A model for the determination of the dimensions of dents for jagged electrodes in electrowetting on dielectric microsystems

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The motion of a droplet from one electrode to the next in electrowetting on dielectric microsystems is not straightforward. Microfabrication imposes a gap separating the electrodes. This hydrophobic gap has the effect of pinning the triple contact line, preventing the motion of the microdrop. To avoid such a drawback, jagged electrodes, i.e., electrodes with crenellated side boundaries have been designed. In this work, an analytical model for dimensioning the size of the dents of the electrodes is derived based on the contact line elasticity theory. This model determines a lower limit for the nondimensional ratio of the length of a dent to its width. The designs of jagged electrodes in the literature have been verified to satisfy the condition, but with very different safety margins. © 2006 American Institute of Physics. [DOI: [10.1063/1.2409626](https://doi.org/10.1063/1.2409626)]

I. INTRODUCTION

Recently, it has been shown that digital microfluidics is a convenient way to handle extremely small volumes of liquids. In particular, electrowetting microsystems [electrowetting on dielectric (EWOD)] have been particularly useful in performing biological and biochemical functions on liquid volumes as small as 50 nl. For example, EWOD microsystems, coupled to a matrix-assisted laser desorption/ionization (MALDI) mass spectrometer have been used for protein analysis,¹ EWOD microsystems have also been used for polymerase chain reaction (PCR) amplification and DNA repairing.² More recently, it has been shown that blood microdrops can be handled by such microdevices.³

In electrowetting microsystems, microdrops are displaced “digitally” on rows of electrodes. However, the motion of a droplet from one electrode to the next is not straightforward. Microfabrication imposes a gap separating the electrodes. This gap is usually of the order of 10–50 μm , depending on the precision of the lithography process. This gap creates a permanent hydrophobic region between two neighboring electrodes. If the droplet has a volume such that it is “contained” or “limited” by the boundaries of the electrode, as shown in Fig. 1, it cannot move to the next electrode when the latter is actuated.

This is frequently the case in covered EWOD microsystems, where droplet volumes are carefully controlled, and the size of the electrodes determines the volume of liquid in each droplet within a margin of a few percent.⁵ In order to remedy such a caveat, jagged or crenellated electrodes have been designed, as shown in Fig. 2. The idea behind such a design is that the droplet contact line with the electrode plane extends over the dents of the next electrode. As soon as the next electrode is actuated, electrocapillary forces act to produce the motion of the droplet. Such jagged electrodes require more complicated microfabrication, but are very efficient for droplet motion provided the dimensioning of the dents is correctly done.

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FIG. 1. Microdrop confined by the electrode boundaries in a covered EWOD microsystem. Surface Evolver simulation (Ref. 4).

In Sec. I A, we show that at the very beginning of the motion, the electrowetting force on a droplet is proportional to the length of the contact line located on the neighboring actuated electrode. This result proves that the electrode's jagged boundary plays a key role in electrowetting actuation, and that its design must be carefully considered for drop motion to commence. We then investigate in Sec. I B the position of the contact line on a jagged electrode. From a theoretical standpoint, this position is related to the theory of partial/total pinning on wettability boundaries, pioneered by de Gennes⁶ and Ondarçuhu.⁷ We first review the theory and then show how a criterion for determining the size of the dents can be derived.

A. Electrowetting force

In this section, we analyze the electrowetting force on the droplet at the very beginning of the motion. The electrowetting force is due to the Maxwell stress tensor⁸ and can be translated as a capillary effect using the Lippmann-Young law. It has been established⁹ that the electrowetting force during full motion from one electrode to the next is given by

$$F_{e,\text{motion}} = e\gamma(\cos \theta_a - \cos \theta_{na}), \quad (1)$$

where e is the width of the electrode, and θ_a and θ_{na} is the actuated and nonactuated contact angles, respectively. In Fig. 2, we have sketched the position of the contact line at the very beginning of the motion.

In this case, the electrowetting force is

FIG. 2. Sketch of the crenellated electrodes and position of the droplet. The force exerted by the neighboring electrode at the beginning of the displacement on the advancing contact line is symbolized by arrows.

FIG. 3. The four different types of pinning on a sinusoidal boundary line. θ_0 is the contact angle far enough from the contact line, where the interface ignores the details of the contact line.

$$F_{e,\text{start}} = e_1 \gamma \cos \theta_a + e_2 \gamma \cos \theta_{na} - e \gamma \cos \theta_{na}, \quad (2)$$

where e_1 and e_2 are the total cross dimensions corresponding to the part of the contact line on the actuated and nonactuated electrodes. The first term on the right-hand side of Eq. (2) is the pulling force exerted on the liquid by the actuated neighbor electrode, and the second term is the resisting force on that part of the contact line located on the nonactuated electrode (usually $\cos \theta_{na} < 0$). The last term of Eq. (2) corresponds to the receding contact line. Note that

$$e_1 + e_2 = e.$$

After substitution in Eq. (2), we find

$$F_{e,\text{start}} = e_1 \gamma (\cos \theta_a - \cos \theta_{na}). \quad (3)$$

Comparing Eqs. (1) and (3) shows that at the beginning of the motion, the force on the droplet is only

$$F_{e,\text{start}} = \frac{e_1}{e} F_{e,\text{motion}}. \quad (4)$$

We verify that if $e_1=0$, i.e., there is no part of the contact line overlapping the neighboring electrode, no electrowetting force acts on the droplet. Relation (4) shows that it is important to have at rest a significant part of the contact line overlapping the next electrode.

FIG. 4. Crenellated electrodes can be approached by a sinusoidal boundary.

TABLE I. Dimension of the dents as a function of the number of dents ($\theta_1=80^\circ$, $\theta_2=110^\circ$, $e=800\text{ }\mu\text{m}$, and $\delta=20\text{ }\mu\text{m}$).

Number of dents	1	2	3	4	5	6
$\lambda\text{ }[\mu\text{m}]$	115	68	52	44	39	36
λ/e	0.14	0.08	0.06	0.05	0.045	0.04

B. Theory of triple contact line elasticity

The position and shape of an interface depends on two constraints: (1) Surface tension that tends to minimize the surface area and (2) the Young contact angles acting directly on the contact line. For a wavy contact line, these effects act oppositely. This is the basis of the elasticity theory for the contact line proposed by de Gennes⁶ and applied by Ondarçuhu⁷ to a sinusoidal contact line. Note that the elasticity theory differs from the line tension theory;^{6,10} the elasticity theory corresponds to a “macroscopic” effect of the interface, whereas the line tension acts at a nanoscopic scale. In the case of this study, line tension theory is negligible compared to interfacial elasticity.

Here we just reproduce the results of Ondarçuhu. The sinusoidal contact line is given by the expression

$$y = \eta(x) = \eta \cos(qx), \quad (5)$$

where η is the amplitude and q the wave vector. The results are obtained under the assumption that $\eta q \ll 1$. It can be shown that four different morphologies of the contact line can be obtained. These morphologies are shown in Fig. 3.

The two lines in Fig. 3 are given by the relations

$$\eta q < 1 - \frac{\theta_1}{\theta_0},$$

FIG. 5. View of a water droplet interface on a jagged boundary. Note that the dimension of the dents is approximately $130\text{ }\mu\text{m}$ for an electrode size of $800\text{ }\mu\text{m}$, which is well above the threshold of $68\text{ }\mu\text{m}$ predicted by the elasticity theory.

FIG. 6. Jagged electrode designs from Duke University (a-left), UCLA (b-middle) and Pohang University (c-right).

$$\eta q < \frac{\theta_2}{\theta_0} - 1, \quad (6)$$

where θ_0 is the uniform angle of the interface at some distance of the contact line, θ_1 and θ_2 are the Young contact angles with the two substrates. We remark that in the case of total pinning, i.e., the contact line follows strictly the sinusoidal line, ηq is quite small.

C. A criterion for the dimensions of the dents

If we approach the crenellated boundary line by a sinusoidal function, as shown in Fig. 4, the analysis in Sec. I B applies. We note that the boundary line depends on the gap between the electrodes δ , so that the amplitude η is a function of the size of the “dents” λ and of the size of the gap δ . Approximately, we have

$$\eta \approx \frac{\lambda - \delta}{2}. \quad (7)$$

Relation (7) shows that if δ increases, the amplitude of the sinusoidal boundary line decreases. The sinusoidal function is then described by

$$\eta(y) = \eta \cos(qy) = \frac{\lambda - \delta}{2} \cos(qx), \quad (8)$$

where x is the horizontal coordinate and y the vertical coordinate based on Fig. 4.

FIG. 7. Jagged electrode design from IMTEK (left) and IEMN (right).

FIG. 8. Two jagged electrode design, by CEA/LETI. Left: a droplet of blood moves to the right under electrowetting actuation.

In the case of electrowetting, we have to design the dents so that the contact line overlaps the concave part of the sinusoidal curve. By doing so, the droplet will experience a capillary pull when the neighboring electrode is actuated. Referring to Sec. I B, only domains 3 and 4 defined in Fig. 3 are acceptable, and the following relation must be satisfied

$$\eta q > \frac{\theta_2}{\theta_0} - 1. \quad (9)$$

In Eq. (9), the exact value of θ_0 is not known. However, if we choose the nondimensional number ηq to be larger than

$$\eta q > \frac{\theta_2}{\theta_1} - 1, \quad (10)$$

we are assured that the contact line behavior lies within domain 4 describing the case of intermediate pinning. If we note e , the electrode width, and n , the number of dents, we find the following relation for the dimensions of the crenellated electrodes

$$\frac{\lambda - \delta}{2} = \eta > \left[\frac{\theta_2}{\theta_1} - 1 \right] \frac{e}{2\pi n}. \quad (11)$$

Equation (11) can be written in the form

TABLE II. Approximate values of the function G for the different EWOD microsystems.

Institute	Value of G
Duke University	3.2
UCLA	1.5
Pohang University	3.1
IMTEK	1.4
IEMN	1.3
LETI 1	3
LETI 2	1.4

FIG. 9. Small overlapping of the contact line in the case of a large wave vector.

$$\lambda > \delta + \left[\frac{\theta_2}{\theta_1} - 1 \right] \frac{e}{\pi n}. \quad (12)$$

In dimensionless form,

$$\frac{\lambda}{e} > \frac{\delta}{e} + \left[\frac{\theta_2}{\theta_1} - 1 \right] \frac{1}{\pi n}. \quad (13)$$

Typical values of the quantities appearing in Eq. (13) are: $\theta_1 = 80^\circ$, $\theta_2 = 110^\circ$, $e = 800 \mu\text{m}$, $\delta = 20 \mu\text{m}$. The ratio λ/e is given in Table I as a function of the number of dents/peaks.

We note that the values of Table I are somewhat overestimated since we have considered the most unfavorable value $\theta_0 = \theta_1$. In reality, this value is probably closer to $\theta_0 = \theta_1 + \theta_2/2$, so that Eq. (13) can be written as

$$\frac{\lambda}{e} > \frac{\delta}{e} + \left[\frac{\theta_2 - \theta_1}{\theta_2 + \theta_1} \right] \frac{1}{\pi n}. \quad (14)$$

Figure 5 shows the position of the interface of a water droplet on a jagged electrode. The interface position corresponds to domain 4 in Fig. 3 (intermediate anchoring).

The results of the theory can be extended to larger values of ηq because the only morphology of interest in our case is morphology 4 (see Fig. 3). For a given wave vector q , if the amplitude η is such that ηq satisfies Eq. (9) and $\eta q \ll 1$, a larger value of η will also produce a partial pinning situation.

D. Examples of jagged electrode designs

In this article, many examples of crenellated electrodes can be found. We examine the value of the function

$$G(\lambda, e, \delta, n) = \frac{\frac{\lambda}{e}}{\frac{\delta}{e} + \left[\frac{\theta_2}{\theta_1} - 1 \right] \frac{1}{\pi n}}, \quad (15)$$

which must be larger than 1 according to Eq. (13). We set the values of the contact angles $\theta_1 = 80^\circ$ and $\theta_2 = 110^\circ$ corresponding approximately to water on Teflon®.

Our first example is that of the electrode design by Duke University,¹¹ shown in Fig. 6(a). In this geometry, the peaks/dents are very pronounced and we have $\lambda/e \sim 0.25$, $\delta/e \sim 1-30$, and $n = 4$. Substituting these values in Eq. (15) we find $G \sim 3.2$.

The second example is that of the UCLA EWOD microsystem^{12,13} shown in Fig. 6(b). In this case, the value of the function G is approximately $G \sim 1.5$. The third example is that of the Pohang University microsystem¹⁴ [see Fig. 6(c)], for this system we find $G \sim 3.1$.

Another example is that of the EWOD microsystem of Fig. 7, designed by the Institut für Mikrosystemtechnik (IMTEK, Mainz, Germany).¹⁵ In this case, the value of function G is approximately equal to $G \sim 1.4$. The Institut d'Electronique, de Microelectronique et de Nanotechnologie (IEMN, Lille, France) design¹⁶ (see Fig. 7) corresponds to a value of $G \sim 1.3$. We finally take the example of EWOD microsystems designed by Laboratoire pour l'Electronique, la Technologie et l'Information (LETI, Grenoble, France) to displace biologic liquids and blood droplets (Fig. 8).⁵ The values of the function G are approximately 3 and 1.4.

The values of G for the different systems are compared in Table II. We verify that in all cases the function G is larger than 1, and that condition (13) is satisfied.

Some of the values of G in Table II are close to 1. However, there is probably a safety margin due to the fact that the values in Table II would have been larger if we had used Eq. (14) instead of Eq. (13).

II. DISCUSSION AND CONCLUSION

The theory of elasticity of the triple line has been used to derive a geometrical condition for the dimensioning of the dents of jagged electrodes in EWOD microsystems. This condition states that the nondimensional ratio of the dent length to the dent width should be sufficiently large, larger than a threshold defined by the actuated and nonactuated contact angles. We have checked that this criterion is obeyed by the different electrode designs found in the literature. As a matter of fact, it was found that smaller dents would still have performed satisfactorily for water on Teflon®. However, a safety margin is required for the use of other combinations of liquids and other water/air systems, particularly for the case in which there is a larger difference between the actuated and equilibrium contact angles, e.g., water/oil or biological buffer/air systems.

An interesting aspect of the geometrical condition derived here concerns the scale down of EWOD microdevices. The current approach is to homothetically scale down the size of the electrode and that of the dents, however, we anticipate that reducing the gap size by the same ratio as the reduction in electrode dimension will prove to be difficult. The condition derived here indicates that this effect could be partly compensated, by increasing the number of dents. However, there is a limit to that increase: a large wave vector, i.e., a small wavelength, is likely to result in a smaller length of the contact line overlapping the neighboring electrode (Fig. 9). In such a case, according to Eq. (3), the electrowetting force at the onset of actuation may be small and not sufficient to overcome hysteresis and/or pinning.

As a consequence, the scaling down of EWOD microsystems will require high performances of the microfabrication process in order to eliminate as much as possible the surface defects and to decrease the gap dimension.

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