Electrowetting-on-dielectric Induced Droplet Actuation in M×N Array of Electrode

Shiraz Sohail[1]*, Debanjan Das[1], Soumen Das[2] and Karabi Biswas[1]
[1]Department of electrical engineering, IIT Kharagpur, India.
[2]School of Medical Scienc and Technology, IIT Kharagpur, India.
*Corresponding Author

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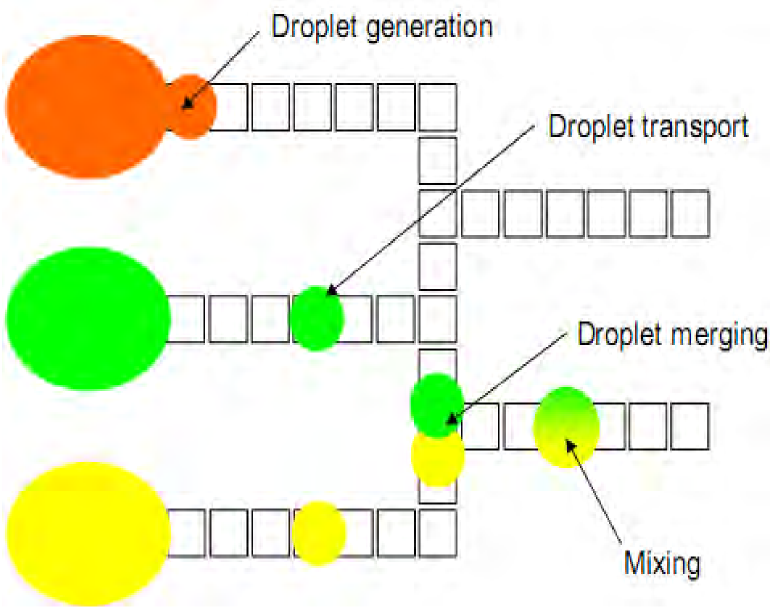
Introduction

Droplet-based microfluidics (Digital microfluidics) is a new and emerging trend in microelectrofluidic systems (MEFS) and micro-total analysis systems (µTAS) in the past decade.

Electrowetting-on-dielectric (EWOD) is arguably the most flexible and powerful tool, used in many Lab-on-a-Chip (LoC) platforms .



Advantages

- Small fluid volumes actuation
- Easy move, split, mix, and dispense operation
- Low power consumption
- Fast switching response
- No external pump
- Simple fabrication
- Low cost

Application

•Liquid displays
•Liquid lenses
•Lab-on-a-chip
•Electrical switches
•Drug delivery
•Chip cooling

EWOD Microsystems

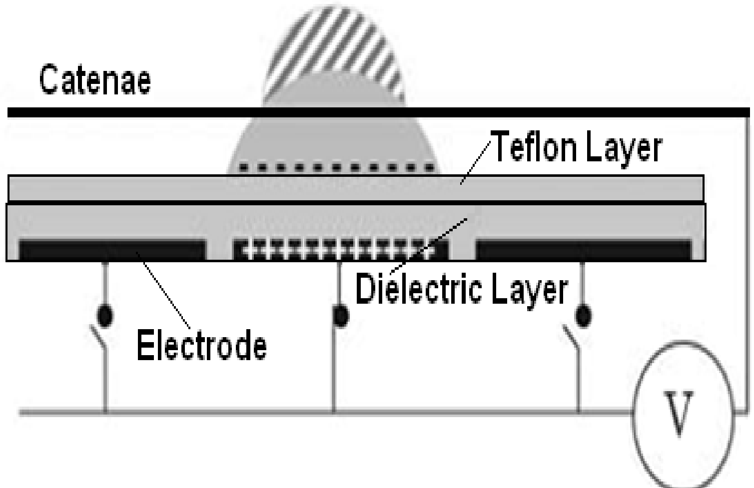


Figure 2a: With top catenae [1]

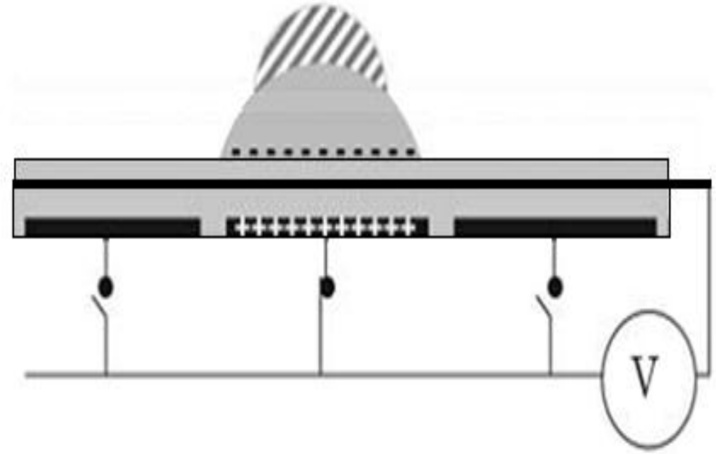


Figure 2b: With buried catenae [1]

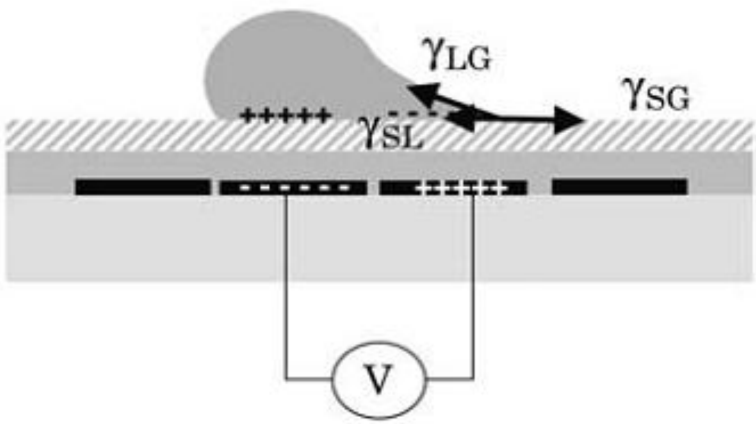


Figure 2c: Without catenae [1]

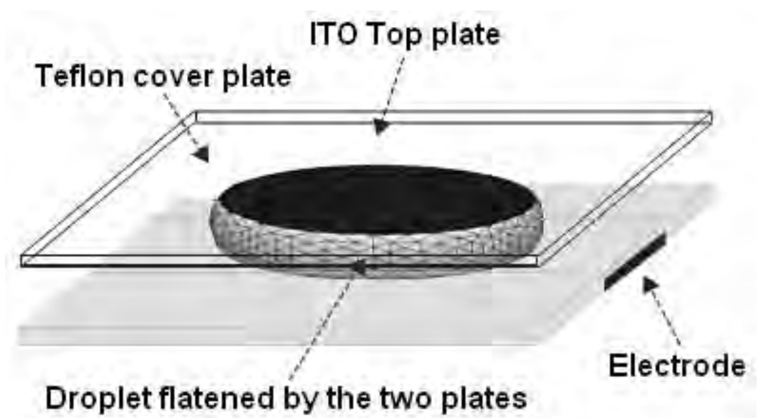


Figure 2d: Covered system [1]

Addressing electrode in 3x3 or greater order matrix

1) Running conduction lines between the electrode gaps [2, 3]
   - Easy to fabricate and cost effective
   - Unwanted wetting of non electrode area
   - Limited to less order matrix

2) Multi-level metallization technique (IC fabrication) [2, 4]
   - Avoid parasitic unwanted wetting effect
   - Less number of bond pads and simple packaging
   - High fabrication cost and lengthy process step

3) Printed circuit board (PCB) technology [3, 5 and 6]
   - Low cost and flexible packaging
   - High actuation voltage
   - Temperature limitation

4) Cross-reference technique [7]
   - Single level metallization
   - Cartesian coordinate system
   - low cost and easy to fabricate

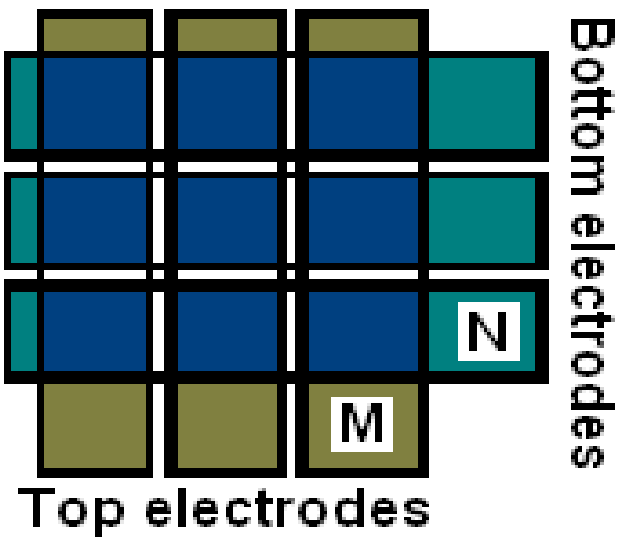
Cross reference scheme

•Orthogonally aligned parallel electrodes in both top and bottom substrate.

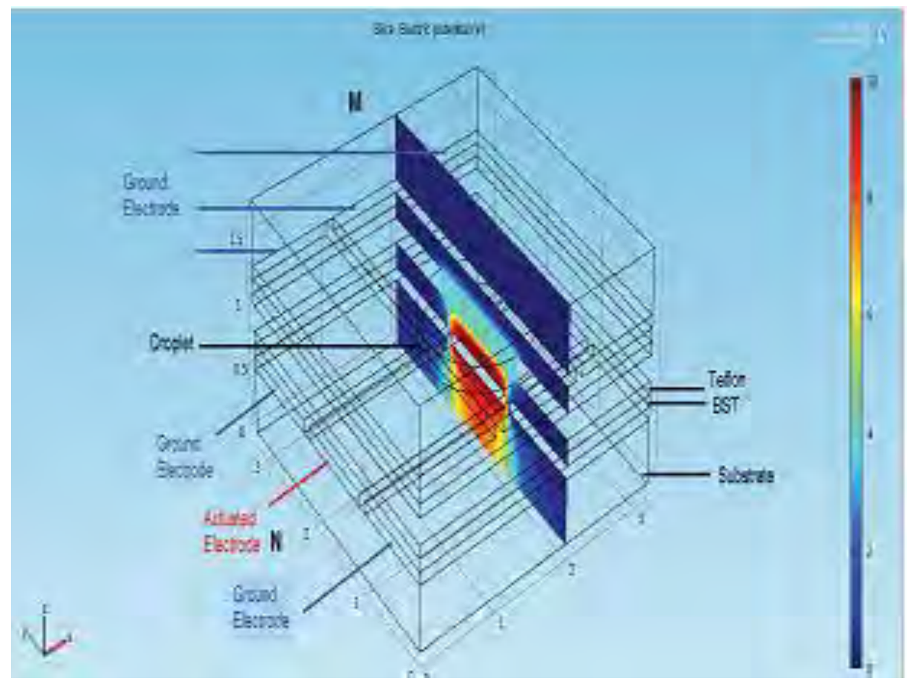
•Row and column electrodes are energized with opposite signals.

•Cartesian coordinate system.

Initially at center (i.e. X-2, Y-2)
X-direction: (1, 2) or (3, 2)
Y-direction: (2, 1) or (2, 3)



Top view of cross-reference design

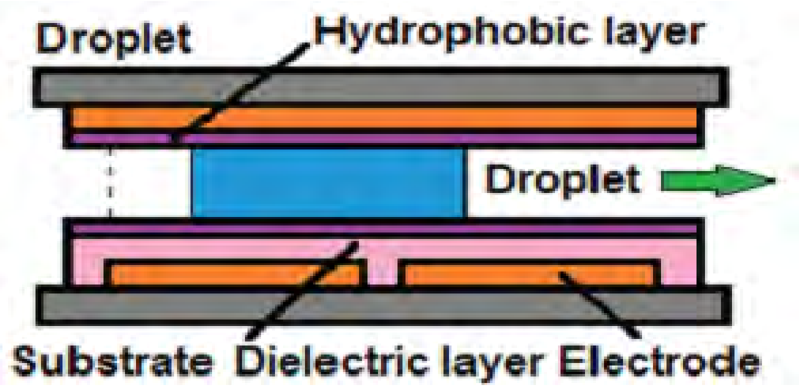


COMSOL setup

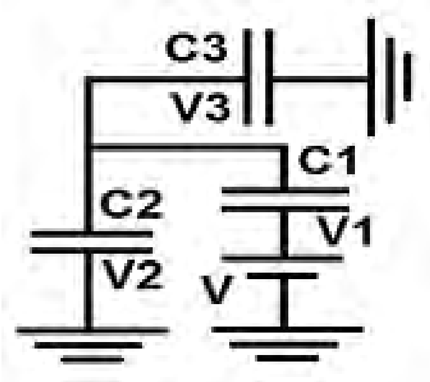
Modeling of cross reference scheme

•Represented by a traditional covered two plate EWOD system.

•Three capacitors in electrical equivalent circuit.
C1 - between actuated electrode and droplet, C2 - between non-actuated electrode and droplet and C3 - between droplet and top ground electrode



Side view of droplet transition in cross reference scheme



Electrical equivalent circuit

•The energy gradient is the driving force according to energy-minimization model (Bahadur 2006 [8]).

Modeling continues

•Droplet free energy is the sum of all the interfacial energy.

$$E(x) = \gamma_{SL} \times A_1(x) + \gamma_{SL} \times A_2(x) + \gamma_{SL} \times A_3(x) + \gamma_{LA} \times A_{SIDE} \qquad (1)$$

Here γ_{SL} , γ_{LA} and A_{SIDE} represent solid–liquid interfacial energy, liquid–air interfacial energy and cylindrical side around the droplet respectively.

•Reduction in interfacial tension is caused by the energy stored in capacitor.

•Lippmann equation [14] is used to quantify the decrease in solid–liquid interfacial energy .

$$\gamma^{V}{}_{SL} = \left(\gamma^{0}{}_{SL} - \frac{k\varepsilon_0 V^2}{2t} \right) \qquad (2)$$

•Droplet free energy on actuation assuming liquid–air interfacial energy remain unchanged [15].

$$E(x) = \left(\gamma^{0}{}_{SL} - \frac{k\varepsilon_0 V_1^2}{2t} \right) \times A_1(x) + \left(\gamma^{0}{}_{SL} - \frac{k\varepsilon_0 V_2^2}{2t} \right) \times A_2(x) + \left(\gamma^{0}{}_{SL} - \frac{k\varepsilon_0 V_3^2}{2t} \right) \times A_3(x) + \gamma_{LA} \times A_{SIDE} \qquad (3)$$

Modeling continues

•Negative derivative of droplet free energy gives actuation force on droplet.

$$
\begin{aligned}
F(x) &= -\frac{dE(x)}{dx} = F_1(x) + F_2(x) + F_3(x) \\
F_1(x) &= \frac{k\varepsilon_0 V_1^2}{2t}\frac{dA_1(x)}{dx} + \frac{k\varepsilon_0 V_1 A_1(x)}{t}\frac{dV_1(x)}{dx} \\
F_2(x) &= \frac{k\varepsilon_0 V_2^2}{2t}\frac{dA_2(x)}{dx} + \frac{k\varepsilon_0 V_2 A_2(x)}{t}\frac{dV_2(x)}{dx} \\
F_1(x) &= \frac{k\varepsilon_0 V_3 A_3(x)}{t}\frac{dV_3(x)}{dx}
\end{aligned}
\qquad (4)
$$

•Actuation force has three components corresponding to the three regions of the droplet surface undergoing interfacial energy change.

•Results obtained from this model are identical to purely electromechanical model [8].

•Actuation force changes due to change in capacitance with droplet leading edge *x* varying from 0 to L (pitch length).

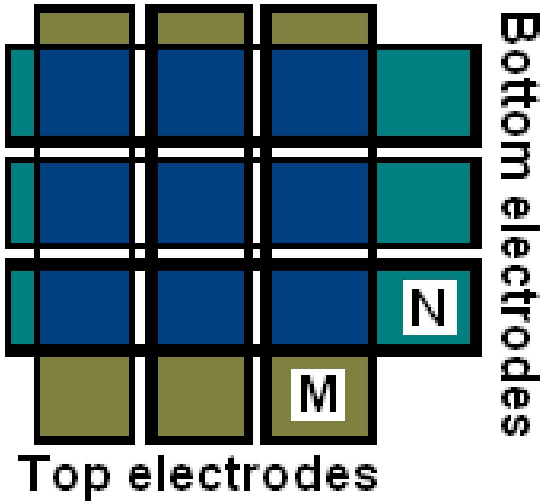
COMSOL simulation

- Dimension:
  - Top substrate- 3.2 mm × 1 mm × 0.1 mm (along X-axis)
  - Bottom substrate- 3.2 mm × 1 mm × 0.1 mm (along Y-axis)
  - Electrode gap- 0.1 mm
  - Electrode area- 1 × 1 mm

- Material property:
  - BST (dielectric)- εr-180, Thick-0.1 mm
  - Teflon (hydrophobic)- εr-2.1, Thick-0.1 mm

- Droplet is circular in shape (dia- L = 2r=1mm) and move as a rigid body maintaining its circular shape.

- Boundary condition: (AC-DC Module)
  - Ground- all electrode except top first electrode
  - Terminal (10V)- top first electrode



Top view of cross-reference design

Simulation Result

•Voltage drop V1, V2 and V3 is calculated with droplet position (x)

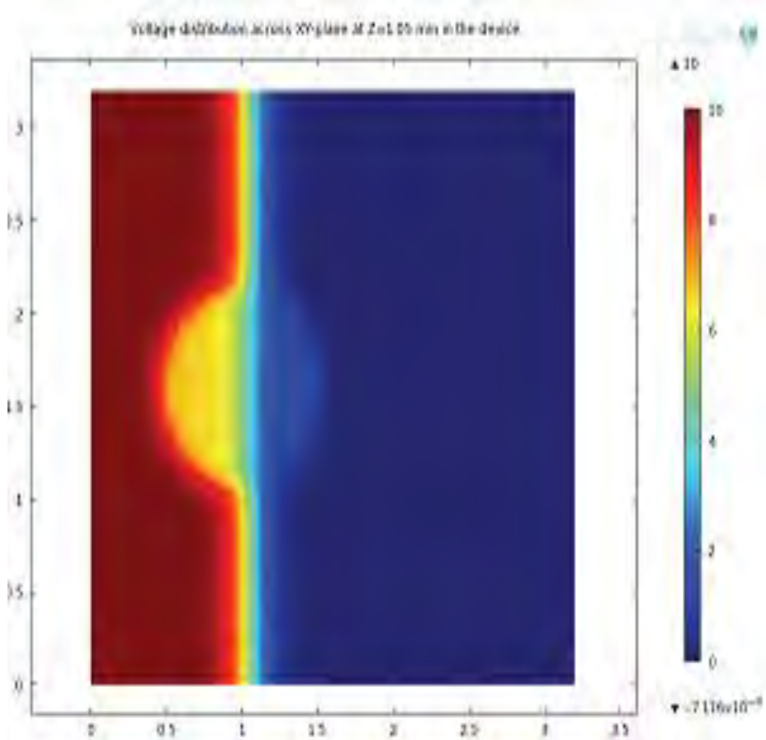
•Droplet can be divided into two parts at a particular position (x)

1. under the actuated electrode
2. under un-actuated electrode

• These two parts have different potential.

• Voltage drops V1, V2 and V3 are calculated from 1D plot of two vertical 2D lines on XZ-plane

- •On actuated electrode
- •On un-actuated



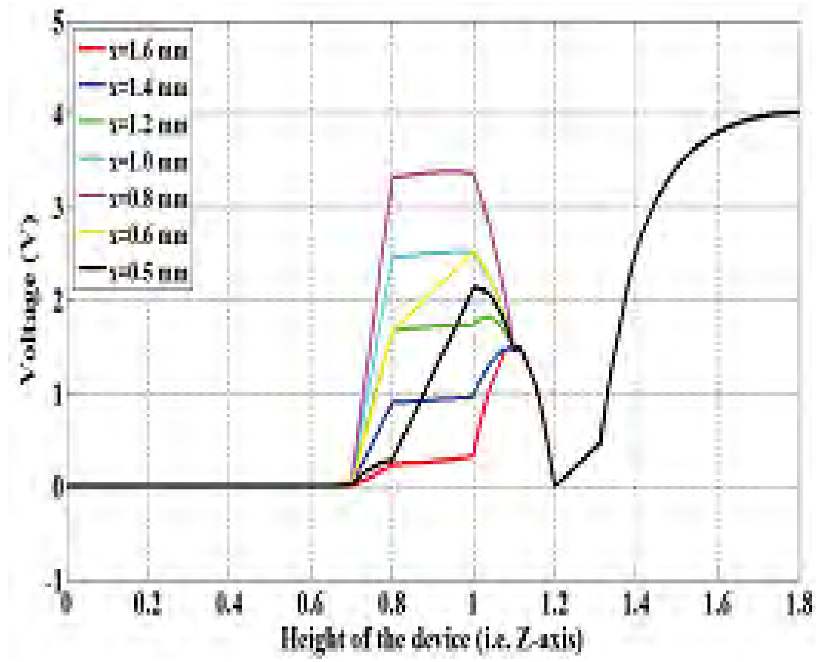
Voltage distribution across XY-plane at Z=1.05 mm when x=1.0

Simulation Result

•Voltage distribution changes across capacitors during transition

•Step transition of 0.1mm from x=1.6 to 0.5 (i.e. complete transition from one electrode to the other) has been considered.

•Chopping the droplet and electrode assembly by a 2D ZX-plane.



Voltage distribution along the height of the device (Z-axis) at x=0.5 to 1.6 mm

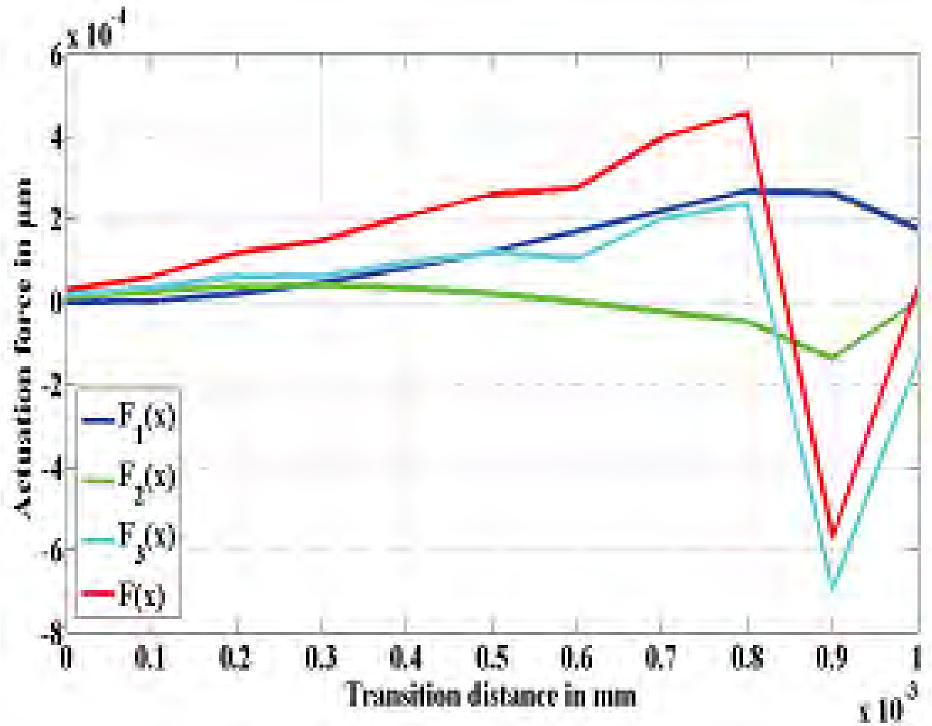
COMSOL Simulation

- Droplet moves from (2, 2) to (1, 2) electrode.
- Chopping by a 2D ZX-plane at Y=1.6 mm. .
- Two vertical 2D lines on the XZ-plane.
  - Actuated electrode (point 1: X=0, Y=1.15 and point 2: X=1.8, Y=1.15 mm)
  - Un-actuated electrode (point 1: X=0, Y=0.95 and point 2: X=1.8, Y=0.95 mm).
- Voltage distribution 1D plot exported to MATLAB.
- Calculate potential difference (p.d.) across capacitors.
- Four interface points along the height (Z-axis) is used .
  - Interface point: 0.6, 0.8, 1.0 and 1.2.

Simulation Result

•Procedure repeated for each step transition „x "to calculate vector V1(x), V2(x) and V3(x).

•Vector V1(x), V2(x) and V3(x) is applied to eqn. 4 to calculate actuation force through MATLAB program.



Actuation force during droplet transition from electrode to the other.

Discussion

- The actuation force F(x) has three components F1(x), F2(x) and F3(x)

- These corresponds to the three capacitors C1, C2 and C3 respectively responsible for interfacial energy change under the influence of the applied voltage.

- Net force is positive up to x=0.8 mm, and it has positive slope as well.

- Beyond x=0.8 mm, the slope and magnitude of F(x) becomes negative

- F3(x) is responsible for the negative slope of F(x) beyond x=0.8.

- This explains braking action to the droplet inertial moment. This helps the droplet finally stops to the actuated electrode and don"t move beyond that.

- Undershoot in the F(x) is responsible for oscillatory motion in droplet before coming to rest.

Conclusion

•The cross reference scheme is easy to fabricate and also does not compromise system performance.

•Adopt the Cartesian coordinate system .

•Equivalent electrical circuit remains same as two plate covered system.

•The force calculation using COMSOL Multiphysics gives better insight into EWOD dynamics without entrapping into long calculation to calculate voltage distribution vectors.

•It also explains braking action and oscillatory motion in the droplet before coming to rest.

•However, the simultaneous driving of multiple droplets in all possible combination in cross-referencing scheme is limited.

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Thank You