**WATER HARVESTING AND CONDENSATION HEAT
TRANSFER ENHANCEMENT INDUCED
WITH ELECTROWETTING-ON-DIELECTRIC**

A Dissertation

presented to

the Faculty of the Graduate School
at the University of Missouri-Columbia

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

by

RUN YAN

Dr. Chung-Lung Chen, Advisor and Dissertation Supervisor

DECEMBER 2019

The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

**WATER HARVESTING AND CONDENSATION HEAT
TRANSFER ENHANCEMENT INDUCED
WITH ELECTROWETTING-ON-DIELECTRIC**

Presented by Run Yan,

A candidate for the degree of: Doctor of Philosophy,

and hereby certify that, in their opinion, it is worthy of acceptance.

Dr. Chung-Lung (C.L.) Chen

Dr. Mahmoud Almasri

Dr. Zaichun “Frank” Feng

Dr. Jacob A. McFarland

Dr. Qingsong Yu

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. C.L. Chen for his guidance, assistance, patience throughout my PhD study. I am very fortune to work with such a respected and responsible research advisor and have the opportunity to study on an interesting research topic. I would also like to thank my committee members: Dr. Mahmoud Almasri, who gives much help on microfabrication, Dr. Qingsong Yu, Dr. Frank Feng, Dr. Jacob A. McFarland who are willing to be my committee members and provided precious advice on my studies. Many thanks for the assistance and participation in my PhD defense.

I would like to thank College of Engineering and the Department of Mechanical & Aerospace Engineering helping with miscellaneous tasks related to my research. Also, I would like to thank my lab colleagues: Dr. Simon Chen, Dr. Sheng Wang, Dr. Zhaoqing Ke, Mr. Haolun Xu, Mr. Thomas S. McClure, and Mr. Robin Pham etc. for their insight and help. I would also like to thank Dr. Mathai, Cherian J and Dr. Barizuddin Syed from the microfabrication center of EECS department of Mizzou, who advised and helped a lot in thin film deposition.

Last but not least, I would like to thank my parents and friends who always stand by me and give support to me during the whole period of my PhD studies. I really want to say thank you to my mother for her selfless support and love. It is impossible for me to complete this journey without all the love and encouragement.

Table of Contents

ACKNOWLEDGEMENTS	ii
LIST OF FIGURES	vi
LIST OF TABLES	xii
LIST OF NOMENCLATURES	xiii
ABSTRACT	xvii
CHAPTER 1 INTRODUCTION	1
1.1 Electrowetting (EW)	1
1.2 Electrowetting-on-Dielectric (EWOD)	6
1.2.1 Theoretical Background of EWOD	7
1.2.2 EWOD Applications	11
1.4 Motivations for Present Work and Applications	13
1.5 Objectives of Present Work	14
1.6 Summary	17
CHAPTER 2 DEVICE MICROFABRICATION	19
2.1 Microfabrication	19
2.1.1 Low-pressure Chemical Vapor Deposition (LPCVD)	19
2.1.2 Photolithography	21
2.1.3 Sputtering Deposition	23
2.1.4 Lift-off	25
2.1.5 Spin Coating	26
2.2 Mask Design	28
2.3 Microfabrication Recipe of EWOD Devices	29
CHAPTER 3 EWOD-INDUCED WATER CAPTURE CAPABILITY ENHANCEMENT ¹	32
3.1 Introduction	32
3.2 EWOD Device	36
3.3 Experimental Setup	37
3.3 Contact Angle Measurement	38
3.4 Experimental Results	40
3.5 Droplet Coverage Analysis	45

3.5.1 Droplet Detection Algorithm	45
3.5.2 Droplet Detection Algorithm Error	49
3.6 Conclusions	50
CHAPTER 4 CONDENSATION DROPLET DISTRIBUTION REGULATED BY EWOD ²	51
4.1 Introduction	51
4.2 EWOD Device Descriptions	56
4.3 Experimental Apparatus and Procedures	59
4.4 Results and Discussion	60
4.4.1 Contact Angle Measurement	60
4.4.2 Droplet Distribution Affected by EWOD	62
4.4.3 Droplet Shedding Moment and Diameter	65
4.4.4 Droplet Dynamics on Thick-wire Stripe-wise Surface	67
4.4.5 Droplet Size Distribution on the Charged and Uncharged Grid-wire Surfaces	68
4.4.5.1 Theoretical Model of Droplet Size Distribution	68
4.4.5.2 Experimental Results of Droplet Size Distribution	70
4.5 Conclusions	73
CHAPTER 5 EWOD-INDUCED CONDENSATION HEAT TRANSFER ENHANCEMENT	75
5.1 Introduction	75
5.2 Experimental Apparatus	77
5.3 Experimental Procedures	81
5.4 Data Reduction	82
5.4.1 Heat Transfer of Copper	83
5.4.2 Heat Transfer of EWOD Devices	84
5.5 Results and Discussion	86
5.5.1 Thermocouple Calibration	86
5.5.2 Calibration of Experimental Setup	89
5.5.3 Heat Transfer Enhancement under EWOD	91
5.6 Conclusion	93
CHAPTER 6 CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK	95
6.1 Scientific Findings and Contributions of This Dissertation	95
6.1.1 Water Harvesting Enhancement via EWOD	95
6.1.2 EWOD-regulated Condensation Droplet Distribution	96

6.1.3 Condensation Heat Transfer Enhancement via EWOD	97
6.2 Recommendations for Future Work.....	97
APPENDIX A ACTIVATION OF BUBBLES' ESCAPE, COALESCENCE AND DEPARTURE VIA EWOD ³	99
A.1 Introduction.....	99
A.2 Experimental Setup	102
A.3 Experimental Procedures	104
A.4 Results and Discussion.....	105
A.4.1 EWOD-Induced Bubble Oscillation	105
A.4.2 EWOD-Induced Bubble Escape—Side View	109
A.4.2 EWOD-Induced Bubble Escape—Top View.....	113
A.4.4 EWOD-Induced Bubble Coalescence and Detachment	115
A.5 Conclusion	116
APPENDIX B VISUALIZATION AND THEORETICAL MODEL OF THE EWOD- DRIVEN INTERFACIAL SURFACE WAVE ⁴	118
B.1 Introduction	118
B.2 Experimental Setup and Procedures.....	119
B.3 Experimental Results and Discussion	120
B.3.1 EWOD-Induced Three-Phase Contact Point Motion on the Lateral Wall	120
B.3.2 EWOD-Induced Surface Wave Oscillation.....	122
B.3.3 Interfacial-Surface-Wave-Assisted Bubble Detachment.....	123
B.4 Theoretical Model of Interfacial Surface Wave	124
B.4.1 Mathematical Model of Surface Tension Effect	124
B.4.2 Interfacial Surface Wave Dispersion	130
B.5 Conclusions	132
BIBLIOGRAPHY	134
VITA	146

LIST OF FIGURES

Figure	Page
Figure 1.1 Schematic view of electrowetting principle.	1
Figure 1.2 Droplet merging and splitting in time-lapse series [12].	4
Figure 1.3 Schematic (a), (b) and experimental (c), (d), (e) cross-sectional views of a liquid-based variable lens in a cylindrical glass housing. Resulting electrostatic force lowered the solid–liquid interfacial contact angle [13]. ..	5
Figure 1.4 One 10^{-4} m KNO ₃ droplet on a AF1600/Parylene C surface at 0V (left) and 200V (right) [16].	6
Figure 1.5 Electric force acting at the interface of a conducting liquid.	8
Figure 1.6 Schematic of electric charge distribution in the vicinity of the triple contact line. Electric charges are at the solid–liquid interface and the liquid–gas interface within an approximate distance d from the solid surface. This is a highly simplified view because the liquid interface is distorted by electric forces close to the triple contact line [22].	10
Figure 1.7 Resultant electric forces on liquid–gas interface [22].	11
Figure 1.8 Popular two-plate configuration EWOD chip with a symmetric electrode arrangement. Once voltage is applied, the change in the meniscus shape (from the dotted shape) caused by contact-angle changes induces a gradient inside the droplet. (a) Top view; (b) cross-sectional view.	15
Figure 1.9 Cross-section view of single-side coplanar electrode device design.	16
Figure 1.10 Electrowetting design: Droplet is grounded from below; ground line goes into and out of the page.	17
Figure 2.1 Schematic of exposure and developing. a) Exposure details; b) Residuals of negative and positive photoresist on the substrates after developing.	23
Figure 2.2 Sputtering system configuration.	24
Figure 2.3 Schematic of lift-off procedures.	26
Figure 2.4 Spin coating procedures. a) Deposition. b) Acceleration. c) Flow domination. d) Evaporation [35].	26

Figure 2.5 Mask drawing of coplanar-electrode design, top view. Red dotted region represents the working region. Electrode material is gold.....	28
Figure 2.6 Mask drawing of double-layer-electrode design, top view.....	29
Figure 2.7 Electrowetting illustration of: (a) coplanar-electrode design and (b) double-layer-electrode design..	30
Figure 3.1 The water-capturing surface of the fused overwings (elytra) of the desert beetle. a) Adult female, dorsal view; b) A ‘bump’ on the elytra; c) Scanning electron micro-graph of the textured surface of the depressed areas. [44] 32	
Figure 3.2 EWOD device design. (a) Side view. (b) Perspective view.....	36
Figure 3.3 Schematic diagram of experimental setup and cross-sectional view of the electrowetting device.....	38
Figure 3.4 Overall experimental setup (left figure) and detailed look of the testing area (right figure).	38
Figure 3.5 Contact angle measurements for a single droplet under different DC voltages.	39
Figure 3.6 Contact angle measurements for a single droplet under different DC voltages.	40
Figure 3.7 At the moment of applying 60V DC to the right side with no voltage applied to the left side, droplet coalescence with wipe-down (a) is observed as well as coalescence without wipe-down (b). Voltage is turned on at $t = 0$ s. Hatched areas represent PDMS insulation regions. Scale bars, 3mm.	43
Figure 3.8 At the moment of withdrawing 60V DC from the right side, with no charge having been applied to the left side, droplet coalescence followed by wipe-down (a) is observed as well as coalescence without wipe-down (b). Voltage is turned off at $t = 0$ s. Hatched areas represent PDMS insulation regions. Scale bars, 3mm.	44
Figure 3.9 Histogram of averaged values for water collected during an 8-minute testing period.	45
Figure 3.10 Typical image from this study (left), image filtered using edge detector (middle), and the circles used to estimate droplet area coverage (right). 46	

Figure 3.11 Circle detection results for the 20V (a), 40V (b), and 60V (c) cases. Subscript 1 represents snapshots from recoded video, with the left side uncharged and right side charged, and subscript 2 represents area coverage vs. time plots generated using image processing data. The black dashed line represents the approximate charging time t_c , gray arrows represent droplet wipe-down events on the charged side, and red ellipses represent droplet wipe-down events on the uncharged side. Hatched areas represent PDMS insulation regions. Scale bars 2mm.....	48
Figure 3.12 Circle detection results for the 40V charged case, immediately before (left), immediately after (middle), and a few seconds after (right) a wipe-down event.	49
Figure 4.1 Double-layer-electrode EWOD designs: (a) thick wire, (b) thin wire and (c) grid wire.	57
Figure 4.2 Coplanar electrowetting zigzag design.....	58
Figure 4.3 Experimental setup diagram: (A) high-speed camera; (B) visualization window (heat-resistant glass); (C) testing chamber; (D) testing sample; (E) cooling block.	59
Figure 4.4 Contact angle measurements: (a)-(b) initial and 40 V DC charged contact angles of double-layer-electrode grid- and thin-wire (50 μm) devices; (c)-(d) initial and 40 V DC charged contact angles of double-layer-electrode thick-wire (1 mm) device; (e)-(f) coplanar-electrode zigzag device. Top view of droplet position for each case on the left. The blue circle represents the droplet; black lines represent electrode region in (a)-(d) and zigzag electrode gap in (e)-(f). Scale bars 1 mm.	61
Figure 4.5 Experimental visualization results: (a) grid-wire design (50- μm wire width, 1-mm wire distance); (b) thin-wire design (50- μm wire width, 1-mm wire distance). Left side uncharged, right side charged under 40 V DC. Scale bars 1 mm.....	63
Figure 4.6 Experimental visualization results: (a) thick-wire design (1-mm wire width, 1- mm wire distance); (b) zigzag design. Left side uncharged, right side charged under 40 V DC. Scale bars 1 mm.	64
Figure 4.7 Droplet first shedding moment comparison for 40 V DC charged and uncharged surfaces with four designs.....	66

Figure 4.8 Experimental visualization of droplet dynamics on vertical thick-wire pattern. (a) to (f) in time sequence. Light bars represent the electrode region. Red circles and yellow circles represent dynamics of two independent droplets. Scale bars 1 mm.	67
Figure 4.9 Droplet measurements with Image Pro Plus software. Representative areas of (a) uncharged grid-wire device, and (b) charged grid-wire device. Yellow circles represent the actual droplet edges. Scale bars 1 mm.	72
Figure 4.10 Droplet size distributions of (black) uncharged grid-wire device and (red) charged grid-wire device compared with Rose's model (black line).	73
Figure 5.1 Schematic diagram of flow loop of the condensation experimental system.	78
Figure 5.2 Testbed schematic—side view. ①③⑤⑧ Stainless steel plate; ② heat-resistant borosilicate glass; ④ stainless steel testing chamber where water vapor flows in from the top and out from the bottom; ⑥ copper to measure temperature gradient (circles represent holes to insert thermocouples: one end of the copper is inserted into the chamber and is attached to the sample by thermal paste); ⑦ cold plate with cooling water running through. T-shaped figures represent stainless steel screws used to tighten the testbed.	79
Figure 5.3 Condensation experimental testbed. a) Front cover (with heat-resistant borosilicate glass); b) Front view of the testbed. c) View of the copper drilled with holes. d) Detailed view of the testing chamber.	80
Figure 5.4 Thermal resistance diagram with EWOD devices. (1) Copper block; (2) thermal paste; (3) silicon substrate; (4) silicon nitride; (5) gold; (6) Teflon.	84
Figure 5.5 Thermocouple calibration results of left-side copper.	87
Figure 5.6 Thermocouple calibration results of right-side copper.	88
Figure 5.7 Thermocouple calibration results of coolant inlet and outlet flow temperature and steam temperature.	89
Figure 5.8 Filmwise condensation heat transfer coefficient of theoretical model and measurement on left-side copper.	90
Figure 5.9 Filmwise condensation heat transfer coefficient of theoretical model and measurement on right-side copper.	91

Figure 5.10 Heat transfer coefficient comparison between uncharged and charged (40V DC) EWOD devices on left and right sides of copper blocks.	92
Figure 5.11 Heat flux comparison between the uncharged and charged (40V DC) EWOD devices on left and right side of the copper blocks.....	93
Figure A.1 Schematic of bubble's contact-angle variation under EWOD effect.	102
Figure A.2 Schematic of testing basin and testing substrate.....	103
Figure A.3 Experimental setup: (a) overall view of setup; (b) enlarged view of testing region. (1) Function generator; (2) voltage amplifier; (3) testing wires; (4) adjustable wire holder; (5) LED light; (6) high-speed camera; (7) testing region; (8) laboratory scissor jack; (9) electrodes with clamp connected to bottom and lateral testing surfaces; (10) clamp hooked with copper wire for insertion into DI water; (11) testing basin substrate and walls made of polydimethylsiloxane; (12) visualization glass; (13) petri dish; (14) horizontal testing substrate.....	104
Figure A.4 Applied potential profile (sine, square, and triangle waveforms).....	106
Figure A.5 Bubble (3 μ L) oscillation at different times within a period of sine wave signal. Scale bar 1mm.	107
Figure A.6 Bubble (3 μ L) oscillation at different times within a period of square wave signal. Scale bar 1mm.	108
Figure A.7 Bubble (6 μ L) escape when electrode is on the left. Applied voltage: V_{peak} 60V, 0.5Hz, square wave. Scale bar 1mm.	111
Figure A.8 Bubble (6 μ L) escape when electrode inserted in DI water is on the right. Applied voltage: V_{peak} 60V, 0.5Hz, square wave. Scale bar 1mm.	112
Figure A.9 Escape behavior of (a) three, (b) four, (c) five, and (d) six bubbles. The first, second, and third columns represent $t=0s$, $t=1s$, and $t=5s$ bubble positions, respectively. Scale bars, 5mm.	113
Figure A.10 Bubble coalescence and detachment in thin film of DI water. Bubble size: 20 μ L each; electrode copper wire inserted on the left. Scale bar, 5mm.	115
Figure A.11 Bubble coalescence and detachment in thick film of DI water. Bubble size: 20 μ L each; electrode copper wire inserted on right. Scale bar, 5mm....	116

Figure B.1 Schematic of experimental setup. Black solid line and red dotted line represent water–air interface before and after applied voltage, respectively.	120
Figure B.2 Contact line movement (contact point at different times, scale bar 1mm).	121
Figure B.3 Surface wave detection (a) without EWOD applied on the lateral wall and (b)–(d) with EWOD applied on the lateral wall. Applied voltage sine wave V_{peak} 70V, frequency 1Hz. Scale bar 1mm.	122
Figure B.4 Interfacial-surface-wave-assisted bubble detachment in liquid water thin film. Scale bar 1mm.	124
Figure B.5 The coordinate system for interfacial wave problems.	124
Figure B.6 The relationship between voltage signal and contact angle change.	131

LIST OF TABLES

Table	Page
Table 3.1 Water collection (g)	42
Table 5.1 Parameters of EWOD devices and thermal paste.	85
Table 5.2 Parameters to calculated theoretical model of FWC heat transfer.....	90
Table A.1 Contact angle variation of sine, triangle, and square waves under different V_{peak}	109
Table B.1 Amplitude of different terms ($f_l=10\text{Hz}$), f is the frequency and A is the amplitude ($\times 10^{-3} m$).	128
Table B.2 Amplitude of different terms ($f_l=50\text{Hz}$) ($\times 10^{-3} m$), f is the frequency and A is the amplitude ($\times 10^{-3} m$).	129
Table B.3 Amplitude of different terms ($f_l=100\text{Hz}$) ($\times 10^{-3} m$), f is the frequency and A is the amplitude ($\times 10^{-3} m$).	129

LIST OF NOMENCLATURES

A	area; amplitude of surface wave; amplitude of the Fourier series expansion; parameters to solve the small sized droplet number
B	parameters to solve the small sized droplet number
c	sound speed
C	constants to solve surface wave contact angle
d	thickness of the dielectric layer
E	electric field
f	frequency
F	net force acting on the liquid volume element
g	gravitational constant
h	heat transfer coefficient; maximum displacement of three-phase contact point
h_{fg}	latent heat of water
k	thermal conductivity
n	normal vector
$\vec{n}$	outward unit normal vector
N	the number of droplets at certain radius size range
p	pressure
q''	heat flux
r	droplet size
$\hat{r}_0$	upper bound for the integration for the coalescence dominated growth droplet
r_e	effective transition radius

r_{max}	maximum droplet radius before shedding
r_{min}	minimum droplet (supersaturation dependent critical) nucleation sites
R	thermal resistance
t	time
T	temperature
u	velocity in x direction
v	velocity in y direction
V	applied voltage
x	characteristic length of the filmwise condensing surface of copper block; x (horizontal) direction of the surface wave propagation
Δx	distance between the thermocouple (that closest to the testing chamber) and the condensation surface
y	one-dimensional conduction heat transfer direction; y (vertical) direction of the surface wave propagation; distance
$\bar{y}$	average distance between the holes on the copper block along the heat transfer direction

Greek symbols

γ	surface tension
δ	thickness
δ_{ik}	Kronecker delta function
ϵ_0	permittivity of free space
ϵ_D	relative dielectric constant
η	displacement
θ	contact angle

θ_A	advancing contact angle
θ_e	equilibrium contact angle
θ_R	receding contact angle
λ	wavelength; frequency
μ	dynamic viscosity
ρ	density
σ	surface tension; electric charge density
φ	celocity function
Ω	surface of control element/control volume

Subscripts

Au	gold
Cu	copper
e	electrostatic
$EWOD$	values under EWOD effect
exp	exposure
f	fluid, liquid, water
FWC	filmwise condensation
i	interface; indicator of x direction
k	indicator of y direction; k-th term
l	liquid water; droplet
LG	liquid gas interface

<i>peak</i>	peak value
<i>s</i>	surface
<i>sat</i>	saturation
<i>Si</i>	silicon
<i>SiN</i>	silicon nitride
<i>Tef</i>	Teflon
<i>th</i>	thermal paste
<i>trough</i>	trough value
<i>n</i>	n-th term
<i>v</i>	vapor
<i>w</i>	wall
<i>x</i>	<i>x</i> -direction component
<i>0</i>	initial status
<i>1</i>	first term, first hole
<i>2</i>	second term, second hole
<i>3</i>	third term, third hole
<i>4</i>	fourth hole
<i>5</i>	fifth term

ABSTRACT

As demand for the world's natural resources continues to rise, energy saving has become an urgent topic. Water harvesting and condensation heat transfer enhancement represent two vital energy-saving objectives. Many researchers have focused on alternating surface wettability by employing advanced materials or complex surface structures to achieve such goals; however, most of these approaches operate in a passive manner. In terms of active methods, electrowetting-on-dielectric (EWOD) has become a popular option owing to its excellent contact angle reversibility, switching speed, and long-term reliability in altering surface wettability.

This dissertation presents a study of the EWOD effect on water harvesting and condensation heat transfer. It describes experimental and analytical studies concerning various characteristics such as EWOD-induced droplet dynamics, water capture capability, and heat transfer performance. It also quantifies water harvesting and condensation heat transfer enhancement. This dissertation is divided into four main studies, each of which considers different aspects of the effects of EWOD on water harvesting and condensation heat transfer.

The first part of this dissertation (Chapter 2) describes microfabrication technologies to obtain EWOD devices, including low-pressure chemical vapor deposition, photolithography, sputtering deposition, and lift-off and spin coating. Mask designs with different electrode configurations and a device microfabrication protocol are also described.

The second part of this dissertation (Chapter 3) presents an experimental investigation of EWOD-induced water harvesting enhancement. EWOD devices were tested in a high-humidity environment under mist flow. Compared with an uncharged

EWOD device, the water capture capability of charged devices improved significantly. These results are of great importance, as they indicate strong potential for improvement in water-harvesting applications.

The third part of this dissertation (Chapter 4) describes a visualization study of EWOD-regulated condensation droplet distribution. Side-by-side experiments were performed to compare charged and uncharged devices. Charged devices exhibited a regulated droplet distribution, faster droplet growth, more dispersed droplet distribution, and more large droplets. These experimental results introduced a novel approach to actively influence droplet distribution on microfabricated condensing surfaces and showed promise for improving the condensation heat transfer rate via EWOD.

The fourth part of this dissertation (Chapter 5) discusses the EWOD effect on the condensation heat transfer coefficient and heat flux. The heat transfer coefficient and heat flux were compared on uncharged and charged (40V DC) EWOD devices. Experimental results demonstrated a positive effect of EWOD on condensation heat transfer. This approach could be incorporated into many industrial applications (e.g., heat exchanger fin surfaces, condensing surfaces of waste heat recovery systems, and components of electronic cooling packages) requiring high-efficiency heat dissipation.

In summary, this work makes valuable contributions to the field of water harvesting and condensation heat transfer, proposing a new approach to research in these areas. Findings also detail a new tool to achieve water harvesting and condensation heat transfer enhancement via an active EWOD method.

CHAPTER 1 INTRODUCTION

1.1 Electrowetting (EW)

The electrowetting phenomenon can be described in terms of forces resulting from an applied electric field [1, 2]. The electric field tends to pull the edges of a droplet down onto the electrode, causing an increase in the droplet contact area and a (macroscale) reduction in the contact angle; thus, electrowetting can be expressed as modification of the wetting properties of a surface, which is typically hydrophobic, using an applied electric field. This working principle is illustrated in Figure 1.1.

Figure 1.1 Schematic view of electrowetting principle.

The fundamentals of electrowetting were first described in 1875 by Lippmann [3]. He discovered that capillary depression of mercury that came into contact with electrolyte solutions could be altered by applying voltage between the mercury and electrolyte. Lippman then formulated a theory of the electrocapillary effect based on his observations along with corresponding applications, including a highly sensitive electrometer and motor. Later, Frumkin [4] used a surface charge to change the shape of water droplets. The term *electrowetting* was introduced by G. Beni and S. Hackwood [5], who described this effect in designing a new type of display device for which they received a patent. They reported general operating parameters of displays based on the

dynamics of liquid moving within a solid matrix with a characteristic length of $1\mu\text{m}$ to $10\mu\text{m}$, noting that electrowetting could serve as the basis for a display device with a low operating voltage and low power consumption. They also conducted experiments on electrowetting of gold to demonstrate the concept of electrowetting displays.

In light of the decades-long technological trend of miniaturization, control of interfacial energies has become an important strategy for manipulating droplets on surfaces. Many approaches have been employed to achieve this goal. Darhuber and Troian [6] reported in a review that liquid–vapor and solid–liquid interfaces must each be influenced to control droplets, suggesting thermal control as a potential strategy. The temperature gradient and gradients in the surfactant concentration across droplets lead to gradients in interfacial energies, mainly at the liquid–vapor interface, and produce forces that can propel droplets due to thermocapillary and Marangoni effects. Aside from thermal control, the chemical and topographical structuring of surfaces has received increasing attention because it can offer finer control of the equilibrium morphology. Local wettability and substrate topography commonly influence boundary conditions within which droplets adjust their morphology to realize the most energetically favorable configuration. However, the main disadvantage of chemical and topographical patterns is their static nature, which prevents active control of liquids. Compared with the aforementioned approaches, electrowetting has been shown to be highly successful in contact angle variations of several tens of degrees, which are routinely achieved. Hundreds of thousands of switching cycles have been performed in long-term stability tests without noticeable degradation [7, 8]. Prins et al. [7] presented

the control of fluid motion in three-dimensional structures with thousands of microchannels. In this manipulation, fluids were controlled via electrocapillary pressure, originating from electrostatic control of solid/fluid interfacial tension in microchannels. They claimed that reversible fluid displacement was achieved for all channel orientations with respect to gravity. Srinivasan et al. [8] presented and characterized an electrowetting-based digital microfluidics platform for eventual real-world application to assay glucose in physiological samples using reversible electrowetting characteristics.

Given encouraging findings related to the excellent contact angle reversibility and switching speed, long-term reliability, and compatibility to alter surface wettability under variable conditions, electrowetting has become one of the most widely used tools for manipulating miniscule amounts of liquids on surfaces. The electrowetting approach has been used in DNA and protein analysis and biomedical diagnostics [9-11]. Besides biomedical research, this method has been applied in many microfabricated systems. Pollack et al. [12] reported using electrowetting to achieve micromanipulation of discrete droplets of aqueous electrolyte. They fabricated a simple open structure, consisting of two sets of opposing planar electrodes on glass substrates, and successfully controlled microdroplets ranging in size from several nanoliters to several microliters under voltages between 15V and 100V. They also presented a highly flexible and reconfigurable system in the absence of permanent channels or structures between plates in their design. They observed rapid and efficient droplet transportation with average velocities exceeding 10cm/s. The smallest droplets (~3nl) transported over

1000 times their length per second. Microdroplet formation, mixing, and splitting were also observed using the same microactuator structures as shown in Figure 1.2. Their work demonstrated a high level of functional integration and flexibility for microfluidic systems via electrowetting. In Figure 1.2, only the left electrode is energized initially as shown in (A). The middle electrode is energized next (B); after a delay, the voltage switches from the middle to the right electrode, resulting in droplet division (C) and (D). The original droplet is then reassembled by switching the voltage on the right electrode back to the middle electrode (E) and (F).

Figure 1.2 Droplet merging and splitting in time-lapse series [12].

Kuiper and Hendriks [13] used electrowetting to change the meniscus between two immiscible liquids and modified the focal distance of an optical lens. Under different amounts of applied voltage, the curvature of the meniscus of the two

immiscible liquids in a capillary could be varied, as shown in Figure 1.3. They demonstrated that the meniscus could act as a lens with an adjustable focal length. They also studied the lens motion during a focusing action by observing the transparent tube wall and then designed a miniature achromatic camera module appropriate for use in portable applications.

Figure 1.3 Schematic (a), (b) and experimental (c), (d), (e) cross-sectional views of a liquid-based variable lens in a cylindrical glass housing. Resulting electrostatic force lowered the solid–liquid interfacial contact angle [13].

Hayes and Feenstra [14] applied the electrowetting approach on reflective displays and demonstrated that it could facilitate rapid manipulation of liquids on a micrometer scale and form the basis of a reflective display that was significantly faster than electrophoretic displays. They used voltage-controlled movement of a colored oil film and determined that the color concept was 4 times brighter than reflective liquid-crystal displays and twice as bright as other emerging technologies. Their research showcased a promising application of electrowetting in a wide range of electro-optic devices.

1.2 Electrowetting-on-Dielectric (EWOD)

A major obstacle has inhibited broader electrowetting applications, namely that the applied voltage often exceeds a few hundred millivolts. In an extended study of electrowetting in the early 1990s, Berge [15] proposed using a thin insulating layer to separate conductive liquid from a metallic electrode to eliminate the electrolysis problem. This concept has since become known as electrowetting-on-dielectric (EWOD). EWOD has been applied in various fields such as liquid manipulation, heat transfer, and fluid dynamics. Welters and Fokkink [16] demonstrated control over the droplet contact angle by applying potential between a water droplet on a hydrophobic coating and the underlying conductive substrate. They drew upon the same phenomenon to control the capillary rise of a liquid in a coated capillary over several centimeters in a short time. Ultimately, they identified a coating system suitable for exploiting the electrowetting effect; in their experiment, they determined the contact angle could be reversibly switched within the range of 110° – 60° , and capillaries could be filled and emptied quickly. Their results are depicted in Figure 1.4.

Figure 1.4 One 10^{-4} m KNO_3 droplet on a AF1600/Parylene C surface at 0V (left) and 200V (right) [16].

1.2.1 Theoretical Background of EWOD

The dependency of the contact angle according to the applied voltage is expressed by the Young–Lippmann equation as follows:

$$\cos \theta = \cos \theta_0 + \frac{\varepsilon_0 \varepsilon_D V^2}{2 \sigma_{LG} d} \quad (1.1)$$

where σ_{LG} is the liquid-to-gas interfacial tension; d is the thickness of the dielectric layer; ε_0 is the permittivity of free space, and ε_D is its relative dielectric constant; V is the applied voltage; θ is the contact angle at the applied voltage; and θ_0 is the initial contact angle before applying the voltage.

The derivation of the Young–Lippmann equation can be obtained using either the classical thermodynamic approach, energy minimization approach, or electro-mechanical approach, each of which appears in the review by Mugele et al. [17]. The ensuing discussions in this section are based on the electromechanical approach; this method elucidates electric forces acting upon a droplet, particularly how the Maxwell force at the solid–liquid interface influences interfacial tension. The approach also addresses the dynamic problem and explicitly determines the force exerted by the electric field.

The electromechanical approach was introduced by Jone et al. [18, 19], Kang [20], and Zeng and Korsmeyer [21]. For liquids, the body force density due to an electric field can be obtained using the Korteweg–Helmholtz relation:

$$\vec{f}_k = \sigma_f \vec{E} - \frac{\varepsilon_0}{2} E^2 \nabla \varepsilon_f + \nabla \left[\frac{\varepsilon_0}{2} E^2 \frac{\partial \varepsilon_f}{\partial \rho} \rho \right] \quad (1.2)$$

where ρ is the mass density of the liquid, ε_f is the permittivity of the liquid, and σ_f

denotes electric charges. In Eq.(1.2), the last term specifies electrostriction and can be neglected if the mass density of the liquid is constant [22]. By integrating the body force density shown Eq.(1.2) over a volume element dV , the electric force on the volume element dV can be obtained. Besides volume integration, the same results of electric force can be derived by integrating the moment flux density (i.e., the Maxwell stress tensor) along the surface dA :

$$T_{ik} = \epsilon_0 \epsilon \left(E_i E_k - \frac{1}{2} \delta_{ik} E^2 \right) \quad (1.3)$$

In Eq.(1.3), the notation E^2 equals $|\vec{E}|^2$, and δ_{ik} is the Kronecker delta function:

$$\delta_{ik} = \begin{cases} 0, i \neq k \\ 1, i = k (= x, y, z) \end{cases} \quad (1.4)$$

By integrating the Maxwell tensor along the surface dA , the net force acting on the liquid volume element is

$$F_i = \oint_{\Omega} T_{ik} n_k dA \quad (1.5)$$

which can be solved using the Einstein summation convention (i.e., summation of the repeated indices). For a perfectly conducting liquid, the electric field is perpendicular to the liquid on the gas side as illustrated in Figure 1.5.

Figure 1.5 Electric force acting at the interface of a conducting liquid.

The surface density of an electric charge is correlated with the electric field under Gauss's law, which is found by the following equation,

$$\sigma_s = \epsilon_0 \vec{E} \cdot \vec{n} \quad (1.6)$$

where $\vec{n}$ is the outward unit normal vector. If the liquid is perfectly conducting, the electric field vanishes in the liquid. Considering the Cartesian system (i.e., the x, y, z axis system) wherein the x -axis is aligned with $\vec{n}$, the electric fields are $E = (E_x, 0, 0)$ and $E = (0, 0, 0)$ in the gas and liquid domain, respectively. In the gas domain, the Maxwell tensor is expressed as

$$[T] = \begin{pmatrix} \frac{1}{2} \epsilon_0 E_x^2 & 0 & 0 \\ 0 & -\frac{1}{2} \epsilon_0 E_x^2 & 0 \\ 0 & 0 & -\frac{1}{2} \epsilon_0 E_x^2 \end{pmatrix} \quad (1.7)$$

In the liquid domain, it becomes

$$[T] = [0] \quad (1.8)$$

When integrating Eq. (1.5), the xy , yz , zx terms become zero; the only non-vanishing term is a force along the outward normal $\vec{n}$,

$$\frac{\vec{F}}{\delta A} = P_e \vec{n} = \frac{\epsilon_0}{2} E^2 \vec{n} = \frac{\sigma_s}{2} \vec{n} \quad (1.9)$$

where δA is an elementary surface area of the interface. In Eq. (1.9), P_e is the electrostatic pressure, denoted as

$$P_e = \frac{\epsilon_0}{2E^2} \quad (1.10)$$

When electrostatic pressure P_e is acting on the liquid surface, the total pressure within the liquid becomes negative and the liquid interface is distorted by electric forces.

Figure 1.6 Schematic of electric charge distribution in the vicinity of the triple contact line. Electric charges are at the solid–liquid interface and the liquid–gas interface within an approximate distance d from the solid surface. This is a highly simplified view because the liquid interface is distorted by electric forces close to the triple contact line [22].

Electric charges at the liquid–gas interface appear near the triple contact line, within a distance equal to the dielectric thickness d as shown in Figure 1.6. A finite Maxwell force at the contact line can be obtained after integrating Eq. (1.9), resulting in

$$F_{horizontal} = \frac{\epsilon_0 \epsilon_D V^2}{2d} \quad (1.11)$$

$$F_{vertical} = \frac{\epsilon_0 \epsilon_D V^2}{2d} \frac{1}{\tan \theta} \quad (1.12)$$

The distribution of electric forces along the liquid–gas interface following the Maxwell stress is limited to a small region near the triple contact line. One can assume that the forces are acting upon the triple line on a macroscopic scale, as indicated in Figure 1.7. Moreover, using Eq. (1.11) and Eq. (1.12), electric and capillary forces in the horizontal direction can be balanced at the triple line. By taking Young’s Law,

$$\sigma_{LG} \cos \theta = \sigma_{SG} - \sigma_{SL} \quad (1.13)$$

the Young–Lippmann equation shown in Eq. (1.1) can be obtained.

Figure 1.7 Resultant electric forces on liquid–gas interface [22].

1.2.2 EWOD Applications

The applications of EWOD have been found to vary from lab-on-a-chip, optical devices to biomedical applications and others. Lee et al. [23] described the fundamental concepts of microfluidic devices based on EWOD principles and presented proof-of-concept experiments, modeling and design, a microfabrication process, and initial testing results. Pollack and Fair [24] developed a microactuator for rapid manipulation of discrete microdroplets where actuation was accomplished via direct electrical control of surface tension using two sets of opposing planar electrodes fabricated on glass. Their prototype device consisted of a linear array of seven electrodes at a 1.5mm pitch. A successful transformation of droplets (0.7μL–1.0μL) of a 100mM KCl solution was investigated between adjacent electrodes at voltages of 40V–80V. Moreover, they also demonstrated repeatable droplet transport at electrode switching rates of up to 20Hz and average velocities of 30mm/s. Kwon et al. [25] reported the completion of four fundamental fluidic operations deemed essential to building digital microfluidic circuits via EWOD: creating, transporting, cutting, and merging liquid droplets. In their experiment, all fluidic movement was confined between two plates, called a parallel-

plate channel, rather than through closed channels or on open surfaces. In addition to verifying droplet transportation and merging, they also studied the criterion for a given set of materials beyond which the droplet simply cannot be cut using an EWOD mechanism with all four operations in a liquid-air environment at 25V voltage.

In the field of fluid mechanics, Wang et al. [26, 27] demonstrated a bubble oscillation effect resulting from voltage modulation. They found voltage modulation to exhibit preferable characteristics of periodic contact angle variation, which has been shown helpful for bubble detachment within a thin liquid film. They also tested different waveforms and frequencies to acquire optimal signal input to induce maximum oscillation effects and achieve bubble detachment; they observed three bubble detachment modes, namely direct detachment, delayed detachment, and non-detachment. The actuation mechanism of the electrowetting effect on bubble behavior within a thin liquid film was also analyzed and identified; when the Weber number exceeds 0.5×10^{-3} , the bubble must break the energy barrier of the ultra-thin film to achieve direct detachment. A larger Weber number can enhance bubble detachment within a thin liquid film with a proper electrowetting actuation mechanism. Xu et al. [28] conducted a numerical study of bubble detachment facilitated by an electrowetting-driven interfacial wave. They theoretically and numerically investigated a novel mechanism of bubble detachment inspired by droplet control and manipulation via electrowetting. The surface wave was generated by contact point movement at the water-air interface in a thin liquid film under the electrowetting effect. Rapid oscillation of the contact line was achieved by a swift voltage change under an AC signal. The

interfacial wave between two immiscible fluids was found to disrupt bubble dynamics. Numerical modeling revealed that an air bubble on a hydrophobic surface could detach by the trough of the associated wave, and the frequency of the interfacial wave was twice the voltage frequency. A higher voltage frequency led to a smaller amplitude and higher celerity of the wave, whereas a lower voltage frequency led to a larger wave amplitude and lower celerity. Xu et al. [28] also determined that the bubble could detach easily at a voltage frequency of 10Hz but failed to detach at a voltage frequency of 100Hz due to the smaller amplitude of the interfacial wave.

1.4 Motivations for Present Work and Applications

In the field of heat transfer, EWOD has been applied to address chip-cooling problems in the past several years. Cheng and Chen [29] used EWOD to actuate liquid droplets and transport them to hot spot targets for adaptive chip cooling. Specifically, they designed coplanar controllable electrodes and transported liquid droplets with relatively low activating voltage and lower power consumption via EWOD to a hot spot. This droplet transportation led to efficient chip-level cooling and demonstrated the potential of adaptive cooling of microdevices via electrowetting. They also reported the electrowetting transport of liquid droplets over a multiscale-roughness-induced superhydrophobic surface and identified a substantial reduction in pressure loss associated with a superhydrophobic surface composed of carbon nanotubes. In 2017, Ke et al. [30] conducted numerical analysis of condensation on microstructured surfaces with wettability patterns. They explored the droplet dynamics and heat transfer

performance of four wettability patterns: a hydrophilic case, a superhydrophobic case, a hybrid wettability case, and a dynamic wettability case. They observed several dynamic droplet phenomena such as droplet coalescence jump, pillar-squeezing droplet jump, and a droplet being dragged up by wettability gradient. By comparing heat flux contours, they revealed that hybrid wettability cases exhibited the highest heat transfer rate compared to hydrophilic and superhydrophobic cases (an approximate 28% enhancement compared to the superhydrophobic case). Hybrid wettability cases increased droplet nucleation density and sustained large liquid–vapor interfacial areas. The authors also suggested the dynamic control of wettability vis-a-vis large-droplet detachment to avoid a flooded state in the hybrid wettability case.

The paper discussed by Ke et al. [30] indicated strong potential to actively control the wettability on hydrophobic surfaces of EWOD devices and achieve higher water-capturing capability, droplet-shedding frequency, and heat transfer rate. This approach would carry great significance for water harvesting systems, and heat transfer systems such as power plants, heat exchangers, and waste heat recovery systems.

1.5 Objectives of Present Work

Based on the electrowetting characteristics of excellent contact angle reversibility, switching speed, and long-term reliability in altering surface wettability, I aimed to couple EWOD with dropwise condensation to achieve active wettability control from an initial hydrophobic surface to a hybrid hydrophobic–hydrophilic surface. The objective of this work was to design and test water-capturing capability and heat

transfer performance on microfabricated electrowetting devices.

Regarding electrowetting device configurations, early studies tended to focus on single droplets. In such cases, a pin was inserted into the liquid (see Figure 1.1) to serve as one electrode. Studies of electrowetting later proceeded to droplet manipulations such as mixing, merging, and separating droplets, which required that droplets move rather than remain in a fixed position. Scholars therefore designed a conductive cover plate to take the place of the pin wire. As shown in Figure 1.8, a top plate with a fixed blanket represents an electrode; the bottom plate represents patterned driving electrodes. Once electrical potential is applied between the top reference electrode and the bottom driving electrode at the droplet edge, the contact angles change accordingly, generating a pressure gradient inside the droplet to achieve droplet manipulation goals.

Figure 1.8 Popular two-plate configuration EWOD chip with a symmetric electrode arrangement. Once voltage is applied, the change in the meniscus shape (from the dotted shape) caused by contact-angle changes induces a gradient inside the droplet. (a) Top view; (b) cross-sectional view.

Although the two-plate configuration has exhibited advantages such as reliable droplet control and gravity insensitivity, it suffers from pitfalls when integrating

additional functions on the chip. Yi and Kim [31] thus proposed a new design: a single-side coplanar electrode device (without a top plate) in which all electrodes for EWOD actuation are located on one side of the droplet, as displayed in Figure. 1.9. This design provides greater flexibility for the EWOD device to be adapted to various mechanisms, such as electrochemical, mechanical, and optical sensing. Yi and Kim further verified EWOD actuation of droplets on the new design by testing contact angle variations and driving droplet behavior. Their results indicated that the newly designed open-plate EWOD devices functioned well.

Figure 1.9 Cross-section view of single-side coplanar electrode device design.

Besides Yi and Kim's open-plate EWOD device design, Cooney et al. [32] demonstrated an electrowetting system in which a droplet could be electrically grounded from below using thin conductive lines on top of the dielectric layer, as shown in Figure 1.10. Instead of using the top plate to ground droplets, they achieved the same goal with grounding-from-below, i.e. by placing an extra layer of wire beneath the droplet. Their design was found to be more robust for droplet translation without

requiring a top plate or wire. They also presented a concise electrical-energy analysis that accurately described the distinction between grounded and non-grounded designs, improvements in droplet motion, and a simplified control strategy associated with grounding-from-below designs. Their double-layer-electrode design also offered flexibility for interfacing to liquid-handling instruments, leveraging droplet inertial dynamics to achieve enhanced mixing of two droplets upon coalescence, and increasing droplet translation speeds.

Figure 1.10 Electrowetting design: Droplet is grounded from below; ground line goes into and out of the page.

Motivated by the prospects of actively controllable condensation heat transfer enhancement and the possibility of an open-plate EWOD device design, research objectives pertaining to EWOD-induced water capture capability and heat transfer enhancement warrant further study.

1.6 Summary

This introduction has surveyed the EWOD approach and its applications while identifying the objectives of the present work: to design EWOD devices and apply the EWOD approach to enhance water harvesting and the condensation heat transfer rate.

This dissertation is divided into four parts based on the study objectives. The first part of the dissertation (Chapter 2) describes relative microfabricated technologies used to obtain EWOD devices. It also addresses mask designs and microfabrication techniques. The second part of the dissertation (Chapter 3) presents experimental investigations on EWOD-induced water harvesting enhancement by comparing uncharged and charged EWOD devices. Effects of different voltage potentials on the water harvesting rate are also compared. The third part of the dissertation (Chapter 4) summarizes studies involving the visualization of condensation droplet distribution regulated by EWOD by discussing droplet dynamics, droplet size distribution, and the droplet-shedding diameter and frequencies of charged and uncharged devices based on side-by-side experimental results. The fourth part of the dissertation (Chapter 5) addresses the impacts of EWOD on condensation heat transfer coefficient and heat flux based on uncharged and charged devices.

Appendices A and B present EWOD-related work outside the fields of water harvesting and condensation heat transfer conducted during my PhD studies. Appendix A describes EWOD-induced bubble dynamics, including bubble contact angle variation, bubble escape, coalescence, and departure. Appendix B presents experimental visualizations and a theoretical model of the interfacial surface wave generated by EWOD.

CHAPTER 2 DEVICE MICROFABRICATION

The preparation of the device is done by microfabrication in the cleanroom of EECS department in University of Missouri except for the first layer low-pressure chemical vapor deposition provided by University Wafer, Inc. The microfabrication steps involve photolithography, sputtering, lift off and spin coating. The detailed discussion of each method and the device fabrication recipe and mask design are presented in this chapter.

2.1 Microfabrication

2.1.1 Low-pressure Chemical Vapor Deposition (LPCVD)

LPCVD is a process used in the deposition of thin films on semiconductors, typically ranging from a few nanometers to many micrometers. LPCVD is used to deposit a wide range of possible film compositions with good conformal step coverage. These films include various materials: polysilicon for gate contacts; thick oxides for isolation; and doped oxides for global planarization, nitrides, and other dielectrics. LPCVD is similar to other types of chemical vapor deposition (CVD) in that LPCVD involves a process in which a gaseous species reacts on a solid surface or wafer and the reaction produces a solid-phase material. Every CVD process involves the same four steps. First, the reacting gaseous species must be transported to the surface. Second, the gaseous species must be absorbed into the surface of the wafer. Third, the heterogeneous surface reaction produces reaction products [33]. Finally, the gaseous reactants need to be removed from the surface.

Low pressure distinguishes LPCVD from atmospheric-pressure CVD (APCVD), i.e. the CVD performed without pressurization or depressurization. The main reason for using LPCVD rather than APCVD is the ratio of mass transport velocity and the velocity of the surface reaction. During APCVD, the ratio is close to one as the two velocities are of the same order of magnitude. The velocity of mass transport depends mainly on the reactant concentration, diffusion, and thickness of the border layer. When the pressure is lowered during LPCVD, the diffusion of gas declines proportionally to the reciprocal of the pressure. The pressure for LPCVD is about 10–1000 Pa (standard atmospheric pressure is 101,325 Pa). If the pressure is lowered from atmospheric pressure to approximately 100 Pa, then diffusion declines by nearly 1000 [33]. The velocity of mass transport will then reduce, in which case the substrates can approach more closely and the deposited films exhibit better uniformity and homogeneity [34]; hence, the resulting layer is less dependent on mass transport velocity.

The LPCVD process uses a quartz tube placed in a spiral heater that begins at a low tube pressure of approximately 0.1 Pa. The tube is then heated to the working temperature level, and the working gas flows through the tube at a preset pressure between 10–1000 Pa. This working gas consists of dilution gas and reactive gas, which will react with the substrate and form a solid-phase layer on the substrate. After the working gas enters the tube, it expands near the hot substrates at the same temperature. The substrate temperature is quite important as it influences which reactions occur. The working gas reacts with the substrates and forms the solid-phase material; excess material is pumped out of the tube. LPCVD has been most successfully utilized in the

deposition of polysilicon thin films. This process can also be used for nitrides intended for dielectric layer formation, specifically by adding compounds such as Silane within temperature range of 700°C–900°C.

Compared with other CVD processes, LPCVD has the advantages such as highly uniform thickness and purity, simple handling, high reliability, homogeneity of deposited layers, and high reproducibility etc. Its disadvantages include lower deposition rates than APCVD and high temperatures (usually above 600°C) required for processing. The deposition rate is controlled by pressure and temperature.

2.1.2 Photolithography

Photolithography, also called optical lithography or UV lithography, is a process used in microfabrication to pattern parts of a thin film or the bulk of a substrate (or a wafer). It uses light to transport designed geometric patterns from a photomask to the substrate, using a chemical "photoresist" that is light-sensitive. A series of chemical treatments then either imprints the pattern into the material or deposit a new material in the desired pattern on the substrate, which is underneath the photoresist. The following six steps describes photolithography procedures in detail.

a) Cleaning wafer

The organic or inorganic contaminations existing on the wafer surface are usually removed by wet chemical treatment, such as acetone, methanol or isopropanol. Wafer is initially heated to a temperature sufficient to drive off any moisture that may be present on the wafer surface. Wafers that have been stored must be chemically cleaned to remove contamination before the photolithography. A liquid or gaseous "adhesion

promoter", is applied to improve adhesion of the photoresist to the wafer, if needed.

b) Photoresist application and Pre-bake (or soft bake)

The wafer is covered with photoresist by spin coating (which will be discussed later). A viscous, liquid solution of photoresist is dispensed onto the wafer, and the wafer is spun rapidly to produce a uniformly thick layer. The spin coating process results in a uniform thin layer. Final thickness is also determined by the evaporation of liquid solvents from the resist. The photo resist-coated wafer is then prebaked to drive off excess photoresist solvent.

c) Exposure, post-exposure bake and developing

After prebaking, the photoresist is exposed to a pattern of intense light. The exposure to light leads to a chemical change that allows some of the photoresist to be removed by a special solution, called "developer" by analogy with photographic developer. Positive photoresist becomes soluble in the developer when exposed; while for the negative photoresist, unexposed regions are soluble in the developer. The details can be found in Figure 2.1.

A post-exposure bake is performed before developing to help reduce standing wave effect resulted from the destructive and constructive interference patterns of the exposure light.

d) Hard bake

The resulting wafer is then "hard-baked" for the residual photoresist. The hard bake solidifies the remaining photoresist, strengthens of resist structure and make it more stable to protect layer in future ion implantation or etchings.

Figure 2.1 Schematic of exposure and developing. a) Exposure details; b) Residuals of negative and positive photoresist on the substrates after developing.

2.1.3 Sputtering Deposition

Sputtering is a physical vapor deposition technique used to deposit thin films of a material onto a substrate. By creating a gaseous plasma and accelerating ions from this plasma into some source material (i.e., a target), the source material is eroded by the arriving ions via energy transfer and is then ejected in the form of neutral particles—either individual atoms, clusters of atoms, or molecules. As these neutral particles are ejected, they travel in a straight line unless they come into contact with an object, such as other particles or a nearby surface. If a substrate such as a Si wafer is placed in the path of these ejected particles, the substrate will be coated by a thin film of the source

material. Sputtered atoms ejected from the target have a wide energy distribution, normally up to tens of eV (100,000K). Sputtered ions (only a small fraction of the ejected particles tends to be ionized, on the order of 1 percent) can ballistically fly from the target in straight lines and impact energetically on the substrate or vacuum chamber. Alternatively, at higher gas pressures, the ions collide with gas atoms which serves as moderators and move diffusively, arriving at the substrate or vacuum chamber wall and condensing after experiencing a random walk. The entire range from high-energy ballistic effect to low-energy thermalized motion is achievable by changing the background gas pressure. The sputtering gas is often an inert gas such as argon. For effective momentum transfer, the atomic weight of sputtering gas should be close to the target atomic weight; neon is preferable for sputtering light elements, whereas krypton or xenon is used for heavy elements. Figure 2.2 shows the configuration of the sputtering system.

Figure 2.2 Sputtering system configuration.

Sputtering is completed using either DC voltage (i.e., DC sputtering) or AC voltage (i.e., RF sputtering). Due to the application of an alternating current, ions inside the plasma oscillate and increase the plasma levels. Physical sputtering is obtained by

the momentum exchange between ions and atoms in the target materials upon collisions.

Our designed device uses reactive sputtering to deposit a second layer of silicon nitride. Reactive sputtering is a process that deposits compounds by introducing a reactive gas (for example nitrogen or oxygen) into the plasma (i.e. an inert gas such as argon, krypton, or xenon). In this process, the reactive gas is ‘activated’ by the plasma and reacts chemically with the target material and then deposit on the substrate. The resultant film composition can be controlled by the relative ratio of inert and reactive gases. Oxides, nitrides, carbides, and mixtures of all three can be generated by reactive sputtering. The reactive sputtering process aims to generate thin films with a precisely controlled stoichiometry and structure. Over the past decade, the reactive DC processes have improved significantly as it has a much higher deposition rates compared to RF sputtering of bulk materials.

2.1.4 Lift-off

Lift-off is a process that exposes a pattern into photoresist and deposits a thin film (such as a metal or dielectric) over the entire area, then washes away the photoresist to leave only the film in the patterned area for future deposition.

In lift-off processing, the coating is applied to existing photoresist structures. The subsequent lift-off removes the resist structures together with the material deposited on it, while the material applied directly to the substrate through the openings of the photoresist remains, as shown in Figure 2.3.

Figure 2.3 Schematic of lift-off procedures.

2.1.5 Spin Coating

Spin coating is a procedure of depositing uniform thin films onto flat substrates. A small amount of coating material is initially applied on the center of the substrate (stable or spinning at a low speed). Then the substrate is rotated at high speed to spread the coating material by centrifugal force. The machine called spin coating is used for spin coating. Spin-coating procedures are depicted in Figure 2.4.

Figure 2.4 Spin coating procedures. a) Deposition. b) Acceleration. c) Flow domination. d) Evaporation [35].

Spin coating is widely used in the microfabrication to form uniform thin films with nanoscale thicknesses [36]. Spin coating is also used in photolithography to deposit

photoresist layers. Great efforts have been devoted to cataloguing the dependence of film thickness and uniformity over the spin-coating recipes [37-40]. Spin coating is advantageous in its ability to quickly and easily produce highly uniform films, ranging from nanometers to a few micros in thickness.

The thickness of a spin-coated film can be considered as proportional to the inverse of the spin speed squared as shown in the Eq. (2.1), where t is the thickness and w is the angular velocity:

$$t \propto \frac{1}{w} \quad (2.1)$$

The exact thickness of a film will depend upon the material concentration and solvent evaporation rate, which is informed by the solvent viscosity, vapor pressure, temperature, and local humidity; thus, spin-coating thickness curves for different materials are often determined empirically. First, a test film is spin coated and the thickness is measured using surface profilometry or ellipsometry. Then, the spin thickness curve can be calculated more accurately based on more data points. Finally, the spin speed can then be adjusted to obtain the desired film thickness.

In most standard spin-coating techniques, the goal is to continue spinning the substrate until the film is fully dry. This process mainly depends on the boiling point and vapor pressure of the solvent as well as the ambient conditions (i.e. temperature and humidity) under when the spin coating is performed. For most solvents, a spin-coating period of 30 seconds is adequate and therefore suggested as a reference for most processes. For solvents with a higher boiling point and/or lower vapor pressure (usually serve as additives or requires extra drying steps), drying may take longer time.

2.2 Mask Design

The mask design is essential, as it determines the geometry of the photolithography structure. I designed two types of masks followed by the two open-plate EWOD designs discussed in Chapter 1.5: a coplanar-electrode design and double-layer-electrode design, illustrated in Figure 2.5. The adjacent electrode is charged by different poles (i.e., positive and negative). The electrode pitch size is 1mm. Between the two electrodes are zigzag-shaped gaps measuring either 0.05mm or 50 μ m. This zigzagged design of the electrode gap is intended to enlarge the droplet contact area to be charged by the device.

Figure 2.5 Mask drawing of coplanar-electrode design, top view. Red dotted region represents the working region. Electrode material is gold.

The double-layer-electrode design is depicted in Figure 2.6. The electrode layout is a grid-wire configuration with a wire width of 50 μ m; the distance between two adjacent wires is 1mm. The device consists of two sections (i.e., the working section and voltage-charging section), and electrode wires are distributed horizontally and vertically to enlarge the effective EWOD areas. The charging region is outside the

testing region to eliminate any influence on the testing results. Both designs were drawn in AutoCAD and sent to a CAD/Art company for a transparent film mask production.

Figure 2.6 Mask drawing of double-layer-electrode design, top view.

2.3 Microfabrication Recipe of EWOD Devices

Cross-sectional views of the two devices are provided in Figure 2.7. The substrate is a 400 μm -thick conductive silicon that serves as one electrode; a grid pattern of 50 μm -wide and 150nm-thick gold wire serves as the other. These electrodes are separated by a 100nm-thick layer of silicon nitride insulation (obtained via LPCVD by University Wafer) to produce a capacitive effect, and the gold is adhered to another 150nm-thick layer of silicon nitride and a 60nm-thick layer of Teflon. In this case, the second silicon nitride layer was added to protect the Teflon from degradation due to electric heating by the gold electrode. A lift-off microfabrication process was also used, which involved the patterning of an S1813 positive photoresist. The S1813 was spin-coated at 2000rpm

(a)

(b)

Figure 2.7 Electrowetting illustration of: (a) coplanar-electrode design and (b) double-layer-electrode design.

for 30s (1000rpm/s acceleration speed) to obtain a photoresist layer with 1.6–2 μm thickness. The substrate was then soft baked on a hotplate at 110°C for 1min. Before exposure, the light intensity of the exposure machine was measured to be 10.83mW/cm².

The exposure time can be calculated as

$$t_{\text{exp}} = \frac{150\text{mJ} / \text{cm}^2}{10.83\text{mW} / \text{cm}^2} = 13.85\text{s} \approx 14\text{s} \quad (2.2)$$

where the required exposure energy of 150mJ / cm² is obtained from the datasheet of the S1813 photoresist. The post-exposure bake was not needed after exposure. The MF321 developer was used in the developing step. The wafer was placed in the

developer for approximately 60s before being cleaned with deionized (DI) water and blown with nitrogen gas. The photoresist coverage was deemed sufficient prior to the next step: sputtering deposition of the Ti/Au electrode layer.

Following photolithography, a sputtering process was performed to add titanium and gold. After sputtering, a lift-off procedure was carried out by soaking the sample in acetone for over 4h, sonicating the sample for 30s, and finally cleaning it with acetone, methanol, and DI water. The Ti/Au layers on top of the photoresist was then removed and ready for the next sputtering step. Before proceeding, the electrode was first covered with Kapton tape (as this part would ultimately be exposed to the charging system). Next, reactive sputtering was applied to obtain a 150nm-thick layer of silicon nitride. The last step was to obtain the top hydrophobic layer by spin-coating Teflon (FluoroPel PFC1601VFS from Cytonix LLC) at 2000rpm for 30s (1000rpm/s acceleration) and heating the sample to 180°C for 30min to optimize adhesion and reduce surface energy to roughly 10 dynes/cm. A Teflon layer has been widely used in EWOD applications due to low contact angle hysteresis (CAH) [41]. To avoid residual Kapton tape adhesion, the tape was peeled off carefully before heating the sample.

CHAPTER 3 EWOD-INDUCED WATER CAPTURE

CAPABILITY ENHANCEMENT¹

3.1 Introduction

As demand for the world's water supply continues to rise, water shortages have become a major concern [42, 43]. Many researchers have investigated efficient methods for capturing more water from air. Parker and Lawrence [44] discovered that large droplets form on an insect's bumpy surface, which consists of alternating hydrophobic, wax-coated and hydrophilic, non-waxy regions. They claimed that a combination of hydrophilic and hydrophobic points was best for collecting water from mist at 22°C and 66°C. The design of this fog-collecting structure motivated the following water-capturing enhancement studies. Figure 3.1 presents detailed images a beetle's back.

Figure 3.1 The water-capturing surface of the fused overwings (elytra) of the desert beetle. a) Adult female, dorsal view; b) A 'bump' on the elytra; c) Scanning electron micro-graph of the textured surface of the depressed areas. [44]

¹The contents of this chapter have been partially published in the following journal article: **Yan, R.**, McClure, T. S., Jasim, I. H., Koppula, A. K. R., Wang, S., Almasri, M., & Chen, C. L. (2018). Enhanced water capture induced with electrowetting-on-dielectric (EWOD) approach. *Applied Physics Letters*,

Bai et al. [45] reported a novel designed surface with star-shaped wettability patterns inspired by water collection of desert beetles and spider silk. By integrating a surface energy gradient and Laplace pressure gradient, surfaces with star-shaped wettability patterns can quickly drive tiny water droplets toward more wettable regions to avoid being lost in the wind. They revealed that this type of surface is more efficient in water collection compared to uniform superhydrophilic, uniform superhydrophobic, or even circle-patterned surfaces. They also tested different pattern sizes (1000 μm , 500 μm , and 250 μm) and found that enhancement by this novel design was more apparent when the size reduced from 1000 μm to 25 μm . Later, Bai et al. [46] revealed that the capture silk of the cribellate spider could deform and exhibit a unique periodic spindle-knot structure, leading to unique wettability and efficient directional water collection. They developed several methods to mimic the silk-spinning process of spiders such as dip-coating, fluid-coating, electrodynamic, and microfluidic technologies. Their results achieved highly efficient liquid transportation along the fiber, leading to a faster water-capturing rate by directionally transporting small water droplets together to coalesce into large droplets.

Hou et al. [47] fabricated bioinspired fibers to investigate the water collection behavior and geometric influence (i.e., periodicity of spindle knots) on hanging-drop ability. They discussed water collection which is related to the periodicity of geometry on the bioinspired fiber and determined the length of the three-phase contact line under threshold conditions together with the maximal volume of a hanging drop in different modes. They demonstrated that the geometrical structure of bioinspired fiber induces a

much stronger water-hanging ability compared with uniform fiber, attributable to unique geometry that effectively increases the three-phase contact line length or limits the contact length to be shorted. Moreover, they controlled tiny water drops collected in large water drops at a given location and investigated the fog collection efficiency enhancement.

He et al. [48] developed a simple and flexible approach for controllable fabrication of spider-silk-like microfibers with tunable magnetic spindle knots using biocompatible calcium alginate for controlled 3D assembly and water collection. Liquid jet templates with volatile oil drops containing magnetic Fe_3O_4 nanoparticles were generated from microfluidics to fabricate spider-silk-like microfibers. They discovered that dehydrated spider-silk-like microfibers, with magnetic spindle knots for collecting water drops, can be controllably assembled into spider-web-like structures for excellent water collection.

Inspired by antireflective mosquito eyes and cicada wings, Mousterde et al. [49] studied antifogging and self-cleaning properties on these surfaces with nanometer-scale-featured special shapes. They examined the underlying antifogging mechanism in model materials designed to mimic nature systems and explained the importance of textural feature sizes and shapes. For hydrophobic surfaces with nano-cone structures, the antifogging efficiency approached unity, and water departure from droplets became smaller than $2\mu\text{m}$.

Heng et al. [50] developed an artificial water-collecting structure inspired by an approach used in a cactus to collect fog. The structure included a large ZnO wire and an array of small ZnO wires branched on the large wire. All wires were conically shaped

with gradually increasing diameters from the wire tip to root. A water drop condensed on the tip of each wire was driven to the root by capillary force induced by the diameter gradient. The lengths of the stem and branched wires in the synthesized structures were in the orders of 1mm and 100 μ m, respectively. They conducted two groups of tests at a relative humidity (RH) of 100% to compare the amounts of water collected by artificial and cactus structures within specific time durations of 2 s and 35 s. The amount of water collected by either structure was in the order of 0.01 μ L, although water collection by the artificial structures was 1.4–5.0 times greater than that harvested by the cactus structures. They also developed a setup to successfully collect approximately 6 μ L of water in 30 min.

Ju et al. [51] reported that a survival system of the cactus *Opuntia microdasys* involves an efficient fog collection system. This system was composed of well-distributed clusters of conical spines and trichomes on the cactus stem; each spine contained three integrated parts that played different roles in the fog collection process based on their surface structural features. The gradient of the Laplace pressure, the gradient of surface-free energy, and multi-function integration endowed the cactus with efficient fog collection. Investigations into the structure–function relationship of this system can inform novel designs for high-efficiency water collection from fog.

However, the abovementioned works to change the relied on advanced materials or complex surface structures that required complicated microfabrication treatments or techniques and operated in a passive manner. In this work, EWOD was employed on a cold surface under a moist air condition to investigate the enhanced surface water

capturing capability. First, a double-layer-electrode design is presented which allows EWOD to affect most of the condensed droplets on the cold surface. Second, the EWOD effect on droplet dynamics was investigated at the moments of turning on and off 60V DC potential. Finally, side-by-side experiments under applied DC voltages of 20V, 40V, and 60V were conducted to compare the mass of water collected and the droplet area coverage between charged and uncharged samples, and an improvement in water capturing capability under the EWOD effect was revealed in all the three cases.

3.2 EWOD Device

The EWOD device utilized in this study is double-layer-electrode design. A side view schematic and a perspective view of the device is illustrated in Figure 3.2 (a) and (b), respectively. The device is composed of two region types: the working region and the voltage charging region. The fabrication of the working region follows exactly the same parameters discussed in Chapter 2.3. The charging region lacks the top layers of silicon nitride and Teflon, which leaves the gold electrode layer exposed so that voltage

Figure 3.2 EWOD device design. (a) Side view. (b) Perspective view.

can be applied directly. As shown in Figure 3.2(b), the wires with 50 μ m width are distributed in a grid pattern to enlarge the effective area of EWOD.

3.3 Experimental Setup

The device shown in Figure 3.2(b) is cut into two pieces for side-by-side testing purposes. Both sides are obtained under the same microfabrication process on the same substrate. The exposed Au electrode and voltage power supply are connected by silver epoxy (MG Chemicals 8331-14G) and a 40 AWG copper wire. To guarantee the device can serve as a good capacitor, the resistance between two electrodes is measured before the test. The devices possess 40-60M Ω resistance, indicating adequate capacitance to achieve the EWOD effect. The testing sample is attached to a cooling block by thermal paste, and the cooling block temperature is kept at 5°C during the experiments by a recirculating chiller (Maxicool RC150). A 2mm $\times$ 2mm $\times$ 50mm PDMS is placed between the two device sections to help position them and provide electrical insulation. A ring light is placed in front of the sample area to provide adequate lighting. The water capturing process is recorded with a high-speed camera. The water is collected using two small beakers beneath the two devices and weight is measured by an Ohaus PX224 Pioneer PX Analytical Balance. Mist is supplied by a humidifier (Crane Drop Ultrasonic Cool Mist) at 25°C—measured by a thermometer during the test. Airflow is from the bottom to the top, and the outlet of the humidifier is placed directly between the two sections to ensure an even distribution of mist over both. In the side-by-side experiments, flow rate is calibrated to ensure the same rate of water capturing on both

sections before the voltage is applied. Compared with the incoming cool mist flow, the humidity change in the environment between tests is negligible. The schematic and real experimental setup is shown in Figures 3.3 and 3.4, respectively.

Figure 3.3 Schematic diagram of experimental setup and cross-sectional view of the electrowetting device.

Figure 3.4 Overall experimental setup (left figure) and detailed look of the testing area (right figure).

3.3 Contact Angle Measurement

In order to ensure that the EWOD effect was present before testing, the contact angle of a single droplet was measured on the devices under different DC voltages ranging from 0 to 60V. These measurements are shown in Figures 3.5 and 3.6. Figure 3.5 illustrates the contact angle measurement with a single droplet of the device in this

study. Figure 3.6 shows a graphic view of contact angle variation under different applied DC voltages, ranging from 10V to 60V. Contact angle recoil was also observed in the experiments, and this is likely due to the “wire grid” design which constitutes a non-homogeneous substrate in this study.

Figure 3.5 Contact angle measurements for a single droplet under different DC voltages.

Figure 3.6 Contact angle measurements for a single droplet under different DC voltages.

3.4 Experimental Results

It has been shown that droplet contact angle decreases as voltage is applied across the droplet in many studies [5, 23, 52, 53]. However, the EWOD effect has never been utilized on a condensing surface to enhance coalescence and wipe-down in numerous droplets. The experimental results in this work demonstrate that, at the moment that 60V DC is turned on or off, droplets on the condensing surface experience strong coalescent behavior and sometimes undergo wipe-down events. These phenomena are not observed on the uncharged side.

Although coalescence is observed in nearly all trials, wipe-down occurs only some of the time. Coalescence occurs when droplets are large enough and spaced closely enough together that they interact with each other when agitated by the changing electric field. Since wipe-down occurs only when a droplet is large enough for gravity

to overcome the forces holding the droplet in place, the only factor affecting wipe-down in this experiment is the size of the coalesced droplet. It was found in this study that droplet coalescence can occur with initial droplets that are small enough such that the resulting coalesced droplet is too small to induce a wipe-down event. In order to effectively demonstrate EWOD's potential for improved water harvesting, this experiment was conducted in such a way as to maximize the probability of coalescent behavior or wipe-down events when switching charge states (turning 60V DC on or off). Voltage was kept in the same charge state for 1-3 minutes before switching, which proved to be enough time to obtain a high density of large droplets near the top of the device. The top portion of the device was targeted for coalescence and wipe-down in this work in order to maximize the effectiveness of wipe-down events. Wipe-down closer to the top allows the droplet to clean off a greater surface area than wipe-down closer to the bottom.

The experimental results reveal that droplet coalescence and wipe-down is enhanced by EWOD. When voltage is applied to or withdrawn from the condensing surface, the sudden change in the electric field elicits droplet motion, which can result in enhanced droplet coalescence and sometimes induces wipe down events. This actively clears condensing surface area for additional droplet nucleation and growth. These results are shown in detail in Figures. 3.7 and 3.8.

Side-by-side tests were conducted to investigate water capturing enhancement due to the EWOD effect. The beakers shown in Figure 3.4 collected water captured by the uncharged and charged devices throughout a testing period of 8 minutes. The initial

weight of each beaker was measured to accurately determine the weight of the water in each beaker after the tests. Voltages of 20V, 40V, and 60V were selected for three reasons. First, the 20V increments allow comparison of the EWOD effect on water capturing efficiency under a range of different applied voltages. Second, the highest voltage of 60V is low enough to avoid the breakdown of the dielectric layer and contact angle saturation. Finally, Wang et al [26] reported 50V to be effective using their device which has the same parameters as the one utilized in this study, and all three selected voltages are close to 50V. Each of the three experiments was repeated three times to ensure repeatability. Experimental results are shown in Table 3.1 and the trial averages are illustrated in Figure 3.9.

Table 3.1 Water collection (g)

Testing time (n)	Uncharged	Charged_20V	Uncharged	Charged_40V	Uncharged	Charged_60V
n=1	0.4091	0.9750	0.409	1.1966	0.4203	1.4512
n=2	0.4177	1.0444	0.4397	1.1968	0.4657	1.4302
n=3	0.4346	0.9948	0.4582	1.1797	0.4778	1.4886
Average	0.42047	1.00473	0.43563	1.19103	0.45460	1.45667

The data shown in the Table 3.1 and Figure 3.9 clearly demonstrate a positive correlation between applied voltage and water capturing. Compared to the uncharged device, the water collection rate on the 20V, 40V, and 60V charged device is improved by 138.96%, 171.87%, 220.43% respectively, which demonstrates a significant enhancement in water capturing capability. Because similar results were recorded for all three trials of each case, it is reasonable to conclude that water capturing enhancement remains constant for each tested voltage.

Figure 3.7 At the moment of applying 60V DC to the right side with no voltage applied to the left side, droplet coalescence with wipe-down (a) is observed as well as coalescence without wipe-down (b). Voltage is turned on at $t = 0\text{s}$. Hatched areas represent PDMS insulation regions. Scale bars, 3mm.

Figure 3.8 At the moment of withdrawing 60V DC from the right side, with no charge having been applied to the left side, droplet coalescence followed by wipe-down (a) is observed as well as coalescence without wipe-down (b). Voltage is turned off at $t = 0\text{s}$. Hatched areas represent PDMS insulation regions. Scale bars, 3mm.

Figure 3.9 Histogram of averaged values for water collected during an 8-minute testing period.

3.5 Droplet Coverage Analysis

3.5.1 Droplet Detection Algorithm

Water capturing capability due to EWOD was also demonstrated by comparing the percent area covered by droplets in the charged and uncharged sections as a function of time. Droplet area coverage was quantified using an automated droplet detection algorithm consisting of a filtering process followed by a circle Hough Transform. First, the video files were decomposed into image frames using OpenCV, then an in-house edge-detection algorithm coded using CUDA was used to filter the images. MATLAB's "imfindcircles" function (which uses the Hough Transform circle detector) was then applied to both the filtered images and the original images. Further MATLAB scripting was used to remove circles that were found to be inside of other circles. The total area of all remaining circles was then assumed to be the droplet area coverage.

The filtering process creates a binary image, where edge pixels are assigned a 1 and all other pixels are assigned a 0. Edge pixels are determined using an edge detecting algorithm developed in this lab for EWOD projects. The edge detector determines whether a pixel is on an edge using three calculated properties of the pixel: the magnitude of the numerical gradient in pixel brightness, the ratio in the brightness of a small area surrounding the pixel to the brightness of a larger area surrounding the pixel, and the variance in the angle difference between the direction of the brightness gradient of the pixel and the direction of the brightness gradient of surrounding pixels along a line perpendicular to the pixel's brightness gradient. These three values are each raised to the power of an adjustable parameter to create gradient, brightness, and variance factors. A pixel is assumed to be part of an edge if the product of an adjustable sensitivity factor, the gradient factor, and the brightness factor is greater than the variance factor. This edge detection strategy is highly adjustable and more effective than standard methods such as Canny for images with many closely spaced small

Figure 3.10 Typical image from this study (left), image filtered using edge detector (middle), and the circles used to estimate droplet area coverage (right).

objects or images that are dim or out of focus. Figure 3.10 shows a typical image from this study along with the image filter and the detected circles.

Video snapshots and corresponding circle detection results are shown in Figure 3.11. Side-by-side experiments with DC voltages of 20V, 40V, and 60V applied for a duration of 4 minutes are selected for analysis. In all three cases, wipe-down events (observed as a sudden drop in droplet area coverage) are stronger on the charged sections than on the uncharged ones. The time when the electric potential is applied to the device is marked in Figure 3.11 as t_c . The time of t_c is delayed in the 20V case compared with the 40V and 60V cases because this was the first experimental test run and calibration was required in order to obtain an equal air-mist flow rate on both sides.

The uncharged side experiences the same number of wipe-down events as the charged side for the 20V and 60V cases, while there is one additional wipe-down event on the charged side for the 40V case. In both the 20V and 60V cases, wipe-down events occurred earlier on the charged side than the uncharged side. Although the charged side in the 40V case experienced its first wipe-down event after the uncharged side, wipe-down events were more frequent on the charged side. Wipe-down frequency is lower in the 60V case than in the 20V and 40V cases, but this may be a result of the stronger electric field holding the droplets in place, and the first wipe-down in the 60V case is stronger than the first wipe-down in the other two cases. The analysis of droplet area coverage clearly shows that the EWOD effect results in stronger and sometimes more frequent wipe-down events. Since wipe-down events free additional space for another cycle of droplet nucleation and growth, it can be inferred from these results that EWOD has a strong positive effect on the water capturing capability of a condensing surface.

Figure 3.11 Circle detection results for the 20V (a), 40V (b), and 60V (c) cases. Subscript 1 represents snapshots from recorded video, with the left side uncharged and right side charged, and subscript 2 represents area coverage vs. time plots generated using image processing data. The black dashed line represents the approximate charging time t_c , gray arrows represent droplet wipe-down events on the charged side, and red ellipses represent droplet wipe-down events on the uncharged side. Hatched areas represent PDMS insulation regions. Scale bars 2mm.

3.5.2 Droplet Detection Algorithm Error

Note that this method of droplet area coverage estimation is not perfect and results in some errors. As shown in Figure 3.8, some droplets are not detected by the algorithm, while erroneous circles are present that do not correspond to any droplet. However, these results are still accurate enough to qualitatively discern large-scale changes in droplet area coverage.

Figure 3.12 shows droplet detection results at three times around a wipe-down event and illustrates that the event can confidently be detected using changes in the estimated area coverage. As shown in Figure 3.12, even though the droplet detection is not perfectly accurate, a wipe-down event will still result in a significant drop in the area coverage estimated using this method, and subsequent nucleation of new droplets will still result in a gradual increase in estimated area coverage. Furthermore, note that the area vs. time curves shown in Figure 3.10 are very similar for the charged and uncharged side until wipe-down events start to occur. This is strong evidence that any

Figure 3.12 Circle detection results for the 40V charged case, immediately before (left), immediately after (middle), and a few seconds after (right) a wipe-down event.

errors in the percent area estimate must be very nearly the same on both the charged side and the uncharged side. The image processing results were used only to generate the area vs. time curves, and the area vs. time curves were used only to compare the charged side with the uncharged side, so it is reasonable to claim that errors in the area estimate do not affect the observations discussed in this work. (This section is helped with Mr. Thomas S. McClure.)

3.6 Conclusions

To conclude, an EWOD device design that enables a separation between droplets and electrodes is presented in this paper. Experiments are carried out to investigate the EWOD effect on water capturing capability enhancement. The observed phenomena when turning on and off 60V DC indicate that the effect of electrowetting on droplet morphology variation leads to increased droplet coalescence and wipe-down events, which improve the water capturing capability of the condensing surface. Side-by-side experiments are carried out for 20V, 40V, and 60V cases using both direct collection of captured water and image processing methods. Compared with the uncharged device, the water collection rates of the 20V, 40V, and 60V charged devices are improved by 138.96%, 171.87%, 220.43%, respectively. The circle detection area coverage analysis also indicates that when DC voltage is applied under same moist air flow rate, the device with EWOD has improved coalescence and wipe-down behavior. This work demonstrates an effective method for controlling droplet coalescence and wipe-down activity and has significant application potential in fields involving enhanced water harvesting and condensation capabilities.

CHAPTER 4 CONDENSATION DROPLET DISTRIBUTION

REGULATED BY EWOD²

4.1 Introduction

Condensation heat transfer is common in everyday life and has been studied extensively. Increasing the efficiency of condensation exerts substantial impacts on energy, material consumption and cost. Condensation can be classified as either filmwise or dropwise based on droplet morphology [54]. Dropwise condensation has been found to enhance heat transfer owing to superior heat transfer performance compared with filmwise condensation modes [55-57]. Effective dropwise condensation occurs when nonwetting superhydrophobic or incompletely wettable surfaces serve as condensing surfaces. These surfaces lead to higher droplet nucleation site densities, stronger coalescence and faster droplet shedding rates, resulting in a higher replenishment frequency with smaller droplet diameters. Many methods have been investigated with the goal of reducing surface wettability [58, 59] over the entire condensing surface to ensure dropwise condensation [60-63].

Miljkovic et al. [60] studied on the highly efficient jumping-droplet condensation heat transfer on a silanized copper oxide surfaces. They experimentally demonstrated a 25% higher overall heat flux and 30% higher condensation heat transfer coefficient compared to state-of-the-art hydrophobic condensing surfaces at low supersaturations. Their works showed significant heat transfer enhancement and indicated the insight and

²The contents of this chapter have been published in the following journal article: **Yan, R.,** & Chen, C. L. (2019). Condensation Droplet Distribution Regulated by Electrowetting. *Journal of Heat Transfer*, 141(11).

avenue to achieve high flux superhydrophobic condensation. Preston et al. [61] showed the effectiveness of ultrathin scalable chemical vapor deposited (CVD) graphene coatings to promote dropwise condensation while achieving robust chemical stability and maintaining low thermal resistance. Heat transfer enhancements were demonstrated compared to filmwise condensation, and the robustness of the CVD coatings was superior to typical hydrophobic monolayer coatings. Their results indicated that graphene was a promising surface coating to promote dropwise condensation of water in industrial conditions with the potential for scalable application via CVD. Torresin et al. [62] investigated on the superhydrophobic surfaces with excellent ability to promote dropwise condensation with high droplet mobility, which could result in enhanced surface thermal transport. They utilized an all-copper superhydrophobic surface with controlled nano-structuring surfaces for minimal thermal resistance. They performed flow condensation tests with saturated vapor at a high temperature (110°C) and discovered the condensing drops could penetrate the surface texture (i.e., attain the Wenzel state with lower droplet mobility). However, at the same time, the vapor shear helped alleviate the mobility and enhanced the thermal transport. They measured a heat flux of $\sim 600 \text{ kW} \cdot \text{m}^{-2}$ at 10K subcooling and 18m/s vapor velocity. Their work highlighted the excellent potential of nanostructured superhydrophobic surface inflow condensation applications.

Furthermore, enhanced condensation on hybrid surfaces with different patterns such as hydrophobic-hydrophilic [64-72], hydrophobic-superhydrophobic [73], hydrophilic-superhydrophilic [74, 75], superhydrophobic-hydrophilic [76-78] has been

explored in heat transfer and water harvesting studies. Alwazzan et al. [64] investigated hydrophobic and hydrophilic regions on a condensing tube. These adjacent regions allowed the wettability gradient to reduce condensation and increase the droplet removal rate. The authors conducted a parametric study to experimentally determine the effect of the area ratio between the two regions on heat transfer performance. An overall enhancement was reported in condensation heat transfer using the designed hybrid patterns compared with filmwise condensation. They found that an optimal ratio between hydrophobic and hydrophilic regions of 2:1 with stripe-region widths of 0.6 mm and 0.3 mm could enhance heat transfer. The heat transfer coefficients were 4.8 and 1.8 times the heat transfer coefficients of complete filmwise and dropwise condensation, respectively. Chatterjee et al. [65] performed an experimental study of condensation heat transfer on surfaces with patterns of distinct 25% hydrophilic and 75% hydrophobic regions (i.e., island and tree patterns) by area. The highest heat transfer coefficient was observed for the patterned surface with a 0.25-mm feature size, and the heat transfer performance was better than with the completely hydrophobic surface. Peng et al. [66] assessed the maximum droplet radius and droplet size distribution adjustment on a hydrophobic–hydrophilic hybrid surface as well as resultant heat transfer performance. They demonstrated that an increment in the hydrophobic region width led to maximal droplet radius enlargement on the hydrophobic region along with a reduction in droplet population density. They also discovered that for appropriate optimal hybrid surfaces, performance could reach 23% higher than complete dropwise condensation at surface subcooling conditions of 2.0 K. The optimal hydrophobic

region width was approximately 0.55 mm, and the heat transfer enhancement factor was greatly affected by subcooling. Under 2.0 K, 4.0 K, and 6.0 K surface subcooling, the optimal heat transfer enhancement factors were approximately 1.23, 1.11, and 1.07, respectively. Yang et al. [67] conducted an experimental investigation of condensation performance on hydrophobic, hydrophilic, superhydrophilic, and hydrophobic–hydrophilic hybrid V-shaped patterned surfaces with air velocity ranging from 0.5 m/s to 4.0 m/s and relative humidity of 85%, 60%, and 40%, respectively. They reported the worst behavior on the superhydrophilic surface. Additionally, the hydrophilic surface consistently performed worse than the hydrophobic surface. The hybrid V-shaped patterned surface showed a heat transfer coefficient increment of 3–9% and 6–16% compared with hydrophobic and hydrophilic surfaces, respectively. This novel V-shaped design provided an efficient means of condensation removal and drainage.

The studies mentioned above delineated passive approaches (i.e. chemically treating surfaces) to form hybrid regions. Ke et al. [30] numerically studied droplet dynamics and condensation enhancement on microstructure surfaces using electrowetting to form different wettability patterns. Inspired by this study, Yan et al. [79] proposed an active approach to achieve a similar objective via EWOD for water harvesting studies. Most recently, researchers have examined the electrowetting impact on condensation in terms of condensation patterns [80] and droplet shedding characteristics [81]. Baratian et al. [80] demonstrated the modification of droplet distribution on a flat hydrophobic surface via electrowetting (EW) with structured electrodes. A single-side coplanar-electrode design was demonstrated, and droplet

distribution was studied using breath figures. The study revealed that droplets on the EW-functionalized surface aligned according to the designed electrode pattern. Dey et al. [81] utilized the AC electrowetting effect to control gravity-driven shedding of droplets. Two electrode designs were presented (i.e., straight and tree-shaped interdigitated electrodes), and the condensation patterns were controlled in both cases. The droplet-shedding rate and corresponding droplet size of the two designs were studied, revealing a faster shedding rate and smaller radii of the straight interdigitated electrodes compared with the tree-shaped electrodes. In recent research by Yan et al. [79], a single-side double-layer-electrode EWOD device was presented and tested in terms of its water capturing ability under high-humidity air mist flow. The alternation of wettability from hydrophobic to hydrophilic was found to promote droplet nucleation and growth as EWOD was applied to the condensing device. Compared with uncharged devices, the charged devices demonstrated water harvesting enhancements of 138.96%, 171.87%, and 220.43% under 20 V, 40 V, and 60 V DC voltage, respectively. These findings indicate great potential for actively generating hybrid surfaces with lower surface-treatment requirements.

In this chapter, we conducted two types of EWOD designs—single-side double-layer-electrode and coplanar-electrode devices were investigated using side-by-side experiments. Visualization was implemented to compare charged and uncharged devices under the same testing environment. We studied three double-layer-electrode designs (grid wire, thin wire and thick wire) and one coplanar-electrode zigzag design. Rather than using a 2- μm thick Parylene C as the dielectric layer and applying 150V

AC with 1kHz frequency [80, 81], we applied 100 nm and 150 nm of silicon nitride as the dielectric layer for the double-layer-electrode and coplanar-electrode EWOD devices with a much lower applied voltage of 40 V DC. Stronger droplet coalescence and earlier droplet-shedding moments were discovered on all charged devices. Droplets on the boundary of the electrode regions were pushed away due to the electric force and tended to stay in and roll down from the electrode-free regions. Droplet distribution varied on the four condensing surfaces with different electrode patterns. Droplets ‘sat’ inside the grid wires and distributed vertically along the thin and thick wires. On the coplanar-electrode zigzag device, droplets covered the electrode gaps and distributed vertically. This paper presents a significant active approach to influence condensation droplet distribution. This method is also promising for further studies on condensation heat transfer enhancement of microfabricated surfaces via EWOD.

4.2 EWOD Device Descriptions

The theoretical background of EWOD was discussed in Chapter 1.2. The designed EWOD devices for the study of this chapter followed the same parameters of the coplanar-electrode design and double-layer-electrode design as discussed in Chapter 2.3. All devices were microfabricated in a clean room in the Electrical Engineering and Computer Science (EECS) Department at the University of Missouri following the recipe mentioned in Chapter 2.3. Notice that the sputtered silicon nitride layer has different functions in the two designs. In the double-layer-electrode design, the first 100-nm silicon nitride layer acts as an insulation layer, and the sputtered 150-nm silicon

nitride layer protects the Teflon from degradation due to electric attack by the gold electrode. The two electrodes consist of a conductive silicon substrate and the designed wire patterns. In the coplanar-electrode design, the two electrodes are in the same layer, forming a capacitance to enable electrowetting to occur. The bottom conductive silicon substrate with a 100-nm silicon nitride layer serves as a nonconductive substrate; 150 nm of sputtered silicon nitride acts as the dielectric layer. Droplets existing in the gap areas will be affected by EWOD.

Based on the working principle of the double-layer-electrode device, the electrode layer can be arranged into different configurations. In Chapter 3.2, we proposed a grid-wire design where the electrode wires were crisscrossed, forming grids with wire widths of 50 μm and wire distance of 1 mm. Based on the cross-sectional view of the double-layer-electrode design illustrated in Figure 2.7, top views of the grid-wire, thin-wire

Figure 4.1 Double-layer-electrode EWOD designs: (a) thick wire, (b) thin wire and (c) grid wire.

and thick-wire electrode designs are demonstrated in Figure 4.1. Devices (a) has a crisscrossed grid pattern; (b) and (c) are patterned with vertical thin and thick wires whose widths are $50\mu\text{m}$ and 1mm , respectively, with 1mm wire distance.

Apart from the double-layer-electrode design, Figure 4.2 illustrates a top view of the coplanar-electrode design with zigzag edges. Compared with the straight and tree-shaped edge studied by Day et al. [81], the zigzag-shaped design enlarges the EWOD area. The gap between two electrodes is $50\mu\text{m}$, and each electrode is 1mm wide.

Figure 4.2 Coplanar electrowetting zigzag design.

Each device consists of two regions: the working region and the charging region. The working region is where droplets form and are subjected to the electrowetting effect (inside the red dotted lines). The charging region (where electrodes exist) is connected with the input electric potentials. The '+' and '-' represent the positive and negative electrodes of the 40 V DC potential, respectively. In Figure 4.1, the electrodes are connected only to the positive pole, as the negative pole (the conducting silicon

substrate) is connected from the back of the device. However, the coplanar design pattern exposes both the positive and negative electrodes.

4.3 Experimental Apparatus and Procedures

Visualization tests were carried out in a condensing chamber filled with steam; the schematic of the testing chamber is depicted in Figure 4.3. The experimental setup includes a high-speed camera, ring-shaped LED light source, testing chamber, testing devices, cooling block, and circulated coolant. In the front of the chamber cover, heat-resistant borosilicate glass was installed for visualization. The glass was heated by attached cartridge heaters when experiments were conducted. The heaters were turned

Figure 4.3 Experimental setup diagram: (A) high-speed camera; (B) visualization window (heat-resistant glass); (C) testing chamber; (D) testing sample; (E) cooling block.

up to avoid unwanted condensation on the glass. The testing chamber was well-insulated during experiments. The microfabricated devices were attached to the cooling block with thermal paste. Two devices were placed on two cooling blocks for side-by-side experiments. The cooling blocks were separated by PTFE plates to diminish electric field and thermal interactions. As the devices were placed in the same condensation testing environment, they differed only by an applied 40 V DC voltage. A T-type thermocouple was inserted into the chamber to measure the inner steam temperature to guarantee a steady state of saturated steam. Dry steam was delivered to the condensation chamber for 10 min until it reached a steady state. The coolant circulant was then pumped through the cooling block to cool the sample. The coolant temperature was set to a fixed constant of 20°C during the test, and the high-speed camera and LED light were turned on for visualization. Visualization tests for each designed device were repeated greater than three times until similar phenomena were repeatedly observed.

4.4 Results and Discussion

4.4.1 Contact Angle Measurement

The contact angle variation of the EWOD devices was measured under charged (40 V DC) and uncharged conditions. The 40 V DC was chosen for safety reasons, as previous research [79] identified the safety range of applied voltage as 0-70 V DC. Additionally, 40 V DC guaranteed clear observation of the EWOD effect compared with lower voltages. Each contact angle value shown in Figure 4.4 was obtained by

Figure 4.4 Contact angle measurements: (a)-(b) initial and 40 V DC charged contact angles of double-layer-electrode grid- and thin-wire (50 μm) devices; (c)-(d) initial and 40 V DC charged contact angles of double-layer-electrode thick-wire (1 mm) device; (e)-(f) coplanar-electrode zigzag device. Top view of droplet position for each case on the left. The blue circle represents the droplet; black lines represent electrode region in (a)-(d) and zigzag electrode gap in (e)-(f). Scale bars 1 mm.

averaging five measurements. The estimated error of the contact angle measurement is less than 2%. Figure 4.4 revealed that the contact angle declined when EWOD was applied to all types of fabricated devices. The initial contact angle of Teflon ranged from 107° to 109°. Top views of the droplet position with respect to the camera and

wires/zigzag electrode gaps are illustrated in Figure 4.4 for each measurement. The contact angle of the grid-wire, thin-wire, and thick-wire devices ranged from 63° to 65° under 40 V DC. In the thick-wire measurement case, a larger droplet was utilized to cover the thick-wire electrode, resulting in a shorter scale bar in Figure 4.4(c)-(d). The contact angle variation of the double-layer-electrode devices did not follow the Young-Lippman's rule directly due to the nonhomogeneous EWOD surface. For the coplanar-electrode zigzag device, the contact angle was approximately 78° when 40 V DC was applied. The contact angle measurement validated that EWOD helped to reduce the droplet contact angle and change the surface wettability of certain regions of the condensing surface, resulting in an actively controlled hybrid surface pattern.

4.4.2 Droplet Distribution Affected by EWOD

Two devices with the same fabricated parameters were utilized in the side-by-side experiments. The right device was charged with a 40 V DC electric potential, and the left device was uncharged for comparison. Figures 4.5 and 4.6 showed that the droplet distribution was affected by different designed surfaces.

When EWOD was applied to the condensing surfaces, the electric field regulated the droplets distribution according to the electrode patterns. In contrast, the uncharged surface exhibited random droplet distribution. Figure 4.5 (a) shows the grid-wire design investigated in the water harvesting study [79]. Droplets were first observed to form at the edge of the electrode wires. As time proceeded, small droplets coalesced and formed large droplets. The large droplets 'sat' inside the grid and grew before rolling down the

surface. The droplet size was nearly equally distributed in the grids. However, such phenomena were not observed on the left side. The average size on the charged side was larger than on the uncharged side at the same moment in the experiments.

Figure 4.5 Experimental visualization results: (a) grid-wire design (50-μm wire width, 1-mm wire distance); (b) thin-wire design (50-μm wire width, 1-mm wire distance). Left side uncharged, right side charged under 40 V DC. Scale bars 1 mm.

Figure 4.6 Experimental visualization results: (a) thick-wire design (1-mm wire width, 1- mm wire distance); (b) zigzag design. Left side uncharged, right side charged under 40 V DC. Scale bars 1 mm.

Similar conditions apply to Figures 4.5 (b) and 4.6 (a): the droplets on the charged surfaces were larger compared with the uncharged surfaces. Droplets became ‘trapped’ between the wires and rolled down along the vertical electrode-free regions. For the coplanar zigzag design in Fig. 4.6 (b), droplets were pulled towards the zigzag gap region, covered the electrode gaps, and formed a vertical droplet distribution on the charged surface, similar to the phenomena found in previous studies [80, 81]. Figures

4.5 and 4.6 indicate that the charged surfaces experienced faster droplet growth and have a larger droplet size and more dispersed droplet distribution. Thus, the droplet-shedding frequency accelerated, and more condensing areas were freed for small-droplet nucleation and growth.

4.4.3 Droplet Shedding Moment and Diameter

The stronger droplet growth rate on the charged surfaces induced earlier droplet wipe-down events. In our previous research [79], we studied droplet shedding using a droplet detection algorithm to observe droplet coverage. Shedding moments were detected when a sudden decline occurred. Following the same approach, the first instance of droplet shedding was recorded and is shown schematically in Figure 4.7. The droplet-shedding diameter was measured with Image-Pro Plus (Cold Spring, USA) and determined to be 1.2–2.5 mm in different cases, i.e. uncharged and charged (on different electrode patterns). Figure 4.7 shows that the initial droplet-shedding moment of all types of charged surfaces happened earlier than on uncharged surfaces, coinciding with the stronger droplet growth rate observed in Figures. 4.5 and 4.6. The charged grid-wire surface exhibited a slower shedding frequency compared with the others, namely, due to the horizontal EWOD area, which acted as a barrier as droplets rolled down. Under 40 V DC, droplets were trapped in each grid, requiring more time to grow and interact with surrounding droplets before shedding, resulting in a larger droplet-shedding diameter of approximately 2.5 mm. The EWOD effective areas were vertical in the other three designs, requiring less time to grow and coalesce before shedding.

Figure 4.7 Droplet first shedding moment comparison for 40 V DC charged and uncharged surfaces with four designs.

The thick-wire and zigzag designs contained more EWOD effective areas compared with the thin-wire design, thus explaining why faster droplet growth was observed on the two designs. In terms of the uncharged surfaces, the droplet-shedding moment of the thin-wire, thick-wire, and zigzag designs was similar. However, the grid-wire design demonstrated earlier droplet shedding due to the more complex surface structures (i.e. the vertical and horizontal wires of grids) than the other designs, which promoted droplet nucleation and growth.

4.4.4 Droplet Dynamics on Thick-wire Stripe-wise Surface

The thick-wire surface illustrated in Figure 4.1 (a) and Figure 4.6 (a) is similar to previously studied hybrid surfaces [64, 66], which revealed droplet dynamics moving from the hydrophobic stripe-wise region towards the hydrophilic stripe-wise region along with increased condensation drainage. As discussed in the theoretical background, EWOD causes droplets to be hydrophilic on a macro scale, resulting in ‘hybrid surfaces’ that enhance the condensation rate. Unlike prior researches [64, 66], our studies indicated that under constant 40 V DC voltage, droplets on the wire boundaries slide away from the electrode region due to electric force, staying in and rolling down from the electrode-free regions as illustrated in Figure 4.8.

Figure 4.8 Experimental visualization of droplet dynamics on vertical thick-wire pattern. (a) to (f) in time sequence. Light bars represent the electrode region. Red circles and yellow circles represent dynamics of two independent droplets. Scale bars 1 mm.

4.4.5 Droplet Size Distribution on the Charged and Uncharged Grid-wire Surfaces

As the droplets were observed to be larger and more regulated on the charged side compared with the uncharged side at the same moment in the experiments, we studied the droplet size distribution over a large area under electrowetting effect.

4.4.5.1 Theoretical Model of Droplet Size Distribution

On a hydrophobic surface, droplet growth happens through two mechanisms: direct growth and coalescence. The first mechanism describes droplet growth on spatially random sites by direct condensation; the second mechanism demonstrates the growth stage where the droplet size becomes large enough to coalesce with neighboring droplets. For water, the first mechanism proceeds into the second mechanism when the droplet radius reaches 0.5–10 μm [82]. Although the dropwise condensation shedding is a highly transient process, it still can be modeled using a steady-state formulation by combining individual droplet conduction analysis with time averaged droplet density functions. In 1970s, Jose et al. [83] proposed a theoretical model to predict droplet size distributions during dropwise condensation. They utilized high magnification cine films to investigate the nature of droplet growth process during dropwise condensation and modeled the droplet size distributions shown in Eq. (4.1),

$$N(r) = \frac{1}{3\pi r^2 \hat{r}_0} \left(\frac{r}{\hat{r}_0} \right)^{-\frac{2}{3}} \quad (4.1)$$

where r is droplet size, $\hat{r}_0$ is the upper bound for the integration for the coalescence dominated growth droplet, N represents the number of droplets at certain radius size. $\hat{r}_0$ is related with the maximum droplet radius before shedding $r_{\max}$. The $r_{\max}$ is

derived based on the force balance on the droplet as it begins to de-pin and slide on a

vertical surface due to the gravitational body force [84] and is expressed in Eq. (4.2)

$$r_{\max} = \left(\frac{6(\cos \theta_R - \cos \theta_A) \sin \theta_e \gamma_l}{\pi(2 - 3 \cos \theta_e + \cos \theta_e) \rho_l g} \right)^{\frac{1}{2}} \quad (4.2)$$

where θ_A , θ_R and θ_e are advancing, receding and equilibrium contact angles, respectively.

γ_l , ρ_l are the droplet surface tension and density, respectively and g is the gravitational constant. The equilibrium contact angle is a function of the first two, which is expressed in Eq. (4.3) as,

$$\theta_e = \cos^{-1}(0.5 \cos \theta_A + 0.5 \cos \theta_R) \quad (4.3)$$

The relationship between $\hat{r}_0$ and $r_{\max}$ was investigated experimentally [85] and expressed in the following equation,

$$\hat{r}_0 = \frac{r_{\max}}{1.3} \quad (4.4)$$

The model in Eq. (4.1) mostly was validated for droplet size larger than the effective transition radius $r_e = 0.5\text{--}10 \mu\text{m}$ —which means most suitable for the second mechanism of droplet growth by coalescing with neighboring droplets.

For droplet size smaller than the effective transition radius r_e , which means droplet growth follows the first mechanism—growing on spatially random sites by direct condensation, Kim et al. [86] derived the droplet size distribution to be

$$n(r) = \frac{1}{3\pi r_e^3 \hat{r}_0} \left(\frac{r_e}{\hat{r}} \right)^{-\frac{2}{3}} \frac{r(r_e - r_{\min})}{r - r_{\min}} \frac{A_2 r + A_3}{A_2 r_e + A_3} \exp(B_1 + B_2) \quad (4.5)$$

where $r_{\min}$ is the minimum (supersaturation dependent critical) nucleation sites [87], which is expressed as

$$r_{\min} = \frac{2T_{sat}\gamma_l}{h_{fg}\rho_l(T_{sat} - T_w)} \quad (4.6)$$

where T_{sat} , T_w are the is the saturation temperature and wall temperature, respectively.

h_{fg} is the latent heat of condensation and again γ_l , ρ_l are the droplet surface tension and density, respectively. The effective transition radius r_e can be measured experimentally.

The A_i and B_i are parameters solved by enforcing a continuous boundary condition [84]

$$n(r_e) = N(r_e) \quad (4.7)$$

and the A_i and B_i can be found to be

$$A_1 = \frac{(T_{sat} - T_w)}{\rho_l h_{fg} (1 - \cos \theta)(2 + \cos \theta)} \quad (4.8)$$

$$A_2 = \frac{\theta}{4k_l \sin \theta} \quad (4.9)$$

$$A_3 = \pi r (R_i + R_s) \quad (4.10)$$

$$B_1 = \frac{A_2}{\tau A_1} \left[\frac{r_e^2 - r^2}{2} + r_{\min} (r_e - r) - r_{\min}^2 \ln \left(\frac{r - r_{\min}}{r_e - r_{\min}} \right) \right] \quad (4.11)$$

$$B_2 = \frac{A_3}{\tau A_1} \left[r_e - r - r_{\min} \ln \left(\frac{r - r_{\min}}{r_e - r_{\min}} \right) \right] \quad (4.12)$$

$$\tau = \frac{3r_e^2 (A_2 r_e + A_3)}{A_1 (11A_2 r_e^2 - 14A_2 r_e r_{\min} + 8A_3 r_e - 11A_3 r_{\min})} \quad (4.13)$$

where k_l is the liquid droplet thermal conductivity. R_s and R_i is the surface structure thermal resistance and interface thermal resistance, respectively, which varies in different study cases.

4.4.5.2 Experimental Results of Droplet Size Distribution

We counted the droplet size distribution experimentally. Experimental data were collected using the high-speed camera. The camera lens was Tokina AT-PRO D F2.8 MACRO and had no magnification. Due to low resolution, the smallest droplet size that could be observed has a 50 μm radius and the theoretical model we compared with is

the model by Jose et al. [83] which is expressed in Eq. (4.1). With the experimental video obtained by high-speed camera, we carried out image analysis for droplet detection and size measurement. The image analysis package in Image-Pro Plus was utilized to measure the droplet radius. The testing areas were first selected, and the image processing systems were calibrated before measurements. Due to the self-similarity feature of droplet size distribution [83], a representative large enough rectangular area including various growth stages was selected to investigate the droplet size distribution for both charged and uncharged surfaces [88]. Once the droplet radius was measured, the data were exported to calculate the droplet number in certain radius ranges. Finally, the droplet size distribution was acquired by counting the droplet number per unit area in a given range and dividing by this range [83]. The droplet measurements on uncharged and charged surfaces were illustrated in Figure 4.9 (a) and (b), respectively. The droplet distribution in Figure 4.9 (b) differed from the droplet distribution shown in Figure 4.5 (a) because for droplets smaller than the grid area, they tended to ‘sit’ inside the grid. As their sizes increased, coalescence happened to adjacent droplets, forming droplets larger than the grid area. The larger droplets rode on the grid-wires rather than ‘sitting’ inside the grids. The selected testing areas shown in Figure 4.9 (a) and (b) were 177mm^2 and 178mm^2 , respectively. A distortion in the light reflection on the droplets was observed, which was due to inaccurate relative positions from the ring-shaped light to the droplets. The light reflection distortions were manually fixed, and the actual droplet edges were represented by the yellow circles in Fig. 10.

Figure 4.9 Droplet measurements with Image Pro Plus software. Representative areas of (a) uncharged grid-wire device, and (b) charged grid-wire device. Yellow circles represent the actual droplet edges. Scale bars 1 mm.

The shedding radius of the uncharged grid-wire surface was measured to be 0.9-1.1 mm. Theoretical results were calculated and compared with the experimental results. Figure 4.10 showed that the dropwise condensation on the uncharged grid-wire surface agreed well with the theoretical model in the range of $100\mu\text{m}$ - $1000\mu\text{m}$. The mismatch in the small droplet region was mainly due to the inaccuracy of the experimental data and the low resolution. The charged grid-wire surfaces demonstrated more droplets compared with the theoretical model. This difference of the charged surface droplet distribution with the theoretical model in large sized droplet range ($100\mu\text{m}$ - $1000\mu\text{m}$) is due to the electrowetting effect. The electrowetting caused a stronger droplet coalescence and growth rate. Another reason for the difference is the droplet morphology. In the theoretical model, Rose and Glicksman assumed the contact angle of all droplets larger than 90° , and derived the theoretical model. However, the droplet contact angle under the electrowetting effect was smaller than 90° as illustrated in Figure 4.4. The difference in droplets morphology led to variation in the droplet size distribution under electrowetting effect.

Figure 4.10 Droplet size distributions of (black) uncharged grid-wire device and (red) charged grid-wire device compared with Rose's model (black line).

4.5 Conclusions

This work presented in this chapter discusses droplet distributions affected by the EWOD approach. Single-side double-layer-electrode (grid-wire, thin-wire, thick-wire) and coplanar-electrode (zigzag) designs are presented with different configurations. Side-by-side experiments demonstrated difference in droplet distribution between charged and uncharged devices. The charged device exhibited regulated droplet distribution in accordance with the EWOD region compared with the uncharged device. The droplet size was nearly equally distributed in the grid-wire surface. On the charged thin-wire and thick-wire devices, droplets were 'trapped' between the wires and rolled down along electrode-free vertical regions. In the zigzag design, droplets were pulled towards and covered the zigzag gap region and were distributed vertically on the

charged device. The average size on the charged surface was larger than on the uncharged surface at the same time during experiments. The charged surfaces exhibited faster droplet growth, with larger and more discrete droplet distribution, which accelerated droplet-shedding frequency and freed up more condensing areas for small-droplet nucleation and growth. Additionally, droplet dynamics on the thick-wire stripe-wise surface were compared with previously studied hybrid surfaces. Different from the hydrophobic–hydrophilic stripe-wise pattern, droplets close to the boundaries of the electrodes were prone to be pushed away from the electrodes and ultimately rolled down from electrode-free regions. This phenomenon can be ascribed to the force exerted on the boundaries of electrode regions to the droplets. The droplet size distributions on the grid-wire surfaces with and without the electrowetting effect were investigated. The droplet size distribution on the uncharged surface agreed well with the theoretical model in 100 μm -1000 μm radius range. On the charged surfaces, the number of large droplets was found to be greater than the theoretical model. As EWOD can be turned on actively to affect droplet condensation distribution, this work is of great significance and provides a possible method to actively influence droplet distribution on microfabricated condensing surfaces, showing great potential in improving condensation heat transfer via EWOD.

CHAPTER 5 EWOD-INDUCED CONDENSATION HEAT TRANSFER ENHANCEMENT

5.1 Introduction

Recently, growing demand for more powerful electronic devices in smaller sizes has led to substantial increases in heat dissipation. High heat generation in electronic devices results in high operating temperatures, which dramatically affect devices' performance and reliability. Therefore, many researchers have investigated the cooling of electronic devices. Several methods have been identified to cool down electronic components, such as the pin-fin heat sink [89-91], confined jet impingement [92-94], heat pipes [95-99], and micro heat sink [100-104]. Site-specific treatment on a heat source, which involves coating the hot spot on a fine copper screen with a special capillary structure to cause droplets to spread and cling to the hot spot more effectively, has also been studied to improve the heat dissipation rate [105]. Condensation heat transfer has been widely studied relative to effective cooling. To investigate further improvement in the condensation heat transfer rate, numerous experiments have been carried out in prior decades, using different surfaces and various experimental setups. Alwazzan et al. [64] performed condensation experiments on chemically treated hybrid-pattern hydrophobic–hydrophilic copper tubes, inside which coolant water could run through and cool down the system. Preston et al. [61] studied condensation heat transfer on a copper tube; different from the hybrid surface discussed by Alwazzan et al. [64], they studied an ultrathin scalable chemical vapor-deposited graphene coating

and discovered the robustness of graphene-coated hydrophobic surfaces. Instead of using copper tubes, Peng et al. [66] measured dropwise condensation on a hydrophobic–hydrophilic hybrid surface on a cylindrical copper block. Miljkovic et al. [106] investigated dropwise condensation on a superhydrophobic nanostructured surface surrounded by a cylindrical copper-grid cage to reveal electric-field-induced droplet jumping phenomena and potential enhancements in heat transfer from such an event. Aside from a copper-based testing surface, Lu et al. [107] performed experiments on silicon-based superhydrophobic silicon nanowires to investigate condensation heat transfer enhancement. Most of the aforementioned studies passively altered surface wettability. Given the promising results from Chapters 3 and 4, experimental investigation of the EWOD effect on the condensation heat transfer rate and heat transfer coefficient is warranted.

This chapter outlines the experimental apparatus and procedures in detail. The calibration results of thermocouples and the test system are presented next, followed by experiments on double-layer-electrode EWOD devices. Data reduction is then completed to compare the heat transfer performance of 40V DC charged and uncharged cases. The heat transfer coefficient and heat dissipation rate of the charged device improved by between 11.73% and 13.33% and 5.54% and 6.50%, respectively. The experimental results also showed that EWOD can clearly improve the condensation heat transfer rate by alternating regions of the hydrophobic surface to hydrophilic, resulting in a hybrid pattern that can enhance overall heat transfer. The study in this chapter reveals great potential for EWOD devices to improve the condensation heat

transfer rate. This approach could be applied in an array of industrial applications, such as heat exchanger fin surfaces, condensing surfaces of waste heat recovery systems, and components of electronic cooling packages, all of which require highly efficient heat dissipation.

5.2 Experimental Apparatus

The EWOD device used for heat transfer measurement in this study was the grid-wire double-layer-electrode design mentioned in Chapters 1 and 4 with the same geometry and parameters. One difference is that an additional layer of silane was added to protect the top Teflon layer from decaying. In our preliminary tests, we discovered that the Teflon film could not survive for 2h under steam flow due to shearing forces exerted by shedding droplets. A broken Teflon layer would destroy hydrophobicity and render the EWOD devices ineffective, causing them to quickly break down. Because the silane layer exhibits higher thermal stability [108], we added it on top of the Teflon to ensure hydrophobic stability of the EWOD device under long-term exposure to steam flow. The silane layer was obtained via vapor deposition. We placed the samples in a vacuum chamber and let the vacuum run for 2h. A monolayer of silane was deposited after vapor deposition [108]. The silane layer was not considered in the thermal resistance calculation due to its negligible thickness.

Experiments were conducted to obtain the condensation heat flux and heat transfer coefficient of the EWOD devices. A systematic flow loop was constructed as shown in Figure 5.1. The loop consists of a steam generator, supply line, testing chamber, flow

meter, cooling water circulation machine, and drain. The entire flow loop was well-insulated to minimize heat loss; see the diagram in Figure 5.1.

Figure 5.1 Schematic diagram of flow loop of the condensation experimental system.

Per this diagram, a steam generator supplies steam to the testing chamber where condensation occurs. The cooling tubes of the cooling machine are connected to a cold plate. The cold plate is clamped to the copper blocks of the test section to cool down the testing devices and obtain subcooling. A flow meter is attached to the cooling tubes to measure the coolant flow rate. The bottom of the test chamber leads to a flask of DI water to collect the uncondensed steam.

The test section consists of a vapor chamber, two copper blocks, a PTFE plate, the EWOD devices, and a visualization window. In this case, insulation was placed on the copper block and the chamber to reduce heat loss. Copper blocks (110 ETP copper) measuring $5\text{cm} \times 2.5\text{cm}$ ($2\text{in} \times 1\text{in}$) were drilled with five evenly spaced 7.45mm holes

(1mm in diameter) to measure temperature gradients. A 1mm hole diameter was selected to guarantee that thermocouples could be inserted and to decrease temperature measurement uncertainties due to overly large holes. The front and back surfaces of the copper blocks were both polished. The front surface was exposed to the testing chamber and attached to the EWOD devices; the back surface was tightly connected to the cold plate by a C-clamp. The PTFE plate measured 2mm $\times$ 5cm and was used to prevent the copper blocks from influencing each other thermally and electrically during side-by-side experiments. The schematic of the testbed side view appears in Figure 5.2.

Figure 5.2 Testbed schematic—side view. ①③⑤⑧Stainless steel plate; ②heat-resistant borosilicate glass; ④stainless steel testing chamber where water vapor flows in from the top and out from the bottom; ⑥copper to measure temperature gradient (circles represent holes to insert thermocouples: one end of the copper is inserted into the chamber and is attached to the sample by thermal paste); ⑦cold plate with cooling water running through. T-shaped figures represent stainless steel screws used to tighten the testbed.

Stainless steel and copper were used to guarantee that the system would operate properly under long-term high-temperature water vapor flow and to obtain more accurate temperature measurements. The designed testbed was fabricated in the machine shop of the College of Engineering at the University of Missouri. Testbeds are presented in Figure 5.3. Two copper blocks were used for side-by-side experiments. Holes were drilled on each of the outer surfaces on the copper blocks. The two copper blocks were separated by a PTFE block to insulate heat transfer and prevent electric

Figure 5.3 Condensation experimental testbed. a) Front cover (with heat-resistant borosilicate glass); b) Front view of the testbed. c) View of the copper drilled with holes. d) Detailed view of the testing chamber.

field interference. Several holes were drilled on the cylindrical testing chamber as indicated in Figure 5.3(d). The charging holes led the charging wires out of the chamber and connected with the DC power supply. One hole on the right was used to mount the pressure transducer, beside which was a small hole to insert a thermocouple. The pressure transducer and thermocouple were intended to measure the pressure and temperature of water vapor inside the chamber, respectively. To further study the effect of non-condensable gas, one could analyze the inconsistency of the measured saturation temperature and saturation pressure.

5.3 Experimental Procedures

Prior to the experiments, thermocouples were inserted into the holes of the two copper blocks. To achieve better thermal contact, thermal paste was added to the tip of each thermocouple. The front cover of the chamber was initially opened to load EWOD devices. Two devices were adhered to the testing surfaces using thermal paste. The charging wires on the EWOD samples were threaded through the charging holes shown in Figure 5.3(d). The wires were also threaded through a small piece of rubber sheet before covering the charging holes for sealing purposes. After loading the samples and sealing the wire outlets, the front cover of the test chamber was reloaded, and the chamber was tightened using stainless steel screws. Another layer of thermal paste was added to the back side of each copper block for better connection with the cold plate. Once the system was set up, insulation foam and fiberglass were used to cover the cooling tubes and the whole test region, respectively, to guarantee the least amount of

heat loss. The coolant flow rate inside the tubes was maintained at 6.53—6.56 L/min, while the inlet temperature of the coolant was fixed at 20°C. The inner temperature of the chamber was monitored to conform to steady-state saturation. Steam was transported to the chamber via a supply line for at least 10 min [64] to obtain steady-state saturation before turning on the coolant circulation and starting the test. Experiments were run three times to ensure reliable experimental results.

5.4 Data Reduction

The temperature of the cooling end of the copper block and the mass flow rate of coolant circulation were obtained using the aforementioned steps. The steam generator and cooling machine were turned on to achieve a steady state inside the testing chamber. After a steady state was reached, temperature and pressure were recorded using a computer-controlled data acquisition system including a National Instruments signal chassis and LABVIEW software. Flow parameters were altered when the coolant temperature changed, after which the entire procedure was repeated to guarantee data reliability. T-type thermocouples were used to measure the chamber steam temperature and inlet and outlet coolant temperatures. The mass flow rate was measured by a flow meter attached to the inlet tube of the cooling machine. Five thermocouples were inserted into holes in each copper block for further calculations of heat flux, the heat transfer coefficient, and wall subcooling.

5.4.1 Heat Transfer of Copper

Applying the one-dimensional Fourier heat conduction law, the heat flux can be expressed as follows (where dT/dy is the temperature gradient along the copper block):

$$q'' = -k_{Cu} \frac{dT}{dy} \quad (5.1)$$

Using the least squares method, heat flux can be expressed as

$$q'' = -k_{Cu} \frac{\sum_{i=1}^5 (y_i - \bar{y})(T_i - \bar{T})}{\sum_{i=1}^5 (y_i - \bar{y})^2} \quad (5.2)$$

where q'' is the heat flux of steam condensation, k_{Cu} is the thermal conductivity of copper, y is the distance between the hole and condensing surface, and T is the temperature. The average temperature and average distance can be respectively calculated as

$$\bar{y} = \frac{y_1 + y_2 + y_3 + y_4 + y_5}{5} \quad (5.3)$$

$$\bar{T} = \frac{T_1 + T_2 + T_3 + T_4 + T_5}{5} \quad (5.4)$$

The temperature of the condensing surface can be obtained according to the temperature distribution in the condensing block using the following equation:

$$T_s = T_1 + \frac{q''}{k_{Cu}} \Delta x \quad (5.5)$$

where T_s is the condensing surface temperature, T_1 is the temperature reading of the thermocouple closest to the condensation surface, and Δx is the distance between the thermocouple (that closest to the testing chamber) and the condensation surface as illustrated in Figure 5.3. The heat transfer coefficient was calculated as follow:

$$h = \frac{q''}{T_{sat} - T_s} \quad (5.6)$$

where h is the heat transfer coefficient, T_{sat} is the measured saturation temperature of the vapor in the chamber, and T_s is the result of Eq. (5.5).

5.4.2 Heat Transfer of EWOD Devices

The aforementioned data reduction concerns pure copper. However, due to multiple structural layers, the surface temperature and heat transfer coefficient needed to be recalculated once EWOD devices were loaded into the system. The thermal resistance diagram after adding an EWOD device is shown in Figure 5.4. R_{th} , R_{Si} , R_{Au} , R_{SiN1} , and R_{Tef} represent the thermal resistance of the thermal paste, silicon substrate, gold, silicon nitride, and Teflon, respectively. The additional silane layer covering the Teflon was not included in the thermal resistance calculation as its monolayer thickness was small thus negligible.

Figure 5.4 Thermal resistance diagram with EWOD devices. (1) Copper block; (2) thermal paste; (3) silicon substrate; (4) silicon nitride; (5) gold; (6) Teflon.

The total extra thermal resistance induced by the EWOD device is calculated as

$$R_t = R_{th} + R_{Si} + R_{SiN1} + \frac{R_{Au} \cdot R_{SiN2}}{R_{Au} + R_{SiN2}} + R_{SiN3} + R_{Tef} \quad (5.7)$$

where the thermal resistance of each terms is expressed as follow:

$$R_{th} = \frac{\delta_{th}}{k_{th}} \quad (5.8)$$

$$R_{Si} = \frac{\delta_{Si}}{k_{Si}} \quad (5.9)$$

$$R_{Au} = \frac{\delta_{Au}}{k_{Au}} \quad (5.10)$$

$$R_{SiN-i} = \frac{\delta_{SiN-i}}{k_{SiN-i}} \quad (5.11)$$

$$R_{Tef} = \frac{\delta_{Tef}}{k_{Tef}} \quad (5.12)$$

The parameters in Eqs. (5.8)–(5.12) are listed in Table 5.1.

Table 5.1 Parameters of EWOD devices and thermal paste.

Materials	Thickness (m)	Thermal Conductivity (W/m-K)
Copper	$(\Delta x) 16 \times 10^{-3}$	401
Thermal paste	0.5×10^{-3}	2.31
Silicon	400×10^{-6}	1.3
Gold	150×10^{-9}	315
Silicon Nitride 1	100×10^{-9}	3.6
Silicon Nitride 2	150×10^{-9}	3.6
Silicon Nitride 3	150×10^{-9}	3.6
Teflon	60×10^{-9}	0.25

The heat flux was obtained using Eqs. (5.1)–(5.4). The condensing surface temperature then needed to be recalculated based on the extra thermal resistance introduced by the EWOD device and thermal paste; the corresponding formula is

$$T_{s_{EWOD}} = T_1 + \frac{q''}{k_{Cu}} \Delta x + \frac{q''}{k_{th}} \delta_{th} + \frac{q''}{k_{Si}} \delta_{Si} + \frac{q''}{k_{SiN1}} \delta_{SiN1} + q'' \frac{\frac{\delta_{Au}}{k_{Au}} \cdot \frac{\delta_{SiN2}}{k_{SiN2}}}{\frac{\delta_{Au}}{k_{Au}} + \frac{\delta_{SiN2}}{k_{SiN2}}} + \frac{q''}{k_{SiN3}} \delta_{SiN3} + \frac{q''}{k_{Tef}} \delta_{Tef} \quad (5.13)$$

and can be further simplified as

$$T_{s_{EWOD}} = T_1 + q'' \left(\frac{\Delta x}{k_{Cu}} + \frac{\delta_{th}}{k_{th}} + \frac{\delta_{Si}}{k_{Si}} + \frac{\delta_{SiN1}}{k_{SiN1}} + \frac{\delta_{Au} \cdot \delta_{SiN2}}{\delta_{Au} k_{SiN2} + \delta_{SiN2} k_{Au}} + \frac{\delta_{SiN3}}{k_{SiN3}} + \frac{\delta_{Tef}}{k_{Tef}} \right) \quad (5.14)$$

Upon entering the corresponding values in Eq. (5.14), the value in parentheses is determined as 5.64353×10^{-4} ; then, Eq. (5.14) becomes

$$T_{s_{EWOD}} = T_1 + q'' \times 5.64353 \times 10^{-4} \quad (5.15)$$

Therefore, the re-calculated expression of the heat transfer coefficient is

$$h_{EWOD} = \frac{q''}{T_{sat} - T_{s_{EWOD}}} \quad (5.16)$$

5.5 Results and Discussion

5.5.1 Thermocouple Calibration

Thermocouple calibration needed to be conducted prior to the experiments to ensure accurate measurements. Calibration was performed using dry block temperature calibration via ThermCal400. The ThermCal400 calibrator provided a safe, dry, constant temperature source ranging from room temperature (around 25°C) to 400°C with a machined aluminum block as the heat transfer medium. The thermocouple temperature was read from the LABVIEW program. The calibrator temperature was set to range from room temperature (25°C) to 70°C with a 2°C increment. When plotting data to determine the calibrated equations, the actual readings of thermocouples served as independent variables (represented by the x axis), and the set temperature of the calibrator served as the dependent variable (represented by the y axis). Calibration plots with linear curve fit formulas are shown in Figures 5.5–5.7.

Figure 5.5 Thermocouple calibration results of left-side copper.

Figure 5.6 Thermocouple calibration results of right-side copper.

Figure 5.7 Thermocouple calibration results of coolant inlet and outlet flow temperature and steam temperature.

5.5.2 Calibration of Experimental Setup

The classic Nusselt model of filmwise condensation (FWC) on a rectangular vertical surface was used to validate and calibrate the experimental setup as presented in Eq. (5.17):

$$h_{FWC} = 0.943 \left[\frac{\rho_l (\rho_l - \rho_v) g h_{fg} x^3}{k_l \mu_l (T_{sat} - T_s)} \right]^{\frac{1}{4}} \quad (5.17)$$

where ρ_l , ρ_v , g , h_{fg} , x , k_l , and μ_l denote the water liquid density, water vapor density, gravity constant, condensation latent heat, characteristic length (in this study, $2in = 51.07mm$), water liquid thermal conductivity, and water liquid viscosity, respectively.

The saturation temperature was measured using a thermocouple inside the chamber; the surface temperature of copper appears in Eq. (5.5). Parameters to calculate the filmwise condensation (FWC) heat transfer coefficient of the theoretical model in Eq. (5.17) are displayed in Table 5.2.

Table 5.2 Parameters to calculated theoretical model of FWC heat transfer

Name	Symbol	Value	Unit
Liquid water density	ρ_l	958.35	kg/m ³
Liquid water thermal conductivity	k_l	672.88×10^{-3}	W/(m-K)
Liquid water viscosity	μ_l	0.0003142	N-s/m ²
Water vapor density	ρ_v	0.0631	kg/m ³
Gravity constant	g	9.81	
Latent heat of condensation	h_{lv}	2266.9×10^3	J/kg
Characteristic length	x	51.07×10^{-3}	m
Saturation temperature of water vapor	T_{sat}	95~98	°C

A comparison between experimental measurements of the heat transfer coefficients of FWC on the two pieces of copper agreed well with the theoretical model, as shown in Figures 5.8 and 5.9 for the two copper blocks.

Figure 5.8 Filmwise condensation heat transfer coefficient of theoretical model and measurement on left-side copper.

Figure 5.9 Filmwise condensation heat transfer coefficient of theoretical model and measurement on right-side copper.

5.5.3 Heat Transfer Enhancement under EWOD

After calibrating the thermocouples and experimental system, EWOD devices were attached to the copper surfaces using thermal paste. The coolant temperature running through the cold plate was kept constant at 20°C. The system took 30–40min to stabilize (i.e. reach a relative constant subcooling temperature). Once the measured temperature was stable, DC voltages were applied to one device, which took another 35min to become stable. The voltage potential applied to the EWOD devices was 40V DC; this potential was selected for safety purposes as mentioned in Chapter 3 (i.e., the EWOD device safety range is from 0 to 70V). Also, as indicated in the visualization study of droplet dynamics in Chapter 4, the EWOD effect was clearly demonstrated under a potential of 40V DC. To avoid heat transfer differences between the EWOD

devices on the two pieces of copper, charged and uncharged results were compared on the same device to obtain more reliable results. The heat transfer behavior of the charged and uncharged devices was determined by averaging data in the stabilized status within a certain period. These results were obtained by averaging three repeated experiments. The EWOD devices the two piece of copper blocks were tested.

Figures 5.10 and 5.11 show the heat transfer coefficient and heat flux comparison between uncharged and charged devices. The results of the left and right sides were close but differed to some extent, mainly due to imperfect temperature distribution on the cold plate (i.e., the left side was closer to the inlet, and the right side was further away, leading to a lower surface temperature and higher subcooling temperature on the left side than the right side). The heat transfer coefficient on the charged EWOD device

Figure 5.10 Heat transfer coefficient comparison between uncharged and charged (40V DC) EWOD devices on left and right sides of copper blocks.

was larger than on the uncharged device, with an average enhancement of 11.73% and 13.33% on the left and right sides, respectively. Heat flux comparisons followed a similar rule: the left side demonstrated a relatively smaller heat flux dissipation rate compared with the right side. Heat dissipation on the charged devices was also larger than the uncharged ones on both sides of the EWOD devices. The heat dissipation enhancement was not as large as that of the heat transfer coefficient, with an average improvement of 5.54% and 6.50% on the left and right sides, respectively.

Figure 5.11 Heat flux comparison between the uncharged and charged (40V DC) EWOD devices on left and right side of the copper blocks.

5.6 Conclusion

This chapter presented an experimental study of the effect of EWOD on condensation heat transfer. A grid-wire double-layer-electrode design was used for testing. The experimental setup and procedures were discussed in detail. The

thermocouples and experimental setup were calibrated before conducting condensation experiments. No-EWOD and EWOD (40V DC) results were compared using the same sample to avoid unnecessary changing variables. As the test section consisted of two copper blocks, experiments were conducted on both sides. All experiments were performed three times to obtain reliable results. The heat flux and heat transfer rate each increased under the 40V DC EWOD effect compared to uncharged conditions. Under the same testing conditions, the left side demonstrated less enhancement than the right side due to an imperfect temperature distribution on the cold plate and higher subcooling temperature on the left side. The heat transfer coefficient was found to improve by 11.73% and 13.33% on the left and right sides under a 40V DC charge, respectively. The heat dissipation rate showed 5.54% and 6.50% enhancement on the left and right sides under a 40V DC charge, respectively. The experimental results further showed that EWOD positively affected the condensation heat transfer by alternating some regions of the hydrophobic surface to hydrophilic, leading to a hybrid condensation pattern. However, this enhancement was not as noteworthy as the water-harvesting enhancement in Chapter 3; the difference was primarily attributable to the multiple device layers, which introduced thermal barriers for and reduced the transmission efficiency of condensation heat transfer. The study in this chapter reveals great potential for EWOD devices to enhance the condensation heat transfer rate. This approach could be valuable in various industrial applications calling for rapid heat dissipation, such as heat exchanger fin surfaces, condensing surfaces of waste heat recovery systems, and components of electronic cooling packages.

CHAPTER 6 CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

This chapter summarizes the key findings of this dissertation and outlines future research directions in EWOD-induced condensation heat transfer enhancement.

6.1 Scientific Findings and Contributions of This Dissertation

This dissertation has made valuable scientific contributions to the field of water harvesting and condensation heat transfer enhancement. Overall, this work conveys a significant development in the coupling EWOD approach through studies of water harvesting and condensation heat transfer. Collectively, these studies can facilitate fundamental understanding of the influence of EWOD on microfabricated surface wettability and the realization of improved water-capturing capability. This research was largely multidisciplinary, involving fluid mechanics, heat transfer, electrostatics, materials, and microfabrication. Major scientific advancements emerging from this work are summarized in the following subsections.

6.1.1 Water Harvesting Enhancement via EWOD

- The effect of electrowetting on droplet morphology variation led to increased droplet coalescence and wipe-down events along with improved water capturing on the condensing surface.
- Compared with an uncharged device, the water collection rates of 20V, 40V, and 60V charged devices improved by 138.96%, 171.87%, and 220.43%, respectively.
- Droplet detection area coverage analysis indicated that when DC voltage was

applied under the same moist air flow rate, the EWOD device exhibited improved coalescence and wipe-down behavior.

6.1.2 EWOD-regulated Condensation Droplet Distribution

- The charged device demonstrated a regulated droplet distribution in accordance with the EWOD region compared with the uncharged device.
- The droplet size was nearly equally distributed on the grid-wire surface.
- On thick-wire stripe-wise surface, droplets close to the electrode boundaries were likely to be pushed away from electrodes and ultimately tended to roll down from electrode-free regions
- In the zigzag design, droplets were pulled towards and covered the zigzag gap region and were distributed vertically on the charged device.
- The average droplet size on the charged surface was larger than on the uncharged surface at the same time during experiments.
- The charged surfaces exhibited faster droplet growth, with larger and more discrete droplet distribution, which accelerated droplet-shedding frequency and freed up condensing areas for small-droplet nucleation and growth.
- The droplet size distribution on the uncharged surface agreed well with the theoretical model within the $100\mu\text{m}$ – $1000\mu\text{m}$ radius range. On charged surface (i.e. under EWOD effect), the number of large droplets was greater than in the theoretical model.

6.1.3 Condensation Heat Transfer Enhancement via EWOD

- The heat flux and heat transfer rate were each enhanced under the 40V DC EWOD effect compared with uncharged conditions.
- Under identical testing conditions, the left side showed lower enhancement than the right side due to imperfect temperature distribution on the cold plate (i.e. a higher subcooling temperature).
- The heat transfer coefficient improved by 11.73% and 13.33% on the left and right sides under a 40V DC charge, respectively.
- The heat dissipation rate showed a 5.54% and 6.50% enhancement on the left and right sides under a 40V DC charge, respectively.

6.2 Recommendations for Future Work

The results of these studies lay a foundation for future research on condensation heat transfer under the EWOD effect. Recommendations for future work include the following. First, condensation heat transfer measurements under different subcooling conditions should be studied further. Results in Chapter 5 were obtained under a fixed coolant temperature. Future work could compare heat transfer with and without EWOD effect under different subcooling conditions as the effect of subcooling on heat transfer performance is also worthwhile to be investigated.

Second, other possible hydrophobic coatings could be identified that exhibit lower contact angle hysteresis and higher thermal stability. As discussed in Chapter 5, a silane layer was added on top of the Teflon coating to guarantee high thermal stability of the hydrophobic layer; however, the contact angle hysteresis of silane was not as good as

expected, the stickier surface led to a slower droplet-shedding frequency. This result may partially explain why the enhancement in heat transfer was not as significant as that for water harvesting. Future studies can examine other potential coatings and compare their thermal performance.

Last but not least, droplet dynamics on charged surfaces (double-layer grid-wire and coplanar zigzag designs) can be investigated numerically. For example, in Chapter 4, droplets were found to be propelled to the electrode-free region on double-layer-electrode devices. Thus, the electrostatic force on the droplet from its nucleation to a sufficiently large size could be analyzed using COMSOL or ANSYS. Droplet motion due to such force can also be compared with the experimental phenomena discussed in Chapter 4.

APPENDIX A ACTIVATION OF BUBBLES' ESCAPE, COALESCENCE AND DEPARTURE VIA EWOD³

A.1 Introduction

In recent years, boiling heat transfer has drawn increasing attention due to greater demand for efficient waste heat removal. In the phase change process of boiling, bubble dynamics play a vital role in determining the overall heat transfer rate. Many studies have been conducted on bubble formation [109, 110], bubble motion [111-113], and bubble removal and departure [114-116]. Bubble dynamics are affected by many factors, such as the buoyancy force and surface tension. The electric field also influences bubble dynamics in nucleate boiling [117-119]. Bubble dynamics under the electrohydrodynamic (EHD) effect with different voltage profiles, such as DC/AC [120] or nonuniform DC [121], have been investigated; however, the EHD approach involves exceedingly high voltages (i.e., tens of kilovolts), which can pose safety issues during experiments. Similar to the idea of applying an electric field to influence surface tension on droplets or bubbles, Lippman [3] discovered the effect of electrowetting that controls surface wetting properties (macro contact angle) once electric potential is applied to a conductive liquid. Following his study, Berge [15] improved the electrowetting design by adding a dielectric insulating layer and introduced the electrowetting-on-dielectric (EWOD) approach. EWOD requires a much smaller voltage to change the surface tension of a droplet or bubble compared with the EHD approach. EWOD can also

³The contents of this chapter have been partially published in the following conference: **Yan, R., & Chen, C. L. (2019). Electrowetting-on-Dielectric Induced Bubble Dynamics and Surface Waves. In *AIAA Aviation 2019 Forum* (p. 3645).**

provide a dynamic and adjustable wettability pattern by varying the voltage amplitude or frequency [27]. The EWOD approach has since been applied to droplet manipulation [23, 25, 122], thermal management [29, 123], water harvesting [79] and bubble detachment [26, 124] among other domains. Yet little research has considered bubble escape and coalescence under the EWOD effect. Bubble escape and augmented coalescence and departure are important for enhancing heat pipe performance [125] and addressing nucleation efficiency improvement issues in boiling heat transfer studies [126]. EWOD provides an active way to further manipulate bubble dynamics during boiling heat transfer.

In this chapter, we present a demonstration in which electrowetting oscillates or propels individual or multiple bubbles under the EWOD effect. EWOD can cause bubbles on a hydrophobic surface to ‘stand up’ (i.e., contact-angle decline), thereby promoting bubble detachment. An electrowetting setup consisting of a substrate electrode and a copper wire electrode that is inserted into deionized (DI) water is discussed herein. Once the electrode wire is inserted right above a bubble, the bubble oscillated at its initial location under EWOD effect. When the electrode wire is placed on one side of the bubble, due to unbalanced contact angle variation at the bubble’s left and right contact points, the bubble can be propelled and escape from the inserted electrode. Furthermore, we found that if the inserted electrode is placed near the geometric center of a shape composed of multiple bubbles (i.e., three, four, five, or six), the bubbles escape from their initial positions. Several larger (20 μ L) bubbles’ escape and coalescence behavior was also investigated. Results indicated that different

distances between bubbles and the inserted electrode led bubbles to escape at different speeds. A bubble closer to the electrode wire traveled faster than one farther from the electrode. Distinct travel speeds induced bubble coalescence. Bubbles coalesced in the case of a thin film, forming a larger bubble. This large bubble then oscillated under the EWOD effect. Oscillation dynamics ultimately overcame disjoint pressure in the thin film and induced bubble detachment. In the thick-film case, the bubbles coalesced first; once the size of a coalesced bubble became sufficiently large, the smaller contact angle evoked by electrowetting lifted the bubble and resulted in its departure from the substrate due to buoyancy force. Controlling bubble dynamics via electrowetting, including escape, coalescence, and departure, provides an active way to move bubbles or increase departure frequency in boiling systems or heat pipe evaporator regions. These developments show promise in enhancing boiling-phase-change heat transfer.

The working principle of this EWOD-induced bubble ‘stand-up’ phenomenon is determined by contact area and a (macroscale) reduction in the contact angle at the three-phase contact point. Contact angle variation in terms of the applied electric field follows the Young-Lippmann equation and is illustrated in Figure A.1. The black solid line and red dotted line denote the non-charged and charged bubble morphology on a hydrophobic surface, respectively. The contact angle declined and the bubble ‘stood up’ when EWOD was applied. The hydrophobic layer could reduce contact-angle hysteresis to reveal the EWOD effect more easily. The dielectric layer was used to separate the conductive substrate and the bubble, which was immersed in a dielectric liquid such as deionized (DI) water.

Figure A.1 Schematic of bubble's contact-angle variation under EWOD effect.

A.2 Experimental Setup

The testing substrate (purchased from University Wafer, Inc.) was composed of 400 μ m conductive silicon (0.001 Ω –0.005 Ω /cm) and 100nm silicon nitride obtained via low-pressure chemical vapor deposition. A 60nm-thick hydrophobic layer of Teflon (PFC1601-FS; Cytonix LLC) was spin-coated after rinsing the surface with acetone, methanol, and DI water. The spin-coating speed was 2000rpm with 1000rpm/s acceleration for 30s, after which the layer was baked at 180°C for 30min to obtain a relatively low surface energy of approximately 10 dynes/cm. A schematic of the testing basin setup is shown in Figure A.2. The region marked by blue dashed lines represents the testing basin filled with DI water. The cap-shaped outline represents the testing bubble; the horizontal blue thin cuboid indicates the test substrate. One end of the test substrate was immersed in the testing basin filled with DI water while the other was exposed to the environment. A portion of the exposed substrate was polished with sandpaper to remove Teflon and silicon nitride and expose the conductive silicon substrate for voltage application. The testing substrate was placed in a testing basin made of polydimethylsiloxane (PDMS).

Figure A.2 Schematic of testing basin and testing substrate.

The applied voltage was provided by a function generator. Due to the limited output voltage range of the function generator, the signal was enlarged 50 times by a voltage amplifier before being applied to the testing substrate. The electrode inserted into DI water was a piece of 40AWG magnet copper wire connected to a small copper clamp hooked onto an adjustable holder to guarantee accurate placement. The other electrode was intertwined with clamps and attached to the sanded region with exposed conductive silicon. The experimental setup is illustrated in Figure A.3. A light-emitting diode (LED) illuminator was used for lighting purposes. Experimental visualizations were obtained using Phantom high-speed cameras. Each camera was connected to the computer via Phantom Camera Control (PCC) software, which includes a built-in manual post-trigger function. The high-speed cameras were triggered instantly following bubble escape, coalescence, and detachment during the experiments. Figure A.3 (a) and (b) depict the experimental setup and provide a detailed view of the sample region for the test, respectively.

Figure A.3 Experimental setup: (a) overall view of setup; (b) enlarged view of testing region. (1) Function generator; (2) voltage amplifier; (3) testing wires; (4) adjustable wire holder; (5) LED light; (6) high-speed camera; (7) testing region; (8) laboratory scissor jack; (9) electrodes with clamp connected to bottom and lateral testing surfaces; (10) clamp hooked with copper wire for insertion into DI water; (11) testing basin substrate and walls made of polydimethylsiloxane; (12) visualization glass; (13) petri dish; (14) horizontal testing substrate.

A.3 Experimental Procedures

The first step of the experiment was to fill the testing basin with DI. Next, the conductive silicon was connected to the negative electrode, and the positive electrode (copper wire) was inserted into DI water. Different-sized bubbles were added to the testing substrate using a Hamilton 1701 10 μ L gastight syringe with a removable flat-tipped needle, which prevented damage to the testing surface when seeding bubbles. The syringe was accurate and helped control and quantify bubble size in the experiments. After adding each bubble to the testing system, a high-speed camera was calibrated and focused to obtain high-quality experimental results. Once the voltage was applied, the high-speed camera was turned on to capture bubble contact angle variation, bubble escape, coalescence, and detachment. Post-processing of the experiment was achieved using PCC software. A built-in tool in PCC was used to measure contact-angle variation.

A.4 Results and Discussion

A.4.1 EWOD-Induced Bubble Oscillation

The first experiment was carried out to observe the single bubble oscillation under EWOD effect. Once the bubble is seeded to the bottom surface, three wave forms—sine, square, and triangle waves—were applied to the bottom testing surface for the bubble dynamics study. The applied potential is shown in Figure A.4, with peak-to-peak voltages of 100V, 120V, and 140V and amplitudes of 50V, 60V, and 70V. Different frequencies of voltage profiles were utilized for the following experiments. The wave frequency and period shown in Figure A.4 is 0.5Hz and 2s, respectively. Once the voltage was applied, the high-speed camera was turned on to capture bubble oscillation, escape, and detachment and surface waves.

According to the Young-Lippman equation, the contact angle of the bubble varies with changes in the applied voltage. A 3 μ L bubble was added for the contact-angle variation test. A copper wire electrode was positioned directly above the bubble. Bubble contact-angle variation under the sine wave and square wave with V_{peak} and V_{trough} 60V and -60V at a frequency of 0.5Hz is illustrated in Figures A.5 and A.6, respectively. The black wire in the top region represents the copper wire electrode. The initial bubble contact angle and reduced forms under V_{peak} of 50V, 60V, and 70V. The frequency of all testing waves was 0.5Hz.

The initial contact angle of the bubble was approximately 117°–118°. The bubble started to oscillate as the voltage varied; the triangle wave and sine wave each exhibited similar contact angle variation trends as shown in Figure A.5. A gradual contact-angle

Figure A.4 Applied potential profile (sine, square, and triangle waveforms).

Figure A.5 Bubble (3 μL) oscillation at different times within a period of sine wave signal. Scale bar 1mm.

Figure A.6 Bubble (3 μ L) oscillation at different times within a period of square wave signal. Scale bar 1mm.

contact angle measured at peak voltage are listed in Table A.1 for different wave change was observed in these two waveforms: when the absolute value of the voltage increased, the contact angle declined and vice versa. When the voltage varied from V_{peak} to 0V and from V_{trough} to 0V, the contact angle increased. Obvious contact angle oscillations were observed when sine- and triangle-shaped signals were applied; however, as the square wave maintained a relatively constant voltage value, the bubble's contact-angle variation was not as strong as in the other two cases; instead, the contact angle remained stable at a small value for a longer time compared with the other two cases as indicated in Figure A.5. Additionally, the contact angle was smaller at a peak value of 60V compared with that at a trough value of -60V for the sine, triangle and square waves, indicating that flipping the electrode poles would affect EWOD even under the same absolute voltage value. Once the voltage absolute value dropped to 0, the contact angle

recovered, but the value could only return to around 107° and 96° for the sine and square waves, respectively; it could not recover to the initial uncharged 117° . This finding was interesting and needs further experimental and numerical investigations.

Table A.1 Contact angle variation of sine, triangle, and square waves under different V_{peak} .

	Sine wave (0.5Hz)	Triangle wave (0.5Hz)	Square wave (0.5Hz)
Initial contact angle	117°	117°	118°
Contact angle at V_{peak} 50V	92°	89°	86°
Contact angle for V_{peak} 60V	84°	81°	78°
Contact angle for V_{peak} 70V	77°	75°	73°

The results displayed in Table A.1 suggest that even under the same V_{peak} value, different wave forms resulted in distinct contact angle variations. The sine wave showed a larger contact angle (weakest EWOD effect), the triangle wave was moderate, and the square wave had the smallest contact angle (strongest EWOD effect). For the same types of wave forms at different V_{peak} , the contact angle differed as well. The larger the V_{peak} value, the smaller the contact angle; this trend was due to the Young-Lippman equation, which indicated the increment of voltage leads to a smaller contact angle.

A.4.2 EWOD-Induced Bubble Escape—Side View

In the preceding experimental investigation of contact angle variation, the electrode wire was positioned directly above the bubble. The bubble escape experiment presented in this section was conducted by applying a square waveform potential to the testing region with the electrode wire positioned on one side of the bubble. Figures A.7 and A.8 indicate that when the electrode was on the left- or righthand side of a 6- μ L bubble, the bubble was repelled to the right or left once EWOD took effect. Once

voltage was applied, the contact point close to the electrode appeared to move first, while the contact point farther from the electrode remained in its initial location. The out-of-pace motion of the two contact points resulted in a deformed bubble compared to its initial spherical-cap shape; see (a)—(c) in Figures A.7 and A.8. This out-of-pace motion arose from the sudden increment of voltage from zero to peak voltage with a square waveform and occurred within a short time: 0.078s and 0.062s in Figures A.7 and A.8, respectively.

The contact angles on the left- and righthand sides of the bubble were unequal during bubble deformation. Similar to the droplet or bubble transportation shown in Figure 1.8, the side with a smaller contact angle was subjected to a greater electric force than the side with a larger contact angle. An unequal contact angle caused unbalanced force to be exerted on the bubble. The smaller contact angle closer to the electrode generated a sudden pulse with an initial kick velocity and pushed the bubble away from the electrode. As time proceeded, the effect of voltage change (i.e., from zero to peak voltage or from zero to trough voltage) vanished while the voltage remained constant. During this period, the bubble morphology was not deformed and returned to its normal shape (i.e., a spherical segment). The bubble kept sliding away from the electrode under its initial kick velocity. However, the bubble's travel speed declined compared with the initial kick velocity because no external pushing force was applied; only the surface frictional force remained as a drag force. Then, the next voltage change occurred (i.e., from zero to the trough voltage). The bubble was thus subjected to another pulsing force under the EWOD effect and began to travel further. Additionally, when the bubble was

closer to the electrode, much less time was needed for the bubble to travel the same distance than when it was farther from the electrode; the bubble took 0.366s and 1.326s to travel across the first half of the view field and 14.056s and 6.132s to travel across the second half (Figures A.7 and A.8, respectively). Sheng et al. [26] minimized this

Figure A.7 Bubble (6 μ L) escape when electrode is on the left. Applied voltage: V_{peak} 60V, 0.5Hz, square wave. Scale bar 1mm.

Figure A.8 Bubble (6 μ L) escape when electrode inserted in DI water is on the right. Applied voltage: V_{peak} 60V, 0.5Hz, square wave. Scale bar 1mm.

bubble escape effect by inserting two electrode wires connected from the same electrode pole; then, they placed the wires at an equal distance from the bubble to examine bubble detachment in a relatively stable position. This bubble escape phenomenon demonstrates a potential active approach to removing bubbles from hydrophobic surfaces in electronic systems.

A.4.2 EWOD-Induced Bubble Escape—Top View

Based on an investigation of bubble escape patterns, we conducted an experiment to observe several bubbles' escape behavior. Rather than performing a side-view experiment, we carried out a top-view experiment. Bubbles were arranged into

Figure A.9 Escape behavior of (a) three, (b) four, (c) five, and (d) six bubbles. The first, second, and third columns represent $t=0s$, $t=1s$, and $t=5s$ bubble positions, respectively. Scale bars, 5mm.

triangular, square, pentagonal, and hexagonal shapes. Three, four, five, or six 2 μ L were seeded to the system. The electrode wire was inserted into the geometric center of each bubble shape, in a relatively one-sided location with respect to each bubble, and bubbles were expected to escape away from the electrode wire. The applied voltage was 60V square wave with 2Hz. As shown in Figure A.9, the bubbles were first observed to be smaller (i.e., they ‘stood up’ as the contact area reduced) and then traveled outward from their initial positions. The bubbles were observed not traveling at the same speed due to variations in their final locations (for example the left bubble in Figure A.9 (d)). The differences in travel speed can be explained in several ways. First, because the bubbles were manually seeded to the surface, their initial shape was not perfectly polygonal. This imprecision was enlarged as the bubbles traveled farther. Second, the inserted copper electrode wire could not be guaranteed to be placed exactly in the geometric center of the triangle, square, pentagon, or hexagon, thus exerting uneven force on each bubble (i.e., some bubbles were subjected to a larger electric force, whereas others were subjected to a smaller electric force). These uneven forces resulted in different acceleration rates among the bubbles, leading to distinct travel distances during the same period. Third, the frictional force exerted on each bubble was not uniform due to the imperfect surface condition of the testing substrate. Uneven surface conditions caused some locations to demonstrate more slippery conditions, which rendered movement easier under certain degrees of electric force. Conversely, other regions exhibited stickier conditions, hindering movement under certain amounts of electric force. This led to different travel distances of bubbles.

A.4.4 EWOD-Induced Bubble Coalescence and Detachment

In addition to several bubbles' escape behavior, we also tested four bubbles' escape and coalescence behavior when the electrode wire was placed on one side of the bubbles. Bubbles closer to the electrode moved faster than those farther from the electrode, and bubble coalescence occurred and induced bubble detachment. Figure A.10 reveals bubble detachment in a thin-film scenario, with four equal-size bubbles of $20\mu\text{L}$ upon applying 60V square wave voltage and 2Hz voltage. Previous studies [26] have explored bubble detachment in thin film, which transpires when EWOD-induced dynamics exceed the disjoint pressure in thin-film water. The bubble detachment in Figure A.10 follows a similar principle.

Figure A.10 Bubble coalescence and detachment in thin film of DI water. Bubble size: $20\mu\text{L}$ each; electrode copper wire inserted on the left. Scale bar, 5mm.

Aside from thin-film bubble coalescence and detachment, Figure A.11 indicates that the coalesced bubble detached even under thick water film conditions (4mm from the bubble top to the water level surface in this experiment). In this case, detachment

accompanied increased bubble size and contact-area decrement. These factors enabled the bubble to overcome its buoyancy force and depart from the substrate. Figure A.11 showed that three bubbles coalesced due to different bubble escape speeds; the 60 μ L bubble stood up and overcame the buoyancy force before departing from the substrate.

Figure A.11 Bubble coalescence and detachment in thick film of DI water. Bubble size: 20 μ L each; electrode copper wire inserted on right. Scale bar, 5mm.

A.5 Conclusion

The study discussed in this Appendix presents an active way to control bubble escape, coalescence, and departure via EWOD. If the electrode wire inserted into the DI water was right above the bubble, the bubble oscillated at its initial position. When voltages were applied to the system, the bubble contact angle declined, and higher voltages caused stronger reductions in the contact angle. A gradual shift in the contact angle was observed in the sine and triangle waves, whereas the square wave demonstrated a sudden change and a relatively small and constant contact angle. Under the same applied voltage potential V_{peak} value, the contact-angle variation differed under

sine, triangle, and square waves: the sine wave demonstrated a weaker EWOD effect, the EWOD effect for the triangle wave was moderate, and the square wave showed the strongest effect. When an electrode was inserted into DI water on one side of a bubble, that bubble tended to escape from its initial position under the EWOD effect. Unequal contact angles at the left and right contact points were observed at the moment of a sudden voltage change (i.e., from zero to peak voltage and from zero to trough voltage). This unequal contact angle resulted in unbalanced force being exerted on the bubble (i.e., a smaller contact angle at the side close to the electrode resulted in a larger electric force), generating an initial kick to the bubble at the moment of voltage change and causing the bubble to depart from its initial position. Multiple bubbles' escapes were also investigated in this study. The bubbles were arranged into triangular, square, pentagonal, and hexagonal shapes, and an electrode wire was positioned in the geometric center of each shape. The bubbles were observed to escape outward from their initial positions. Bubble coalescence and departure were examined using four 20 μ L large bubbles in a line with an electrode inserted on one side. Due to different relative distances from the electrode, the bubbles escaped at varying speeds: closer bubbles escaped faster, whereas farther bubbles escaped slower. This travel speed difference led to bubble coalescence. Once a bubble could overcome either disjoint pressure in the thin film or buoyancy force in the thick film, the coalesced large bubble departed from the substrate. This study makes important contributions by providing a possible method to deal actively with bubbles on boiling surfaces or heat pipe evaporating regions. Bubble propulsion due to EWOD can increase bubble departure frequency and potentially enhance heat transfer behavior in relative systems.

APPENDIX B VISUALIZATION AND THEORETICAL MODEL OF THE EWOD-DRIVEN INTERFACIAL SURFACE WAVE⁴

B.1 Introduction

Electrowetting-on-dielectric (EWOD) is a surface-wetting phenomenon resulting from electrical control of the surface wetting properties through the application of an electric potential. The advantage of electrowetting is that it can provide a dynamic and adjustable wettability pattern via the variation of voltage amplitude or frequency. By applying an AC voltage, the droplet can repeatedly be stretched and recoiled; such electrowetting-on-dielectric (EWOD) oscillations have been used for efficient microfluidic mixing [127]. EWOD has also been incorporated into fluid dynamics, such as surface perturbation and surface wave generation. Kwon et al. [128] introduced a vertical air-to-water interface (oscillated by ac electrowetting) that generated a quasi-steady ‘streaming’ flow. They utilized the flow to propel water-floating objects and observed a boat moving speed up to 5 mm/s along a curvilinear path line. Their study introduced a possible EWOD approach to propel water-floating mini/microrobots for water/air quality monitoring or surveillance/security purposes. Inspired by their work, we conducted experiments to visualize the EWOD-driven interfacial surface wave as EWOD can be used to modulate the contact point movement at the water-air interface in a thin liquid film. Rapid oscillation of the contact line is achieved by a swift change

⁴The contents of this chapter have been published in the following journal and conference: Xu, H., **Yan, R.**, Wang, S., & Chen, C. L. (2017). Bubble detachment assisted by electrowetting-driven interfacial wave. *Physics of Fluids*, 29(10), 102105. **Yan, R.**, & Chen, C. L. (2019). Electrowetting-on-Dielectric Induced Bubble Dynamics and Surface Waves. In *AIAA Aviation 2019 Forum* (p. 3645).

of voltage under an AC signal. By applying a 70V peak voltage and 1Hz frequency voltage on the lateral wall, surface waves generated via motion of the three-phase contact point were detected. The visualization of the interfacial surface wave disturbance to a bubble's departure in thin film of liquid water was also demonstrated. Besides the experimental studies, a theoretical model was introduced to predict the relationship between generated surface wave frequency and amplitude affected by the applied voltage frequency. The frequency of interfacial wave and contact point displacement was found to be twice of the voltage frequency. A higher voltage frequency would lead to a smaller amplitude and higher celerity of the wave, while a lower voltage frequency leads to a larger wave amplitude and lower celerity of the wave.

B.2 Experimental Setup and Procedures

The EWOD device utilized in this study shared the same parameter as discussed in Appendix A.2, but displayed both horizontally and vertically. A schematic of the experimental setup is illustrated in Figure B.1. The testing region consisted of bottom and lateral testing surfaces. The bottom surface was designed in case bubble seedings were need, whereas the lateral surface was used to observe three-phase contact point motion and detect surface perturbation. As displayed in Figure B.1, if there's a seeded bubble sitting on the bottom surface and the bottom, the contact angle declined and the bubble 'stood up' when EWOD was applied. On the lateral wall, the initial air-water-substrate contact angle was initially larger than 90° due to hydrophobic coating. When EWOD was applied, the contact angle declined and the contact point moved up compared with its initial condition.

Figure B.1 Schematic of experimental setup. Black solid line and red dotted line represent water–air interface before and after applied voltage, respectively.

The experimental setup is the same as that shown in Figures A.2 and A.3. The high-speed camera was utilized for the visualization of surface wave generation. The experimental procedure was similar to that discussed in Appendix A.3. The basin was initially filled with DI water for the test. The conductive silicon was connected to the negative electrode, and the positive electrode (the copper wire) was inserted into DI water. The different voltage potentials will be applied to the lateral wall to generate interfacial surface waves.

B.3 Experimental Results and Discussion

B.3.1 EWOD-Induced Three-Phase Contact Point Motion on the Lateral Wall

The effect of EWOD was investigated on the lateral wall. The three-phase contact point (i.e., the intersection between the wall, water level, and atmosphere) moved as electrical potential was applied to the system as indicated in Figure B.2. This motion was consistent with the reduction in contact angle due to the EWOD effect. The sine wave, triangle wave, and square wave were tested, and the first two demonstrated better

periodic motion. The square wave did not cause the three-phase contact point to move up and down because it had constant V_{peak} and V_{trough} and had a constant voltage most of the time. The sine wave with V_{peak} 70V and 2Hz frequency evoked contact point motion as illustrated in Figure B.2; the red solid line represents the lateral wall, and the red dot represents the three-phase contact point. As the absolute value of the voltage increased, the contact point moved upward (i.e., the contact angle declined) as shown in Figure B.2 (a)–(b) and (c)–(d). As the absolute value of the voltage declined, the contact point moved downward (i.e., the contact angle increased); see Figure B.2 (b)–(c). Note the contact point of Figure B.2 (c) did not fully recover to that shown in Figure B.2 (a) (i.e., the contact angle did not return to its initial status). The three-phase contact point motion verified surface perturbation produced by the lateral wall via EWOD and thus provides a way to actively introduce surface waves to the testing system.

Figure B.2 Contact line movement (contact point at different times, scale bar 1mm).

B.3.2 EWOD-Induced Surface Wave Oscillation

The three-phase contact point caused slight perturbations on the water surface and introduced some surface waves. An 8 μ L bubble was seeded to the bottom surface in this test. The voltage signal, with sine wave V_{peak} 70V and a frequency of 1Hz, was applied to the lateral wall. The EWOD induced surface wave was detected by the high-speed camera, and the phenomenon experimentally validated surface wave studies by Xu et al. [28]. The bubble did not detach due to a thick layer of water (the bubble top line was more than 2mm away from the water level). The white curves in Figure B.3 indicate reflection and do not represent the true water level, which was farther away from the top of the bubble; however, the white curves do reveal water-level dynamics. Several snapshots of obvious white curves (with surface waves) are illustrated in Figure

Figure B.3 Surface wave detection (a) without EWOD applied on the lateral wall and (b)–(d) with EWOD applied on the lateral wall. Applied voltage sine wave V_{peak} 70V, frequency 1Hz. Scale bar 1mm.

B.3 (b)–(d) compared with the straight white line (no surface waves) in Figure B.3 (a).

This validation of surface waves produced by contact point motion of the lateral wall via EWOD demonstrates a sound approach to disturb the water surface, influence bubble dynamics, and potentially enhance detachment efficiency.

B.3.3 Interfacial-Surface-Wave-Assisted Bubble Detachment

Previous results showed that EWOD influenced bubble dynamics. The study by Sheng et al. [26] also demonstrated EWOD induced bubble detachment. If surface perturbation were added to the system, it should induce a stronger effect on bubble dynamics and easier bubble detachment. An 8 μ L bubble was seeded to the bottom surface in the present study. The bottom and lateral walls were attached simultaneously to the negative electrode, and the copper wire was inserted into DI water to function as the positive electrode. Once the voltage was turned on, EWOD caused surface waves and bubble oscillation, which enhanced droplet detachment. A sine wave with a peak value of 70V and a frequency of 1Hz served as the EWOD voltage potential. The bubble stayed on the horizontal surface under a thin-film condition (i.e., the water level was tangential to the top of the bubble) and was initially undetached. Once voltage was applied to the bottom and lateral surfaces, the bubble began to stand up and oscillate. At the same time, surface waves were generated from the lateral wall, which further agitated the bubble. The standing-up motion made the top film of the bubble thinner, while the oscillation and surface wave introduced additional perturbations. These three factors collectively resulted in bubble detachment as displayed in Figure B.4.

Figure B.4 Interfacial-surface-wave-assisted bubble detachment in liquid water thin film. Scale bar 1mm.

B.4 Theoretical Model of Interfacial Surface Wave

B.4.1 Mathematical Model of Surface Tension Effect

To study on the mathematical parameter of the generated surface wave, we should firstly analyze the effect of three-phase surface tension. To capture the effect of surface tension, we take an element of the interfacial wave and balance the force acting on this element, as shown in Figure B.5. If we consider small amplitude waves with small free

Figure B.5 The coordinate system for interfacial wave problems.

surface displacement $\eta(x, t)$ and small fluid velocity (u, v) , the governing equations for interfacial wave motions regarding velocity potential can be considered as Eqs. (B.1)—(B.4) [129]. Equation (B.1) is the differential equation to be satisfied by the velocity potential in the x - y plane. Equation (B.2) is the kinematic boundary condition on the free surface. Equation (B.3) is the dynamic boundary condition on the free surface. The boundary condition on the lower boundary is described as Equation (B.4).

$$\nabla^2 \phi = 0 \quad (\text{B.1})$$

$$\frac{\partial \eta(x, t)}{\partial t} = \frac{\partial \phi(x, 0, t)}{\partial y} \quad \text{on } y = \eta \quad (\text{B.2})$$

$$\frac{\partial^2 \phi(x, 0, t)}{\partial t^2} + \frac{1}{\rho} \frac{\partial p(x, t)}{\partial t} + g \frac{\partial \phi(x, 0, t)}{\partial y} = 0 \quad \text{on } y = \eta \quad (\text{B.3})$$

$$\frac{\partial \phi(x, -h, t)}{\partial y} = 0 \quad (\text{B.4})$$

In order to take consideration of the surface-tension effect, we take an element of interfacial wave and balance the force acting on this element, as shown in Figure B.5. The pressure along the edge of the liquid differs from the atmospheric pressure due to the surface tension effect. The balance of force on the surface of wave requires,

$$(p - p_0)\Delta x + \left(\sigma + \frac{\partial \sigma}{\partial x} \Delta x\right) \left(\frac{\partial \eta}{\partial x} + \frac{\partial^2 \eta}{\partial x^2} \Delta x\right) - \sigma \frac{\partial \eta}{\partial x} = 0 \quad (\text{B.5})$$

Expanding the terms in Eq. (B.5) and neglecting terms that are quadratic in the length Δx gives the pressure at the edge of liquid,

$$p(x, t) = p_0 - \sigma \frac{\partial^2 \eta}{\partial x^2} \quad (\text{B.6})$$

Eq. (B.2) can enter through the term $\partial P / \partial t$. Consider P_0 is the constant, Eq. (B.3) is:

$$\frac{\partial^2 \varphi(x, 0, t)}{\partial t^2} + \frac{\sigma}{\rho} \frac{\partial^3 \varphi(x, 0, t)}{\partial x^2 \partial y} + g \frac{\partial \varphi(x, 0, t)}{\partial y} = 0 \quad (\text{B.7})$$

Assuming a small-amplitude plane wave is traveling along the surface and the form of the wave is taken to be sinusoidal, with the wave amplitude A and its wavelength λ .

Thus, the equation of the free surface will be,

$$\eta(x, t) = A \sin \frac{2\pi}{\lambda} (x - ct) \quad (\text{B.8})$$

Substituting Eq. (B.8) into Eq. (B. 2) and the solution for $\Phi(x, y, t)$ becomes,

$$\frac{c^2}{gh} = \frac{\lambda}{2\pi h} \left[1 + \frac{\sigma}{\rho g} \left(\frac{2\pi}{\lambda} \right)^2 \right] \tanh \frac{2\pi h}{\lambda} \quad (\text{B.9})$$

If the parameter inside the brackets is sufficiently large that,

$$\frac{\sigma}{\rho g} \left(\frac{2\pi}{\lambda} \right)^2 \gg 1 \quad (\text{B.10})$$

Then the expression for the propagation speed will reduce to the following,

$$\frac{c^2}{gh} = \frac{2\pi\sigma}{\rho g \lambda h} \quad (\text{B.11})$$

From Eq. (B.11), the propagation speed of a capillary wave depends upon the wavelength λ . The larger the wavelength becomes, the smaller the propagation speed, which means an arbitrarily shaped wave will disperse because of the different propagation speeds of its Fourier components.

Equation (B.8) indicated the generated wave is sinusoidal. However, waves of the arbitrary form may be decomposed into several pure sinusoidal waves and treated using Fourier analysis. To make derivation more accurate, we consider the generated wave as a combination of many sinusoidal waves with different amplitude and different frequency which can be illustrated as follow,

$$\eta(x,t) = \sum_{n=1}^k A_k \sin\left(\frac{2\pi}{\lambda_k}\right)(x-ct) \quad (\text{B.12})$$

changing wavelength term to frequency expression, we obtained,

$$\eta(x,t) = \sum_{n=1}^k A_k \sin(2\pi f_k)\left(\frac{1}{c}x-t\right) \quad (\text{B.13})$$

The relationship between wave equation and contact angle profile is that the contact angle indicates wave's curvature slope at $x=0$: the wall position. In this case, if the curvature slope can be derived, which is the first derivative of the wave with respect to x , then given different frequencies, the amplitude in terms of each frequency is ready to be figured out. The curvature slope is,

$$\frac{d\eta(x,t)}{dx} = \sum_{n=1}^k \left(\frac{2A_k \pi f_k}{c}\right) \cos\left(2\pi f_k\left(\frac{1}{c}x-t\right)\right) \quad (\text{B.14})$$

According to the curvature slope function and its relation with contact angle profile, the following expression can be obtained,

$$\theta(t) = \left.\frac{d\eta(x,t)}{dx}\right|_{x=0} \quad (\text{B.15})$$

Thus, if n terms of sinusoidal function are set for the wave equation, the sinusoidal amplitude of these n terms can be determined by plugging different time in Eq. (B.15).

According to Eq. (B.11), the wave speed is also a function of frequency. The definition of wave speed in terms of wavelength and frequency can be found as,

$$c^3 = \frac{2\pi\sigma f}{\rho} \quad (\text{B.16})$$

Tables B.1, B.2 and B.3 showed results under different given frequencies of applied voltage. The results were calculated using MATLAB. In the tables, the following representation is defined by

$$f_n = n \cdot f_1 \quad (\text{B.17})$$

which indicates different sinusoidal components' frequencies.

The tables display the n terms from 11 to 19. The dominant term is $2f_1$, which means the frequency of contact angle change is two times the frequency of the voltage signal. Considering nineteen terms in the Fourier series model, the wave amplitudes are 0.3866mm, 0.155mm, 0.9346mm for frequencies of 10Hz, 50Hz, and 100Hz (the amplitude fixed at 16V); the wave speed in terms of 10Hz, 50Hz, and 100Hz are 0.18045 m/s, 0.37865 m/s, and 0.494852 m/s.

Table B.1 Amplitude of different terms ($f_1=10\text{Hz}$), f is the frequency and A is the amplitude ($\times 10^{-3}m$).

	n terms	11	13	15	17	19
f_1	A_1	0.1034	0.1001	0.098	0.0964	0.0953
f_2	A_2	0.347	0.3676	0.3772	0.3828	0.3866
f_3	A_3	-0.1627	0.2869	0.1262	0.0915	0.0758
f_4	A_4	0.143	0.0311	0.3723	-0.4671	-0.178
f_5	A_5	0.0195	-0.1879	-0.1732	-0.2681	-0.7978
f_6	A_6	-0.0068	0.0188	-0.1764	0.3929	0.0756
f_7	A_7	0.0067	-0.0081	0.0356	0.1209	0.5529
f_8	A_8	-0.0073	0.0059	-0.0179	-0.0324	0.0395
f_9	A_9	0.0147	-0.0058	0.0128	0.0168	-0.0125
f_{10}	A_{10}	0.0156	0.0082	-0.0119	-0.0118	0.0066
f_{11}	A_{11}	-0.023	-0.028	0.0144	0.0105	-0.0046
f_{12}	A_{12}		-0.0122	-0.026	-0.0116	0.0039
f_{13}	A_{13}		0.0309	0.2645	0.0168	-0.0041
f_{14}	A_{14}			0.0317	-0.04	0.0052
f_{15}	A_{15}			-0.2444	-0.3957	-0.0091
f_{16}	A_{16}				0.0428	0.0307
f_{17}	A_{17}				0.3337	0.0961
f_{18}	A_{18}					-0.0299
f_{19}	A_{19}					-0.0786

Table B.2 Amplitude of different terms ($f_l=50\text{Hz}$) ($\times 10^{-3}m$), f is the frequency and A is the amplitude ($\times 10^{-3}m$).

	n terms	11	13	15	17	19
f_1	A_1	0.0081	-0.0019	0.0006	-0.0181	0
f_2	A_2	0.1524	0.1531	0.1631	0.1659	0.155
f_3	A_3	0.0072	0.0008	0.0014	-0.0014	0.0007
f_4	A_4	0.0007	0.0009	0.001	0.0005	0
f_5	A_5	0.0019	0.0045	-0.0052	0.0018	0.0007
f_6	A_6	-0.0007	0.0005	0.0005	0.0013	0.0006
f_7	A_7	0	0.0005	-0.0029	-0.0009	-0.0004
f_8	A_8	-0.0029	-0.003	0.0026	-0.0013	0.0004
f_9	A_9	0.0006	-0.0002	-0.0004	0.0011	0.0001
f_{10}	A_{10}	-0.001	-0.0001	0.0021	0.0008	0
f_{11}	A_{11}	0.0014	0.0002	0.0002	-0.0005	-0.0003
f_{12}	A_{12}		-0.0001	-0.0001	-0.001	0.0002
f_{13}	A_{13}		0.0007	-0.0014	0	-0.0001
f_{14}	A_{14}			0.0003	0.0008	-0.0001
f_{15}	A_{15}			0.001	-0.0018	0.0002
f_{16}	A_{16}				0.0009	0
f_{17}	A_{17}				0.0003	-0.0001
f_{18}	A_{18}					0
f_{19}	A_{19}					0.001

Table B.3 Amplitude of different terms ($f_l=100\text{Hz}$) ($\times 10^{-3}m$), f is the frequency and A is the amplitude ($\times 10^{-3}m$).

	n terms	11	13	15	17	19
f_1	A_1	0.0143	-0.0072	0.0024	-0.0429	0.9155
f_2	A_2	0.9656	0.9966	0.9829	0.9823	0.9346
f_3	A_3	0.0143	0.0048	0.0159	-0.0066	0.2289
f_4	A_4	0.0048	0.0191	0.0131	-0.0113	-0.0012
f_5	A_5	0.0055	0.0167	0.0036	-0.0042	0.0095
f_6	A_6	-0.0004	0.0027	0.006	0.0077	0
f_7	A_7	-0.0006	0.0018	0.0033	-0.0042	0.0143
f_8	A_8	-0.0077	-0.0095	-0.003	0.0167	-0.0286
f_9	A_9	0.0012	-0.0095	-0.0006	-0.0107	-0.0006
f_{10}	A_{10}	-0.0009	-0.0021	-0.0012	0.0009	0.0036

f_{11}	A_{11}	0.0078	-0.0036	-0.0039	-0.0018	0.0191
f_{12}	A_{12}		0.0012	-0.0038	0.0019	-0.0083
f_{13}	A_{13}		0.0087	-0.0019	0.0043	0
f_{14}	A_{14}			-0.0001	0.0003	-0.0072
f_{15}	A_{15}			0.007	-0.0009	-0.0128
f_{16}	A_{16}				0.0027	-0.0381
f_{17}	A_{17}				0.0073	0.0095
f_{18}	A_{18}					-0.0381
f_{19}	A_{19}					0.0073

B.4.2 Interfacial Surface Waver Dispersion

The boundary between two immiscible fluids is susceptible to waves when disturbed, because of exchange between the kinetic energy of the fluids and the potential energy due to gravity and surface tension [130]. EWOD can be used to create an interfacial wave at the liquid-fluid interface. The contact angle changes at the three-phase contact line can be controlled by the AC voltage signal. Rapid movement of the contact line can be achieved by swift changes of the voltage at the electrodes, leading to the rise and drop of interfacial waves under the strong influence of surface tension. The relationship between voltage signal and contact angle change from COMSOL is illustrated in Figure B.6. The voltage frequencies of Figure B.6 (a), (b) and (c) are 10Hz, 50Hz, and 100Hz, respectively. The blue lines in the figures are the change of voltage and the black lines are the variation of contact angles. The figures showed that the frequency of contact angle change is twice that of the frequency of voltage signal. The analytical solution from Young-Lippmann's equation also leads to this conclusion. The Young-Lippmann's equation indicated that the contact angle is influenced by the applied voltage. Given the applied voltage profile as shown in Eq. (B.18),

(a) Voltage frequency :10Hz

(b) Voltage frequency :50Hz

(c) Voltage frequency :100Hz

Figure B.6 The relationship between voltage signal and contact angle change.

$$V(t) = A \sin(2\pi f_1 t) \quad (\text{B.18})$$

where A and f_1 are the amplitude and frequency of the applied voltage, which can be obtained by the Young-Lippman's equation and Eq. (B.18). And Eq. (B.18) can be re-expressed as follow,

$$\cos \theta = \cos \theta_0 + \frac{A^2 \varepsilon_0 \varepsilon_1}{4\gamma d} - \frac{A^2 \varepsilon_0 \varepsilon_1}{2\gamma d} \cos(2\pi(2f_1)t) \quad (\text{B.19})$$

with the form

$$\cos \theta = C_1 + C_2 \cos(2\pi(2f_1)t) \quad (\text{B.20})$$

where the C_1 and C_2 are found to be

$$\begin{aligned} C_1 &= \cos \theta_0 + \frac{A^2 \varepsilon_0 \varepsilon_1}{4\gamma d} \\ C_2 &= -\frac{A^2 \varepsilon_0 \varepsilon_1}{2\gamma d} \end{aligned} \quad (\text{B.21})$$

Then the contact angle variation profile can be derived from Eq. (B.20), shown in the following expression

$$\theta(t) = \arccos(C_1 + C_2 \cos(2\pi(2f_1)t)) \quad (\text{B.22})$$

From Eq. (B.22), the frequency of contact angle change is $2f_1$, which is twice that of the frequency of voltage signal. This is in accordance with the mathematical analysis in the previous section.

B.5 Conclusions

In this chapter, we discussed the visualization of EWOD-induced interfacial surface wave. When a sine wave with a V_{peak} 70V and frequency of 1Hz was applied to the lateral wall, a surface wave generated by the motion of the three-phase contact point

and the water level shape variation were detected. The interfacial-surface-wave-assisted bubble detachment was demonstrated when a square wave potential with 70V peak voltage and 1Hz frequency was applied. A theoretical model of EWOD-induced interfacial surface wave propagation properties was then discussed. An arbitrarily shaped interfacial wave can be considered as a combination of various frequencies due to different propagation speeds when Fourier analysis is carried out. Results reveal that the dominant frequency of the resultant wave is twice as the applied AC voltage frequency. The amplitude and celerity of the propagation wave are also closely related to the applied AC signal. An AC voltage frequency of 100Hz leads to a smaller amplitude and higher celerity of the surface, while a frequency of 10Hz leads to a larger wave amplitude and lower celerity of the wave. This phenomenon is due to the frequency dispersion, which means waves of different wavelengths travel at different phase speeds. In our cases, water with a free surface is a dispersive medium and waves propagate on the surface due to gravity and surface tension. The results discussed in this chapter indicated another possibility to actively generate interfacial surface waves via EWOD in some microfabricated fluid mechanics systems.

BIBLIOGRAPHY

- [1] L. Y. Yeo, H. C. Chang, P. P. Chan, and J. R. Friend, "Microfluidic devices for bioapplications," *small*, vol. 7, no. 1, pp. 12-48, 2011.
- [2] B. J. Kirby, *Micro-and nanoscale fluid mechanics: transport in microfluidic devices*. Cambridge university press, 2010.
- [3] G. Lippmann, "Relations entre les phénomènes électriques et capillaires," Gauthier-Villars, 1875.
- [4] A. Frumkin, "Phenomena of wetting and adhesion of bubbles. I," *Zh. Fiz. Khim*, vol. 12, no. 337, pp. 337-45, 1938.
- [5] G. Beni and S. Hackwood, "Electro-wetting displays," *Applied Physics Letters*, vol. 38, no. 4, pp. 207-209, 1981.
- [6] A. A. Darhuber and S. M. Troian, "Principles of microfluidic actuation by modulation of surface stresses," *Annu. Rev. Fluid Mech.*, vol. 37, pp. 425-455, 2005.
- [7] M. Prins, W. Welters, and J. Weekamp, "Fluid control in multichannel structures by electrocapillary pressure," *Science*, vol. 291, no. 5502, pp. 277-280, 2001.
- [8] V. Srinivasan, V. K. Pamula, and R. B. Fair, "Droplet-based microfluidic lab-on-a-chip for glucose detection," *Analytica Chimica Acta*, vol. 507, no. 1, pp. 145-150, 2004.
- [9] J. W. Hong and S. R. Quake, "Integrated nanoliter systems," *Nature biotechnology*, vol. 21, no. 10, p. 1179, 2003.
- [10] S. C. Jakeway, A. J. de Mello, and E. L. Russell, "Miniaturized total analysis systems for biological analysis," *Fresenius' journal of analytical chemistry*, vol. 366, no. 6-7, pp. 525-539, 2000.
- [11] A. Manz and H. Becker, *Microsystem technology in chemistry and life sciences*. Springer Science & Business Media, 2003.
- [12] M. G. Pollack, A. D. Shenderov, and R. B. Fair, "Electrowetting-based actuation of droplets for integrated microfluidics," *Lab on a Chip*, vol. 2, no. 2, pp. 96-101, 2002.

- [13] S. Kuiper and B. Hendriks, "Variable-focus liquid lens for miniature cameras," *Applied physics letters*, vol. 85, no. 7, pp. 1128-1130, 2004.
- [14] R. A. Hayes and B. J. Feenstra, "Video-speed electronic paper based on electrowetting," *Nature*, vol. 425, no. 6956, p. 383, 2003.
- [15] B. Bruno, "Electrocapillarité et mouillage de films isolants par l'eau," *Comptes Rendus de L'Academie des Sciences Paris, Serie, II*, vol. 317, pp. 157-163, 1993.
- [16] W. J. Welters and L. G. Fokkink, "Fast electrically switchable capillary effects," *Langmuir*, vol. 14, no. 7, pp. 1535-1538, 1998.
- [17] F. Mugele and J.-C. Baret, "Electrowetting: from basics to applications," *Journal of physics: condensed matter*, vol. 17, no. 28, p. R705, 2005.
- [18] T. B. Jones, "An electromechanical interpretation of electrowetting," *Journal of Micromechanics and Microengineering*, vol. 15, no. 6, p. 1184, 2005.
- [19] T. B. Jones, J. D. Fowler, Y. S. Chang, and C.-J. Kim, "Frequency-based relationship of electrowetting and dielectrophoretic liquid microactuation," *Langmuir*, vol. 19, no. 18, pp. 7646-7651, 2003.
- [20] K. H. Kang, "How electrostatic fields change contact angle in electrowetting," *Langmuir*, vol. 18, no. 26, pp. 10318-10322, 2002.
- [21] J. Zeng and T. Korsmeyer, "Principles of droplet electrohydrodynamics for lab-on-a-chip," *Lab on a Chip*, vol. 4, no. 4, pp. 265-277, 2004.
- [22] J. Berthier, *Micro-drops and digital microfluidics*. William Andrew, 2012.
- [23] J. Lee, H. Moon, J. Fowler, T. Schoellhammer, and C.-J. Kim, "Electrowetting and electrowetting-on-dielectric for microscale liquid handling," *Sensors and Actuators A: Physical*, vol. 95, no. 2-3, pp. 259-268, 2002.
- [24] M. G. Pollack, R. B. Fair, and A. D. Shenderov, "Electrowetting-based actuation of liquid droplets for microfluidic applications," *Applied Physics Letters*, vol. 77, no. 11, pp. 1725-1726, 2000.
- [25] S. K. Cho, H. Moon, and C.-J. Kim, "Creating, transporting, cutting, and merging liquid droplets by electrowetting-based actuation for digital microfluidic circuits," *Journal of microelectromechanical systems*, vol. 12, no. 1, pp. 70-80, 2003.

- [26] S. Wang, B. J. Hernan, and C.-L. Chen, "Towards enhanced bubble detachment within a thin liquid film by electrowetting with voltage modulation," *Physics of Fluids*, vol. 30, no. 6, p. 062102, 2018.
- [27] S. Wang, J. Shi, H.-H. Chen, T. Xu, and C.-L. C. Chen, "Numerical and experimental investigation of bubble dynamics via electrowetting-on-dielectric (EWOD)," in *ASME 2016 5th International Conference on Micro/Nanoscale Heat and Mass Transfer*, 2016: American Society of Mechanical Engineers, pp. V001T04A003-V001T04A003.
- [28] H. Xu, R. Yan, S. Wang, and C.-L. Chen, "Bubble detachment assisted by electrowetting-driven interfacial wave," *Physics of Fluids*, vol. 29, no. 10, p. 102105, 2017.
- [29] J.-T. Cheng and C.-L. Chen, "Adaptive chip cooling using electrowetting on coplanar control electrodes," *Nanoscale and Microscale Thermophysical Engineering*, vol. 14, no. 2, pp. 63-74, 2010.
- [30] Z. Ke, J. Shi, B. Zhang, and C.-L. Chen, "Numerical investigation of condensation on microstructured surface with wettability patterns," *International Journal of Heat and Mass Transfer*, vol. 115, pp. 1161-1172, 2017.
- [31] U.-C. Yi and C.-J. Kim, "Characterization of electrowetting actuation on addressable single-side coplanar electrodes," *Journal of Micromechanics and Microengineering*, vol. 16, no. 10, p. 2053, 2006.
- [32] C. G. Cooney, C.-Y. Chen, M. R. Emerling, A. Nadim, and J. D. Sterling, "Electrowetting droplet microfluidics on a single planar surface," *Microfluidics and Nanofluidics*, vol. 2, no. 5, pp. 435-446, 2006.
- [33] A. Stoffel, A. Kovacs, W. Kronast, and B. Müller, "LPCVD against PECVD for micromechanical applications," *Journal of Micromechanics and Microengineering*, vol. 6, no. 1, p. 1, 1996.
- [34] M. Ivanda, "Implementation and Development of the LPCVD Process," 2003.
- [35] T. Kerdcharoen and C. Wongchoosuk, "Carbon nanotube and metal oxide hybrid materials for gas sensing," in *Semiconductor Gas Sensors*: Elsevier, 2013, pp. 386-407.
- [36] D. Hanaor, G. Triani, and C. Sorrell, "Morphology and photocatalytic activity of highly oriented mixed phase titanium dioxide thin films," *Surface and Coatings Technology*, vol. 205, no. 12, pp. 3658-3664, 2011.

- [37] B. Chen, "Investigation of the solvent-evaporation effect on spin coating of thin films," *Polymer Engineering & Science*, vol. 23, no. 7, pp. 399-403, 1983.
- [38] W. Daughton and F. Givens, "An Investigation of the Thickness Variation of Spun-on Thin Films Commonly Associated with the Semiconductor Industry," *Journal of The Electrochemical Society*, vol. 129, no. 1, pp. 173-179, 1982.
- [39] J. H. Lai, "An investigation of spin coating of electron resists," *Polymer Engineering & Science*, vol. 19, no. 15, pp. 1117-1121, 1979.
- [40] D. Meyerhofer, "Characteristics of resist films produced by spinning," *Journal of Applied Physics*, vol. 49, no. 7, pp. 3993-3997, 1978.
- [41] O. N. Tretinnikov and Y. Ikada, "Dynamic wetting and contact angle hysteresis of polymer surfaces studied with the modified Wilhelmy balance method," *Langmuir*, vol. 10, no. 5, pp. 1606-1614, 1994.
- [42] A. Lee, M.-W. Moon, H. Lim, W.-D. Kim, and H.-Y. Kim, "Water harvest via dewing," *Langmuir*, vol. 28, no. 27, pp. 10183-10191, 2012.
- [43] M. W. Rosegrant, X. Cai, and S. A. Cline, "Global water outlook to 2025," *Averting impending crisis. A*, vol. 2020, 2002.
- [44] A. R. Parker and C. R. Lawrence, "Water capture by a desert beetle," *Nature*, vol. 414, no. 6859, p. 33, 2001.
- [45] H. Bai, L. Wang, J. Ju, R. Sun, Y. Zheng, and L. Jiang, "Efficient Water Collection on Integrative Bioinspired Surfaces with Star-Shaped Wettability Patterns," *Advanced Materials*, vol. 26, no. 29, pp. 5025-5030, 2014.
- [46] H. Bai, J. Ju, Y. Zheng, and L. Jiang, "Functional fibers with unique wettability inspired by spider silks," *Advanced materials*, vol. 24, no. 20, pp. 2786-2791, 2012.
- [47] Y. Hou, Y. Chen, Y. Xue, Y. Zheng, and L. Jiang, "Water collection behavior and hanging ability of bioinspired fiber," *Langmuir*, vol. 28, no. 10, pp. 4737-4743, 2012.
- [48] X.-H. He *et al.*, "Microfluidic fabrication of bio-inspired microfibers with controllable magnetic spindle-knots for 3D assembly and water collection," *ACS applied materials & interfaces*, vol. 7, no. 31, pp. 17471-17481, 2015.
- [49] T. Moutherde *et al.*, "Antifogging abilities of model nanotextures," *Nature materials*, vol. 16, no. 6, p. 658, 2017.

- [50] X. Heng, M. Xiang, Z. Lu, and C. Luo, "Branched ZnO wire structures for water collection inspired by cacti," *ACS applied materials & interfaces*, vol. 6, no. 11, pp. 8032-8041, 2014.
- [51] J. Ju, H. Bai, Y. Zheng, T. Zhao, R. Fang, and L. Jiang, "A multi-structural and multi-functional integrated fog collection system in cactus," *Nature communications*, vol. 3, p. 1247, 2012.
- [52] G. Beni and M. Tenan, "Dynamics of electrowetting displays," *Journal of applied physics*, vol. 52, no. 10, pp. 6011-6015, 1981.
- [53] H. Moon, S. K. Cho, R. L. Garrell, and C.-J. C. Kim, "Low voltage electrowetting-on-dielectric," *Journal of applied physics*, vol. 92, no. 7, pp. 4080-4087, 2002.
- [54] A. Faghri, Y. Zhang, and J. R. Howell, *Advanced heat and mass transfer*. Global Digital Press, 2010.
- [55] J. Rose, "Dropwise condensation theory and experiment: a review," *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, vol. 216, no. 2, pp. 115-128, 2002.
- [56] G. Koch, D. Zhang, and A. Leipertz, "Condensation of steam on the surface of hard coated copper discs Wasserdampfkondensation auf der Oberfläche hartstoffbeschichteter Kupferscheiben," *Heat and mass transfer*, vol. 32, no. 3, pp. 149-156, 1997.
- [57] K. Rykaczewski and J. H. J. Scott, "Methodology for imaging nano-to-microscale water condensation dynamics on complex nanostructures," *Acs Nano*, vol. 5, no. 7, pp. 5962-5968, 2011.
- [58] P. Wang, J. Su, M. Shen, M. Ruths, and H. Sun, "Detection of liquid penetration of a micropillar surface using the quartz crystal microbalance," *Langmuir*, vol. 33, no. 2, pp. 638-644, 2017.
- [59] J. Su *et al.*, "Effect of wetting states on frequency response of a micropillar-based quartz crystal microbalance," *Sensors and Actuators A: Physical*, vol. 286, pp. 115-122, 2019.
- [60] N. Miljkovic *et al.*, "Jumping-droplet-enhanced condensation on scalable superhydrophobic nanostructured surfaces," *Nano letters*, vol. 13, no. 1, pp. 179-187, 2012.

- [61] D. J. Preston, D. L. Mafra, N. Miljkovic, J. Kong, and E. N. Wang, "Scalable graphene coatings for enhanced condensation heat transfer," *Nano letters*, vol. 15, no. 5, pp. 2902-2909, 2015.
- [62] D. Torresin, M. K. Tiwari, D. Del Col, and D. Poulikakos, "Flow condensation on copper-based nanotextured superhydrophobic surfaces," *Langmuir*, vol. 29, no. 2, pp. 840-848, 2013.
- [63] M. Alwazzan, K. Egab, P. Wang, Z. Shang, X. Liang, and C. Li, "Condensation heat transfer on nickel tubes: The role of atomic layer deposition of nickel oxide," *International Journal of Heat and Mass Transfer*, vol. 133, pp. 487-493, 2019.
- [64] M. Alwazzan, K. Egab, B. Peng, J. Khan, and C. Li, "Condensation on hybrid-patterned copper tubes (I): Characterization of condensation heat transfer," *International Journal of Heat and Mass Transfer*, vol. 112, pp. 991-1004, 2017.
- [65] A. Chatterjee, M. M. Derby, Y. Peles, and M. K. Jensen, "Enhancement of condensation heat transfer with patterned surfaces," *International Journal of Heat and Mass Transfer*, vol. 71, pp. 675-681, 2014.
- [66] B. Peng, X. Ma, Z. Lan, W. Xu, and R. Wen, "Experimental investigation on steam condensation heat transfer enhancement with vertically patterned hydrophobic–hydrophilic hybrid surfaces," *International Journal of Heat and Mass Transfer*, vol. 83, pp. 27-38, 2015.
- [67] K.-S. Yang, K.-H. Lin, C.-W. Tu, Y.-Z. He, and C.-C. Wang, "Experimental investigation of moist air condensation on hydrophilic, hydrophobic, superhydrophilic, and hybrid hydrophobic-hydrophilic surfaces," *International Journal of Heat and Mass Transfer*, vol. 115, pp. 1032-1041, 2017.
- [68] A. Kumar and G. M. Whitesides, "Patterned condensation figures as optical diffraction gratings," *Science*, vol. 263, no. 5143, pp. 60-62, 1994.
- [69] V. G. Damle and K. Rykaczewski, "Nano-striped chemically anisotropic surfaces have near isotropic wettability," *Applied Physics Letters*, vol. 110, no. 17, p. 171603, 2017.
- [70] G. P. Lopez, H. A. Biebuyck, C. D. Frisbie, and G. M. Whitesides, "Imaging of features on surfaces by condensation figures," *Science*, vol. 260, no. 5108, pp. 647-649, 1993.

- [71] K. K. Varanasi, M. Hsu, N. Bhate, W. Yang, and T. Deng, "Spatial control in the heterogeneous nucleation of water," *Applied Physics Letters*, vol. 95, no. 9, p. 094101, 2009.
- [72] D. M. Anderson *et al.*, "Using amphiphilic nanostructures to enable long-range ensemble coalescence and surface rejuvenation in dropwise condensation," *Acs Nano*, vol. 6, no. 4, pp. 3262-3268, 2012.
- [73] C. W. Lo, C. C. Wang, and M. C. Lu, "Spatial control of heterogeneous nucleation on the superhydrophobic nanowire array," *Advanced Functional Materials*, vol. 24, no. 9, pp. 1211-1217, 2014.
- [74] A. Ghosh, S. Beaini, B. J. Zhang, R. Ganguly, and C. M. Megaridis, "Enhancing dropwise condensation through bioinspired wettability patterning," *Langmuir*, vol. 30, no. 43, pp. 13103-13115, 2014.
- [75] P. S. Mahapatra, A. Ghosh, R. Ganguly, and C. M. Megaridis, "Key design and operating parameters for enhancing dropwise condensation through wettability patterning," *International Journal of Heat and Mass Transfer*, vol. 92, pp. 877-883, 2016.
- [76] B. Mondal, M. Mac Giolla Eain, Q. Xu, V. M. Egan, J. Punch, and A. M. Lyons, "Design and fabrication of a hybrid superhydrophobic–hydrophilic surface that exhibits stable dropwise condensation," *ACS applied materials & interfaces*, vol. 7, no. 42, pp. 23575-23588, 2015.
- [77] L. Mishchenko, M. Khan, J. Aizenberg, and B. D. Hatton, "Spatial control of condensation and freezing on superhydrophobic surfaces with hydrophilic patches," *Advanced functional materials*, vol. 23, no. 36, pp. 4577-4584, 2013.
- [78] Y. Hou, M. Yu, X. Chen, Z. Wang, and S. Yao, "Recurrent filmwise and dropwise condensation on a beetle mimetic surface," *ACS nano*, vol. 9, no. 1, pp. 71-81, 2014.
- [79] R. Yan *et al.*, "Enhanced water capture induced with electrowetting-on-dielectric (EWOD) approach," *Applied Physics Letters*, vol. 113, no. 20, p. 204101, 2018.
- [80] D. Baratian, R. Dey, H. Hoek, D. Van Den Ende, and F. Mugele, "Breath figures under electrowetting: electrically controlled evolution of drop condensation patterns," *Physical review letters*, vol. 120, no. 21, p. 214502, 2018.

- [81] R. Dey, J. Gilbers, D. Baratian, H. Hoek, D. Van Den Ende, and F. Mugele, "Controlling shedding characteristics of condensate drops using electrowetting," *Applied physics letters*, vol. 113, no. 24, p. 243703, 2018.
- [82] P. B. Weisensee, Y. Wang, H. Qian, D. Schultz, W. P. King, and N. Miljkovic, "Condensate droplet size distribution on lubricant-infused surfaces," *International Journal of Heat and Mass Transfer*, vol. 109, pp. 187-199, 2017.
- [83] J. Rose and L. Glicksman, "Dropwise condensation—the distribution of drop sizes," *International Journal of Heat and Mass Transfer*, vol. 16, no. 2, pp. 411-425, 1973.
- [84] N. Miljkovic, R. Enright, and E. N. Wang, "Modeling and optimization of superhydrophobic condensation," *Journal of Heat Transfer*, vol. 135, no. 11, p. 111004, 2013.
- [85] J. Rose, "Further aspects of dropwise condensation theory," *International Journal of Heat and Mass Transfer*, vol. 19, no. 12, pp. 1363-1370, 1976.
- [86] S. Kim and K. J. Kim, "Dropwise condensation modeling suitable for superhydrophobic surfaces," *Journal of heat transfer*, vol. 133, no. 8, p. 081502, 2011.
- [87] X. Liu and P. Cheng, "Dropwise condensation theory revisited: Part I. Droplet nucleation radius," *International Journal of Heat and Mass Transfer*, vol. 83, pp. 833-841, 2015.
- [88] R. Wen, Z. Lan, B. Peng, W. Xu, and X. Ma, "Droplet dynamics and heat transfer for dropwise condensation at lower and ultra-lower pressure," *Applied Thermal Engineering*, vol. 88, pp. 265-273, 2015.
- [89] Y. Peles, A. Koşar, C. Mishra, C.-J. Kuo, and B. Schneider, "Forced convective heat transfer across a pin fin micro heat sink," *International Journal of Heat and Mass Transfer*, vol. 48, no. 17, pp. 3615-3627, 2005.
- [90] H. A. El-Sheikh and S. Gurimella, "Enhancement of air jet impingement heat transfer using pin-fin heat sinks," *IEEE Transactions on Components and Packaging Technologies*, vol. 23, no. 2, pp. 300-308, 2000.
- [91] J. Maveety and H. Jung, "Design of an optimal pin-fin heat sink with air impingement cooling," *International Communications in Heat and Mass Transfer*, vol. 27, no. 2, pp. 229-240, 2000.

- [92] D. Wadsworth and I. Mudawar, "Cooling of a multichip electronic module by means of confined two-dimensional jets of dielectric liquid," *Journal of Heat Transfer*, vol. 112, no. 4, pp. 891-898, 1990.
- [93] M. Chaudhari, B. Puranik, and A. Agrawal, "Heat transfer characteristics of synthetic jet impingement cooling," *International Journal of Heat and Mass Transfer*, vol. 53, no. 5-6, pp. 1057-1069, 2010.
- [94] S. G. Kandlikar and A. V. Bapat, "Evaluation of jet impingement, spray and microchannel chip cooling options for high heat flux removal," *Heat Transfer Engineering*, vol. 28, no. 11, pp. 911-923, 2007.
- [95] Y.-C. Weng, H.-P. Cho, C.-C. Chang, and S.-L. Chen, "Heat pipe with PCM for electronic cooling," *Applied Energy*, vol. 88, no. 5, pp. 1825-1833, 2011.
- [96] Z. J. Zuo, M. T. North, and K. L. Wert, "High heat flux heat pipe mechanism for cooling of electronics," *IEEE Transactions on Components and Packaging Technologies*, vol. 24, no. 2, pp. 220-225, 2001.
- [97] V. G. Pastukhov, Y. F. Maidanik, C. Vershinin, and M. Korukov, "Miniature loop heat pipes for electronics cooling," *Applied Thermal Engineering*, vol. 23, no. 9, pp. 1125-1135, 2003.
- [98] Y.-W. Chang, C.-H. Cheng, J.-C. Wang, and S.-L. Chen, "Heat pipe for cooling of electronic equipment," *Energy Conversion and Management*, vol. 49, no. 11, pp. 3398-3404, 2008.
- [99] Y. F. Maydanik, S. V. Vershinin, M. A. Korukov, and J. M. Ochterbeck, "Miniature loop heat pipes-a promising means for cooling electronics," *IEEE Transactions on Components and Packaging Technologies*, vol. 28, no. 2, pp. 290-296, 2005.
- [100] K. Vafai and L. Zhu, "Analysis of two-layered micro-channel heat sink concept in electronic cooling," *International Journal of Heat and Mass Transfer*, vol. 42, no. 12, pp. 2287-2297, 1999.
- [101] X. Wei and Y. Joshi, "Optimization study of stacked micro-channel heat sinks for micro-electronic cooling," *IEEE transactions on components and packaging technologies*, vol. 26, no. 1, pp. 55-61, 2003.
- [102] J. Lee and I. Mudawar, "Two-phase flow in high-heat-flux micro-channel heat sink for refrigeration cooling applications: Part I—pressure drop characteristics," *International Journal of Heat and Mass Transfer*, vol. 48, no. 5, pp. 928-940, 2005.

- [103] M. B. Bowers and I. Mudawar, "Two-Phase Electronic Cooling Using Mini-Channel and Micro-Channel Heat Sinks: Part 2—Flow Rate and Pressure Drop Constraints," *Journal of Electronic Packaging*, vol. 116, no. 4, pp. 298-305, 1994.
- [104] A. Husain and K.-Y. Kim, "Shape optimization of micro-channel heat sink for micro-electronic cooling," *IEEE Transactions on Components and Packaging Technologies*, vol. 31, no. 2, pp. 322-330, 2008.
- [105] J. Cheng and C.-L. Chen, "Spot cooling using electrowetting-controlled thin film heat transfer," in *ASME 2012 Third International Conference on Micro/Nanoscale Heat and Mass Transfer*, 2012: American Society of Mechanical Engineers, pp. 275-281.
- [106] N. Miljkovic, D. J. Preston, R. Enright, and E. N. Wang, "Electric-field-enhanced condensation on superhydrophobic nanostructured surfaces," *Acs Nano*, vol. 7, no. 12, pp. 11043-11054, 2013.
- [107] M.-C. Lu, C.-C. Lin, C.-W. Lo, C.-W. Huang, and C.-C. Wang, "Superhydrophobic Si nanowires for enhanced condensation heat transfer," *International Journal of Heat and Mass Transfer*, vol. 111, pp. 614-623, 2017.
- [108] J. Zhong, J. Chinn, C. B. Roberts, and W. R. Ashurst, "Vapor-Phase Deposited Chlorosilane-Based Self-Assembled Monolayers on Various Substrates for Thermal Stability Analysis," *Industrial & Engineering Chemistry Research*, vol. 56, no. 18, pp. 5239-5252, 2017.
- [109] L. H. Thamdrup, F. Persson, H. Bruus, A. Kristensen, and H. Flyvbjerg, "Experimental investigation of bubble formation during capillary filling of Si O₂ nanoslits," *Applied Physics Letters*, vol. 91, no. 16, p. 163505, 2007.
- [110] Z. Hammadi, R. Morin, and J. Olives, "Field nano-localization of gas bubble production from water electrolysis," *Applied Physics Letters*, vol. 103, no. 22, p. 223106, 2013.
- [111] N. Cheng, Y. Guo, and C. Peng, "A numerical simulation of single bubble growth in subcooled boiling water," *Annals of Nuclear Energy*, vol. 124, pp. 179-186, 2019.
- [112] S. Kandlikar, "Controlling bubble motion over heated surface through evaporation momentum force to enhance pool boiling heat transfer," *Applied Physics Letters*, vol. 102, no. 5, p. 051611, 2013.

- [113] Y. Chang and Y. Ferng, "Experimental investigation on bubble dynamics and boiling heat transfer for saturated pool boiling and comparison data with previous works," *Applied Thermal Engineering*, 2019.
- [114] F.-M. Chang, Y.-J. Sheng, S.-L. Cheng, and H.-K. Tsao, "Tiny bubble removal by gas flow through porous superhydrophobic surfaces: Ostwald ripening," *Applied Physics Letters*, vol. 92, no. 26, p. 264102, 2008.
- [115] K. Dastafkan, Y. Li, Y. Zeng, L. Han, and C. Zhao, "Enhanced surface wettability and innate activity of iron borate catalyst for efficient oxygen evolution and gas bubble detachment," *Journal of Materials Chemistry A*, 2019.
- [116] H. Setoodeh, W. Ding, D. Lucas, and U. Hampel, "Prediction of Bubble Departure in Forced Convection Boiling with a Mechanistic Model that Considers Dynamic Contact Angle and Base Expansion," *Energies*, vol. 12, no. 10, p. 1950, 2019.
- [117] M. Markels Jr and R. L. Durfee, "The effect of applied voltage on boiling heat transfer," *AIChE Journal*, vol. 10, no. 1, pp. 106-110, 1964.
- [118] J. Ogata and A. Yabe, "Augmentation of boiling heat transfer by utilizing the EHD effect—EHD behaviour of boiling bubbles and heat transfer characteristics," *International journal of heat and mass transfer*, vol. 36, no. 3, pp. 783-791, 1993.
- [119] T. G. Karayiannis and Y. Xu, "Electric field effect in boiling heat transfer. Part A: Simulation of the electric field and electric forces," *Journal of Enhanced Heat Transfer*, vol. 5, no. 4, 1998.
- [120] Y. Kweon, M. Kim, H. Cho, and I. Kang, "Study on the deformation and departure of a bubble attached to a wall in dc/ac electric fields," *International Journal of Multiphase Flow*, vol. 24, no. 1, pp. 145-162, 1998.
- [121] Y. Kweon and M. Kim, "Experimental study on nucleate boiling enhancement and bubble dynamic behavior in saturated pool boiling using a nonuniform dc electric field," *International Journal of Multiphase Flow*, vol. 26, no. 8, pp. 1351-1368, 2000.
- [122] E. Colgate and H. Matsumoto, "An investigation of electrowetting-based microactuation," *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films*, vol. 8, no. 4, pp. 3625-3633, 1990.

- [123] J.-T. Cheng and C.-L. Chen, "Active thermal management of on-chip hot spots using EWOD-driven droplet microfluidics," *Experiments in fluids*, vol. 49, no. 6, pp. 1349-1357, 2010.
- [124] S. Wang, H. Chen, and C. Chen, "Electrowetting-on-dielectric assisted bubble detachment in a liquid film," *Applied Physics Letters*, vol. 108, no. 18, p. 181601, 2016.
- [125] A. A. Abdulshaheed, P. Wang, G. Huang, and C. Li, "High performance copper-water heat pipes with nanoengineered evaporator sections," *International Journal of Heat and Mass Transfer*, vol. 133, pp. 474-486, 2019.
- [126] X. Dai, P. Wang, F. Yang, X. Li, and C. Li, "Decoupling the influence of surface structure and intrinsic wettability on boiling heat transfer," *Applied Physics Letters*, vol. 112, no. 25, p. 253901, 2018.
- [127] F. Mugele, J.-C. Baret, and D. Steinhauser, "Microfluidic mixing through electrowetting-induced droplet oscillations," *Applied Physics Letters*, vol. 88, no. 20, p. 204106, 2006.
- [128] S. K. Chung, K. Ryu, and S. K. Cho, "Electrowetting propulsion of water-floating objects," *Applied Physics Letters*, vol. 95, no. 1, p. 014107, 2009.
- [129] I. G. Currie, *Fundamental mechanics of fluids*. CRC press, 2016.
- [130] D. J. Acheson, "Elementary fluid dynamics," ed: ASA, 1991.

VITA

I'm Run "Elle" Yan, a Chinese girl majoring in mechanical engineering in University of Missouri, Columbia. My PhD research work conveys a development of great potential in the coupling EWOD approach through studies of water harvesting and condensation heat transfer. My graduate studies at the University of Missouri-Columbia is meaningful, memorable and priceless. When I firstly came to Mizzou in my senior year as an exchange student in 2013, I never imagined I would spend my next six years in this city. Flashing back on so much happened ever since: happiness and laughter, sadness and tears, being confident, feeling hopeless, struggling with troubles in my life and studies, fighting illness, being anxious and depressed, conquering bad moods, getting used to loneliness...too many to be listed here, I'm grateful to the joys and pains, the good and bad things passed through in my life, as they enriched my experiences and carved a better me. I would like to thank my advisor again as the memory is still fresh when he talked with me time and time again, pointing out problems and helping improve my work. I am grateful for his guidance, patience, and for never giving up on this student who may not be the most talented but at least hard working and willing to improve. I would like to thank my mom here as well, for her selfless love and support. Without encouragement from her and my dad, I guess I probably would have quit my PhD studies hundreds of times. Thanks to them for trusting me and for patiently listening and talking on the phone to relieve my depression and homesickness countless times. Lastly, I would like to thank my favorite singer JJ (Wayne) Lin, as I'm listening to his song now while writing this paragraph, thank him for writing so many wonderful songs which have kept me company, comforted me, and encouraged me since my fifth grade.