Optoelectrothermic Control of Highly Integrated Polymer-Based MEMS Applied in an Artificial Skin

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During the last thirty years microelectronics changed our lives and work significantly and consequently one should wonder about the potential of microelectromechanical systems (MEMS) that contain hundreds or even thousands of components. Would the impact of microprocessors with the ability of processing chemical or biological information within minutes or hours instead of weeks or years not be just as remarkable as the impact of modern electronic microprocessors processing electric information within milliseconds instead of weeks?^[1] And would an enhancement of imaging array systems for media presentations to provide additional mechanical impressions not be a comparable step forward? However, the initial expectation that modified semiconductor fabrication technologies would be readily adapted to many other large-scale integration applications (LSI, 100 to 10000 components) has only been fulfilled in very few cases such as the digital micromirror devices (DMD).^[2] For most other microactuator applications the semiconductor technology is too expensive and does not offer sufficient performance and/or the necessary functionalities. Polymeric MEMS and their inexpensive fabrication techniques could offer a solution to this.^[3] The first concept to fabricate and control microfluidic LSI devices based on poly(dimethylsiloxane) (PDMS) was presented by Quake et al.^[4] These devices consist of an integrated fluidic circuit controlled by several pneumatically driven control layers and are preferably used in high-throughput screening applications, simultaneously performing thousands of identical operations.^[5] Using pneumatic row and column multiplexers these devices can individually address a large number of elements, while a simultaneous control of several random elements is not possible.^[6]

Here, we present a further material-based approach of polymeric large-scale integrated MEMS based on a stimuli-responsive polymer, which itself acts as the active functional unit, i.e., the actuator. These devices provide a simple singlelayer set-up and allow simultaneous but individual control of a large number of random elements. Using an imaging array system, a so-called "artificial skin", as example we demonstrate the generation of visual and physical artificial impressions of a surface.

Similar to molluscs, which can change their appearance using their skin's *musculi cutanei*, our device changes its palpable

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surface through changes in its active polymer layer, which consists of a multitude of single, tiny, cell-like actuators (Fig. 1a). The active polymer is a stimuli-responsive hydrogel and can reversibly change its volume by more than 90% swelling or shrinking in response to small alterations in certain physical,^[7] or chemical properties,^[8] of its environment. Here, we use a temperature-sensitive hydrogel of poly(*N*-isopropylacrylamide) (PNIPAAm).

The active gel layer is patterned by photolithographic polymerization of *N*-isopropylacrylamide and covalently bound to a PDMS cover foil with knobs as well as fixed to a black polyester substrate. The pitch within the active array is 580 μ m, which comprises the actuators with a footprint of 300 μ m × 300 μ m and swollen height of 500 μ m as well as a 280 μ m spacing between individual actuators. The spacing room is used as swelling agent supply for the actuators, i.e., storing and releasing water. The actuator array unit is connected to 18 channels providing finely tunable control over the supply of swelling agent. Our artificial skin consists of 65 × 65 actuators arranged array-like with a spatial actuator density of 297 elements per cm².

Due to its volume phase transition behavior PNIPAAm can be reversibly switched from a completely shrunken state to a swollen state by simple temperature alteration between 29 °C and 35 °C (Fig. 1b). This corresponds to a "switching on" or "switching off" of a PNIPAAm actuator between the two extreme states (fully swollen or shrunken). The control mechanism simply has to provide a small temperature difference of 6 K (Fig. 1c). A parallel control of individual elements of the actuator array is provided by optoelectronic control of a light-induced temperature field. A digital micromirror device or a highly light-transmissive liquid crystal display (LCD) device can control the projection of a powerful light beam onto the substrate of the artificial skin. The black substrate converts the absorbed light into heat and transmits it directly to the actuators that are attached on the surface. The light-induced temperature field on the surface of the black substrate occurs in nearly real-time. As shown in Figure 1d to 1f and the Video S1 in the Supporting Information, the temperature field is completed after 400 ms. The temperature within the illuminated area is at least 35 °C while the temperature outside this area does not exceed 29 °C. Active water cooling on the bottom side of the substrate dissipates excess heat and keeps the dolphin-shaped temperature field stable for a desired period of time (Fig. 1g). Furthermore, the active tempering provides independence from the ambient temperature. The actuators within the T-field are heated above their phase transition temperature and map the dolphin by shrinking (see also Fig. 3c discussed in more detail below).



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Figure 1. Design and functionality of the "artificial skin". a) A photograph of the device, which contains 4 225 actuators within an area of 37.7 mm × 37.7 mm (scale bar = 1 cm). b) The skin comprises an active hydrogel layer consisting of multiple individual actuators, an elastic cover foil equipped with knobs, and a black substrate. The bottom side of the substrate is actively tempered. c) Swelling behavior of poly(*N*-isopropylacrylamide). To switch the actuators from their completely shrunken to swollen state a small change in working temperature ($\Delta T_{Work} = 6 \text{ K}$) has to be performed. d–g) An optoelectronically controlled illumination generates a dolphin-shaped temperature field in nearly real time, which is maintained by active tempering (thermographic camera VarioCAM hr). The length of the dolphin from mouth to tail is 14.5 mm.

The physical sharpness of information to be represented is defined by the spatial actuator density and the pitch of the artificial skin, respectively. The correlation between pitch x_P and actuator density D_A is given by Equation 1.

$$D_A = \frac{1}{x_p^2} \tag{1}$$

The pitch is determined by functional requirements of the device, but also by the ability of the control to provide an independent individual control of two neighboring actuators between their antagonistic extreme states "fully swollen" und "fully shrunken". As shown in Figure 2a, in order to perform the switching operations, a difference in working temperature of $\Delta T = 6$ K has to be realized. This temperature difference requires a certain spacing x_{Res} between the two actuators, which in turn represents the highest feasible resolution of the device. When the working temperature difference ΔT_{Work} of the optoelectrothermic control is bigger than 6 K, then a minimum size of the actuators has to be adhered to. In an asymmetric

case the minimum sizes of the swollen $(2x_{A1})$ and shrunken $(2x_{A2})$ actuators are different and the pitch x_P of the actuator array is given by Equation 2.

$$x_P = x_{\text{Res}} + x_{A1} + x_{A2}$$
 (2)

As ΔT_{Work} is smaller than the highest possible temperature difference realizable with the optoelectrothermic control, the position of ΔT_{Work} is adjusted through active water cooling on the bottom side of the substrate.

At a working temperature difference of $\Delta T_{Work} = 6$ K the contribution of x_A vanishes and the pitch $x_{\rm P}$ equals the resolution $x_{\rm Res}$ (Fig. 2b). At this working point the pitch has its lowest value of 420 µm providing an actuator density of 566 elements per cm². An increase of ΔT_{Work} improves the resolution but increases the smallest possible actuator size x_A and therefore the pitch. For an artificial skin the working point at $\Delta T_{\text{Work}} = 6$ K is inappropriate because the resolution is too high. Our optoelectrothermic control shows at $\Delta T_{\text{Work}} = 7.8 \text{ K}$ the required performance to operate an actuator array of a 480 µm pitch corresponding to a spatial actuator density of 434 actuators per cm². Due to functional aspects, especially the mechanical stability of the actuators (determined by the aspect ratio of the actuator's height : size x_A) and the second functionality of the spacing between the actuators as storage for the swelling agent, a pitch $x_{\rm P}$ of 580 µm consisting of $x_{\rm A} = 300$ µm and $x_{\text{Res}} = 280 \,\mu\text{m}$ can be defined. In order to achieve these parameters the working temperature difference has to be between 7.8 K and 10.6 K.

The maximum achievable spatial actuator density is a function of the design parameters and the effective applied heating power. With respect to the design parameters the material and the thickness of the actuator array substrate are of particular importance. Its material should have a low specific heat conductivity λ_s and exhibit good optical transmission at the wavelength of the applied light. Transparent standard polymers, such as polymethacrylate, polyester, polystyrene, and PDMS provide suitable heat conductivities in the range of 0.14 to $0.22 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. Here, we use polyester as substrate material, which exhibits a heat conductivity of $\lambda_{\rm S} = 0.2 \, \rm W \cdot m^{-1} \cdot \rm K^{-1}$. The substrate is printed with black color, because black most effectively converts the energy of the white light that is emitted by the halogen lamp into heat. The thickness of the substrate, $d_{\rm S}$, determines the performance of the optoelectrothermic control at a given light intensity. However, the lowest possible pitch can be obtained with an appropriate thickness of the substrate, which in our case was 200 µm (Fig. 2c). Substrates that are too thick or too thin significantly decrease the highest achievable actuator density.



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Figure 2. Optoelectrothermic control of the "artificial skin". a) Temperature characteristics of the optoelectrothermic control at $\Delta T_{Work} = 7.8$ K on a black polyester substrate with $d_{\rm S} = 200 \,\mu$ m thickness. This behavior allows controlling an actuator array with a pitch of 480 μ m (observed with thermographic camera VarioCAM hr). b) Pitch, actuator size, and resolution of the actuator array as functions of the working temperature ΔT_{Work} . c) Influence of the substrate's thickness on the minimal pitch of the actuator array for different working temperatures. d) The pitch as a function of the applied heating power ($\Delta T_{Work} = 6$ K).

The heating power density determines the size of the controllable area and therefore the actuator density. Figure 2d indicates that for the case of the working point being at $\Delta T_{Work} = 6 \text{ K}$ (where $x_{\rm P} = x_{\rm Res}$) a higher actuator density can be achieved with an increased heating power density. The used Christie business video projection system (Xenon bubble lamp 3000 W, 20000 ANSI lumens) provides a heating power density of about $4 \text{ W} \cdot \text{cm}^{-2}$ on the actuator array substrate and therefore an actuator density of 566 cm^{-2} at a pitch of $420 \,\mu\text{m}$, while the controllable size of the actuator array is $4 \text{ cm} \times 5.5 \text{ cm}$, or 22 cm^2 . However, a heating power density of 4 W cm⁻² can also be obtained with an optoelectronic control based on a halogen lamp (1 200 W, 27 600 lm) and a high transmission monochrome display, and for some applications even a common video projector would be sufficient. For example, an EPSON EMP-820 device (200 Whalogen lamp, 2 500 lm) equipped with additional optics is able to control an area of 2.66 cm^2 and provides an actuator density of about 100 cm^{-2} at a resolution of 960 µm (see Fig. 2d). Performance enhancement of the optoelectrothermic control requires more powerful light sources such as metal halide lamps (MHL), but with an improved set-up significantly larger controllable areas and a further improved actuator density will be possible.

While both, generation of ΔT_{Work} and cooling down of the temperature field occur in nearly real-time the actuator response is more time-consuming.^[9] However, the response time of the swelling and shrinking processes can be lowered by increasing the working temperature ΔT_{Work} . At a working temperature of 10 K the shrinking time is about 900 ms, while the swelling process is more time-consuming and occurs within seconds.

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The artificial skin can display different types of information. Immediately after heating beyond the phase transition temperature (about 34 °C), the PNIPAAm actuators change their color from transparent to opaque within the dolphin-shaped temperature field. The artificial skin displays monochrome visual information (Fig. 3a). After completion of the shrinking process the artificial skin maps the dolphin with single pixel accuracy (Fig. 3b). The palpable information is based on changes in height (Fig. 3c, here from 500 µm at swollen state to about 250 µm at shrunken state) and softness of the actuators. A smooth surface of the skin's cover primarily displays differences in softness. Transferable impressions reach from the softness of fatty tissue (Young's modulus Y = 13 kPa at $21 \degree$ C) to wood-like surfaces (Y (40 $^{\circ}$ C) = 100 kPa) displayed at the swollen PNIPAAm state or by the shrunken gel, respectively.

Because differences in height are hardly noticeable on soft hydrogel surfaces, the cover foil was equipped with knobs, which intensify possible edges (Fig. 3d). Thereby, the tactile information is determined by size, shape, and sharpness of the knob edges. While sharp-edged larger knobs are primarily qualified to show outlines, smaller and round knobs improve the diversity of displayable textures.

A higher knob density seems to enable the display of both, outline and softness information. An interesting option of "freezing" the skin's image is offered by evacuating of the actuator array's swelling agent.

The artificial skin would allow physical-auditory interaction with the virtual world of simulators and game engines by mapping of computer-generated data. This feature can also offer an improved communication of visually impaired persons with electronic media. Furthermore, the need for illustrative material as well as didactic animal experiments in medicine could be reduced by simply substituting them with digital databases of palpable images. If the artificial skin is combined with image-based diagnostics such as computed tomography and ultrasonography then new features will be provided in teleoperations and diagnostics due to the virtual tactile access to inaccessible regions. The palpable recognition of objects inside the body without the necessity to open it would improve diagnoses and allow preliminary simulation of surgical operations. Introducing tactile information within minimally invasive robotic surgery (MIRS) would combine the advantages of conventional open surgery, in particular the tactile recognition of the operation field, with those of MIRS, e.g., reduction of the operative trauma for patients.

Further, we believe that our large-scale integration technology will have a strong influence on the development of polymeric microfluidic systems. In microfluidics, PNIPAAm hydrogels offer multi-functionality including microvalves, micropumps, microchemostat valves, micro sensors and liquid lenses,^[10] which in such a diversity is only known from the material silicon that is



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Figure 3. Generation of visual and palpable information by the "artificial skin". a) When the phase transition temperature of PNIPAAm is exceeded, the hydrogel immediately changes its color from transparent to opaque. The "artificial skin" displays monochrome visual information. b) After finishing the shrinking process the skin maps the sharp outlines of a dolphin. The length of the dolphin from mouth to tail is 14.5 mm. c) The hydrogel actuator array maps the dolphin with sharp contours and single pixel accuracy (freeze-dried hydrogel array, investigated by laser profilometer NanoFOCUS μ Scan AF200). d) In order to improve the palpation of edges and outlines, a knob is placed on top of each actuator (scale bar = 500 μ m).

widely applied in microelectronics. The simple monolithic integration of hundreds and thousands of microfluidic components based on one functional material in the single chip will facilitate microfluidic processors that provide a currently not achievable performance.

Experimental

Materials: N-isopropylacrylamide (NIPAAm), crosslinking agent N,N'-methylenebis (acrylamide) (99%) (BIS), photoinitiator 2-hydroxy-4'- (2-hydroxyethoxy)-2-methylpropiophenone (98%), and pure ethanol (99.9%) were obtained from Aldrich. Adhesion promoter 3-(dimethylchlorosilyl) propyl methacrylate (DPMA) (85%) was received from Fluka. Distilled water was used to prepare photopolymerizable solutions. Poly(dimethylsiloxane) was obtained from Momentive Performance Materials (No. RTV 615 A/B) and TypoPhot TO-G from Typon Graphic Systems AG was used as black polyester substrate.

Photo-patterning of the Hydrogel: Photolithographic polymerization of NIPAAm was achieved by exposure of the monomer to UV light. A mercury (Hg) lamp (HBO 100W/2, Osram), a filter with low-pass characteristics (>200 nm), and an aperture were used to parallelize and bundle the UV light. The polymerization chamber was rinsed with argon and filled with the polymerizable aqueous solution containing 14.3 wt% NIPAAm, 2 wt% crosslinking agent BIS, and 2 wt% photoinitiator. UV exposure was performed at 5 °C through a photomask (TypoPhot TO-G, plotted by a Herkules Imagesetter with 5080 dots per inch) using an intensity of 75 mW \cdot cm⁻². Nonpolymerized residual monomer was removed by rinsing with ethanol and water. The quality of the hydrogel layer varies with polymerization time, which depends on the pitch of the polymerization mask and the thickness of the hydrogel layer. We obtained optimal

results with an exposure time of 60 s for a pitch of 200 μ m and hydrogel thickness of 100 μ m, 28 s for a pitch of 580 μm and a thickness of 300 $\mu m,$ and 22 s for a pitch of $1000 \,\mu\text{m}$ and a thickness of $500 \,\mu\text{m}$. Shorter exposure times affect both, adhesion properties and pattern accuracy, while slightly longer times have no significant influence on the exposure result. The aspect ratio of the actuators is restricted to 2.5 times height to width for mechanical stability reasons. In order to obtain covalent linkage of the gel actuators to the cover foil, it was pre-treated with the adhesion promoter DPMA. Briefly, the foil was treated in a low-pressure oxygen plasma (Plasma-Cleaner Harrick Sci. PDC-002) for 45 min and subsequently stored for 48 h in an ethanol/DPMA mixture (99.5:0.5 v/v). After rinsing with pure ethanol and drying with argon, the materials were processed immediately. The hydrogel adheres to the polyester substrate without any pretreatment.

Fabrication of Large-size Master Molds: Prototyping of the master moulds is based on a modified dry photoresist technology that was originally used in the printed circuit-board fabrication. This technology is inexpensive and rapid, does not require microfabrication facilities, and allows fabrication of large-size masters of up to 200 mm \times 155 mm. After laminating the dry photopolymer Dynamask 5030 onto standard, copper-coated board material FR 4 (0.2 m · min⁻¹ at 105 °C, Bungard RLM 419P), the photoresist was exposed to UV light through a photomask, then developed by rinsing with potassium hydroxide (KOH) solution, and finally dried.

Fabrication of the Cover Foil and the Device: Fabrication of the PDMS device was based on the multilayer soft lithography method [4]. In order to fabricate the PDMS cover foil a mixture of base A and curing agent B (ratio

3:1) was filled into the knob master mould, degassed, covered with a glass substrate, and subsequently polymerized (1.5 h at 80 °C). The device body, which includes the chamber with the active layer and the channels for supplying the swelling agent, was also realized by PDMS replica molding (A:B ratio = 30:1). At the bonding areas the polyester substrate was coated with a thin layer of 3:1 PDMS mixture. Finally, all components of the artificial skin (i.e., cover foil, active layer, and PDMS coated substrate) were bonded by heating to 80 °C and holding this temperature for 1.5 h, after which they were permanently compressed into a metal housing.

Optoelectrothermic Control: A business video projector Christie Roadster S+ 20K (digital light processing DLP, 3 000 W Xenon Bubble lamp, 20 000 ANSI lumens) equipped with special optics consisting of a zoom lens 4.5–7.3:1 and a convex lens f=300 mm was used as optoelectronic control. Alternatively, a second system comprising a continuously dimmable 1 200 W halogen lamp (Philips 6897 P) and optics consisting of a mirror, two convex lenses, a Fresnel lens and triplet objective, and a high transmission monochrome thin film transistor LCD NL160120AM27 (NEC LCD Technologies) were used.

The active tempering of the bottom side of the skin's substrate was realized by water cooling using a refrigerated circulator Julabo F33-EH. For experiments with a common video projection system an unmodified common EPSON EMP-820 was used, which was additionally equipped with optics consisting of a convex lens $f_1 = 90$ mm and an objective with $f_2 = 80$ mm.

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