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# Hot embossing as a method for the fabrication of polymer high aspect ratio structures

Holger Becker *,1, Ulf Heim

*Jenoptik Mikrotechnik, Göschwitzer Str. 40, D-07745 Jena, Germany*

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**Abstract**

Polymer microfabrication methods are becoming increasingly important as low-cost alternatives to the silicon or glass-based MEMS technologies. We present in this paper the technology of hot embossing as a flexible, low-cost microfabrication method for polymer microstructures, which uses the replication of a micromachined embossing master to generate microstructures on a polymer substrate. With this fabrication technology high aspect ratio structures can be fabricated over large surface areas, which allows a commercially successful manufacturing of polymer microcomponents. 

*Keywords:* Polymer microfabrication; Hot embossing; Microfluidics; μ-TAS

## 1. Introduction

The commercialization of microsystem technology requires low-cost microfabrication methods, which are suitable for high-volume production. Particularly in the field of microsystems in the Life Sciences with applications like DNA sequencing or clinical diagnostics, disposable devices on a biocompatible substrate are in great demand. These devices often require large surface areas to allow either a massively parallel processing of samples [1] or long microchannel length for good analysis performance. The same trend can be found in micro-optics, where particularly waveguide applications [2] tend to be comparatively large devices with several centimeters in length. In contrast to the substrates silicon, glass, or quartz, which are still used in most microfluidic systems (for a review see, e.g., [3]), polymers offer a variety of advantages:

- Wide range of material properties and surface chemistries available, to optimize the substrate according to the application.
- Suitable microfabrication technologies for a large variety of geometries (rectangular, rounded, high aspect ratios, etc.).
- Low conductivity for electrokinetic pumping or electrophoretic separation.
- Low material cost for high-volume fabrication (necessary for disposable devices).
- Ease of manufacturing due to replication methods.

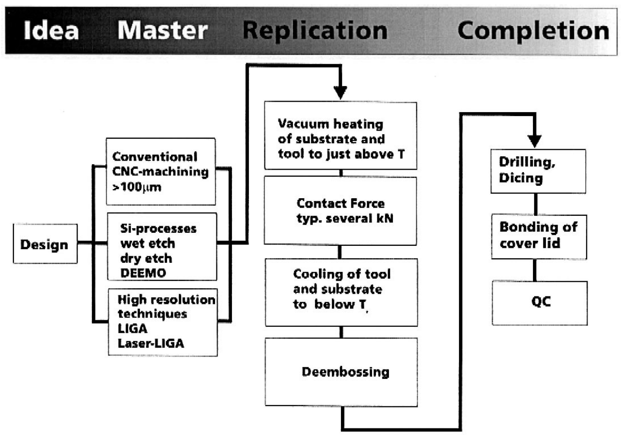


Fig. 1. Process schematics of the hot embossing process.

* Corresponding author. Tel.: +49-3641-652464; fax: +49-3641-653562.
*E-mail address:* holger.becker@jenoptik.com (H. Becker).
[1] www.jo-mikrotechnik.com.

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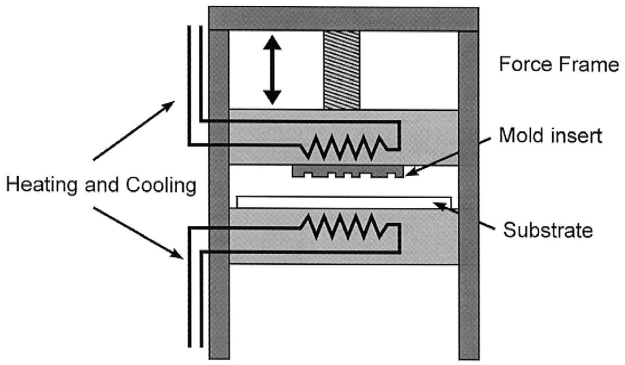


Fig. 2. Schematic drawing of the hot embossing equipment.

In many of these Life Science applications, a trend towards high aspect ratio structures can be seen recently. This tendency has several reasons:

- Achievement of a higher active surface area per unit substrate surface area. This is particularly important for chemical or biochemical applications like microreactors [4], micromixers, chromatographic columns [5] or DNA concentrators [6].
- Possibility of higher packing densities of microstructural elements, which can be observed in trends of massive parallelization of MEMS functions, e.g. in DNA separations [1] or nanowell-plates [7].
- Higher throughput in continuos flow systems due to higher cross-sections per unit substrate area (alternatively lower flow back pressure at constant flow).

The solution to the fabrication and material problems for the production of these structures lies in the use of polymers as substrate materials and replication methods for the component fabrication.

## 2. Microfabrication by hot embossing

We already have established hot embossing as a suitable and flexible process for the fabrication of polymer micro-components [8]. The process is shown schematically in Fig. 1. After designing the microstructure, a replication master is fabricated. In most cases, the embossing master is fabricated photolithographically, the patterned photoresist can be electroplated in a nickel galvanic bath, which, after resist stripping, yields a nickel embossing tool. Alternatively, in the so-called DEEMO-process [9], the resist is patterned on a silicon substrate, which is then dry etched and consecutively electroplated. Silicon can also be used directly as an embossing tool [10], which allows a low cost access to high aspect ratio structures due to the advances in silicon deep dry etching. While in the past tool fabrication with advanced silicon etch processes (ASE or BOSCH-process) suffered from the high roughness of the etched silicon and undercuts at the bottom of etched trenches, novel process developments [11] show great potential for the use of dry etched silicon structures as embossing tools. Finally, LIGA [12] is a well established method for the production of high aspect ratio structures, but so far lacks the commercial viability due to its cost structure.

After obtaining the embossing master, it is mounted in the embossing machine (see Fig. 2). This machine mainly consists of a force frame which delivers the embossing force via a spindle and a T-bar to the boss. The embossing tool and the planar polymer substrate are mounted on heating plates, which contain also cooling channels. In these channels, a high heat capacity oil is circulated in the cooling phase which allows active cooling with cooling times equivalent to heating times at about 1 minute between upper and lower cycle temperatures. This configuration allows an isothermal heating and cooling of both tool and substrate. At the beginning of the embossing cycle, both are heated separately in a vacuum chamber at about $10^{-1}$ mbar to a temperature just above the glass transition temperature $T_g$ of the polymer material. For most standard thermoplastic materials like polymethylmetacrylate (PMMA) or polycarbonate (PC) this temperature is in the range of 100–180°C (PMMA 106°C, PC 150°C). The tool is brought into contact with the substrate and then embossed with a sensor feedback controlled force, typically of the order of 20–30 kN. Still applying the embossing force, the tool–substrate sandwich is then cooled to just below $T_g$ to stabilize again the polymer microstructure.

To minimize thermally induced stresses in the material as well as replication errors due to the different thermal expansion coefficients of tool and substrate (typical values for the thermal expansion coefficient of polymers are of the order of $7 \times 10^{-5}$/K, while silicon has about $1.5 \times 10^{-6}$/K and nickel around $1 \times 10^{-5}$/K), this thermal cycle should be as small as possible, in our case currently about 30°C. After reaching the lower cycle temperature,

Table 1
Material and process conditions for the embossing of PMMA and PC
Process data range represents the dependence on structural design parameters.

| Material | Density ($10^3$ kg/m$^3$) | $T_g$ (°C) | Young's modulus (MPa) | Embossing temperature (°C) | Deembossing temperature (°C) | Embossing force (4 in.) (kN) | Hold time [s] |
|---|---|---|---|---|---|---|---|
| PMMA | 1.17–1.20 | 106 | 3100–3300 | 120–130 | 95 | 20–30 | 30–60 |
| PC | 1.20 | 150 | 2000–2400 | 160–175 | 135 | 20–30 | 30–60 |

the embossing tool is mechanically driven apart from the substrate, which now contains the desired features. It now can be processed further.

Table 1 gives an overview for the process parameters used for the embossing of PMMA and PC. For every design of a microstructure, the process conditions vary slightly, as properties of the design like the distribution of large and small structures over the wafer area, total processed wafer area and geometry of the structures (i.e., radius of curvature, free-standing structures or connected structures) come into play. Therefore the parameters given in Table 1 vary in the range indicated. The term ''Hold Time'' denotes the time at the upper cycle temperature with applied embossing force. The main difference in this process in comparison to existing replication techniques like in the CD industry lies in the fact that both the tool and the substrate are thermocycled here, while for CD manufacturing, the heated material is molded in a cool cavity which remains at a constant temperature below $T_g$. To achieve higher aspect ratios than on a CD (aspect ratio of CD pits about 0.2) and a good mold fill, this thermocycling, however, is necessary.

To emboss high-aspect-ratio structures, in addition the following process and material properties have to be taken into account:

· Sidewall roughness of the embossing master: To obtain an undamaged structure, the frictional forces between the embossing tool and the polymer microstructures in the deembossing process have to be minimized. The microstructure is destroyed if the frictional forces become larger than the local tensile strength of the polymer. Therefore in the master fabrication process care has to be taken to insure a minimal sidewall roughness; 80 nm RMS is an empirical limit for the fabrication of structures with an aspect ratio larger than 0.5. For this reason, the LIGA process is perfectly suited for the high aspect ratio structure fabrication as the side wall roughness can be as little as 10 nm RMS. Recently, surface roughnesses of only 8 nm have been reported for ASE processed silicon [11], which would allow for very good replication properties.

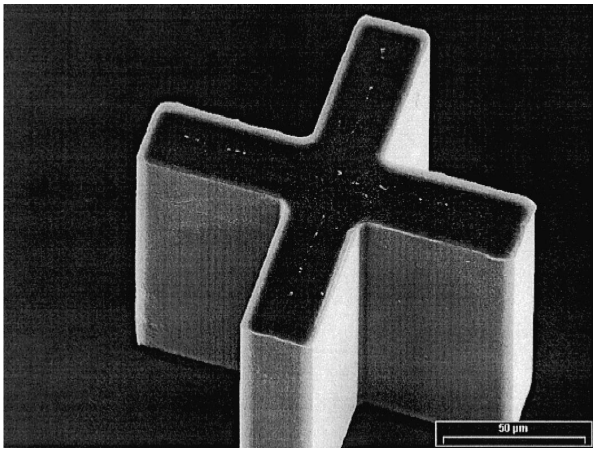


Fig. 4. Free standing test structure in PC with an aspect ratio of 7.

· Sidewall angles: The above described friction between master and substrate is particularly critical in microstructures with vertical sidewalls. Already, a small deviation from the vertical eases this constraint, as mechanical contact between tool and substrate is immediately lost in the deembossing step. If the application and master fabrication allow wall angles different from 90° [13], this is advantageous in the fabrication process.

· The chemical interface between master and substrate. To minimize stiction between embossing master and the polymer material, which creates an additional force in the deembossing step, both surfaces should offer as little chemical surface bonding sites as possible. Although release agents can be added to the polymer which allow the realization of aspect ratios of up to 50 [15], applications in the Life Sciences prohibit the use of these materials due to a potential sample contamination.

· Temperature coefficients: As in the hot embossing, a temperature gradient is involved, the difference in the temperature coefficients of tool and substrate material has

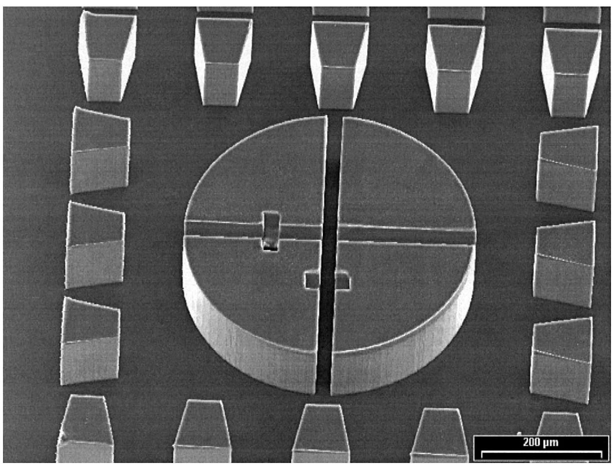


Fig. 3. Test structures in polycarbonate (PC).

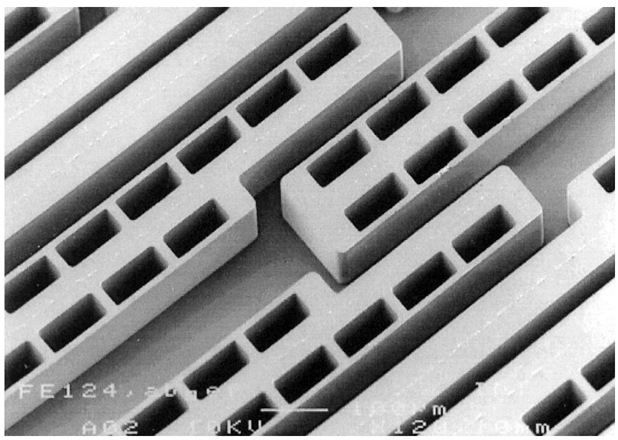

Fig. 5. PMMA structure made from a LIGA mold for the fabrication of a three-dimensional acceleration sensor.

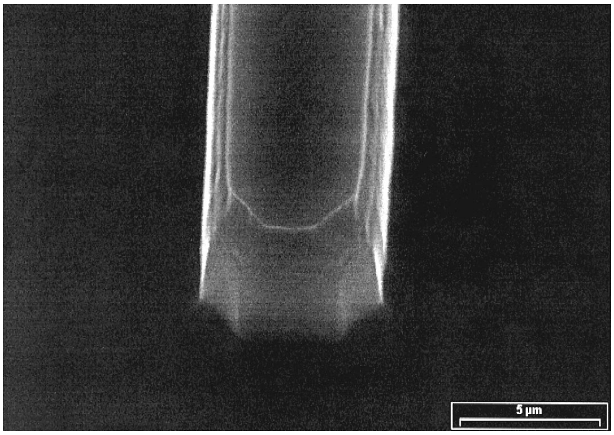


Fig. 6. Detail of a silicon tool fabricated with an RIE process. Width of the ridge is 8 μm, the height is 12 μm.

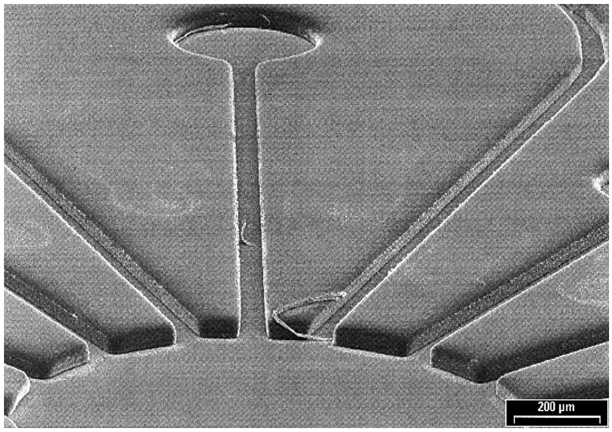


Fig. 8. Channel array of a flow cytometry system on a PC substrate fabricated with a silicon RIE-tool.

to be taken into account to avoid the creation of additional forces due to the larger shrinkage of the polymer material in comparison to the tool material.

For any commercial production of microstructured components, a high throughput of the fabrication technology is crucial. In the replication methods this translates to a multiple tool or to an as large area for embossing as possible. We have generally utilized a 4-in. embossing area to fabricate our polymer microstructures, which requires embossing forces of the order of up to 30 kN.

## 3. Experimental devices

To demonstrate typical geometries and the homogeneity of the fabrication process, Figs. 3 and 4 show test structures fabricated in polycarbonate (PC) with a LIGA fabricated nickel tool. While Fig. 3 shows a channel with an aspect ratio of 7 (20 μm wide, 140 μm deep) in the circular middle structure, Fig. 4 shows a free standing cross-structure with the same dimensions. It is important to demonstrate this ability of producing positive (i.e., pillar-like structures, e.g., for elements like filters or chromatographic columns) and negative (e.g. channels and wells) shaped features with respect to the substrate surface. The verticality of the side walls and their very smooth surface are characteristic for the LIGA process and allows a very good replication of the master structures.

In Fig. 5, a LIGA tool was used to prepare PMMA structures as electroplating cavities for the seismic masses of a three-dimensional acceleration sensor [14,15]. The height of the structure is 150 μm, the width of the small beams is 8 μm, therefore an aspect ratio of 19 could be realized. These aspect ratios can only be achieved with additional plastizisers and release agents in the polymer material. These additives however increase the autofluorescence of the material. For microfluidic applications they are therefore normally not suited, which in some cases can limit the achievable aspect ratios. For practical applications in the form of capillary electrophoresis (CE) manifolds, 4-in. silicon masters were fabricated using various reactive ion etching techniques. The channel networks thereby covered the complete area of the 4-in. wafer. Fig. 6 shows a reactive ion etched silicon tool for the fabrication of microchannels with a cross-section of 8 by 12 μm. The

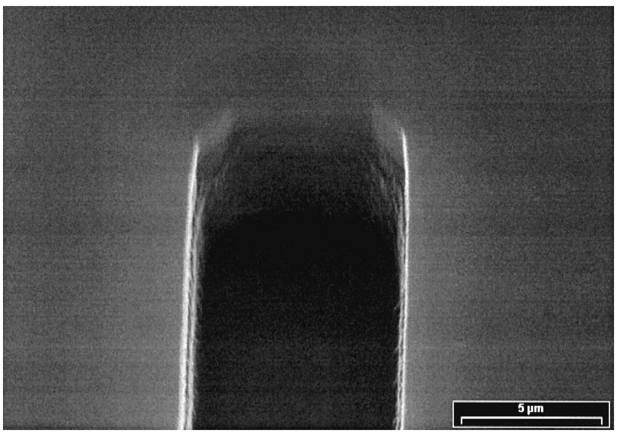


Fig. 7. The structure from Fig. 5 replicated in PMMA.

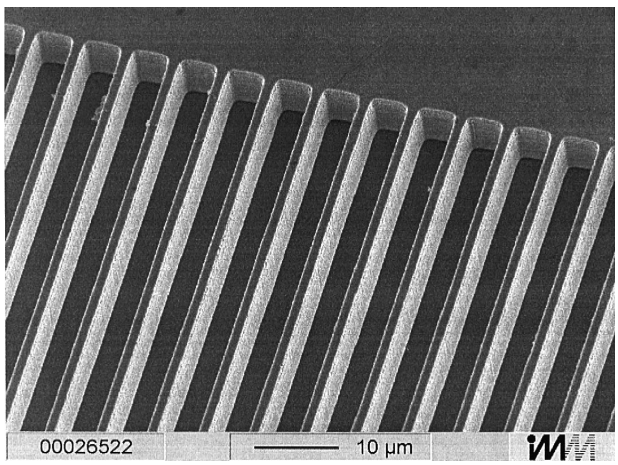


Fig. 9. Silicon tool fabricated using an advanced silicon etch process.

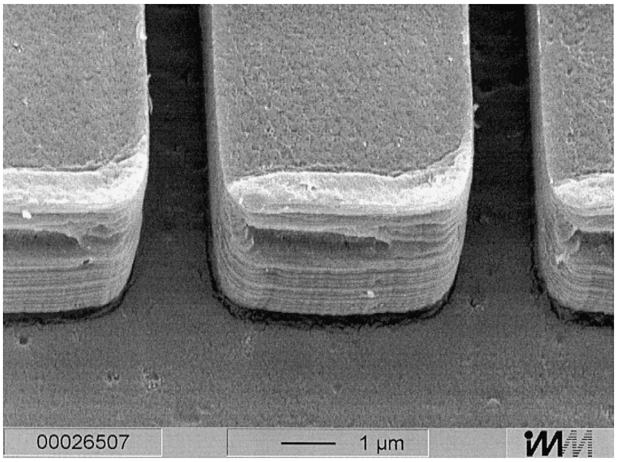


Fig. 10. Replication of this structure in PMMA. The channels are 0.8 μm wide.

master fabrication involved an RIE process developed at the TU Ilmenau, which allows an etch depth of up to 100 μm with an etch rate of up to 2 μm/min. Fig. 7 shows a detail of the resulting embossed structure in a PMMA substrate, the groove having an aspect ratio of about 1.5. The wall angle of the structures resulting from this process deviates several degrees from the vertical, a fact which proves to be useful in the deembossing step.

With this tool-fabrication technology, several CE devices with single channels or channel arrays were fabricated. Fig 8. shows a more complex structure for flow cytometry with channels with a cross-section of 50 by 50 μm in a polycarbonate substrate (Structural design: O. Geschke, MIC, Lyngby, Denmark).

For even higher aspect ratios, an advanced silicon etch process in an STS-ICP-reactor was used. The layout of the structure, a two-dimensional channel array for 2D-capillary electrophorsis, was previously reported elsewhere [16]. A cross-section of the silicon tool can be seen in Fig. 9, the ridges being 0.8 μm wide, 5 μm high with a 5-μm pitch. In Fig. 10, this tool has been replicated in PMMA, the submicron channel array can be clearly seen, as well as the slight structural distortion due to the mold release.

## 4. Conclusions

We have demonstrated the fabrication of large area high aspect ratio polymeric structures in PC and PMMA. These structures were realized using the hot embossing process, which allows low cost, flexible fabrication of polymeric microsystems, e.g., microfluidic devices for μ-TAS applications. To achieve these aspect ratios over wafer-scale areas the critical parameters prove to be the embossing tool surface quality and the process temperature cycle. Further work will include the extension of the range of usable materials to high performance, high $T_g$ polymers, glass and metals, the reproduction of features in the deep submicrometer range as well as achieving higher aspect ratios on large areas.

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## References

[1] P.C. Simpson, D. Roach, A.T. Woolley, T. Thorsen, R. Johnston, G.F. Sensabaugh, R.A. Mathies, High-troughput genetic analysis using microfabricated 96-sample capillary array electrophoresis microplates, Proc. Natl. Acad. Sci. U.S.A. 95 (1998) 2256–2261.

[2] A. Rogner, W. Ehrfeld, Fabrication of light guiding devices and fiber coupling structures by the LIGA process, in: Proc. SPIE 1506, 1991, pp. 80–91.

[3] H. Becker, A. Manz, Integrated capillary electrophoresis for chemical analysis, in: H. Baltes, W. Göpel, J. Hesse (Eds.), Sens. Update Vol. 3 VCH, Weinheim, 1998, pp. 208–238.

[4] W. Ehrfeld (Ed.), Proc. 1st International conference on Microreaction Technology, Frankfurt, Springer, Heidelberg, 1998.

[5] D.W. Arnold, C.G. Bailey, M.G. Garguilo, C.M. Matzke, J.R. Wendt, W.C. Sweatt, S.H. Kravitz, M.E. Warren, D.J. Rakestraw, Microseparations and microfluidic studies, in: Proc. Micro-TAS '98, Banff, Canada, 1998, pp. 435–438.

[6] L. Christel, K. Petersen, W. McMillan, M.A. Northrup, Nucleic acid concentration and PCR for diagnostic applications, in: Proc. Micro-TAS '98, Banff, Canada, 1998, pp. 277–280.

[7] R.J. Jackman, D.C. Duffy, E. Ostuni, N.D. Wilmore, G.M. Whitesides, Fabricating large arrays of microwells with arbitrary dimensions and filling them using discontinous dewetting, Anal. Chem. 70 (1998) 2280–2287.

[8] H. Becker, W. Dietz, P. Dannberg, Microfluidic manifolds by polymer hot embossing for μ-TAS applications, in: Proc. Micro-TAS '98, Banff, Canada, 1998, pp. 253–256.

[9] J. Elders, H.V. Jansen, M. Elwenspoek, W. Ehrfeld, DEEMO: A New Technology for the Fabrication of Microstructures, in: Proc. MEMS '95, Amsterdam, 1995, pp. 238–243.

[10] H. Becker, U. Heim, Silicon as tool material for polymer hot embossing, in: Proc. MEMS '99, Orlando, 1999, pp. 228–232.

[11] M. Chabloz, Y. Sakai, T. Matsuura, K. Tsutsumi, Improvement of sidewalls roughness in deep silicon etching, in: Proc. HARMST '99, Kisarazu, Japan, 1999, pp. 26–27.

[12] E.W. Becker, W. Ehrfeld, P. Hagmann, A. Maner, D. Münchmeyer, Fabrication of microstructures with high aspect ratios and great structural heights by synchrotron radiation lithography, galvanoforming and plastic moulding (LIGA Process), Microelectronics Engineering 4 (1986) 35–56.

[13] H. Becker, T. Klotzbücher, Polymer nanowell plates with variable well slope angles, in: Proc. 3rd International conference on Microreaction Technology, Frankfurt, 1999, In press.

[14] O. Rötting, M. Heckele, W. Bacher, Technology for movable microstructures — transfer of laboratory processes to industrial production, Microsystem Technologies 4 (3) (1998) 120–121.

[15] O. Rötting, B. Köhler, F. Reuther, H. Blum, W. Bacher, Production of movable microstructures by aligned hot embossing and reactive ion etching, Proceedings of SPIE 3680 (2) (1999) 1038–1045.
[16] H. Becker, K. Lowack, A. Manz, Planar quartz chips with submicron channels for twodimensional capillary electrophoresis applications, J. Micromech. Microeng. 8 (1998) 24–28.

## Biographies

*Dr. Holger Becker*. Born in 1964, undergraduate studies in physics at University of Heidelberg, postgraduate studies of surface physics at University of Western Australia, Perth (1990), PhD in physics awarded from University of Heidelberg, thesis about chemical sensing with surface acoustic waves (1995), 1995–1997 Research Associate at Imperial College London, Department of Chemistry (Prof. Andreas Manz), with work on miniaturised chemical analysis systems. Joined Jenoptik Mikrotechnik in 1998 as head of New Technologies and Technology Marketing. He was appointed Managing Director of this company in 1999. His main interest lies in the application of microsystem technologies in the Life Sciences.

*Dr. Ulf Heim* was born in 1965. He received his diploma in precision engineering from the Technical University Ilmenau (TUI). Following to fellowships in Tokyo and Sofia he completed his PhD thesis at the TUI and held responsible for an industrial research project. Presently he is with JENOPTIK Mikrotechnik as the R&D principal. His main interests are in the fields of silicon and non-silicon microsystems.