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Short communication

Fabrication of poly(dimethylsiloxane) microfluidic system based on masters directly printed with an office laser printer

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Abstract

Applications of poly(dimethylsiloxane) (PDMS)-based microfluidic systems are more popular nowadays. Previous fabrication methods of the masters for PDMS microchannels require complicated steps and/or special device. In this paper, we demonstrated that the toner printed on the transparency film with the office laser printer (1200 dpi) can be used as the positive relief of the masters. The transparency film was printed in two steps in order to obtain the same printing quality for the crossed lines. With the laser-printed master, the depth of the fabricated PDMS microchannels was ca. 10 μm and the smallest width was ca. 60 μm. Surface characteristics of the PDMS/PDMS microchannels were performed with SEM. Their electrokinetic properties were investigated by the aids of the measurement of electroosmotic flow (EOF) and the Ohm's curve. Using the PDMS/PDMS microchip CE systems, electroactive biological molecules and non-electroactive inorganic ions were well separated, respectively. This simple approach could make it easy to carry out the studies of PDMS microfluidic systems in more general labs without special devices.

Keywords: PDMS; Master; Microchannel; Amperometric detection; Instrumentation

1. Introduction

The burst development of micro total analytical systems (μTAS) has become the inaugural event during the past 14 years. μTAS can bring about improved performance and low cost of time and reagents as well as high integration of laboratory functions such as reaction, injection, separation and detection, etc. [1–3], Recent developments demonstrated that μTAS would provide both miniaturized analytical instruments [4–7] and powerful platforms for multidisciplinary studies such as biological mimic study [8,9] and biological synthesis [10,11].

Benefited from the well-developed electronic technologies, glass- or silica-based microfluidic systems dominated in the early days of μTAS study due to their similar properties to that of fused silica capillaries [12–15]. But the extensive application of the glass or silica microchips has been greatly limited by their expensive price and long period of production. As a result, polymers [16], such as PMMA [17] and PET [18], etc. were introduced as the substitutes for silica or glass in the fabrication of microfluidic systems because of their cheap price. The application of poly(dimethylsiloxane) (PDMS) has become more and more popular due to its easy fabrication [19,20]. The fabrication of PDMS-based microfluidic systems can be simply performed by: (1) putting the mixture of PDMS monomer and curing agent on the master and (2) heating the mixture under moderate temperature (65–70 °C) [21].

Various methods for the fabrication of the masters have been advanced in the study of PDMS microfluidic systems [22,23,28,29]. In the beginning, Effenhauser et al. used silica wafers with positive surface relief as the masters [22]. Whitesides and co-workers created a rapid prototyping process to make the masters through combining the high-resolution (3386 dpi) printer with contact photolithography [23]. These two processes have been extensively applied in previous reports [24–27] and well reviewed [19,20]. To

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further simplify and accelerate the fabrication of the masters, Whitesides and co-workers improved the above prototyping process using the photographic reduction with office laser printers (600 dpi) to replace the high-resolution printers [28]. In order to fabricate the masters with varying heights, Folch and co-workers developed a μ-FPM (microfluidic photomask) method on the basis of microfluidic channels filled by UV-absorbing water-soluble dye with different concentrations [29]. Ugaz and co-workers fabricated the masters with the photosensitized copper clad circuit board substrates in conventional printed circuit technology [30]. Although such fabrication methods are rapid, they still required photoresisting technology in which complicated steps are inevitable. Thus, some special devices and technology were also introduced for simple fabrication of masters [31–33]. To fabricate three-dimensional PDMS microfluidic structures, Whitesides and co-workers used the solid-object printers to make the master directly [31]. Glennon and co-workers [32] developed the fast fabrication of the masters using the photocopying machine to transfer the printed structure onto the transparency film. Vulto et al. [33] developed a method using the dry film resist to pattern the microfluidic networks. They demonstrated that this protocol could be used in both a well-equipped clean room and a general laboratory. These approaches avoid the photolithographic process but special devices or technology are still needed.

Recently, do Lago et al. constructed the microfluidic systems using two printed mirror-symmetrical transparency films with an office laser printer (600 dpi) [34]. Because the thickness of the printed toner is only ca. 6 μm, the microfluidic device was composed of two transparency films and the printed toner. In this paper we use the transparency film directly printed with the office laser printer (1200 dpi) as a master for PDMS microchannels, which is convenient and inexpensive to fabricate microchannels, because the laser printer is more popular for every common lab than the photocopying machine [32]. The use of laser-printed transparency film as the master is direct and avoids the step of transferring the printed pattern to the transparency film that is necessary for the use of the photocopying machine, which eliminates any error in the transferring step. The height of the printed toner on the transparency film can reach ca. 10 μm so that the toner can be used as the positive relief of the master. Thus, the laser-printed transparency film can become a cheap and good platform for developing new functional parts (such as microreactors and micromixers, etc.) on the PDMS microchip.

Here, with this protocol, the transparency film was printed in two steps in order to obtain the same quality of the orthogonal printing lines. The electrokinetic properties of the PDMS/PDMS microchannels were investigated with the Ohm's curve and electroosmotic flow (EOF) mobility. Moreover, PDMS/PDMS microchip CE systems integrated with end-channel and in-channel electrochemical detectors were constructed for the separation of electroactive biological molecules and non-electroactive inorganic ions, respectively.

2. Experimental section

2.1. Materials and reagents

All reagents were of analytical grade. Sylgard 184 (including PDMS monomer and curing agent) was from Dow Corning (Midland, MI, USA). Dopamine and catechol were purchased from Sigma (St. Louis, MO, USA). NaCl, LiCl, Na_2HPO_4, KH_2PO_4, and NaOH were purchased from Nanjing Chemical Reagents Factory (Nanjing, China). All solutions were prepared with doubly distilled water and passed through a 0.22 μm cellulose acetate filter (Xinya Purification Factory, Shanghai, China). NaCl, LiCl, dopamine and catechol were dissolved in a 20 mM phosphate buffer solution (PBS) (pH 6.98).

2.2. Fabrication procedure of masters and PDMS microchannels

The commercial transparency film was selected as the printing medium. HP 4050 laser printer with cartridge c4127× [35] was used and its highest printing resolution is 1200 dpi. The width of printed lines on the transparency film was set with the graphic software (Adobe Freehand). The printing procedure is described later. The PDMS microchannels were fabricated on the laser-printed transparency film using the procedure of soft lithography [21].

2.3. Apparatus

The homemade microchip holder made of plexiglass has been described previously [36]. Briefly, a precise three-dimensional adjustor (Shanghai Lian Yi Instrument Factory of Optical Fiber and Laser, Shanghai, China) for locating the amperometric detector was integrated on this holder. The interface between the working electrode and the microchannel outlet was adjusted under a stereoscopic microscope equipped with micro-ruler (XTB-1; Jiangnan Optical Instrument Factory, Nanjing, China). A homemade power supply provides two outputs of voltage ranging from 0 to 5000 V. The parameters such as injection voltage, injection time, separation voltage and separation time can be set up via a personal computer. A Hitachi X-650 (Japan) scanning electron microscope (SEM) was employed for the characterization of the printed masters, the crossing part and section of the PDMS microchannels. The calibration of printed line width was performed with Leica DMIRE2 invert fluorescence microscope.

3. Microchip CE procedure

The PDMS microchannel and the PDMS substrate were ultrasonically cleaned orderly with acetone, methanol and water for 10 min each and then dried under infrared lamp before they were sealed to form a PDMS microchip. The constructed PDMS microchannel was firstly conditioned with

100 mM NaOH solution and then the running buffer (PBS) for fifteen minutes. The homemade computer program for power supply controlled the output voltage switching from injection to separation and showed the separation or injection current in the computer screen. For electrophoretic separation, the simplest injection mode without pinch was used. Normally, the solution in the three reservoirs (separation, sample and sample waste) and detection cell should be refreshed after four or five running times.

3.1. Microchip CE with end-channel and in-channel amperometric detection

Amperometric detection was carried out with the three-electrode system including the carbon disk electrode or the coated carbon fiber micro disk electrode, Ag/AgCl reference electrode and Pt wire counter electrode on the Electrochemical Workstation 660 A (CH Instruments, USA) connected to a personal computer. For end-channel amperometric detection mode, the carbon micro disk working electrodes with the diameter of 300 μm was prepared as previously reported [37]. The distance between the working electrode and the microchannel outlet was adjusted to be 10 μm. With this detection mode, dopamine and catechol were used as models of biological molecules. For in-channel amperometric detection mode, the coated carbon fibre micro disk electrode with the diameter of 8 μm was prepared as previously reported [36]. The coated working electrode was mounted into the end of the microchannel outlet with the distance of ca. 60 μm. The theory about this detection mode was also described in previously report [36]. With this detection mode, Na^+ and Li^+ were used as models of non-electroactive inorganic ions. The EOF mobility in PDMS microchannels was also measured with this method.

4. Results and discussion

4.1. Optimization of printing parameters

Presently, a commercial laser printer can offer the resolutions of 1200 and 600 dpi. We compared the performance of a HP 6L laser printer with 600 dpi resolution and a HP 4050 laser printer with 1200 dpi resolution. To fabricate a useful master for PDMS microchannels, the height of the positive relief should be the most important because the height directly determines the aspect ratio of the microchannels [34]. The height of the toner printed with the HP 6L laser printer was only ca. 6 μm [34] that resulted in a small aspect ratio of the fabricated PDMS microchannels. While with the HP 4050 laser printer, the height of printed toner reached ca. 10 μm that resulted in a great improvement of the aspect ratio of the microchannel.

For HP 4050 laser printer (1200 dpi), in order to obtain the identical printing quality for the crossed lines, we printed the two orthogonal lines in two steps (Fig. 1 b and c). Firstly, the transparency film was cut to be a square (21 cm × 21 cm). Then the horizontal lines were printed on the transparency

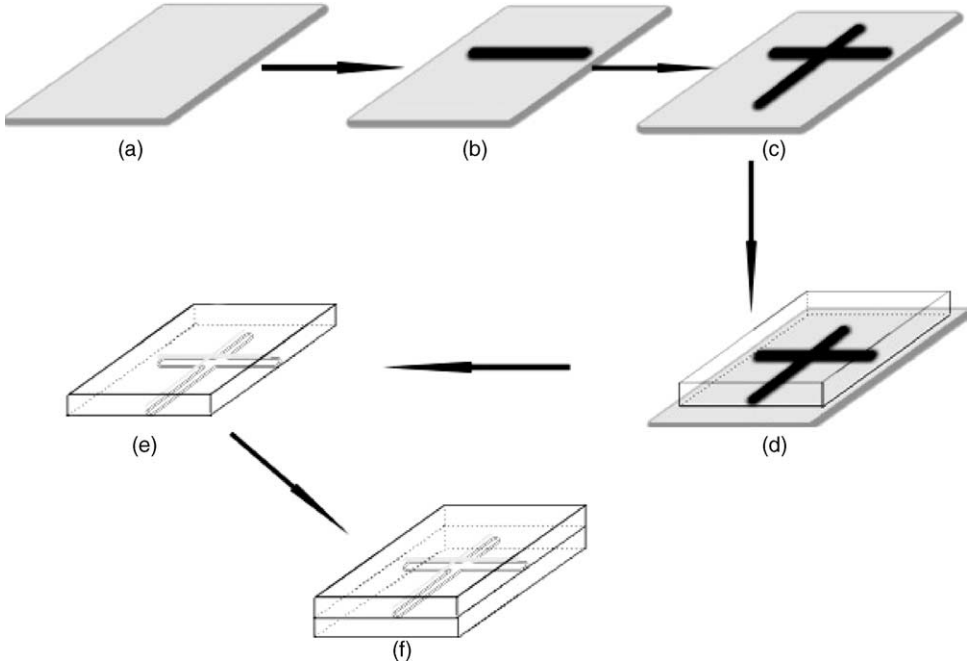

Fig. 1. The whole fabrication procedure of the PDMS microfluidic system with the directly printed master. (a) A transparency film was cleaned and cut to be 21 cm wide and 21 cm long. (b) A horizontal line was printed on the transparency film. (c) After the transparency film was turned 90° another horizontal line was printed on it. (d) The mixture of PDMS monomer and curing agent was cast on the printed transparency film and heated at 70 °C for 1.5 h. (e) The formed PDMS replica with the negative relief was peeled from the transparency film. (f) The PDMS replica was combined with a flat PDMS substrate to construct the PDMS/PDMS microfluidic system.

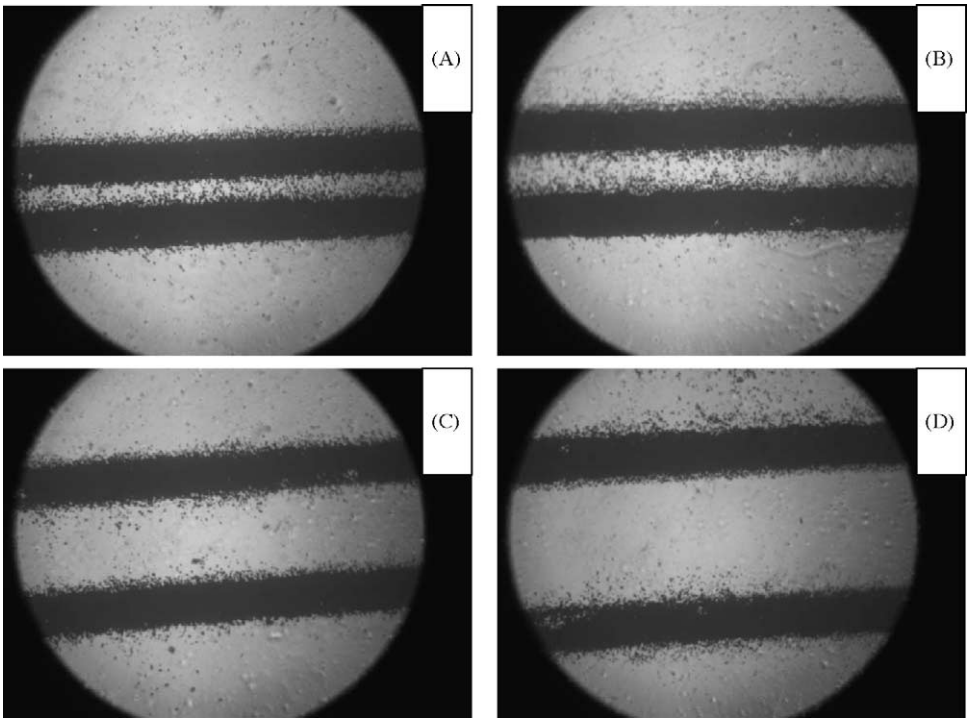

Fig. 2. Images of the two closed lines with the distance of: 100 μm (A); 200 μm (B); 400 μm (C) and 600 μm (D). The width of every line was set to be 200 μm.

film. After that, the transparency film was turned around 90°. Thus, the vertical lines were also printed horizontally. It concerned that the cross section of the printed toner high would be higher than the other parts of the toner. Under the microscope, the height of double printed cross section was measured to be 15 ± 1.5 μm, that was 1.5 higher than that of the printed lines. We also investigated the printing quality of two closed lines with different distance (Fig. 2 A–D). When the distance between the two lines was less than 400 μm, there was some toner between the two printed lines. Therefore, it is feasible to fabricate the microchannel arrays with the presented approach when the distance between the two closed lines in the array was over 400 μm.

In the following experiments, the smallest width of the printed line with good quality was determined. Corresponding to the resolution of 1200 dpi (dots per inch), the size of every printed point is ca. 20 μm (2.54 cm/1200). This means that with the presented resolution, the smallest width of the printed line may be 20 μm. When the line width was set to be less than 50 μm, the actual printed line was dispersed and irregular. While the line width was set over 50 μm, the toner in the printed lines was tight. Here, referencing the concept "the ratio of signal to noise" and assuming the size of every point printed on the transparency as the noise, the actual line width could be regarded as the signal. When the ratio of signal to noise is more than 3, the good printed quality could be obtained. Therefore, the smallest line width with good quality was estimated to be 60 μm.

It should be pointed out that with present approach the total time from the design of the masters to the construction for the PDMS microfluidic systems can be greatly reduced (less than 3 h) without the need of special devices. Moreover, the laser-printed transparency film could be easily treated and the masters can be further improved through the combination with other materials and techniques. Although the surface and edge roughness of the obtained PDMS microchannels need to be further improved and it is difficult to print the curved shapes with satisfactory quality, the separation performance of the obtained microchip (Fig. 4) is similar to that of PDMS microchip based on a master composed of a positive relief structure of GaAs by using standard microphotolithographic technology [37].

4.2. Characteristics of the new PDMS microchannels

We investigated the surface characteristics of the master and the new PDMS microchannels with SEM (Fig. 3). The width of the PDMS microchannels was ca. 175 μm, and the height of the microchannels was ca. 10 μm. Because the toner is the micro-sized particles, there are some defects on the surface and the edge of PDMS microchannel. As far the influence of surface roughness on the separation efficiency, it has been demonstrated to be not significant [23]. The ohm's curve (not shown) for this PDMS/PDMS microchannels was determined with the running buffer of 20 mM PBS. The linearity between current and electric field could maintain well when the electric field is lower than 350 V/cm. When the electric field is larger than 400 V/cm, the departure from linearity becomes larger.

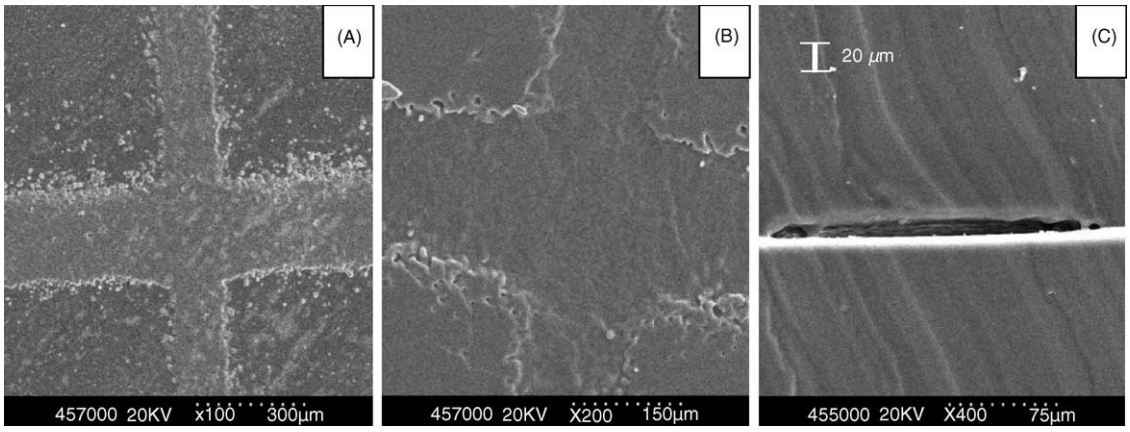

Fig. 3. SEM image of the printed master (A), the cross part (B) and the cross section (C) of the PDMS microchannel.

The EOF mobility in this PDMS/PDMS microchannels was determined with the indirect amperometric detection mode using 20 mM PBS as the running buffer (not shown). The effective separation channel was average 175 μm wide and 4 cm long. The injection channel was 125 μm wide [38]. It is convenient to insert the painted carbon fiber electrode with a diameter of ca. 8 μm into the end of the PDMS microchannel. The migration time of the diluted running buffer (as the neutral marker) was 60.6 s under the applied separation voltage of 1000 V. The EOF mobility (μ_{eo}) of 3.0×10^{-8} m^2/Vs matched well with that previous report [39] under the same pH value.

4.3. Performance of the PDMS/PDMS microchip CE

The PDMS/PDMS microchannel was used for the separation of dopamine and catechol and the end-channel amperometric method was used for their detection. From Fig. 4A, it can be observed that dopamine and catechol are effectively separated. For dopamine, the limit of detection was 2.0 μM. 0.8 mM Na^+ and 1 mM Li^+ were separated and detected with indirect amperometric detection mode (in-channel) [36]. Fig. 4B showed that they were also well separated. With the same running buffer (20 mM PBS), 80 μM Na^+ and 100 μM Li^+ can also be detected (not shown). In our previous work [36,37], the PDMS microchannel was fabricated with the GaAs master. The previous PDMS microchannels consisted of the separation channel with the average width of 50 μm and the average depth of 18 μm. Comparing the separation of biological molecules [37] and inorganic ions [36] in the previous PDMS/PDMS microchannels, present experimental results demonstrated that the fabrication of PDMS/PDMS micrfluidic systems could be performed in more general labs.

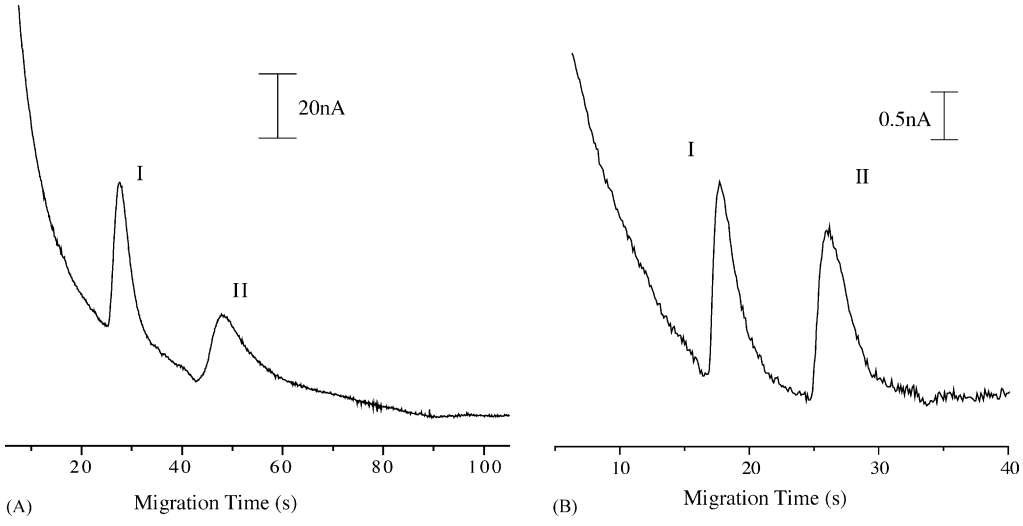

Fig. 4. Electrophoregrams of 100 μM dopamine (I) and 150 μM catechol (II) (A), and 800 μM Na^+ (I), 1 mM Li^+ (II) (B) in the new PDMS microchannel. Experimental parameters: running buffer 20 mM PBS; separation voltage 1200 V (A), 1000 V (B); injection voltage 800 V (A), 600 V (B); injection time 5 s (A), 2 s (B); length of the effective separation channel 4.0 cm; length of the total separation channel 4.5 cm.

5. Conclusion

With the office laser printer and the transparency film, a simple approach to fabricate the masters for PDMS microfluidic system was successfully developed. Experimental results showed that the new PDMS microchannels could be used for the separation of biological molecules and inorganic ions. Due to its low cost and easier combination with other materials and techniques, its extensive application for the study of PDMS microfluidic systems in more general labs can be promising. It is worth to carry out the further studies on presented approach for the construction of microreactors and micromixers in PDMS microfluidic systems.

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References

[1] D.J. Harrison, A. Manz, Z.H. Fan, H. Luedi, H.M. Widmer, Anal. Chem. 64 (1992) 1926.
[2] D.J. Harrison, K. Fluri, K. Seiler, C.S. Effenhauser, A. Manz, Science 261 (1993) 895.
[3] T. Vilkner, D. Janasek, A. Manz, Anal. Chem. 76 (2004) 3373.
[4] S.R. Liu, A. Guttman, Trends Anal. Chem. 6 (2004) 422.
[5] D. Bandilla, C.D. Skinner, J. Chromatogr. A. 1044 (2004) 113.
[6] N. Lion, T.C. Rohner, L. Dayon, I.L. Arnaud, E. Damoc, N. Youhnovski, Z.Y. Wu, C. Roussel, J. Josserand, H. Jensen, J.S. Rossier, M. Przybylski, H.H. Girault, Electrophoresis 24 (2003) 3533.
[7] J. Khandurina, A. Guttman, Curr. Opin. Chem. Biol. 7 (2003) 595.
[8] M.K. Runyon, B.L. Johnson-Kerner, R.F. Ismagilov, Angew. Chem., Int. Ed. 43 (2004) 1531.
[9] C.J. Gerdts, D.E. Sharoyan, R.F. Ismagilov, J. Am. Chem. Soc. 126 (2004) 6327.
[10] T. Thorsen, S.J. Maerkl, S.R. Quake, Science 298 (2002) 580.
[11] C.L. Hansen, E. Skordalakes, J.M. Berger, S.R. Quake, Proc. Natl. Acad. Sci. U.S.A. 99 (2002) 16531.
[12] S.C. Jacobson, A.W. Moore, J.M. Ramsey, Anal. Chem. 67 (1995) 2059.
[13] S.C. Jacobson, J.M. Ramsey, Anal. Chem. 69 (1997) 3212.
[14] K. Seiler, D.J. Harrison, A. Manz, Anal. Chem. 65 (1993) 1481.
[15] C.S. Effenhauser, A. Manz, H.M. Widmer, Anal. Chem. 65 (1993) 2637.
[16] H. Becker, L.E. Locascio, Talanta 56 (2002) 267.
[17] J.Y. Cheng, C.W. Wei, K.H. Hsu, T.H. Young, Sens. Actuators B 99 (2004) 186.
[18] F. Bianchi, H.J. Lee, H.H. Girault, J Electroanal. Chem. 523 (2002) 40.
[19] J.C. McDonald, D.C. Duffy, J.R. Anderson, D.T. Chiu, H.K. Wu, O.J.A. Schueller, G.M. Whitesides, Electrophoresis 21 (2000) 27.
[20] S.K. Sia, G.M. Whitesides, Electrophoresis 24 (2003) 3563.
[21] J.C. Mcdonald, G.M. Whitesides, Acc. Chem. Res. 35 (2002) 491.
[22] C.S. Effenhauser, G.J.M. Bruin, A. Paulus, M. Ehrat, Anal. Chem. 69 (1997) 3451.
[23] D.C. Duffy, J.C. McDonald, O.J.A. Schueller, G.M. Whitesides, Anal. Chem. 70 (1998) 4974.
[24] C.C. Wu, R.G. Wu, J.G. Huang, Y.C. Lin, H.C. Chang, Anal. Chem. 75 (2003) 947.
[25] N.J. Sniadecki, C.S. Lee, P. Sivanesan, D.L. DeVoe, Anal. Chem. 76 (2004) 1942.
[26] T. Buranda, J.M. Huang, V.H. Perez-Luna, B. Schreyer, L.A. Sklar, G.P. Lopez, Anal. Chem. 74 (2002) 1149.
[27] R.S. Martin, A.J. Gawron, S.M. Lunte, C.S. Henry, Anal. Chem. 72 (2000) 3196.
[28] T. Deng, H.K. Wu, S.T. Brittain, G.M. Whitesides, Anal. Chem. 72 (2000) 3176.
[29] C.C. Chen, D. Hirdes, A. Folch, Proc. Natl. Acad. Sci. U.S.A. 100 (2003) 1499.
[30] A.P. Sudarsan, V.M. Ugaz, Anal. Chem. 76 (2004) 3229.
[31] J.C. McDonald, M.L. Chabinyc, S.J. Metallo, J.R. Anderson, A.D. Stroock, G.M. Whitesides, Anal. Chem. 74 (2002) 1537.
[32] A.M. Tan, K. Rodgers, J.P. Murrihy, C. O'Mathunab, J.D. Glennon, Lab Chip 1 (2001) 7–9.
[33] P. Vulto, N. Glade, L. Altomare, J. Bablet, L. Del Tin, G. Medoro, I. Chartier, N. Manaresi, M. Tartagnia, R. Guerrieria, Lab Chip 5 (2005) 158.
[34] C.L. do Lago, H.D.T. da Silva, C.A. Neves, J.G.A. Brito-Neto, J.A.F. da Silva, Anal. Chem. 75 (2003) 3853.
[35] Material Safety Data Sheet for the HP LaserJet Print Cartridge C4127×, Hewlett-Packard: Boise, ID, 2002.
[36] J.J. Xu, N. Bao, X.H. Xia, Y. Peng, H.Y. Chen, Anal. Chem. 76 (2004) 6902.
[37] N. Bao, J.J. Xu, Y.H. Dou, Y. Cai, H.Y. Chen, X.H. Xia, J. Chromatogr. A 1041 (2004) 245.
[38] C.X. Zhang, A. Manz, Anal. Chem. 73 (2001) 2656.
[39] A.M. Spehar, S. Koster, V. Linder, S. Kulmala, N.F. de Rooij, E. Verpoorte, H. Sigrist, W. Thormann, Electrophoresis 24 (2003) 3674.