Electrostatic Comb-drive Microactuator

What does it do?

The comb-drive actuator is one of the widely used and well-developed prime movers for microelectromechanical systems (MEMS). It is a reciprocating linear actuator driven by electrostatic force. The stroke length of this actuator is usually in the range of a few microns to a few tens of microns. It is capable of delivering force in the range of μN and up to a few mN with a good design. The stroke length and the force depend on the overall lateral size of the actuator and its thickness.

Historical details, if any.

The electrostatically actuated micromachined comb-drive actuator was developed and prototyped in 1989 by Tang et al. [1, 2].

What does it look like?

The electrostatic comb consists of the following components:

- A *shuttle mass*
- An *array of moving comb fingers* attached to the shuttle mass
- A *suspension* that is anchored to the substrate and attached to the shuttle mass
- An *array of anchored comb fingers*
- *Electrical leads* to supply voltage
- An *extended arm* attached to the shuttle mass to connect to the driven member(s)

A scanning electron microscope (SEM) image of the first comb-drive microactuator is shown in Fig. 1a, which is taken from [1]. All the above components except the extended arm are marked in Fig. 1a. The early version did not have this arm as it was simply intended as a resonator. The later versions, which are intended as actuators, included this arm as it can be seen in Fig. 1b [3]. This contains two comb-drives connected in tandem.

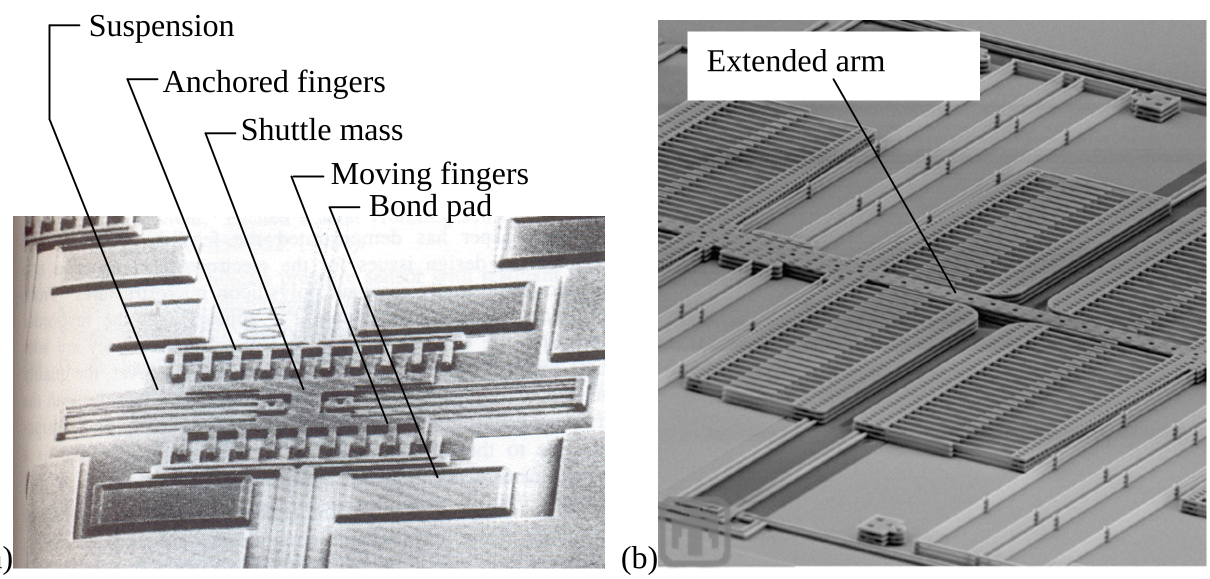
(a)


Figure 1. SEM images of two comb-drive microactuators (a) one of the first prototypes reported by Tang et al. [1], (b) a more recent one built by Sandia laboratories [3].

The components are also marked in the schematic shown in Fig. 2.

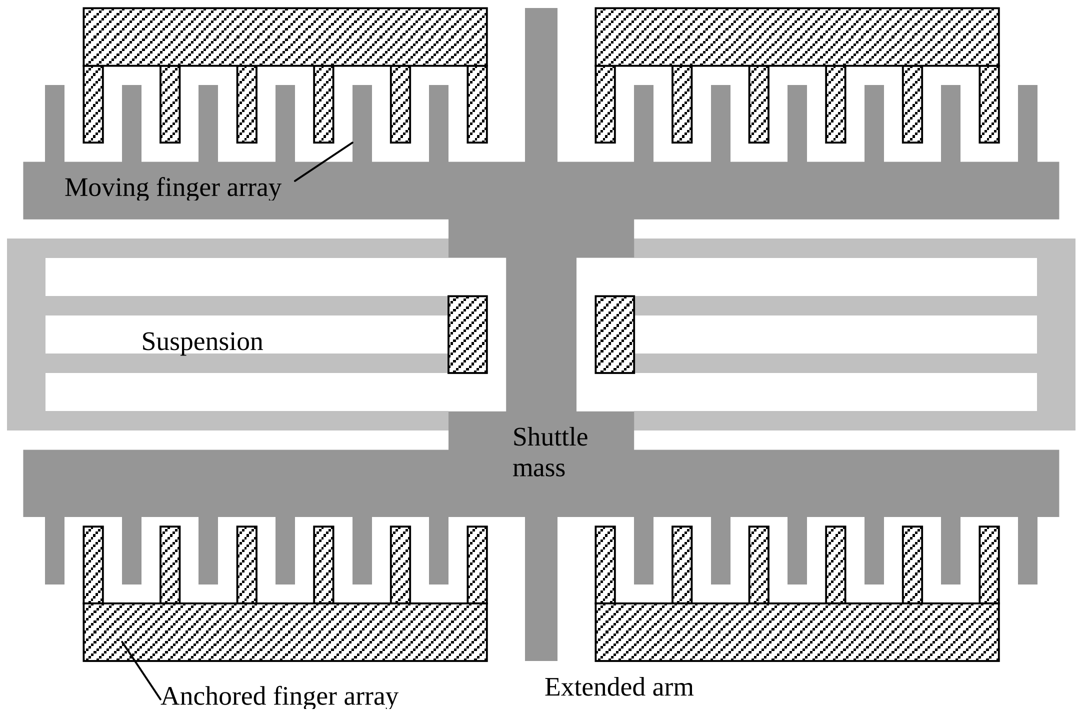


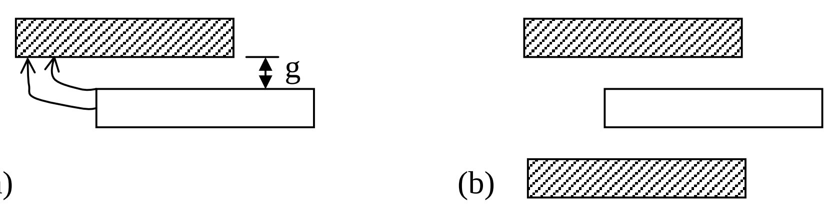
Figure 2. Schematic of the comb-drive actuator

What is the principle of operation?

The comb-drive actuator works on the basis of electrostatic force acting between a pair of misaligned comb fingers. Consider two prismatic solids whose top view is shown in Fig. 3a. As depicted in the figure, assume that they are misaligned in the longitudinal direction with voltage applied between them. Then, there will be an electrostatic force as indicated approximately by the field lines. If one of the fingers is held fixed, the other will then be moved so as to align them. This is how the motion is created in this device. The force of attraction between the fingers is given by the following formula.

$$F_e = \frac{\varepsilon_0 t V^2}{2g}$$

where F_e is the electrostatic force, ε_0 is the permittivity of free space, t is the thickness of the fingers, V is the applied voltage, and g is the gap between the fingers.



(a) (b)

Figure 3. Principle of operation of the comb-drive (a) a pair of fingers with electrostatic force interaction (b) two pairs with two anchored fingers.

The force between two fingers is very small. It helps to use an inter-digitated configuration with two anchored fingers on either side of the moving finger. This is shown in Fig. 3b. Furthermore, by using an array of moving and anchored fingers, the generated force is made larger. But the stroke length is limited by the permitted displacement of the moving fingers.

All the moving fingers are attached to a mass, a rectangular block. An array of moving fingers is attached to the mass on either side as can be seen in Figs. 1 and 2. There are also corresponding anchored array of comb fingers on either side. By keeping the mass and the moving fingers at ground voltage and alternatively actuating the anchored comb arrays on either side, the mass can be shuttled forward and backward. Hence, it is called a shuttle mass. This is suspended freely above the substrate wafer by means of a suspension. The suspension is designed such that it provides significant elastic flexibility to move in the intended direction but significant stiffness in the perpendicular direction in the lateral plan. This enables the mass to be guided along a straight line as it is sliding in a slot. Having a slot in a micromachined structure is not a good idea because of the friction and wear problems, which are dominant at the micro scale.

Scaling issue: does it have to be made at the micron scale?

To see how the ratio of the stroke length to the overall size of the actuator scales for a fixed voltage, consider a simplified lumped-model of the comb-drive as a spring-mass system. The mechanical stiffness of the suspension in the direction of the movement is denoted by k and has the form (to be derived later):

$$k = \frac{2Etw^3}{l^3}$$

where l is the length of the suspension, w is its width, and t its thickness, and E is the Young's modulus of the material. Assuming N force interactions between pairs of fingers, the electrostatic force is given by

$$F_e = \frac{N\varepsilon_0 tV^2}{2g}$$

Then, the displacement of the shuttle mass will be

$$\delta = \frac{F_e}{k} = \left(\frac{N\varepsilon_0 V^2}{4E}\right)\frac{l^3}{gw^3}$$

from which we can write relative deflection taking the length of the suspension beams as the indicator of the overall size.

$$\frac{\delta}{l} = \left(\frac{N\varepsilon_0 V^2}{4E}\right)\frac{l^2}{gw^3} \propto L^{-2}$$

It can be seen that for a fixed voltage, the relative deflection scales as L^{-2}. This means that the stroke length dramatically increases with downsizing whereas it would be negligibly small when it is made at the large size scale.

Another way to look at this is by looking at the voltage for a desired relative stroke length as shown below.

$$V = \sqrt{\left(\frac{\delta}{l}\right)\left(\frac{4E}{N\varepsilon_0}\right)\left(\frac{gw^3}{l^2}\right)} \propto L$$

Now, the required voltage decreases with decreasing size scale—once again in favor of miniaturization. Thus, it is imperative that the comb-drive be micromachined with micron dimensions.

References

1. Tang, W. C., Nguyen T.-H., and Howe, R. T., "Laterally Driven Polysilicon Resonant Microstructures," *Proceedings of the IEEE Microelectromechanical Systems Conference*, February, 1989.
2. Tang, W. C., Nguyen, C., Judy, M. W., and Howe, R. T., "Electrostatic Comb-Drive of Lateral Polysilicon Resonators," *Sensors and Actuators A*, 21 (1), 1990, pp. 328-331.
3. http://mems.sandia.gov/scripts/images.asp