COMMUNICATION

www.rsc.org/loc

A miniaturized high-voltage integrated power supply for portable microfluidic applications

David Erickson,[a] David Sinton[b] and Dongqing Li*[a]

[a] *Department of Mechanical and Industrial Engineering, University of Toronto, 5 Kings College Road, Toronto, Ontario, Canada M5S 3G8. E-mail: dli@mie.utoronto.ca; Fax: +1 416-978-7753; Tel: +1 416-978-1282*

[b] *Department of Mechanical Engineering, University of Victoria, PO Box 3055 STN CSC, Victoria, British Columbia, Canada V8W 3P6*

Received 6th January 2004, Accepted 28th January 2004
First published as an Advance Article on the web 16th February 2004

In this work a portable microfluidic device with a reusable integrated high voltage power supply is presented, which allows for quick exchange of inexpensive disposable poly(dimethylsiloxane) (PDMS) microfluidic chips on a carrier only slightly larger than a microscope slide. The device is powered by an onboard MN21 cell battery (5 mm radius, 30 mm long) and is demonstrated through the rapid and controlled transport of a fluorescent dye through an expansion chamber geometry. Power consumption experiments demonstrate the device's ability to complete over 40 dispense–flushing cycles on a single battery.

Introduction

Integrated microfluidic devices,[1] or Labs-on-Chips, are set to revolutionize the way analytical chemistry is performed, promising to do for large scale chemical and biological analyses what the integrated circuit has done for the electronics industry. Of the many advantages associated with these devices[2,3] one of the more significant is the increased potential for automation and portability, thereby reducing the amount of hands-on labour and enabling more immediate on-site analytical testing.[4]

At present however the majority of microfluidic chips are microscale devices coupled to a macroscale operational infrastructure. This contradiction has led a number of researchers to engineer microfluidic systems that can be decoupled from their bench top infrastructure. Wang[4] recently reviewed current progress geared towards the development of portable electrochemical systems. Kappes *et al.*[5,6] developed a portable capillary electrophoresis instrument using a conventional fused silica capillary. García *et al.*[7] developed a battery operated 3-channel HV power supply for capillary electrophoresis chips. One of the more impressive devices presented to date was the portable power supply and detection circuitry developed by Jackson *et al.*[8] to be used with the capillary electrophoresis chip introduced in an earlier paper by Baldwin *et al.*[9] The device (10 cm by 15 cm by 2.5 cm in size and weighing 350 g) used 4 rechargeable AAA batteries to operate the power supply (a 9 V battery was also used for the detection circuitry) and the processed detection signals were fed to a DAQ card in a notebook computer. Other researchers have focused on downsizing the energy sources themselves, for example the miniaturized fuel reformer developed by Holladay *et al.*[10] and the portable device intended for military field use based on this technology.[11]

Many current lab-on-chip devices also suffer from a cost/integration problem. That is, highly integrated devices, often made of glass or silicon, are very expensive and thus typically must be reused. This tends to be a difficult sell for many biomedical applications that require mass produced, disposable devices to guarantee against cross contamination. There are some commercially available disposable glass devices, such those used by McCaman[12] and Sohni,[13] but these tend to have a high cost/use ratio. The demand for disposability has led to the widespread use of low-cost polymeric materials such as poly(dimethylsiloxane) (PDMS),[14–17] poly(methyl methacrylate) (PMMA),[18–20] polycarbonate plastic[21,22] and a host of others (see Becker and Locascio[23] for a review). While many very impressive disposable devices have been manufactured from these (*e.g.*, a microscale sperm sorter,[24] capillary electrophoresis devices with integrated optical fibers[25,26] and a credit card sized DNA hybridization chip[21]), attempts to increase the degree of integration of these polymeric chips necessarily increases the manufacturing cost/complexity per unit, thereby counteracting one of their great advantages. An alternative approach has been the development of integrated microfluidic devices consisting of an reusable carrier containing the integrated components coupled with a disposable chip in which the analysis is done.[25,27,28] These types of devices provide the high level of integration possible with traditional microfabrication techniques, while enabling disposability and a low cost per test ratio.

In this work we present a reusable integrated microfluidic device, only slightly larger than a microscope slide, which allows for quick exchange of disposable PDMS microfluidic chips. A self contained, adjustable high voltage supply, powered by an onboard battery, is incorporated onto the chip and for controlled electrokinetic species transport. The unique "punch through" coupling system and chip design allows for both open air (*i.e.* those which can be accessed from above throughout an experiment) and sealed (*i.e.* those which are sealed beforehand and protected from airborne contamination) chips to be used. The device is demonstrated through the controlled transport of a fluorescent dye through an expansion chamber geometry. The device is shown to be able to complete over 40 dispense–flushing cycles on a single charge.

Results and discussion

A miniaturized high-voltage integrated power supply for portable microfluidic systems

A labelled photograph and physical description of the system are given in Fig. 1a. With overall dimensions of 2.1 cm (tall) × 10 cm (long) × 2.5 cm (wide) the device is compatible with common microscope stage slide holders and may be clipped directly into place. The main platform is black acrylic plastic, which is chemically inert, machinable, inexpensive, and electrically and thermally insulating. A channel was machined on the underside of the platform for electrical connections to be made between components in circuit-board fashion.

Powering microfluidic chips without embedded electrodes has typically involved inserting electrodes into the liquid reservoirs from above. Such 'free-electrode' methodologies have several shortcomings: During set-up, electrodes must be manipulated (with tweezers or otherwise) to make contact with the liquid. Routine handling of electrodes increases the risk of electrical shock, contamination, mechanical damage to the chip and electrode failure

DOI: 10.1039/b316916b

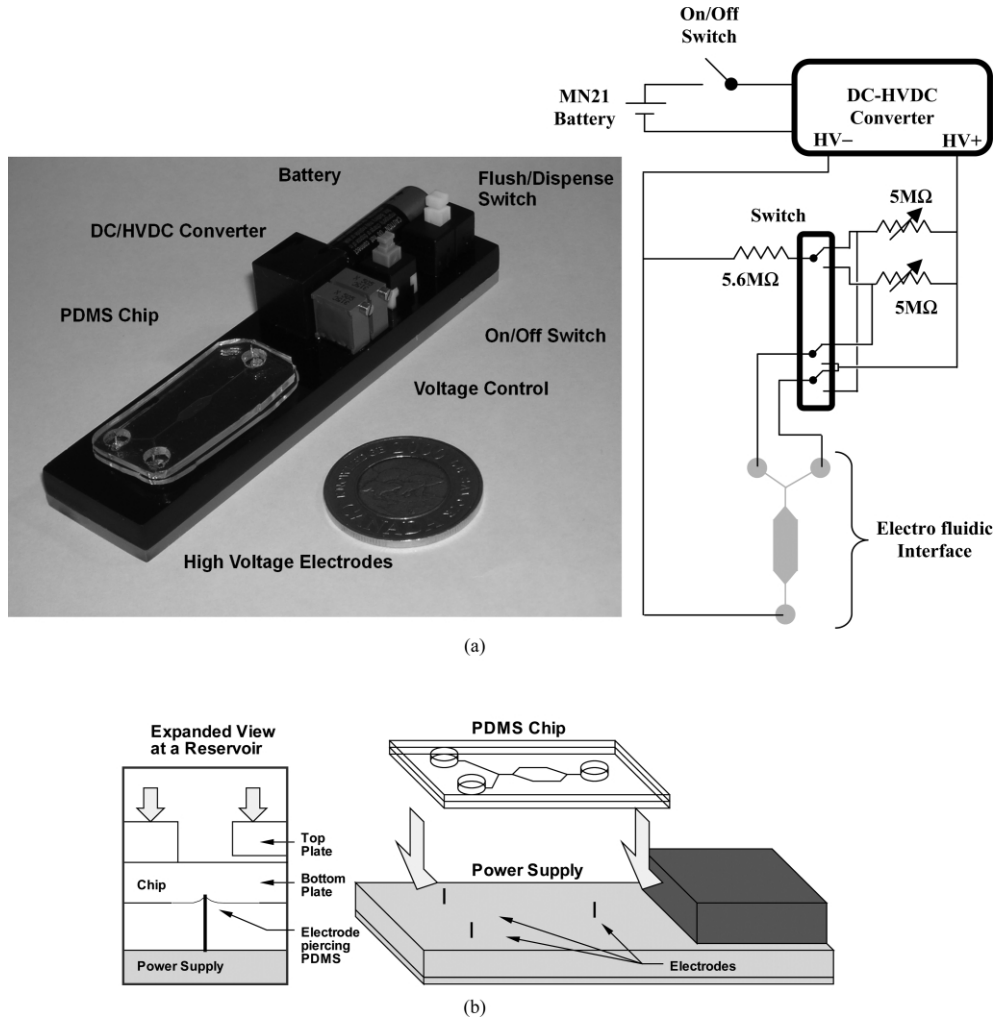

Fig. 1 A PDMS chip in operation with the miniaturized high-voltage integrated power supply. The footprint of the unit is the same in width as a microscope slide and only slightly longer. The chip platform is 0.9 cm thick and total height of the system does not exceed 2.1 cm. PDMS chips are integrated with the power supply at the point-of-use *via* punch-through electrodes. Punch-though coupling provides an elegant and effective method to connect and power the chip (described further in the text). The combined unit may be clipped directly into most microscope stage slide holders. (a) Photograph of the device with an overview of the control circuit. (b) Schematic illustration of punch-through polymer chip coupling.

due to fatigue. During operation, high-voltage electrodes can be accessible to the user, particularly during the refilling of reservoirs. Although some systems have a shielded environment that ensures hands-off operation, this infrastructure does not lend itself well to miniaturization. Electrode contact with the optical infrastructure, especially metallic components such as microscope objectives, is another hazard. In typical upright fluorescent microscopes, the objective must compete with the electrodes for space. Using longer working-distance objectives can reduce the risk of electrical connection; however, this imposes restrictions on the optical hardware and typically results in the use of reduced numerical aperture lenses and therefore reduced sensitivity. Chips with extended channel lengths to separate reservoirs from observation areas require more space and increased applied voltages and are thus not an ideal solution. Finally, the introduction of an electrode (typically hydrophilic) into a reservoir from above increases the mean radius of curvature of the free surface and can induce capillary-based pressure-driven flow, typically highly undesirable in electrokinetic microfluidic chip applications.[29] Powering chips with embedded electrodes circumvents many of these problems associated with free-electrode systems. Embedding non-removable electrical infrastructure at the point-of-fabrication, however, significantly increases the complexity of the manufacturing process and the cost per chip.

Here we describe a technique to physically embed electrodes into polymer chips at the point-of-use. We connected PDMS-fabricated chips to the power supply (both physically and electrically) by means of punch-through electrode coupling. A schematic of the punch-through process is given in Fig. 1b. The bottom plate of the chip is punctured at each electrode location by applying a light downward pressure with round-tipped tweezers to the top plate of the chip surrounding the corresponding reservoir. This puncture anchors the chip to the power supply, brings the electrode into contact with the working liquid, and forms a quality liquid seal around the electrode. This mechanical sealing attribute of PDMS is another aspect of this material that makes it well suited to microfluidic chips. The electrodes used were 0.5 mm in diameter, and made of platinum with 5% ruthenium for added stiffness. The tips of the electrodes were angled to facilitate a clean entrance into the polymer. The electrodes could withstand repeated punctures into PDMS plates up to 2 mm in thickness without bending or showing signs of fatigue. When the chip is removed, the PDMS base reseals well and, if desired, may be reapplied to the power supply at a latter date. Although in most anticipated applications, the chips are likely to be used only once, multiple on–off couplings were found to be possible with a single PDMS chip. The chip thickness and the electrode length were matched such that each electrode was long enough to make appreciable contact with, and yet be wholly contained within, the reservoir liquid. By not impinging on the free surface, additional capillary-based pressure disturbances are avoided, as are the safety, optical and operational issues associated with free-electrode systems. The punch-through

methodology combines the simplicity, cost, and convenience aspects of single-material polymer chips, with the functional and operational advantages of chips with embedded electrical infrastructure. A similar approach was used by Sanders *et al.*[30] in the development of their PDMS based electrofluidic interface.

Electrical operation and control of the power supply is straightforward. An overview of the simple control circuit used here is shown in Fig. 1a. As can be seen, an onboard switch provides power to the chip and a second onboard switch allows the user to instantly switch between two preset output voltage settings (flush/dispense, or load/dispense *etc.*). Output voltages in each set were adjustable using the 5 Ω potentiometers onboard the power supply up to a maximum of 700 V at 12 V input voltage. High resistance potentiometers were used in the voltage divider circuit to reduce the total power load. The onboard controls provide basic, ready-to-operate control; however, the device may also be readily attached to common timing control devices, such as a pulse or delay generator, to achieve precise timing between cycles, modulated operation to dilute a sample to an intermediate concentration, or more complicated objectives such as the 'ramping' of concentration exposure. The electrical workings of the device are straightforward, using DC voltage amplification *via* a micro-transformer (EMCO High Voltage, Sutter Creek, CA) in conjunction with a high impedance 2-stream parallel voltage divider. It is important to note that the details of the electrical design are somewhat application specific. Particularly regarding the placement of the electrodes, their locations must match that of the reservoirs on the chips they are intended to power. Thus in the lab, different designs are required for different analytical processes. In the context of capital costs, however, these power supplies are quite inexpensive, with a projected mass production cost of less than $100.

Electrokinetic transport in an expansion chamber

The device is designed for use with an electrokinetically operated DNA hybridization chip[31,32] currently under development. The use of electrokinetic transport in DNA hybridisation chips has many advantages, perhaps the most significant of which is the efficiency and speed with which non-specific adsorption can be removed due to the high fluidic shear force near the surface. This chip design, shown in Fig. 2a, consists of a relatively large expansion chamber (5 mm long by 2.5 mm wide by 7 μm high) connected to two inlet reservoirs, for dispensing and flushing, and a single downstream waste reservoir. The expansion chamber platform is designed for use with a temperate gradient perpendicular to the flow (along the 2 mm axis of the sensor surface) in order to better discriminate against single base pair mismatches as is described by Erickson *et al.*[32] in the hybridisation chip.

The PDMS microchips used here were manufactured using a rapid prototyping soft lithography technique[33,34] and sealed through bonding the microchannel cast to another piece of PDMS by placing both sides in a plasma cleaner (PDC-32G, Harrick Scientific, Ossining, New York) for 30 s. After sealing, the chip was coupled to the power supply, using the punch through technique described above, and 25 mM bicarbonate buffer was introduced to the hydrophilic system using capillary driven flow. As mentioned above the soft elastomer conformed well to the electrodes and thus no leaking was detected (even after multiple couplings using the same chip).

Fig. 2b and 2c demonstrate the dispensing and subsequent flushing of Rhodamine 110 dye in bicarbonate buffer (T = 25 °C, pH = 9) using the device. Switching between the two flow modes is accomplished by varying the voltage applied at the sample and buffer reservoirs in such a way that during the dispensing phase the maximum voltage is applied at the sample (Buffer + Rhodamine 110 from Fig. 2) and a lower potential (selectable through the on-board potentiometers as shown in Fig. 1a) applied at the buffer reservoir. Similarly for the flushing stage the maximum potential is applied at the buffer reservoir and a lower potential is applied at the sample reservoir. At pH = 9, Rhodamine 110 is expected to carry charge of −1, and exhibit an approximate electrophoretic mobility of -1.7×10^{-4} cm^2 V^{-1} s^{-1} (this was verified through electrophoretic separations conducted with fluorescein reference standard). Thus the profiles shown in Fig. 2b and 2c are the result of combined convective and electrophoretic transport. The battery output voltage for these cases was recorded as 10.6 V corresponding to a maximum chip supply voltage of approximately 620 V. As can be seen, both the steps were completed in less than 40 s despite the relatively low magnitude of the potential field gradients within the large expansion chamber. A very uniform concentration was obtained over the expansion chamber surface at the completion of the dispensing step, a requirement for quantitative analysis of hybridization kinetics.

Power usage

As the device is designed to be a reusable power supply, it is important to quantify the number of dispensing–flush cycles that can be completed on a single battery. As described above the entire system is run off a single 12 V type MN21 cell battery, shown in Fig. 1, chosen for its compact size, relatively high voltage and common availability. To do the test, the device was processed through a power cycling experiment, using an equivalent resistor circuit, with a 2 min on period (equivalent to that required for the dispensing stage), followed by an 6.3 min no flow dwell time, a second 2 min on period (equivalent to that required for the flushing stage) and a final 6.3 min no flow dwell time. The results of these experiments are shown in Fig. 3. As can be seen the maximum chip supply voltage was approximately 620 V (corresponding to a battery output of 10.6 V, equivalent to the conditions for the experiments shown in Fig. 2). 40 cycles were completed until the

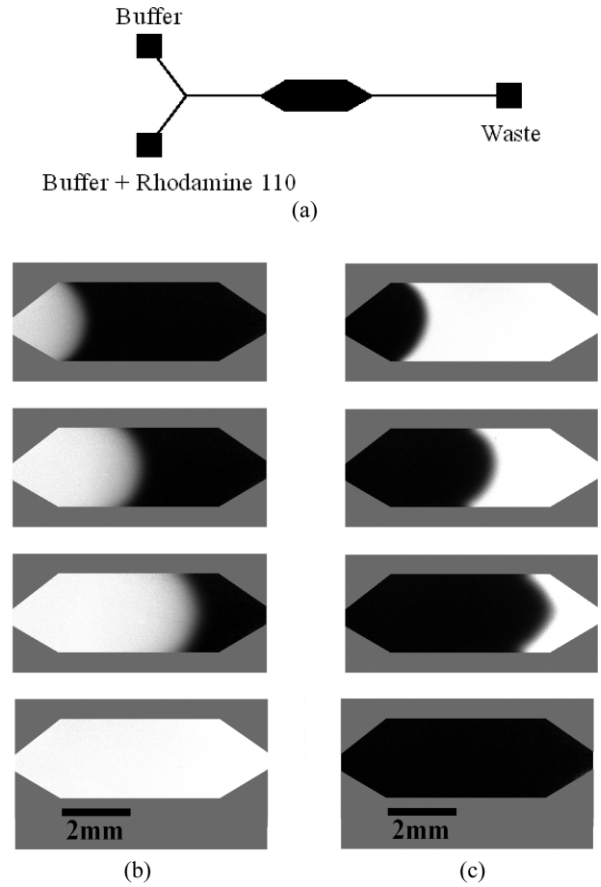

Fig. 2 Transport of Rhodamine 110 dye in a PDMS microfluidic system using the integrated power supply chip. (a) Diagram of channel structure showing 2 mm × 5 mm expansion chamber sensor surface. Time step images taken at 10 s intervals during (b) dispensing stage and (c) flushing stage. Battery voltage during experiments was 11 V resulting in a maximum chip supply voltage of approximately 620 V.

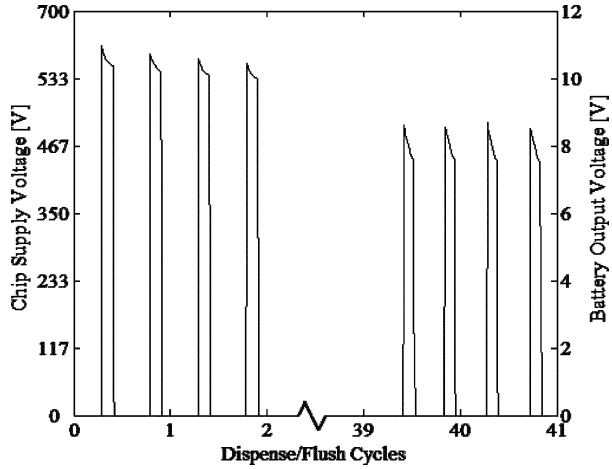

Fig. 3 Battery usage for integrated power supply chip. The equivalent of 40 consecutive dispense–flushing cycles (2 minute dispense, 6.3 minute dwell, 2 minute flush, 6.3 minute dwell) could be completed using a single MN21 cell battery while maintaining 75% of the original output voltage.

battery was unable to maintain the supply voltage above 75% of the initial output (465 V). Total power consumption of the device ranged from 145 mW initially at the maximum voltage down to 71 mW after 40 cycles. An examination of the power usage of the device revealed that roughly 55% of the input power was consumed in the DC-HVDC converter, a further 37% was consumed in the control circuitry (depending on the voltage set points, see Fig. 1a) and the remaining 8% load was consumed in the microfluidic chip. The chip used here had a relatively large channel size, particularly in the expansion chamber, and thus represented a relatively large power/current load compared to most what most electrokinetic chips would consume. Since the chip power consumption represents only a small fraction of the total power consumption, the number of cycles will not depend significantly on the type of chip used.

Summary

In this work we have presented a portable microfluidic device with a reusable integrated high voltage power supply. The device allows for quick exchange of inexpensive disposable poly(dimethylsiloxane) microfluidic chips on a carrier only slightly larger than a microscope slide and is powered by a single onboard battery. A unique electrode "punch-through" system for coupling of the disposable PDMS components has also been described. The power supply is demonstrated through the dispensing and flushing of a fluorescent dye in an expansion chamber geometry. As little as 40 s is required to complete each of these steps and the technique is proven to be very efficient at removing non-specific adsorption. Power cycling experiments demonstrate that the device can be used to accomplish as many as 40 successive flushing–dispensing cycles on a single MN21 cell battery.

Acknowledgements

The authors are thankful for the financial support of the Natural Sciences and Engineering Research Council through a scholarship to D. Erickson and through a research grant to D. Li. Financial support from Glynn Williams, through scholarships to D. Erickson and D. Sinton, is also acknowledged.

References

1 D. Erickson and D. Li, *Anal. Chim. Acta*, in press.
2 Manz, N. Graber and H. M. Widmer, *Sens. Actuators B*, 1990, **1**, 244.
3 M. Kock, A. Evans and A. Brunnschweiler, *Microfluidic Technology and Applications*, Research Studies Press, Hertfordshire, UK, 2000.
4 J. Wang, *Trends Anal. Chem.*, 2002, **21**, 226–232.
5 T. Kappes, P. Schnierle and P. C. Hauser, *Anal. Chim. Acta*, 1999, **393**, 77–82.
6 T. Kappes, B. Galliker, M. A. Schwarz and P. C. Hauser, *Trends. Anal. Chem.*, 2001, **20**(3), 133–139.
7 C. D. García, Y. Liu, P. Anderson and C. S. Henry, *Lab Chip*, 2003, **3**(4), 324.
8 D. J. Jackson, J. F. Naber, T. J. Roussel Jr., M. M. Crain, K. M. Walsh, R. S. Keynton and R. P. Baldwin, *Anal. Chem.*, 2003, **75**, 3311.
9 R. P. Baldwin, T. J. Roussel Jr., M. M. Crain, V. Bathlagunda, D. J. Jackson, J. Gullapalli, J. A. Conklin, R. Pai, J. F. Naber, K. M. Walsh and R. S. Keynton, *Anal. Chem.*, 2002, **74**, 3690.
10 J. D. Holladay, E. O. Jones, M. Phelps and J. Hu, *J. Power Sources*, 2002, **108**, 21.
11 D. R. Palo, J. D. Holladay, R. T. Rozmiarek, C. E. Guzman-Leong, Y. Wang, J. Hu, Y.-H. Chin, R. A. Dagle and E. G. Baker, *J. Power Sources*, 2002, **108**, 28.
12 M. T. McCaman, P. Murakami, E. Pungor Jr., K. M. Hahnenberger and W. S. Hancock, *Anal. Biochem.*, 2001, **291**, 262.
13 Y. R. Sohni, J. P. Burke, P. J. Dyck and D. J. O'Kane, *Clin. Biochem.*, 2003, **36**, 35.
14 J. M. K. Ng, I. Gitlin, A. D. Stroock and G. M. Whitesides, *Electrophoresis*, 2002, **23**, 3461–3473.
15 J. C. McDonald and G. M. Whitesides, *Acc. Chem. Res.*, 2002, **35**(7), 491–499.
16 M. L. Chabinyc, D. T. Chiu, J. C. McDonald, A. D. Stroock, J. F. Christian, A. M. Karger and G. M. Whitesides, *Anal. Chem.*, 2001, **73**, 4491–4498.
17 E. Delamarche, A. Bernard, H. Schmid, B. Michel and H. Biebuyck, *Science*, 1997, **276**, 779–781.
18 R. D. Johnson, I. H. A. Badr, G. Barrett, S. Lai, Y. Lu, M. J. Madou and L. G. Bachas, *Anal. Chem.*, 2001, **73**, 3940–3946.
19 G. B. Lee, S. H. Chen, G. R. Huang, W. C. Sung and Y. H. Lin, *Sens. Actuators B*, 2001, **75**, 142–148.
20 D. L. Pugmire, E. A. Waddell, R. Haasch, M. J. Tarlov and L. E. Locascio, *Anal. Chem.*, 2002, **74**, 871–878.
21 Y. Liu, C. B. Rauch, R. L. Stevens, R. Lenigk, J. Yang, D. B. Rhine and P. Grodzinski, *Anal. Chem.*, 2002, **74** , 3063.
22 R. C. Anderson, X. Su, G. J. Bogdan and J. Fenton, *Nucleic Acids Res.*, 2000, **28**, E60.
23 H. Becker and L. E. Locascio, *Talanta*, 2002, **56**, 267–287.
24 B. S. Cho, T. G. Schuster, X. Zhu, D. Chang, G. D. Smith and S. Takayama, *Anal. Chem.*, 2003, **75**, 1671.
25 M. L. Chabinyc, D. T. Chiu, J. C. McDonald, A. D. Stroock, J. F. Christian, A. M. Karger and G. M. Whitesides, *Anal. Chem.*, 2001, **73**, 4491.
26 S. Qi, X. Liu, S. Ford, J. Barrows, G. Thomas, K. Kelly, A. McCandless, K. Lian, J. Goettert and S. A. Soper, *Lab Chip*, 2002, **2**, 88.
27 S. Hediger, A. Sayah, J. D. Horisberger and M. A. M. Gijs, *Biosens. Bioelectron.*, 2001, **16**, 689.
28 T. Yamamoto, T. Nojima and T. Fujii, *Lab Chip*, 2002, **2**, 197.
29 H. J. Crabtree, E. C. S. Cheong, D. A. Tilroe and C. J. Backhouse, *Anal. Chem.*, 2001, **73**, 4079.
30 J. C. Sanders, M. C. Breadmore, P. S. Mitchell and J. P. Landers, *Analyst*, 2002, **127**, 1558.
31 X. Liu, D. Erickson, D. Li and U. J. Krull, *Anal. Chim. Acta*, in press.
32 D. Erickson, D. Li and U. J. Krull, *Anal. Biochem.*, 2003, **317**, 186.
33 D. C. Duffy, J. C. McDonald, O. J. A. Schueller and G. M. Whitesides, *Anal. Chem.*, 1998, **70**, 4974.
34 D. Erickson, D. Sinton and D. Li, *Lab Chip*, 2003, **3**(3), 141–149.