OPTIMIZED COMB DRIVE FINGER SHAPE FOR SHOCK-RESISTANT ACTUATION

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ABSTRACT

This work presents the analytical solution, realization and measurement of a comb drive with finger shapes optimized for shock-resistant actuation. The available force for actuating an external load determines how large shock forces can be compensated for. An analytical expression is presented for the finger shape that provides a constant large available force over the actuation range. The finger shape is asymmetric, resulting in a 20% smaller unit cell width compared to a symmetric shape. This finger shape provides 4 times more available force than the standard straight finger shape.

INTRODUCTION

Electrostatic comb drives are commonly used as MEMS actuators, and may also be used for actuation in *x*/*y*-positioners (scanners) for probe-storage [1, 2]. Two challenges in using comb drives for a probe-storage scanner are the large required stroke and force. A scanner using a stepped finger shape with improved stroke was reported at Transducers'09 [3]. Shock resistance of the comb drive actuator is important, especially for operation in mobile devices. To compensate shock forces, the actuation force at any given position *x* must exceed the suspension spring restoring force. The available force is equal to the maximum comb drive force minus the suspension springs force,

$$F_{\text{avail}}(x) = F_{\text{comb}}(x, V_{\max}) - kx \tag{1}$$

$$F_{\text{avail}}(x) = \frac{1}{2}N\frac{\partial C}{\partial x}V_{\max}^2 - kx. \tag{2}$$

The minimum value of the available force throughout the displacement range determines the maximum shock force that can be compensated for. A constant available force throughout the comb drive's operating range is the optimal solution for shock resistance and large stroke, combining the highest available force with the largest side-stability.

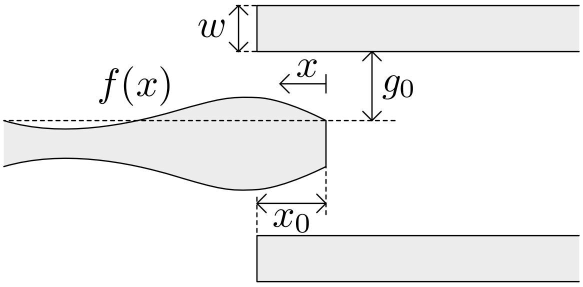


Figure 1: A generic comb drive unit cell with one finger straight and the other (symmetrically) shaped with function $f(x)$. When $f(x)$ is zero, the finger gap equals g_0; x_0 is the initial overlap, x equals zero at the tip of the shaped finger and increases towards the base.

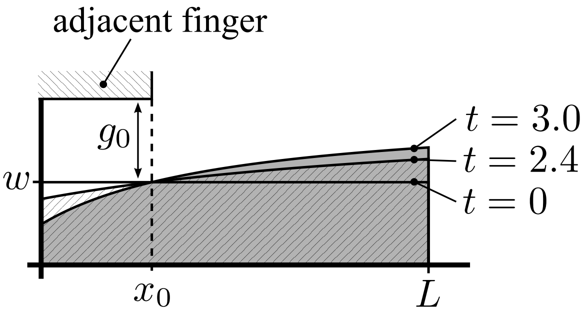


Figure 2: Different finger shapes (eq. (6)) for different suspension spring stiffnesses (indicated by the spring width t; $t = 0$ means zero spring stiffness). The spacing g_0 at the initial overlap x_0 is determined by the fabrication process.

DESIGN

The comb drives available force at every position can be tailored by modifying the finger shape [4, 5]. Jensen *et al.* describe an analytical model for calculating the force of a comb drive with arbitrary finger shapes [4]. The model uses a parallel-plate approximation, giving accurate predictions for comb drive fingers (electrodes) with continuous shapes that are approximately parallel to each other. If one of the fingers is straight (see Figure 1), the capacitance of one comb-drive unit cell is approximated by

$$C = 2\varepsilon_0 h \int_0^{x_0+x} \frac{1}{g(x')}\, dx', \tag{3}$$

where h is the height of the fingers (thickness of silicon), x_0 the initial overlap, x the displacement, and $g(x) = g_0 - f(x)$ the gap profile between fingers. The force of the total comb drive then equals

$$F_{\text{comb}}(x,V) = \frac{\varepsilon_0 h N V^2}{g(x+x_0)}, \tag{4}$$

for a comb drive with N finger pairs and an applied voltage V. Note that the force at location x depends only on the gap at the tip of the straight finger $(x+x_0)$, rather than the complete profile. Intuitively, this can be understood as follows: the force depends on the change in capacitance between the fingers, and the only change in capacitance happens at the tip of the straight finger whose distance to the other finger varies with the displacement.

For shock-resistant constant available force, the comb drive force should equal

$$F_{\text{comb}}(x, V_{\max}) = F_{\text{avail},0} + kx, \tag{5}$$

where $V_{\max}$ is the maximum voltage, $F_{\text{avail},0}$ the available force at $x = 0$, and k the suspension spring stiffness. The maximum value of $F_{\text{avail},0}$ is determined by the initial gap size g_0 as dictated by the minimum etch trench width. Combining equations (4) and (5), we obtain the solution for the optimal shock-resistant finger shape

$$f(x') = w + g_0 - \frac{\varepsilon_0 h N V_{\max}^2}{k(x'-x_0) + F_{\text{avail},0}} \tag{6}$$

$$F_{\text{avail},0} = \frac{\varepsilon_0 h N V_{\max}^2}{g_0}, \tag{7}$$

where x' ranges from 0 (finger tip) to L (base), and w is the finger width at the initial finger overlap x_0. Figure 2 shows this shape for different spring stiffnesses. Note that because both F_{comb} and k are proportional to h, the shape does not depend on the height of the comb drive.

The obtained result is not only valid for symmetrically shaped fingers but also for the asymmetric fingers with one straight edge and one shaped edge shown in Figure 3. The smaller unit cell of the asymmetric fingers results in more force per unit comb drive length. In our case, the asymmetric 'straight/shaped' finger shape leads to 20% reduction in unit cell width, compared to the symmetric finger shape. The unit cell width is equal to a comb drive with straight fingers. Therefore, using the finger shape presented in this work will not increase the footprint of the comb drive, and a fair force comparison is made when comparing the unit cells of standard straight and the shaped fingers. The asymmetric shape leads to a torque on the combs (in Figure 3, the left comb will experience a clockwise torque, the right *vice versa*); this issue can be solved by mirroring the finger shape for one half of the comb drive.

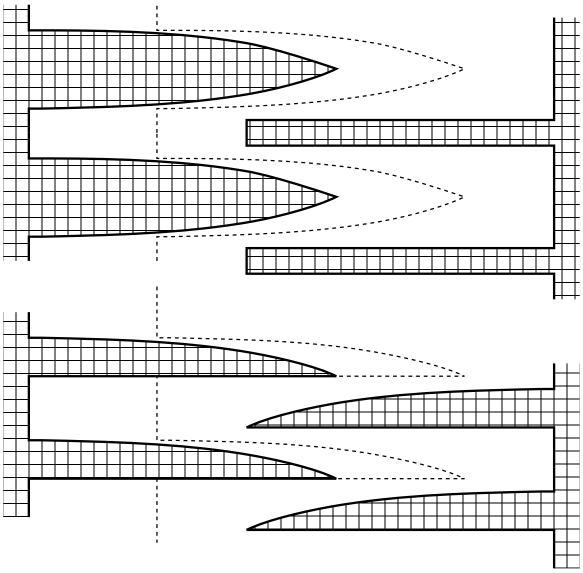


Figure 3: Schematic view of the comb drive geometry with optimized fingers (not to scale). The top drawing represents the initial design; the bottom figure shows the space optimized geometry (20% smaller).

FABRICATION

The comb drives are fabricated from a (100) single-crystal highly-doped silicon-on-insulator wafer, with a 25 μm thick device layer (h) and an oxide thickness of 1 μm. The structures are made by deep reactive-ion etching, after which the (movable) structures are released by HF vapor phase etching of the oxide layer.

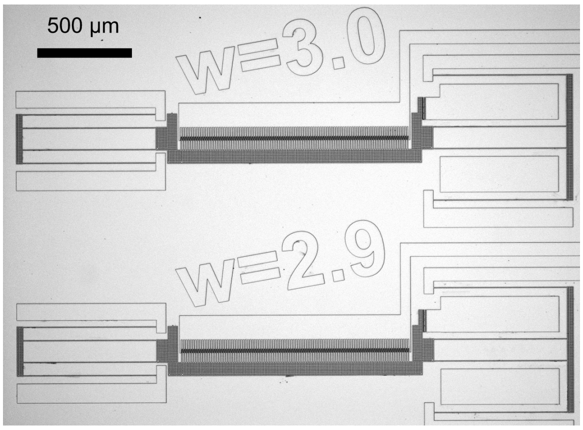
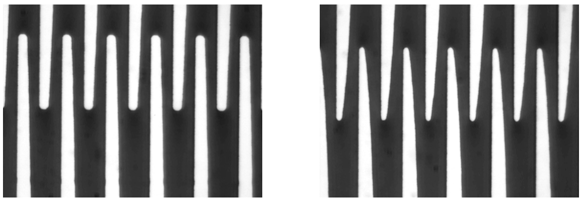


Figure 4: Microscope image of two complete comb drives. The moving structures are perforated for silicon oxide underetch, which is why they appear darker in the image.



(a) $t = 2.4$ µm *(b)* $t = 3.0$ µm

Figure 5: Microscope images of the tips of the fabricated fingers for two different suspension spring widths. The finger overlap equals 20 µm.

Equation (6) is used for the shape of the comb drive fingers; $w = 3$ µm, $g_0 = 3$ µm, $N = 100$ fingers, $V_{\text{max}} = 70$ V, $x_0 = 20$ µm. Identical spring suspensions, with 3 µm spring width, are used for each comb drive, so k is the same for each comb drive. However, for testing purposes, shapes for several values of k are made by varying the spring width t in the calculation of k. Figures 4 and 5 show images of fabricated structures.

RESULTS

The available force curve is measured indirectly from spring deflection measurements at equilibrium voltages V_{eq}. Using the equilibrium condition

$$\frac{1}{2}N\frac{\partial C}{\partial x}V_{\text{eq}}^2 = kx, \tag{8}$$

$\frac{\partial C}{\partial x}$ can be calculated; combining the result with equation (2),

$$F_{\text{avail}}(x) = kx\frac{V_{\text{max}}^2}{V_{\text{eq}}^2}. \tag{9}$$

The obtained spring stiffness $k = 0.83$ N/m after fabrication is calculated from resonance frequency measurements, using $k = m\omega_r^2$.

Figure 6 shows the obtained available force curves of two finger shapes designed for different spring stiffnesses, and the available force of a standard straight comb drive for comparison. The suspension springs width is 3 µm; however, the obtained spring stiffness is slightly larger than expected, causing the curve for the optimal fingers to go slightly downward (‘optim t=3.0’), instead of horizontal; the available force at 35 µm is 4 times larger than for straight fingers.

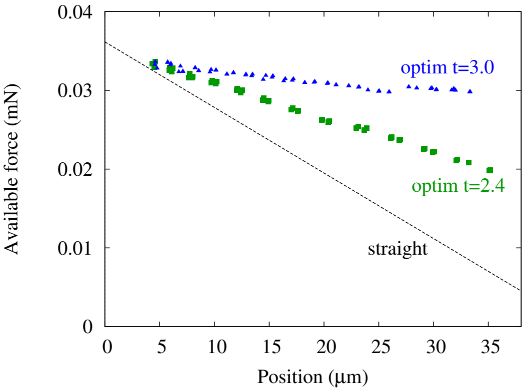


Figure 6: Available force curves, determined from equilibrium displacement measurements, of shaped ‘optim’ fingers. The dashed line is a theoretical curve for the standard straight finger shape.

CONCLUSION

We designed and successfully fabricated comb drives with shaped fingers optimized for shock-resistant actuation. The analytical solution for the optimal finger shape is given in equation (6). The calculation assumes a comb drive with straight fingers on one side and shaped fingers on the other. However, it is also valid for a comb drive where each finger has a straight edge and a shaped edge. This makes it possible to reduce the size of the unit cell as is shown in Figure 3. The unit cell width of the presented finger shape is equal to a comb drive with straight fingers. Measurements on the fabricated structures show that the presented finger shape delivers up to 4 times more available force in the operating range. The available force is a straight line and will be constant if the spring constant of the suspension matches the spring constant used to calculate the finger shape. The finger shape can be used to create comb drives with a large force output and is especially useful in applications where shock-resistant actuation is important.

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