Introducing natural thermoplastic shellac to microfluidics: A green fabrication method for point-of-care devices

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We present a sustainable fabrication method for cheap point-of-care microfluidic systems, employing hot embossing of natural shellac as a key feature of an energy-efficient fabrication method that exclusively uses renewable materials as consumables. Shellac is a low-cost renewable biomaterial that features medium hydrophilicity (e.g., a water contact angle of ca. 73°) and a high chemical stability with respect to common solvents such as cyclohexane or toluene, rendering it an interesting candidate for low-cost microfluidics and a competitor to well-known systems such as paper-based or polydimethylsiloxane-based microfluidics. Moreover, its high replication accuracy for small features down to $30\text{ }\mu\text{m}$ lateral feature size and its ability to form smooth surfaces (surface roughness $R_a = 29\text{ nm}$) at low embossing temperatures (glass transition temperature $T_g = 42.2^\circ\text{C}$) enable energy-efficient hot embossing of microfluidic structures. Proof-of-concept for the implementation of shellac hot embossing as a green fabrication method for microfluidic systems is demonstrated through the successful fabrication of a microfluidic test setup and the assessment of its resource consumption. *Published by AIP Publishing.* [<http://dx.doi.org/10.1063/1.4955062>]

I. INTRODUCTION

A. Novel microfabrication methods for minimal environmental impact

In recent years, sustainability has gained more and more attention, visible in an increased public awareness, as well as in industry's efforts to satisfy the increased demand for more sustainable products and services. MEMS products span a wide range of applications and are highly complex systems based on an elaborate but standardized fabrication technology, which determine their particular environmental impact during production, usage, and end-of-life. In order to estimate the environmental impact connected to the fabrication process of microsystems, single indicators such as energy consumption of the fabrication of MEMS products of certain complexity, fabrication technology, and application field have been reviewed.¹ Additional data related to the environmental impact of microsystems fabrication can be adopted from the semiconductor industry,^{2,3} as fabrication technologies of MEMS and semiconductor manufacturing are similar in terms of basic processes, as well as processing environment (e.g., cleanroom). Reviewing these data, three conclusions can be drawn:

- (i) Microfabrication is energy-intensive. For example, Branham and Gutowski showed that the fabrication process for accelerometer and gyroscope chips consumes approximately 2 kW h per cm^2 chip area.¹

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- (ii) Microfabrication consumes many different materials in relatively large quantities. For example, fabricating accelerometer and gyroscope chips consumes approximately 30 kg of water and 750 g of elemental gases per cm² chip area (data from supporting information in Ref. 1). Additionally, fabrication of semiconductor chips consumes approximately 45 g of chemicals (e.g., solvents, photolithographic chemicals) per cm² chip area.² One important detail to be considered is that microsystem fabrication uses subtractive processes, such as etching, and many of the materials used are supplementary materials, such as water or nitrogen for cleaning steps. Therefore, most of the materials used for microsystems fabrication are actually not incorporated within the microsystem product, ending up as environmentally unfriendly production waste.
- (iii) Microfabrication produces large amounts of toxic and corrosive waste. For example, for the fabrication of logic chips, at least 4 g of toxic substances and 10 g of corrosive substances are generated per cm² chip area (data derived from Ref. 3, for more information please refer to the [supplementary material](#) of this paper).

Acknowledging that these three conclusions are deduced from examples of a particular application field, complexity, and fabrication technology, they, however, precisely illustrate fundamental aspects of the environmental impact connected to microfabrication. Our approach to address these issues, namely, to render microsystems fabrication less (i) energy- and (ii) materials-consuming and (iii) generate less toxic and corrosive waste, is to employ biomaterials which are non-standard for microfabrication, as well as to adapt the existing microfabrication processes to the new materials. Such materials should be abundant, non-toxic, and non-corrosive and should be micromachined using energy-efficient techniques, preferably with additive processes.

B. Application areas of shellac

Hereby, we introduce the biomaterial shellac in the MEMS fabrication circuit, a material formerly used for one of the first large-scale micro-structuring processes, namely, record-pressing. Shellac is an excretion of *Kerria lacca*, a species of lice living in India and Thailand.⁴ The refined lac mainly consists of the shellac resin, a polyester of different acids and wax. Shellac was used from 1897 as a material for phonograph record pressing until being gradually replaced by polyvinyl chloride (PVC) beginning from 1948.⁵ Phonograph records composed of shellac and fillers⁶ were stamped using a metal stamp,⁷ yielding lateral feature sizes in the order of tens of micrometers (see Figure 1). Today, shellac is used as a coating material for drug release^{8,9} and is an approved food additive.^{10,11} Additionally, shellac already was employed as a substrate and dielectric layer material in environmentally friendly transistors, because of its insulating properties and capability to form smooth surfaces.¹²

FIG. 1. Scanning electron microscopy images of a shellac record fabricated in 1956.

C. Alternative materials used in microfluidics

For the fabrication of microfluidic systems, various materials such as glass, silicon, elastomers, thermosets, thermoplastics, hydrogels, and paper have been successfully implemented.¹³ Due to its simple fabrication even for highly sophisticated systems, as well due to its beneficial material properties such as flexibility and transparency, the elastomer polydimethylsiloxane (PDMS) has been widely employed in research. Nevertheless, PDMS (ca. 180€ per 1.1 kg Kit)¹⁴ is more expensive compared with many renewable materials as shellac (ca. 35€/kg)¹⁵ or paper (ca. 2€/kg) and therefore not well suited for very cheap point-of-care (POC) systems, which are intended to be consumables. Furthermore, PDMS swells considerably if exposed to certain solvents as cyclohexane or toluene,^{16,17} which render PDMS incapable of transporting and handling these fluids reliably. Paper is another material that has been extensively used in the past five years, especially for the implementation of paper-based microfluidic systems in low-cost POC applications. Paper is an extremely cheap material, whose properties and structure can be altered in various ways to define microfluidic structures.¹⁸ However, paper suffers from drawbacks as sample retention¹⁸ and limited feature size (hundreds of microns to millimeters),¹⁹ which could prevent the implementation of paper-based fluidic systems for applications where very low sample volumes are specified or highly integrated fluidic features are required. We have previously demonstrated that shellac can be hot embossed and implemented in simple microfluidic structures.²⁰ We believe its low price and small reproducible feature size render shellac a promising candidate for low-cost capillary-driven POC devices. However, the material properties of shellac for being used as a microfluidic material, its hot embossing performance for extended embossing conditions, and its environmental impact still have to be investigated. In Section II, we evaluate the material properties of shellac for fluidic applications. Afterwards, hot embossing experiments on shellac are conducted and analyzed with respect to the achievable resolution, aspect ratio, and appropriate process conditions. At last, a process scheme for the fabrication of simple microfluidic systems is presented. For its verification, a fluidic demonstrator is fabricated and tested. Here, we had the explicit goal to employ as much sustainable materials and processes as possible, to demonstrate our general approach.

II. SHELLAC AS A MATERIAL FOR MICROFLUIDIC SYSTEMS

In order to evaluate the compatibility of shellac with the requirements for microfluidic applications, the wetting and absorption behavior for relevant solvents such as water, cyclohexane, toluene, and dimethyl sulfoxide (DMSO) are determined and compared to PDMS Sylgard 184, which is a commonly used material for the fabrication of microfluidic devices.

A. Contact angle measurements

For determination of the contact angles, an EasyDrop Standard measurement device (KRUESS, Germany) was used. Five droplets of the respective solvents were deposited on lab slides either coated with PDMS Sylgard 184 or with dewaxed, bleached shellac (DICTUM, Germany) and analyzed using the drop shape analysis software. The averaged contact angles and their standard deviations are displayed in Table I.

The measurement data show that shellac has smaller contact angles than PDMS for all tested solvents. Therefore, capillary filling of microfluidic structures should be easier for shellac-based fluidic systems. However, cyclohexane and toluene wet shellac so strongly that no exact measurement data could be obtained.

B. Solvent uptake measurements

The absorption behavior for the solvents water, cyclohexane, toluene, and DMSO was determined by immersing cylindrical test specimen of 3 cm diameter and ca. 1 mm height in the respective solvents and comparing their weights after a certain immersion time to their initial weights. The solvent uptake $SU(\%)$ is calculated as follows:

TABLE I. Contact angles and standard deviations of solvents on shellac and PDMS.

Solvent	Shellac	PDMS
Water	$72.9 \pm 1.4^\circ$	$119.9 \pm 6.6^\circ$
DMSO	$19.2 \pm 0.9^\circ$	$79.2 \pm 1.9^\circ$
Cyclohexane	$<10^\circ$	$51.1 \pm 5.1^\circ$
Toluene	$<10^\circ$	$52.0 \pm 1.8^\circ$

$$SU(\%) = 100 \cdot \frac{m_t - m_i}{m_i}, \quad (1)$$

where m_i is the initial weight and m_t is the weight of each test specimen after an immersion time t in the respective solvent. Four test specimens were immersed in the respective solvents and weighed after 2 h, 6 h, 24 h, 48 h, and 96 h immersion time. The mean solvent uptake of the different specimens and their standard deviations are shown in Figure 2. For PDMS, they are in good agreement with the already published data.¹⁷

The data show that shellac has a slightly higher water uptake than PDMS. However, shellac does not take up cyclohexane, whereas PDMS strongly swells if immersed in it. For toluene, shellac shows a more pronounced uptake than for water, but PDMS exhibits a higher degree of swelling. DMSO swells PDMS to a low extent but dissolves the shellac samples within 6 h and is therefore not shown in Figure 2. Nevertheless, it might be useful for short term applications.

III. SHELLAC AS A THERMOPLASTIC MATERIAL

Hot embossing is a technique for structuring of thermoplastic polymers heated above their glass transition temperatures²¹ using stamps, allowing for a wide range of devices to be fabricated.²² For materials with low glass transition temperatures, this process enables fast processing using little energy.

A. Differential scanning calorimetry (DSC) measurements

To find the appropriate temperature range for performing the subsequent hot embossing experiments, the glass transition temperature of the amorphous material shellac was determined

FIG. 2. Solvent uptake of shellac and PDMS Sylgard 184 for different solvents. Solid line—shellac, dotted line—PDMS, and symbols/shape is assigned to each solvent, respectively. Error bars represent standard deviations.

through differential scanning calorimetry (DSC) using a DSC 204F1 Phoenix (Netzsch, Germany) measurement device. A shellac flake was put in the measurement crucible. The DSC sensor signal for the tested temperature range at a heating rate of 10 K/min is displayed in Figure 3. The glass transition of the first heating ramp is superimposed by an endothermic peak due to structural relaxation, which can occur for amorphous materials which have been stored below the glass transition temperature over a longer time period.^{23,24} The endothermic peak vanishes for the second heating ramp and the glass transition is visible more clearly. The measured glass transition temperature T_g (defined as the inflection point of the curve) is 42.2 °C, which is comparable to the findings from other authors.^{4,25} Thus, for the following, process temperatures between 30 °C and 80 °C were chosen.

B. Shellac hot embossing

So far, the replication performance of shellac hot embossing for 10 μm high test structures already had been evaluated.²⁰ However, the intended feature depth of the fluidic structures (fabrication is described in Section IV A) was approximately 50 μm . In order to validate the process of shellac hot embossing for the aspired feature height of approximately 50 μm , the performance of reproducing defined test structures of similar height was systematically examined. Therefore, a master silicon wafer was fabricated by spin-coating 45 μm thick SU-8 photoresist, followed by exposure using a test pattern on a photo-plotted foil mask, and developed. The test pattern comprised arrays of pillars, holes, and lines of different lateral feature sizes between 30 μm and 100 μm (see Figure 4). For all lateral feature sizes w_{fs} , the ratio of w_{fs} to the cavity width w_c is kept constant, so that $w_{fs}/w_c = 1$. Then, the PDMS Elastosil 4642 (Wacker Chemie AG, Germany) was used to generate a negative replica of the developed SU-8 master structure which served as hot embossing mold in the following. For hot embossing, test wafers coated with shellac were prepared. To assure that enough volume of shellac can be provided to flow into the PDMS cavities during hot embossing, the thickness of the shellac coating h_s of the test wafers was set to be at least twice the feature height of the test structures h_f (see Figure 4). Therefore, 8 g of shellac shellac was dissolved in 8 ml ethanol, dispensed on 4 in. glass wafers, and let dry, resulting in shellac layer thicknesses of approximately 90 μm . Then, the PDMS stamps were placed on the dried shellac films and air bubbles trapped between the shellac film and the PDMS through applying a vacuum of 25 mbar. Hot embossing was performed under different temperatures and force conditions. During hot embossing, a lab press (VOGT LaboPress 150H) was first heated to the specified temperature, and then the preassigned force

FIG. 3. DSC graph of shellac used for hot embossing: For the first ramp up, an endothermic peak due to structural relaxation is observed at the glass transition. For the second ramp up, the endothermic peak disappears. Exothermic (exo) heat flow occurs for negative heat flow values.

FIG. 4. Scheme for shellac hot embossing experiments: The test pattern used for evaluation of hot embossing performance comprises arrays of pillars, lines, and holes of feature sizes between $30\ \mu\text{m}$ and $100\ \mu\text{m}$. During hot embossing, the shellac flows into the cavities of the PDMS stamp.

was applied for 10 min before the setup was cooled to room temperature, at which the pressing force was released. The fabricated shellac test structures as well as the SU-8 master structures were inspected and characterized using white light interferometry (WLI) with a $20\times$ Mirau objective, yielding a lateral resolution of $1.1\ \mu\text{m}$. Examples of the replicated shellac structures comprising pillars, holes, and lines are shown in Figure 5. To evaluate the hot embossing performance of shellac under different process conditions, the WLI measurement data from test structures of pillars, holes, and lines were analyzed: First, the average heights of the bottom and top surface and their standard deviations were calculated. Second, the feature height of the pillars, holes, and lines was calculated as the difference of the average heights of bottom and top surface. Last, the feature height standard deviation was calculated as the square root of the sum of the squares of the standard deviations of the bottom and top surface heights. The better the agreement of the feature heights from the replicated test structures with the master structures, the more accurate the hot embossing could be performed. A higher feature height standard deviation indicates scratches, ripples, waves, and unevenly replicated structures as well. However, the WLI measurement is only capable of evaluating surface topologies with less than 14.56° slope with the magnification used. The obtained feature height and standard deviation

FIG. 5. Example WLI measurement data mesh plots for pillar, hole, and line test structures (from left to right) of $50\ \mu\text{m}$ lateral feature size and $45\ \mu\text{m}$ feature height.

therefore can be over-resp. underestimated, especially for wafers with a higher percentage of areas with slopes higher than 14.56° , as these areas yield no valid data points.

C. Replication of test structures

For embossing with applied force ($F=4\text{ kN}$), operating temperatures between 30°C and 50°C were tested. Additionally, for embossing without force ($F=0\text{ kN}$), operating temperatures between 50°C and 70°C were tested. For these conditions, mainly capillary forces contribute (see [supplementary material](#)), whereas the compressive force caused by the weight of the PDMS stamp of approximately 15 g is negligible. The results of the WLI data evaluation are displayed in Figure 6. The data show that for embossing at $F=4\text{ kN}$, pillars and lines down to $30\text{ }\mu\text{m}$ and holes down to $50\text{ }\mu\text{m}$ lateral feature size could be embossed successfully for temperatures just above the glass transition temperature ($T_g=42.2^\circ\text{C}$), e.g., between 45°C and 50°C , visible in a good agreement of master and replica structures and a low feature height deviation. For lower temperatures, an increasing deviation between the master and replica feature heights as well as an increasing feature height standard deviation is observed. For embossing without force ($F=0\text{ kN}$), pillars and lines down to $30\text{ }\mu\text{m}$ and holes down to $50\text{ }\mu\text{m}$ lateral feature size could be embossed successfully for temperatures between 55°C and 70°C . For lower temperatures, the embossing was incomplete. This shows that without applied force, hot embossing is still possible; however, temperatures of at least 10°C above the glass temperature are required to achieve satisfying embossing results. For the wafer embossed at 60°C and $F=0\text{ kN}$, a second WLI measurement using a higher magnification (lateral resolution = $0.44\text{ }\mu\text{m}$) was performed for evaluation of the surface roughness, on an area of $30\text{ }\mu\text{m} \times 30\text{ }\mu\text{m}$ on the bottom surface between $50\text{ }\mu\text{m}$ wide pillars. The surface roughness for this area was determined to be 29 nm .

IV. SHELLAC MICROFLUIDIC DEMONSTRATOR

A. Fabrication

In the following, a novel sustainable method for the fabrication of microfluidic systems is presented. This fabrication method is targeted at achieving the least environmental impact by

FIG. 6. Evaluated WLI data for replication of $45\text{ }\mu\text{m}$ high SU-8 test structures. Hot embossing was performed with $F=4\text{ kN}$ (upper row) and $F=0\text{ kN}$ (lower row) to replicate shellac structures comprising pillars (left column), holes (middle column), and lines (right column). Initial shellac film thickness was approximately $90\text{ }\mu\text{m}$ prior to embossing. Error bars represent standard deviations.

using solely renewable consumable materials, such as shellac, paper, or ethanol, and concurrently utilizing their beneficial material properties that allow for low-energy lab scale processing, e.g., shellac's low glass transition temperature which enables energy-efficient hot embossing. Nevertheless, additional materials besides shellac, paper, or ethanol were used during the fabrication of the fluidic master structure or the hot embossing stamp. However, both of them can be used many times during processing and therefore do not strongly increase the environmental impact. At first, the PDMS stamp for hot embossing was prepared. 1 ml of a shellac/ethanol (0.1 g/ml) solution (which in this case serves as natural glue for glue for the following layer) was dispensed on a 4 in. glass wafer and let dry. Then, a polyimide foil (thickness = 50 μm), which served as an alternative to the formerly used SU-8, was attached to the solidified shellac by pressing with 1 kN at 80 °C (Figure 7(a)). Afterwards, a UV laser was used to laser-cut the fluidic master structure in the polyimide foil (Figure 7(b)). As the UV radiation of the laser did hardly attack the shellac layer and the glass substrate, the channel depth could simply be set by choosing the appropriate polyimide foil thickness. A thin layer of the opaque PDMS Elastosil 4642, which is well suited as an embossing stamp material, was deposited on the fluidic master wafer through spin-coating at 3000 rpm (Figure 7(c)). After curing at 100 °C on a hotplate for 30 min, a thick layer of the transparent PDMS Sylgard 184 was cast on the thin Elastosil layer and cured at 100 °C for 30 min (Figure 7(d)). Thus, a semitransparent

FIG. 7. Fabrication scheme of microfluidic demonstrator: (a) Glueing of polyimide foil to glass wafer, (b) laser structuring of polyimide foil, (c) spin-coating of opaque PDMS Elastosil 4642, (d) casting of transparent PDMS Sylgard 184, (e) dispensing of shellac/ethanol solution on paper, (f) hot embossing of fluidic structures into shellac/paper bilayer, (g) casting of shellac foil, (h) sealing of fluidic structures using shellac foil, and (i) punching of fluidic inlets and outlets.

PDMS stamp allowing to perform alignment to marks in the substrate and having the beneficial surface properties of Elastosil 4642 on the embossing surface was fabricated. As shellac is a brittle material, it was deposited onto a paper substrate before hot embossing. To prepare the paper/shellac substrate, the wafer and chip outlines were printed with a conventional office laser-printer on copy paper. After cutting out the paper wafer based on the outline, it was soaked in 3 ml of shellac/ethanol (0.1 g/ml) solution and let dry. Thereafter, 4 ml of shellac/ethanol (0.2 g/ml) was dispensed on the dried paper wafer (Figure 7(e)). The previously deposited shellac served as a barrier for the newly deposited shellac/ethanol solution, allowing it to dry on the paper surface. After the second shellac solution had dried, hot embossing was conducted at 50 °C and 4 kN (Figure 7(f)). To seal the hot embossed channels, a thin shellac film was prepared through dispensing a shellac/ethanol solution on a PDMS substrate in the middle of a thin paper rim cut out from copy paper and letting it dry. To avoid leakage of the shellac/ethanol solution, the paper rim was primed with 0.25 ml of shellac/ethanol (0.1 g/ml) solution before dispensing 2 ml of shellac/ethanol (0.2 g/ml) solution (which later forms the shellac) in the middle of the paper rim (Figure 7(g)). The paper rim prevented the shellac/ethanol solution to shrink laterally during drying and therefore defined the diameter of the dried shellac film. The dried shellac film was attached to the embossed microfluidic channel in the shellac/paper substrate by heating it to 58 °C for 10 min (Figure 7(h)). For defining fluidic inlets and outlets, holes were manually punched at the desired positions using tweezers (Figure 7(i)). Separation into single chips was performed through cutting with scissors along the laser-printed chip outlines.

B. Test of microfluidic demonstrators

To evaluate the fabricated microfluidic structures for potential leakage, the fluidic demonstrators were filled with an ink-water mixture. The fluid was transported purely through capillary forces without external actuation, filling the channels as intended. Images of the hot embossed shellac/paper bilayer and a fabricated microfluidic demonstrator chip are shown in Figure 8.

C. Resource consumption during fabrication

In order to access the environmental impact of this novel method for microfluidic systems fabrication, a survey of its primary consumed resources was evaluated (see Table II). For better comparison to other process data, the survey was normalized to the processed input wafer area. The resource consumption for the fabrication of the PDMS stamps used (including the fluidic

FIG. 8. Big picture: Hot embossed shellac/paper bilayer. The transparent PDMS stamp allows alignment to the chip outlines printed on the paper substrate. Small picture: Fabricated microfluidic test chip.

TABLE II. Survey of primary resources consumed by fabrication method.

Resource	Amount/4 in. wafer	Unit	Amount/wafer area	Unit
<i>El. energy</i>				
Hot embossing	0.17	kW h	0.0021	kW h/cm ²
Channel sealing	0.10	kW h	0.0013	kW h/cm ²
Total	0.27	kW h	0.0034	kW h/cm²
<i>Shellac</i>				
Substrate	1.10	g	0.0140	g/cm ²
Shellac foil	0.43	g	0.0054	g/cm ²
Total	1.53	g	0.0194	g/cm²
<i>Ethanol</i>				
Substrate	5.52	g	0.0703	g/cm ²
Shellac foil	1.78	g	0.0226	g/cm ²
Total	7.30	g	0.0929	g/cm²
<i>Paper</i>				
Substrate	0.63	g	0.0080	g/cm ²
Shellac foil	0.10	g	0.0013	g/cm ²
Total	0.73	g	0.0093	g/cm²

master) was not included in this survey, as there were no data on wear of fabrication tools during processing available. Additionally, manual fabrication such as cutting with scissors, punching of inlets and outlets, or alignment of the stamp or shellac foil, as well as the amount of toner used for printing the chip and wafer outline on the paper, was not included. As the cooling water consumption for the hot embossing is strongly dependent on the required processing time and can be completely omitted if longer processing times are tolerated, it was neither included in this survey.

As the data presented in Table II show, the highest share of the energy consumed was used for the hot embossing, because this process requires a mechanical press which had to be heated from room temperature to the pressing resp. embossing temperature and cooled down afterwards for each processed component. The sealing of the channels could be carried out in an oven which consumes less energy for heating up to the process temperature. Additionally, the oven used is able to handle multiple substrates at once, so the energy consumption could be reduced further if more wafers are being processed in parallel. Approximately 25% of the shellac was used to fabricate the shellac sealing foil, whereas 75% was used to fabricate the substrate. The amount of ethanol was more than 4 times bigger than the amount of shellac used during fabrication. However, Capello *et al.* stated that ethanol is a comparably green solvent.²⁶ Furthermore, ethanol can be produced from renewable biomass as corn or sugar beet. In comparison to our novel fabrication method for shellac microfluidic systems described here, the fabrication of state-of-the-art microfluidic chips made of PDMS and glass would consume similar amounts of electrical energy, as the PDMS must be cured, usually at temperatures between 60 °C and 100 °C.^{27,28} The energy demand for the fabrication of the particular materials used was not investigated specifically. However, data for the energy demand for the fabrication of comparable materials do exist, which allow to estimate the energy demand connected to their fabrication: The (electrical and thermal) energy demand for the manufacture of shellac is approximately 4 kW h/kg.²⁹ The manufacture of bioethanol (thermal and electric energy consumption of corn ethanol dry mill = 2.8 kW h/kg)³⁰ and paper (thermal and electric energy consumption = 3.0 kW h/kg)³¹ needs less energy. The energy intensity for the fabrication of glass depends strongly on the glass composition, cullet percentage, and other factors, thus accurate estimates are hard to be set.³² However, we account the fabrication of glass with approximately 1.8 kW h/kg (exemplary value for flat glass).³² The manufacture of PDMS is quite energy-intensive (el. energy consumption is ca. 6.4–8.4 kW h/kg).³³

V. CONCLUSION AND OUTLOOK

In this work, we have demonstrated a fabrication method for microfluidic systems, which uses renewable materials, employs an energy-efficient fabrication method, and produces biodegradable end-products. Thus, the fabrication method can be labelled as being “green.” The fabrication of microfluidic structures was conducted by hot embossing of the renewable biomaterial shellac, which enables low processing temperatures and therefore little energy consumption. Further, the good wettability, low water uptake, and simple structuring method of shellac render it a promising material for the usage within cheap single-use point-of-care systems. Therefore, future work should investigate the performance of shellac-based fluidic systems for more advanced measurement/detection systems, e.g., for immunoassay setups. Besides, shellac-based simple microfluidic systems can be potentially implemented within modular analysis systems where fluidic handling and analysis are performed by separate subsystems, e.g., an elaborate analysis subsystem and a cheap fluidic handling chip.³⁴ Furthermore, shellac degrades if buried in soil,³⁵ which could be exploited for applications in regions where proper garbage disposal is not available, e.g., within cheap disease detection chips for usage in rural areas of non-developed countries. As paper is being used as a passive substrate material, further revised systems could also feature a co-integration of “classical” channel-based and novel paper-based microfluidic features.

SUPPLEMENTARY MATERIAL

See [supplementary material](#) for the description of the calculation of the toxic and corrosive waste generated by the fabrication of logic chips, additional experiments on the capillary filling of shellac into PDMS stamp cavities, and viscosity measurements of shellac performed.

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