UNIVERSITI PUTRA MALAYSIA

PAPER-BASED DISPOSABLE ELECTROWETTING CHIP FOR MICROFLUIDIC APPLICATION

NOOR FAEZAH BINTI ISMAIL

FK 2018 190

PAPER-BASED DISPOSABLE ELECTROWETTING CHIP FOR MICROFLUIDIC APPLICATION

By

NOOR FAEZAH BINTI ISMAIL

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

October 2018

Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of requirement for the degree of Master of Science

PAPER-BASED DISPOSABLE ELECTROWETTING CHIP FOR MICROFLUIDIC APPLICATION

By

NOOR FAEZAH BINTI ISMAIL

October 2018

Chairman : Associate Professor Nurul Amziah Md Yunus, PhD
Faculty : Engineering

In biology and chemical industries, there are lots of works to do in a laboratory with micron and nano-sized of samples, therefore these industries need low-cost disposable chips to able to repeat the testing frequently without consuming high cost. One example of a low cost chip is an electrowetting chip which using the electrowetting technique where it is one of the microfluidic system techniques. It is used to manipulate the microdroplet such as transportation, mixing, separation and microdroplet generation.

In this work, the development of a microfluidic chip is demonstrated using an electrowetting technique to automate the microdroplet transportation. The volume of droplet used is 5 µl.

The shape of the electrode is designed and fabricated using a few layers of thin sheets consist of flexible cellulose thin sheet, adhesive transparent thin sheet, double-sided pressure-adhesive sheet and Aluminum, Al, thin film. The dimension of electrode is 0.2 cm x 1.5 cm (width x length). The lubricant oil is used to smoothen the surface of the electrode and become a dielectric medium in between electrode and droplet. The droplet used is made from potassium chloride (KCl) solution with conductivity of 1400 µS/m.

During the experiment, the chip is connected to the AC power supply where the voltage and frequency are controlled. The result and analysis are made of the contact angle of droplet analysis, the velocity of droplet flow analysis and displacement of droplet analysis. With a power supply range of 8 Vpp – 14

Vpp, using 10 Hz of frequency, the droplet is able to flow along the activated electrode track.

In conclusion, this work has successfully opened the window towards improving the transportation of microdroplet flow with automated transportation system under the operation of low voltage and frequency.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

CIP ELEKTROPEMBASAH PAKAI BUANG BERASASKAN KERTAS UNTUK APLIKASI MIKROBENDALIR

Oleh

NOOR FAEZAH BINTI ISMAIL

Oktober 2018

Pengerusi : Profesor Madya Nurul Amziah Md Yunus, PhD
Fakulti : Kejuruteraan

Dalam industri biologi dan kimia, terdapat banyak kerja yang perlu dilakukan di makmal dengan sampel bersaiz mikro dan nano, oleh itu industri-industri ini memerlukan cip pakai buang berkos rendah untuk dapat mengulangi ujian dengan kerap tanpa memakan kos yang tinggi. Salah satu contoh cip berkos rendah ialah cip elektropembasah yang menggunakan teknik elektropembasah di mana ia merupakan salah satu daripada teknik sistem mikrobendalir. Ia digunakan untuk memanipulasi titisan mikro seperti pengangkutan, pencampuran, pemisahan dan penjanaan titisan mikro.

Dalam kerja ini, pembangunan cip mikrobendalir ditunjukkan dengan teknik elektropembasah untuk mengautomasikan pengangkutan titisan mikro. Jumlah titisan yang digunakan adalah 5 µl.

Bentuk elektrod direkabentuk dan diperbuat menggunakan beberapa lapisan kepingan nipis yang terdiri daripada lembaran nipis selulosa yang fleksibel, kepingan nipis pelekat telus, lembaran tekanan pelekat bermuka dua dan filem nipis Aluminum, Al. Dimensi elektrod adalah 0.2 cm x 1.5 cm (lebar x panjang). Minyak pelincir digunakan untuk melancarkan permukaan elektrod dan menjadi medium dielektrik di antara elektrod dan titisan. Titisan yang digunakan dibancuh daripada larutan kalium klorida (KCl) dengan kekonduksian sebanyak 1400 µS/m.

Semasa ujikaji, cip disambungkan kepada bekalan kuasa AC di mana voltan dan frekuensi dikawal. Hasil dan analisis dibuat dari sudut hubungan analisis titisan, halaju analisis aliran titisan dan anjakan analisis titisan. Dengan rangkaian bekalan kuasa 8 Vpp - 14 Vpp, menggunakan frekuensi 10 Hz, titisan boleh mengalir sepanjang trek elektrod diaktifkan.

Kesimpulannya, kerja ini berjaya membuka tingkap ke arah meningkatkan pengangkutan aliran titisan mikro dengan sistem pengangkutan automatik di bawah operasi voltan dan frekuensi yang rendah.

ACKNOWLEDGEMENTS

Alhamdulillah praised to Almighty God, Allah s.w.t for make me able to finish this project. This dissertation would not have been possible without the guidance and help of several individuals who are assist me to prepare, planning and complete this study.

First and foremost, I would like to thank to my helpful supervisor, Associate Professor Dr. Nurul Amziah Md Yunus for her encouragement, support and ideas throughout the entire duration of this work and I will never forget those things. She has given me a great freedom of study and her ideas also is one of the source and inspiration for this work.

Also thanks to both of my co-supervisor, Dr. Nasri Sulaiman and Dr. Mohd Nazim Mohtar for their support and guidance to my work. Further thanks to Assistant Engineer of Microelectronic and Nanoelectronic Laboratory, Mr. Mohd Shaiful Nizam Kamaruzzaman for assisting me when I was doing my lab works in the laboratory. A great help from my labmate, Mr. Abdullah Abdulhameed Gumaan who has guided me to use the COMSOL software.

Last but not least, I would like to express my gratitude to my family and my colleagues for their support and love.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Nurul Amziah Md Yunus, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Nasri Sulaiman, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Nazim Mohtar, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature:________________________ Date: ___________________

Name and Matric No.: Noor Faezah Binti Ismail (GS42673)

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: ______________________
Name of Chairman of
Supervisory Committee: Nurul Amziah Md Yunus

Signature: ______________________
Name of Member of
Supervisory Committee: Nasri Sulaiman

Signature: ______________________
Name of Member of
Supervisory Committee: Mohd Nazim Mohtar

TABLE OF CONTENTS

LISTS OF TABLES

LIST OF FIGURES

LISTS OF ABBREVIATIONS

LoC	Lab-on-a-Chip
EWOD	Electrowetting-on-dielectric
EW	Electrowetting
DEP	Dielectrophoresis
C.A.	Contact Angle

CHAPTER 1

INTRODUCTION

1.1 Background

Nowadays people are exposed to so many types of diseases over the world. The number of patients in the hospital increasing day by day. This situation caused the hospital treatment and diagnosis become a high demand especially in medicine production, clinical laboratory and operation machine. In clinical laboratory, the technology of biomedical such as microfluidic chip and Lab-on-Chip (LoC) is the field that has been studied until now to improve and simplify the protocol of laboratory works. The development of this technology has been running over a decade by a scientist and researcher.

Microfluidic is defined as “the science and technology of systems that process or manipulate small amounts of fluid, using a channel with dimensions of ten to hundreds of micrometers” [5]. Microfluidic has the potential to diverse on areas from chemical synthesis and biological analysis to optics and information technology.

A smart chip as an integral microfluidic analytical device has been developed in microfluidic technology, where it able to perform standard laboratory functions such as sample handling, mixing, transportation and separation. Those process are supported by microfluidic components including micropumps, micromixers, and microvalves. This has led to the miniaturization and commercialization of fully integrated microfluidic systems [8, 9].

The technology has a wider field of application including DNA amplification [10], clinical and forensic analysis [11], optical sensing systems [12], microfluidic mixing device and system [13] and biological analysis [14]. The technology has evolved and one promising fluidic actuation method in digital microfluidics has emerged and it is known as Electrowetting-On-Dielectric (EWOD) which using electrowetting effects principles [15, 16].

Previous work has discovered the potential and capability of EWOD microfluidic and it gives a variety applications of a microfluidic system, which helpful for the advancement of the technology [17]. It has also been reported that the fluidic behavioral properties variable enable the development of various devices and systems such as valves, pump, and flow sensor as a single function device and as an integrated complex device. Microfluidic research has undergone development process and produce a complex microfluidic handling systems which has been used in Lab-on-a-Chip (LoC) devices. This technology can be directly involved with chemical analysis, bio-chemical and medical analysis where usually would take place in a laboratory and take longer time for the sample to be analyzed.

Electrowetting is one of the most promising and famous methods used to manipulate the fluid in shape of the droplet. Electrowetting is a combination from electro and wetting where the electrical is used to manipulate and control the wettability of droplet [18]. Electrowetting first discovered by the Gabriel Lippmann in 1875 in his work where he observed the mercury and other fluid behavior to the changes of surface tension [3]. In 1981 the term of electrowetting has been introduced based on the proposed designed that was a new type of display device using bare electrode to manipulate the droplet controlled by the electrical source [1].

In recent works researcher has been trying to develop flexible and transparent electrowetting chip using various material for electrode and dielectric [19, 20]. This is because of the demand of this technology in display and optical applications. This technology will be able to produce superior flexible electronic display technology [21] and for the tunable high definition of optical lense [22].

1.2 Problem Statement

Most of the biomedical laboratory works is done manually. It is tedious and prone to human error. For example, to do a separation from a mother droplet or mixing of two different solvent, the process would require it to be done one by one and time consuming to go from one step to another. This work is trying to automated the system. The system will have the ability to control and manipulate the microdroplet. This is what we called as miniaturisation of biomedical laboratory instrumentation and it leads to the creation of integrated microfluidic device and system. Thus, the EWOD chip is one of the miniaturised and automated microfluidic device that used for those applications.

The current EWOD device need to utilise under a relative high voltage of 100 V [16, 23]. This is considered high in this field. This range of voltage can cause electrolysis and excessive heating of the device. These has led to limitations of the device. Therefore the need of low voltage EWOD device is very crucial to improve performance and reliability of the device.

This work will produce a low voltage automated microfluidic transportation system to solve the electrolysis and heating problem and reduce time consumption of the laboratory works.

1.3 Aim and Objectives

The aim of this work is to produce a low voltage electrowetting disposable chip using a low-cost material and simple fabrication method. This work proposed to study the efficiency and performance of the disposable chip in term of droplet velocity and displacement.

The objectives of this work are:

a. To fabricate a disposable paper-based electrowetting chip platform using a material with low voltage.

b. To automatically transport the droplet on the paper-based chip using electrowetting technique.

c. To study the efficiency using contact angle, C.A. and performance of the designed disposable chip based on the droplet motion.

1.4 Overview Of Thesis

The thesis is divided into 5 Chapters, which starts from a general elaboration on the field of microfluidic and Lab-on-a-Chip (LoC) in Chapter 1. Chapter 2 will present about the background of the microfluidic systems. This chapter will explain on Electrowetting (EW) and Electrowetting-On-Dielectric (EWOD), which is the main technique used for this research work. This chapter will also discuss on the application available under EWOD technology. Chapter 3 will explore the method used to run the work and also present the setup for the experiment. It will elaborate in a very specific for each step that has been done throughout this research progress. Chapter 4 will discuss on the result of each experiment and the theoretical simulation. This chapter will also analyse the results obtained in Chapter 3. Chapter 5 will conclude the overall research work. Some recommendations for improvement and possible future works will also be highlighted in this Chapter.

REFERENCES

[1] Beni, G. and S. Hackwood, *Electro-wetting displays.* Applied Physics Letters, 1981. **38**(4): p. 207-209.

[2] Anderson, J.R., et al., *Fabrication of microfluidic systems in poly (dimethylsiloxane).* Electrophoresis, 2000. **21**: p. 27-40.

[3] Lippmann, G., *Relations entre les phénomènes électriques et capillaires*. 1875, Gauthier-Villars.

[4] Frumkin, A., *On the wetting phenomena and attachment of bubbles.* Zhur. Fiz. Khim.(J. Phys. Chem.), 1938. **12**(4): p. 337-345.

[5] Whitesides, G.M., *The origins and the future of microfluidics.* Nature, 2006. **442**(7101): p. 368-373.

[6] Berge, B., *Electrocapillarité et mouillage de films isolants par l'eau.* Comptes rendus de l'Académie des sciences. Série 2, Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de la Terre, 1993. **317**(2): p. 157-163.

[7] McDonald, J.C. and G.M. Whitesides, *Poly (dimethylsiloxane) as a material for fabricating microfluidic devices.* Accounts of chemical research, 2002. **35**(7): p. 491-499.

[8] Dittrich, P.S., K. Tachikawa, and A. Manz, *Micro total analysis systems. Latest advancements and trends.* Analytical chemistry, 2006. **78**(12): p. 3887-3908.

[9] Zhang, C., D. Xing, and Y. Li, *Micropumps, microvalves, and micromixers within PCR microfluidic chips: advances and trends.* Biotechnology advances, 2007. **25**(5): p. 483-514.

[10] Zhang, Y. and P. Ozdemir, *Microfluidic DNA amplification—a review.* Analytica chimica acta, 2009. **638**(2): p. 115-125.

[11] Verpoorte, E., *Microfluidic chips for clinical and forensic analysis.* Electrophoresis, 2002. **23**(5): p. 677-712.

[12] Kuswandi, B., J. Huskens, and W. Verboom, *Optical sensing systems for microfluidic devices: a review.* Analytica chimica acta, 2007. **601**(2): p. 141-155.

[13] Lee, C.-Y., et al., *Microfluidic mixing: a review.* International journal of molecular sciences, 2011. **12**(5): p. 3263-3287.

[14] Kraly, J.R., et al., *Review: Microfluidic applications in metabolomics and metabolic profiling.* Analytica chimica acta, 2009. **653**(1): p. 23-35.

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

[16] Pollack, M.G., R.B. Fair, and A.D. Shenderov, *Electrowetting-based actuation of liquid droplets for microfluidic applications.* Applied Physics Letters, 2000. **77**(11): p. 1725-1726.

[17] Zhang, J., et al., *Fundamentals and applications of inertial microfluidics: a review.* Lab on a Chip, 2016. **16**(1): p. 10-34.

[18] Samad, M., et al. *Analysis of droplet mixing and splitting operations by a low actuation voltage electrowetting-on-dielectric device*. in *Engineering Technology and Technopreneuship (ICE2T), 2014 4th International Conference on*. 2014. IEEE.

[19] Hu, L., et al., *Electrowetting devices with transparent single-walled carbon nanotube electrodes.* Applied Physics Letters, 2007. **90**(9): p. 093124.

[20] Li, C. and H. Jiang, *Fabrication and characterization of flexible electrowetting on dielectrics (EWOD) microlens.* Micromachines, 2014. **5**(3): p. 432-441.

[21] Tröls, A., H. Enser, and B. Jakoby. *Modeling and fabrication of low-cost electrowetting actuators for flexible microfluidic display applications*. in *SENSORS, 2016 IEEE*. 2016. IEEE.

[22] Yu, C.-C., J.-R. Ho, and J.-W.J. Cheng, *Tunable liquid iris actuated using electrowetting effect.* Optical Engineering, 2014. **53**(5): p. 057106-057106.

[23] Jin, H. *An improved crescent electrode in electrowetting-based microfludic*. in *Manipulation, Manufacturing and Measurement on the Nanoscale (3M-NANO), 2016 IEEE International Conference on*. 2016. IEEE.

[24] Paidoussis, M.P. and N. Issid, *Dynamic stability of pipes conveying fluid.* Journal of sound and vibration, 1974. **33**(3): p. 267-294.

[25] Yang, G., et al., *Large-scale MR fluid dampers: modeling and dynamic performance considerations.* Engineering structures, 2002. **24**(3): p. 309-323.

[26] Shehzad, S., et al., *Effects of mass transfer on MHD flow of Casson fluid with chemical reaction and suction.* Brazilian Journal of Chemical Engineering, 2013. **30**(1): p. 187-195.

[27] Byrappa, K., S. Ohara, and T. Adschiri, *Nanoparticles synthesis using supercritical fluid technology–towards biomedical applications.* Advanced Drug Delivery Reviews, 2008. **60**(3): p. 299-327.

[28] Madison, A.C., M.W. Royal, and R.B. Fair, *Fluid Transport in Partially Shielded Electrowetting on Dielectric Digital Microfluidic Devices.* Journal of Microelectromechanical Systems, 2016. **25**(4): p. 593-605.

[29] Ramos, A., et al., *Ac electrokinetics: a review of forces in microelectrode structures.* Journal of Physics D: Applied Physics, 1998. **31**(18): p. 2338.

[30] Moon, I. and J. Kim, *Using EWOD (electrowetting-on-dielectric) actuation in a micro conveyor system.* Sensors and Actuators A: physical, 2006. **130**: p. 537-544.

[31] Geukens, L., D. Reynaerts, and R. Puers, *Towards an electrowetting-driven microconveyor: an investigation of the load-dependent droplet shape.* Journal of Micromechanics and Microengineering, 2016. **26**(8): p. 084004.

[32] Paik, P., et al., *Electrowetting-based droplet mixers for microfluidic systems.* Lab on a Chip, 2003. **3**(1): p. 28-33.

[33] Hu, Q., et al., *Fluid flow and mixing induced by ac continuous electrowetting of liquid metal droplet.* Micromachines, 2017. **8**(4): p. 119.

[34] Cho, S.K., H. Moon, and C.-J. Kim, *Creating, transporting, cutting, and merging liquid droplets by electrowetting-based actuation for digital microfluidic circuits.* Microelectromechanical Systems, Journal of, 2003. **12**(1): p. 70-80.

[35] Wang, Y., Y. Zhao, and S.K. Cho, *Efficient in-droplet separation of magnetic particles for digital microfluidics.* Journal of Micromechanics and Microengineering, 2007. **17**(10): p. 2148.

[36] Li, Y., *Portable High Throughput Digital Microfluidics and On-Chip Bacteria Cultures.* 2016.

[37] Mugele, F. and J.-C. Baret, *Electrowetting: from basics to applications.* Journal of Physics: Condensed Matter, 2005. **17**(28): p. R705.

[38] Aghdaei, S., *Electrodynamic droplet actuation for lab on a chip system*. 2011, University of Southampton.

[39] Kilaru, M., et al., *Strong charge trapping and bistable electrowetting on nanocomposite fluoropolymer: Ba Ti O 3 dielectrics.* Applied Physics Letters, 2007. **90**(21): p. 212906.

[40] Xu, S., et al., *A novel adaptive mechanical-wetting lens for visible and near infrared imaging.* Optics express, 2010. **18**(12): p. 12430-12435.

[41] Cheng, H.-C., et al., *Adaptive mechanical-wetting lens actuated by ferrofluids.* Optics Communications, 2011. **284**(8): p. 2118-2121.

[42] Gerlanc, M., et al., *Ultrasonic study of normal and fractured bone.* Clinical orthopaedics and related research, 1975. **111**: p. 175-180.

[43] Rich, C., et al., *Measurement of Bone Mass from Ultrasonic Transmission Time.∗.* Proceedings of the Society for Experimental Biology and Medicine, 1966. **123**(1): p. 282-285.

[44] Stor-Pellinen, J., T. Karppinen, and M. Luukkala, *Air-coupled ultrasonic measurement of the change in roughness of paper during wetting.* Measurement Science and Technology, 2001. **12**(8): p. 1336.

[45] Li, S., et al., *High-frequency acoustic for nanostructure wetting characterization.* Langmuir, 2014. **30**(25): p. 7601-7608.

[46] Lee, M.-Y., et al., *Development of a non-continuous micro-flow opto-wetting droplet manipulation technology.* Biomedical Engineering: Applications, Basis and Communications, 2005. **17**(06): p. 293-299.

[47] Chiou, P.Y., et al., *Light actuation of liquid by optoelectrowetting.* Sensors and actuators A: physical, 2003. **104**(3): p. 222-228.

[48] Bavière, R., J. Boutet, and Y. Fouillet, *Dynamics of droplet transport induced by electrowetting actuation.* Microfluidics and Nanofluidics, 2008. **4**(4): p. 287-294.

[49] Geng, H., et al., *Dielectrowetting manipulation for digital microfluidics: creating, transporting, splitting, and merging of droplets.* Lab on a Chip, 2017. **17**(6): p. 1060-1068.

[50] Berry, S. and J. Kedzierski, *New Methods to Transport Fluids in Micro-Sized Devices*. 2008, MIT, Lincoln Laboratory Journal.

[51] Samad, M., A. Kouzani, and M. Samad. *Design and analysis of a low actuation voltage electrowetting-on-dielectric device*. in *Complex Medical Engineering (CME), 2013 ICME International Conference on*. 2013. IEEE.

[52] Lee, J., et al., *Electrowetting and electrowetting-on-dielectric for microscale liquid handling.* Sensors and Actuators A: Physical, 2002. **95**(2): p. 259-268.

[53] Quinn, A., R. Sedev, and J. Ralston, *Contact angle saturation in electrowetting.* The journal of physical chemistry B, 2005. **109**(13): p. 6268-6275.

[54] Ko, H., et al., *Active Digital Microfluidic Paper Chips with Inkjet-Printed Patterned Electrodes.* Advanced Materials, 2014. **26**(15): p. 2335-2340.

[55] Samad, M., et al., *Design and Fabrication of an Electrode for Low-actuation-Voltage Electrowetting-on-Dielectric Devices.* Procedia Technology, 2015. **20**: p. 20-25.

[56] Dhindsa, M., et al., *Electrowetting without electrolysis on self-healing dielectrics.* Langmuir, 2011. **27**(9): p. 5665-5670.

[57] Lin, Y.-Y., E.R. Welch, and R.B. Fair, *Low voltage picoliter droplet manipulation utilizing electrowetting-on-dielectric platforms.* Sensors and Actuators B: Chemical, 2012. **173**: p. 338-345.

[58] Chae, J.B., et al., *Optimum thickness of hydrophobic layer for operating voltage reduction in EWOD systems.* Sensors and Actuators A: Physical, 2014. **215**: p. 8-16.

[59] Yi, U.-C. and C.-J. Kim, *Characterization of electrowetting actuation on addressable single-side coplanar electrodes.* Journal of Micromechanics and Microengineering, 2006. **16**(10): p. 2053.

[60] Liu, H., et al., *Dielectric materials for electrowetting-on-dielectric actuation.* Microsystem technologies, 2010. **16**(3): p. 449.

[61] Lee, J. and C.-J. Kim, *Surface-tension-driven microactuation based on continuous electrowetting.* Journal of Microelectromechanical Systems, 2000. **9**(2): p. 171-180.

[62] Kang, K.H., *How electrostatic fields change contact angle in electrowetting.* Langmuir, 2002. **18**(26): p. 10318-10322.

[63] Yang, J., *Novel Electrowetting Microvalve*. 2010, University of Cincinnati.

[64] Li, Y., R.J. Baker, and D. Raad. *A highly efficient and reliable electrowetting on dielectric device for point-of-care diagnostics*. in *Circuits and Systems Conference (DCAS), 2015 IEEE Dallas*. 2015. IEEE.

[65] Samad, M.F. and A.Z. Kouzani. *Design and analysis of a low actuation voltage electrowetting-on-dielectric microvalve for drug delivery applications*. in *Engineering in Medicine and Biology Society (EMBC), 2014 36th Annual International Conference of the IEEE*. 2014. IEEE.

[66] Wei, X., et al., *Fabrication on low voltage driven electrowetting liquid lens by dip coating processes.* Thin Solid Films, 2016. **608**: p. 16-20.

[67] Hadidimasouleh, R., et al., *Prediction of the contact angle of colloids and microfluids during electrowetting.* Micro & Nano Letters, 2016. **11**(11): p. 783-788.

[68] Green, N.G. and H. Morgan, *Dielectrophoresis of submicrometer latex spheres. 1. Experimental results.* The Journal of Physical Chemistry B, 1999. **103**(1): p. 41-50.

[69] Schramm, M., S. Eimerl, and E. Costa, *Serum and depolarizing agents cause acute neurotoxicity in cultured cerebellar granule cells: role of the glutamate receptor responsive to N-methyl-D-aspartate.* Proceedings of the National Academy of Sciences, 1990. **87**(3): p. 1193-1197.

[70] Jones, T.B., et al., *Dielectrophoretic liquid actuation and nanodroplet formation.* Journal of applied Physics, 2001. **89**(2): p. 1441-1448.

[71] Yunus, N.A.M., H. Nili, and N.G. Green, *Continuous separation of colloidal particles using dielectrophoresis.* Electrophoresis, 2013. **34**(7): p. 969-978.

[72] Tan, X., et al. *Electrowetting on flexible, transparent and conducting single-layer graphene*. in *Micro Electro Mechanical Systems (MEMS), 2012 IEEE 25th International Conference on*. 2012. IEEE.

[73] Srinivasan, V., V.K. Pamula, and R.B. Fair, *Droplet-based microfluidic lab-on-a-chip for glucose detection.* Analytica Chimica Acta, 2004. **507**(1): p. 145-150.

[74] Clement, C.E., S.K. Thio, and S.-Y. Park, *An optofluidic tunable Fresnel lens for spatial focal control based on electrowetting-on-dielectric (EWOD).* Sensors and Actuators B: Chemical, 2017. **240**: p. 909-915.

[75] Kim, D.Y. and A.J. Steckl, *Electrowetting on paper for electronic paper display.* ACS applied materials & interfaces, 2010. **2**(11): p. 3318-3323.

[76] Lin, Y.-Y., et al., *Low voltage electrowetting-on-dielectric platform using multi-layer insulators.* Sensors and Actuators B: Chemical, 2010. **150**(1): p. 465-470.

[77] Rajabi, N. and A. Dolatabadi, *A novel electrode shape for electrowetting-based microfluidics.* Colloids and Surfaces A: Physicochemical and Engineering Aspects, 2010. **365**(1): p. 230-236.

[78] Pollack, M., A. Shenderov, and R. Fair, *Electrowetting-based actuation of droplets for integrated microfluidics.* Lab Chip, 2002. **2**(2): p. 96-101.

[79] Khodayari, M., J. Carballo, and N.B. Crane, *A material system for reliable low voltage anodic electrowetting.* Materials Letters, 2012. **69**: p. 96-99.

[80] Li, C. and H. Jiang, *Electrowetting-driven variable-focus microlens on flexible surfaces.* Applied physics letters, 2012. **100**(23): p. 231105.

[81] He, F. and S.R. Nugen, *Automating fluid delivery in a capillary microfluidic device using low-voltage electrowetting valves.* Microfluidics and nanofluidics, 2014. **16**(5): p. 879-886.

[82] You, H. and A. Steckl, *Electrowetting on flexible substrates.* Journal of Adhesion Science and Technology, 2012. **26**(12-17): p. 1931-1939.

[83] Nilghaz, A., et al., *Advances of Paper-Based Microfluidics for Diagnostics The Original Motivation and Current Status.* ACS Sensors, 2016. **1**(12): p. 1382-1393.

[84] Lisowski, P. and P.K. Zarzycki, *Microfluidic paper-based analytical devices (μPADs) and micro total analysis systems (μTAS): development, applications and future trends.* Chromatographia, 2013. **76**(19-20): p. 1201-1214.

[85] Delaney, J.L., et al., *Electrogenerated chemiluminescence detection in paper-based microfluidic sensors.* Analytical chemistry, 2011. **83**(4): p. 1300-1306.

[86] Cheng, C.M., et al., *paper-based elisa.* Angewandte Chemie International Edition, 2010. **49**(28): p. 4771-4774.

[87] Martinez, A.W., et al., *Patterned paper as a platform for inexpensive, low-volume, portable bioassays.* Angewandte Chemie International Edition, 2007. **46**(8): p. 1318-1320.

[88] Martinez, A.W., et al., *Simple telemedicine for developing regions: camera phones and paper-based microfluidic devices for real-time, off-site diagnosis.* Analytical chemistry, 2008. **80**(10): p. 3699-3707.

[89] Hayes, R.A. and B. Feenstra, *Video-speed electronic paper based on electrowetting.* Nature, 2003. **425**(6956): p. 383-385.

[90] Nyholm, L., et al., *Toward flexible polymer and paper-based energy storage devices.* Advanced Materials, 2011. **23**(33): p. 3751-3769.

[91] Ratnarathorn, N., et al., *Simple silver nanoparticle colorimetric sensing for copper by paper-based devices.* Talanta, 2012. **99**: p. 552-557.

[92] Srinivasan, V., V.K. Pamula, and R.B. Fair, *An integrated digital microfluidic lab-on-a-chip for clinical diagnostics on human physiological fluids.* Lab on a Chip, 2004. **4**(4): p. 310-315.

[93] Mollerup, J.M. and M.P. Breil, *Modeling the permittivity of electrolyte solutions.* AIChE Journal, 2015. **61**(9): p. 2854-2860.

[94] LAKRARI, K., et al., *Study of electrical properties of vegetable oils for the purpose of an application in electrical engineering.* African Journal of Food Science, 2013. **7**(11): p. 404-407.

[95] Daniel, S., et al., *Ratcheting motion of liquid drops on gradient surfaces.* Langmuir, 2004. **20**(10): p. 4085-4092.

[96] Paranjpe, G. and P. Deshpande. *Dielectric properties of some vegetable oils*. in *Proceedings of the Indian Academy of Sciences-Section A*. 1935. Springer.

[97] Kleinert, J., et al., *The dynamics and stability of lubricating oil films during droplet transport by electrowetting in microfluidic devices.* Biomicrofluidics, 2015. **9**(3): p. 034104.

[98] Gunji, M. and M. Washizu, *Self-propulsion of a water droplet in an electric field.* Journal of Physics D: Applied Physics, 2005. **38**(14): p. 2417.

[99] Fontanella, J., C. Andeen, and D. Schuele, *Pressure and Temperature Derivatives of the Low-Frequency Dielectric Constants of LiF, NaF, NaCl, NaBr, KCl, and KBr.* Physical review B, 1972. **6**(2): p. 582.

[100] Gui, L. and C.L. Ren, *Analytical and numerical study of joule heating effects on electrokinetically pumped continuous flow PCR chips.* Langmuir, 2008. **24**(6): p. 2938-2946.

BIODATA OF STUDENT

Noor Faezah Ismail was born on 7th July 1991 in Kelantan-Malaysia. She completed her study in bachelor of engineering in Electrical and Electronics from Universiti Putra Malaysia in the year of 2014. She works as a research assistant at Faculty of Engineering at Universiti Putra Malaysia for 6 months and after that she started as a official full-time student of Master of Science in same university during 2015 with scholarship sponsored by Ministry of Higher Education, Malaysia (MOHE) via Fundamental Research Grant Scheme (FRGS). The research in her Master is about Microfluidic Application uner Electronic Engineering.

LIST OF PUBLICATIONS

Journal Paper

Nurul Amziah Md Yunus, **Noor Faezah Ismail**, Nasri Sulaiman, Mohd Nazim Mohtar and Desa Ahmad, "Microdroplet Electrowetting Actuation on Flexible Paper-Based Platform Chip", Journal Of Solid State Science & Technology, 2018. (Indexed And Abstracted In Chemical Abstracts (American Chemical Society) and MYAIS (Malaysian Abstracting And Indexing System).

Noor Faezah Ismail, Nurul Amziah Md Yunus, Nasri Sulaiman, Izhal Abdul Halin And Mohd Nazim Mohtar, "Microdroplet Electrowetting on Flexible Paper-Based Microfluidic Chip", Journal Of Solid State Science & Technology, 2018. (Indexed And Abstracted In Chemical Abstracts (American Chemical Society) and MYAIS (Malaysian Abstracting And Indexing System).

Nurul Amziah Md Yunus, **Noor Faezah Ismail**, Nasri Sulaiman, Mohd Nazim Mohtar and Desa Ahmad, "Microdroplet Electrowetting Actuation on Flexible Paper-Based Platform Lab on a Chip", Results in Physics Journal 2018 Elsevier. (Abstracting and Indexing: Directory of Open Access Journals (DOAJ), Scopus and Science Citation Index)

Conference Paper

Noor Faezah Ismail, Nurul Amziah Md Yunus, Nasri Sulaiman, Mohd Nazim Mohtar, Izhal Abdul Halin And Desa Ahmad, "Joule heating effect on microdroplet electrowetting platform chip", Asia Pacific Conference on Postgraduate Research in Microelectronics and Electronics. Volume 2017-October, 2 February 2018, Pages 77-80.

Others

Khamis, M. N., **Ismail, N. F.**, Yunus, N. A. M., & Ahmad, D. (2017, October). LED lighting with remote monitoring and controlling system for indoor greenhouse. In Postgraduate Research in Microelectronics and Electronics (PrimeAsia), 2017 IEEE Asia Pacific Conference on (pp. 81-84). IEEE.

Hong, C. K., **Ismail, N. F.**, Yunus, N. A. M., & Ahmad, D. (2017, October). Sensitivity of piezoresistive pressure sensor with inner diaphragm. In Postgraduate Research in Microelectronics and Electronics (PrimeAsia), 2017 IEEE Asia Pacific Conference on (pp. 129-132). IEEE.

Yunus, N. A. M., **Ismail, N. F.**, Green, N. G., & Ahmad, D. (2017, October). Analysis of dielectrophoresis AC electrokinetic in equilibrium using Matlab. In Postgraduate Research in Microelectronics and Electronics (PrimeAsia), 2017 IEEE Asia Pacific Conference on (pp. 85-88). IEEE.

Yunus, N. A. M., Halin, I. A., Sulaiman, N., **Ismail, N. F**., & Aman, N. H. N. (2015). A Compilation of Nanotechnology in Thin Film Solar Cell Devices. World Acad. Sci. Eng. Technol. Int. J. Electr. Comput. Energ. Electron. Commun. Eng, 9(8), 724-728.

Yunus, N. A. M., Halin, I. A., Sulaiman, N., **Ismail, N. F.**, & Sheng, O. K. (2015). Valuation on MEMS Pressure Sensors and Device Applications. Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering, 9(8), 834842.

Mohtar M.N.[1], Ziaudin Ahamed M.U.[2], **Ismail N.F.** [3], Yunus N.A.M.[4] and Shafie S.[5]. (2016). Effect of Interelectrode Gap to the Manipulations of Particle Using AC Electroosmosis. IJCTA, International Science Press, 9(31), pp. 31-36.

UNIVERSITI PUTRA MALAYSIA

STATUS CONFIRMATION FOR THESIS / PROJECT REPORT AND COPYRIGHT

ACADEMIC SESSION : ____________________

TITLE OF THESIS / PROJECT REPORT :

PAPER-BASED DISPOSABLE ELECTROWETTING CHIP FOR MICROFLUIDIC APPLICATION

NAME OF STUDENT : NOOR FAEZAH BINTI ISMAIL

I acknowledge that the copyright and other intellectual property in the thesis/project report belonged to Universiti Putra Malaysia and I agree to allow this thesis/project report to be placed at the library under the following terms:

1. This thesis/project report is the property of Universiti Putra Malaysia.
2. The library of Universiti Putra Malaysia has the right to make copies for educational purposes only.
3. The library of Universiti Putra Malaysia is allowed to make copies of this thesis for academic exchange.

I declare that this thesis is classified as :

*Please tick (√)

☐	**CONFIDENTIAL**	(Contain confidential information under Official Secret Act 1972).
☐	**RESTRICTED**	(Contains restricted information as specified by the organization/institution where research was done).
☐	**OPEN ACCESS**	I agree that my thesis/project report to be published as hard copy or online open access.

This thesis is submitted for :

☐	**PATENT**	Embargo from____________ (date) until ____________ (date)

Approved by:

____________________	____________________
(Signature of Student)	(Signature of Chairman of Supervisory Committee)
New IC No/ Passport No.:	Name:
Date :	Date :

[Note : If the thesis is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization/institution with period and reasons for confidentially or restricted.]