicon layer is removed from the Poly0, a blanket layer of thick 2 μm , PSG) is deposited on the structure using LPCVD as the first sacrificial layer, which helps to define the actuation gap. The deposited layer is annealed @1050 °C for 1 h in argon. The first sacrificial layer is patterned (figure 4(b)(II)) to define the etch holes down to Poly0 to open windows for the mechanical anchoring of T1 and T2. This Poly0 has a sheet resistance in the range of 15–45 Ω/square [32].

The protruded cantilever structure for the T1 and T2 uses the second polysilicon layer (Poly1) with a thickness of 2 μm . Poly1 is again coated with photoresist, patterned, and etched to remove the unwanted Poly1 layer on top of the sacrificial layer (see figure 4(b)(III)). The sheet resistance of Poly1 is in the range of 1–20 Ω/square [32]. The second sacrificial layer comprising PSG with a thickness of 0.75 μm is then deposited on top of the structure to define the contact gap. This second oxide layer is patterned using the Poly1_Poly2_VIA level mask, forming etch holes down to the Poly-1 layer and providing a mechanical and electrical connection between the Poly1 and Poly2 layers at the anchoring terminals. Subsequently, the oxide is lithographically patterned and RIE-etched as illustrated in figure 4(b)(IV).

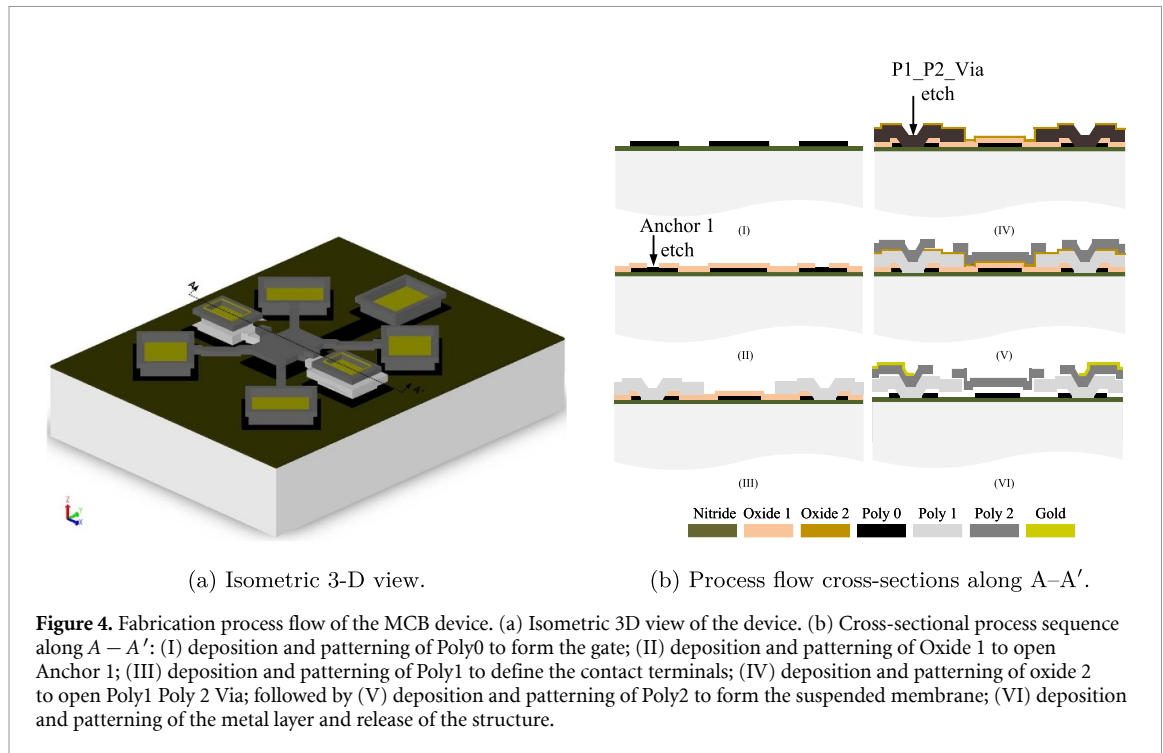


Figure 4. Fabrication process flow of the MCB device. (a) Isometric 3D view of the device. (b) Cross-sectional process sequence along A – A': (I) deposition and patterning of Poly0 to form the gate; (II) deposition and patterning of Oxide 1 to open Anchor 1; (III) deposition and patterning of Poly1 to define the contact terminals; (IV) deposition and patterning of oxide 2 to open Poly1 Poly 2 Via; followed by (V) deposition and patterning of Poly2 to form the suspended membrane; (VI) deposition and patterning of the metal layer and release of the structure.

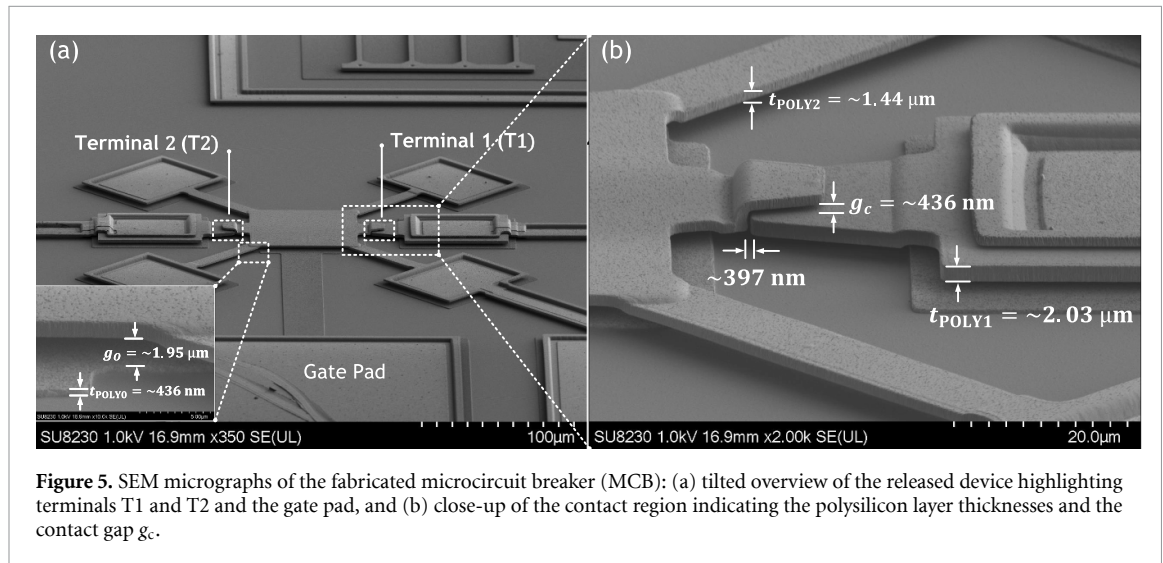


Figure 5. SEM micrographs of the fabricated microcircuit breaker (MCB): (a) tilted overview of the released device highlighting terminals T1 and T2 and the gate pad, and (b) close-up of the contact region indicating the polysilicon layer thicknesses and the contact gap g_c .

The third polysilicon layer (Poly2) with a thickness of $1.5 \mu\text{m}$ is then deposited on the structure by LPCVD, as shown in figure 4(b)(V), to pattern the suspended membrane. This layer has a sheet resistance of $10\text{--}30 \Omega/\text{square}$ [32]. The final deposition step is a deposition of a $0.5 \mu\text{m}$ -thick gold (Au) metal layer to define the bonding pads and electrical routing. Following the metal deposition, patterning is achieved using liftoff.

Due to the conformal type of deposition, the gap g_o that separates the gate (Poly0) and the membrane (Poly2) is defined by both sacrificial layers. Therefore, $g_o = 2.75 \mu\text{m}$, whereas g_c between the terminals and the membrane is defined only by the second sacrificial layer, as such $g_c = 750 \text{ nm}$. The final release of the MCB device is performed by immersing the structure in 49% hydrofluoric acid at room temperature for up to 2 min, followed by several minutes in DI water and then alcohol to reduce stiction, followed by at least 10 min in an oven at 110°C as described in [32].

Figure 5 presents representative scanning electron microscopy (SEM) micrographs of the fabricated MCB, providing direct verification of the as-fabricated geometry and the vertical clearances defined by the PolyMUMPs process. Figure 5(a) shows a tilted overview of the released device, with terminals T1 and T2 as well as the gate pad clearly identified. Figure 5(b) provides a magnified view of the contact region, highlighting the polysilicon layer thicknesses and the resulting contact gap g_c .

Table 2. Values (μm) of fabricated versus designed parameters.

Parameter	Designed	Fabricated
Poly0 thickness	0.50	0.436
Poly1 thickness	2.0	2.03
Poly2 thickness	1.5	1.44
Actuation gap (g_o)	2.75	1.95
Contact gap (g_c)	0.75	0.436

As summarized in table 2, the gate-to-membrane gap and contact gap were measured to be $g_o = 1.95 \mu\text{m}$ and $g_c = 0.436 \mu\text{m}$, respectively, compared to the designed values of $2.75 \mu\text{m}$ and $0.75 \mu\text{m}$. The reported contact gap was extracted from SEM measurements at the contact tip after release and represents an effective gap rather than the nominal sacrificial oxide thickness. The reduction from the oxide thickness is attributed to residual stress-induced membrane curling and local geometric non-idealities, such as step coverage and edge effects, which decrease the vertical separation at the contact interface, as reflected in table 2.

4. Measurement results

The characterization of the fabricated MCBs was carried out using two test setups. First, its electromechanical characterization was evaluated, including the optical characterization to determine the actuation voltage required for ON/OFF operation based on the displacement of the suspended membrane as a function of the applied voltage (V_{GM}). Second, the electrical performance of the device was assessed, which involved measuring the MCB resistance (R_{MCB}) under direct contact conditions with high-voltage actuation applied between the gate and the membrane to establish a strong ohmic contact, then passing (I_{MCB}) between T1 and T2. Additionally, the thermal tripping and reset behavior of the switch were analyzed to evaluate its performance under thermal stress.

4.1. Electromechanical characterization

The membrane displacement under an applied gate-to-membrane voltage V_{GM} was characterized using an OLS4100 optical microscope (Olympus, Tokyo, Japan) interfaced to a PC running image-processing software, as depicted in figure 6. A programmable DC supply (Tektronix PWS4205, Beaverton, OR, USA) applied V_{GM} and swept it from 0 V to 72 V in 1 V steps. The gate bias was applied through a large current-limiting resistor R_d (hundreds of $k\Omega$) to mitigate current in the event of accidental contact.

Electrical closure and post-closure resistance were measured concurrently using a source-measure unit (SMU) (Keithley SMU, Tektronix, Beaverton, OR, USA), which applied a small sensing voltage V_{sen} between terminals T1 and T2 and measured the corresponding sensing current i_{sen} . A series sensing resistor R_{sen} was included to facilitate current/voltage readout, and an additional resistor was placed between the membrane and ground to enable extraction of the membrane resistance R_m together with the contact resistance R_c . This network was designed to satisfy $R_d \gg R_c, R_{sen}, R_m$, ensuring that the T1-T2 sensing current does not leak to ground through the membrane. As illustrated in figure 6(a), the contacts are open at $V_{GM} = 0$. When V_{GM} reaches the pull-in (contact-closure) voltage V_C (figure 6(b)), the contacts close and i_{sen} flows from T1 to T2 through the contact resistance R_c (and the membrane path characterized by R_m).

The contact-closure voltage V_C , determined by optical inspection, was measured to be approximately 55 V, which is lower than the nominal design value of 75 V. This reduction is attributed to fabrication-induced variations, including membrane-thickness nonuniformity and stress gradients in the suspension beams that lead to post-release gap variations, which modify the effective stiffness and the electrostatic gap. Figures 7(a) and (b) show SEM micrographs of the device in the open and actuated (i.e. closed/ON) states, respectively. Although the applied bias was sufficient to reach the intended closure regime, the contact remained only partially closed, with a residual tip separation of approximately 100 nm.

This residual separation prevented the formation of a true ohmic interface and therefore precluded a reliable extraction of the ON-state resistance. Further increasing V_{GM} beyond V_C (overdrive) did not produce additional displacement of the protruded cantilever contact structure. Instead, the membrane exhibited significant out-of-plane deformation near its center, consistent with global curvature/curling,

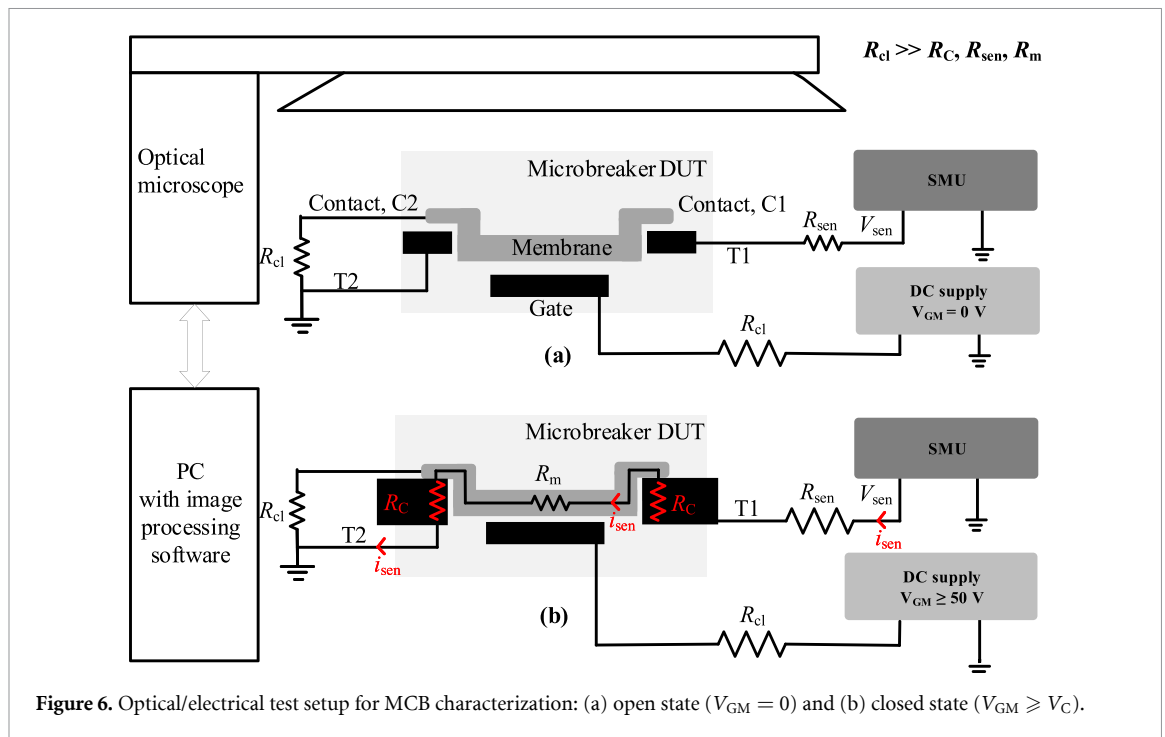


Figure 6. Optical/electrical test setup for MCB characterization: (a) open state ($V_{GM} = 0$) and (b) closed state ($V_{GM} \geq V_C$).

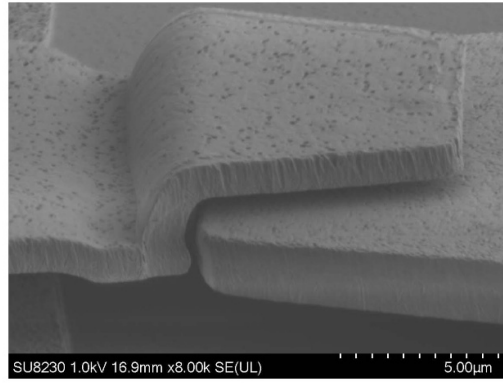
which effectively lifted or detached the switching contact and reopened the interface. Optical inspection revealed a parabolic membrane profile with maximum curling near the center, consistent with the persistence of a > 100 nm gap even at biases exceeding the pull-in threshold. The height profiles in figure 7(c) corroborate this interpretation by indicating that the actuation is dominated by central membrane deflection rather than additional tip closure at the contact.

To further analyze this behavior, an optical surface scan was performed along the $X - X'$ axis of the fabricated device, as shown in figure 7(c). A baseline topography was first acquired at $V_{GM} = 0$ V to establish the OFF-state reference. The actuator was then biased to the measured closure voltage, $V_C 55$ V. At this bias, the vertical displacement at the contact tip, referenced to a fixed point on the substrate, was 819 nm, whereas the displacement at the membrane center was 750 nm relative to the same reference. The resulting mismatch implies a residual tip-to-center separation of approximately 69 nm, indicating that contact initiation is localized near the periphery rather than forming a uniform interface across the contact area. Increasing V_{GM} beyond V_C exacerbated membrane curling and led to an unintended reopening of the MCB, preventing a stable latched state. This difficulty in establishing a repeatable ohmic contact is attributed primarily to: (i) residual stress effects that degrade contact engagement; (ii) insufficient membrane rigidity, which increases susceptibility to out-of-plane deformation and buckling; and (iii) surface nonidealities in the contact region that hinder uniform electrical conduction.

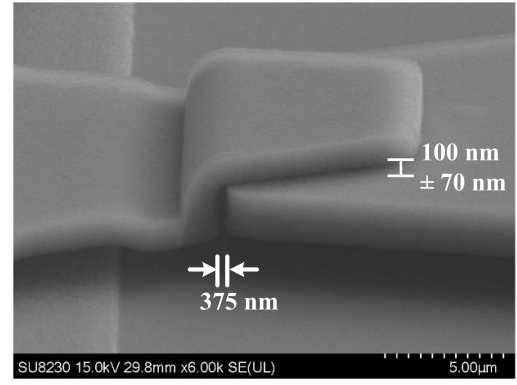
Simulation results corroborate this interpretation. As V_{GM} exceeds 75 V, the membrane curvature increases: at moderate overdrive it can assist contact formation, whereas at higher bias it promotes tip-edge buckling and inhibits full latching, leaving a residual gap of approximately 360 nm, as illustrated in figures 8(a) and (b). The extracted simulated displacement profile along the x -axis is shown for the open state, the first-contact (near-threshold) closed state, and an overdriven condition, highlighting that near pull-in the membrane can detach further, producing a gap on the order of 500 nm with only partial tip contact. In addition, step coverage and the protruded contact cantilever introduce a lateral offset of approximately 397 nm, which can further impede full-area contact and aggravate membrane buckling.

4.2. Current–voltage curve and contact resistance measurement

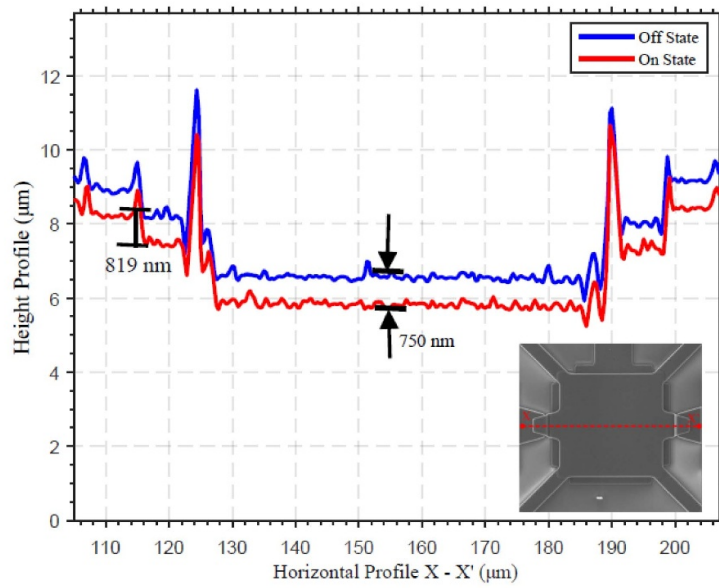
As discussed above, the applied voltage reached the threshold required for contact closure; however, a residual gap persisted, preventing the formation of an optimal ohmic contact. To promote full engagement in the ON-state, the switching interface was therefore driven with a higher electrostatic actuation voltage, typically in the range of 75 V, as suggested by the $V_{pull-in}$ simulations, to ensure latching down of the membrane. In the configuration shown in figure 9, the membrane pad was grounded, while both T1 and T2 were connected to the high-voltage DC supply.



(a) Open state.



(b) Actuated state showing a residual tip gap.



(c) Height profile along the X-X' cross section in the open (Off) and closed (On) states.

Figure 7. Mechanical characterization of the fabricated MCB.

A large current-limiting resistor R_d was inserted in series between the high-voltage DC supply and terminals T1/T2 to protect the MCB during electrostatic actuation, as shown in figure 9(a). Upon actuation, as shown in figure 9(b), the contacts engaged and remained latched due to adhesion/stiction forces typical of PolyMUMPs-based structures. When the adhesion force at the contact interface exceeded the restoring force of the suspended membrane, the contacts remained engaged after the high-voltage supply was disconnected, thereby maintaining a stable ON-state without continuous bias.

After mechanical stabilization, the SMU was used to characterize the electrical resistance with a low sensing voltage V_{sen} and a series sensing resistor R_{sen} , as illustrated in figure 9(c). The measured resistance of the closed device is given by:

$$R_{MCB} = R_m + 2R_c, \quad (5)$$

$$R_c \approx R_{MCB}/2 = 162.5 \Omega. \quad (6)$$

where R_m is the membrane resistance and R_c is the resistance of a single contact interface. The current-voltage ($I - V$) characteristics were obtained by forcing a compliance-limited test current of $100 \mu A$

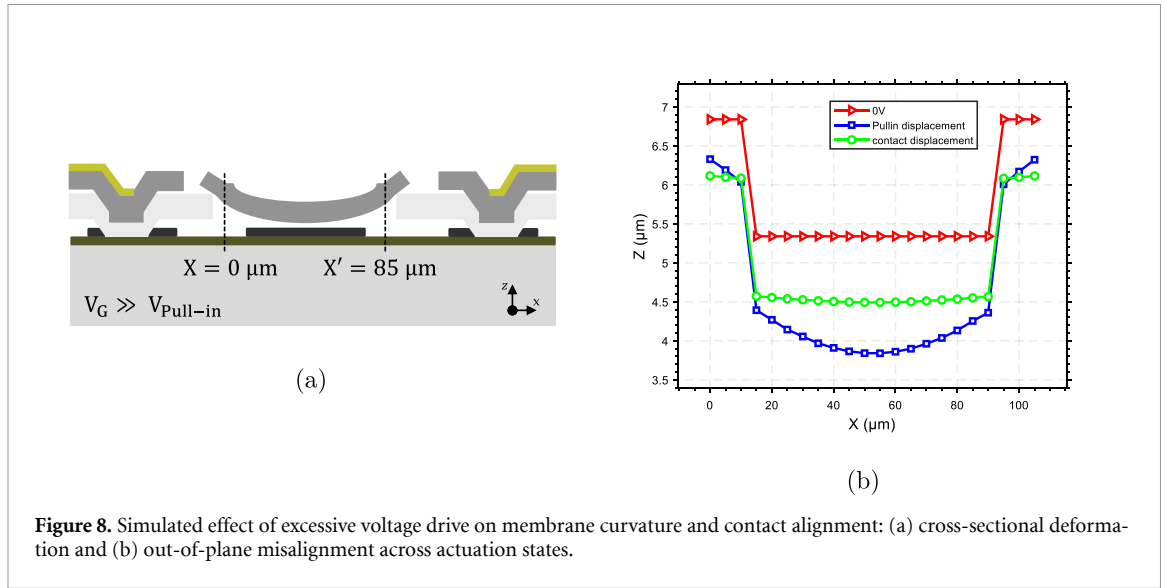


Figure 8. Simulated effect of excessive voltage drive on membrane curvature and contact alignment: (a) cross-sectional deformation and (b) out-of-plane misalignment across actuation states.

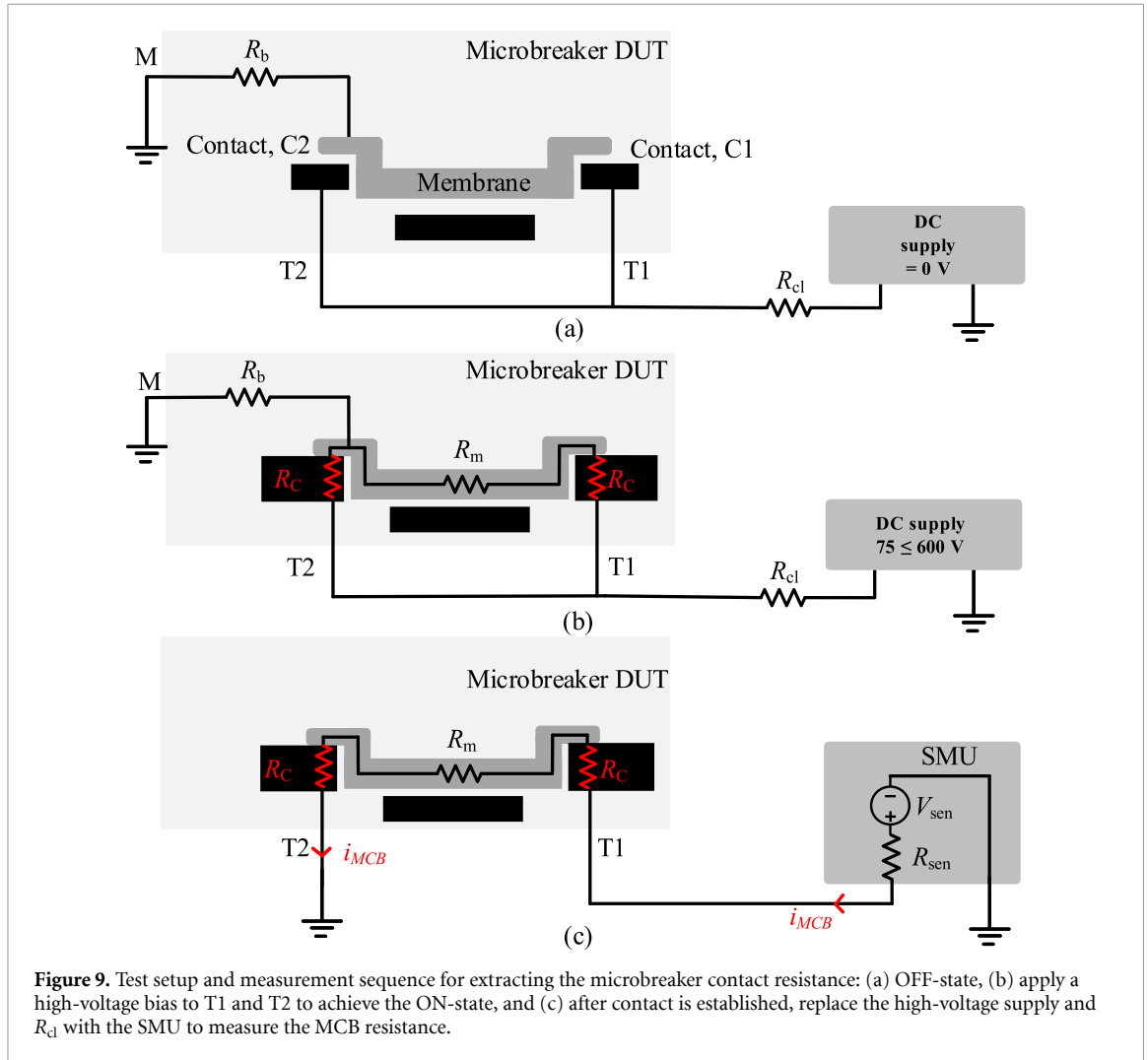


Figure 9. Test setup and measurement sequence for extracting the microbreaker contact resistance: (a) OFF-state, (b) apply a high-voltage bias to T1 and T2 to achieve the ON-state, and (c) after contact is established, replace the high-voltage supply and R_{cl} with the SMU to measure the MCB resistance.

through the series path (including R_{sen} and the closed contact pair). The extracted ON-state resistance was $R_{\text{MCB}} = 325 \Omega$, indicating stable electrical conduction, as plotted in figure 10.

Using a Poly2 sheet resistance of approximately $20 \Omega \text{sq}^{-1}$ and an effective conduction path of ~ 1.4 squares, the membrane resistance is estimated as $R_m \approx 28 \Omega$, which is much smaller than the total measured resistance of 325Ω . This indicates that the ON-state behavior is dominated by a relatively high-resistance polysilicon–polysilicon contact interface, where conduction is limited by constriction

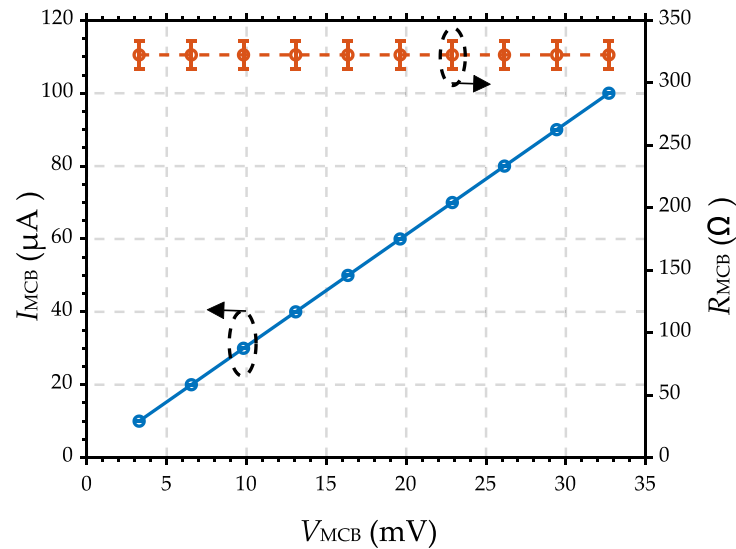


Figure 10. Measured $I - V$ characteristics of the latched microbreaker in the ON-state and the extracted resistance R_{MCB} .

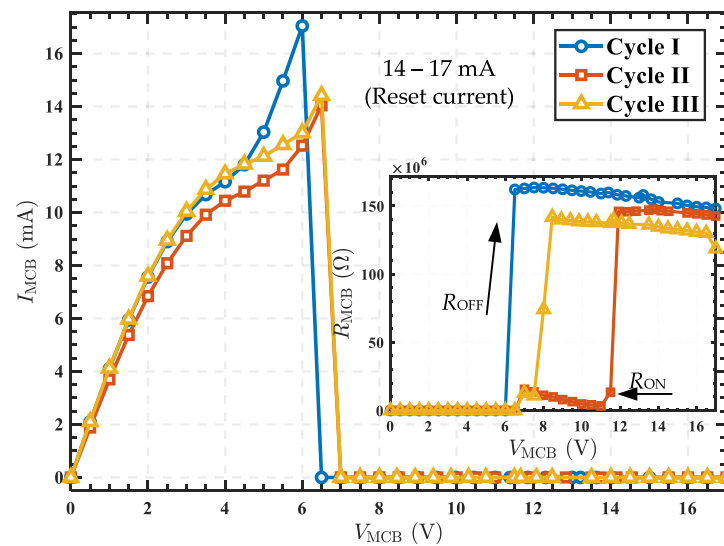


Figure 11. Opening of the microbreaker due to Joule-heating induced by the current in the ON-state. The inset shows a comparison of ON-state and OFF-state MCB resistances.

effects, reduced real contact area, and interfacial surface phenomena. This result is consistent with a low-resistance Si-Si conduction path.

To restore the MCB to the open (OFF) state, Joule heating was induced by increasing the current through T1 and T2 beyond a threshold value. The resulting localized temperature rise at the contact interface reduces adhesion/stiction forces and enables separation of the contacts, thereby resetting the device to the open state. Figure 11(a) shows the switching behavior over three consecutive cycles. The reset current decreases from approximately 17 mA in the first cycle to 15 mA and 14 mA in subsequent cycles. This progressive reduction suggests a contact conditioning effect, likely associated with thermally induced modifications at the interface, such as reduced adhesion strength or slight changes in surface morphology.

In the open state, the device exhibits an isolation resistance on the order of $10^8 \Omega$ (approximately 130–160 M Ω), as shown in the inset of figure 11. This resistance remains relatively stable until the next switching event. It is important to note that this value is limited by the measurement resolution and current compliance of the experimental setup, and therefore represents a lower bound on the intrinsic OFF-state resistance of the device.

Figure 12 shows the measured current I_{MCB} and extracted resistance R_{MCB} as functions of time during a switching event. In the ON-state, the current increases progressively while the resistance remains

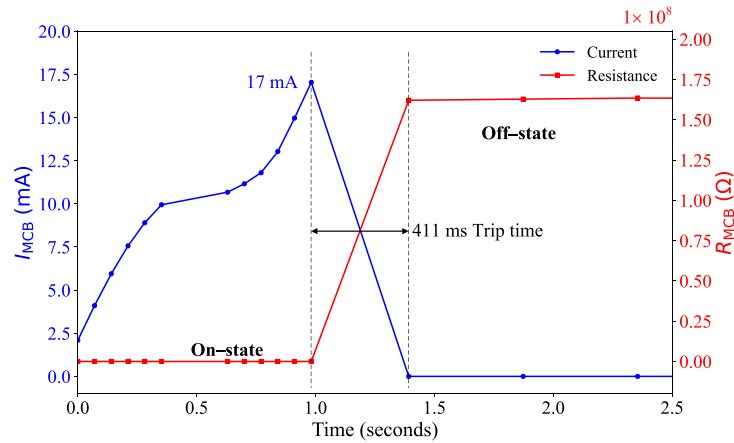


Figure 12. Measured trip transient response of the MCB, showing the temporal evolution of I_{MCB} and R_{MCB} during electrothermal reset due to I_{MCB} .

low, indicating stable conduction. When the current reaches the reset threshold, approximately 17 mA, the device begins to switch: the current rapidly decreases to near zero and the resistance simultaneously rises to the OFF-state value of approximately $10^8 \Omega$, indicating contact separation.

The reset time, defined as the interval between reaching the reset threshold and complete current interruption, is measured to be approximately 411 ms. This response includes the electrothermal delay associated with Joule heating, adhesion weakening, and mechanical separation, confirming effective transition from the conductive ON-state to the insulating OFF-state.

5. Discussion

The proposed MCB demonstrates the feasibility of electrostatically actuated polysilicon devices for compact, low-power circuit protection. The architecture employs a contact gap that is significantly smaller than the actuation air gap, enabling the use of overdrive voltage to increase the contact force at the switching interface. While this approach improves the likelihood of contact engagement, it also introduces a key challenge: achieving a stable, low-resistance ohmic contact when actuation is performed solely through electrostatic gate biasing.

As demonstrated in section 4, applying a high-voltage bias across the contact terminals with effectively zero current compliance promotes mechanical latching and enables a stable electrical connection. The fabricated device achieved an ON-state resistance of approximately 325Ω and could be reset thermally using Joule heating.

The thermal recovery behavior was further supported by a repeatable reduction in the opening current over consecutive cycles. Cycle-to-cycle variations are attributed to contact-surface evolution (e.g. roughness changes and oxidation), as well as thermomechanically induced deformation during heating. Encapsulation and environmental control may improve repeatability by stabilizing the contact chemistry and reducing contamination.

Consistent with the simulated trends in figure 8(b), latching quality degraded when V_{GM} exceeded the closure threshold V_C . The observed behavior indicates that out-of-plane deformation (curling) reduces contact conformity and redistributes the contact force, resulting in partial engagement and an increased likelihood of reopening. In addition, the conformal deposition and step coverage over the protruded cantilever contribute to non-planarity at the interface, further limiting uniform force distribution.

To enable quantitative comparison with the fabricated device, the electromechanical model was re-simulated using the measured gaps ($g_o = 1.95 \mu\text{m}$ and $g_c = 0.436 \mu\text{m}$), replacing the nominal values previously inferred from the sacrificial layer thicknesses ($g_o = 2.75 \mu\text{m}$ and $g_c = 0.75 \mu\text{m}$). Two simulation cases were considered in the displacement–voltage response of figure 13(a): (i) without contact modeling and (ii) with contact detection enabled between the membrane and the T1/T2 contact electrodes. Without contact modeling, pull-in occurs at 51.9 V, with a maximum downward displacement of $-0.71 \mu\text{m}$. When contact detection is included, first contact occurs at 50 V, which is lower than the previously simulated nominal closure voltage of 80 V and close to the experimentally measured value of approximately 55 V. The corresponding downward displacement at this voltage is $-0.452 \mu\text{m}$,

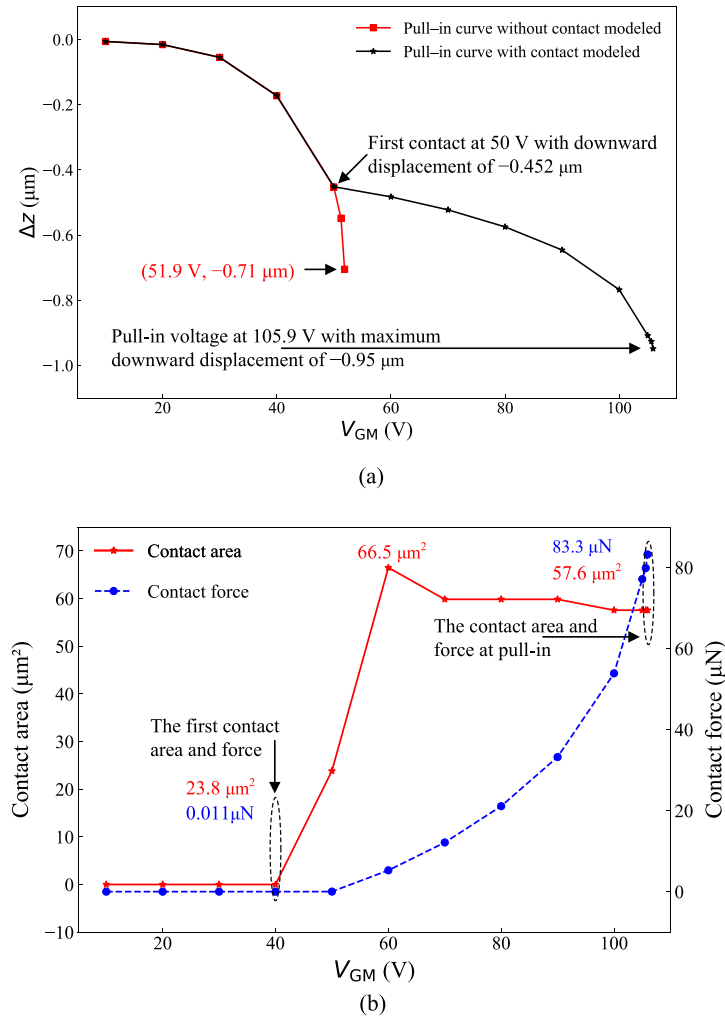


Figure 13. Electromechanical simulation results using the fabricated device dimensions showing (a) the Pull-in displacement of the membrane with and without contact modeling and, (b) the corresponding contact force and contact area as a function of actuation voltage, including an additional pull-in curve without contact interaction between T1/T2 and the membrane.

which agrees closely with the measured contact gap (-0.436 μm) within 3.7%. With contact modeling included, the $V_{\text{pull-in}}$ is extended to 105.9 V, with a maximum downward displacement of -0.95 μm . The corresponding contact area and contact force are shown in figure 13(b). At first contact, the simulated contact area and force are 23.8 μm^2 and 0.011 μN , respectively. As the actuation voltage increases, the contact force increases monotonically, while the contact area first increases to a maximum of 66.5 μm^2 and then decreases due to membrane bending, reaching 57.6 μm^2 at pull-in, where the contact force reaches about 83.3 μN . Using the fabricated geometry, the updated model therefore predicts a closure voltage of approximately 50 V, compared with the measured value of $V_{\text{C}} \approx 55$ V, corresponding to a relative error of approximately 9%.

Table 3 situates this work relative to prior MEMS relays and microbreakers. While metal–metal (predominantly Au–Au) contacts dominate the literature due to their low initial resistance, polysilicon contacts are of interest for robustness and process compatibility in PolyMUMPs. However, polysilicon-based DC contact microbreakers remain underexplored for power switching, largely because stiction and elevated contact resistance complicate reliable operation and scaling. The present results highlight both the opportunity for a fully polysilicon implementation and the remaining limitations that must be addressed.

Future work will focus on three complementary directions. First, dimple (stopper) structures will be integrated beneath the suspended membrane or on the fixed substrate to limit over-travel, prevent inadvertent gate-membrane shorting, and reduce sensitivity to out-of-plane deformation. Second, the contact force will be increased by refining the membrane geometry and the actuation strategy, with the goal of improving contact conformity and reducing the ON-state resistance. Third, an on-chip, self-actuated Joule-heating mechanism will be incorporated to enable rapid MCB reset, leveraging localized thermal expansion to release the interface while minimizing global thermal stress.

Table 3. Comparison of the proposed microbreaker with state-of-the-art MEMS switching approaches.

References	Actuation	Actuation voltage/current	ON-state resistance	Switching time	Leakage current	Contact material	Reset / reopen method
[26]	Electrostatic	20–26 V	—	—	—	Au	Yes (Joule heating)
[27]	Thermal	300 mA	$<1\ \Omega$	$<50\ \text{ms}$	—	Au	Thermal / latching (300 mA)
[28]	Thermal	55 V	$40\ \Omega$	—	—	Au	Thermal / embedded heater (45–55 mA)
[33]	Thermal	0.7 V	$2.6\ \text{k}\Omega$	—	$< 10^{-9}\ \text{A}$	W (90 nm)	No
This work	Electrostatic	55 V	$325\ \Omega$	411 ms	$\sim 10^{-8}$ – $10^{-9}\ \text{A}$	Polysilicon	Yes (Joule heating, 1417 mA)

6. Conclusion

This work presented a resettable MCB fabricated using the commercial PolyMUMPs surface-micromachining process. The device combines electrostatic actuation for low-power switching with a Joule-heating-enabled thermal reset mechanism for contact release. A dual-gap contact configuration and a straight-beam suspension were employed to improve alignment and contact force, reduce the ON-state resistance, and mitigate stiction-related failure modes. While a controlled level of stiction was beneficial for achieving robust mechanical latching in the ON-state, the design incorporated measures to avoid excessive adhesion that would impede thermal reset. The prototype demonstrated a stable ON-state total resistance of $R_{\text{MCB}} = 325\ \Omega$. The fabricated prototype exhibits reliable reset behavior at trip currents ranging from 14 mA to 17 mA, along with a stable ON-state resistance of $325\ \Omega$. The measured reset time is approximately 411 ms, reflecting the electrothermal delay associated with Joule heating, adhesion weakening, and mechanical separation. These characteristics make the device suitable for low-current microsystem protection. This work establishes a foundation for next-generation MEMS-based circuit protection devices, with future improvements aimed at reducing contact resistance and extending applicability to higher-current systems.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Author contributions

Abdurrashid Hassan Shuaibu  0009-0000-7376-0009

Conceptualization (equal), Investigation (equal), Methodology (equal), Resources (equal), Software (lead), Validation (equal), Writing – original draft (equal), Writing – review & editing (equal)

Almur A S Rabih

Conceptualization (equal), Methodology (equal), Supervision (equal), Validation (equal), Writing – original draft (equal)

Yves Blaqui re  0000-0001-6204-7427

Conceptualization (equal), Funding acquisition (equal), Supervision (equal), Validation (equal), Visualization (equal), Writing – review & editing (equal)

Frederic Nabki

Conceptualization (equal), Funding acquisition (equal), Resources (equal), Supervision (equal), Validation (equal), Visualization (equal), Writing – review & editing (equal)

References

- [1] Moore G 1998 *Proc. IEEE* **86** 82–85
- [2] Nobert G, Alameh A H, Ly N, Constantin N G and Blaqui re Y 2021 Towards an LTCC SiP for control system in safety-critical applications 2021 *IEEE Int. Symp. on Circuits and Systems (ISCAS)* (IEEE) pp 1–5 (available at: <https://ieeexplore.ieee.org/document/9401066/>)
- [3] Zheng Z, He Y and Ren W 2022 Switching performance and capability of multiple breaks within electromechanical relays used for power backup application 2022 *6th Int. Conf. on Electric Power Equipment - Switching Technology* pp 166–71 (available at: <https://ieeexplore.ieee.org/document/9757068/>)
- [4] Liu A Y, Xingwen Li B, Lei C W, Zhaozi Zhang D and Gao E C 2024 A review of research progress on low-voltage DC solid-state circuit breakers 2024 *IEEE 10th Int. Power Electronics and Motion Control Conf. (IPEMC2024-ECCE Asia)* (IEEE) pp 3551–6 (available at: <https://ieeexplore.ieee.org/document/10567620/>)
- [5] Rodrigues R, Du Y, Antoniazzi A and Cairoli P 2021 *IEEE Trans. Power Electron.* **36** 364–77
- [6] Maciel B, Majumder S, Lampen J and Guthy C 2012 Rugged and reliable ohmic MEMS switches 2012 *IEEE/MTT-S Int. Microwave Symp. Digest* pp 1–3
- [7] Zhang Y, Liu W, Kou L, Liu Y F and Keimel C 2018 Design of a high power MEMS relay with zero voltage switching and isolated power and signal transfer 2018 *IEEE Applied Power Electronics Conf. and Exposition (APEC)* pp 1974–80
- [8] Zhu Y and Pal J 2021 *Micromachines* **12** 1237
- [9] Okamoto Y, Oda R, Usami J, Nakashima R, Ohara K, Gorwadkar S, Takei Y and Okada H 2025 Electrostatic MEMS switch with isolated switching path and state-holding mechanical latch structures 2025 *IEEE 38th Int. Conf. on Micro Electro Mechanical Systems (MEMS)* (IEEE) pp 732–5 (available at: <https://ieeexplore.ieee.org/document/10917499/>)
- [10] Smith B, Ataul Mamun M, Horstmann B, Ozg r   and Avrutin V 2025 *J. Microelectromech. Syst.* **34** 231–9
- [11] Pan Y, Khan N, Lu M and Jeon J 2016 *IEEE Trans. Electron Devices* **63** 832–40
- [12] Ma B, You Z, Ruan Y, Chang S and Zhang G 2016 *Microsyst. Technol.* **22** 911–20
- [13] Wang L and Jin Y 2017 *Microsyst. Technol.* **23** 2257–62
- [14] Cao T, Hu T and Zhao Y 2020 *Micromachines* **11** 694
- [15] Jiang L, Wang L, Huang X, Huang Z and Huang M 2024 *Micromachines* **15** 155
- [16] Bansal D, Kumar A, Sharma A, Kumar P and Rangra K J 2014 *Microsyst. Technol.* **20** 337–40
- [17] Uvarov I and Kupriyanov A 2019 *Microsyst. Technol.* **25** 3243–51
- [18] Shuaibu A H, Rabih A A S, Blaqui re Y and Nabki F 2024 *Micromachines* **15** 1295
- [19] Joshi K M, Arya D S, Garg M, Kumar P and Singh P 2025 Mitigating stiction failures in in-use M/NEMS-based sensors using a reliable piezoelectric RESET mechanism 2025 *IEEE Applied Sensing Conf. (APSCON)* pp 414–7 (available at: <https://ieeexplore.ieee.org/document/11144448/>)
- [20] Singh P, Li C G, Pitchappa P and Lee C 2013 *IEEE Electron Device Lett.* **34** 987–9
- [21] Repchankova A and Iannacci J 2009 Heat-based recovery mechanism to counteract stiction of RF-MEMS switches 2009 *Symp. on Design, Test, Integration & Packaging of MEMS/MOEMS* pp 176–81 (available at: <https://ieeexplore.ieee.org/document/4919512/>)
- [22] Barbato M and Meneghesso G 2015 *IEEE Electron Device Lett.* **36** 177–9
- [23] Marukhin N V and Uvarov I V 2019 *J. Phys.: Conf. Ser.* **1410** 012205
- [24] Shim Y H, Kim T S, Lee S J, Kim S H, Lee S Y, Jung S Y, Noh S B, Lee Y B and Yoon J B 2025 CMOS BEOL-compatible See-Saw microelectromechanical non-volatile memory with low on-resistance 2025 *23rd Int. Conf. on Solid-State Sensors, Actuators and Microsystems (Transducers)* (IEEE) pp 858–61 (available at: <https://ieeexplore.ieee.org/document/11110596/>)
- [25] Kim B C and Kasim R 2010 *J. Microelectron. Electron. Packag.* **7** 169–74
- [26] Iannacci J 2021 *Microsyst. Technol.* **27** 183–7
- [27] Gear M, Yeatman E, Holmes A, Syms R and Finlay A 2004 *J. Microelectromech. Syst.* **13** 887–94
- [28] Kedia S and Wang W 2015 *J. Microelectromech. Syst.* **24** 232–40

- [29] Yoon Y H, Han C H, Lee J S and Yoon J B 2018 *J. Microelectromech. Syst.* **27** 1124–34
- [30] Dennis J O, Rabih A A S, Md Khir M H, Ahmed M G A and Ahmed A Y 2016 *J. Sens.* **2016** 1–14
- [31] Lee S W, Johnstone R W and Parameswaran A M 2005 MEMS mechanical logic units: design and fabrication with micragem and polymumps *Canadian Conf. on Electrical and Computer Engineering (Saskatoon, SK, Canada)* ed J C Chiao, A S Dzuras, C Jagadish and D V Thiel pp 1513–6
- [32] Cowen A, Hardy B, Mahadevan R and Wilcenski S 2005 *Polymumps Design Handbook* (MEMSCAP Inc)
- [33] Lee Y, Choi P, Kang M, Kim S, Lee S, Kim T, Lee S and Yoon J 2024 *Adv. Electron. Mater.* **10** 2400045