Large Displacement Microactuators In Deep Reactive Ion Etched Single Crystal Silicon

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ABSTRACT

A comparison of three different large-displacement microactuator technologies fabricated by deep reactive ion etching (DRIE) in silicon-on insulator (SOI) substrates is presented. Electrothermal, curved electrode electrostatic, and combdrive electrostatic actuator designs are considered, with each actuator design capable of producing more than 100\( \mu \)m of displacement. Analytic models for each actuator type are reviewed, and both theoretical and experimental data for fabricated devices are analyzed and compared with respect to displacement, force, and power consumption.

1. INTRODUCTION

Microactuators capable of delivering large displacements and forces are important components of a variety of microsystems including optical [1-2], safety and arming [3], and microfluidic [4-5] applications. Both electrostatic and thermal silicon microactuators based on deep reactive ion etching (DRIE) have been demonstrated for such applications by a number of groups [6-12]. This paper seeks to evaluate the relative merits of different DRIE-based microactuator technologies in order to provide selection criteria for the microsystem designer. Three different types of large displacement micro actuators fabricated in 50 and 100\( \mu \)m silicon-on insulator (SOI) wafers have been modeled, designed, fabricated, and tested. Each device was fabricated with a nominal dimension of 3mm for the actuation element. The relative performance of each type of microactuator is assessed in terms of displacement, force, and power consumption. The specific actuator designs investigated, shown in Figure 1, are electrothermal, curved electrode electrostatic, and combdrive electrostatic actuators. These actuation schemes were selected based on their suitability for applications requiring displacements on the order of hundreds of microns.

![Micrographs of typical fabricated microactuators](image)

Figure 1 - Micrographs of typical fabricated microactuators, (a) curved electrode electrostatic, (b) comb drive electrostatic, and (c) V-beam electrothermal.

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2. ANALYTICAL MODELS

Specific design configurations for each microactuator technology are described here. Existing models from the literature used to predict actuator performance are summarized, with modeled results compared to experimental data from fabricated devices in the following section.

2.1 Curved Electrode Electrostatic Design

The curved electrode actuator design is characterized by a long cantilevered beam situated next to a curved electrode, as shown in Figure 2(a). An electrical potential applied between the beam and the electrode attracts the beam electrostatically to the electrode, as depicted in Figure 2(b). When the voltage reaches a critical limit (the pull-in voltage), the electrostatic force is sufficient to overcome the mechanical stiffness of the beam, which snaps in to the electrode. Isolation structures, such as the element shown in Figure 3, are built into the electrode to prevent the beam from making contact and shorting with the electrode after pull-in.

The curved electrode actuators were designed and analyzed using an analytical model established by Legtenberg et al. [7]. This model was originally used to predict the pull in voltage of 5µm high polysilicon curved electrode actuators, but is also applicable to the present high aspect ratio DRIE curved electrode microactuators:

\[
V_{pi}^2 = \frac{E_s I}{\varepsilon_0 h} \int_0^L \left[ \frac{d^2 g(x)}{dx^2} \right]^2 dx
\]

\[
= \int_0^L \left[ \frac{d}{\varepsilon_s} + s(x) - c_{pi} g(x) \right] \left[ \frac{d}{\varepsilon_s} + s(x) - c_{pi} g(x) \right] dx
\]

In this model, \( V_{pi} \) is the pull in voltage of the actuator, \( E_s I \) is the bending stiffness, \( \varepsilon_0 \) is the dielectric constant, \( h \) is the thickness of the SOI active layer, \( d \) is the initial gap at the base of the cantilever, and \( L \) is the beam length. \( g(x) \) is the deflection profile of a uniformly loaded cantilever beam and is used for the admissible trial function: \( x^2(6L^2-4Lx+x^2) \).
\( s(x) \) is the shape of the electrode as fabricated and is given by \( s(x) = \delta_{\text{max}} \left[ \frac{x}{L} \right]^n \) where \( \delta_{\text{max}} \) (displacement) is the maximum gap distance at the beam tip and \( n \) is the order of the curve. These equations may be solved simultaneously to predict pull-in voltage.

### 2.2 Commdrive Electrostatic Design
Commdrive electrostatic actuators have been used extensively for a wide range of microsystems applications. For large displacement applications, a design demonstrated by Grade et al. [13] provides several important benefits over traditional combdrive designs. A traditional combdrive is shown in Figure 4(a), and a modified design is shown in Figure 4(b).

![Figure 4 - Electrostatic combdrive actuator designs, (a) traditional combdrive (5mm x 8mm) 200um displacement, and (b) modified combdrive (3mm x 3.7mm) 200um displacement.](image)

The electrostatic force \((F)\) for the modified design is given as,

\[
F = \left( N - 1 \right) \varepsilon h x + \frac{\varepsilon h V^2}{2g^2} \tag{3}
\]

where \( N \) is the number of comb teeth, \( h \) is the structure height, \( x \) is the displacement, \( g \) is the finger gap between the 2 interlacing structures, \( h \) is the height of the springs, \( L \) is the length of the springs, \( w \) is the spring width. The axial spring constant at zero deflection, \( k_{x1} \), given by Eqn 8 and is a good approximation of the \( k_x \) throughout its displacement.

\[
k_{x1} = \frac{Ehb}{L} \tag{4}
\]

And the lateral stability is given by,

\[
k_{\text{side}} = \frac{Ehw}{L} \left( \frac{3(x - x_{pb})^2}{8w^2} + 1 \right)^{-1}, \tag{5}
\]

where \( x_{pb} \) is the amount the flexures are pre-bent. The pre-bent folded flexures depicted in the comb drive actuator of Figure 4(b) become straight when fully actuated, increasing the effective lateral spring constant. This reduces the problem of lateral instability, allowing tighter comb spacing and higher electrostatic force. Another way of increasing lateral stability used in the comb drive actuator of Figure 4(b) is to vary the length of the comb teeth to reduce the total sidewall capacitance under full actuation.

### 2.3 V-Beam Electrothermal Design
The second large displacement actuator design evaluated was a V-beam electrothermal actuator. This actuator has two anchors with a released beam connecting them. The center the beam is offset from the anchor connection point by \( \sim 1\% \) of the total beam length. An applied current results in Joule heating of the beam, with deflection of the center point occurring due to thermal expansion as depicted in Figure 5.
The deflection predictions were made using a model developed by Maloney et al. [12] for a single beam thermal actuator. For the designs fabricated in this work, the parameters used are shown in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap between beams and substrate</td>
<td>g</td>
<td>2 μm</td>
</tr>
<tr>
<td>Height of beams</td>
<td>h</td>
<td>50 &amp; 100 μm</td>
</tr>
<tr>
<td>Thermal conductivity, air</td>
<td>kₐ</td>
<td>0.026 W/m-K</td>
</tr>
<tr>
<td>Thermal conductivity, silicon</td>
<td>kₛ</td>
<td>148 W/m-K</td>
</tr>
<tr>
<td>Length</td>
<td>L</td>
<td>1.5-3mm</td>
</tr>
<tr>
<td>Offset (1% of length)</td>
<td>d</td>
<td>15-30 μm</td>
</tr>
<tr>
<td>Current Density</td>
<td>J</td>
<td>(varies)</td>
</tr>
<tr>
<td>Thermal expansion coefficient, silicon</td>
<td>α</td>
<td>2.6 x 10⁻⁶ K⁻¹</td>
</tr>
<tr>
<td>Resistivity, silicon</td>
<td>ρ</td>
<td>0.010 Ω-cm</td>
</tr>
</tbody>
</table>

An approximation of the actuator deflection \( u_t \) as a function of current density \( J \) can be found from Eqns. 6 and 7,

\[
\begin{align*}
\frac{2a}{sk_m} &= Sg_kw = 4(10^{-6} + g) + 1 \quad \text{(8)}
\end{align*}
\]

where \( S \) is the shape factor which must be derived for a specific actuator geometry. For the 50μm tall devices fabricated on SOI wafers with a 2μm SiO₂ layer as discussed here, the shape factor is given approximately by Eqn. 8:

\[
S = \frac{4}{w}(10^{-6} + g) + 1
\]

Eqns. 6 and 7 gives a close approximation to the current displacement curve, yet would predict infinite deflection as the current is continually increased. The maximum actuator deflection is in fact limited by the current density at which the actuator hits its intrinsic point temperature. At this point, the intrinsic and dopant charge carriers are equal, and the resistivity is at a maximum. The intrinsic temperature is a function of the doping level used in a particular microactuator design. The maximum temperature occurs at the beam midpoint \( x=L/2 \) as given by Eqn. 9 [12].

\[
T_{x=L/2} = T_{io} + \frac{j^2 \rho}{k_s m^2} \left[ 1 - \frac{1}{\cosh(mL/2)} \right]
\]
3. EXPERIMENTAL RESULTS

3.1 Electrostatic Curved Electrode
36 different curved electrode designs were fabricated and tested in both 6μm and 10μm wide beams, with 1, 2, and 3 mm lengths. All electrode designs were 2nd order polynomials, but with a varied maximum displacement. The initial gaps at the base of the cantilever of the actuator were 3μm and 6μm. The data for the 6μm wide beams is shown in Figure 6. Note that the model pull-in is higher than the experimental data. This is caused by the fabricated beam thickness reduction and therefore wider initial gaps than ideally designed. Total Displacement is the maximum amount the actuator can move.

![Figure 6 - Predicted and experimental data from curved electrode electrostatic actuators (6mm beam width). Each point represents a separate actuator design.](image1)

3.2 Combdrive Electrostatic
The combdrive actuators were designed with a goal of achieving 200μm displacement with a 50V DC drive signal. Although it is possible to design combdrives with much lower pull in voltages, the 100μm SOI substrates used in this study required gaps to be on the order of 6-7μm, leading to higher voltages due to relatively low electrostatic forces which scale inversely with the gap. In tests, the pull in voltage of the combdrives was consistently 50-55V when the actuator experienced a step voltage immediately at the pull in voltage. However, due to the linear variation in the length of the comb teeth, when using a slower ramp the actuator required a higher voltage than the calculated pull-in value to

![Figure 7 - Predicted and experimental data from 3mm x 3.7mm combdrive actuators. Ramp input was applied in 5V increments.](image2)
reach maximum deflection. This behavior can be seen from the data in Figure 7. This discrepancy is due to the inertial overshoot upon application of a step input, leading to a higher displacement than would be expected by a DC input. Parallel-plate effects between the anchors and comb teeth tips provide additional force for fully-actuated devices, allowing the maximum deflection to be held at a lower voltage after experiencing sufficient overshoot.

3.3 V-Beam Electrothermal
The largest actuator tested was 3mm from anchor to anchor and the highest deflection achieved was 60µm. Between 1.5mm to 3mm beam length, maximum deflection is linearly related to beam length. Figure 8 shows the importance of measuring the resistivity of the wafer before fabrication. This point is raised because this was not done before our fabrication. A 4-point probe could not be used since no wafers remained unetched after our devices were fabricated. The model is based on vendor specifications of 0.01-0.03 Ω-cm. Figure 9 shows a comparison of 50µm and 100µm tall. The 50µm structure has a greater current density for the same current so therefore it has a higher deflection.

4. DISCUSSION

When designing systems with high displacement actuators, several tradeoffs must be considered. The tradeoffs for an actuator with a nominal 3mm dimension are shown in Table 2. The nominal dimension refers to the beam length for the curved electrode and V-beam actuators, and the spring length for the combdrives. The parametric tradeoffs are shown visually in Figure 10. As indicated by the log scale used on the force and power axes, V-beam electrothermal actuators uses significantly more power, but can provide significantly more force than the electrostatic devices. The variation in required power between the two electrostatic actuators reflects the fact that in AC applications, combdrives tend to consume more power than the curved electrode due to the higher capacitance of the comb teeth. Overall, the power required for the electrostatic designs is negligible for very low frequency operation, but increases with frequency. In steady state operation (0 Hz), the electrothermal devices require significant power to remain actuated compared to the electrostatic designs.

The overall free displacement attained experimentally of each actuator is given in Table 2. The curved electrode actuators achieve the highest tip displacements, but require fairly high voltages, as shown previously in Figure 6. The curved electrode displacement is also difficult to control close to the unstable pull-in point. This makes them well suited for bistable actuator applications such as microswitches and microgrippers. The combdrives provide significantly more control of displacement throughout the operational range. Ultimately, lateral stability limits the maximum combdrive displacement, and 200µm was used in this study as a conservative design goal. The V-beam electrothermal design has

![Figure 8- Modeled and experimental data for a single V-beam electrothermal actuator (beam dimensions: 2mm length, 10µm width, \(\rho=0.01-0.03\ \Omega\text{-cm},\ \text{1}\%\ \text{center offset})

![Figure 9 - Experimental data from 10-element array of 50µm and 100µm tall actuators (beam dimensions: 3mm length, 10µm width, \(\rho=0.01-0.03\ \Omega\text{-cm},\ \text{1}\%\ \text{center offset})

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the lowest overall displacement compared to electrostatic devices of a similar in size. However, the significant force output invites leveraging schemes to increase displacement.

In Figure 10, the force of the curved electrode is indicated to be higher than the combdrive. This is because very close to the pull-in point of the curved electrode actuator, the parallel plate electrostatic force generated is higher than a combdrive with similar dimensions. The force of the v-beam electrothermal is the highest among the actuator type, but it drops off at the end of the actuator displacement. The available force of the electrostatic actuators increases as it gets displaced.

<table>
<thead>
<tr>
<th>Actuator Type</th>
<th>Power</th>
<th>Displacement</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curved Electrode</td>
<td>LOW</td>
<td>500+ μm</td>
<td>LOW</td>
</tr>
<tr>
<td>Combdrive</td>
<td>LOW</td>
<td>0-200 μm</td>
<td>LOW</td>
</tr>
<tr>
<td>V-Beam Thermal</td>
<td>HIGH</td>
<td>0-100+ μm</td>
<td>HIGH</td>
</tr>
</tbody>
</table>

Figure 10 - General operational regimes for each microactuator design.

4.1 Curved Electrode Electrostatic
A significant design parameter of a curved electrode actuator is the initial gap at the base of the cantilever. The electrostatic force of a Parallel plate actuator is given by:

\[ F = \frac{\varepsilon A}{2g^2}v^2 \]  

A lower initial gap significantly increases the force on the beam for a given voltage, and thus pull-in voltage is reduced. Deviation from predicted data is due to the initial gap being fabricated ~1μm larger than designed. The minimum gap that can be fabricated in DRIE is determined by the device wafer thickness. Currently acceptable yield can be achieved with a 15:1 (trench height to width) aspect ratio. This translates to a 6μm minimum gap for a 100μm thick device. As device thickness increases, this type of actuator becomes less feasible since acceptable gaps become increasingly difficult to fabricate. While a very useful design tool, the Legtenburg model was found to consistently predict lower pull-in voltages than the experimental data. This category of actuator is very well suited to low force and high displacement actuation, but relatively high voltages are required.
4.2 Comdrive Electrostatic

The combdrive design employed in this study provides several design advantages over traditional comb drive actuators [13]. First reducing the number of folded flexures by 4, reduces the required actuation force by 4. The reduction of flexures also drops the footprint from 40 mm$^2$ to 11 mm$^2$. In addition, the prebent springs increase the lateral stability of the actuator, enabling larger deflections for a given flexural spring constant. In a traditional combdrive the stability decreases with larger displacements. With prebent springs, stability actually increases; this effectively increases the maximum actuator displacement. Finally since side stability is increased, gap spacing can be decreased and the pull-in voltage is lowered.

Angling the teeth of the comb also increase side stability, effectively reducing comb overlap. Though this reduces side instability it causes a discrepancy between the ramped up voltage and the step input response (see Figure 7). The discrepancy between a ramped up input and a step input is attributed to the inertial effects of the step input pushing it beyond the normal ramped up voltage displacement. The actuator is held at this increased displacement because of the angled teeth. The angled teeth increase the number of teeth engaged and therefore require less voltage. In other words, it takes a lower voltage to hold the actuator in place than it does to get it there slowly.

4.3 V-Beam Electrothermal

While electrostatic actuators can provide high displacement for relatively low power, electrothermal actuators provide the most force on the order of (>N) [4]. These actuators are best suited to the application where power is not a concern because they can draw power on the order of 0.5 for one beam and up to 8 Watts with 10 beams. This is at the maximum displacement and power scales linearly with displacement. Although the largest actuator tested was 3mm from anchor to anchor and the highest deflection achieved was 60µm, it is believed that much higher deflections can be achieved in longer beam. Since maximum deflection is linearly related to beam length between 1.5mm to 3mm, this suggests that 6mm beams of the same design would yield 120µm of deflection and 8 mm beams 160µm of deflection etc. When designing electrothermal actuators, one very important design consideration is the resistivity of the wafer. A lower resistance wafer allows much higher current for a given voltage and therefore higher beam temperatures. Furthermore, for the model to give accurate predictions very accurate measurements of resistivity of the wafer must also be obtained.

4.4 Design Modifications

The standard combdrive is the hardest to make work with large displacements. When designing systems requiring relatively large displacements in the hundreds of microns complications can arrive in processing. Because the combdrive force is relatively low, this leads to long, thin folded flexure springs. As mentioned earlier no traditional combdrives yields because the design was too close to the process limits. Stiction, complete undercut of beams, broken beams, and shorting teeth are all problems that make this device difficult to fabricate. There are several techniques that have been used to deal with these issues. This technique can be applied all devices to increase device yield.

The thin flexures used in combdrives tend to break during processing if they are undercut by the DRIE. One way to combat this problem is to use “beam dots”, depicted in Figure 11. These are 20 micron diameter structures placed every 100 microns used to anchor the 4mm x 7micron undercut beam to the substrate at ~400 micron intervals. This method has little affect on the mechanical properties of the beam but it makes it more robust to processing.

![Figure 11 - SEMS of the combdrive beams showing “beam dots”](image-url)
Another way to prevent beam under cut during DRIE of long thin beams is to build dummy walls as shown in Figure 12 along the beam. The DRIE etch rate is highly dependent upon the aspect ratio of the trench. Narrow trenches etch slower than wider trenches. Once the wider trench is etched to the oxide layer it begins to etch laterally into the side of the structure. Dummy walls are placed along the beam to reduce the trench width. Since the beam becomes the last structure to etch completely, it is not undercut.

This result can also be achieved by using fallout structures, as shown in Figure 13, which fully release and float away when the silicon dioxide is etched in HF. The smallest dimension in the fallout structure should be less than the largest feature to be released. The fallout structures also help to minimize the amount of the Si being etched. Reducing the amount of etched silicon increases DRIE etch uniformity.

5. CONCLUSION

High displacement, curved electrode, combdrive electrostatic and V-beam electrothermal actuators with nominal dimensions of 2-3mm have been demonstrated with displacement of, 500µm, 200µm and 60µm respectively. The models for each of the designs are presented and the accuracy of the model analyzed for the SOI-DRIE application for 50 & 100µm thick nominal structures. Based on experimental data, the models appear to be valid design tools for rough actuator performance predictions. The design tradeoffs of three actuator designs have been presented. Tradeoffs between actuator power, displacement, and force dictate general regions of applicability for each technology, with the electrothermal devices providing the most force and the electrostatic devices providing significantly more displacement. Combdrives falls somewhere in-between. Additionally electrostatic devices require much less power than the electrothermal designs. Higher displacement performance is expected out of devices with larger nominal dimensions.

ACKNOWLEDGMENTS

The authors would like to thank DARPA and the Office of Naval Research for their support of this research.

REFERENCES


