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A reliable MEMS switch using electrostatic levitation

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In this study, a microelectromechanical system (MEMS) beam is experimentally released from pull-in using electrostatic levitation. A MEMS cantilever with a parallel plate electrode configuration is pulled-in by applying a voltage above the pull-in threshold. An electrode is fixed to the substrate on each side of the beam to allow electrostatic levitation. Large voltage pulses upwards of 100 V are applied to the side electrodes to release the pulled-in beam. A large voltage is needed to overcome the strong parallel plate electrostatic force and stiction forces, which hold the beam in its pulled-in position. A relationship between bias voltage and release voltage is experimentally extracted. This method of releasing pulled-in beams is shown to be reliable and repeatable without damaging the cantilever or electrodes. The proposed approach is of great interest for any MEMS component that suffers from the pull-in instability, which is usually irreversible and permanently destroys the device, as electrostatic levitation allows pulled-in structures to be released and reused. It has a promising application in MEMS switches by creating a normally closed switch as opposed to current MEMS switches, which are normally open. *Published by AIP Publishing.*
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Microelectromechanical Systems (MEMS) are of key importance for a large number of commercial devices to achieve the performance required by manufacturers and consumers alike. Smartphones, computers, automobiles, airplanes, microscopes, laser printers, and much more would not function properly without MEMS components. With the increasing demand for smart devices that interact with the environment and their user, the demand for highly functional and reliable MEMS devices is expanding.

In application, most MEMS actuators and sensors use electrostatics to induce or detect motion of a micro-structure. MEMS switches,[1–4] accelerometers,[5,6] microphones,[7,8] micro-mirrors,[9–13] and pressure sensors[14] use electrostatics to operate. The working principle behind electrostatic actuation can be explained through a parallel plate capacitor, where two fixed parallel plates are given some initial charge to create an electric field between them. The electric field creates electrostatic forces that pull the two plates together. In MEMS, one of the fixed plates is replaced with a small micro-structure, typically a beam or a movable plate, which can be pulled toward the fixed plate by applying a voltage between them. This method of actuation allows precise control of the micro-structure's movement that follows the profile of the electronic signal applied to the fixed electrode. Electrostatic forces are desirable because of their fast response time and simplicity in fabrication; however, they have drawbacks.[15]

One common undesirable phenomenon associated with electrostatic actuation is the pull-in instability. Pull-in failure occurs when the electrostatic force pulling the two electrodes together overcomes the mechanical forces separating them and the structure collapses. In many cases, pull-in results in permanent damage to the device as the electrodes become stuck together and cannot be separated even if the voltage is removed. Stiction forces such as van der Waals become much more significant at the micro-scale, and the parallel plate electrostatic force is only capable of pulling objects together, so release is often impossible.[15] Stiction can be mitigated by placing dimples on the bottom face of the beam or movable plate, thus reducing the contact area and minimizing the force holding the plates together. However, even beams with dimples can frequently become stuck after pull-in, and therefore, many electrostatic devices are designed to avoid pull-in entirely.

Much effort has been placed in creating electrostatic MEMS designs that do not experience pull-in at all. One method actuates a structure with electrostatic levitation.[9–13,16–23] Electrostatic levitation involves a slightly different electrode configuration than the standard parallel plate design, with two extra electrodes that help induce an effectively repulsive force instead of an attractive one. This electrode configuration, first proposed by He and Ben Mrad[9] for large travel ranges, is shown in Fig. 1 for a MEMS beam.

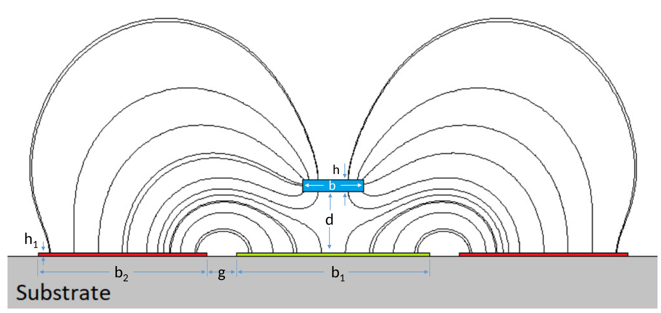

FIG. 1. Repulsive force electrode configuration with electric field lines. The beam (top) and middle electrode are grounded, and side electrodes are charged (side voltage). The middle electrode can be given a DC voltage (bias voltage) to produce both attractive and repulsive forces on the beam simultaneously.

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The beam and the fixed middle electrode are kept at the same voltage level (typically ground), while the fixed side electrodes are supplied with a large voltage. When the beam is close enough to the middle electrode, the electrostatic fringe-field produced by the side electrodes pulls on the top of the beam more than the bottom, resulting in a net force upwards. It is not the case of a purely repulsive force that would occur between two positively charged particles but rather an attractive force that acts in the opposite direction of the substrate and is commonly referred to as repulsive to differentiate it from the attractive parallel plate force. The middle electrode acts as a shield protecting the bottom face of the beam from the electric field and associated electrostatic force. As shown in Fig. 1, some of the electric field lines that would have normally pulled on the bottom face of the beam are now moved to the middle electrode instead. The electric field at the top of the beam is relatively unaffected by the presence of the middle electrode, and therefore, the direction of the net force on the beam becomes upward instead of downward when the beam-electrode gap is small.

If the beam is held to just one degree of freedom, which is common for thin, wide beams, it will not pull-in at all because the side electrodes are not in the beams' path of motion. The middle electrode will not create attractive electrostatic forces on the beam because they are both at the same voltage potential, and thus, pull-in will not occur. The authors have previously demonstrated in an experiment that when excited with a harmonic voltage signal, the beam can collide with the middle electrode, but instead of sticking, it simply bounces off.[23]

A major drawback to electrostatic levitation is that it requires a very high voltage potential because it utilizes the weak fringe fields. To generate an electrostatic levitation force comparable to the one generated by a standard parallel plate configuration, the voltage must be more than an order of magnitude larger than the parallel plate voltage. In a previous study by the authors, voltages upwards of 150 V were applied to achieve around 10 μm of static tip deflection for a 500 μm long beam.[22] However, the large voltage potential and elimination of the pull-in instability allow repulsive actuators to move more than an order of magnitude farther than their initial gap,[22] as opposed to parallel plate actuators, which are typically limited to one-third of the initial gap because of pull-in.[15]

Another advantage of electrostatic levitation is that it can be easily combined with parallel plate electrodes to enable bi-directional actuation.[24] Applying a bias to the middle electrode, along with the voltage on the side electrodes, creates attractive and repulsive forces on the beam. The beam and middle electrode act as parallel plates, while the side electrodes produce the levitation force. As with other bi-directional devices, such as double-sided parallel plates, bi-directional actuation requires multiple voltage inputs with each controlling the magnitude of the force in a single direction.

In this study, a MEMS beam is toggled between its pulled-in and released positions using a combination of parallel plate actuation and electrostatic levitation. A bias voltage is applied to the middle electrode to induce pull-in, and then, a high voltage pulse is applied to the side electrodes to release the beam from its pulled-in state. The authors demonstrate experimentally that the repulsive force is capable of overcoming the stiction forces holding the beam to the substrate. The capability of recovering from what was once permanent pull-in failure of a MEMS structure is a great advancement and addresses a fundamental issue that has existed since the inception of electrostatically actuated MEMS. This feature can make MEMS devices more reliable and reusable. It also opens the possibility of new applications for electrostatic MEMS by allowing them to use the pulled-in state as a functional element of the device, rather than a limitation. Almost all electrostatic MEMS are designed around pull-in, and by using a combination of attractive and repulsive forcing, this limitation can be relaxed or removed entirely. This attribute has great potential for MEMS switches that will be normally closed,[24] as opposed to current MEMS switches, which are normally open. It also has a promising application in micromechanical memories to read and erase bits as it can switch back and forth between two functional states: pulled-in and released.[25]

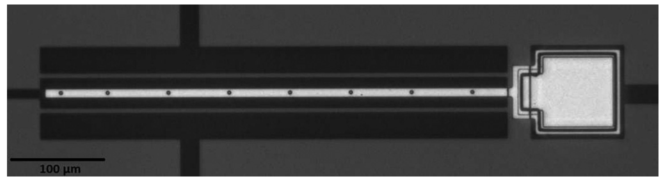

FIG. 2. Optical image of a fabricated beam.

MEMS cantilevers are fabricated using PolyMUMPs standard fabrication by MEMSCAP.[26] An optical image of a fabricated beam is shown in Fig. 2. The dimensions and material properties can be found in Table I. Dimples are placed on the bottom of the beam to reduce the contact area and the associated stiction forces. While dimples can aid with release, the beams still suffer from stiction when pulled-in, as discussed later. The cantilevers have the electrode layout shown in Fig. 1. Images of both pulled-in and released beams are shown in Fig. 3. The beam can be modeled as an Euler-Bernoulli beam with electrostatic forcing, which can be calculated numerically with a 2D COMSOL simulation. A comparison of pure repulsive, pure attractive, and combined repulsive and attractive forces can be seen in Fig. 4.

TABLE I. Beam parameters.

Parameter	Variable	Value
Beam length	L	500 μm
Beam width	b	10 μm
Beam thickness	h	2 μm
Beam anchor height	d	2 μm
Side electrode gap	g	5 μm
Middle electrode width	b_1	32 μm
Side electrode width	b_2	28 μm
Electrode thickness	h_1	0.5 μm
Dimple length	L_d	0.75 μm
Elastic modulus	E	150 GPa
Density	ρ	2330 kg/m^3
Poisson's ratio	v	0.22

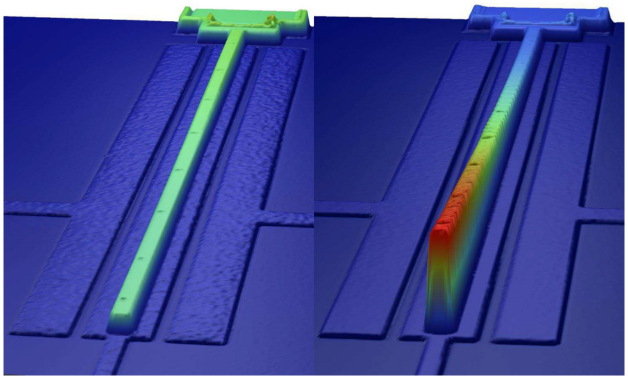

FIG. 3. Image of the beam showing pull-in (left) at 2 V_{bias} and 0 V_{side} and release (right) at 2 V_{bias} and 120 V_{side}. The images were captured with a Wyko NT1100 Optical Profiler.

A schematic for the experimental setup is shown in Fig. 5. The cantilevers are placed in air, and the tip displacement is measured with a Polytec MSA-500 Laser Vibrometer interfaced with MATLAB through a National Instruments USB 6366 Data Acquisition (DAQ). A B&K Precision 9110 power supply and a Krohn-Hite 7600 Wideband Power Amplifier supply the bias and side electrode voltage, respectively. The bias voltage is measured directly with the DAQ; however, the side voltage is well over the 10 V limitation of the DAQ and is measured with a Keithley 6514 electrometer, which is also controlled with MATLAB.

In the experiment, a bias voltage is applied to the middle electrode to start the beam in its pulled-in position. The bias is then adjusted to a specified level and held constant before a series of short, high voltage pulses are applied to the side electrodes. The beam displacement is observed to determine whether the beam was released during the voltage pulses. A relationship between bias voltage and release side voltage is obtained to demonstrate the working principle of the repulsive switch.

Figure 6 shows the recorded switch motion and applied voltages. The bias voltage is initially set at 0 V, increased to

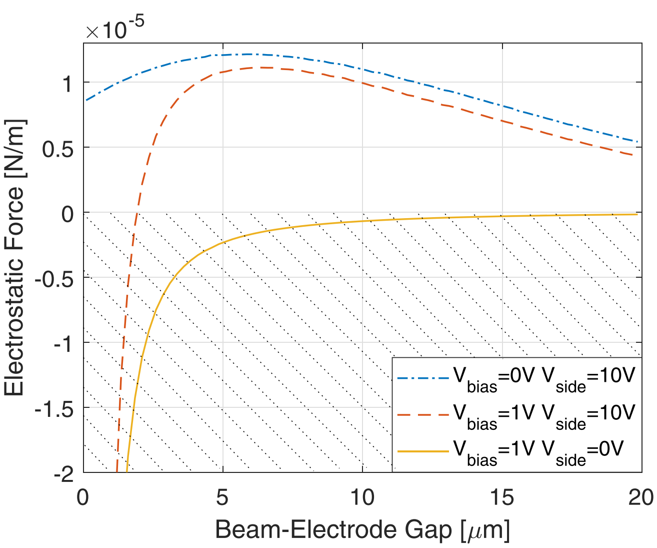

FIG. 4. Electrostatic force on the beam versus the gap distance simulated in COMSOL. The dashed area shows the attractive regime, and the rest is the repulsive regime. The combined force with bias and side voltages behaves similar to the attractive force at low gaps and the repulsive force at large gaps. Applying 10 V on the side electrodes can change the force from attractive to repulsive outside of very small gaps.

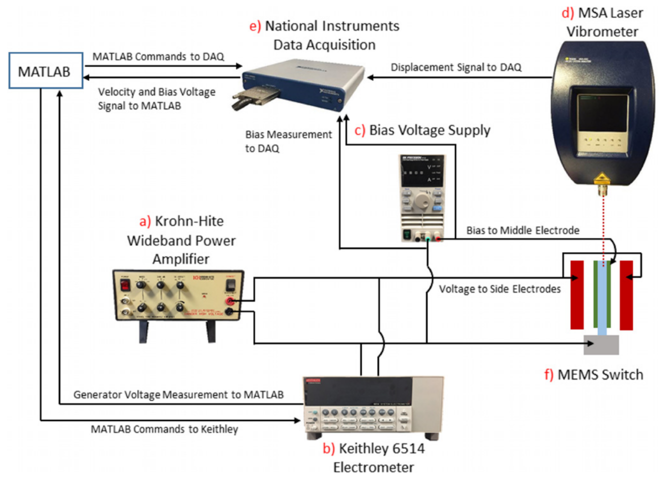

FIG. 5. Experimental setup with (a) Krohn-Hite 7600 Wideband Power Amplifier, (b) Keithley 6514 Electrometer, (c) B&K Precision 9110 Power Supply, (d) Polytec MSA-500 Laser Vibrometer, (e) NI USB 6366 Data Acquisition, and (f) the MEMS repulsive switch. The DAQ and electrometer are interfaced with MATLAB.

the pull-in voltage of 4.5 V, and then held constant. As the bias voltage ramps up, the beam is pulled down slightly before suddenly becoming unstable and collapsing, which can be observed at approximately 1.2 s. Two pulses of 195 V are applied to the sides after the beam is in the pulled-in position. The cantilever releases during both pulses, which can be observed jumping 20 μm in the displacement signal. When the side voltage drops to zero, the beam immediately pulls back in and sticks to the substrate. The beam can be toggled to and from pull-in many times without failure or causing noticeable damage to the device by applying and removing a voltage on the side electrodes. The bias voltage determines the minimum side voltage needed to open the switch.

The experiment was repeated by adjusting the bias voltage and determining the associated release voltage. Figure 7 shows the release voltage for various bias levels. For biases that are less than the 4.5 V pull-in voltage, first pull-in is initiated at 4.5 V, and then, the bias is reduced to the specified level. When the bias voltage is removed completely, the beam continues to stick to the middle electrode, and 70 V is required to release the beam. At the pull-in voltage, 195 V is needed for release. Because of limitations with the PolyMUMPs chips, voltages above 200 V were not applied.

Figure 7 demonstrates that the release voltage can be adjusted by changing the bias voltage. This is useful for a MEMS switch, which can be tuned to open at different threshold voltage levels. If paired with a transducer that is converting mechanical energy to electrical energy, the entire system can be designed to trigger the opening of a switch when the input passes a threshold.[24] In addition to the tunability, it also can act as a normally closed switch, which is not possible with a standard two-electrode parallel plate configuration.

A MEMS cantilever is experimentally released from its pulled-in position using electrostatic levitation. This method provides a safe and effective way of releasing and reusing pulled-in MEMS beams, which would have otherwise been permanently stuck to the substrate, rendering them unusable.

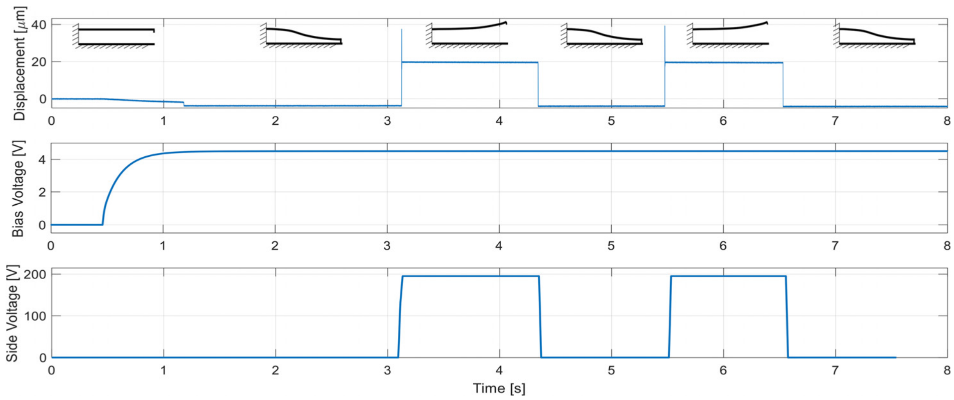

FIG. 6. Measured beam-tip displacement, bias voltage, and side voltage versus time. The beam pulls in as the bias voltage ramps up to 4.5 V and is released by supplying 195 V on the side. The illustrations at the top of the displacement signal roughly show the profile of the beam during each phase of the experiment.

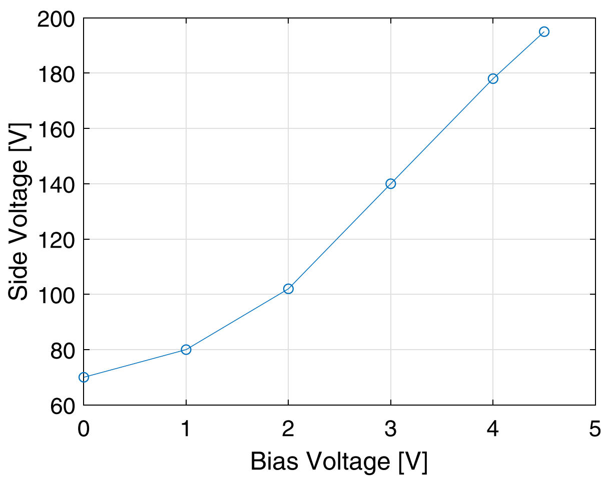

FIG. 7. Bias voltage versus threshold release voltage.

The obtained results are very promising for the field of MEMS research by increasing the longevity MEMS beams and allowing researchers to salvage and reuse devices that would have been discarded. It was also demonstrated that the release voltage can be controlled by changing the bias voltage, which opens up the possibility of a tunable, normally closed, and bi-directional MEMS switch. Combining parallel plate actuation with electrostatic levitation allows for more robust MEMS devices while also increasing functionality for new MEMS sensors and switches that can overcome limitations of current designs.

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