Sensors and Materials, Vol. 11, No. 5 (1999) 297–304
MYU Tokyo

S & M 0373

Polymer Hot Embossing with Silicon Master Structures

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(Received May 31, 1999; accepted August 9, 1999)

Key words: polymer microfabrication, hot embossing, microfluidics

Polymer microfabrication methods have become increasingly important as low-cost alternatives to silicon or glass-based MEMS (Micro-Electro-Mechanical Systems) technologies, mainly for applications in the fields of microoptics and the Life Sciences. In this paper, we present experiments where silicon which has been micromachined with various technologies is used as a tool material for the hot embossing of polymers. This represents a significant reduction in cost and fabrication time of an embossing master in comparison to the previously used electroplated nickel tools, as well as allows access to high aspect ratio structures without the need for complex technologies such as LIGA (Lithographie, Galvanoformung, Abformung = lithography, electroplating, molding) . In addition, the mechanical wear of a silicon tool is much less than that of a conventional nickel tool.

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 chemistry or the Life Sciences,[1] disposable devices on a biocompatible substrate are in great demand. Another field already on the verge of commercial production is microoptics, where many applications require optically transparent materials. The solution to these material problems lies in the use of polymers as substrate materials. Polymers offer a large variety of material properties which allow their optimization for a specific application, and are often available at a reasonable cost. For the manufacture of polymer microcomponents, replication methods, where the relatively expensive step of microfabrication is only performed once and the resulting microstructure is replicated by simple processes into a polymer material, have been established in previous years.[2–7]

These replication methods hold the key for large scale fabrication of polymer microstructures.

We have already established hot embossing as a suitable and flexible process for the fabrication of polymer microcomponents,[8,9] mainly for microfluidic components; applications in microoptics have also been reported.[10–12] Another field where hot embossing has become an important fabrication method is nanotechnology, where the process known as "nanoimprinting" has been used to fabricate structures with features below 100 nm.[13–15]

2. Embossing Process

The hot embossing fabrication process is shown schematically in Fig. 1. After designing the microstructure, an embossing master, which represents the inverse of the final structure, is fabricated. Depending on geometries and dimensions, a variety of technologies are available.

For comparatively large structures with dimensions of the order of 100 μm and above, this can be done with conventional CNC-machining methods in materials such as stainless steel or with micro-electro-discharge machining (μ-EDM). For smaller microstructures, however, one usually requires photolithographic methods. Conventionally, the patterned photoresist is electroplated in a nickel galvanic bath, which after resist stripping yields a nickel embossing tool. Alternatively, in the so-called DEEMO process,[16] the resist is patterned on a silicon substrate, which is then dry-etched and subsequently electroplated. For structures with a very high aspect ratio, processes such as LIGA[17] are suitable for the fabrication of an embossing tool. In all cases, this embossing tool is made of electroplated

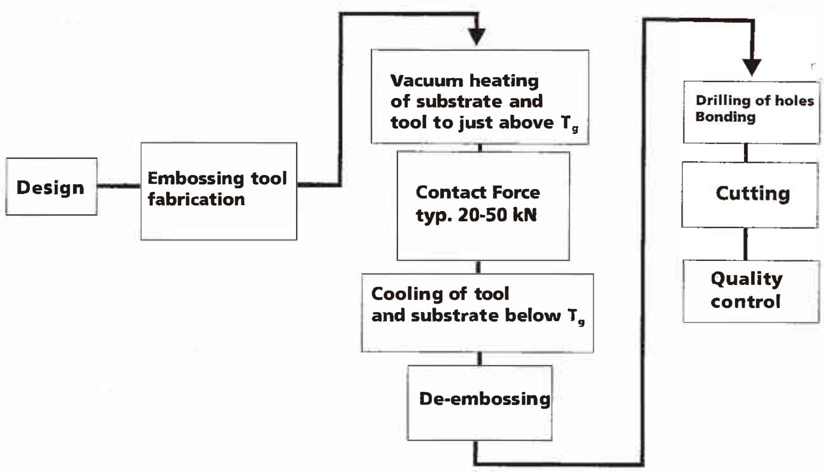

Fig. 1. Schematic of the hot embossing process for the fabrication of microfluidic devices.

nickel or another metal. Important for all fabrication technologies is an exceptional surface quality, as any roughness in the embossing tool creates frictional forces in the mold release step which can destroy the microstructures or damage the tool itself. Typical roughness values R_a for good embossing tools are of the order of 20–50 nm. The above-mentioned tool fabrication processes, however, have several disadvantages:

- nickel is a relatively soft material; therefore, it is prone to abrasion and wear, which limits the number of replication cycles which can be performed with a single tool when emphasis is placed on replication accuracy;
- electroplating is a slow process; therefore, tool manufacturing is not suitable for rapid production, particularly in the case of structures with a high aspect ratio or large absolute heights (30 μm and above);
- voids within the tool can arise in special geometries of the resist structure, particularly in high aspect ratio structures, due to nickel growth not only from the floor of the structure but also from the walls, or due to different growth rates in the middle and close to the wall of deep trenches;
- if the electroplating process takes place on a silicon substrate, due to the growth mechanism of the nickel, high stresses are induced, which bend the substrate dramatically and prevent the formation of flat embossing areas.

  To avoid these critical problems, particularly for industrial production, we performed embossing experiments that substitute nickel tools with silicon structures used directly as embossing tools. Several methods for silicon surface micromachining have been used. Silicon tools have the following advantages:

- suitable material constants in terms of hardness, tensile strength, linear thermal expansion coefficient and thermal conductivity;
- rapid fabrication and low production cost due to the widespread use of silicon in various industries;
- variety of fabrication methods for different geometries readily available;
- very flat and even surfaces, allowing for good mold release.

For nanoimprint applications, silicon and silicon dioxide have been reported to be suitable materials for master fabrication.[13]

After the embossing master is obtained, it is mounted in an embossing machine together with a planar polymer substrate and heated separately in a vacuum chamber to a temperature immediately above the glass transition temperature T_g of the polymer material. For most thermoplastic materials, this temperature is in the range of 120°C – 180°C. The tool is then brought into contact with the substrate, at first with only 10 N to calibrate the force sensor, and then embossed with a controlled force, typically of the order of 20–50 kN for 50–60 s. Still applying the embossing force, the tool-substrate sandwich is then cooled to a temperature immediately below T_g to stabilize the polymer microstructure again. To minimize thermally induced stresses in the material as well as replication errors due to the different thermal expansion coefficients of the tool and the substrate, this thermal cycle should be as small as possible, in our current case, 40°C, but it can be reduced to as low as 25°C. After reaching the lower cycle temperature, the embossing tool is mechanically driven apart from the substrate which now exhibits the desired features. It can now be processed further, e.g., by drilling holes or bonding it to a cover lid to close the channels.

3. Experimental Results

The examples shown are all planar microchannel structures used for miniaturized chemical and biochemical analysis systems (μ-TAS [18]). In the first example, microchannels for capillary electrophoresis chips were fabricated using a master which was fabricated from silicon anisotropically etched with KOH. Embossing in PMMA, this yields channels with the well-known 54.7° wall angle which has the advantage that in the mold release step, the physical contact between embossing tool and structure is immediately lost and therefore, structural deformation due to frictional or shear forces between the embossing master and the substrate is avoided. The resulting structure, the intersection of several microchannels, is shown in Fig. 2. The accuracy of the replication process can be assessed in the inset,

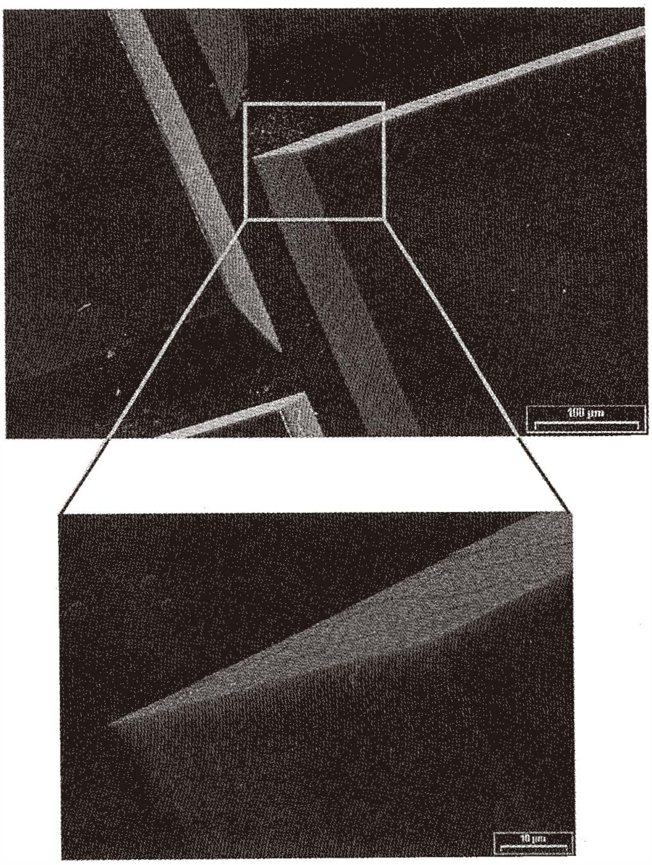

Fig. 2. Microchannel structure fabricated with an anisotropically wet etched silicon tool. The inset shows replication accuracy as etching defects of the tool are clearly visible.

where etching defects of the tool, which were probably caused by a slight misalignment in crystal direction, are clearly replicated. The estimated step height is less than 100 nm.

For more geometrical flexibility, in particular, for forming laterally smooth round curves, circles and vertical walls, and for realizing higher aspect ratios, dry etching under different conditions was employed. Figure 3 shows the details of a reactive ion etched silicon tool for the fabrication of microchannels with a cross section of 8 μm width by 12 μm height. A relatively steep wall angle of approximately 85° is observed, allowing almost vertical walls in the embossed sample with good release properties. The fabrication procedure involved a RIE (reactive ion etching) process developed at TU Ilmenau, which allows an etch depth of up to 100 μm with an etch rate of up to two μm per min. Figure 4 shows the corresponding details of the resulting embossed structure, the groove has an aspect ratio of about 1.5. An exact replication of the lateral structures can be observed, particularly at the edges of the structure. Also, no deformation due to mold release, which usually manifests itself in the form of a lip around the edges, is visible.

For even higher aspect ratios and for structures with truly vertical walls, an advanced silicon etch process (ASE) in an ICP (inductively coupled plasma) reactor was used. The design of the structure, a two-dimensional microchannel array for capillary electrophoresis applications such as protein analysis, was previously reported elsewhere.[19] To achieve maximum separation efficiency, very small channels with a high aspect ratio had to be fabricated. A cross section of the silicon tool can be seen in Fig. 5, the ridges being 0.8 μm wide and 5 μm high, with a 5 μm pitch and a total of 500 channels. In Fig. 6, this tool has been replicated in PMMA: the submicron channel array with an aspect ratio of about 5 can be clearly seen, as well as the slight structural distortion due to mold release. In this case,

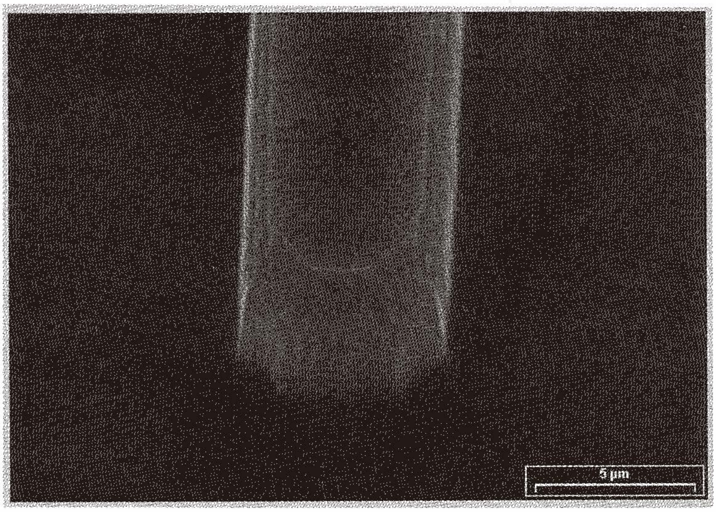

Fig. 3. Details of a silicon tool fabricated by an RIE process. Aspect ratio is approx. 1.5.

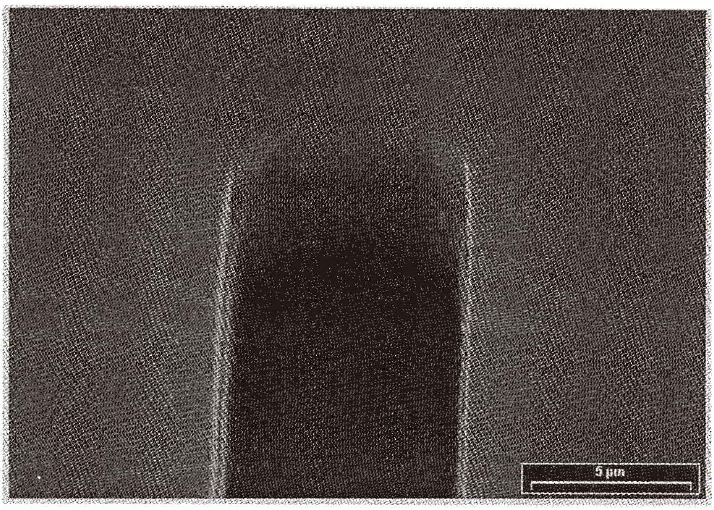

Fig. 4. Details of a structure embossed in PMMA with the tool shown in Fig. 3.

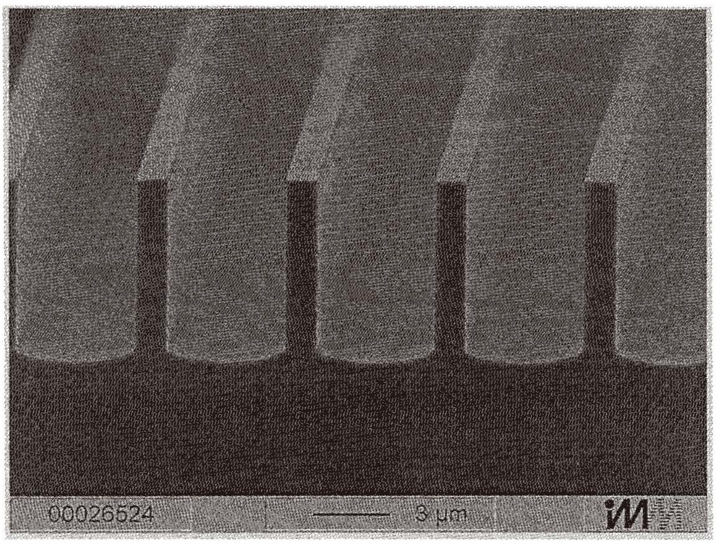

Fig. 5. Silicon tool fabricated by an ASE process. The ridges are 800 nm wide. Very high aspect ratios (>10) are easily realized with this technology.

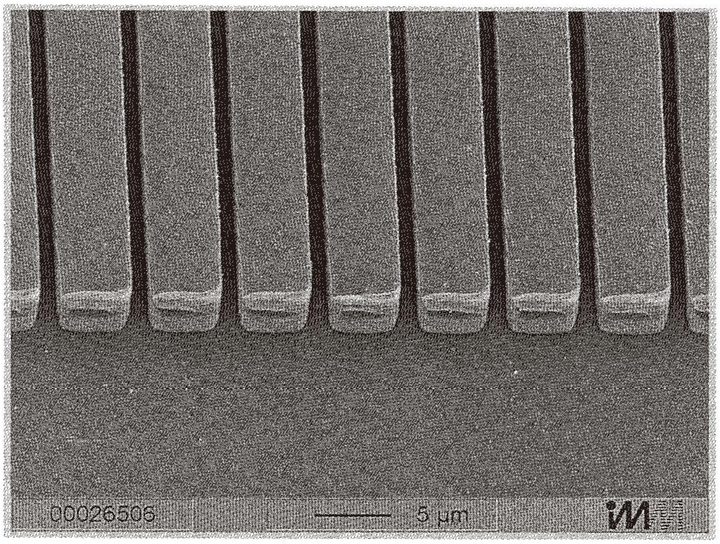

Fig. 6. Embossed microchannels in PMMA. The embossed structure is characterized by vertical sidewalls and very smooth surfaces.

mold release was performed manually, which led to the slight damage around the edges of the structure due to some shear force. Nevertheless, these deformations are on the order of approximately 50–100 nm and do not limit the functionality of the device. On the other hand, the structures display vertical walls and very smooth surfaces, which allow a wide range of applications of structures fabricated with this technology.

4. Conclusions

We have demonstrated with various examples the usability of silicon micromachined structures as tools for the fabrication of polymer micro-components by hot embossing. Embossing tools have been fabricated with wet etched silicon, dry etched silicon and with an advanced silicon dry etch process. All tools yielded very good replication results, no detectable wear and good de-embossing properties due to low stiction and friction. The material properties of silicon and the wide range of available silicon micromachining techniques make it superior to the nickel embossing tools used thus far. Due to the widespread availability of silicon micromachining technologies, these tools are particularly suitable for rapid prototyping applications, where a short turnaround time is desired. The only remaining drawback is the brittleness of silicon, which limits the lifetime of the tools, as small features on the tool tend to break off easily. The lifetime of silicon tools therefore strongly depends on the aspect ratio as well as the individual design. As a rule of thumb, tools with an aspect ratio around one last for several hundred embossing cycles, while for lower aspect ratios we have not yet approached a limit of embossing cycles. The breaking of the silicon is however a statistical process, therefore only average numbers for the lifetime can be given. This is in contrast to nickel based tools, which show gradual wear. Earlier damages of the silicon wafer, which can lead to stress fracture, also influence the lifetime. The applications shown in this study are, however, limited to the field of microfluidics. The question of whether the wall roughness of various silicon processes is sufficient for microoptical applications such as waveguides or microlenses will be subject to further investigation. The latest reports on the advances of ASE processes[20] suggest that the surface roughness approaches values which are acceptable also for optical applications.

Acknowledgements

Part of the work was carried out under the tutelage of Professor Andreas Manz at the Department of Chemistry, Imperial College, London and at IMM Mainz under EU-LSF contract CHGE-CT-0052. We would like to thank Norbert Schwesinger from TU Ilmenau for the fabrication of RIE silicon tools.

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