MANIPULATING FLUIDS: ADVANCES IN MICRO-FLUIDICS, OPTO-FLUIDICS AND FLUIDIC SELF ASSEMBLY

Thesis by

Saurabh Vyawahare

In Partial Fulfillment of the Requirements for the

degree of

Doctor of Philosophy

CALIFORNIA INSTITUTE OF TECHNOLOGY

Pasadena, California

2006

(Defended 16th May, 2006)

The efforts of most human-beings are consumed in the struggle for their daily bread, but most of those who are, either through fortune or some special gift, relieved of this struggle are largely absorbed in further improving their worldly lot. Beneath the effort directed toward the accumulation of worldly goods lies all too frequently the illusion that this is the most substantial and desirable end to be achieved; but there is, fortunately, a minority composed of those who recognize early in their lives that the most beautiful and satisfying experiences open to humankind are not derived from the outside, but are bound up with the development of the individual's own feeling, thinking and acting. The genuine artists, investigators and thinkers have always been persons of this kind. However inconspicuously the life of these individuals runs its course, none the less the fruits of their endeavors are the most valuable contributions which one generation can make to its successors….

-Albert Einstein in Emmy Noether's obituary (1935)[1]

[1] Quote in my graduate school application, circa 2001. I am happy to report that grad school has not blunted this belief, as yet.

ACKNOWLEDGEMENTS

No one works in isolation, and this dissertation would not have happened without the direct or indirect contribution of many individuals. I would like to thank everyone who made it possible and take some space to acknowledge some of those I know. Any errors in this thesis are, of course, all mine.

I would like to thank my advisor, Axel Scherer, for providing me a fantastic environment to facilitate work. Axel is that rare bird – a combination of an exceptional scientist, and an exceptional human being. His knowledge, kindness and sense of humor have made my stay special. I am much indebted for his providing me an opportunity when I was in crisis mode, and uncertain of my future.

I would also like to thank Steve Quake. I worked with Quake's group until he decided to move to Stanford and I chose to stay back at Caltech. Steve has an uncommon ability to take something complicated and distill it into something simple. His energy, vision and high standards have made a deep impact on me.

I have been very fortunate to have a series of gifted collaborators – Mike van Dam, Koichi Okamoto, George Maltezos, Sven Mathias, and Emil Kartalov. Thanks, too, to the band of undergrad students that I mentored - I certainly learnt more from you than I taught you – Aziel C. Epilesia, Kate M. Craig, Brian Zhou, Javier Soliz and Fiona Heung. Thanks also to present and former members of the Scherer and Quake groups – especially Michael Hochberg, Terrell Neal, Teresa Emery, Frederick Balagadde, Chris Lacenere, Zhaoyu Zhang, Larry Wade, Jong Wook Hong, Robert Bao, Heun Jin and Brett Maune. I also want to thank Baiyang Li, James Adleman and David Erikson.

Thanks to Ali Ghaffari for keeping the micro-nano facility humming, to Christina, Alejandra and Kenneth for their efforts at the Caltech Microfluidics Foundry and Connie, Kate, Irene, and Lyn Hein for keeping things running smoothly.

To Jim and Athena, at the International Students Program, for their dedication to helping international students and to Doug Smith, editor of Engineering and Science, who tries hard to coax good science writing out of me. Thanks also to Daryl Denning, for providing respite from academics in his guitar classes.

Thanks to my thesis committee - Axel Scherer, Scott Fraser, Marc Bockrath and Michael Elowitz for taking time from your busy schedules.

Special thanks to Michelle D. Friedman, Jeff Fingler, Sotiris Masmanides, Chaitanya Rao, Shwetank Kumar and Chris Lacenere for friendship and making the world a better place, at least for me.

Finally, I would like to thank my family – my sister Pallavi, and my parents, Sonal and Makarand K. Vyawahare – for support, advice and love. This thesis is dedicated to them.

Saurabh Vyawahare

2nd May 2006

ABSTRACT

This dissertation describes work in three inter-related areas – micro-fluidics, opto-fluidics and fluidic self-assembly. Micro-fluidics has gotten a boost in recent years with the development of multilayered elastomeric devices made of poly (dimethylsiloxane) (PDMS), allowing active elements like valves and pumps. However, while PDMS has many advantages, it is not resistant to organic solvents. New materials and/or new designs are needed for solvent resistance. I describe how novel fluorinated elastomers can replace PDMS when combined with the three dimensional (3-D) solid printing. I also show how another 3-D fabrication method, multilayer photo-lithography, allows for fabrication of devices integrating filters. In general, 3-D fabrications allow new kinds of micro-fluidic devices to be made that would be impossible to emulate with two dimensional chips.

In opto-fluidics, I describe a number of experiments with quantum dots both inside and outside chips. Inside chips, I manipulate quantum dots using hydrodynamic focusing to pattern fine lines, like a barcode. Outside chips, I describe our attempts to create quantum dot composites with micro-spheres. I also show how evaporated gold films and chemical passivation can then be used to enhance the emission of quantum dots.

Finally, within fluids, self assembly is an attractive way to manipulate materials, and I provide two examples: first, a DNA-based energy transfer molecule that relies on quantum mechanics and self-assembles inside fluids. This kind of molecular photonics mimics parts of the photosynthetic apparatus of plants and bacteria. The second example of self-assembly in fluids describes a new phenomena - the surface tension mediated self assembly of particles like quantum dots and micro-spheres into fine lines. This self assembly by capillary flows can be combined with photo-lithography, and is expected to find use in future nano- and micro-fabrication schemes.

In conclusion, advances in fluidics, integrating materials like quantum dots and solvent resistant elastomers along with 3-D fabrication and methods of self assembly, provide a new set of tools that significantly expand our control over fluids.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS AND/OR TABLES

Number *Page*