Microfluidic design for bio-sample delivery to silicon nanowire biosensor - a simulation study

To cite this article: S J Tan *et al* 2006 *J. Phys.: Conf. Ser.* **34** 103

View the article online for updates and enhancements.

Microfluidic design for bio-sample delivery to silicon nano-wire biosensor – a simulation study

S J Tan, I K Lao[1], H M Ji, A Agarwal, N Balasubramanian and D L Kwong

Institute of Microelectronics, 11 Science Park Road, Singapore Science Park II, Singapore 117685

Email: laoik@ime.a-star.edu.sg

Abstract. We examine various microfluidic channel designs for sample delivery to silicon nano-wire biosensors pertaining to the modeling and simulation. Nano-wires with its high sensitivity permits label free detection of bio-molecules. Without careful considerations to its fluidic delivery network, effects of detection can be limited. Different micro-channel designs of relatively larger width aid in fluid release and sensors are placed strategically to attain high efficiency in bio-sample delivery. One design establishes the viability of hydrodynamic focusing through splitting a single flow into two and permits focusing of bio-samples at the flow recombination region. It avoids the delicated fluidic delivery systems generally used in hydrodynamic focusing. A focusing effect of 71.3% based on the movement of a massless particle in the fluid is achieved using a straight channel design with a partition wall inside. Moreover, sample is focused in low velocity region which maintains minimal impact to nano-wire sensor. This provides a simple and efficient delivery system for the nano-wire sensor upon integration.

1. Introduction

Possibilities of using silicon nano-wires for biological species detection are both immense and enticing [1-3]. The large surface area to volume ratio of nano-wire provides high sensitivity, permitting real time label-free electrical detection. Various applications such as pH sensing [1], detection of single viruses [2] and identification of cancer markers [3] have been reported, paving the interest in using nano-wires for more biological related activities. However, efficacy is restricted by detection limits which relates to the amount of bio-molecules that pass the sensor. Detection is limited if the amount of samples that interact with the sensor are lesser than required. Hence, this validates the importance of an efficient sample delivery system [4].

There are various considerations for designing a sample delivery system whereas efficiency of sample deliverance to the nano-wire sensors becomes the paramount concern. It aims to bring a higher efficiency permitting greater probabilities of interactions between bio-samples and nano-wire sensors.
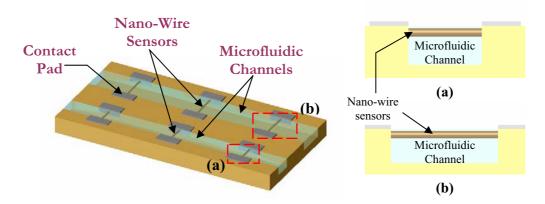
Figure 1. Schematic of a microfluidic device to attain bio-samples delivery efficiency. (a) Channel of shorter width. (b) Channel of larger width.

High efficiency can be attained through direct lining of nano-wires across fluidic channels as shown in figure 1. All bio-samples that are introduced into the microfluidic channel will pass through the sensor. Flaw of the design is the limitation in channel widths to conform to the length of the nano-wires. The problems lie with the sophistication of fluidic delivery systems for small volumetric flow rates as well as the large pressure drop due to the diminutive channel width. Large mechanical impact as a result of the high pressure inside the channel is deemed undesirable to the nano-wire.

Hydrodynamic focusing used in flow cytometery permits control of fluidic streams [5-8]. Conventional methods employ shielded buffer flow to focus samples into a minute streak, utilizing multiple inlets fluidic systems. Complex setup poses complications at integration with the nano-wire sensor.

In this work, the objective is to design a fluidic delivery system that is eligible to integrate with our nano-wire process [9] for a complete biosensor. Various micro channel designs for bio-sample delivery of a silicon nano-wire biosensor are studied numerically. A broader channel is desired for ease of fluid delivery while accounts for the poor mechanical properties of nano-wires. To enhance efficiency, bio-molecules directed to the sensor can be achieved by hydrodynamic focusing.

2. Modelling and Approach

Figure 2 illustrates four different models investigated in this report. The first model shown in figure 2(a) is a constriction design. Its principle is to maintain the high efficiency as brought out with the schematics depicted in figure 1. In order to alleviate the impact on nano-wire due to high pressure and the sophistication of fluidic delivery systems for small volumetric flow rates, the channel width gradually decreases along the flow direction and then increases after a constriction. Nano-wire is placed across the constriction of its length restricted to the limitations of fabrication.

Figure 2(b), figure 2(c) and figure 2(d) represent the differing approach for hydrodynamic focusing. The width of channels is maintained as in the constriction design to alleviate fluid delivery issues. The dissimilarity lies in the designs to create a split flow. The buffer channel denotes a region where the main bulk of the solution passes while the sample channel designates the entry location of bio-samples.
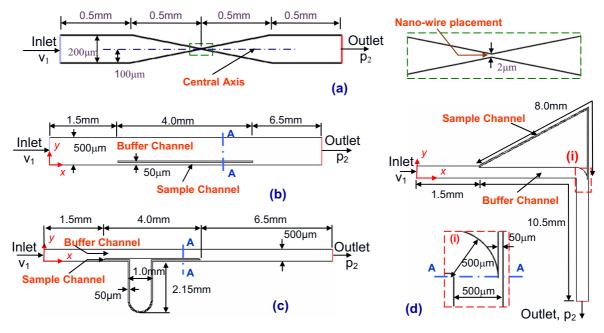
Figure 2. Designs of different micro channel. (a) Design 1 (Constriction Design). Creating velocity variations with split channel designs (b) Design 2. (c) Design 3. (d) Design 4.

Upon separation of fluid stream in the channel, a higher average velocity is deduced in the buffer channel relative to the sample channel due to larger width of the buffer channel. The approach is to make use of the velocity disparities to create the effect of compression upon recombination of streams after section AA of design 2 to design 4 (figure 2(b) to figure 2(d)).

Variations within the three designs are due to the additional considerations given to increase the ratio of the velocity disparities upon recombination of fluid streams. Design 3 has an increased sample channel length. This brings down the velocity magnitude in the sample channel at the exit of split flow. Design 4 attaches the effect of centrifugal forces through the 90° bend in the split flow.

Simulations for the micro channel designs are performed on commercial CFD software. Modeling is based on continuity criterion and momentum conservation relations. Inlet and outlet conditions are kept invariable for ease of comparisons. Given the sheer dimensions of microfluidic devices, laminar associations are denoted valid with predicted low Reynold's numbers. A parabolic velocity profile is thus linked to fluid flow in fully developed phase. Grid independence tests are employed in every simulation analysis to ascertain the validity for convergence of solutions.

3. Results and Discussion

Figure 3 shows the velocity plot surrounding the constriction of 2μm for design 1. Evidently, the velocity has a vast increment across the constriction on the basis of mass balance. The interaction time for bio-samples to the sensor is therefore reduced. Another flaw can be clearly seen from the pressure against displacement graph along the central axis of the model in figure 4. The distinctive fall of gauge pressure at the position of the constriction highlights a large pressure drop across the nano-wire. This induces a large impacting force on the nano-wire.
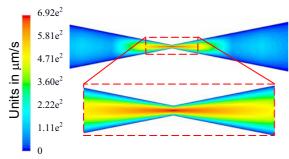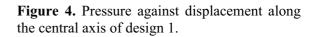
Figure 3. Velocity magnitude contour plot of design 1.

Figure 4. Pressure against displacement along the central axis of design 1.

The effect of hydrodynamic focusing for design 2, design 3 and design 4 are discussed comparing their velocity characteristics and streamline contour plots. Figure 5 shows the velocity profiles at the cross sectional view of line AA in figure 2. In these three designs, the velocity disparities formed due to the split of fluid streams are apparent. The ratio of buffer to sample flow velocity shows design 3 obtains the highest value (116.3) while the ratio in design 2 (66.7) is the smallest among three.
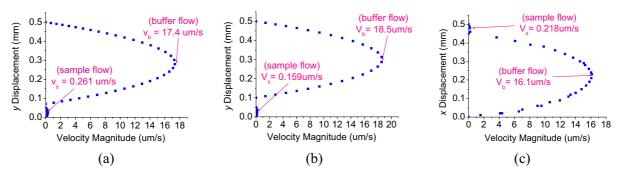

(a)

(b)

(c)

Figure. 5. Velocity profile at section AA from figure 2. (a) Design 2. (b) Design 3. (c) Design 4.

The implications would be transferred to compression effect after recombination region. This is analogous to hydrodynamic focusing in conventional flow cytometmetery, which make use of multiple inlet flow streams with different velocities to achieve control of fluidic streams [5-8]. The multiple inlets pose complications at integration with the nano-wire sensor. In these three models, structural designs provided a single inlet control for utilizing hydrodynamic focusing through momentum balance at splitting a common flow. This reduces the complications of fluidic setups compared with conventional means.

Focusing effects have been simulated in figure 6. The inclination of streamlines to the side wall indicates the focusing effects. In flow cytometry, sample is focused at the center of a flow stream for optical detection. Large mechanical impact is expected if applied to nano-wire sensor due to high sample flow velocity in focused stream. While in the split flow designs, sample is directed towards the side as a result of shear forces, instantaneous velocity near the side wall is relatively lower than at the center owing to the parabolic velocity profile of a laminar flow. Nano-wire sensors placed in this section benefit from minimal disturbances and longer interaction periods of bio-molecules to the sensor.
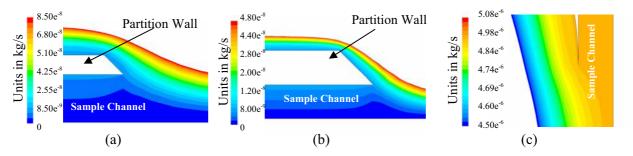
Figure. 6. Contour streamline plots of merging flow at regions adjacent to section AA from figure 2. (a) Design 2. (b) Design 3. (c) Design 4.

To facilitate the integration with silicon nano-wire, design should be chosen based on the delivery efficiency as well as other factors such as space requirements and complication of design. Movement tracking of a massless particle released at mid sample channel is simulated to evaluate the focusing of a sample molecule. Results show that design 2 attains a 71.3% focusing effect based on the ratio of changes in displacement of the particle to the original displacement from the side wall. The other two designs produce similar effects but deem to yield much space requirements.

4. Conclusions

Evaluations of four different simulation models for a microfluidic delivery system to silicon nano-wire sensor are discussed. The constriction design has flaws of a large impact force and relatively high velocities at the sensor region that minimises interaction time for bio-molecules to the sensor. The other three designs established that hydrodynamic focusing is a viable method for bio-sample delivery. The design of a simple straight channel with partition affirms a 71.3% focusing effect upon the recombination fluid streams with minimized space requirement. Sensor placed at the focused stream of low velocity flow reduces the mechanical impact while attaining delivery efficiency from the effect of hydrodynamic focusing. Future bearings will encompass the optimization of the dimensions in both channels. Integration with the group's silicon nano-wire [9] for a complete bio-sensing system will be the final target.

References
[1]   Cui Y, Wei Q, Park H and Lieber C M 2001 *Science* **293** 1289
[2]   Patolsky F, Zheng G, Hayden O, Lakadayali M, Zhuang X and Lieber C M 2004 *PNAS* **101** 14017
[3]   Zheng G, Patolsky F, Cui Y, Wang W U and Lieber C M 2005 *Nature Biotechnol.* **23** 1294
[4]   Sheehan P E and Whitman L J 2005 *Nano Lett.* **5** 803
[5]   Chung S, Park S J, Kim J K, Chung C, Han D C and Chang J K 2003 *Microsystem Technologies* **9** 525
[6]   Chein R and Tsai S H 2004 *Biomedical Microdevices* **6** 81
[7]   Lee G B, Hung C I, Ke B J, Huang G R, Hwei B H and Lai H F 2001 *J. of Fluids Engineering* **123** 672
[8]   Stiles T, Fallon R, Vestad T, Oakey J, Marr D W M, Squier J and Jimenez R 2005 *Microfluid Nanofluid* **1** 280
[9]   Agarwal A, Balasubramanian N, Ranganathan N and Kumar R 2005 *ICMAT 2005 & IUMRS-ICAM 2005*