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Nanoimprint lithography process chains for the fabrication of micro- and nanodevices

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Abstract. The nanoimprint lithography (NIL) process with its key elements molding and thin film pattern transfer refers to the established process chain of resist-based patterning of hard substrates. Typical processes for mass fabrication are either wafer-scale imprint or continuous roll-to-roll processes. In contrast to this, similar process chains were established for polymeric microelements fabricated by injection molding, particularly when surface topographies need to be integrated into monolithic polymer elements. NIL needs to be embedded into the framework of general replication technologies, with sizes ranging from nanoscopic details to macroscopic entities. This contribution presents elements of a generalized replication process chain involving NIL and demonstrates its wide application by presenting nontypical NIL products, such as an injection-molded microcantilever. Additionally, a hybrid approach combining NIL and injection molding in a single tool is presented. Its aim is to introduce a toolbox approach for nanoreplication into NIL-based processing and to facilitate the choice of suitable processes for micro- and nanodevices. By proposing a standardized process flow as described in the NaPANIL library of processes, the use of establish process sequences for new applications is facilitated.
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Keywords: nanoimprint lithography; injection molding; microcantilever; micromechanical element; polymer film.

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1 Introduction

Molding processes leading to surface-patterned polymer components typically consist of three principal processes: origination, tooling, and replication, often followed by post-processing steps, such as assembly, integration into frames with a macroscopic interface, and packaging. This is valid for replication processes of components with different structure sizes and applications, such as surface topographies for diffractive optical elements (DOE)[1–4] or high-aspect-ratio (HAR) microstructures for micromechanical elements with microfluidic channels.[5–9] These principal processes involve many more process steps, i.e., design, process simulation, stamp copying, transformation into a working tool with appropriate structural resolution, area enlargement, and even the integration of mixed micro- and nanostructures with three-dimensional (3-D) features.

When combined into a sequence, this is called the process chain. For production, design issues are closely interlinked with each process step and determine whether the goals of the end user can be met. This results in a value chain for which not only technological aspects, but also cost of ownership need to be considered, i.e., costs of equipment, need for backup, infrastructure, and manpower. Where standard processes are difficult to establish, processes need to be selected from a process pool ranging from established microfabrication processes to approaches and materials used in research. This is called replication toolbox. In the following, two main processes using this toolbox are presented: the first process is nanoimprint lithography (NIL), because it is a high-resolution pattern technique method based on molding of thin polymer layers, and has become a candidate to replace the existing photolithography techniques based on exposure. The second process is injection molding for polymeric microelements, which uses an established mass fabrication technique that has been downscaled to meet the requirements of polymer elements with only a few cubic millimeters of volume. As an example, we have chosen microcantilevers, which are micromechanical elements with lateral dimensions of a few micrometers. By using hybrid molds for injection molding, these elements can be surface patterned to add functionalities. The aim of this is not only to illustrate the similarities of the process chain library concepts, but also to demonstrate how NIL and injection molding complement each other in future toolbox concepts.

2 Nanoimprint Lithography

NIL relies on the same toolbox as that for typical replication processes but with two main differences:[10–13] It uses cleanroom-based micromachining techniques for stamp fabrication and silicon or comparable materials (semiconductors, fused silica, glass, and sapphire) as substrates, and it heads toward thin polymeric films where the sizes and heights of the structures become comparable to the films to be patterned. While it exhibits a large potential as a manufacturing process for a range of nanoscale surface topographies, its definition as "lithography" is only valid for specific applications. The process chain is, therefore, often composed of origination, replication, and pattern transfer, in which the last step is the transformation of the surface topography in the thin polymer film into a different material, e.g., by using it as a masking layer for etching into the substrate or for metallization. The three principle processes are depicted in Fig. 1.

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The existence of many choices of processes and variants thereof, with a high interdependence of steps, makes it difficult to select them for a process chain without knowing their requirements from previous and consequences for following steps in the chain. In Fig. 1, the left column of processes depicts the standard NIL process (with its main replication variants thermal and UV-assisted NIL). While stamp copying and tooling are added to the origination, step and repeat and roller NIL variants are added to the replication section. Particularly interesting are resolution enhancement methods by using spacer etching techniques and directed self-assembly of block copolymers.[14,15] For pattern transfer, only the most prominent processes are displayed. In Fig. 2, the resulting process chain is presented.

Because mold manufacturing needs the knowledge base of specialists coming from other disciplines than toolmakers, mold origination uses a range of processes with specific restrictions in design, sizes, and material. The original sometimes may be directly used for replication, but often does not yet fulfill the requirements of the molding process in terms of size, flexibility, or durability. Therefore, a replication process is used for generation of single, or even multiple mold copies. For several reasons, metal molds are preferred by industrial customers using injection molding and roll embossing, and electroplating made it possible to copy the surface topography of an original in polymer or silicon into a metal tool, which meets the prerequisites for high-throughput manufacturing processes outside a cleanroom. For manufacturing, the original with the surface

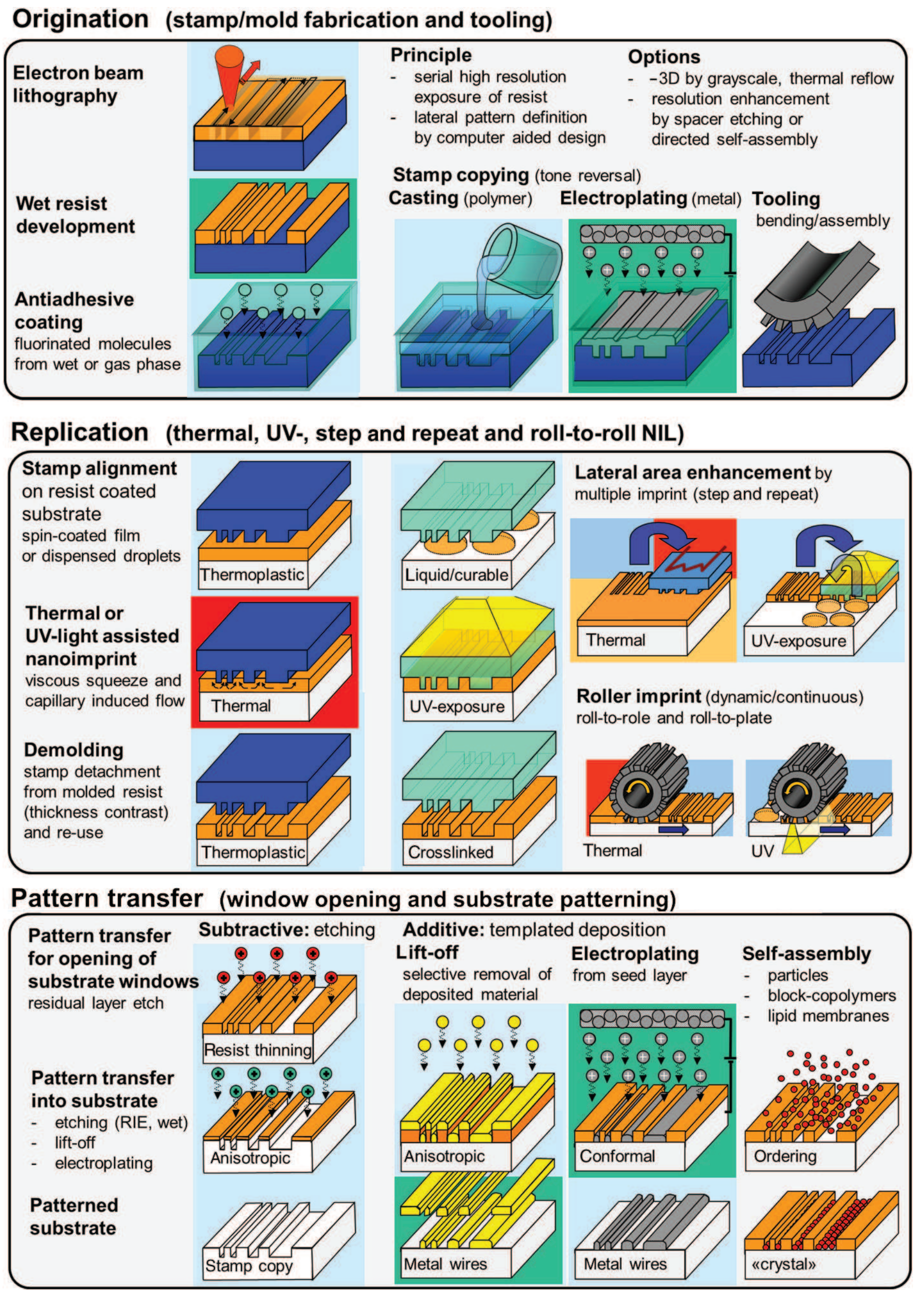


Fig. 1 Nanoimprint lithography (NIL) consists of the three major process steps: origination, replication, and pattern transfer.

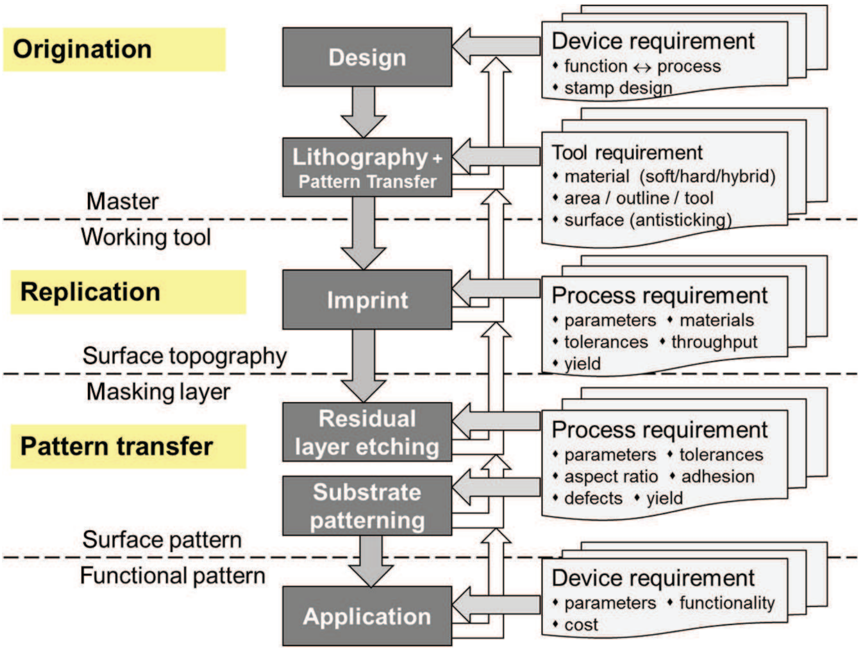


Fig. 2 NIL process chain including feedback loops for process and device requirements.

topography has, therefore, to be transformed into a working tool adapted to the molding process, which means that a suitable mold outline has to be generated, that can be integrated into the tool, e.g., by inserting, clamping, or gluing. The original surface polarity is inverted during this copying process. Once such a mold is generated, it can be repeatedly used to generate identical copies without intentional degradation of the mold. Special tooling efforts are needed if the original needs to be transformed or copied into different material, to be enlarged in area or simply to be fitted into a standardized tool or holder.

Replication techniques are manifold; most prominent are casting, imprint (embossing), and injection molding. The basic process is shaping of a material in its viscous state by molding and hardening before the mold is separated (demolding). In most cases, the final element exhibits the exact shape of the mold outlines including surface patterns, however, with a "negative" tone, as already mentioned for mold copying. Depending on the viscosity of the molded material, the viscous material wets and covers the mold surface and the voids by pressure or capillary-driven filling. The mold is designed to be either hard enough that it can be reused without damage, or soft and flexible enough that it allows being detached without substantial adhesion, friction, and wear. The latter is often highly dependent on the feature size and aspect ratio. While molding processes dealing with surface structures with moderate aspect ratio structures often rely on flat stamper and roll-to-roll embossing, and injection molding enables to mold entire components with defined outlines. This is used for a range or polymeric products, such as compact disks (CDs). Here, a thin metal stamper is electroplated from a resist-coated glass substrate and inserted into an injection molding tool. Thus, the submicrometer data pits, which have been patterned into the resist by a focused laser beam, are replicated onto the surface of a polycarbonate (PC) disk with 120-mm diameter. While for commercialized products, a pit size of 100 nm is achieved, research projects went much further. For this, silicon wafers were used instead of electroplated stampers.[16–19] Also, stamps with surface structures in hybrid organic–inorganic polymers (e.g., Ormostamp® from micro resist technology GmbH, Berlin), or hydrogen silsesquioxane (HSQ) were used and sub-100-nm patterning demonstrated.[20–24] Using this, down to 18-nm resolution was achieved using standard injection molding.

Pattern transfer is often not needed if the end product is made from polymer or, as in case of NIL, a stamp copy is fabricated by surface replication.[20] However, pattern transfer makes it possible to use the polymer pattern as a masking layer and transform its lateral design into a different material. In practice, this is used in manufacturing of microchips, i.e., for the lithographic patterning of single or multiple layers. For polymeric elements, also thin-film generation and processes are essential to generate additional functionalities, e.g., for enhancement of reflectivity or hydrophobicity. For CDs, as presented before, a metal coating step has to be integrated in the process chain to enhance reflection and enables the readout by a focused laser. In the case of the CDs, this would be readout of single information pits with a focused laser with about 1-μm beam size. Many more products of our daily life rely on molding processes and use surface topographies with an additional coating. Two further examples are patterned magnetic media, in which entire disks have to be patterned with dense 15-nm-sized islands before a magnetic film is added, or thin holographic security labels which cover bank notes and credit cards. In all these processes, replication is one essential process to replicate an original surface pattern. Process chains based on replication have been developed for a range of other products, e.g., microoptical components for, e.g., smartphone cameras by Heptagon advanced micro-optics[25] or displays in eBook-readers (e.g., the front light waveguide in the Amazon's Kindle Paperwhite[26]). Although the processes for origination, replication, and pattern transfer often look quite different, their "ingredients" come from the same family of processes. In the following, this is exemplified on the basis of polymeric microcantilevers (μC), which use the process chain similar to that employed in CD molding. By adding surface patterns to these μCs, injection molding is combined with NIL surface patterning capabilities.

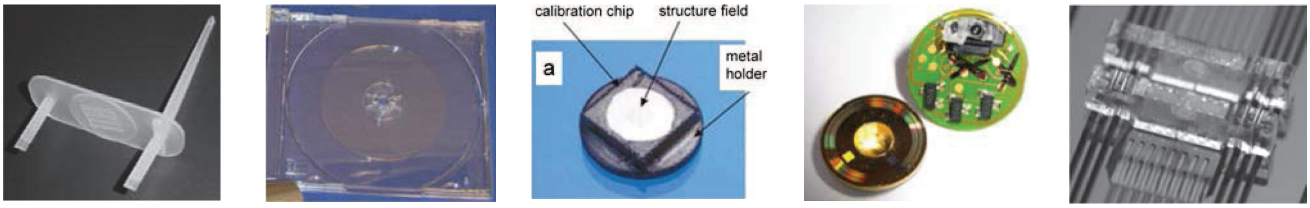
3 Hybrid Molds for Injection Molding

In an injection molding process, a closed cavity is filled with viscous polymer. Often a hot melt is injected at high pressure into a cold cavity, where it cools down instantaneously upon contact with the mold surface. When the melt solidifies, a polymer component is formed with the exact shape of the cavity, replicating both the overall outlines of the cavity as well as its surface roughness. All cavity extensions have to be wide enough for enabling enough flow before solidification is complete. Air inclusions are avoided by adding venting channels/gaps of a few micrometers' width. They are considered too narrow for the polymer to stay viscous and thus by freezing the melt flow starves immediately when penetrating into these gaps. Therefore, a micromechanical device with a long film- or fiber-like extension will form only when using high mold temperature, high pressure, and a polymer with good flow properties. Additionally, molds can be designed in a way that cooling in critical areas is slowed down. This can be done by variothermal heating schemes, e.g., by local heating over the polymer's glass transition temperature near critical element details, or by mold materials with retarded heat transfer from the melt to the mold.[23]

The concept of injection molding enables the replication of surface patterns by integrating relief patterns onto the surface of the mold cavity. Hybrid mold concepts have been developed, which enable the manufacture of mold cavity and surface pattern independently. The shape of the final component is defined by the mold cavity and its surface texture by an exchangeable part (e.g., an insert). This enables patterning of specific areas without modifying the overall shape of the cavity. The enhanced flexibility is, e.g., needed in CD manufacturing, where the polymer disk is a mechanical carrier with defined outlines and the music encoded digitally into one of the disk's surfaces. By fast exchange of nickel shims with different encoded music patterns, a few hundreds to tens of thousands of disks can be molded in an automated manner.

Figure 3 depicts different polymer components made with hybrid molds. For the rotary encoder, the nickel shims were

Injection molded polymer elements: photographs

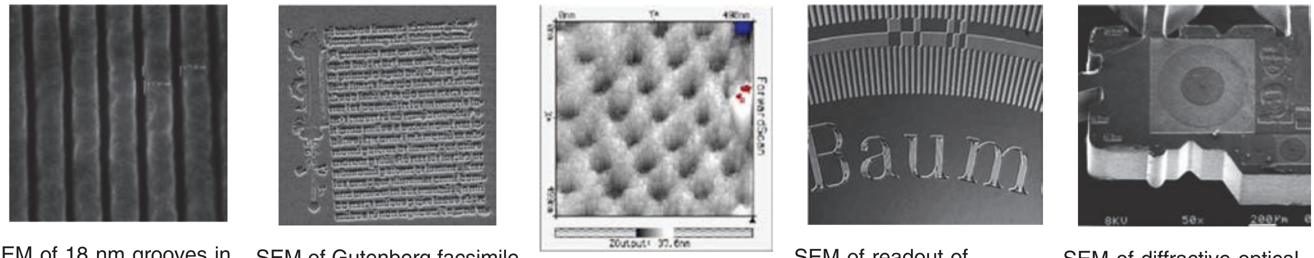


Test component	Compact disk	Calibration chip	Rotary encoder	Optical component
with replication from HSQ-coated silicon chip in PP	in CD box (diameter 80 mm, thickness 1.2 mm)	glued on round metal plate (7×7 mm^2)	minidisk with read-out electronics (diameter 12 mm)	with registration pins for micro-optical bench (5×2 mm^2)

Techniques for integration of surface pattern

Diced silicon chip which is glued onto mold insert surface	Clamped silicon wafer (diameter 100 mm) with etched surface patterns	Square polymer chip cut from large polymer disk or using mold for single chip	Thin metal (nickel) insert electroplated from resist coated wafer	Combined insert from electroplated molds (lenses and LiGA frame)

Surface pattern/relief: micrographs from scanning electron microscopy (SEM) and tunneling microscopy (STM)



Linear grating	2-D surface pattern	Crossed line grating	Line grating (radial)	3-D surface reliefs
SEM of 18 nm grooves in cyclo olefin copolymer (COC)	SEM of Gutenberg facsimile (10×10 μm^2) with 20 nm resolution in PC	STM of calibration grating with 160 nm period (0.5×0.5 μm^2)	SEM of readout of radial position of gratings (1 μm period) in PC	SEM of diffractive optical element for light focusing in PC

Fig. 3 Examples for injection molding of surface patterns on polymer elements with different outlines, showing a test component,[27] compact disk,[16,28] calibration chip,[17,18] rotary encoder,[29] and optical component.[30]

fabricated from electron beam lithography-exposed resist patterns as known from CD fabrication. This method was also employed for the fabrication of 3-D molds with DOE. For devices with lower requirements on throughput, nickel shims were replaced by silicon wafers. Thus, fast prototyping can be achieved using a mold with etched surface structures or, in case of test structures, with a HSQ resist directly patterned by EUV interference lithography.[24] Using etched silicon wafers instead of nickel, up to 1600 CDs were fabricated in a modified CD molding tool.

As an alternative to hybrid molds, the sequential molding of micro and nanostructures using different processes is possible. For example, hot embossed, injection molded, or extruded polymer components can be subsequently imprinted at the surface with nanopatterns. This was applied to surface structuring of extruded textile fibers using roll embossing and by fast thermal NIL by a stamp with integrated heater.[31,32] This is, however, often accompanied by distortions of the shape of the original component.

4 Polymer Microcantilevers

A μC array is a micromechanical device that exhibits flexible, finger-like extensions from a macroscopic carrier which can bend if subjected to surface stress or excited by mechanical forces. This can be, e.g., by loading a μC with biomolecules which will result in a decrease of its resonance frequency. To achieve local chemical sensitivity, the μC is coated on one side with a thin gold film. This serves both as a layer for selective adsorption of biomolecules (e.g., by using thiol-based chemistry) and for enhancing the reflection of a laser beam, which is used to measure the deflection of the μC. Typically, a silicon μC is 500 μm long, 50 to 100 μm wide, and around 1 μm thick (see Fig. 4). As a device with multiple sensors, an array of μCs is attached to a $2.5 \times 3.5 \times 0.5\text{-mm}^3$ carrier. While the size of the carrier is determined by practical considerations (handling with tweezers, economy of space, and thickness of standard silicon wafers), the size of the μCs is often determined by the selectivity needed to detect small amounts of loaded biomolecules and variations thereof. Silicon is the preferred material for these micromechanical elements, due to the established capabilities of cleanroom-based micromachining technologies. However, particularly for sensors in a modern bio-lab environment, single-use low-cost devices are highly desired. For this purpose, polymeric alternatives are most promising. The preferred manufacturing process for those μCs is polymer injection molding, and for microelements of a few millimeter size special microinjection molding (μIM) tools and concepts for making of mold inserts have been developed. To achieve comparable mechanical properties, the polymer μCs needs to be around seven times thicker than their silicon counterparts. However, even a cavity height of 10 μm, i.e., a cavity with an aspect ratio of 50∶1, is difficult to fill with a polymer melt in an isothermal process, i.e., in which the mold is kept at a temperature below the melt's glass transition temperature. Here, the thermoplastic polymer needs to keep its ability to flow and fill the extended cavity, while it is freezing upon contact with the mold surface. However, as demonstrated, complete filling can be achieved if the mold cavity height is chosen between 30 to 50 μm (see Fig. 4). From the process point of view, the molding of an entire CD with 120-mm diameter and 1.2-mm thickness (DVD 0.6 mm) or a millimeter-sized polymer holder with some 500-μm-long and 25-μm-thick fiber-like extensions is not different. Even for 25-μm-thick μCs, their aspect ratio is much higher than 10∶1 and rarely achieved in NIL processes. This is also true if the μCs are patterned on their surface with sub-μm-sized holes or pillars. Since the surface patterning is achieved by using a NIL fabricated hybrid mold, the NIL toolbox approach is needed. A process for this is schematically depicted in Fig. 5. Opposite to the microcavity with the μC outlines on the tool side, a foil containing the surface pattern is attached to the injection (mirror) side of the mold. Thus, by composing a hybrid mold cavity during closing of the tool, instead of the flat surface, a surface pattern is generated on the μC during molding (Fig. 6).

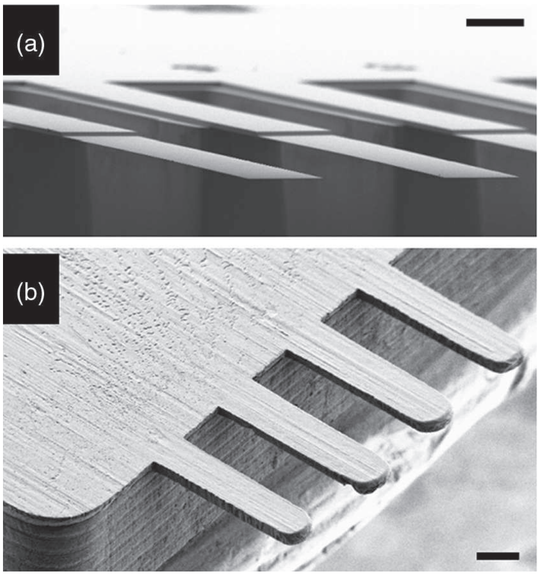


Fig. 4 SEM micrographs of an array of (a) silicon and (b) polymer microcantilevers (μC), with 1- and 25-μm thickness, respectively. On the polymer surface, the roughness of the metal mold is well replicated. Scale bars, 100 μm.

Most of the process details have already been presented. In Refs. 33 and 34, the fabrication of polymer μCs was described, including the integration of surface corrugations by hybrid molds. This concept has also similarities with the so-called "in-mold labeling" of consumer goods, were a foil is integrated into a mold and permanently reinforced by the injected polymer. Thus, a printed film can be used to decorate products, yielding high wear resistance. By interchanging the foil, different surface patterns can be applied without changing the entire mold. In this process, NIL is only used for the "hybrid part" of the replication, resulting in a "decoration" of the μC, without an impact on their mechanical properties. In Fig. 6, three surface topographies leading to different degrees of area enhancements are shown (pyramids, compartments, and ridges).[35] The surface area can be doubled with gratings of an aspect ratio of 1∶1 (e.g., for ridges with lines and spaces of 1 μm each, and 1-μm depth), and may enhance the sensitivity of the μC's surface. Even then, because of the low depth of the microgratings with respect to the μC's thickness, the mechanical properties are only slightly modified. For gratings with depths similar to the μC's thickness, the beam can be made stiffer or softer.[36] Other applications of gratings involve the measurement of forces of biological cells during their growth depending

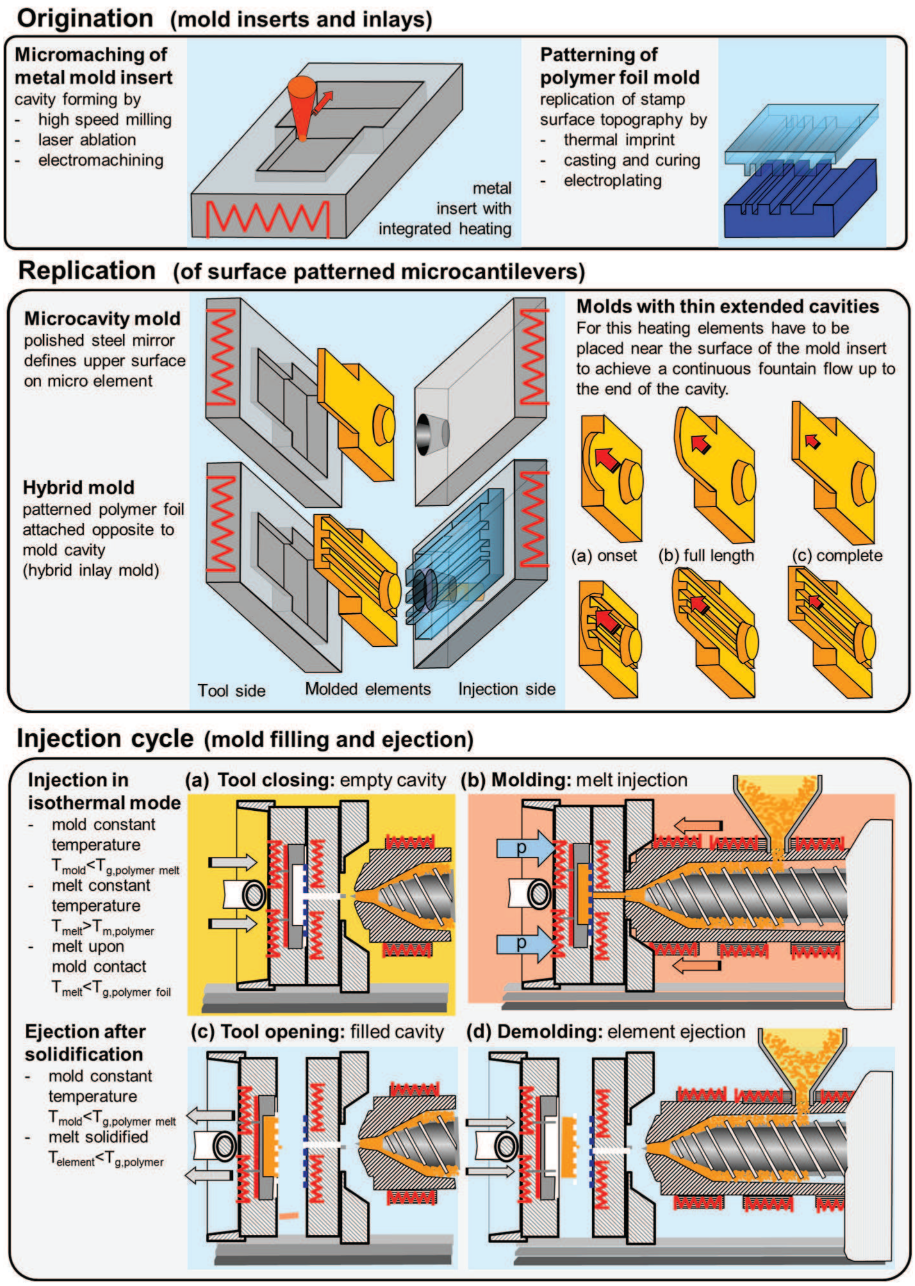


Fig. 5 Process for the fabrication of a surface patterned microcantilever device by microinjection molding.

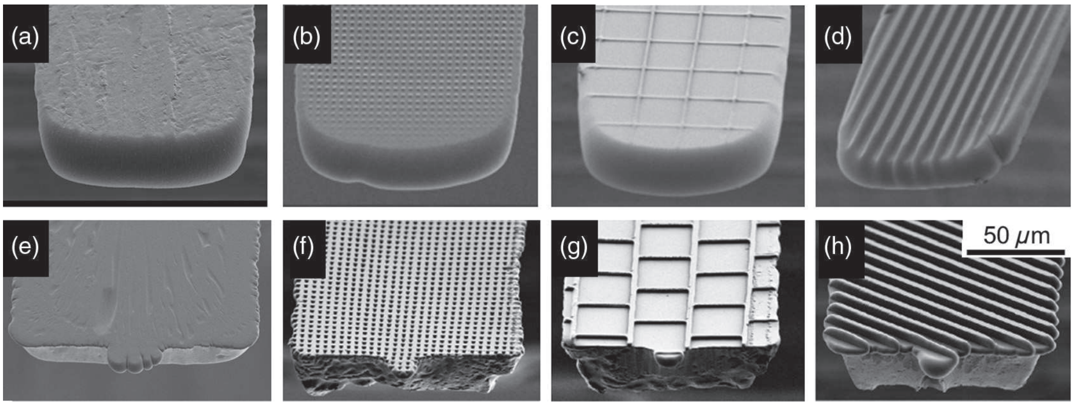


Fig. 6 SEM micrographs of (a)–(d) incompletely molded polymer μCs, (a) with bare steel "mirror," (b) with pyramids of 2-μm footprint, (c) compartments, (d) periodic 5-μm ridges; (e)–(g) completely molded polymer μCs, (e) with polished steel "mirror," (b) with 2-μm inverted pyramids, (c) compartments, (d) periodic 5-μm ridges.

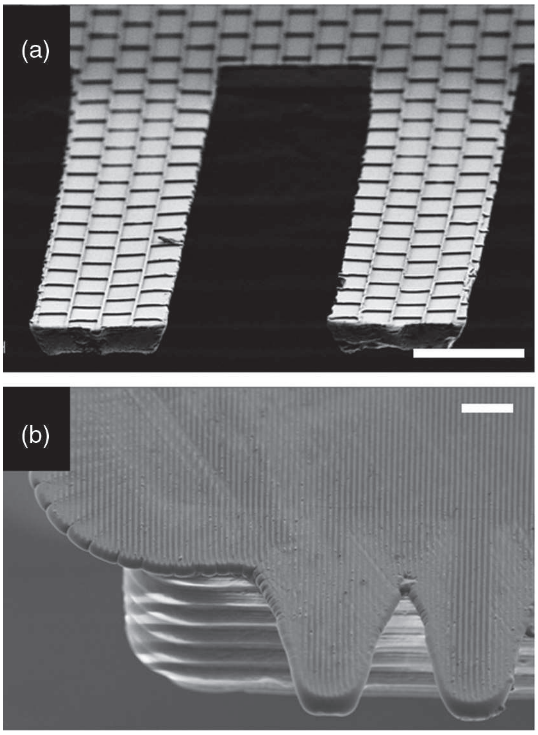


Fig. 7 SEM micrographs of polymer μCs with typical defects: (a) bending during demolding, (b) polymer overflow due to gap between tool and injection side. Scale bars, 100 μm.

on surface topography, optical diffraction, and fluidic channels.[37] Finally, it is also possible to add a sharp tip structure on the μC, which would enable to use the μC beam as a scanning probe. However, for practical reasons, this tip needs to be positioned at the μC end with a precision well below 10 μm, which would require an alignment of the inlay mold and a reproducible positioning of both mold parts on the mold and injection side upon closing. Furthermore, the tip would need to be hard enough to avoid wear. As an example, in Fig. 6(b), an array of pyramidal structures with tip radius below 50 nm is shown. For all these applications, there are possibilities to add functionality to a microelement by modifying its surface. While all μCs in Fig. 6, even those with incompletely molded beams, would qualify for micromechanical experiments, Fig. 7 shows the defects that are less reproducible and would significantly modify the μCs' mechanical behavior. The bending results from enhanced adhesion during demolding and polymer overflow from an insufficient tool closing.

In Fig. 8, the process chain for μC manufacturing by μIM is depicted. As seen for the NIL process in Fig. 2, its main task for origination is the fabrication of the two mold parts. The microcavity of the μC array is milled into a prefabricated tool insert made from tool steel. Interestingly, while each microcavity is an original, the patterned foil has to be fabricated using a replication process. Therefore, different original molds can be used and polymer backups can be provided. Furthermore, instead of the pattern transfer, the micromechanical device has to undergo a post-treatment, by cleaning it from organic residues and coating it with a thin gold layer.[38–40] Both processes modify the mechanical and even chemical characteristics of each μC. Once this functionalization is done, the device is finished and can be used as a sensor device, e.g., in the Cantisens® cantilever sensor platform by Concentris GmbH in Basel, Switzerland.[41]

Devices with thin membrane-like elements have been fabricated with a range of other methods, which would also be suitable for μCs, e.g., by microembossing of thin foils, by photolithography of thick resists or even by NIL. In all cases, single processes or entire process chains differ from the fabrication of μCs. By using this, free-standing membranes with 1-μm thickness were fabricated as sieves or as photonic crystal slabs.[42]

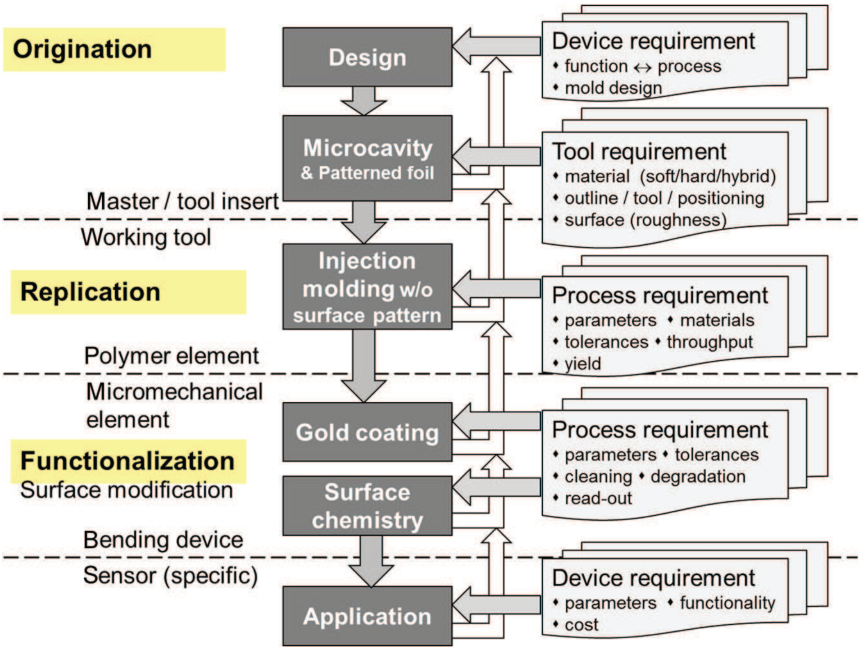
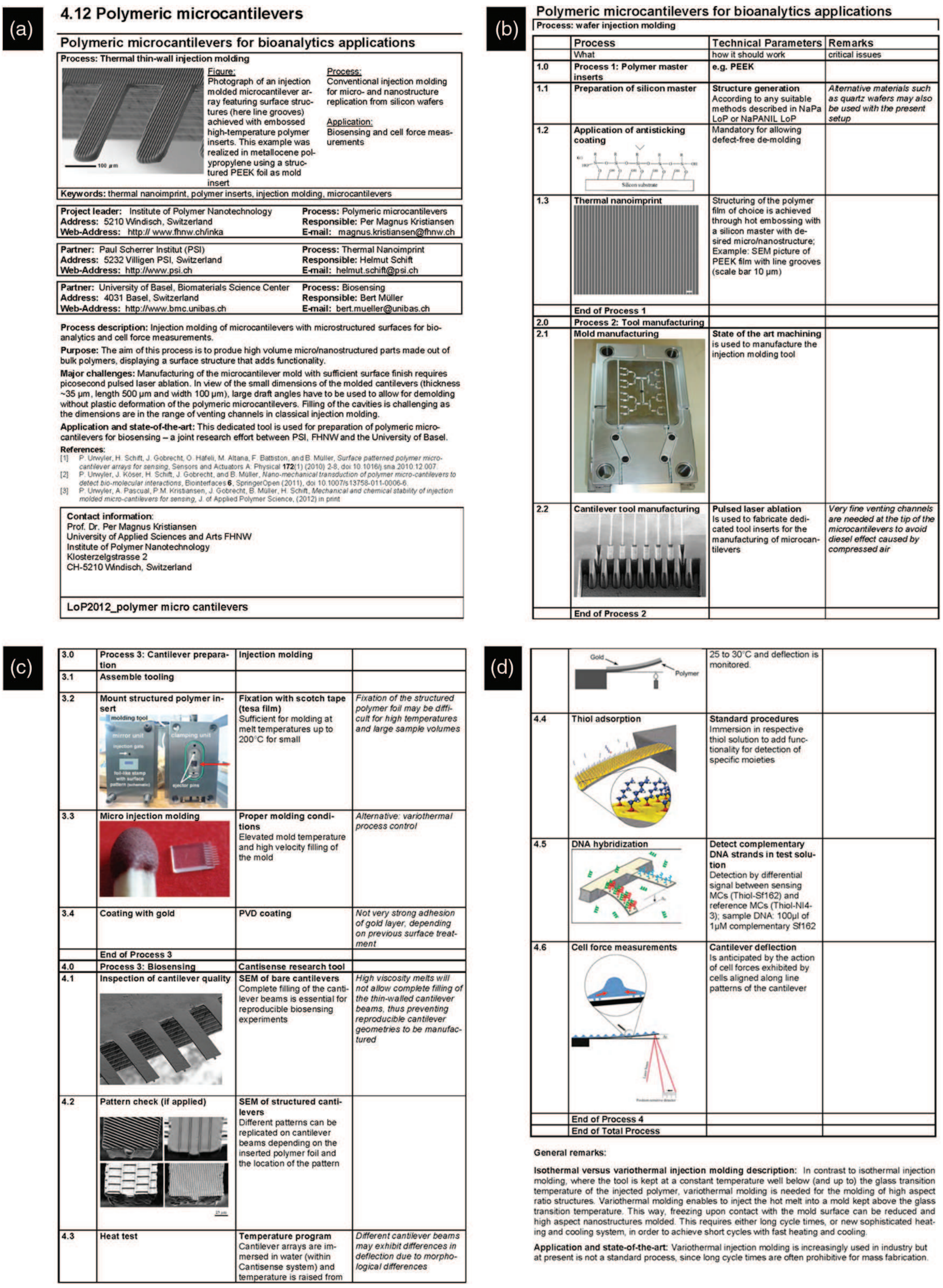


Fig. 8 μC process chain including feedback loops for process and device requirements. In contrast to the NIL process chain, pattern transfer is replaced by surface functionalization.

5 Process Chain Library Concept

Many scientific publications, particularly those relying on state-of-the-art manufacturing techniques, present process details for the processing of devices with which research results were obtained. Although scientific publication requires proofing of results, with the aim to make it possible for others to verify the results, processes can be rarely considered as consolidated. The lack of standardization in research is commonly acceptable for those who work on similar issues, follow developments, and are able to find



4.12 Polymeric microcantilevers

Polymeric microcantilevers for bioanalytics applications

Process: Thermal thin-wall injection molding

Figure:
Photograph of an injection molded microcantilever array featuring surface structures (here line grooves) achieved with embossed high-temperature polymer inserts. This example was realized in metallocene polypropylene using a structured PEEK foil as mold insert

Process:
Conventional injection molding for micro- and nanostructure replication from silicon wafers

Application:
Biosensing and cell force measurements

Keywords: thermal nanoimprint, polymer inserts, injection molding, microcantilevers

Project leader: Institute of Polymer Nanotechnology
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Process: Polymeric microcantilevers
Responsible: Per Magnus Kristiansen
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Address: 5232 Villigen PSI, Switzerland
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Process: Thermal Nanoimprint
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Partner: University of Basel, Biomaterials Science Center
Address: 4031 Basel, Switzerland
Web-Address: http://www.bmc.unibas.ch
Process: Biosensing
Responsible: Bert Müller
E-mail: bert.mueller@unibas.ch

Process description: Injection molding of microcantilevers with microstructured surfaces for bioanalytics and cell force measurements.

Purpose: The aim of this process is to produe high volume micro/nanostructured parts made out of bulk polymers, displaying a surface structure that adds functionality.

Major challenges: Manufacturing of the microcantilever mold with sufficient surface finish requires picosecond pulsed laser ablation. In view of the small dimensions of the molded cantilevers (thickness ~35 µm, length 500 µm and width 100 µm), large draft angles have to be used to allow for demolding without plastic deformation of the polymeric microcantilevers. Filling of the cavities is challenging as the dimensions are in the range of venting channels in classical injection molding.

Application and state-of-the-art: This dedicated tool is used for preparation of polymeric microcantilevers for biosensing – a joint research effort between PSI, FHNW and the University of Basel.

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LoP2012_polymer micro cantilevers

Polymeric microcantilevers for bioanalytics applications

Process: wafer injection molding

	Process	Technical Parameters	Remarks
	What	how it should work	critical issues
1.0	**Process 1: Polymer master inserts**	**e.g. PEEK**	
1.1	**Preparation of silicon master**	**Structure generation** According to any suitable methods described in NaPa LoP or NaPANIL LoP	*Alternative materials such as quartz wafers may also be used with the present setup*
1.2	**Application of antisticking coating**	Mandatory for allowing defect-free de-molding	
1.3	**Thermal nanoimprint**	Structuring of the polymer film of choice is achieved through hot embossing with a silicon master with desired micro/nanostructure; Example: SEM picture of PEEK film with line grooves (scale bar 10 µm)	
	End of Process 1		
2.0	**Process 2: Tool manufacturing**		
2.1	**Mold manufacturing**	**State of the art machining** is used to manufacture the injection molding tool	
2.2	**Cantilever tool manufacturing**	**Pulsed laser ablation** Is used to fabricate dedicated tool inserts for the manufacturing of microcantilevers	*Very fine venting channels are needed at the tip of the microcantilevers to avoid diesel effect caused by compressed air*
	End of Process 2		
3.0	**Process 3: Cantilever preparation**	**Injection molding**	
3.1	**Assemble tooling**		
3.2	**Mount structured polymer insert**	**Fixation with scotch tape (tesa film)** Sufficient for molding at melt temperatures up to 200°C for small	*Fixation of the structured polymer foil may be difficult for high temperatures and large sample volumes*
3.3	**Micro injection molding**	**Proper molding conditions** Elevated mold temperature and high velocity filling of the mold	*Alternative: variothermal process control*
3.4	**Coating with gold**	**PVD coating**	*Not very strong adhesion of gold layer, depending on previous surface treatment*
	End of Process 3		
4.0	**Process 3: Biosensing**	**Cantisense research tool**	
4.1	**Inspection of cantilever quality**	**SEM of bare cantilevers** Complete filling of the cantilever beams is essential for reproducible biosensing experiments	*High viscosity melts will not allow complete filling of the thin-walled cantilever beams, thus preventing reproducible cantilever geometries to be manufactured*
4.2	**Pattern check (if applied)**	**SEM of structured cantilevers** Different patterns can be replicated on cantilever beams depending on the inserted polymer foil and the location of the pattern	
4.3	**Heat test**	**Temperature program** Cantilever arrays are immersed in water (within Cantisense system) and temperature is raised from 25 to 30°C and deflection is monitored.	*Different cantilever beams may exhibit differences in deflection due to morphological differences*
4.4	**Thiol adsorption**	**Standard procedures** Immersion in respective thiol solution to add functionality for detection of specific moieties	
4.5	**DNA hybridization**	**Detect complementary DNA strands in test solution** Detection by differential signal between sensing MCs (Thiol-Sf162) and reference MCs (Thiol-NI4-3); sample DNA: 100µl of 1µM complementary Sf162	
4.6	**Cell force measurements**	**Cantilever deflection** Is anticipated by the action of cell forces exhibited by cells aligned along line patterns of the cantilever	
	End of Process 4		
	End of Total Process		

General remarks:

Isothermal versus variothermal injection molding description: In contrast to isothermal injection molding, where the tool is kept at a constant temperature well below (and up to) the glass transition temperature of the injected polymer, variothermal molding is needed for the molding of high aspect ratio structures. Variothermal molding enables to inject the hot melt into a mold kept above the glass transition temperature. This way, freezing upon contact with the mold surface can be reduced and high aspect nanostructures molded. This requires either long cycle times, or new sophisticated heating and cooling system, in order to achieve short cycles with fast heating and cooling.

Application and state-of-the-art: Variothermal injection molding is increasingly used in industry but at present is not a standard process, since long cycle times are often prohibitive for mass fabrication.

Fig. 9 Process for manufacturing of polymeric μCs, reproduced from the NaPANIL library of processes,[43] pages 199–202 [here named (a)–(d)], as an example for a process which enables user to identify process steps. The process was performed together with the University of Applied Sciences and Arts Northwestern Switzerland (FHNW).

their own solutions which profit from the published details but are often not a direct copy of the processes presented. The need for standard processes is, however, not only a wish to facilitate the setup of new processes, but also a need to extract relevant information about single processes and their mutual interdependence in a process chain. This is particularly important if the suitability of a process for scale-up and transfer into a real product has to be assessed. A process chain description, even if not yet defined as a standard, can be valuable help to understand novel processes and compare results based on own processing knowledge. It can be simply a way to find and learn from processes which may be described in publications, but are not presented in a useful structure and logic.

Figure 9 presents four pages of a process chain for the fabrication of surface patterned polymeric μCs from the NaPa library of processes (NaPa LoP).[43] This LoP is the result of the European Integrated Project NaPa (2004–2008) and the Large-Scale Project NaPANIL (2008–2012), which during a total of 8 years gathered scientists and engineers to develop a range of nanopatterning method.

The library concept is not new, but it has been proven to be a valuable tool for documentation and dissemination. The benefit from bachelor, master, or PhD works within an academic environment is often lost if this knowledge is not translated into a form which can be read by the technologically experienced researcher or engineer. The LoPs' main aim was, therefore, the leverage of technology take-up, particularly by small- or medium-sized enterprises, which rarely follow the technological progress in scientific publications. These documents do not necessarily need to disclose confidential information or go beyond the range of details already presented in the publication, but help to structure the process and enable to assess the state of the art. It gives information about both the toolbox and the process chain. It may contain work in progress, since many process variations were needed to achieve intermediate or final results. However, even if a standard process is not yet established, the description of a semi-standard will allow learning process routes, the logic of steps and the resulting achievements. For this, in the column next to that presenting technical parameters, remarks should be added. They are essential to put single steps or preliminary results into context. Apart from the fact that copying of the exact process is often not possible or intended, the starting at a point zero $+\,\Delta$ will allow enhancment of the learning curve.

The NaPa LoP with more examples for NIL-based microfabrication can be downloaded from the first author's webpage at Paul Scherrer Institute,[43] and templates can be easily composed according to the example described above. The results are all coming from project partners of the NaPa and NaPANIL, and have already proven to be a valuable resource for students and engineers starting with microfabrication processing. It is our aim that researchers and engineers take up this idea to present their processes in a similar format in web-based annexes of their publications.

6 Conclusion

Many process chains for micro- and nanofabrications of devices have been established in research environments and are particularly important in industry for process control and documentation. The aim, here, is directed toward technology-oriented research projects, and does not cover the cost-of-ownership-oriented value chains guided by technological roadmaps. However, particularly, because both NIL and μIM are replication techniques with the intrinsic potential for large-scale manufacturing, the viability of process routes for scale-up needs to be addressed. This can be described by different technology readiness levels (TRL).[44] TRL is a measure used to assess the maturity of evolving technologies (devices, materials, components, software, work processes, etc.) during its development and in some cases during early operations. In research, single elements of the chain are often labeled with different maturity levels, and are highly dependent on structural designs and complexity. The aim of this publication is not to define these TRLs for the process chain presented, but to help establish these process chains for future developments. The NIL process chain with its main elements origination, replication, and pattern transfer (functionalization) is a good example to demonstrate this capability.

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