Electrostatically Actuated Microswitches; Scaling Properties

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ABSTRACT

The continuing need for small switches with very high ratios of off impedance to on impedance has sparked interest in microfabricated switching devices. By scaling the vertical dimensions of electrostatically-actuated, surface-micromachined, micromechanical switches, we have reduced the threshold voltage from approximately 130 V to 24 V, while maintaining the contact and separation forces constant. By increasing the number of contacts, the current handling capacity has been increased by an order of magnitude to 150 mA.

INTRODUCTION

Development of microfabricated switching devices is being stimulated by a continuing need for small switches with very large ratios of off impedance to on impedance. Low on-state resistances are achieved by bringing two conductors into physical contact; high off-state impedances are a result of using small contact areas to minimize capacitance. Examples of such microfabricated switching devices employing electrostatic [1,2,3,4,5,6,7,8,9,10], magnetic [11,12], and thermal [13,14] actuation have been reported. The ideal actuation method would operate both at low power levels and at low voltages. In contrast to magnetic or thermally actuated devices, electrostatically actuated switches inherently operate at very low power levels, and are relatively simple to fabricate. However, with the exception of some low-force devices prone to contact sticking, devices reported to date generally have had threshold voltages for contact closure of over 50 V.

In previous publications, we have described the design, fabrication, and preliminary electrical characteristics of electrostatically-actuated, surface-micromachined, micromechanical switches and relays. [1,15,16,17] An SEM micrograph of such a microswitch is shown in Figure 1. When a voltage is applied to the gate electrode the beam bends down and brings the contact tip under the beam into contact with the drain electrode. When the voltage is removed, the restoring force of the beam pulls the contact away from the drain, overcoming stiction forces. These devices typically had threshold voltages for contact closure of 50 to 200 V. In this work, we have reduced the threshold voltage of our devices by nearly an order of magnitude, to 21 Volts, while maintaining the same contact and separation forces. This threshold voltage reduction was guided by one of the simple scaling laws described in the next section. Lower contact force switches of the same design have operated at voltages as low as 6V. We have also increased the current handling capacity of the microswitches, to at least 150 mA, by increasing the number of contacts from 2 to 64, again maintaining the same force per contact. The devices discussed here have gold-gold contacts. Individual microswitch contacts typically have an initial resistance

of 0.1-1 Ω , and a current handling capability of over 15 mA with no visible contact damage after 10⁸ cycles.

Figure 1. SEM micrograph of a microswitch before scaling. The indentations at the free end of the cantilever correspond to contact bumps underneath the beam.

SCALING LAWS

Scaling laws for electrostatically actuated switches, analogous to the well-known constant-field scaling law for MOS devices, can be derived using plate theory and the fact that the electrostatic force is proportional to the square of the electric field. These simple scaling laws are useful in rapidly transforming designs in force, actuation voltage, horizontal dimensions, vertical dimensions, and resonant frequency. To simplify this discussion, it will be limited to the scaling of a *fixed design*. In this context, a *design* means a given shape as viewed from above; the size may vary, but all the horizontal dimensions must vary proportionally such that the shape is unchanged. The concept of a *fixed design* is attractive practically as well as conceptually. If the lateral dimensions do not change the scaling can be performed without changing the photomasks used in the microfabrication. Even when the lateral dimensions are scaled proportionally, certain important properties remain constant. One of these is the overvoltage factor, which we define as the ratio V_m/V_t , where V_m is the maximum voltage that can be applied without bringing the beam into contact with the gate, and V_t is the threshold voltage of the device. A second conserved property is the ratio of the contact capacitance to the gate capacitance. One can therefore optimize a design for several important properties, and the design can subsequently be transformed to a more desirable operating voltage, force, or size, depending on the limitations of the fabrication process.

Three scaling laws are described in the following paragraphs, followed by a discussion of the limits of their applicability. The scaling laws describe how the operating voltage, the operating force, or the device size can be changed while

holding the other two parameters constant. These changes are achieved by adjusting the beam thickness and the separation between the beam and the gate, in addition to the horizontal size. The three scaling laws are summarized in Table 1.

Constant-Horizontal-Size, Constant-Force Scaling to Reduce Actuation Voltage

In this type of scaling the horizontal dimensions remain the same. The vertical dimensions are scaled to reduce the actuation voltage, while keeping the contact and separation forces constant. The three as-fabricated vertical dimensions of interest are shown in Figure 2. They are the gap between the beam and the underlying metallization (d), the tip height (t), and the thickness of the beam (h).

Figure 2. a. Top view of microswitch showing horizontal dimensions w and l . b. Side view of microswitch showing beam thickness (h), beam-gate gap (d), and tip height (t).

The electrostatic force per unit area at the conductor surfaces is given by $\frac{1}{2} \epsilon E^2$, where ϵ is the permittivity of the dielectric and E is the electric field at the surface. Since the electrostatic force depends only on the electric field, the force pulling the beam down will remain the same if the electric field does not change with scaling. In the limit of nearly parallel electrodes, and ignoring fringing fields, the electric field will be the same if the vertical dimensions of the dielectric gap (d and t), the vertical deflection of the beam, and the actuating voltage are all multiplied by the same scaling factor, k_1 ($k_1 < 1$).

To complete the scaling, the restoring forces exerted by the scaled beam for the scaled deflection must be equal to the original restoring forces. The restoring forces are proportional to the deflection and to the stiffness of the beam. Since the deflection is scaled down by the factor k , the stiffness must be scaled up by the factor $1/k_1$. The stiffness is proportional to h^3 , so this may be achieved by increasing the beam thickness by the factor $k_1^{-1/3}$.

Constant-Force, Constant-Voltage Scaling to Reduce Size

The object here is to reduce the horizontal dimensions of the device, keeping the actuation voltage and the contact and separation forces constant. All horizontal dimensions are reduced by a scaling factor k_2 . For example, w and l , shown in Fig. 2, are both reduced. This leads to reduction of the actuator area by a factor k_2^2 . To keep the total electrostatic force pulling the beam down constant, the electrostatic force/unit area must be increased by a factor $1/k_2^2$. The force is proportional to the square of the

electric field, so the electric field must be increased by a factor $1/k_2$. This is achieved by decreasing the vertical dielectric gap by a factor k , and holding the actuation voltage constant.

Again, the restoring force must kept the same, considering both the reduced horizontal extent of the beam and the reduced deflection of the beam. The stiffness of the structure must be scaled up by a factor of $1/k_2$, since the deflection is scaled down by a factor of k_2 . The stiffness is proportional to the width of the beam, w , and to the inverse cube of the beam length, l , and to the cube of the beam thickness (h). Therefore, to increase the stiffness by the factor $1/k_2$, with both horizontal dimensions scaled down by a factor k_2 , the beam thickness, h , must be decreased by the factor $k_2^{1/3}$.

Constant-Voltage, Constant-Horizontal-Size Scaling to Increase Force

Here the horizontal size of the design and the actuation voltage remain constant, but the dielectric gap and the thickness of the beam are adjusted to give higher contact and separation forces. Following the earlier discussion, to increase the electrostatic force by a scaling factor $1/k_3$, the electric field must be increased by the factor $k_3^{1/2}$. To do this at a constant actuation voltage, the gap must be decreased by the factor $k_3^{1/2}$.

The restoring force is adjusted by increasing the beam thickness. The goal here is to increase the restoring force by the factor $1/k_3$, to match the increase in the electrostatic force. This is done by increasing the beam thickness (h) by the factor $k^{-1/2}$, which increases the beam's stiffness by a factor of $k_3^{-3/2}$. Coupled with the factor of $k_3^{1/2}$ in deflection, the restoring force is increased by the desired factor of $1/k_3$.

	Actuation Voltage	Device Size	Contact Force	Dielectric Gap	Beam Thickness	Resonant Frequency
Reduce voltage	k_1	1	1	k_1	$k_1^{-1/3}$	$k_1^{-1/3}$
Reduce Size	1	k_2	1	k_2	$k_2^{1/3}$	$k_2^{-1.67}$
Increase Force	1	1	$1/k_3$	$k_3^{1/2}$	$k_3^{-1/2}$	$k_3^{-1/2}$

Table 1. Summary of the three scaling laws described in the text in terms of the scaling parameters k_1 , k_2 , k_3 . Note that $k_1 < 1$, $k_2 < 1$, $k_3 < 1$ to reduce voltage, reduce size, or increase force, respectively.

Experimental Results

In this work, one scaling goal was to reduce the actuation voltage of the microswitches, without changing the photomasks, maintaining the same contact force. We chose the constant-horizontal-size, constant-force scaling law to reduce the actuation voltage. This scaling law dictates that the gap between the cantilever beam and the actuation electrode be multiplied by a factor k_1 ($k_1 < 1$) to achieve the same electric field, and consequently the same electrostatic force, at a lower voltage. The beam thickness is multiplied by $k_1^{-1/3}$ to increase its stiffness and maintain the original separation force with the smaller deflection.

The original 120V devices had gold beams, 2.8 μm thick, with a beam-electrode gap of 1.8 μm , similar to the device shown in Figure 1. The length of the device is 70 μm and the width is 30 μm . The contact tip is typically 1/2 of the gap in thickness. The 24 V devices had the gap scaled down by a factor of 8 to 0.23 μm , with a tip 0.11 μm high and a beam thickness of

6.4 μm . A scaled switch is shown in Figure 3. Figure 4 compares the threshold voltages predicted by the simple scaling law above with the measured threshold voltage of scaled switches. Preliminary results indicate that the electrical performance changes little over this range of scaling.

a.

b.

c.

Figure 3. SEM micrographs of scaled microswitch. a - switch, b - contact end, c - tip detail. Beam thickness 5.8 μm , beam-gate gap 0.33 μm .

Figure 4. Threshold voltage predicted by the scaling law and measured. The increase in beam thickness with reduction in the beam-gate gap is also shown. The contact total force is approximately 80 μN for the two-contact switch.

A second type of scaling increased the number of contacts in a switch from 2 to 64, as shown in Figure 5. Figure 6 shows that the current handling capacity increases with the number of contacts.

Figure 5. Layout Drawings of single beam multiple contact switches with 4, 8, 16, 32, and 64 contacts.

Figure 6. Data from eight devices, two of each number of contacts, showing the improvement in the lifetime with increasing number of contacts, for cold-switched currents. One of the 64 contact devices continued to survive after 10^9 cycles.

The contact resistance is expected to decrease inversely with the number of contacts. Since the contact resistance itself is not

directly accessible, the standard deviation of the contact resistance the first ten cycles is shown in Figure 7 below. The sequence of five switches increase in the number of contacts from 4 to 64 in factors of two. If the contacts were acting equally and in parallel, we would expect a decrease in the standard deviation of a factor of the square root of sixteen for an increase from 4 to 64 contacts, which is approximately what is observed.

Figure 7. The graph shows plots of the Standard Deviation and the Mean of the total switch resistance as a function of the number of contacts. Two curves are also presented. The linear projection of the standard deviation is based on the value of the formula $Sid(4)/\sqrt{n/4}$ where $Sid(4)$ is the standard deviation of the resistance of the four contact switch and n is the number of contacts. The projected mean is derived from an estimate of the numbers of squares in the leads to each of the switches shown in Figure 5. The lead resistance of the 64 contact switch is divided by the number of squares for that switch and used as a measure of the sheet resistance for the leads (0.78 Ohms/sq). This is then used to calculate the lead resistance for the other switches and plotted as shown.

DISCUSSION

The scaling laws described above can be applied over a wide range of switch dimensions. However, certain limitations do exist. For example, due to the fabrication process the beams have a residual stress gradient, creating an initial downward curvature. If that stress gradient were constant through the beam thickness, then the downward deflection due to curvature would scale with the square of the beam length and would be independent of the beam thickness. Thus the scaling used in order to reduce the gap would be limited. Fortunately, however, the stress gradients are greatest in the bottom of the beam. Thus as the beam thickness is increased in order to reduce the gap, the effect of the stress gradients on the initial curvature decreases and the thicker beams have less initial curvature.

Another potential limitation is associated with the beam thickness-to-length ratio. For a cantilever beam, if that ratio is greater than 0.1, the correction factor due to shear deformation is less than 1%. However for a beam fixed at one end and pinned at the other end, the shear correction is about 10%. Prior to closing, the switch acts as a cantilever beam, whereas the deformation after closure may approach that of a fixed-pinned beam.

Small horizontal size and low actuation voltage are desirable properties in a microswitch. In addition, relatively large contact and separation forces are desirable to overcome stiction forces and lower the contact resistance.[1,15,18] The scaling laws predict that we can achieve all these goals simultaneously, provided that the gaps between the beam and the gate and between the upper and lower contacts can be reduced sufficiently.

Alternatively, the voltage and force goals can be achieved at a larger gap if the horizontal dimensions of the device are increased.

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