Tolerance analysis for comb-drive actuator using DRIE fabrication

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Abstract

Deep reactive ion etching (DRIE) process is specially invented for bulk micromachining fabrication with the objective of realizing high aspect ratio microstructures. However, various tolerances, such as slanted etched profile, uneven deep beams and undercut, cannot be avoided during the fabrication process. In this paper, the origins of various fabrication tolerances together with its effects on the performances of lateral comb-drive actuator, in terms of electrostatic force, mechanical stiffness, stability and displacement, are discussed. It shows that comb finger with positive slope generates larger electrostatic force. The mechanical stiffness along lateral direction increases when the folded beam slants negatively. The displacement is 4.832 times larger if the comb finger and folded beam are tapered to +1° and −1°, respectively. The uneven deep fingers generate an abrupt force and displacement when the motion distance reaches the initial overlap length. The undercut reduces both the driving force and the mechanical stiffness of the lateral comb-drive actuator. The fabricated comb-drive actuator, with comb finger of +1° profile and 0.025 μm undercut, and folded beam of −1° slope and 0.075 μm undercut, is measured and compared with the models where both show consistent results. These analytical results can be used to compensate the fabrication tolerances at design stage and allow the actuators to provide more predictable performance.

Keywords: Etching tolerances; Deep RIE; Comb-drive actuator; MEMS

1. Introduction

Deep reactive ion etching (DRIE) process [1] is one of the most popular fabrication techniques due to its flexibility between anisotropic and isotropic etching, and high etching selectivity. However, this fabrication technique has a major drawback as it always leads to variations in microstructure and induces various fabrication tolerances. These fabrication tolerances, which affect the performances of fabricated actuator in terms of electrostatic force, mechanical stiffness, stability and displacement, occur due to micro loading effect [2,3], notching effect of silicon on insulator (SOI) based process [4,5] and different undercut for deep etched high aspect ratio structures. The fabrication tolerances of footing effect and in-plane misalignment have been studied [6,7]. In this paper, various fabrication tolerances such as profile of comb fingers and folded beams, uneven depth of overlap and non-overlap portions of the comb fingers and undercut are discussed from the aspect of the DRIE process by employing Surface Technology Systems (STS) Multiplex Inductively Coupled Plasma (ICP). With special reference to lateral comb-drive actuator, the effects of these fabrication tolerances on the performances of the actuator are analyzed. This analysis will then be used to estimate the performances of the fabricated actuator and to explain the variations between the measured results and designed values.

Various fabrication tolerances of DRIE are discussed in terms of fabrication and designed features in Section 2. The effects of these fabrication tolerances on performances of comb-drive actuator are analyzed in Section 3. A summary together with some discussions on potential applications is provided in Section 4.

2. Various tolerances of DRIE fabrication

High aspect ratio microstructures are commonly employed in many MEMS devices. Large lateral capacitance and compliance
fabrication techniques to fabricate high aspect ratio microstructures such as RIE, electron cyclotron resonance (ECR) and ICP DRIE have been developed. Among these techniques, only the DRIE technique meets the requirements of high etch rate, good selectivity to masking materials, and anisotropy, and is compatible with other fabrication processes. In this study, the alternating etching cycle flowing only etching gas of SF$_6$ and then switching to sidewall passivation cycle using only C$_4$F$_8$ is used. However, the etching results depend on the process conditions such as gas flow rate, electrode power, pressure, temperature and cycling time. Design feature is another factor that influences the etching result under the same process conditions. The dimensions of the etched slanted trench are schematically shown in Fig. 1, where $a$ is the width of the trench top and $b$ the width of the trench bottom, $h$ the overall height of the trench and $\alpha$ is the angle between the sidewall of the trench and the vertical reference line.

2.1. Profile of the etched beams

The etched profile is gauged by the angle $\alpha$ (anticlockwise from the reference vertical line to sidewall) which depends on the process conditions and designs. Three possible profiles are observable, i.e. positive (convex), negative (concave, reentrant) and vertical ($\alpha = 0$). The etched profile depends significantly on applied electrode power and chamber pressure [8]. Generally, more vertical profile is associated with higher electrode power. On the other hand, the response to pressure is relatively different. At the initial stage, the profile is less sloped with higher pressure, as thicker polymer films are deposited to protect the sidewalls. However, as pressure increases further, the fall in the average ion energy and the rise in the incident ion angle reduce the verticality. It is also experimentally observed that lower etching gas flow rate is beneficial in producing vertical trenches at the price of slow etching rate. In general, the physical ion bombardment and the formation and preservation of protective films on the sidewalls are adjusted to achieve the prescribed profile.

The designed feature influences the etched profile with the same process parameters. Generally, wider trenches tend to become more reentrant. Thus, trenches with dissimilar widths have various sloped sidewalls, which are positive in one case and negative in the other and vertical to some particular wide trench. This phenomenon is observed to the etched trenches with different widths under the same conditions of base pressure of 1.0 mTorr and gases flow and durations listed in Table 1. Fig. 2a is the scanning electron micrograph (SEM) of the trenches with different widths after etching for 30.0 min. Obviously, the top is wider than the bottom for the narrow trenches while the reversed is true for the wide trenches. The relationship between the slope and the width of trench is plotted in Fig. 2b. This figure confirms that the trench sidewalls have positive angle when the width of the trench is less than 5.0 $\mu$m and the trench sidewalls have negative slope when the width of the trench is larger than 20.0 $\mu$m. Least deviation from verticality is observed for trenches with width falls between 6.0 and 20.0 $\mu$m.

2.2. Uneven deep high aspect ratio beams

RIE lag or micro loading effect [9], the etching rate decreases when trench width increases, is commonly observed in fluorinated plasmas etching. The etching parameters, such as etching gas flow, passivation gas flow, pressure and automatic pressure
control valve (APC), are contributory factors to the micro loading effect, among which the flow rate of etching gas, SF$_6$, is the main parameter that influences the RIE lag. This result has already been widely reported by some researchers [9,10] and it is thought to be related to the reduction of the production species in the discharge. As shown in the SEM micrograph of Fig. 2 and the plotted curve in Fig. 3, the depth increases from 23.7 to 31.7 μm when the width of the trench increases from 0.4 to 2.0 μm, and the trench depth increases further to 40.0 μm when the trench width increases to 200.0 μm. Thereafter, the increase in the width of trench has negligible effect on the depth of the trench.

Usually a single crystal silicon wafer or a SOI substrate is employed to fabricate the MEMS devices. During the fabrication process, uneven movable deep beams occur. Single crystal reactive etching and metallization (SCREAM) [11] process and lateral isolation silicon accelerometer (LISA) [12] are two well developed processes to realize the released MEMS structure on a monolithic silicon wafer, in which the sidewalls of the etched trenches are protected by deposition and isotropic etch is used to release the movable structures. Hence, the beams with wider trenches are deeper than those with narrow trenches after release. However, the reverse occurs for the SOI based process as a consequence of notching effect because of the charging on the insulator buried oxide layer [13]. Wider trenches are etched faster than the narrow ones due to the micro loading effect. Hence, the wider trenches arrive at the buried oxide layer first followed by the notching which continues until the narrow trenches reach the interface. Consequently, the beams with wider trenches suffer from lateral etching more seriously compared to the narrow ones. Therefore, the beams with narrow trenches are deeper than those with wide trenches.

### 2.3. Undercut of the etching

The feature patterning is realized by lithography and hard mask etching to deep silicon etching. During this transfer, some deviations from the photoresist to hard mask can be observed because of imperfect anisotropic etching. This problem appears to be more serious when transferring the pattern to the high aspect ratio silicon microstructures, especially when the process starts from the etching cycle with SF$_6$ because it is an isotropic chemical process. It can be observed from Fig. 4 that the width of the silicon beam is smaller by 0.3 μm than the upper hard mask of 3.0 μm. When this process is continued, this undercut appears to be more serious and this result is similar to cryogenic enhancement deep etching, where 18 μm undercut is observed for a 275 μm deep etch and 8 μm undercut is observed for a 125 μm deep etch [14].

Table 2 provides a summary of the tolerances due to the DRIE process. These fabrication tolerances are expected to affect the performances of MEMS devices. In the following section, different types of tolerances are analyzed theoretically with special reference to lateral comb-drive actuator, and compared with the experiment results.

### 3. Tolerances effects on lateral comb-drive actuator

The schematic structure of the comb-drive actuator, consisting of two sets of comb fingers, folded beams and anchors, is shown in Fig. 5, where $b$ and $H$ are the width and the depth of the finger, respectively, $g$ the gap between the adjacent overlapped fingers and $L_1$ is the initial overlap length of the fingers. Lateral
The effective stiffness in lateral direction is expressed as:

\[ k_x = \frac{2AEI_z}{L^3} \]  

(2a)

where \( I_z \) is the second moment of inertia of the flexure beam and \( V \) is the applied voltage within the range of 0.3L \( (L_3 + \Delta x) \) < 0.7L, where \( L_3 \) is the entire length of the fingers. The folded beam supports the movable suspended structures and provides elastic force to balance the electrostatic force \( F_x \) and provides elastic force to balance the electrostatic force \( F_x \). The electrostatic force generated can be expressed as \( F_x = \frac{nH}{\alpha \Delta x} = \frac{\tilde{h} V^2}{\alpha \Delta x} = \frac{\tilde{h} V^2}{\alpha \Delta x} = \frac{\tilde{h} V^2}{\alpha \Delta x} = \frac{\tilde{h} V^2}{\alpha \Delta x} \)

(1)

where \( n \) is the number of the movable comb fingers, \( e \) the permittivity of the media and \( V \) is the applied voltage.

Table 2

<table>
<thead>
<tr>
<th>Tolerance</th>
<th>Actuator (effect)</th>
<th>Combin finger (electrostatic force, ( F_x ))</th>
<th>Folded beam</th>
<th>Displacement (( \Delta x ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile</td>
<td></td>
<td>Stiffness ( k_x )</td>
<td>Stability ( k_x/k_\alpha )</td>
<td></td>
</tr>
<tr>
<td>Positive</td>
<td>Increase</td>
<td>Increase</td>
<td>Decrease</td>
<td>Relies on the comb finger</td>
</tr>
<tr>
<td>Negative</td>
<td>Decrease</td>
<td>Decrease</td>
<td>Increase</td>
<td>and folded beam</td>
</tr>
<tr>
<td>Uneven deep beam</td>
<td>Decrease, jump</td>
<td>Increase</td>
<td>–</td>
<td>Decrease, jump</td>
</tr>
<tr>
<td>H_1 &gt; H_2</td>
<td>Increase, jump</td>
<td>Increase</td>
<td>–</td>
<td>Increase</td>
</tr>
<tr>
<td>Undercut</td>
<td>Decrease</td>
<td>Increase</td>
<td>–</td>
<td>Relies on the comb finger</td>
</tr>
</tbody>
</table>

due to the fabrication tolerances as discussed in the previous section.

3.1. Profiles of the comb fingers and folded beam

As discussed in Section 2.1, trenches with different widths have different profiles. Let \( \alpha \) be the slope angle of the comb finger (positive in this case) and \( \beta \) be the slope angle of the folded beam (negative due to the reentrant structure) as shown in Fig. 6a and c, respectively. Fig. 6b and d is the SEM micrographs of the comb fingers and the folded beam. Assuming that the top gap between two comb fingers is \( g_0 \), then the gap between two adjacent comb fingers is a function of the height, \( h \), and can be expressed as:

\[ g(h) = g_0 - 2h \tan \alpha \]

(4)

Accordingly, the capacitance changes to:

\[ C_{\text{slope}} = \int_0^H \frac{2n(hL_3 + \Delta x)}{g(h)} dh = \int_0^H \frac{2n(hL_3 + \Delta x)}{g_0 - 2h \tan \alpha} dh = \frac{n(\alpha \Delta x + \Delta x)}{\tan \alpha} \ln \left( \frac{g_0}{g_0 - 2H \tan \alpha} \right) \]

(5)

where \( dC \) is the micro capacitance of a small section with height of \( dh \). Therefore, when the same voltage is applied, the ratio of the electrostatic force generated by the sloped comb fingers to that of the vertical fingers is expressed as:

\[ \frac{F_{\text{slope}}}{F_{\text{design}}} = \frac{\alpha \Delta x_{\text{slope}}}{\Delta x_{\text{design}}} = \frac{\alpha \Delta x_{\text{slope}}}{\Delta x_{\text{design}}} = \frac{\alpha \Delta x_{\text{slope}}}{\Delta x_{\text{design}}} = \frac{\alpha \Delta x_{\text{slope}}}{\Delta x_{\text{design}}} = \frac{\alpha \Delta x_{\text{slope}}}{\Delta x_{\text{design}}} = \frac{\alpha \Delta x_{\text{slope}}}{\Delta x_{\text{design}}} \]

(6)

Fig. 7 shows that the relative electrostatic force is a function of the slanted angle \( \alpha \) under the conditions of \( H = 50 \mu m \) and \( g_0 = 2.5 \mu m \), where \( \alpha \) varies from \(-1.0^\circ \) to \(+1.0^\circ \). It shows that the electrostatic force generated by the negatively sloped comb finger is smaller and verse to positive sloped comb finger, which is more significant. For instance, only 0.758 electrostatic force is generated when the comb finger has an angle of \(-1.0^\circ \), but...
Fig. 6. DRIE etched sloped beams: (a) schematic of cross section of the narrow trench comb fingers, (b) SEM micrograph of the comb finger, (c) schematic of cross section of the wide trench folded beam and (d) SEM micrograph of the sloped folded beam.

Fig. 7. Relative electrostatic force vs. angle of comb finger.

this force increases by 1.716 times when the comb finger has an angle of $+1.0^\circ$.

Similarly, imperfect vertical profile can be observed for the folded suspension beam inducing the deviation of the stiffness and stability of the actuator. The top width and height of the trapezoidal cross-section of the beam are $b_0$ and $H$, respectively, while the cross profile has an angle of $\beta$ as shown in Fig. 6c and d. The width of the folded beam becomes the function of the depth as expressed as:

$$b(t) = b_0 + 2t \tan \beta \quad (7a)$$

The second moment of inertia $I_z$ can be rewritten as:

$$I_{z,\text{slope}} = \frac{H}{12} \left( b_0^3 + 3Hb_0^2 \tan \beta + 4H^2b_0 \tan^2 \beta + 2H^3 \tan^3 \beta \right) \quad (7b)$$
The stiffness ratio along the lateral direction of the slanted beams to the vertical beam is:

$$k_{x\text{slope}} = \frac{b_0 + 3Hb_0^2 \tan \beta + 4H^2b_0 \tan^2 \beta + 2H^3 \tan^3 \beta}{b_0}$$

(7c)

Fig. 8 shows the normalized stiffness along the lateral direction with tapered profile under the conditions of $b_0 = 2.5\, \mu m$ and $H = 50\, \mu m$. The stiffness of negatively sloped folded beam decreases, while it increases non-linearly with a positively sloped beam. The stiffness decreases to only 36% when $\beta$ is equal to $-1.0^\circ$ and rises by 2.62 times for folded beam with $\beta$ of $+1.0^\circ$.

The stability of the comb-drive actuator evaluated by the ratio of stiffness along transverse and lateral direction is also influenced by the tapered deep etched folded beam. The relative stiffness along transverse direction is expressed as:

$$\frac{k_{x\text{slope}}}{k_{x\text{design}}} = \frac{b_0 + H \tan \beta}{b_0}$$

(8)

The stiffnesses along lateral and transverse directions decrease with positive angled beam at different speed, which affects the stability of the system. The relative stiffness ratio between transverse direction and lateral direction is expressed as:

$$\frac{k_{x\text{slope}}}{k_{y\text{slope}}} = \frac{k_{x\text{slope}}}{k_{x\text{design}}} \times \frac{k_{y\text{slope}}}{k_{y\text{design}}}$$

$$\frac{k_{x\text{slope}}}{k_{x\text{design}}} = \frac{b_0 + 2b_0H \tan \beta + 2H^2 \tan^2 \beta}{b_0}$$

(9)

The stability gauged by the stiffness ratio with sloped profile under the same condition is shown in Fig. 9, which indicates that the actuator can provide more stable motion when the deep etched folded beams are negatively sloped. The displacement obtained by the slanted comb fingers and the sloped folded beam differs from the designed motion provided by vertical microstructures. The normalized displacement under the external voltage $V$ can be expressed as:

$$\frac{\Delta \text{slope}}{\Delta \text{design}} = \frac{F_{x\text{slope}}}{F_{x\text{design}}} \times \frac{F_{y\text{slope}}}{F_{y\text{design}}}$$

$$= \frac{b_0}{H \tan \alpha} \ln \left( \frac{b_0 + 2H \tan \alpha}{b_0} \right)$$

$$\times \frac{b_0 + 3Hb_0^2 \tan \beta + 4H^2b_0 \tan^2 \beta + 2H^3 \tan^3 \beta}{b_0}$$

(10)

The relative displacement, which is expressed as a function of the slope of the comb fingers $\alpha$ and the folded beam $\beta$, is illustrated in Fig. 10. It shows that outwards comb fingers combining with inwards folded beam provides larger displacement, for example, 4.832 times displacement is achieved when the slope of comb finger $\alpha$ is $+1.0^\circ$ and that of folded beam $\beta$ is $-1.0^\circ$.

The slanted profile also influences the properties of the transverse, vertical and rotational actuators, which can be analyzed in the similar way.
3.2 Uneven deep comb fingers

As shown in Fig. 5, the finger gap of the overlapped portion is smaller than that of the non-overlapped. As a result of the microloading and the notching effect as discussed in Section 2.2, the beam depth of these two parts are different when they are fabricated under the same conditions. Fig. 11a and b are the SEM micrograph and the schematic of the uneven deep comb fingers, respectively. The overlapped part has depth of \( h_1 \) while the non-overlapped part has depth of \( h_2 \). The right finger is movable and located between the two fixed fingers. Either \( h_2 > h_1 \) or \( h_1 < h_2 \) occurs depending on the substrate, which is silicon or SOI and the process employed. The capacitance, electrostatic force and corresponding displacement differ from that of the even depth design. The initial capacitance is expressed as:

\[
C_0 = \frac{2\pi \varepsilon_0 t_0 h_1 L_1}{g_0} \quad (11a)
\]

When \( h_1 < h_2 \) and the displacement along lateral direction is \( \Delta x \), the capacitance is:

\[
C_1 = \frac{2\pi \varepsilon_0 t_0 (L_1 + \Delta x)h_1}{g_0} \quad (0 \leq \Delta x < L_1) \quad (11b)
\]

\[
C_2 = \frac{2\pi \varepsilon_0 t_0 [(\Delta x - L_1)h_2 + 2L_1h_1]}{g_0} \quad (L_1 \leq \Delta x) \quad (11c)
\]

When \( h_1 > h_2 \),

\[
C_1' = \frac{2\pi \varepsilon_0 t_0 [2\Delta xh_2 + (L_1 - \Delta x)h_1]}{g_0} \quad (0 \leq \Delta x \leq L_1) \quad (11d)
\]

When \( 0 \leq \Delta x \leq L_1 \), the electrostatic force under the applied voltage \( V \) is:

\[
F_1 = \frac{\partial}{\partial (\Delta x)} \left( \frac{1}{2} C_1 V^2 \right) = \frac{n \varepsilon_0 V^2}{g_0} h_1 \quad (h_1 < h_2) \quad (12a)
\]

\[
F'_1 = \frac{\partial}{\partial (\Delta x)} \left( \frac{1}{2} C'_1 V^2 \right) = \frac{n \varepsilon_0 V^2}{g_0} [2h_2 - h_1] \quad (h_1 > h_2) \quad (12b)
\]

When \( \Delta x \geq L_1 \),

\[
F_2 = F'_2 = \frac{\partial}{\partial (\Delta x)} \left( \frac{1}{2} C_2 V^2 \right) = \frac{n \varepsilon_0 V^2}{g_0} h_2 \quad (12c)
\]

Substituting the designed force as expressed in Eq. (1), the relative forces can be expressed as:

\[
F_1' = \frac{F_1'}{F_0} = \frac{h_1}{h_0} \quad (H_1 < H_2) \quad (13a)
\]

\[
F'_2 = \frac{F'_2}{F_0} = \frac{2h_2 - h_1}{h_0} \quad (H_1 > H_2) \quad (13b)
\]

when the displacement is less than the initial overlap length, or \( 0 \leq \Delta x \leq L_1 \). The electrostatic force changes abruptly when the displacement is over the initial overlap, or \( \Delta x \geq L_1 \):

\[
F_2' = \frac{F_2'}{F_0} = \frac{h_2}{h_0} \quad (13c)
\]

Fig. 12 shows the relative electrostatic force as a function of the displacement of the comb-drive actuator. The electrostatic force increases abruptly when the displacement is equal to the initial overlapped length no matter which part is deeper. The force is weaker than the designed value when the initial non-overlapped section is shallower than the overlapped part whose depth is equal to the designed value. While the opposite fabrication result will generate a greater electrostatic force when the displacement is over the initial overlapped length. Consequently,
the displacement can be expressed as:

$$\Delta x = \frac{F_1}{k_x} = \frac{n \varepsilon_0 V^2}{8 \varepsilon_{\varepsilon} H_1} (0 \leq \Delta x \leq L_1 \text{ and } H_1 < H_2)$$

(14a)

$$\Delta x' = \frac{F'_1}{k_x} = \frac{n \varepsilon_0 V^2}{8 \varepsilon_{\varepsilon} H_1} (2H_1 - H_1)$$

(0 \leq \Delta x' \leq L_1 \text{ and } H_1 > H_2)$$

(14b)

$$\Delta x_2 = \frac{F_2}{k_x} = \frac{n \varepsilon_0 H_2 V^2}{8 \varepsilon_{\varepsilon} H_1} (0 \leq \Delta x \leq L_1)$$

(14c)

Let $k_x = 1 \mu N/\mu m$, $n = 150$, $g_0 = 2.5 \mu m$ and $\varepsilon = 1.0$, the displacement which is a function of the applied voltage is illustrated in Fig. 13. It shows that the displacement jumps when it reaches the overlapped length. It is more significant when the non-overlapped portion is shallower than the designed depth and the displacement obtained is always less than the designed value.

3.3. Effect of undercut

Undercut is another observed phenomenon during the fabrication as analyzed in Section 2.3, which may affect the performances of the actuator. Let $\Delta a$ and $\Delta b$ denote the undercuts at each side of the comb finger and the folded beams, respectively. When the gap of the consequent finger increases to $g + 2 \Delta a$, a smaller driving force is generated. When the folded beam narrows to $h_1 - 2 \Delta b$, the stiffness along the lateral direction decreases. The displacement depends on the two undercuts. By substituting the gap and beam width to Eq. (3b), the relative displacement can be expressed as:

$$\frac{\Delta x_{\text{undercut}}}{\Delta x} = \left( \frac{b_1}{h_1 - 2 \Delta b} \right)^3$$

(15)

Fig. 14 illustrates the effects on the displacement of the undercuts of the comb finger and the folded beam. The displacement decreases when the undercut is observed on the comb fingers only. However, the displacement increases when the undercut is observed on the folded beams.

Stability changes because of the variation of stiffness along lateral and transverse directions. The relative stability is expressed as:

$$\left( \frac{\Delta x}{\Delta x_{\text{design}}} \right)^2 = \left( \frac{b_1}{b_1 - 2 \Delta b} \right)^2$$

(16)

The relative stability increases with the rise in the undercut because the stiffness along lateral direction decreases faster than that along transverse direction.

The summary of the effects of each individual DRIE fabrication tolerances on the performances of lateral comb-drive actuator is provided in Table 2. Positive slanted comb finger generates greater force as a result of larger capacitance of narrower gap while negative sloped folded beam decreases the stiffness along motion direction. These two effects provide larger displacement than designed corresponding value. Uneven depth of different ports of individual comb finger makes the force and displacement jump when the displacement reaches at the overlap length. The last kind of tolerance, undercut, reduces the electrostatic force and the stiffness along the movement direction as well. These two effects decide the displacement of the actuator. However, in actual experiment, a combination of these fabrication tolerances is observed. To investigate the effects of these fabrication tolerances on the lateral comb-drive actuator, one deep etched planer comb-drive actuator with comb finger gap, $g$ of 2.5 $\mu$m, depth of the released beams, $H$ of 30 $\mu$m, folded beam width, $b_0$ of 2.0 $\mu$m was fabricated. The slope of the comb finger, $\alpha$ is $+1.0^\circ$ and the slope of the folded beam, $\beta$ is $-1.0^\circ$.

The undercut for comb finger, $\Delta a$ is 0.025 $\mu$m and undercut for folded beam, $\Delta b$ is 0.075 $\mu$m. Substituting all the values to Eqs. (10) and (15), the theoretical relative displacement compared to the ideal vertical microstructures is:

$$\frac{\Delta x_{\text{undercut}}}{\Delta x_{\text{design}}} = 3.023$$

(17)
The experimental results are plotted in Fig. 15 and the designed curve is plotted according to \( \Delta x_{\text{nom}} = 0.011 \delta \), which is modified to \( \Delta x_{\text{nom}} = 0.033 \delta \) by considering the fabrication tolerances for comparisons. Consistency between the modified designed curve and the experimental results is observed except at a higher driving voltage range. This is the result of more significant fringe effect because the distance between the finger-tip and the frame of the fixed comb-set is reduced with the motion of the movable comb-set. Additional term of the capacitance of the comb-sets expressed as \( C_{\text{range}} = \frac{1}{2} \varepsilon_0 \left[ \left( 1 + \frac{x}{a} \right)^2 - 1 \right] \) has to be considered [18]. Hence, the electrostatic force becomes to \( F_1 = \frac{1}{2} \varepsilon_0 \left[ \left( 1 + \frac{x}{a} \right)^2 - 1 \right] \left( 1 - \frac{x}{b} \right)^2 \left( 1 - \frac{x}{H_0} \right)^2 \). When the overlap length of the two comb-sets is over 70% of the total length of \( x \), the electrostatic force is no longer quadratic to the applied voltage. It depends on the displacement as well.

4. Conclusions

Various fabrication tolerances of DRIE process are discussed and analyzed. The profile of the deep etched beam depends on trench width and process conditions. Microloading is more significant when the width of the trenches vary much. Hence, the released microstructures have uneven depth and undercut widely exists at DRIE fabrication. All of these tolerances influence the performances of comb-drive actuator, such as the electrostatic force, stiffness, stability and displacement. The electrostatic force increases with positive sloped comb fingers and vice versa. The lateral stiffness decreases dramatically when the folded beam is negatively sloped. The stability changes due to the alteration in the orthogonal stiffness. As a result, the displacement varies according to the profiles of the comb fingers and the folded beams. The uneven depth of the individual comb fingers due to the microloading or notching effect results in an abrupt jump of the electrostatic force and the in-plane displacement when it reaches the initial overlap length. The effect of the third tolerance, undercut is that the displacement increases for most cases as the consequence of cubic relation between the displacement and the width of the folded beam. These analysis results are investigated by the fabricated comb-drive actuator whose profile of the comb finger and folded beam is 89° and the undercutting is 0.025 and 0.075 \( \delta \), respectively. The theoretical displacemen is 3.023 times larger than the designed value based on the tolerance analysis, which agrees well with the experimental results.

These results are useful to analyze the performances of the DRIE fabricated comb-drive actuator and serve as guidance for a predictable design when the tolerance of the fabrication is taken into consideration.

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References

Biographies

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