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EFFECTS OF ELECTRODE SWITCHING SEQUENCE ON EWOD DROPLET MANIPULATION: A SIMULATION STUDY

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ABSTRACT

Electrowetting-on-dielectric (EWOD) is a new method for handling droplets on the microfluidic chips. By applying electrical potential, the interfacial energy of liquid-solid interface changes, results altering of droplet contact lines. To increase the flow rate of such a digital microfluidic system one way is to raise the droplet velocity. One important factor for enhancing droplet velocity in EWOD systems is the proper switching the electrodes or "switching sequence". To examine the effect of switching in EWOD, the EDEW 1.0 simulation tool is used in this paper. By simulating the motion of a 1μL water droplet in a 1D electrode array, the resultant surface energy curves during the motion of droplet in different electrode switching sequences are obtained. The results show proper electrode switching has a remarkable effect on increasing of droplet velocity. To enhance the droplet velocity, the electrode, which is placed next to the droplet at forward direction, should be powered after droplet passed over it. In addition, it would be more efficient to first turn on the next electrode, and then turn off the previous one.

INTRODUCTION

An approach in microfluidic systems is the manipulation of a liquid as a unit-size discrete microdroplet often refers to "*Digital Microfluidic System*" (DMS) [1-7].

The EWOD is the most common droplet manipulation method in DMS. It works base on control of surface tension of a liquid-solid interface by applying electrical potential.

The wetting behavior of a droplet on a surface, measured by contact angle, can be altered by applying electrical potential to the droplet [8]. Figure 1 shows this effect.

Where γ_{LG} the liquid/gas surface tension, θ_o is contact angle when the electric field across interfacial layer is zero (i.e. zero potential), ε_o is free space permittivity and ε_r are the relative permittivity (also called dielectric constant) and d is the dielectric layers thickness.

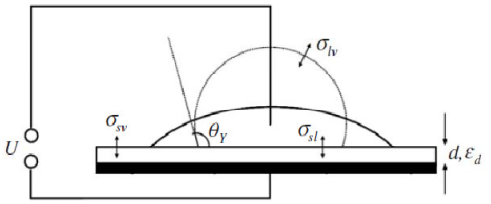


Fig 1 Definition of contact angle and surface energies at different interfaces, after application of an electric potential [5].

Variation of contact angle can be expressed by Young-Lipmann's equation as [7,9]:

$$\cos\theta(V) = \cos\theta_0 + \frac{\varepsilon_0\varepsilon_r}{\gamma_{LG}2d}V^2 \qquad \text{Eq. (1)}$$

Figure 2 demonstrates the droplet actuation mechanism after voltage application. By applying voltage to the electrode which is placed at the forward direction (not to the electrode that droplet is sitting on), the droplet seeks to increase its area on that electrode and therefore a motion takes place [10].

The shape of a droplet on a surface when no external influences are present is corresponding with the smallest surface area for a given volume. The effect that leads to minimization area is surface tension measured as energy per area and can be calculated with the surface integral [10-12]:

$$E = \int_A \gamma_{LG} dA' \qquad \text{Eq. (2)}$$

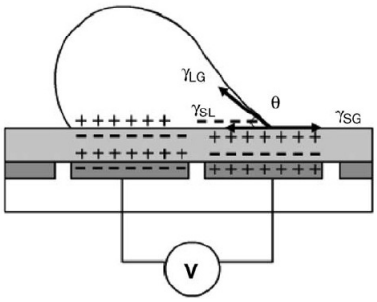


Fig 2 Charge distribution and droplet actuation mechanism [9].

In EWOD systems, the basic liquid unit volume is fixed by the system geometry [1]. Therefore, to increase the transport flow rate one way is to increase the droplet speed. One of the most important parameters toward increasing of droplet velocity is the proper switching sequence or correct switching of the electrodes. Understanding the dynamic effects at the beginning of droplet motion (when the droplet reaches to the beginning of the next electrode) is crucial in the optimization of switching time with respect to fast switching. This paper will address this issue by a simulation approach.

For this purpose, 1D-path simulation module of EDEW 2.0 has been used to simulate a droplet on a series of electrodes (not sandwiched). Based on our previous work [13], the parameters are chosen as Table 1. A 1D path with three electrodes considered and in all of the simulations, the droplet volume is constant and equal to 1µl.

MATERIALS AND METHODS

"*The Surface Evolver*" [14] is a freely available command line interactive program for the study of surfaces shaped by surface tension and other energies. A surface is implemented as a union of triangles. For a facet with edges $\vec{S}_0$ and $\vec{S}_1$ the facet energy due to surface tension γ can be calculated by:

$$E = \frac{\gamma}{2}\left|\vec{S}_0 \times \vec{S}_1\right| \qquad \text{Eq. (3)}$$

The surface energy of the free droplet surface can be calculated by Equation 2 and the surface energy on the substrate is calculated by line integral along the contact line using the divergence theorem [11]:

$$E_{SL} = \int_S \gamma_{SL} dA = \int_S (\nabla.\vec{v}) dA = \int_{\partial S} \vec{v}.dl \qquad \text{Eq. (4)}$$

With a $\vec{v}$ such that $\nabla.\vec{v} = \gamma_{SL}$.

For modeling with surface evolver, it is needed to know about the software and its programming language. To solve this problem, Lienemann et. al. [15-16] provided a user-friendly graphical user interface (GUI) called EDEW, which is incorporated with surface evolver. The dimensional parameters used for simulation are defined in Figure 3.

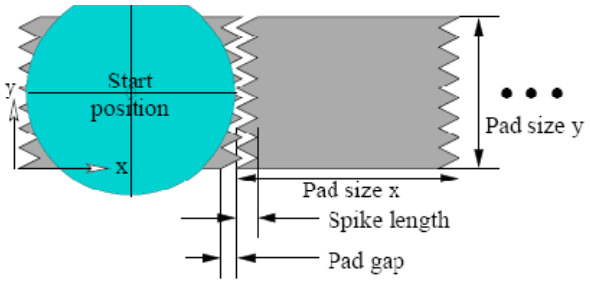


Fig 3 Dimensions for the 1D path simulation [15].

For our purpose, 1D-path simulation module of EDEW 1.0 has been used to simulate a droplet on a series of electrodes (not sandwiched). The parameters are chosen as Table 1. In all of simulations, the droplet volume is considered to be constant and equal to 1µl. The resulting force in each position can be estimated by [11,15]:

$$F = -\partial E / \partial x \approx -\partial E / \partial x_c \qquad \text{Eq. (4)}$$

Tab 1 The value of parameters for 1D path simulations

Parameter	Value
Surface tension	72 J/m2
Contact angle bottom	110o
Droplet volume	1µL
Actuation voltage	50V
Dielectric layer thickness	1µm
Rel. dielectric constant	3
Electrode (pad) size x	1000µm
Electrode (pad) size y	1700µm
Electrode (pad) gap	50µm
Spike length	200µm
Start position x	500µm

Where E is the total energy or total surface energy and x_c is the droplet centroid, which can be calculated by calculating the integral $x_c = \int_V xdv \Big/ V$. So by plotting the droplet energy versus its centroid x position, also called "energy curve", one can easily estimate the resulting force acting on the droplet.

To study the effects of electrode switching, the energy curve corresponding to each case is plotted. Figure 4 shows a typical of our simulation.

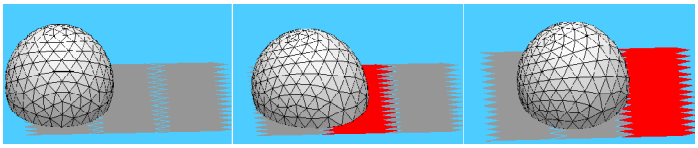


Fig 4 A typical simulation: droplet at rest (left) and during movement toward activated electrode (right)

RESULTS AND DISCUSSION

For simulating the effect of switching sequence, here we have two aspects that should be taken into account.

1. The position of the water droplet related to the face forward electrodes in the movement direction.
2. The sequence (or timing) of switching between the electrodes (2^{nd} and 3^{rd} electrodes here) in gear with the process.

The first aspect determines the best position of droplet with respect to the face forward electrode for powering this electrode. The second aspect determines the best timing for switching between two electrodes.

To determine the switching effect some scenarios have been simulated includes all possible cases for switching of electrodes. Note that as the surface evolver tool performs the simulation in steps or iterations, instead of performing in time domain, so we can control the simulation by the number of steps. This means that during the simulation we cannot define a specific time for activating the next electrode, but we can define a specific simulation step (which is proportional to time) for activating the electrode instead.

For the first aspect the afterward electrode has been powered in several situations. It varies from the case before droplet reaches to the electrode to the case which we let the droplet to be settled on the electrode completely. The numbers of iterations varies between 5-step (or iterations) to 10-step. Here by powering the electrode number 3 the second electrode will turn off simultaneously. Figure 5 schematically demonstrates how the position of the water droplet determines the sequence of powering of the electrodes. In addition, the relation between the number of iteration and the position of electrode is shown.

For the second aspect, the sequence of switching of two electrodes that contain the droplet differs. For a specific position of the droplet, we have three classes:

1. Second electrode is first turned off and then the next electrode (third electrode) is turned on. This case simulated in one-step and two-step switching timing in EDEW.
2. The next electrode turned on and simultaneously the previous one (2^{rd} electrode) is turned off.
3. The next electrode is turned on first and then the middle electrode is turned off. This case also simulated in one-step and two-step switching timing in EDEW.

Figure 6 shows the different timing cases for timing sequence related simulations. Comprehensively, the first aspect (for position-related switching simulation) includes six separate simulations, which are 5-step to 10-step simulating. The second aspect (for time-related switching sequence simulation) includes five separate simulations, which are:

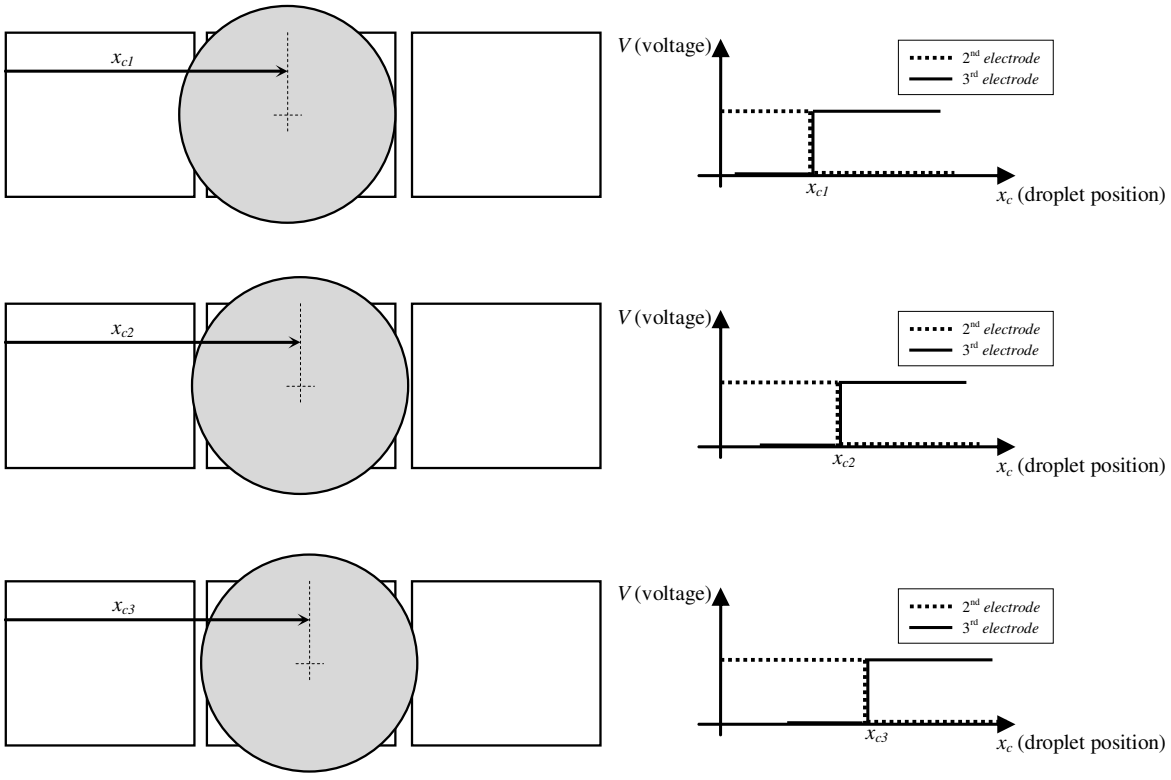


Fig 5 Schematic representation of the position of the water droplet for powering the 3rd electrode.
(Up) before the droplet touch the electrode, (middle) as soon as the droplet touch it, (down) after the droplet mover toward it

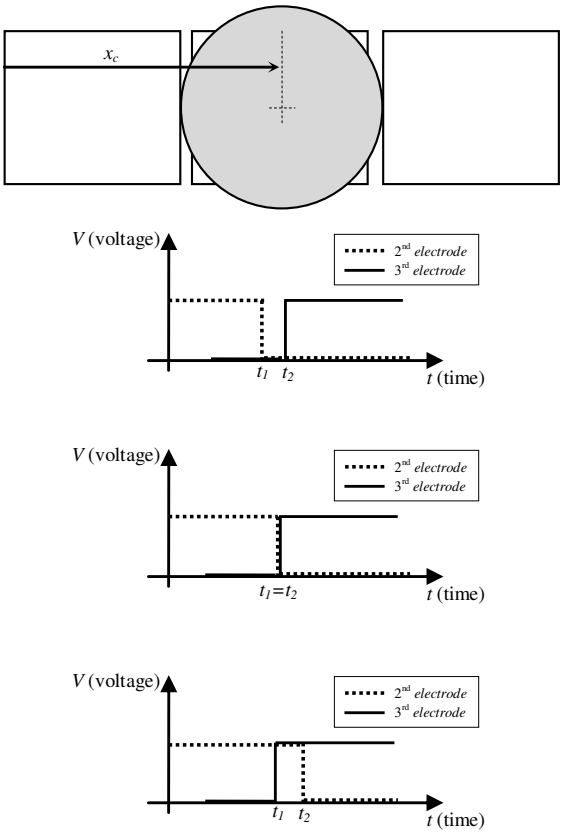


Fig 6 Switching between the electrodes. (Up) first turn off the second electrode and then turn on the third one, (middle) switching simultaneously, (down) turn on the third electrode at first.

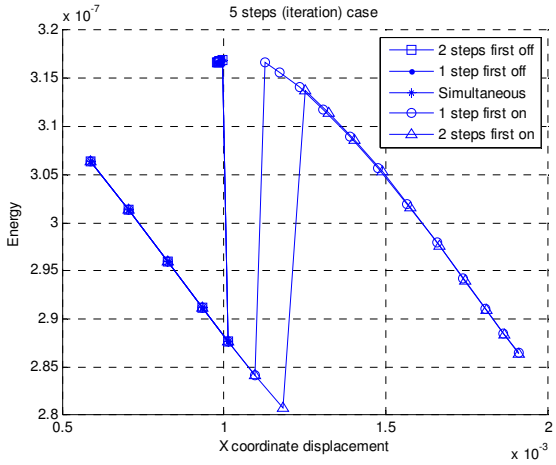


Fig 7 Energy curve for 5-iteration case.

• Turn off the second electrode first, then after two-step /one-step simulation turn on the next electrode. (two cases)

• Switch between two electrodes simultaneously (one case).

• Turn on the third electrode first, then after one-step/two-step simulation turn off the previous electrode. (two cases)

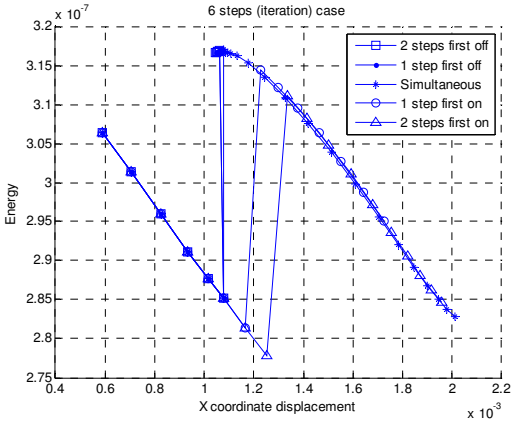
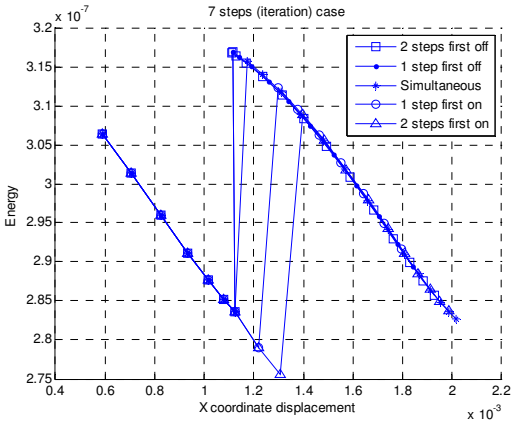


Fig 8 Energy curve for 6-iteration case



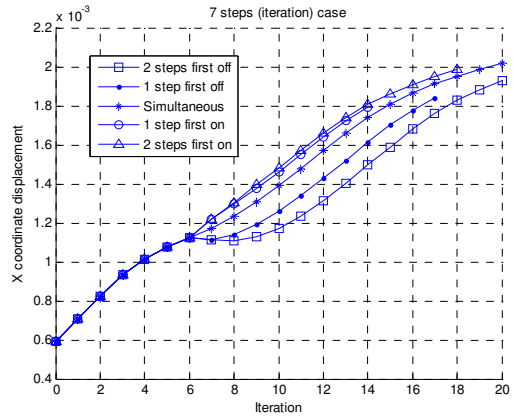


Fig 9 Energy curve and position with respect to iteration for 7-iteration case

The energy curves (as described above) for all six case simulations (regarding first aspect) in different switch timing (regarding second aspect) is shown in Figures 7 to 12. Furthermore, for one case, an extra graph, which is centroids x-position of droplet versus solving iteration (steps), is shown. We call it position diagram.

From the figures, one can easily find the effect of both switching time and switching sequence. For example in Figure

7, when we switch the electrode switched on very soon, the droplet remains in its place. Increasing the number of steps (or moving the droplet more toward the third electrode), prevent this problem.

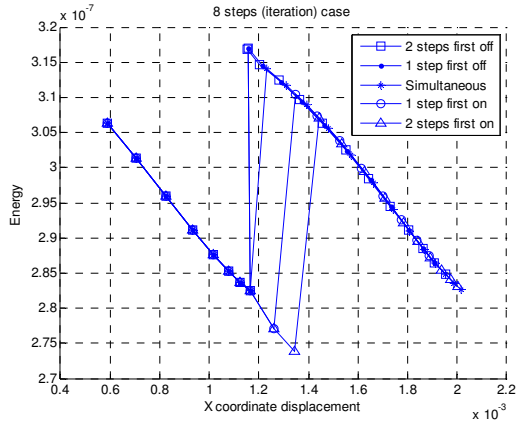


Fig 10 Energy curve for 8-iteration case

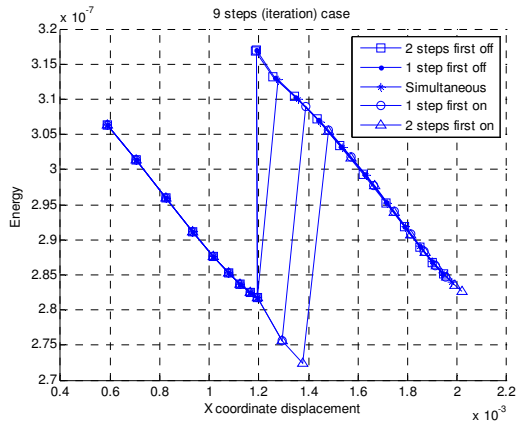


Fig 11 Energy curve for 9-iteration case

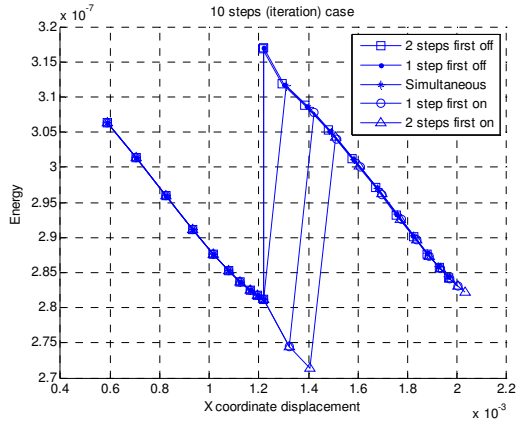


Fig 12 Energy curve for 10-iteration case.

Note that one issue is the smoothness of the position diagram, which represent the velocity of droplet during the motion. For example in position diagram of Figure 9, we can found that when we turn off the current electrode (second electrode) and after a while turn of the next electrode (third electrode), the droplet motion is not completely smooth. By changing the timing sequence (in this figure), the diagram becomes more smooth that means the motion of the droplet is more continuous is therefore droplet velocity would be higher.

In addition, the level of energy of droplet in every case is another important issue. Lower energy level causes easier motion of droplet. The energy level difference of droplet in Figures 10 and 11 shows droplet motion is more continuous when first we turn on the next electrode and the turn off the previous one.

CONCLUSIONS

In this paper, the effects of electrode switching of Electrowetting On-Dielectric (EWOD) with respect to fast switching sequence for obtaining the maximum possible droplet velocity are discussed by simulating this phenomenon using Surface evolver and EDEW 2.0.

From the results, it is clear that for applying a force that is more effective on droplet to have higher droplet velocity, the position of droplet with respect to electrode is more important than that was thought. The sequence of switching is important as well.

The results show the best position of the droplet for switching the face forward electrode is where the droplet just passes over that electrode. Late or early powering the forward electrode caused stopping the movement of the droplet or discontinuity in the velocity (non-smooth motion) respectively, which both of them decrease the droplet velocity. In addition, it is much more effective to first turn the forward electrode on and after a while turns the previous electrode off. This timing of power switching has an optimum value that can be found for a specific geometry and voltage.

Future works should be focused on implementing the results in a real case setup. In addition, it would be more precise to model and calculate the surface energy and resulting force while the droplet is passing over the electrode gap and not the overall surface energy. Another interesting work is the simulation and experimental study of the similar work on other configuration types of EWOD especially when the droplet is sandwiched.

REFERENCES

[1] Berthier J., "MICRODROPS AND DIGITAL MICROFLUIDICS", William Andrew Inc., 2008, Norwich, NY, ISBN: 978-0-8155-1544-9.

[2] Fair R. B., "Digital microfluidics: is a true lab-on-a-chip possible?", Microfluidics and Nanofluidics, 2007, **3**(3); pp. 245-281.

[3] Fair R.B., Khlystov A., Tailor T.D., Ivanov V., Evans R.D., Griffin P.B., Vijay Srinivasan Pamula V.K., Pollack M.G., Zhou J., "Chemical and Biological Applications of Digital-

Microfluidic Devices", IEEE Design & Test of Computers, 2007, **24**(1); pp. 10-24.
[4] Pollack MG, Fair RB, Shenderov AD, "Electrowetting-based actuation of liquid droplets for microfluidic applications", Applied Physics Letters, 2000, **77**:1725–1727.
[5] Mugele F., Baret J. C., "TOPICAL REVIEW: Electrowetting: from basics to applications", JOURNAL OF PHYSICS: CONDENSED MATTER, 2005, **17**; pp. R705–R774.
[6] H. Aminfar, M. Mohammadpourfard, Lattice Boltzmann method for electrowetting modeling and simulation, Comput. Methods Appl. Mech. Engrg. **198** (2009) 3852–3868.
[7] LEE J, MOON H, FOWLER J., SCHOELLHAMMER T., KIM C. J., "Electrowetting and electrowetting-on-dielectric for microscale liquid handling", Sensors and actuators. A, Physical, 2002, **95**(2-3); pp. 259-268.
[8] Dolatabadi A., Mohseni K., Arzpeyma A., "Behaviour of a Moving Droplet under Electrowetting Actuation: Numerical Simulation", THE CANADIAN JOURNAL OF CHEMICAL ENGINEERING, 2006, **84**; pp. 17-21.
[9] Moon I, Kim J, "Using EWOD (electrowetting-on-dielectric) actuation in a micro conveyor system", Sensors and Actuators A: physical, 2006, **130–131**; pp. 537–544.
[10] Lienemann J., Greiner A, Korvink J.G., "Modeling, Simulation, and Optimization of Electrowetting", IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, 2006, **25**(2); pp. 234-247.
[11] Brakke K., "The surface evolver," Experimental Mathematics, 1992, **1**(2); pp. 141–165.
[12] Brakke K. A., "Surface evolver manual", Version 2.20, Susquehanna University, Selinsgrove, PA, 17870, 2003.
[13] Hamid SadAbadi, Ion Stiharu, Muthukamaran Packirisamy, Rolf Wuthrich, "A Parametric Study of Interdigital Electrodes for Achieving High Droplet Speed In Electrowetting", in proceeding of 2nd IEEE Microsystems and Nanoelectronics Research Conference-Ottawa (MNRC), 2009. pp. 76 – 79.
[14] http://www.susqu.edu/facstaff/b/brakke/evolver.
[15] Lienemann J., Greiner A., Korvink J. G., "EDEW Version 1.0, A Simulation Tool for Fluid Handling by Electrowetting Effects", Freiburg, Germany: IMTEK, Albert Ludwig Univ., Jan. 2004.
[16] Lienemann J., Greiner A., Korvink J. G., "EDEW Version 2.0, A Simulation and Optimization Tool for Fluid Handling by Electrowetting Effects", Freiburg, Germany: IMTEK, Albert Ludwig Univ, Apr. 2004.