Electrostatically driven micropump with peristaltically moving membrane

Bonghwan Kim

Department of Electronics Engineering, Catholic University of Daegu, Gyeongsan, Republic of Korea
E-mail: bhkim@cu.ac.kr

Published in Micro & Nano Letters; Received on 16th May 2013; Revised on 23rd August 2013; Accepted on 19th September 2013

An electrostatically driven valveless micropump with a peristaltically moving membrane for gas chromatography is presented. The one-chamber micropump has a peristaltically moving membrane formed by polyimide with four electrodes used to separate the single chamber into four pump chambers. For a peristaltically moving membrane, several dielectrics were tested for their ability to endure high-voltage breakdown, and the PI-2545 polyimide was finally chosen to reduce the operating voltage. After testing a single-sided micropump (SSM), a double-sided micropump (DSM) was fabricated to enhance pump efficiency. Theoretically, the flow rate of the DSM is quadruple that of the SSM, and the electrodes in the membrane can recover from the motion of pulling down and pulling up with ease. To verify the peristaltic motion of the micropump, a transparent indium tin oxide (ITO) electrode was used. An ITO–ITO micropump was fabricated, and to measure flow rate, an ITO–Si micropump was fabricated as well. The micropump was fabricated on a glass substrate with ITO and on a silicon substrate with a polyimide membrane. A maximum flow rate of 27.19 µl/min was measured at 4 Hz and 100 V DC. The micropump was operated by four electrodes with a four-phase sequencing actuation.

1. Introduction: Gas chromatography is a common chromatography method used in analytical chemistry for separating and analysing compounds that can be vaporised without decomposition. To analyse gases, a microfluidic system in which fluid flows in miniature devices is essential. The common target applications of microfluidic systems include chemical/biological sensing and analyses, drug delivery, molecular separation, amplification, sequencing and synthesis for environmental monitoring [1]. Most microfluidic systems require pumps and valves that are reliable, consume less power, have a moderate actuation voltage and can be fabricated easily and cost effectively [1, 2].

Micropumps play an important role in applications such as microfluidic devices, labs-on-a-chip and micrototal analysis systems (µTAS). There have been several designs for micropumps [3] based on different working principles, such as valve-based and valveless designs [3, 4]. The micropump driving forces are categorised as follows: piezoelectric [3], electrostatic [3], thermo-pneumatic [3] and pneumatic [4]. Among these types of micropumps, valveless and electrostatic micropumps are more compatible with respect to scaling compared with piezoelectric micropumps [4], have faster response times (several milliseconds) compared with other actuators (several seconds) [5] and require fewer fabrication steps during manufacture compared with valve-based micropumps. Therefore electrostatically driven valveless peristaltic pumps are a good candidate for micropumps in gas chromatography owing to their reliability, low-power consumption, moderate actuation voltage and ease and cost of fabrication.

Unlike conventional peristaltic micropumps, in this study, only a single chamber was required because the electrodes of the membrane can divide a single chamber according to the number of electrodes. In addition, a double-sided micropump (DSM) was used to enhance the flow rate and reduce the recovery time of the membrane after pull-up and pull-down motion. Fig. 1 shows the top view and cross-sectional view of the proposed micropump as well as the four-phase sequencing actuation of peristaltic motions and its switching circuit. In some cases, the chamber can have more than four electrodes, for example 4, 8 or 12 electrodes [6]. In general, the flow rate of a double-sided chamber is four times that of a single-sided chamber [6–8]. To operate the micropump peristaltically, a four-phase sequencing circuit was designed and customised [6–8]. The basic concept is to operate the micropump with several electrodes, to apply the four-phase signal to the membrane electrodes, with the top electrodes supplying positive voltage, whereas the bottom electrodes are grounded. The membrane electrodes can move up and down to contact the top and bottom electrodes, respectively. An ITO electrode was used to observe the membrane while the pump was operated. The switching circuit consists of high-voltage switching transistors and a logic circuit for switching signals [6–8].

In peristaltic motion with a one-pump chamber, the peristaltically moving membrane plays a very important role. Electrostatic micropumps should consume less energy. In this study, several dielectric materials were tested for the moving membrane, and their breakdown voltage was investigated.

2. Experimental: In this Letter, we propose a new membrane design, see Fig. 1, to reduce the energy required to stretch the membrane (i.e. to make it more compliant to tensile loads), whilst increasing the energy required to bend the membrane (i.e. to make it stiffer to bending loads). Decreasing the energy required for stretching is essential because if the membrane is too stiff under tension, all the energy supplied electrostatically is used up in stretching the membrane rather than in pressure/volume work that is intended for a pump [8]. Increasing the stiffness during bending is essential because when the membrane pulls in to compress gas, a bubble can form [8]. When a bubble forms, no amount of energy can compress the gas. If the membrane is stiff during bending, it is harder for a bubble to form. Finally, with the old membrane design, as the dielectric is made thinner to facilitate the transfer of more electrostatic energy for a given voltage [electrical energy is proportional to $(V/g)^2$, where g is the thickness of the dielectrics], the stiffness is reduced during tension by g and reduced during bending by g^3. In other words, we make it much, much worse. Therefore the idea proposed with a compliant elastomer of thickness h in the centre layer increases the stiffness during tension by much less than h if the modulus of the elastomer is much lower than that of the dielectric, but increases the stiffness during bending by h^3, regardless of the modulus of the elastomer. In this way, we can gain a huge amount. Therefore selection of the dielectric material of the membrane is important.

The proposed peristaltic micropump is driven by an electrostatic force. The applied force is proportional to the square of the distance between the two electrodes, and the flow rate is proportional to the

doi: 10.1049/mnl.2013.0328

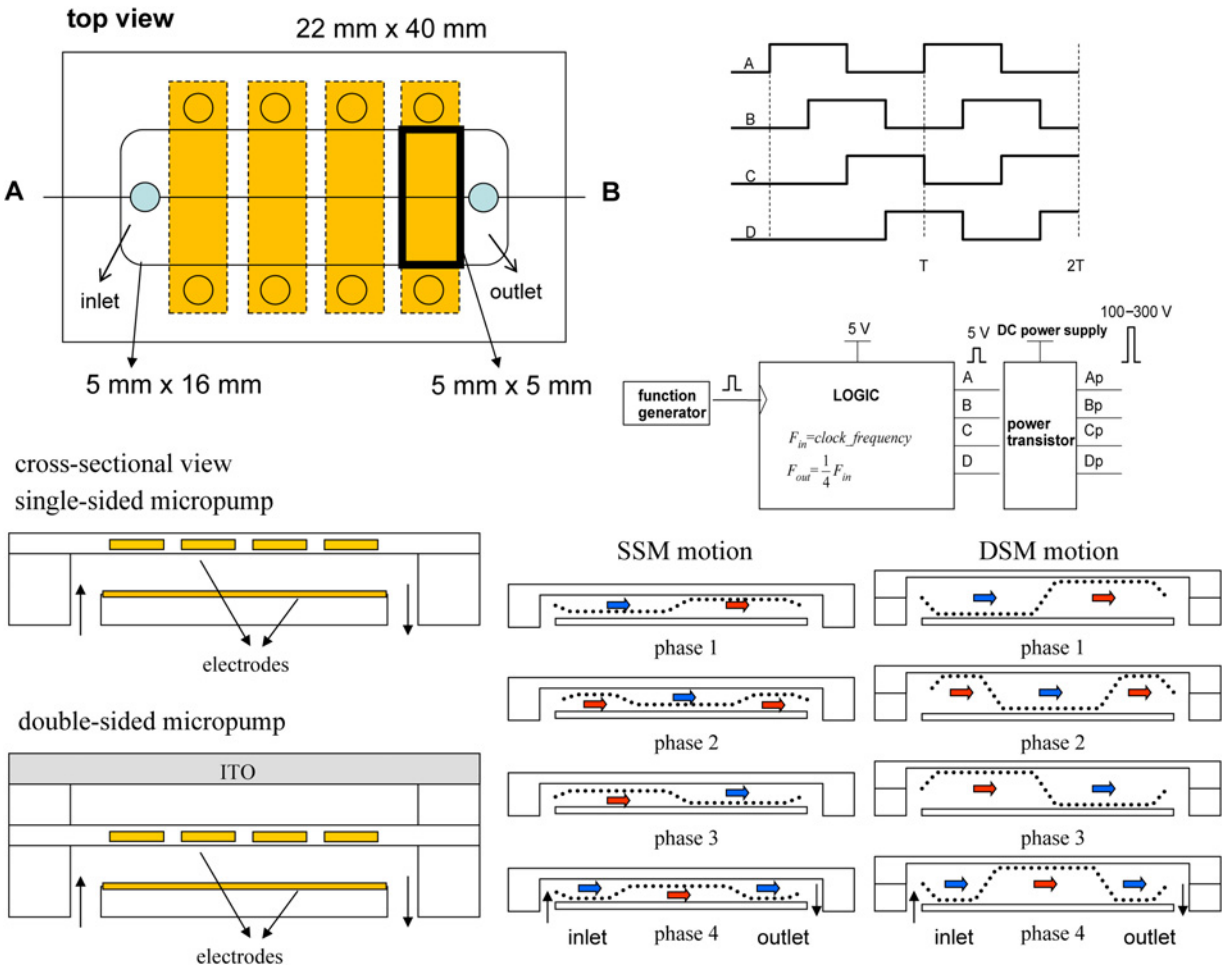

Figure 1 *Schematics of SSM and DSM and four-phase operation sequence*

volume of the pump chamber. Therefore the thickness of the membrane and the depth of the pump chamber should be reduced. Since the flow rate is proportional to the volume of the pump chamber, reducing the distance between the two electrodes is more effective. Generally, membrane dielectrics should have large deformation, fast response, high efficiency and low cost. When subjected to a voltage, the membrane reduces its thickness and expands its area, converting electrical energy into mechanical energy. To select a dielectric material whose breakdown voltage is more than hundreds of volts, several dielectrics were tested, such as PI-2545 [9], PI-5848G [9], Avatrel [10, 11], benzocyclobutene (BCB) [12] and parylene [13].

3. Fabrication: The test sample was formed with a 4-inch Si wafer. As shown in Fig. 2, circle and square patterns were fabricated on the wafer. First, silicon dioxide was deposited by using plasma-enhanced chemical vapour deposition (PECVD) after initial cleaning of the Si wafer. The Au/Cu metal layer was sputtered after spin coating or deposition of dielectrics such as PI-2545, PI-5848G, Avatrel, BCB and parylene. Finally, a Cr/Au/Cr electrode was patterned to test the breakdown voltage of the dielectrics.

In this work, we designed and fabricated a double-sided peristaltic pump for gas chromatography. The reason for fabricating a double-sided peristaltic pump is to have only a single chamber with a membrane that moves up and down by an electrostatic force to contact an array of electrodes. To verify the concept, ITO

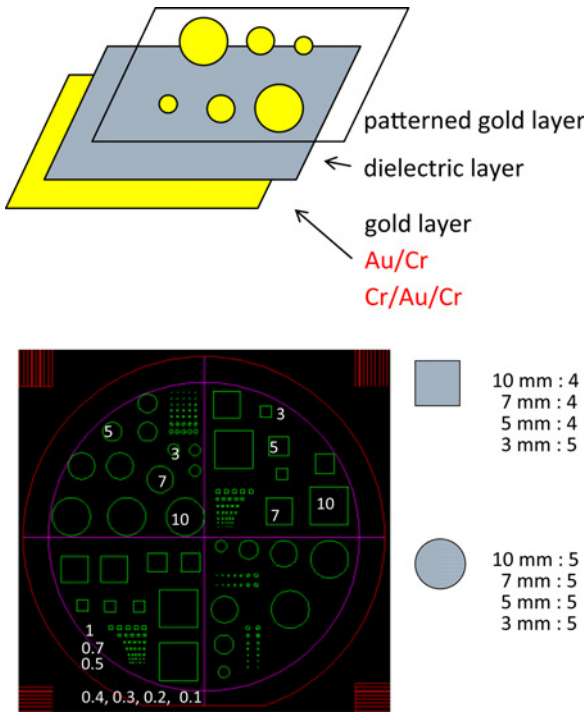

Figure 2 *Process of the breakdown voltage test sample*

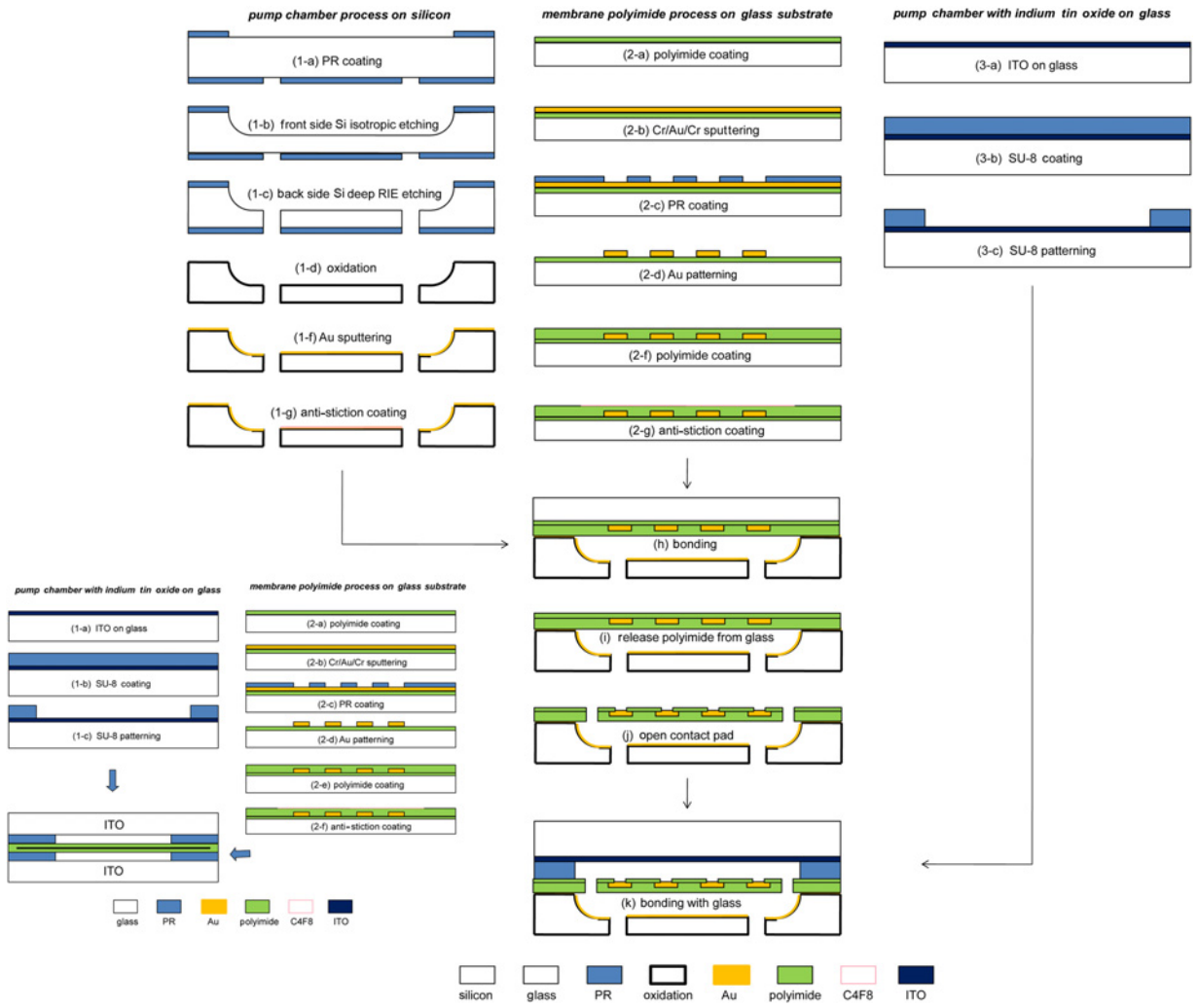

Figure 3 *Process flow of the ITO–ITO micropump and the double-sided peristaltic pump with ITO electrode*

electrodes were used to observe the membrane while the pump was operated. The micropump with ITO electrodes measures 22 mm (W) × 40 mm (L) × 0.5 mm (H), with the area of the pump bottom chamber being 8 × 40 mm and the area of the top chamber being 8 × 40 mm with a depth of 10 µm [6, 8]. The ITO–ITO double-sided pump was fabricated as follows. The processes are divided among the ITO chamber, the polyimide membrane and the ITO-polyimide-IPO bond. For the ITO chamber, a cover glass was cleaned with solvent and spin-coated with a photoresist by using 10 µm-thick SU-8. After photolithography, the ITO chamber was formed. For the metallised flexible membrane, a conducting flexible membrane was fabricated by using a stack of polyimide/metal/polyimide/anti-stiction layers on the cover glass. First, polyimide (PI-2545, HD Microsystems) [7], was spin-coated onto the cover glass measuring 22 mm (W) × 40 mm (L) × 0.5 mm (H) (Fig. 3(2-a)). Cr/Au/Cr layers were deposited by sputtering (Fig. 3(2-b)), and electrodes were patterned by Cr/Au/Cr wet etching after photolithography with PR AZ 1512 (Fig. 3(2-c-d)). An anti-stiction layer of C4F8 was deposited after the second coating of PI-2545 onto the metal layer (Fig. 3(2-e-f)) [6, 8]. The pump chamber and the metallised membrane were bonded with a custom-made adhesive [14–16] and then soaked in deionised water to release the membrane from the cover glass. The membrane was selectively etched with a shadow mask to fabricate a contact pad.

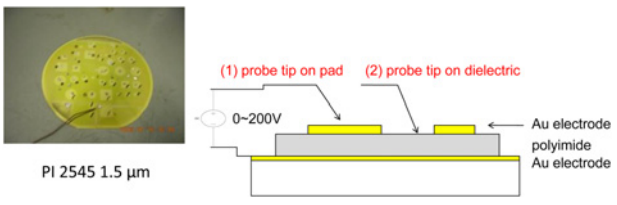

Figure 4 *Fabricated dielectrics and test method*

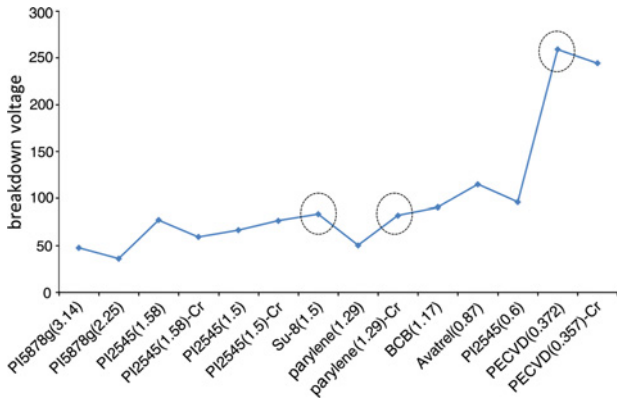

Figure 5 *Breakdown voltage of various films*

doi: 10.1049/mnl.2013.0328

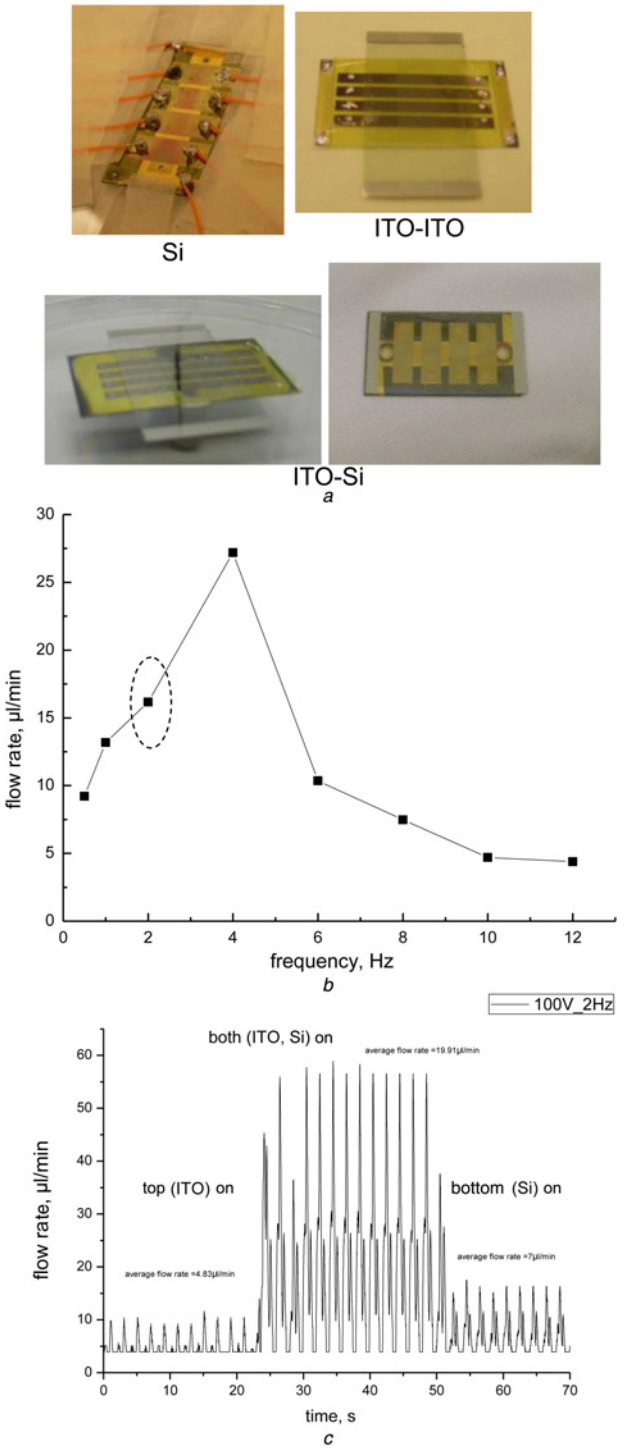

Figure 6 *Fabricated Si single-side micropump and ITO–ITO and ITO–Si DSM with four electrodes, and test results*
a Fabricated Si single-side micropump and ITO–ITO and ITO–Si DSM with four electrodes
b Average flow rate against frequency
c Flow rate against time at 2 Hz

The area of the ITO–Si peristaltic pump is 22 mm (W) × 40 mm (L) × 350 µm (H), with the area and the depth of the pump chamber being 5 × 32 mm and 15 µm, respectively. Fig. 3 shows the process flow of the ITO–Si peristaltic pump. The fabrication process can be divided into three parts. The ITO chamber and polyimide membrane were fabricated using the same ITO–ITO process. A silicon pump chamber was used for the inlet and the outlet, and polyimide was used for the membrane. First, the starting material was a 4-inch (100)-type silicon wafer. For the silicon pump chamber, both sides of the silicon wafer were patterned with a photoresist. The pump chamber was etched with XeF_2 etcher, potassium hydroxide solution or deep reactive-ion etching (RIE), and the inlet and outlet were etched by deep RIE. Secondly, a metallised flexible membrane was fabricated using a polyimide/metals/polyimide/anti-stiction layer on a cover glass. The pump chamber and the conducting membrane were bonded using the same method as the ITO–ITO micropump.

4. Results and discussion: Fig. 4 shows the breakdown voltage test sample and the test method. As shown in Fig. 5, the breakdown voltage of the silicon dioxide deposited by using PECVD was the highest in the test. However, the breakdown voltages were similar among coatable dielectrics. PI-2545 can moderate viscosity and mechanically sustain large deformation.

Fig. 6*a* shows the fabricated Si single-side micropump and ITO–ITO and ITO–Si DSM with four electrodes. To observe the micropump motion, ITO–ITO was used. For electrostatic actuation, four-phase sequence signals were generated by using a custom-made logic circuit and power transistors [6, 7]. From the visual test, the up–down actuation of each top and bottom electrode was verified. To measure the flow rate, a gas flow meter (Omega FMA 1615A) was connected to the outlet of the ITO–Si DSM, and a data acquisition board (LabJack U3, LabJack Co., USA) was used to log the signal from the flowmeter [6, 7]. Figs. 6*b* and *c* show the test results for the micropump. It was found that the flow rate was about 20 µl/min when both electrodes (bottom electrode and Si electrode) were activated simultaneously at a frequency of 2 Hz. However, the flow rate was only about 4.8–7 µl/min when the electrodes were activated separately. Therefore the flow rate of the DSM was about four times that of an SSM.

5. Conclusions: In this work, an electrostatically driven peristaltic micropump, fabricated on an ITO glass substrate and a silicon substrate with a polyimide membrane was designed, built and characterised. A maximum flow rate of 27.19 µl/min was measured at 4 Hz and 100 V DC, and the pump was operated by four electrodes with a four-phase sequencing actuation. This peristaltic motion eliminates the need for valves or a nozzle/diffuser for flow control, which reduces the dead volume and the need for valve timing at the expense of increased electrical driving complexity.

6. Acknowledgment: This work was supported by the Catholic University of Daegu.

7 References

[1] Abhari F., Jaafar H., Yunus N.A.M.: 'Review paper: a comprehensive study of micropumps technologies', *Int. J. Electrochem. Sci.*, 2012, **7**, pp. 9765–9780
[2] Karanth P.N., Desai V., Kulkarni S.: 'Modeling of single and multi-layer polyvinylidene fluoride film for micro pump actuation', *Microsyst. Technol.*, 2010, **16**, p. 641
[3] Laser D.J., Santiago J.G.: 'A review of micropumps', *J. Micromech. Microeng.*, 2004, **14**, pp. R35–R64
[4] Nguyen N.-M., Huang X., Chuan T.K.: 'MEMS-micropumps: a review', *J. Fluid Eng.*, 2002, **124**, pp. 384–392
[5] Sounart T.L.: 'Electrostatic actuation without electrolysys in microfluidic MEMS'. Transducers '03, Boston, MA, USA, pp. 615–618
[6] Kim K., Lee K.S., Shannon M.A.: 'Electrostatically driven single chamber bidirectional peristaltic gas micropump with four electrodes', *J. Korean Phys. Soc.*, 2010, **57**, (6), pp. 1494–1499
[7] Lee K.S., Kim B., Shannon M.A.: 'An electrostatically driven valveless peristaltic micropump with a stepwise chamber', *Sens. Actuators A, Phys.*, 2012, **187**, pp. 183–189 (ISSN 0024-4247)
[8] Kim B., Lee K.S., Shannon M.A.: 'An electrostatically driven double-sided one-chamber peristaltic pump with 4 electrodes', *Jpn. J. Appl. Phys.*, 2013, **52**, p. 06 GLOS
[9] HD Microsystems, available at: http://www.hdmicrosystems.com (accessed 13 May 2013)

[10] McDougall W.C., Farling S., Shick R., *ET AL.*: 'Avatrel™ dielectric polymers for HDP applications'. Proc. Int. Conf. and Exhibition on High Density Interconnect and Systems Packaging, IMAPS, Denver, CO, USA, April 1999, pp. 1–4
[11] Shick R.A., Jayaraman S.K., Goodall B.L., Rhodes L.F., McDougall W.C.: 'Avatrel™ dielectric polymers for electronic packaging', *Adv. Microelectron.*, 1998, **25**, (5), pp. 13–14
[12] Lee L.-K., He J., Singh A., Kim B.: 'Benzocyclobutene (BCB) based intracortical neural implant'. Proc. Int. Conf. MEMS, NANO and Smart Systems, Banff, Alta, Canada, July 2003, pp. 418–422
[13] Sasaki H., Onoe H., Osaki T., Kawano R., Takeuchi S.: 'Parylene-coating in PDMS microfluidic channels prevents the absorption of fluorescent dyes', *Sens. Actuators B, Chem.*, 2010, **150**, (1), pp. 478–482
[14] Han J., Flachsbart B.R., Masel R.I., Shannon M.A.: 'Characteristics of electrostatic gas micro-pump with integrated polyimide passive values', *J. Micromech. Microeng.*, 2008, **18**, p. 095015
[15] Flachsbart B.R., Wong K., Iannacone J.M., *ET AL.*: 'Design and fabrication of a multilayered polymer microfluidic chip with nanofluidic interconnects via adhesive contact printing', *Lab on a chip*, 2006, **6**, p. 667
[16] Bae B., Han J., Masel R.I., Shannon M.A.: 'A bidirectional electrostatic microvalve with microsecond switching performance', *J. Microelectromech. Syst.*, 2007, **16**, p. 1461

doi: 10.1049/mnl.2013.0328