Basic 5
Micro-actuator
- Electrostatic actuator -

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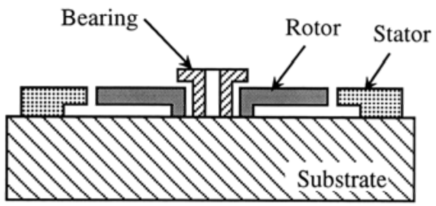
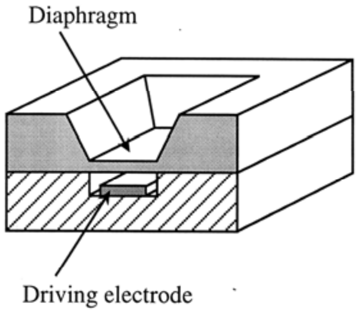
Micro-actuator

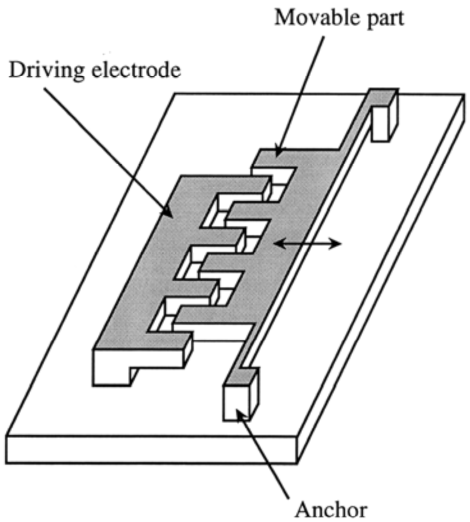
Electrostatic force



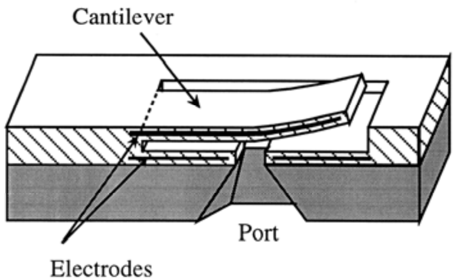
Rotational type



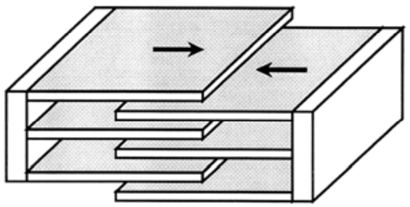
Diaphragm type



Comb drive type



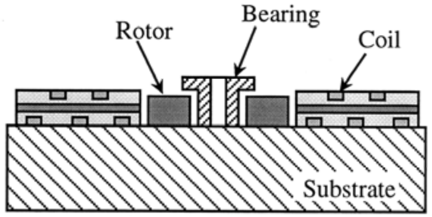
Cantilever type



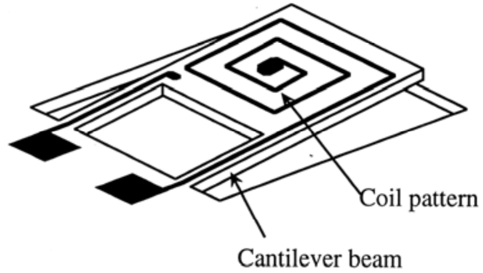
Stacked film type

図 2-2. 静電力駆動アクチュエータのデバイス構造

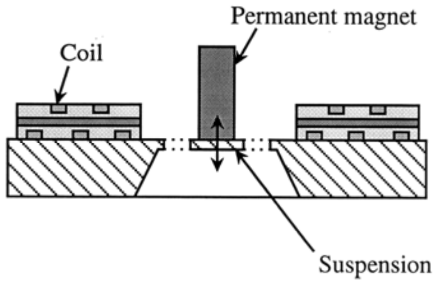
Magnetic force



Rotational type



Cantilever type

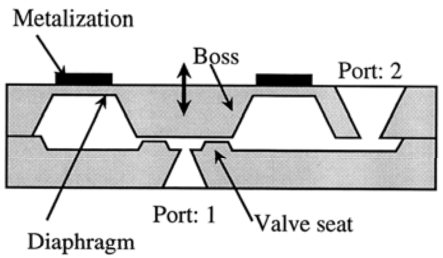


Linear drive type

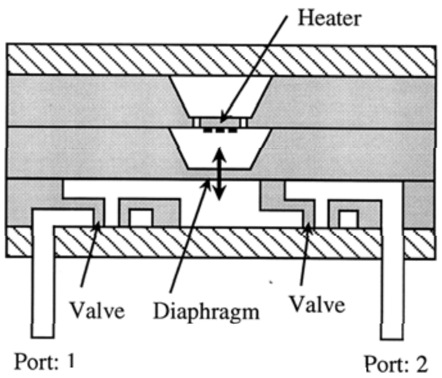
図 2-3. 電磁力駆動アクチュエータのデバイス構造

Micro-actuator

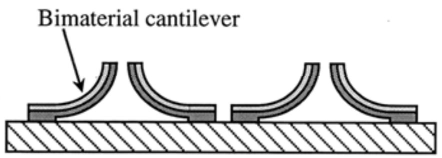
Thermal force



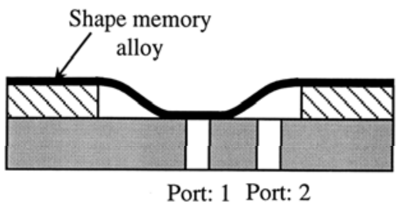
Bi-metal
(Diaphragm type)



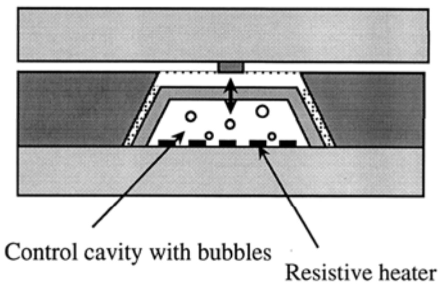
Pneumatic type



Bi-metal
(Cantilever type)



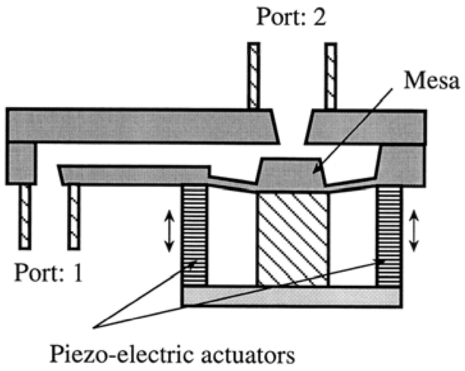
SMA type



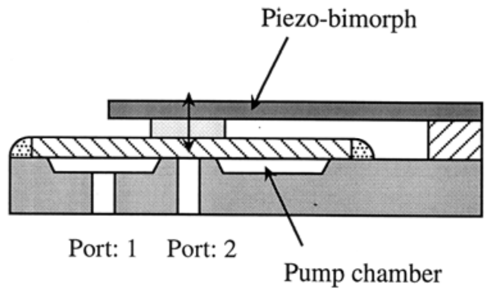
Thermal expansion type

図 2-5. 熱駆動アクチュエータのデバイス構造

Piezoelectric force



Diaphragm type



Cantilever type

図 2-4. 圧電駆動アクチュエータのデバイス構造

Micro-actuator

Comparison of various force applied in Micro-actuator

	Force	Response	Power consumption	Integration
Electrostatic force	＋	＋＋＋	＋＋＋	＋＋＋
Magnetic force	＋＋＋	＋＋＋	＋	＋
Thermal force	＋＋＋	＋	＋	＋＋
Piezo electric force (Stack type)	＋＋	＋＋＋	＋＋	＋
Piezo electric force (Film type)	＋	＋＋＋	＋＋＋	＋＋＋

Electrostatic actuator

The reason why electrostatic force is applied in micro-sized actuator

✓Scale effect
✓Simple structure
✓Compatible with MEMS fabrication process
✓Integration with IC and micro-sensor

Generative force

Comparison between electrostatic and magnetic forces (Force per unit area)

$$U_E = \frac{\varepsilon}{2} E^2,$$

$$U_M = \frac{\mu}{2} H^2,$$

ε: Dielectric constant, E: Electrical field
μ: Permeability, H: Magnetic field

$$E = 3 \times 10^6 (V/m)$$

$$B = 1(T)$$

$$U_E \approx 10^1 (N/m^2)$$

$$U_M \approx 10^5 (N/m^2)$$

Generative force

Scale effect

$$U_E = \frac{\varepsilon}{2} E^2,$$

ε: Dielectric constant, E: Electrical field

↓

$$F_E = \frac{\varepsilon}{2} k E^2 S,$$

k: Constant, S: Surface area

↓

$$F_E \propto L^2 \quad (@E : const)$$

Generative force

Scale effect

$$U_M = \frac{\mu}{2} H^2,$$

μ: Permeability, H: Magnetic field

$$F_M \propto L^{2\sim 3}$$

(In the case of permanent magnet)

$$F_M \propto L^{3\sim 4}$$

(In the case of electric magnet)

Electrostatic force

Electrostatic energy

$$U_E = \frac{1}{2}QV = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2,$$

C: Capacitance, Q: Charge,
V: Potential

Electrostatic force

$$F_x = -\left(\frac{\partial U_E}{\partial x}\right)_{Q=const}$$

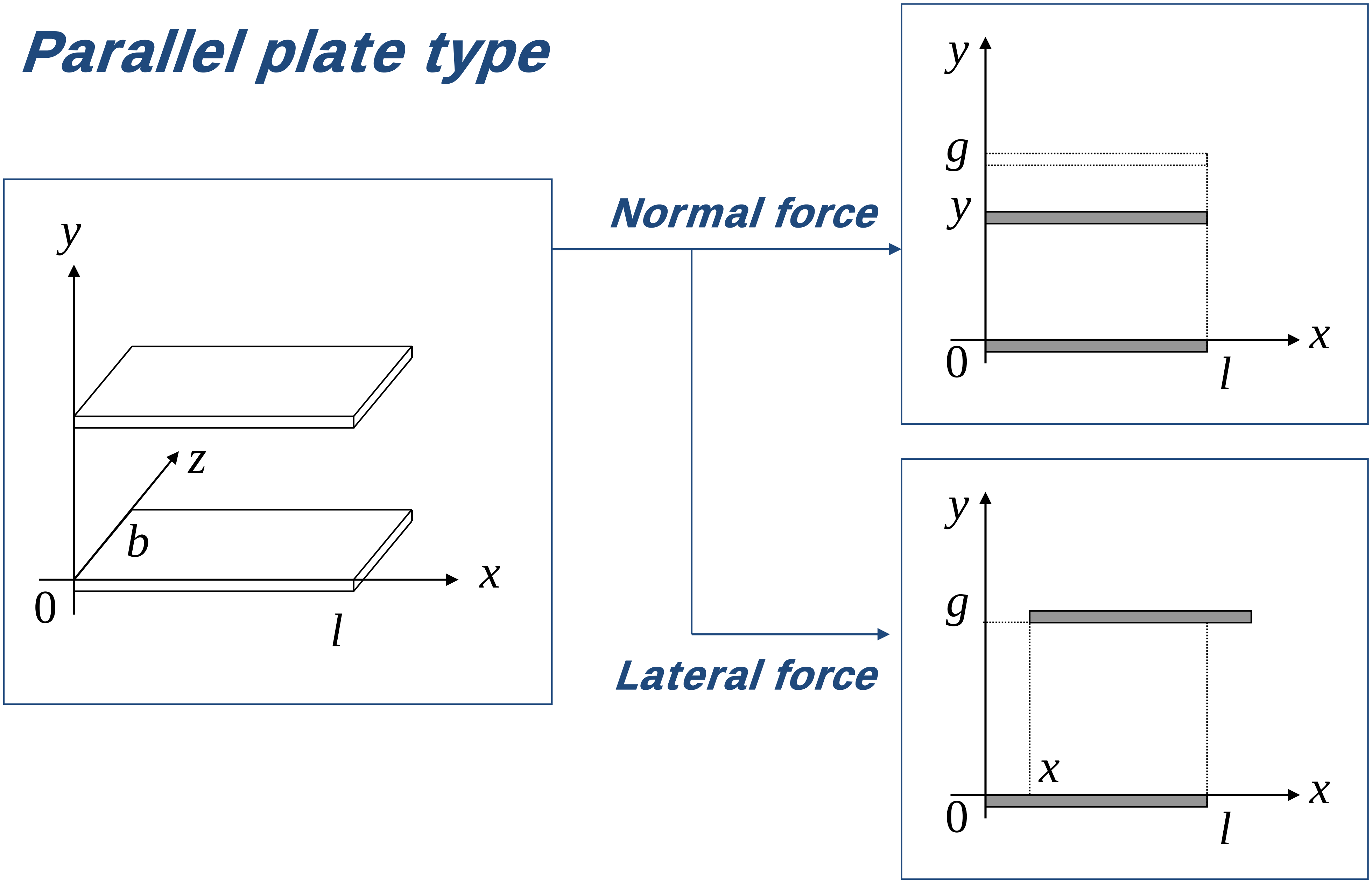
In the case of Q=constant

$$F_x = \left(\frac{\partial U_E}{\partial x}\right)_{V=const}$$

In the case of V=constant
Energy is supplied by electrical power source

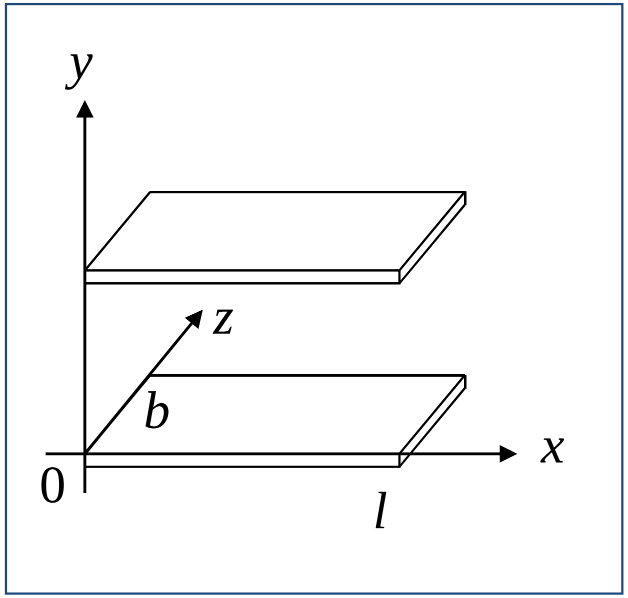
Electrostatic force

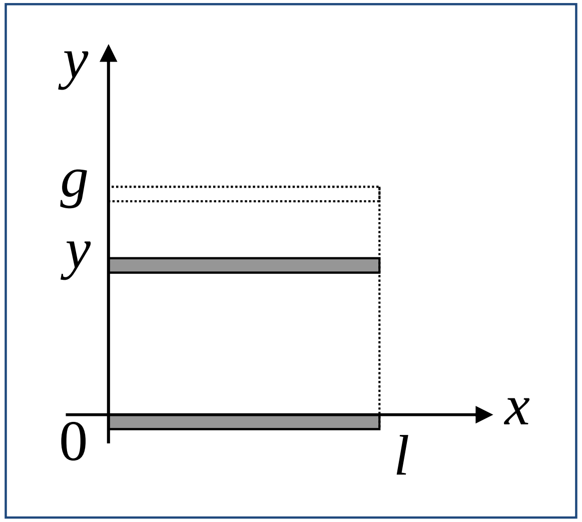
Parallel plate type



Electrostatic force

Normal component force





$$C = \varepsilon \frac{lb}{y}$$

$$U_E = \frac{y}{2\varepsilon lb} Q^2 = \frac{\varepsilon lb}{2y} V^2$$

Force

$[Q = const.]$

$$F_y = -\left(\frac{\partial U_E}{\partial y}\right)_{Q=const} = -\frac{Q^2}{2\varepsilon lb}$$

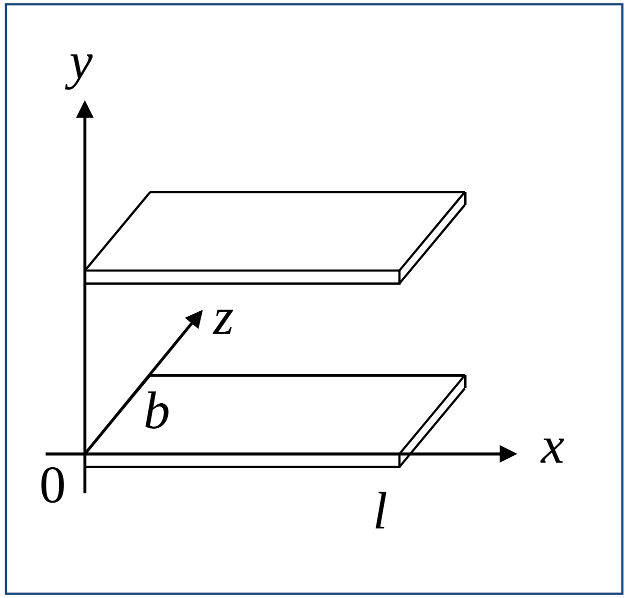
$[V = const.]$

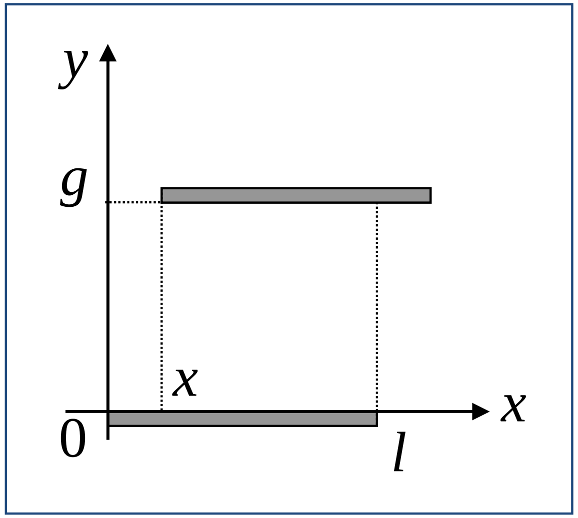
$$F_y = \left(\frac{\partial U_E}{\partial y}\right)_{V=const} = -\frac{\varepsilon lbV^2}{2y^2}$$

Force is inverse square function of distance

Electrostatic force

Lateral component force





$$C = \varepsilon \frac{(l-x)b}{g}$$

$$U_E = \frac{g}{2\varepsilon (l-x) b} Q^2 = \frac{\varepsilon (l-x) b}{2g} V^2$$

Force

$[Q = const.]$

$$F_x = -\left(\frac{\partial U_E}{\partial x}\right)_{Q=const} = -\frac{g}{2\varepsilon (l-x)^2 b} Q^2$$

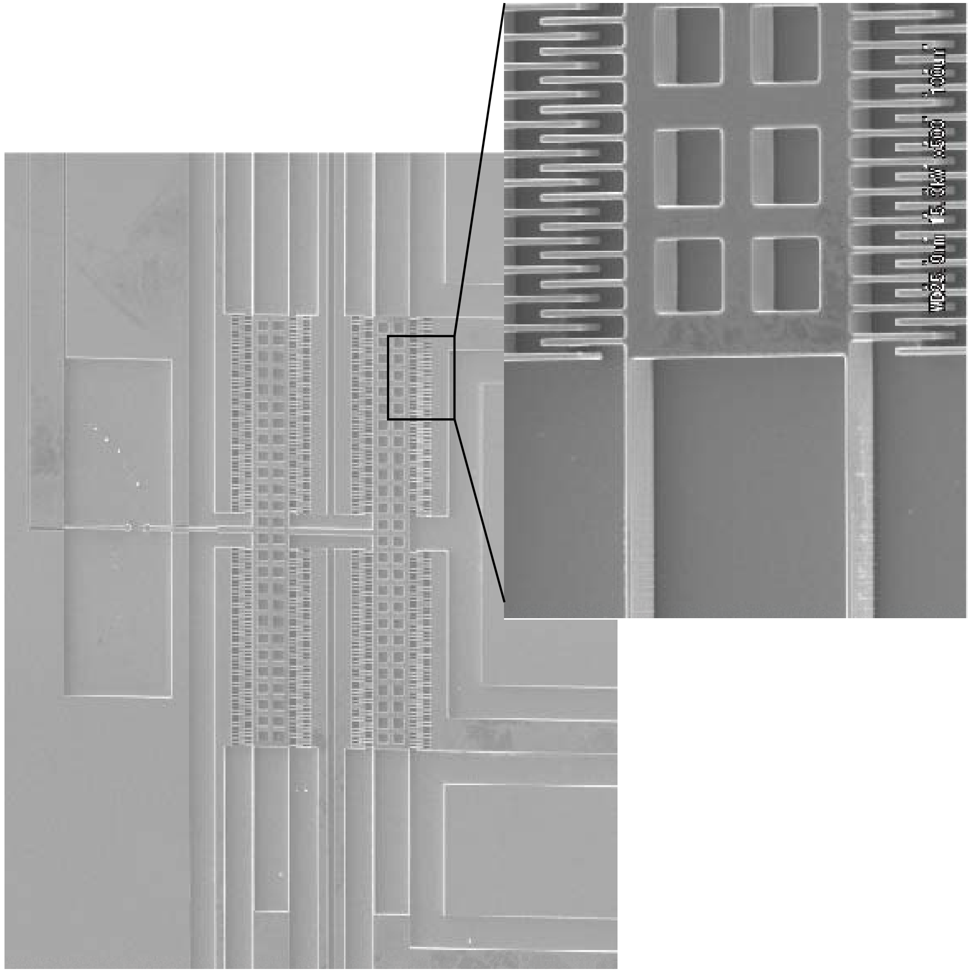
$[V = const.]$

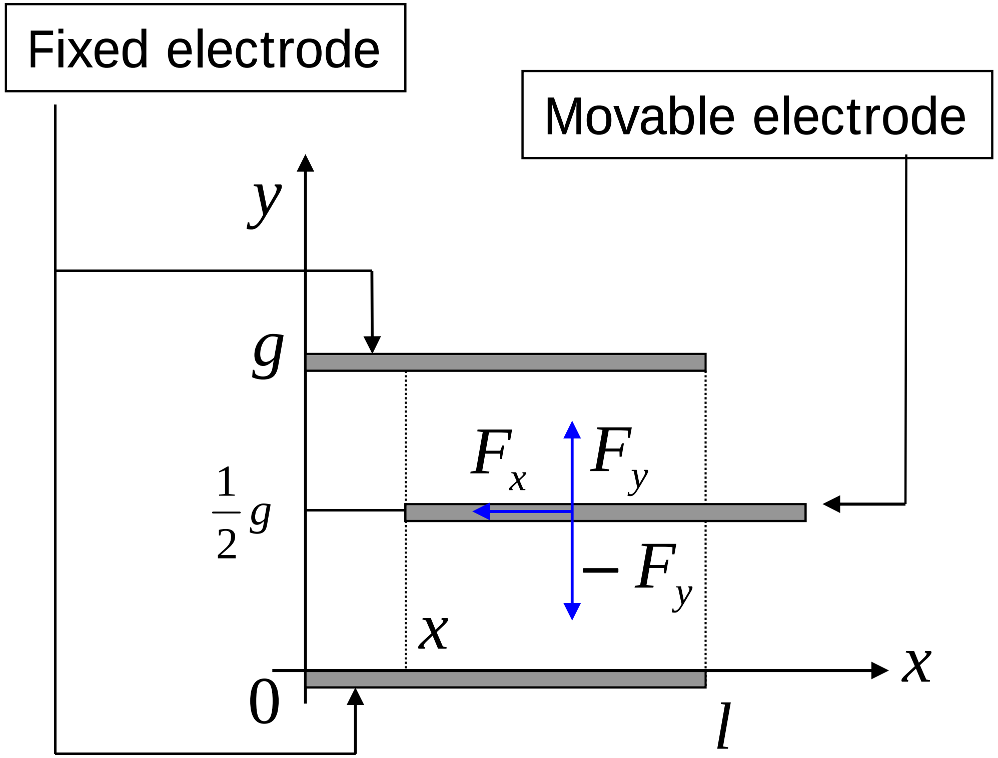
$$F_x = \left(\frac{\partial U_E}{\partial x}\right)_{V=const} = -\frac{\varepsilon b}{2g} V^2$$

Force does not depend on distance

Electrostatic force

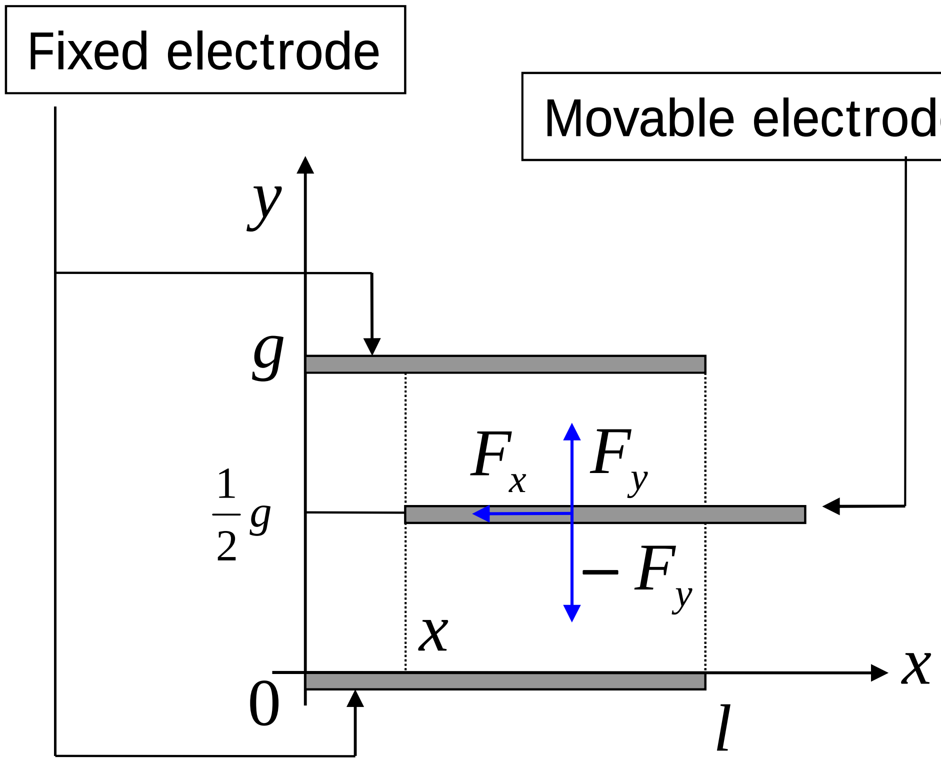
Comb-drive actuator
Lateral movement





Electrostatic force

Comb-drive actuator
Lateral movement



$$C = \frac{4\varepsilon(l-x)b}{g-h}$$

$$U_E = \frac{2\varepsilon(l-x)b}{g-h}V^2$$

$$F_x = \left(\frac{\partial U_E}{\partial x}\right)_{V=const} = -\frac{2\varepsilon b}{g-h}V^2$$

h: thickness of electrode

·Electrostatic force is independent of distance.
·It is proportional of number of electrodes.

Electrostatic force

Comb-drive actuator _ Vertical movement type

$$C = \frac{\varepsilon YZ}{g}, \quad U_E = \frac{\varepsilon YZ}{2g} V^2, \quad F_z = \left(\frac{\partial U_E}{\partial z} \right)_{V=const} = \frac{\varepsilon Y}{2g} V^2$$

Rotational type

$$T_1 \propto \frac{1}{2} \frac{\partial C(\theta)}{\partial \theta} V^2$$

Rotational type (Wobble motor)

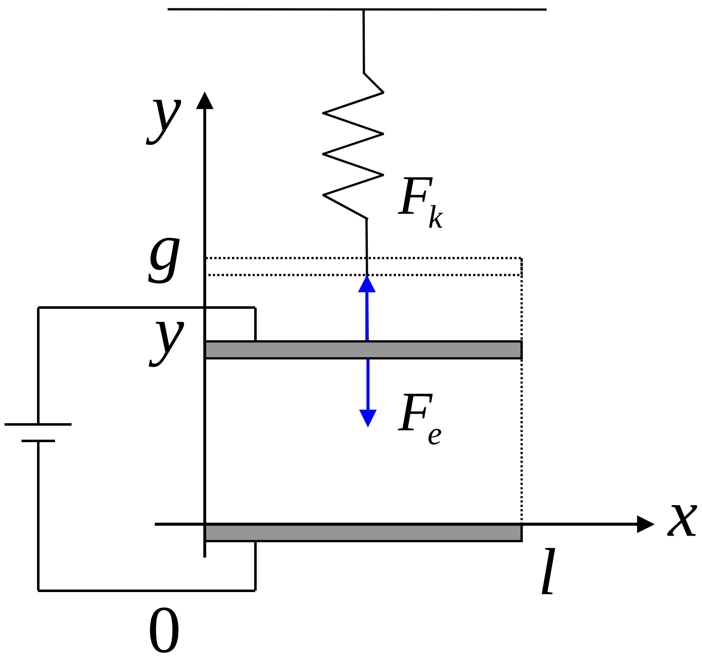
$$T_2 \propto \frac{1}{2n} \frac{\partial C(\theta)}{\partial \theta} V^2, \quad n = \frac{R_i - r_0}{R_i}$$

Torsion bar type

$$C(\theta) = \int_{x_1}^{x_2} \frac{\varepsilon b}{\theta x} dx \rightarrow C(\theta) = \frac{\varepsilon b}{\theta} \log\left(\frac{h}{h - h\theta} \right), \quad U_E(\theta) = \frac{1}{2} \frac{\varepsilon b}{\theta} \log\left(\frac{h}{h - h\theta} \right) V^2$$

Electrostatic force

Pull-in phenomenon



Electrostatic force

$$F(y) = k(g-y) - \frac{\varepsilon l b}{2y^2} V^2$$

Spring force

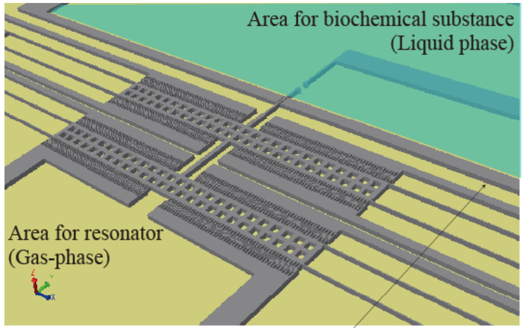
$$F(y) = -k(g-y)$$

Pull-in voltage

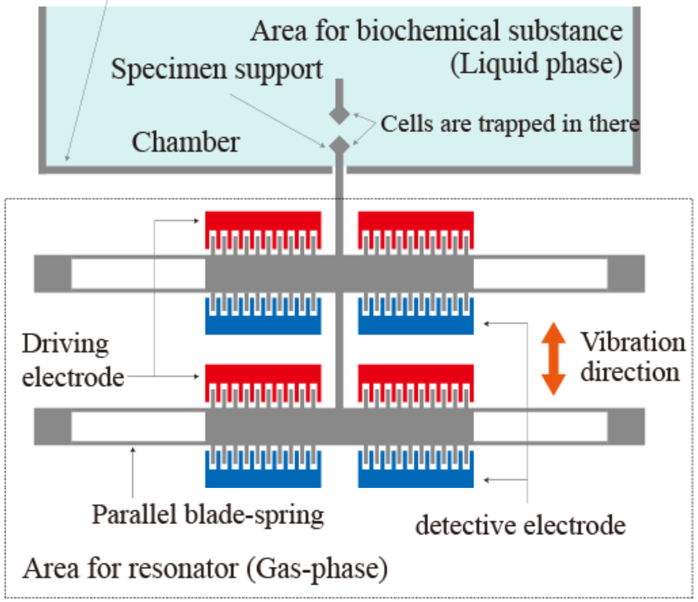
$$V_{pull-in} = \left(\frac{8kg^3}{27\varepsilon lb} \right)^{\frac{1}{2}}, \qquad y_{pull-in} = \frac{2}{3} g$$

Comb-drive-actuator

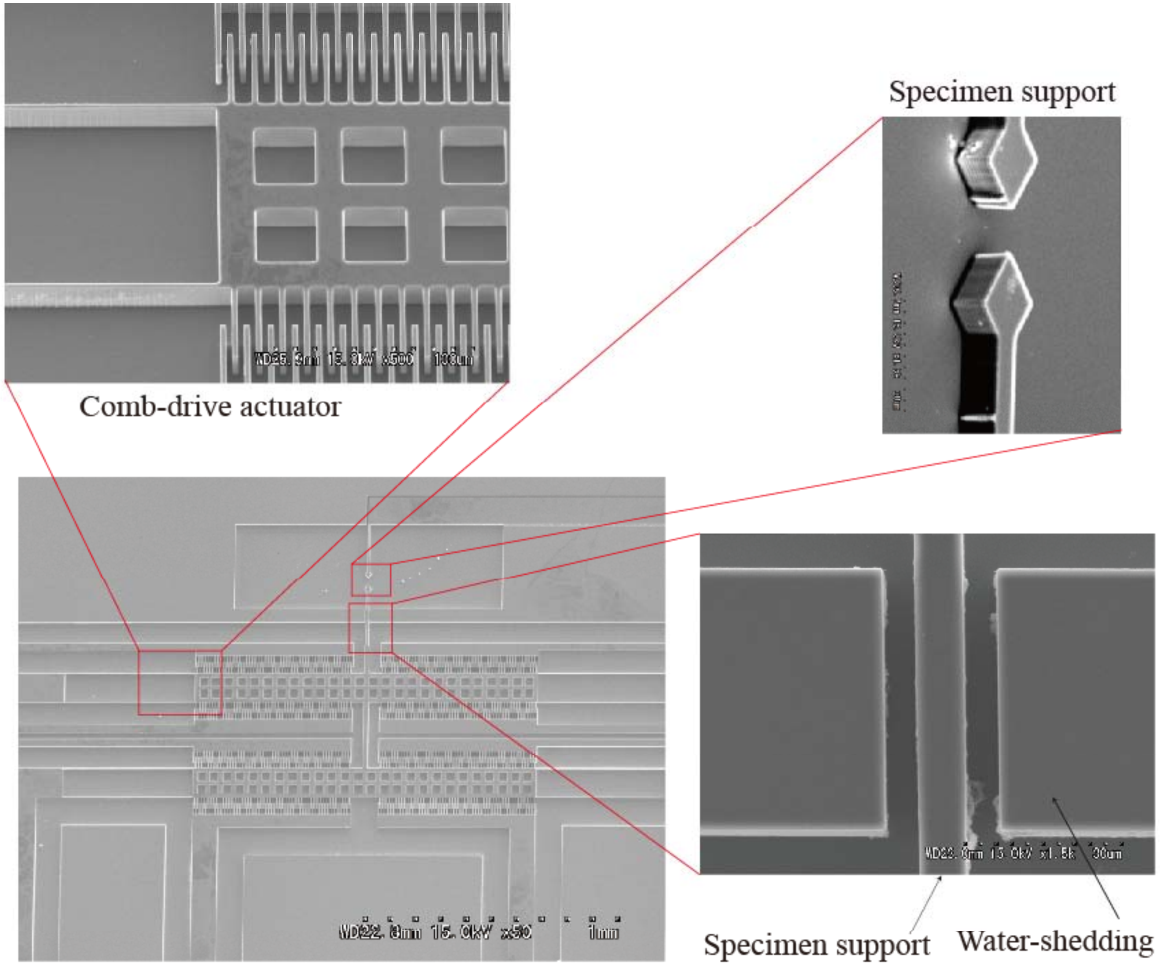
Cell handling based on comb drive actuator



(a) Schematic view of gas-liquid separated resonator



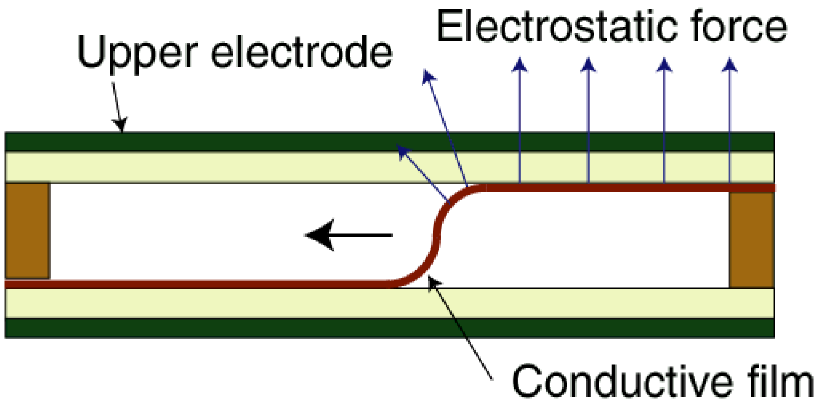
(b) Detailed view of gas-liquid separated resonator



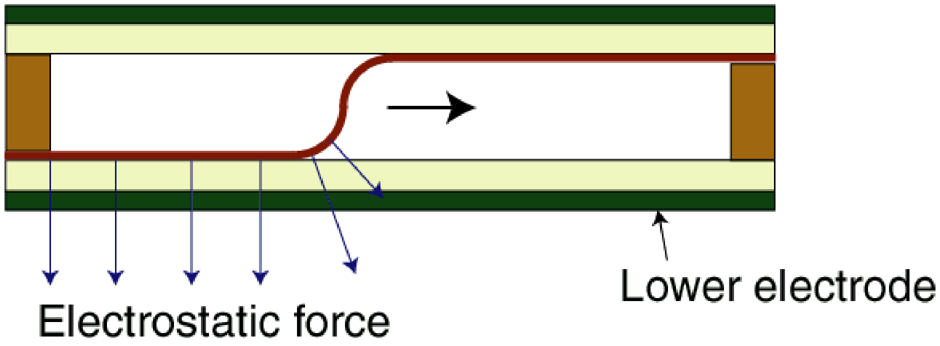
Over view of fabricated gas-liquid separated resonator

H. Hida, et al., Tech. Dig. of IEEE MEMS, 2009, 912-915.

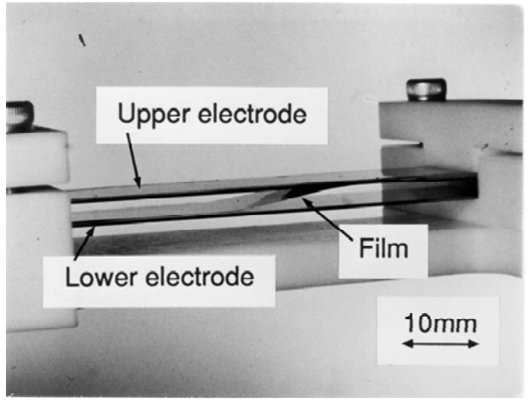
S-shaped film actuator

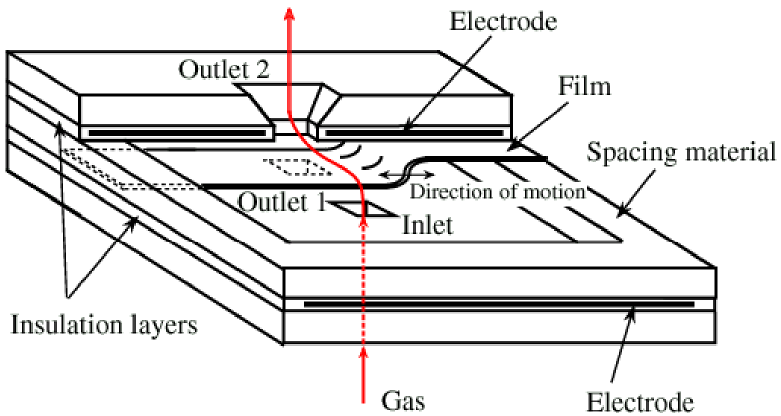


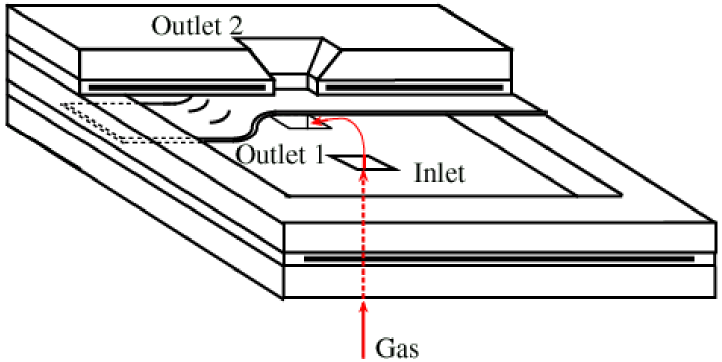
(a) Voltage applied between upper electrode and conductive film.



(b) Voltage applied between lower electrode and conductive film.

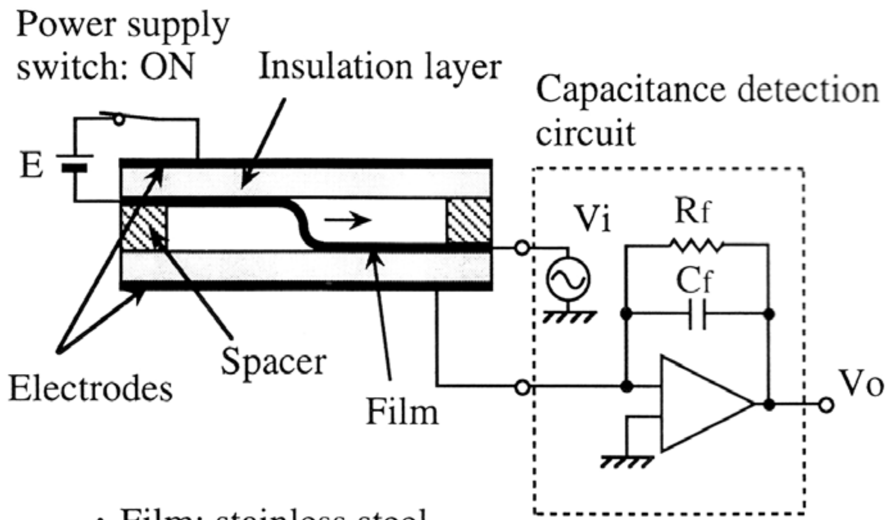






S-shaped film actuator

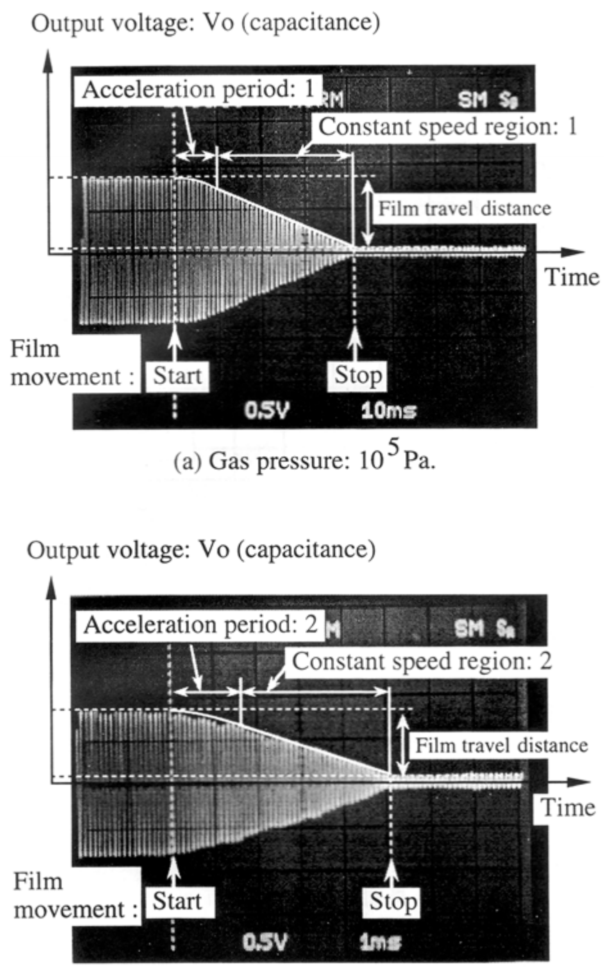
Characteristics in air



- Film: stainless steel
  thickness: 10 µm, width: 12 mm
- Electrode: Si wafer
  thickness: 390 µm
- Insulation layer: SiO_2
  thickness: 1.9 µm
- Spacer: glass plate
  thickness: 2.0 mm

図 2　実験に用いたアクチュエータとフィルムの移動速度測定回路図

Fig. 2. Measurement scheme of film movement.



(a) Gas pressure: 10^5 Pa.

(b) Gas pressure: 10^{-2} Pa.

図 4　フィルムの移動にともなう静電容量検出回路の出力波形の変化

Fig. 4. Measured capacitance change between film and lower electrode (applied voltage: 140 V).

M. Shikida., T. IEE Japan, 116-E, 1996, 395-401

S-shaped film actuator

Characteristics in air

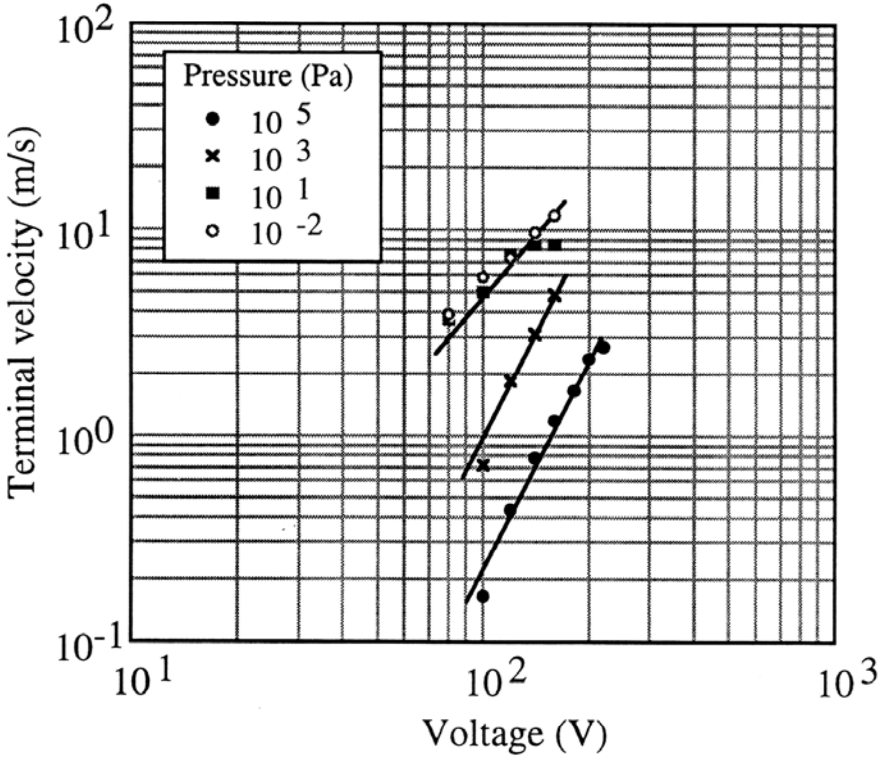


図 7　フィルムの終端速度と駆動電圧との関係

Fig. 7. Relationship between terminal velocity of the S-bend and applied voltage.

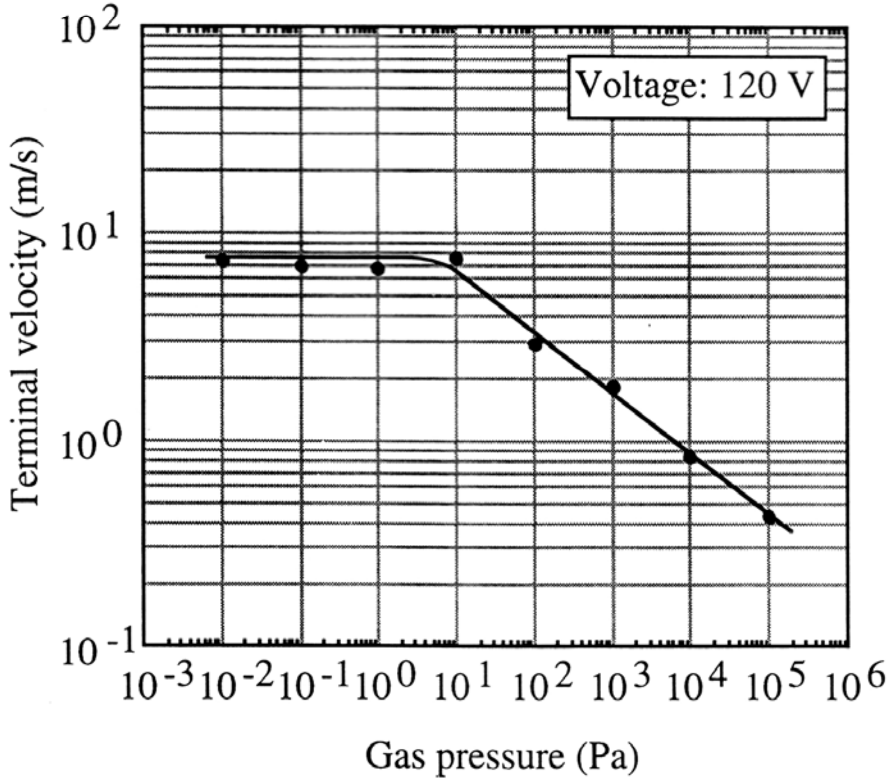


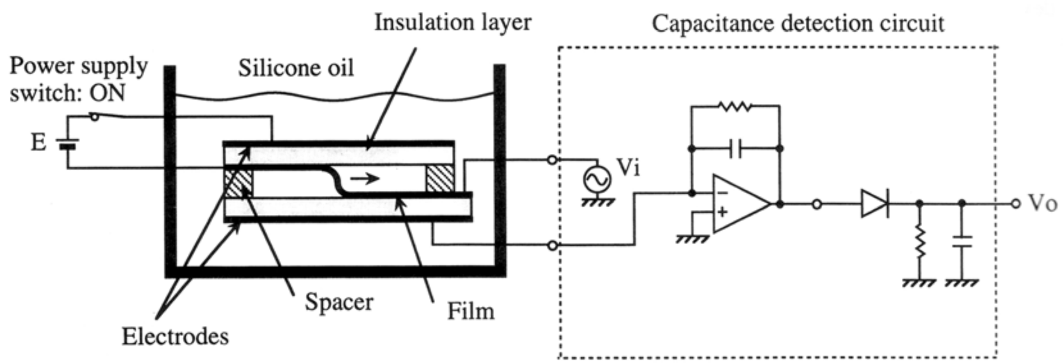
図 8　雰囲気圧力がフィルムの終端速度に及ぼす影響

Fig. 8. Experimental results showing gas pressure dependence of terminal velocity.

M. Shikida., T. IEE Japan, 116-E, 1996, 395-401

S-shaped film actuator

Characteristics in liquid



- Film: stainless steel (thickness: 10-20 μm, width: 12 mm)
- Electrode: Si wafer (thickness: 390 μm)
- Insulation layer: SiO_2 (thickness: 1.9 μm)
- Spacer: glass plate (thickness: 2.0 mm)

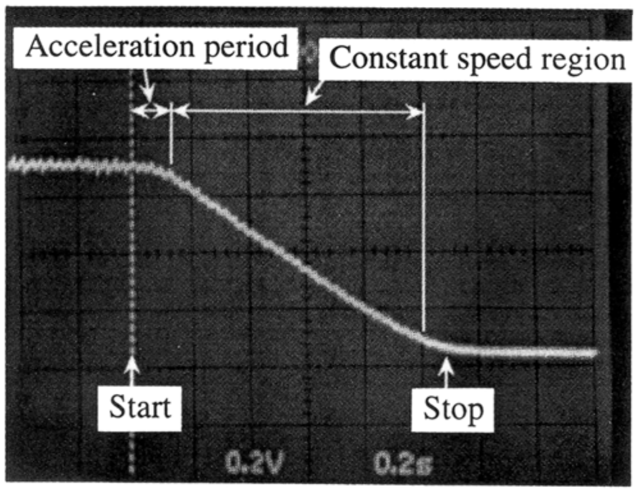
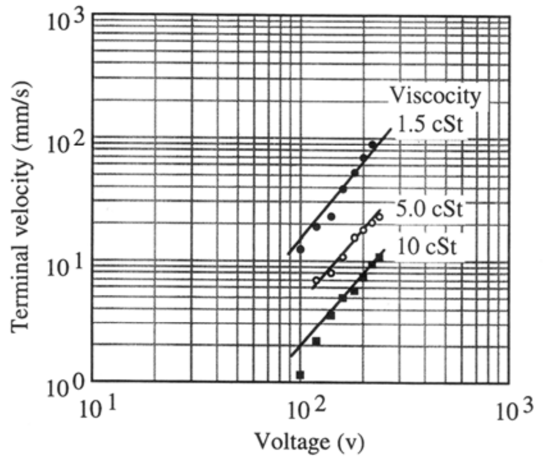


Fig. 3. Measured capacitance change between film and lower electrode (applied voltage: 180V).



(b) Viscosity influence

Fig. 4. Relationship between terminal velocity of the S-bend and applied voltage.

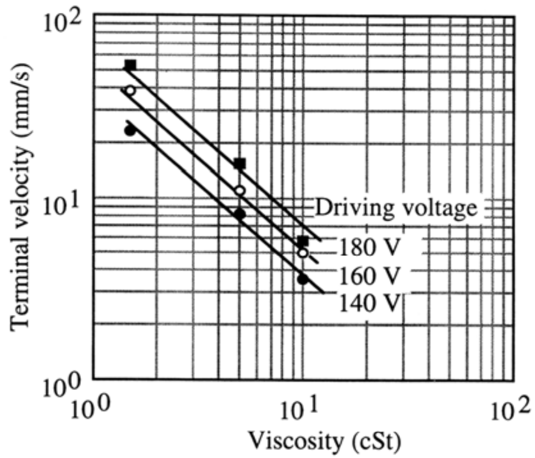


Fig. 5. Relationship between terminal velocity of the S-bend and viscosity.

M. Shikida., T. IEE Japan, 117-E, 1997, 227-231

S-shaped film actuator

Gas valve application

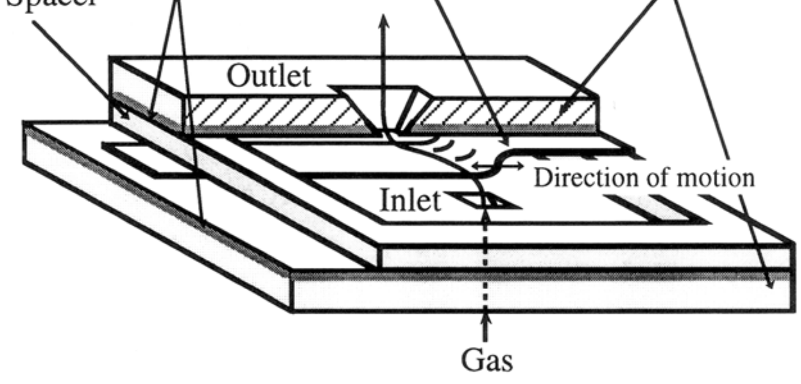


Fig. 1. Configuration of an electrostatically-driven two-port valve.

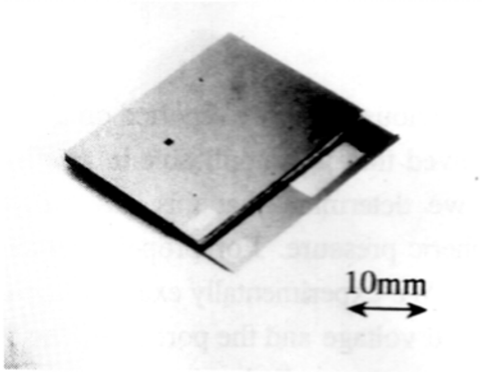


Fig. 2. Photograph of an experimental model.

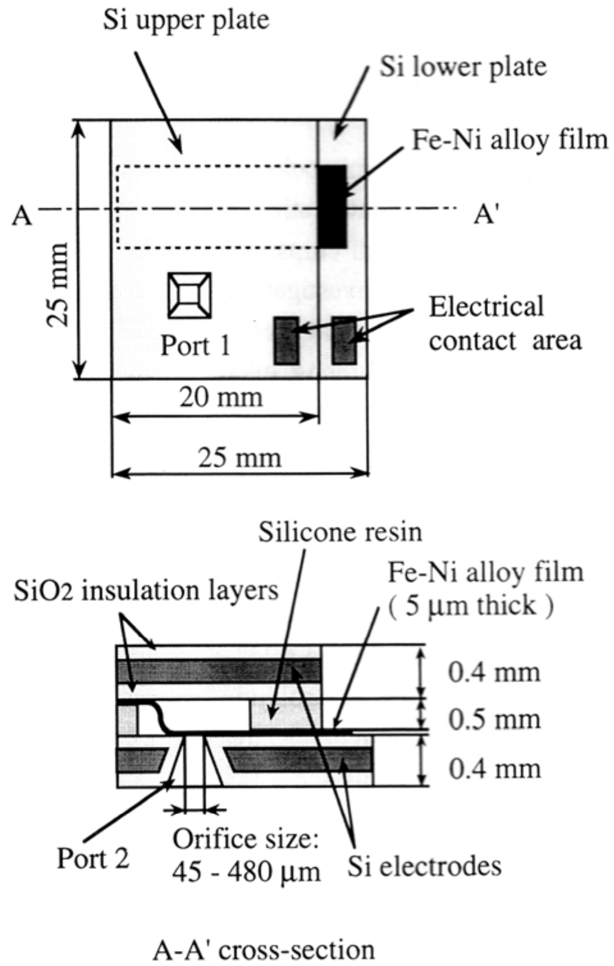


Fig. 3. Schematic top view and cross-section of an experimental model.

M. Shikida., T. IEE Japan, 116-E, 1996, 219-223

S-shaped film actuator

Gas valve application

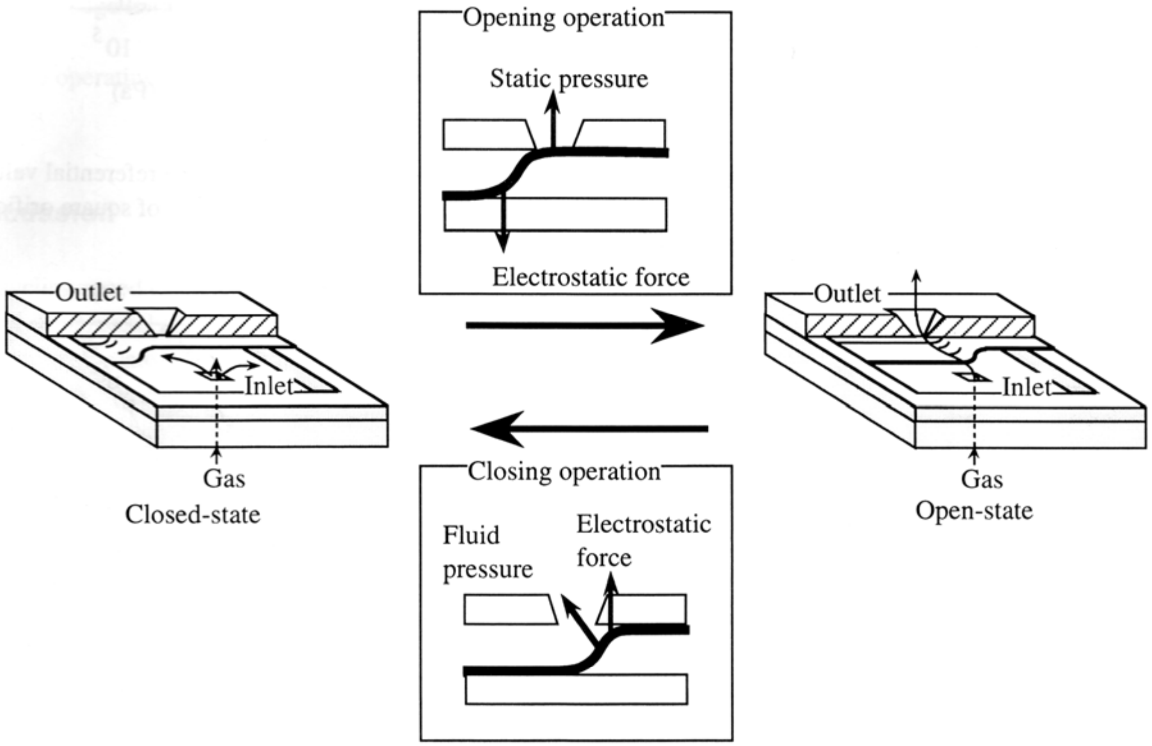


Fig. 5. Relationship between the electrostatic force and fluid pressure during valve operation.

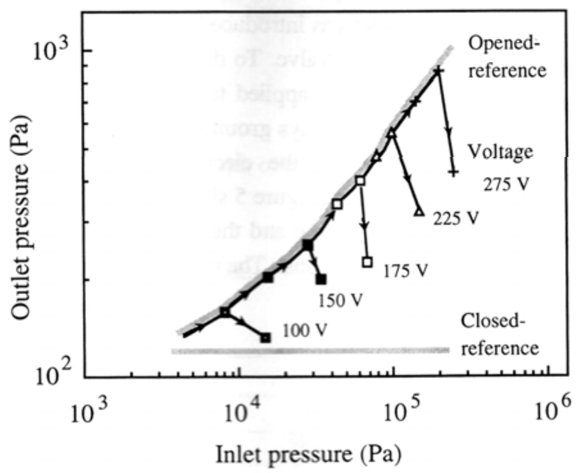


Fig. 7. Relationship between the referential values and outlet pressure (edge length of square orifice: 275 μm).

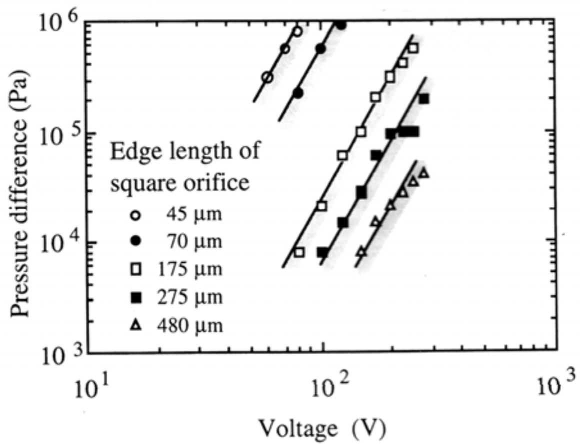
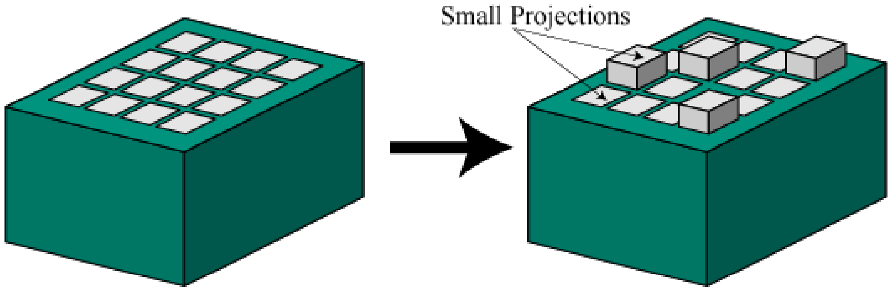


Fig. 8. Valve operating ranges (pressure difference vs. dc voltage) for various orifice sizes.

M. Shikida., T. IEE Japan, 116-E, 1996, 219-223

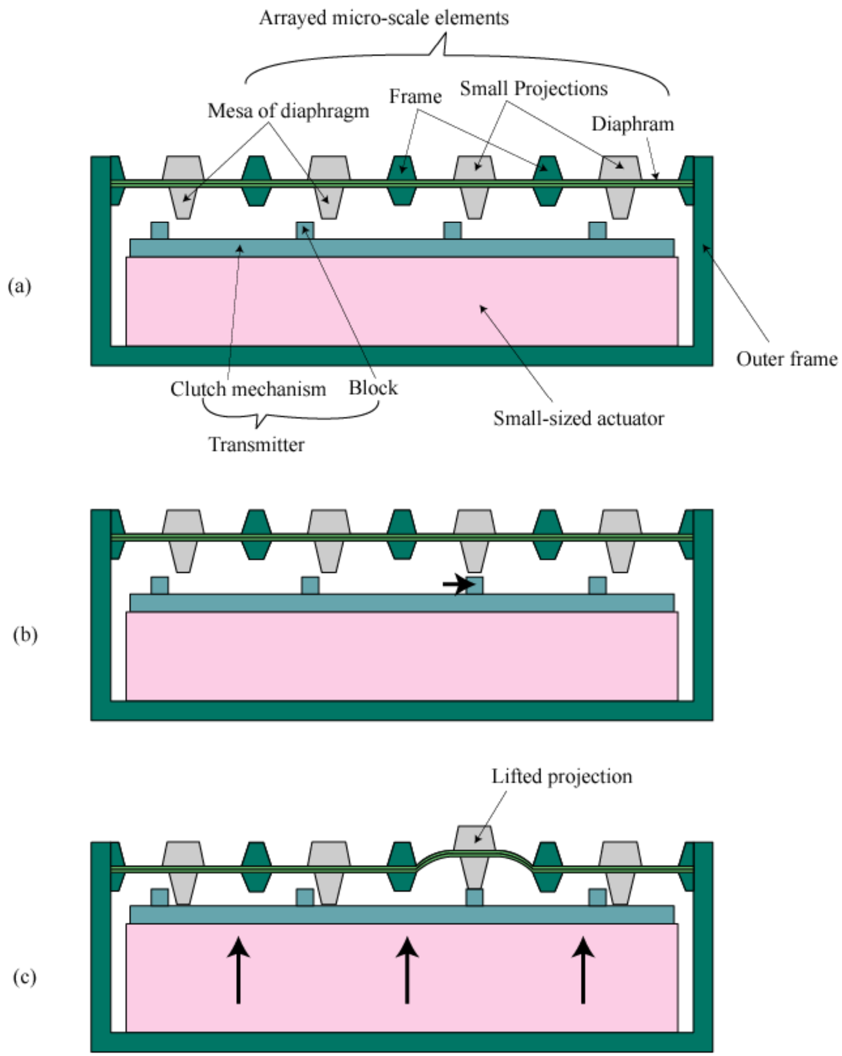
Tulip-shaped actuator for haptic display

Haptic display



Display
Clutch produced by micro-actuator
Stepping motor

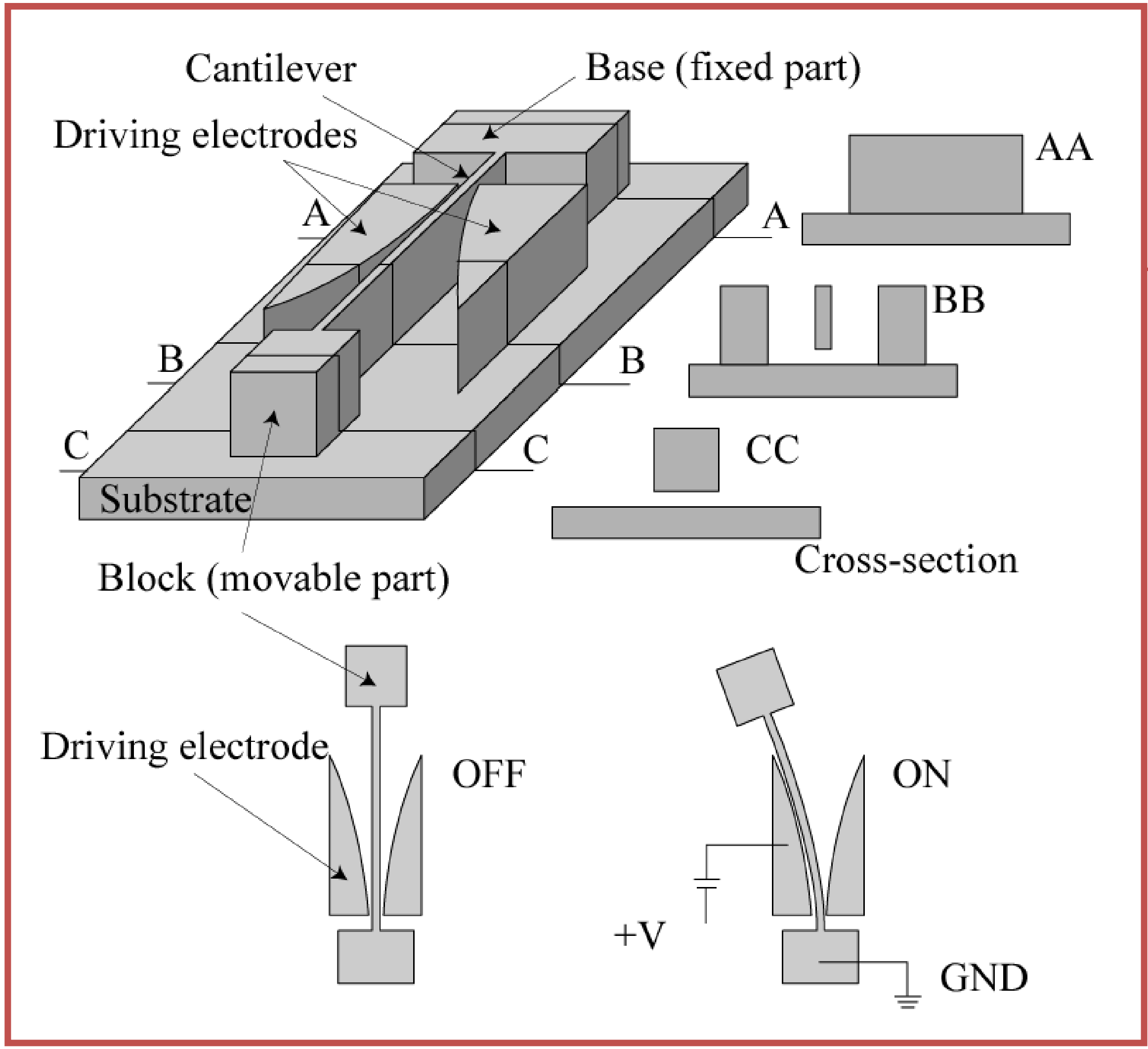
Operation principle

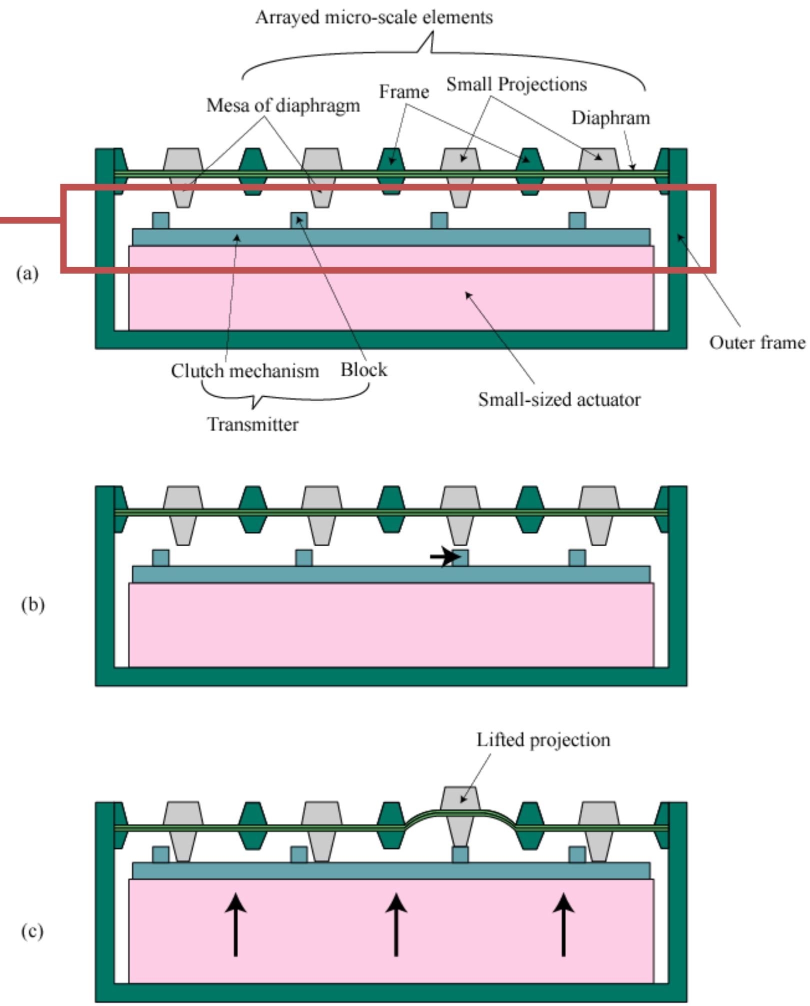


H. Sasaki, et al., J. Micromech. Microeng., 16, 2006, 2673-2683.

Tulip-shaped actuator for haptic display

Tulip-shaped actuator for clutch

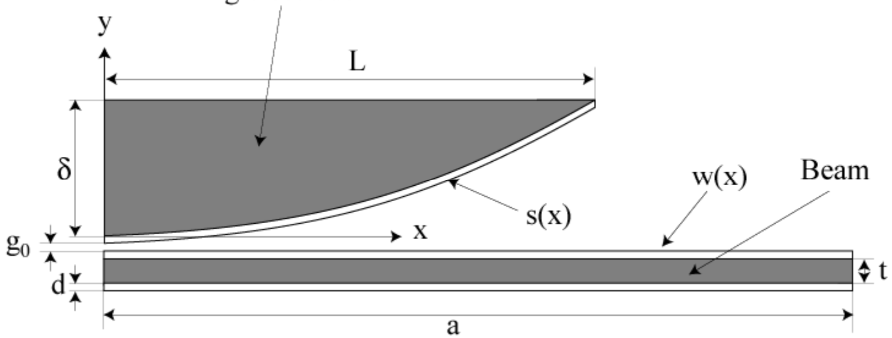


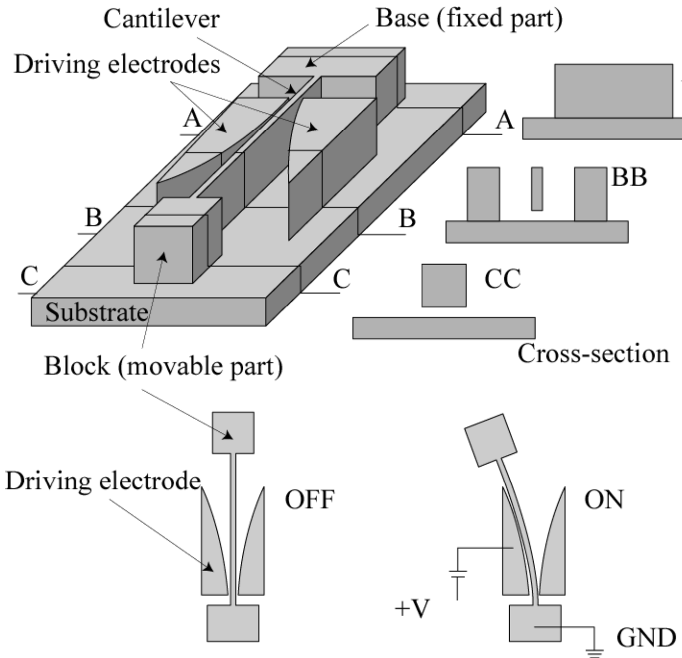


H. Sasaki, et al., J. Micromech. Microeng., 16, 2006, 2673-2683.

Tulip-shaped actuator for haptic display

Tulip-shaped actuator for clutch _ analysis





$$s(x)=\delta\left(\frac{x}{L}\right)^2$$

$$w(x)=cx^2(6L^2-4Lx+x^2)$$

$$U_{el}=-\frac{1}{2}\int_0^L \frac{\varepsilon_0 h V^2}{\frac{d}{\varepsilon_r}+s(x)-w(x)+g_0}dx$$

$$U_b=\frac{1}{2}\int_0^L EI\left\{\frac{d^2w(x)}{dx^2}\right\}^2 dx$$

$$U=U_b+U_{el}=0\rightarrow V=\sqrt{\frac{EI}{\varepsilon_0 h}\cdot\frac{\frac{1}{2}\int_0^L EI[\frac{d^2w(x)}{dx^2}]^2dx}{\int_0^L \frac{1}{\frac{d}{\varepsilon_r}+s(x)-w(x)+g_0}dx}}$$

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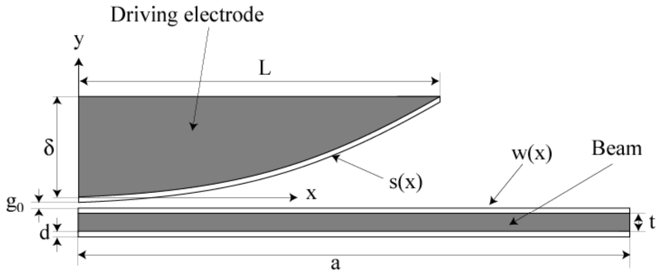
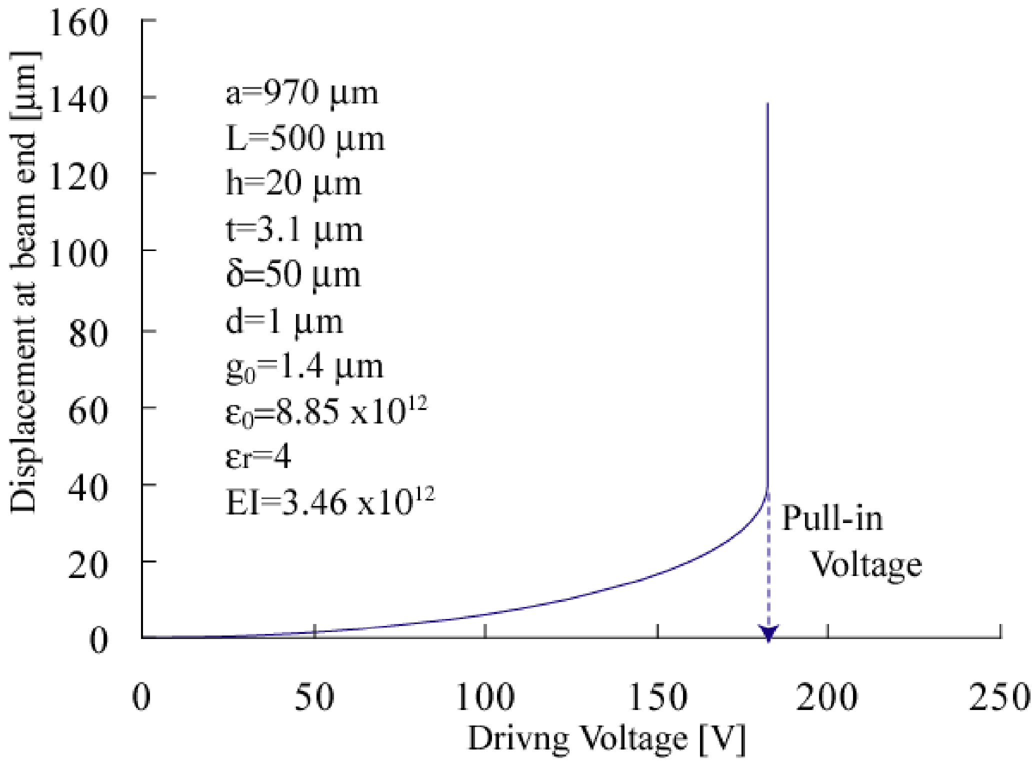
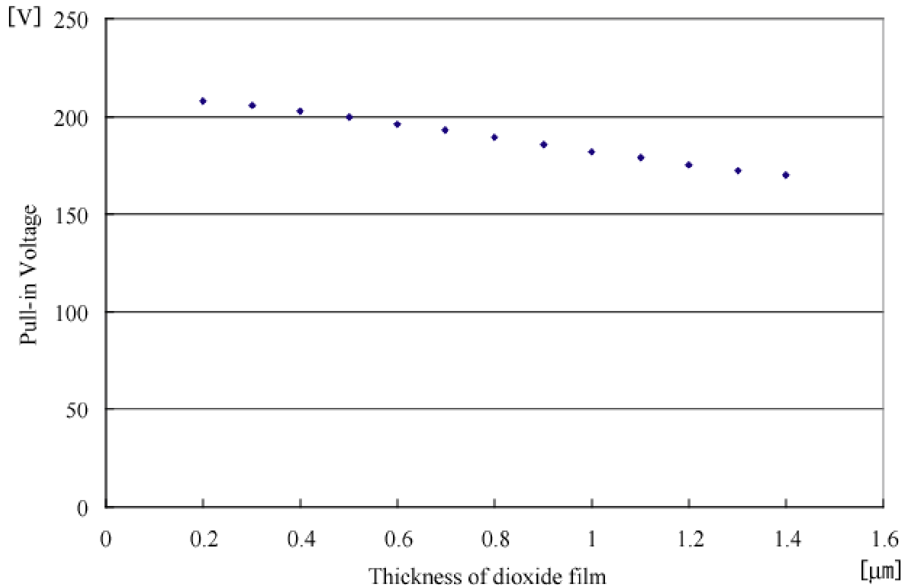
Tulip-shaped actuator for haptic display

Tulip-shaped actuator for clutch _ analysis







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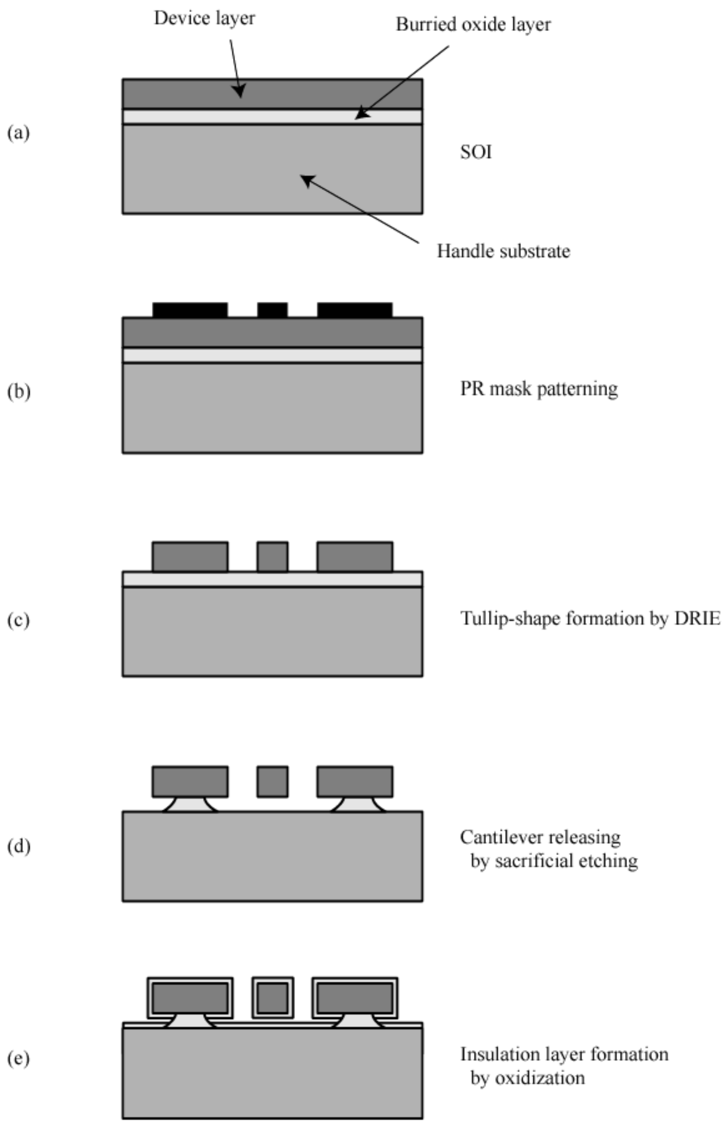
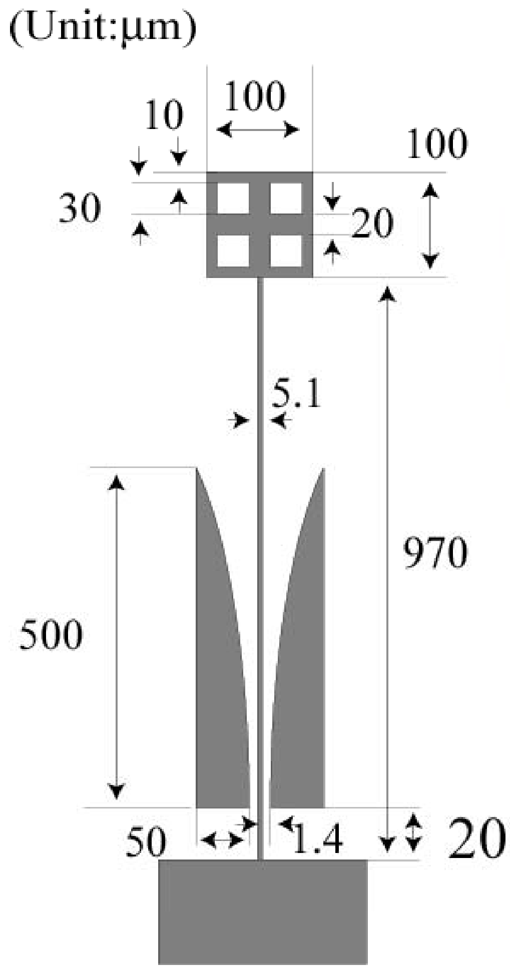
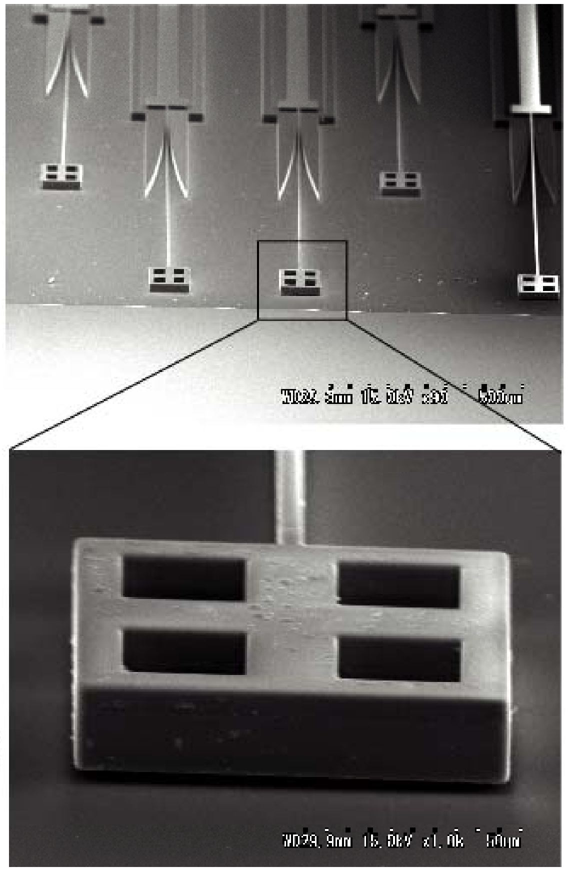
Tulip-shaped actuator for haptic display

Tulip-shaped actuator for clutch _ fabrication







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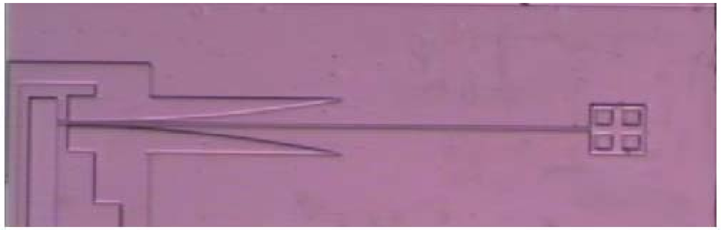
Tulip-shaped actuator for haptic display

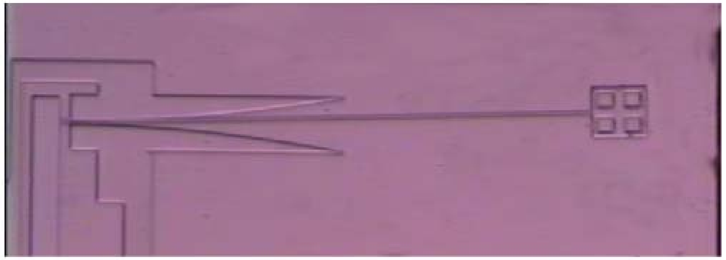
Tulip-shaped actuator for clutch _ operation

(a)



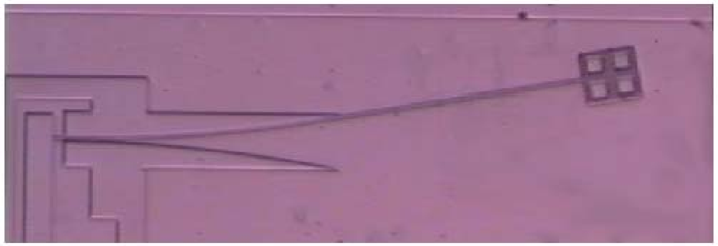
V=50V Deflection=0 μm

(b)

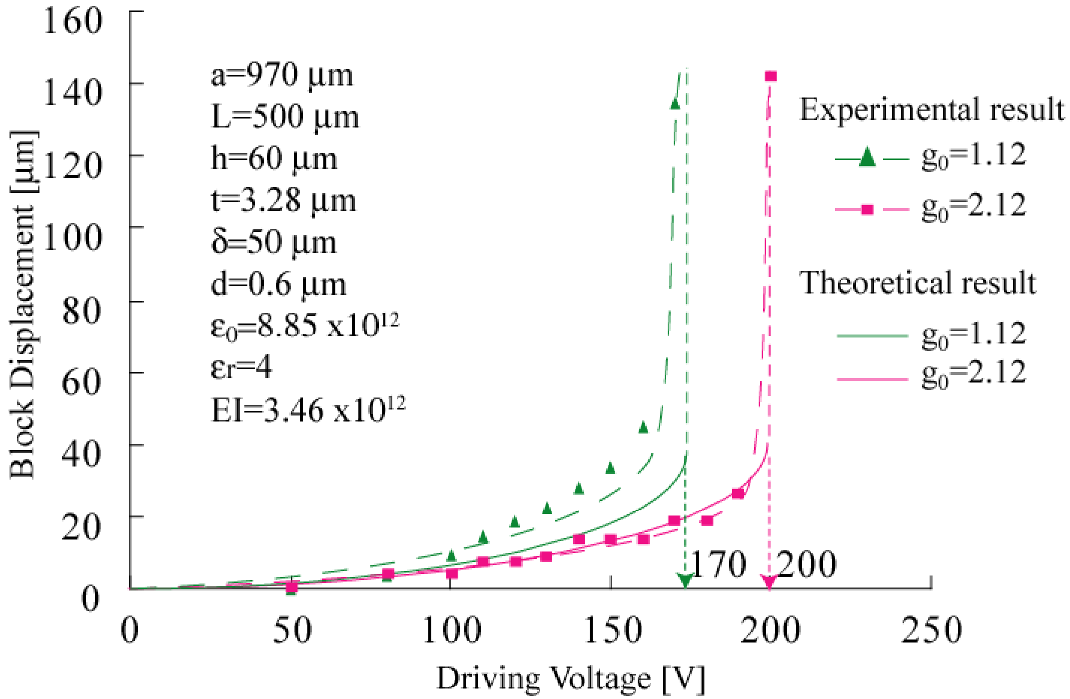


V=140V Deflection=32 μm

(c)



V=200V Deflection=138 μm



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Tulip-shaped actuator for haptic display

Assembled haptic display

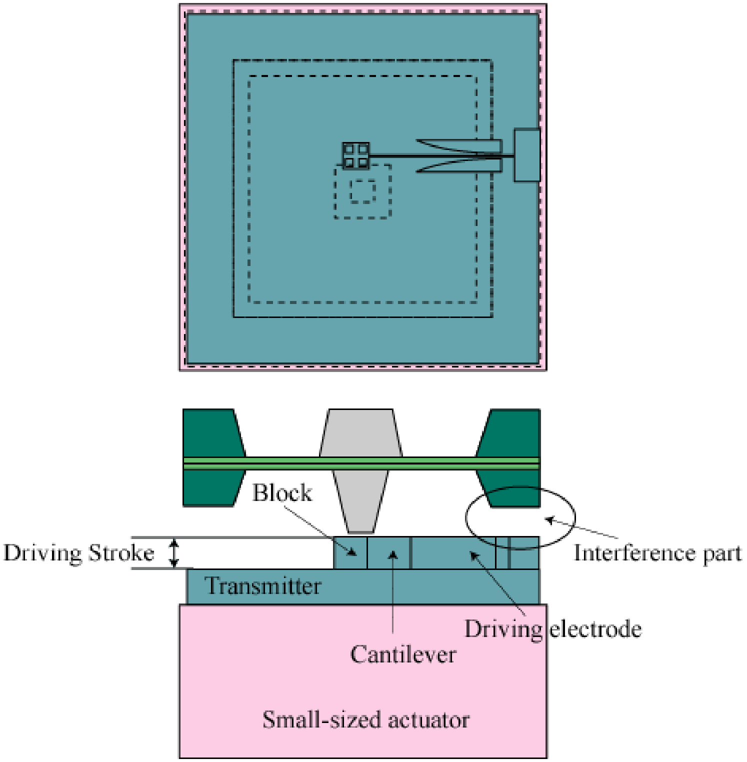
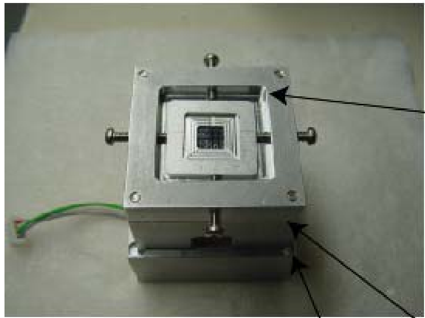
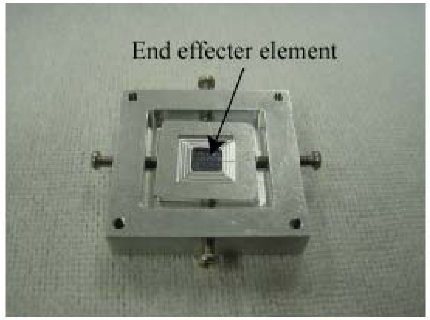


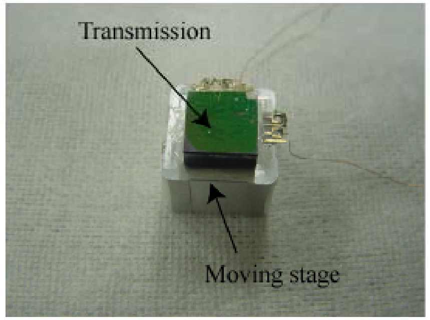
Image of a packaged element



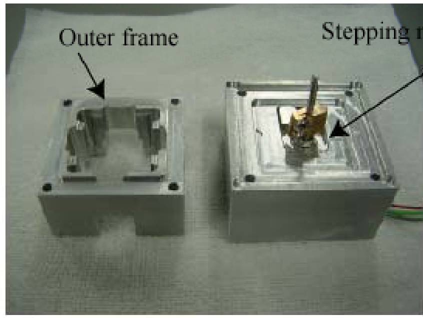
(a) Packaged Mechanical Power Transmission System



(b) Arrayed end effecter element



(c) Tulip-shaped electrostatic clutch device and moving stage



(d) Small-sized actuator

Displacement :20-60 μm
Generative force: 600 mN
Size: 30 mm x 30 mm x 40 mm

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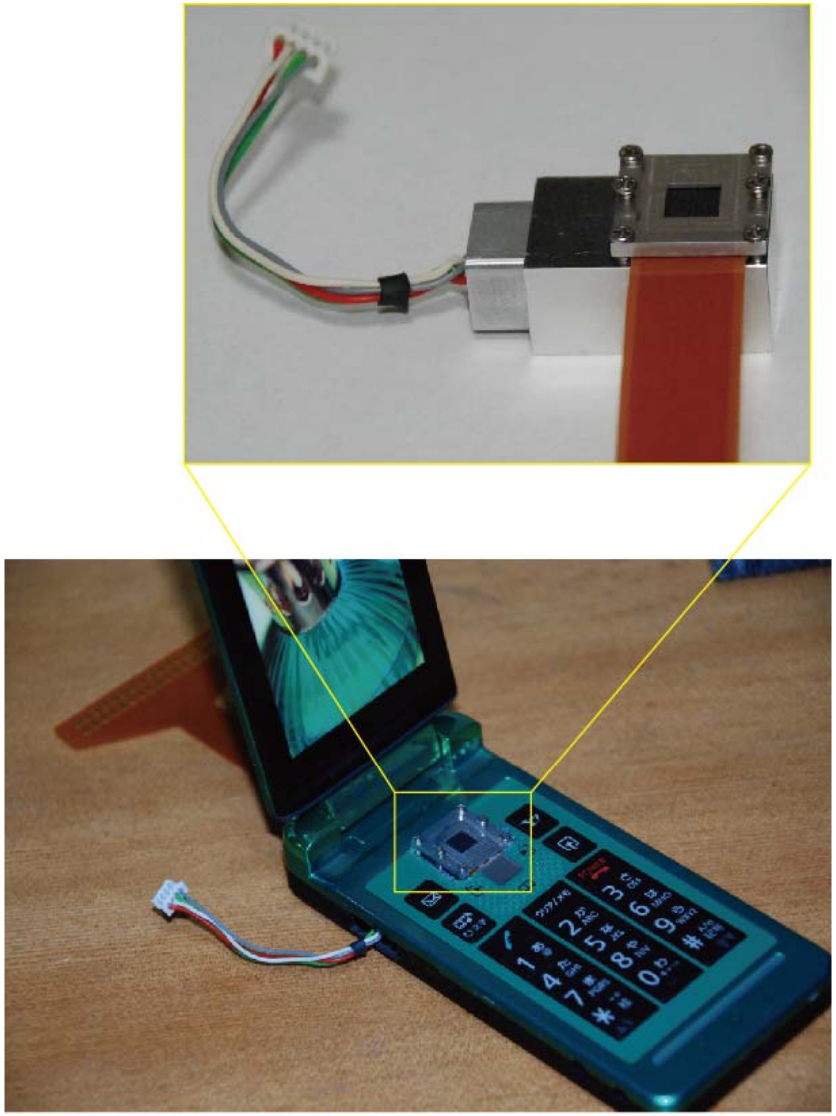
Tulip-shaped actuator for haptic display

Demonstration of haptic display



Summary

- ✓Overview of Micro-actuator
- ✓Electrostatic force
  - ✓Generative force
  - ✓Comb-drive actuator
  - ✓Pull-in phenomenon
- ✓S-shaped film actuator for gas valve application
- ✓Tulip-shaped actuator for haptic display