Modelling and Analysis of Wirelessly Interrogated SAW based Micropumps for Drug Delivery Applications

by

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Thesis submitted for the degree of

Doctor of Philosophy

in

School of Electrical and Electronic Engineering,
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April 2010

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Contents

Abstract

Many types of life threatening global health problems such as cardiovascular deceases, cancer, and diabetes have placed human life at high risk. These critical health problems may be eliminated and/or controlled with effective early diagnostic and/or targeted treatment methodologies. Conventional drug delivery methods such as oral tablets or injections consist of various limitations. Among them, the problem with variable absorption profiles and need of frequent dosing are yet to be successfully addressed. Therefore conventional methods are not effective for delivering the drug within their therapeutic range. The implementation of targeted micro drug delivery methods is recognised as a critical solution space for twenty first century healthcare.

Micro Electromechanical Systems (MEMS) based typical micropump is a fundamental part of a drug delivery system which provides the actuation source to effectively transfer an accurate amount of fluid/drug to a targeted location. However, the lack of availability of accurate and easy to use, implantable and low-powered micropumps has been identified as a significant problem. Furthermore, the ease of control of implantable biological devices would be greatly improved by incorporation of wireless and secure actuator mechanism with no battery attached with the device. Therefore, in this thesis, several significant contributions to address the above highlighted issues are presented and discussed.

In this thesis, various types of actuation and micropump mechanisms were reviewed; in addition to investigating how Surface Acoustic Wave (SAW) devices can be used for secure, wireless and batteryless actuation. Consequently, SAW based novel transcutaneous interrogation mechanism was proposed for low–powered electrostatic actuations, without the need for active electronics to meet the biocompatibility requirements. A SAW correlator was used for the secure interrogation, where the device responds only to a uniquely coded RF signal, which has to be matched with the code implanted in the SAW correlator. The proposed micro actuation mechanism was demonstrated by utilising a Finite Element Model (FEM). This allowed the investigation of this device performance using a sophisticated computational numerical method. A new theoretical analysis was also developed to derive both electric potential and electrostatic force equations for SAW based microactuators. Then the Rayleigh-Ritz method based theoretical model was developed to validate the FEM results. Based on these results the SAW based low-powered actuator is able to achieve displacements up to 3 μm at low operating voltages.

Once the proposed mechanism was verified both analytically and using FEM, the modelling was then extended to analyse the performance of SAW based microdiaphragms, as a critical performance dictator for the diaphragm part of the micropumps. Several new methods were developed and modelled to overcome the existing drawbacks in flat microdiaphragms, such as the incorporation of highly effective corrugated profiles, and effective use of flexible materials. As a result a number of these corrugation profiles were examined using FEA. As a result it is demonstrated that the proposed design approaches have substantially enhanced microdiaphragm performance, compared to a flat diaphragm.

As much as the effectiveness of microdiaphragms, the flow rectification mechanism also dictates a critical role in micropumps. In this research, the proposed micropump was designed to be valveless for simplicity and ease of fabrication, and used diffuser elements for flow rectification. However, most of the existing computational analyses of diffusers are mainly based on 2D or simplified 3D models. Hence, the relationship between diffuser parameters, Reynolds number, and the diffuser performance at microscale, are not well established. Therefore, FEM based Computational Fluid Dynamic (CFD) was successfully utilised to analyse flat–walled diffuser elements. These analyses provide a qualitative and quantitative relationship between the diffuser efficiency and Reynolds numbers for laminar flow.

Building on the developed actuation mechanism and various corrugated micro diaphragms, and diffuser models, an integrated device analysis are presented. This includes a full 3D model of the SAW based electrostatically actuated, diffuser micropump, and complex microfluidic behaviour of the micropump was analysed. A strong emphasis was given in utilising CFD to analyse the Fluid–Solid Interaction (FSI) phenomena of the micropump and the overall pumping effect was successfully demonstrated. The knowledge and new contributions made in this thesis in modelling, simulation, and analysis of implantable drug delivery micropumps, will be able to effectively utilise in a range of fields such as advanced computational numerical modelling of Bio–MEMS, secure transcutaneous communication, and implantable drug delivery systems and other biomedical aplications.

Statement of Originality

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published written by another person, except where due reference has been made in the text.

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Date

Acknowledgments

First and foremost I would like to sincerely thank my principle supervisor **Dr. Said Al–Sarawi** from the School of Electrical and Electronic Engineering at the University of Adelaide, for his encouraging guidance, advice, and assistance throughout my research. He continuously supported me to improve my critical thinking and make substantial progress in my research with recognised achievements. His advice, fruitful discussions, and expectations motivated me to stay focused and carry out my research towards a successful completion.

In that same vein, I would like to thank my co-supervisors **Prof. Derek Abbott** from the School of Electrical and Electronic Engineering at the University of Adelaide, and **Dr. Tien-Fu Lu** from the School of Mechanical Engineering at the University of Adelaide, for their advice and support during my research. Prof. Abbott always took action to provide valuable insight towards my project by making it possible to meet and discuss fruitful ideas with other experts in the field.

I would like to acknowledge the support and the expertise provided by Dr. Igor Switala at MicroEngineering Services Branch at Defence Science and Technology Organisation (DSTO), at Edinburgh, South Australia, as well as Mr. Lenonard Green from the Adelaide Microscopy at The University of Adelaide, during the efforts taken while fabricating some components of the device. Their ability to deliver creative engineering solutions and exchange of ideas have been encouraging, and guided the way towards some exciting contributions during my research.

I would like to thank the academic and professional staff at the School of Electrical and Electronic Engineering at the University of Adelaide, for providing their support in various aspects. Especially, I would like to mention Mr. David Bowler, Mr. Mark Innes, and Mr. Pavel Simcik from IT and technical support staff for their unlimited support and patience throughout.

I would also like to convey my gratitude to the Australian Research Council (ARC) and the School of Electrical and Electronic Engineering (The University of Adelaide) for the funding and the support provided for this research, to make it a success.

I am deeply grateful for several colleagues and friends for their motivational encouragements and fruitful conversations along the way. Especially, I convey my gratitude to Mr. Ajay Tikka for sharing his time, knowledge and expertise to keep me motivated and focused throughout my research project. I would also like to thank Mr. Jonathan Boan, for setting up an example of persistence, as well as for sharing his experience as a PhD student to encourage me in achieving my goals. I wish to thank Mr. Riki Sutherland for his encouraging comments and valuable feedback on my technical writing, Dr. Kelvin Wong for his advice and directions in achieving a successful completion, and Mr. Jayesh Minase for offering his time in helping me to carry out testing of fabricated components. I am also thankful to all my teachers and lecturers, starting from my first school days up to my tertiary education for guiding me towards the success.

Lastly but certainly not least, I wish to convey my gratitude to my fiance, Ashika Liyanapathirana, whom I met towards second half of my research project. I thank her for all the unconditional love, emotional support, and words of encouragement, especially during difficult times.

Finally, and most importantly I would like to thank my parents and siblings who have been emotional anchors through out my entire life, for the life principles that they installed in me, for their belief in my ability to succeed, for their unlimited encouragements, and for the love and support. I dedicate this thesis to my parents.

Don W. Dissanayake

March 2010

Conventions

1. **Formatting:** This thesis it typeset using the $\LaTeX$2e software. WinEdt build 5.4 was used as an effective interface to $\LaTeX$. Plots and images were generated using Matlab 7.0 (Mathsworks Inc.) and MS Excel 2007.
2. **Spelling:** Australian English spelling is adopted, as defined by the Macquarie English Dictionary (Delbridge 2001).
3. **Referencing:** Harvard style is used for referencing and citation in this thesis.

Awards

Student Excellence Awards

State Finalist in the 2009 AusBiotech–GSK Student Excellence Awards, Australia, for outstanding research project.

Presentation Title: Wireless micropump for implantable biomedical applications.

Competition: 2009 AusBiotech-GST Student Excellent Awards, Australia.

Best Presentation Award

Best Presentation Award at the 3rd International Conference on Sensing Technology, ICST 2008, Tainan, Taiwan.

Presentation Title: Corrugated micro–diaphragm analysis for low-powered and wireless bio–MEMS.

Authors: Don W. Dissanayake, Said Al–Sarawi & Derek Abbott.

Conference: 3rd International Conference on Sensing Technology (ICST 2008), Taiwan, 30th Nov–3th Dec 2008.

Publication: Proceedings of the 3rd International Conference on Sensing Technology, pages 125-129, 2008.

Publications

Book Chapters

Dissanayake-D. W., Al-Sarawi-S. F., and Abbott-D. (2009). *Recent Advances in Sensing Technology*, Lecture Notes in Electrical Engineering, Springer–Verlag, chapter Wireless interrogation of a micropump and analysis of corrugated micro-diaphragms, pp. 139–151, In Press.

Dissanayake-D. W., Al-Sarawi-S. F., and Abbott-D. (2008). *Smart Sensors and Sensing Technology*, Vol. 20 of *Lecture Notes in Electrical Engineering*, Springer–Verlag, chapter Electrostatic micro actuator design using surface acoustic wave devices, pp. 139–151.

Journals

Dissanayake-D. W., Al-Sarawi-S., Lu-T.-F., and Abbott-D. (2009). Finite element modelling of SAW device based corrugated micro–diaphragms, *Smart Materials and Structures*, **18**(9), pp. 095030: 1–11.

Conferences (Full Paper)

Dissanayake-D. W., Al-Sarawi-S., and Abbott-D. (2009). Advanced modeling and simulation of wirelessly interrogated valve–less microfluidic devices, *Proc. of 2009 IEEE Regional Symp. on Micro and Nano Electronics*, pp. 332–336.

Dissanayake-D. W., Al-Sarawi-S., Lu-T.-F., and Abbott-D. (2008). Finite element analysis of wirelessly interrogated implantable bio–MEMS, *Proc. of SPIE–Biomedical Applications of Micro– and Nanoengineering IV and Complex Systems*, **7270**, pp. 727004: 1–10.

Dissanayake-D. W., Al-Sarawi-S., and Abbott-D. (2008). Corrugated micro–diaphragm analysis for low–powered and wireless Bio–MEMS, *Proc. of 3rd International Conference on Sensing Technology*, pp. 125–129.

Dissanayake-D. W., Al-Sarawi-S., Lu-T.-F., and Abbott-D. (2008). Design and characterisation of micro-diaphragm for low power drug delivery applications, *Proc. of SPIE–Active and Passive Smart Structures and Integrated Systems*, **6928**, pp. 6928P: 1–8.

Dissanayake-D. W., Al-Sarawi-S., and Abbott-D. (2007). Surface acoustic wave device based wireless passive microvalve for microfluidic applications, *Proc. of SPIE–BioMEMS and Nanotechnology III*, **6799**, pp. 67990H: 1–10.

Dissanayake-D. W., Al-Sarawi-S., and Abbott-D. (2007). Surface acoustic wave device based electrostatic actuator for microfluidic applications, *Proc. of 2nd International Conference on Sensing Technology*, pp. 381–386.

Dissanayake-D. W., Tikka-A. C., Al-Sarawi-S., and Abbott-D. (2006). Radio frequency controlled microvalve for biomedical applications, *Proc. of SPIE–Smart Materials IV*, **6413**, pp. Article 64130D: 1–13.

Conferences (Abstract)

Dissanayake-D. W., Tikka-A. C., Al-Sarawi-S., and Abbott-D. (2006). Biomedical applications of a wireless controlled microvalve, *Proc. of Australian Health and Medical Research Congress (AHMRC) 2006*, Abs. No. 1059.

Dissanayake-D. W., Tikka-A. C., Al-Sarawi-S.(2006). Use of ANSYS in design and analysis of piezoelectrically actuated microvalves for biomedical applications, *Proc. of ANSYS Australasian User Conference 2006*.

News Articles

Dissanayake-D. W., and Al-Sarawi-S. F. (2007). Designing remotely activated microvalves for biomedical applications. SPIE news letter, *http://spie.org/x14241.xml*.

List of Symbols

Notation	Description
2θ	Diverging diffuser angle
A	Effective plate area
AR	Area ratio
A_1	Cross section of the inlet of the diffuser
A_2	Cross section of the outlet of the diffuser
A_L	Laplace coefficient
A_e	Cross section of the exit of the outlet duct
A_i	Cross section of the entrance of the inlet duct
B_L	Laplace coefficient
C_p	Pressure recovery coefficient
C_+	Correlated positive signal
D	Electric flux density
E	Electric field intensity
E_{act}	Total energy of the actuator
E_{dia}	Total energy of the microdiaphragm
H	Corrugation height
I	Moment of inertia
K_P	Actuator displacement coefficient
K_D	Microdiaphragm displacement coefficient
K_d	Total pressure loss coefficient in diffuser direction
K_n	Total pressure loss coefficient in nozzle direction
L	Corrugation wavelength
N	Number of corrugation wavelengths
N_p	Number of IDT finger pairs
N_s	Divisions per finger gap
Q	Flow rate
$Q(t)$	Instantaneous volume averaged flow rate
Q_d	Flow rate in diffuser direction
Q_n	Flow rate in nozzle direction
Q_{avg}	Average flow rate

Notation	Description
T	Mechanical stress
V	Fluid velocity vector
V_{gap}	Electric potential at IDT gap
V_+	Electric potential at positive finger
V_-	Electric potential at negative finger
V_{in}	Input voltage
$W1$	Diffuser neck width
W_D	Instantaneous microdiaphragm deflection
W_P	Instantaneous plate deflection
X_l	Direction along corrugations
X_w	Direction across corrugations
Ω	Electric potential at IDT finger gap
Φ	Electric potential
Ψ	Electric potential at positive finger
α	Kinetic–energy correction factor
α_j^m	Linear coefficients of the plane waves
η	Diffuser efficiency
λ	Wavelength
$\mathbb{D}$	Bending stiffness
$\mathbb{E}$	Modulus of elasticity
L	Diffuser length
μ	Viscosity
ν	Poisson ratio
$\overline{v}$	Volume–averaged velocity
ρ	Density of piezoelectric substrate
ρ_D	Density of the microdiaphragm
i	Standard imaginary unit $=\sqrt{-1}$
ε_0	Permittivity of air
b^m	Decaying constant
c_{ijkl}	Stiffness tensor
e_{ijk}	Piezoelectric coupling tensor
f_{RF}	trigger frequency
f_{SAW}	SAW frequency
f_l	IDT finger length

Notation	Description
f_w	IDT finger width
g	Gravitational acceleration
$g_{(+)}$	Positive square wave
h	Air–gap height
k	Wave vector
l	largest characteristic dimension
p	Hydrostatic pressure across the cross–section
p_c	Hydrostatic pressures in the chamber
p_o	Hydrostatic pressures in the inlet/outlet
u	Mechanical displacement
u_a	Axial velocity across diffuser cross section
v	Phase velocity
$F_{(+)}$	Electrostatic force from positive IDT finger
$F_{(-)}$	Electrostatic force from negative IDT finger
$F_{(tot)}$	Total electrostatic force
$F_{(\lambda)}$	Electrostatic force per wavelength
Φ_L	Laplace electric potential
η_{rec}	Flow rectification efficiency
∇^4	double Laplacian operator
$\overline{v}_1$	Volume–averaged velocity at diffuser inlet
$\overline{v}_2$	Volume–averaged velocity at diffuser outlet
ρ_L	Fluid density
ε_{ij}	Permittivity
t_D	Corrugation thickness

Abbreviations

$KNbO_3$	Potassium Niobate	53
$LiTaO_3$	Lithium Tantalate	53
$Pb_2KNb_5O_{15}$	Lead Potassium Niobate	53
Si_3N_4	Silicon Nitride	52
2D	Two Dimensional	10, 38
3D	Three Dimensional	7
ASI	Air–Structure Interface	147
BEM	Boundary Element Method	6
CAD	Computer Aided Design	4
CAM	Computer Aided Modelling	4
CFD	Computational Fluid Dynamics	5, 126
CRPS	Complex Regional Pain Syndrome	4
DC	Direct Current	148
DoF	Degree–of–Freedom	75
EHD	Electrohydrodynamic	16, 27
EO	Electroosmotic	16
EO	electroosmotic	27
EW	Electrowetting	16
EW	electrowetting	30
FDM	Finite Difference Method	6
FEA	Finite Element Analysis	5
FEM	Finite Element Modelling	5
FPW	Flexural Planar Wave	16, 32
FSI	Fluid–Structure Interaction	6
FVM	Finite Volume Method	6

IC	Integrated Circuit	4
ICPF	Ionic Conductive Polymer Film	16, 24
IDT	Inter Digital Transducers	32, 40
LoC	Lab–on–a–Chip	14
MEMS	Micro Electro Mechanical Systems	1
MHD	Magnetohydrodynamic	16, 25
MnD	Mid–node Displacement	100
PCB	Printed Circuit Board	110
PCR	Polymerase chain reaction	14
PVMD	Percentage Variation in Mid–node Displacement	100
PZT	Lead Zirconate Titanate	19
RF	Radio Frequency	8
RFID	Radio Frequency Identification Device	87
SAW	Surface Acoustic Wave	8, 40
Si	Silicon	52
SMA	Shape Memory Alloy	16, 22

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