SEMI-CONTACT WRITING TECHNOLOGY & APPLICATIONS

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ABSTRACT

We present an adaption of a direct ink writing approach to facilitate prevalent standard applications like fabricating masters for PDMS casting, conducting path structuring and generation of open microfluidic structures towards gel electrophoresis. In all presented applications, flexibility is increased and standard structuring processes can be substituted offering the ability for low-cost fabrication with less required expertise. In contrast to existing approaches low to medium viscous liquids are applied due to passive capillary forces.

KEYWORDS

Open microfluidics; Semi-contact writing; Droplet jetting

INTRODUCTION

In the past direct ink writing approaches have been presented to satisfy the need for flexible and low-cost material structuring [1] across various disciplines like physics, chemistry or biology enabling the implementation of customized structure designs in a fast and comfortable manner. Structures are generated using a viscous paste released out of a nozzle during pressure application to the dispensing system. A more common method for structure generation based on low viscous materials is droplet jetting/dispensing where structures are realized by merging of subsequently dispensed droplets (Fig. 1 a) [2]. A related method is droplet dispensing in pre-fabricated open channels, where structures are formed by capillary forces. While direct ink writing methods primarily address pasty materials, droplet jetting of low viscous liquids is challenging owed to the adjustment of optimum droplet spacing. The semi-contact writing (SCW) approach presented here is a convenient method to process low or even medium viscous liquids onto a variety of common substrate materials.

SEMI-CONTACT WRITING TECHNOLOGY

Figure 1 b represents the SCW working principle. Here, the nozzle (ID: 200 µm) of a PipeJet™-dispenser (BioFluidix GmbH, Germany) [3] mounted to a software-controlled 3-axis robot is primed with the desired structural liquid and moved in close proximity (~100 µm) to a planar substrate (perpendicular to the nozzle orifice). The ejection of a single droplet bridges the detached dispenser nozzle and the substrate surface. Due to controlled nozzle-displacement in x- & y-direction liquid is released out of the nozzle by capillary force, only. Previously, similar techniques have been demonstrated by pressure-driven release of viscous liquids or pastes [1]. Using the SCW-method, structure width and height largely depend on the liquid-substrate combination (attributed by contact angle and viscosity) and can be controlled by process parameters like displacement-velocity, hydrostatic pressure, nozzle diameter & nozzle-substrate-distance. Varying these parameters

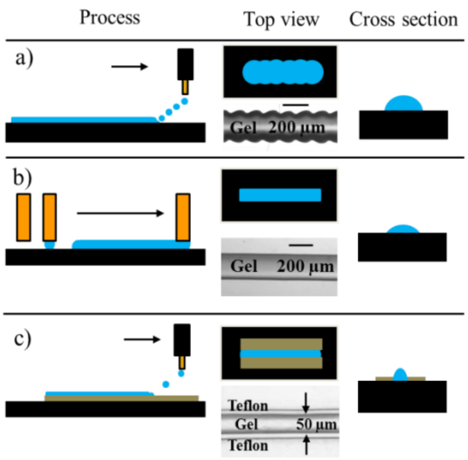

Figure 1: a) Periodic droplet jetting to produce linear structures on planar substrates. b) Semi-contact writing method. The nozzle of a dispenser is moved close to the substrate (~100 µm). The ejection of a single droplet establishes a capillary bridge between nozzle and substrate. Complex fluidic structures are generated due to capillary flow by controlled displacement of the substrate along the x-y-plane. c) Combined method of the SCW-technology and droplet jetting.

enables processing of liquids with viscosities up to 500 mPas as demonstrated for polyacrylic acid (50 wt-%) (PAA) on planar Polyimide (PI) substrates exhibiting widths down to 120 µm. Narrower structures can be achieved by decreasing the nozzle diameter which in turn complicates the process due to an increased

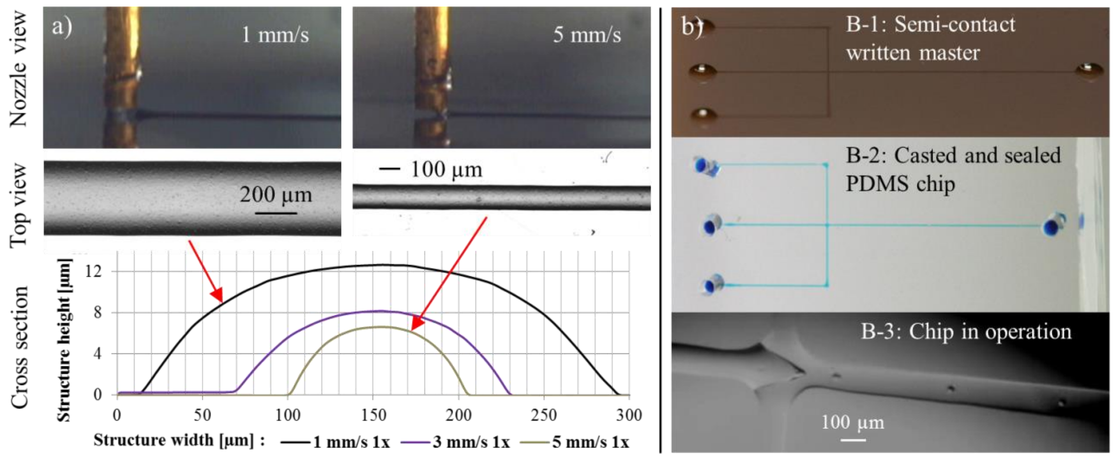

Figure 2: a) Nozzle observation during line generation process (Polacrylic acid 50 w-% on a Polyimide foil substrate) and profiler cross sections at different displacement velocities. Stacking structures on top of each other leads to a linear increase in height. b) Processing steps for PDMS prototyping. B-1) Written master-structure (5 mm/s; 5 stacks) for PDMS casting ($A_{channel}$: 100x35 µm²). B-2) Casted, sealed and ink-filled PDMS chip. B-3) Microfluidic droplet generator in operation.

fluidic resistance restricting the flow out of the nozzle. To overcome these challenges SCW- & droplet jetting methods are combined writing hydrophobic boundary structures (Teflon®, Dupont, USA) in parallel at an in-between distance of about 50 µm using SCW (Fig. 1 c). The formed space is filled up *via* liquid dispensing (droplet jetting) resulting in droplet merging to form line shaped structures, for instance. Thus structure width can be further decreased while the impact of the structural liquid on dimensions is reduced as dimensions mainly depend on the generated boundary geometry.

APPLICATIONS

PDMS prototyping

The SCW-method can be used to fabricate master-structures in conventional PDMS prototyping [5]. The integration of SCW allows for the rapid change of chip designs bypassing cleanroom facilities and time-consuming mask fabrication which also reduces required expertise. For this purpose, an aqueous polyacrylic acid solution (50 wt-%) was applied to a standard Polyimide foil substrate using a software-based implemented design. After master fabrication Parylene-C was vapor deposited on the structures to prevent liquefaction and adhesion during PDMS casting enabling multiple casting procedures using the same master. The applicability of the process was demonstrated by fabricating a microfluidic droplet generator within less than 4 hours (from individual design to chip, Fig. 2b). Adjusting flow rates to 30 µL/h for water and 200 µL/h for two perpendicularly crossing oil streams periodic droplet generation can be observed with a frequency of ~60 Hz and a volume of about 15 pL per single droplet. Summarized, the process features the following specifications:

- Stack width ∝ displacement velocity (Fig 2a)
- Stacking of structures (multiple writing cycles) → linear increase in height without significant structure broadening (max. aspect ratio for PAA on PI: 0.36)
- Local height adjustment possible *via* selective structure stacking
- Channel width: 100-500 µm
- Channel height: 7-200 µm
- Semi-circular cross-section
- Multiple casting due to hydrophobic coating

To demonstrate the accuracy of SCW-based fabrication two fluids of differing physico-chemical properties where applied upon a PI substrate to form channels, junctions, corners and intersections (Fig. 3). Implementation of velocity

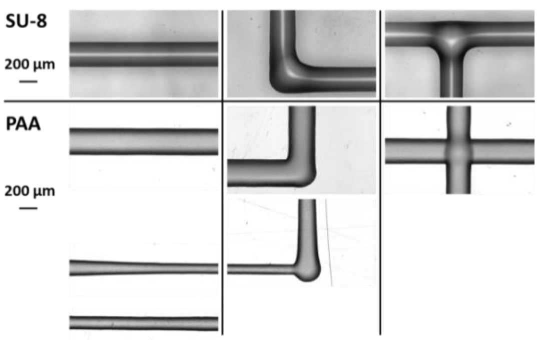

Figure 3: Structure examples generated using the semi-contact writing method applying SU-8 photo resist and PAA as structural material on PI.

gradients during nozzle displacement leads to the formation of tapered channel structures (Fig. 3, PAA bottom left).

Reproducibility was tested by writing 5 lines (length: 5 cm) next to each other with a certain pitch and multiple writing cycles (structure stacking) on a microscopic glass slide. Effects of displacement velocity and the number of stacks on channel dimensions are shown in Table 1.

Table 1: Structure dimensions in dependence on displacement velocity and number of stacks.

Displacement velocity [mm/s]	**No. of stacks *n***	**Mean structure width [µm]**	**Mean structure height [µm]**
1	10	396 ± 6	88 ± 4.5
3	8	278 ± 3.7	47.5 ± 0.9

Conducting path & substrate prototyping

As described for PDMS prototyping, SCW was used to generate simple conducting paths upon flexible, isolating polymer foils. A sintering-customized ink containing silver nanoparticles (Metalon JS-B25HV, Novacentrix) was used as basic conductive material and was modified towards our purpose. The alcoholic solvent was replaced by water to achieve desired wetting properties. For the use of Kapton 500B as substrate material the silver nanoparticles were centrifuged and alcohol was removed *via* pipetting and desiccation. Afterwards, silver particles were rehydrated with equal amounts of DI-water in respect to the removed solvent, resulting in a similar viscosity as the stock ink but with substrate-adapted surface properties. During processing substrates are mounted to a substrate carrier with small through-holes and buried channels to implement vacuum fixation. Thus a planar substrate surface is ensured whereas no substrate displacement takes place.

Linear structures of different widths are generated by single semi-contact writing, larger areas could be realized by line merging of side by side written liquid structures.

Fig. 4a displays conducting paths directly after generation on a Kapton 500B substrate. Following solvent evaporation (~5 min), common soldering paste was used to mount a SMD resistor and a SMD LED on the fabricated circuit. Both, nanoparticles and paste were soldered during a single standard reflow process within about 10 minutes.

The SCW-method presented here enables simple and rapid prototyping of low-cost

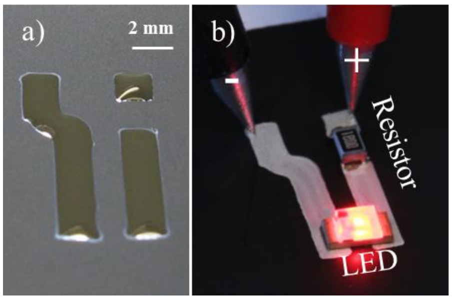

Figure 4: Semi-contact writing method was used to apply a water-based silver-nanoparticle ink on a planar Kapton 500B substrate. To achieve area structures multiple lines were written side by side with a pitch of 300 µm. a) Silver-ink right after structure generation. b) Silver nanoparticle layer after solvent evaporation with mounted SMD-electronics via soldering paste.

customized and compact electric circuits especially for low to medium unit numbers, where specifically designed printed circuit boards (PCB) are not cost-efficient, e.g. when fabricating prototypes. Moreover, it can be used to modify standard circuit boards in case of adding additional components or to prototype flexible PCBs.

Structure generation in open microfluidics

A third application is the generation of liquid structures in open microfluidics [6] like separation channels in open microfluidic gel electrophoresis (OMGE) [7] (Fig. 4). Using the SCW-method a ~200 µm wide channel of linear acrylamide is written across two flat platinum-electrodes on a planar Kapton 500B substrate. To perform electrophoretic separations the open microfluidic system requires two additional dispensers, one to handle the sample and a second to cover the structure with oil to prevent evaporation. A Nano-Jet [8] module is used as a picoliter-dispenser for the contact-free injection of the sample into the separation channel. In this case 150 pL of a fluorescently labeled (Cy5) ssDNA-fragments mixture at a concentration of 1 µM (56-&112-bp, equimolar) was injected. The other dispenser is a conventional syringe pump to apply the oil (Mineral oil PCR Reagent, Sigma-Aldrich). Due to small channel dimensions the substrate needs to be temperature controlled (here: ~14°C) to prevent evaporation during the SCW-process. Furthermore, gel reservoirs were established on both electrodes for an enhanced coupling of the electric field and to prevent charge carrier depletion during electrophoretic separation. Fig. 4 details the process flow (a) and

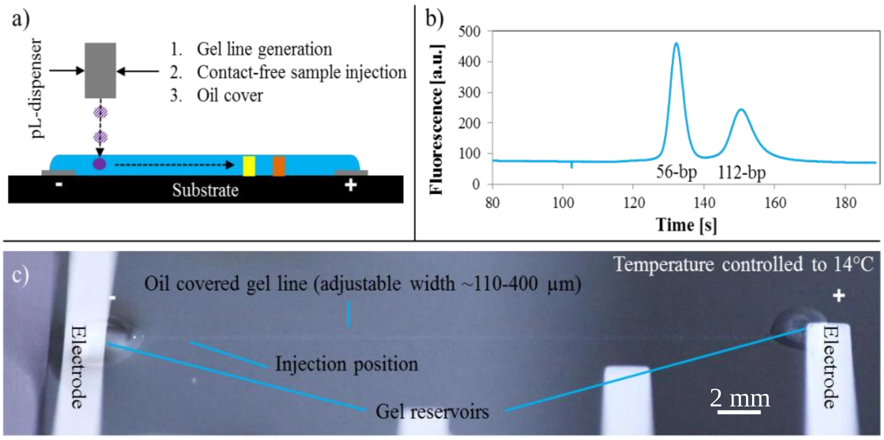

Figure 5: Semi-contact writing used to generate gel separation channels for capillary electrophoresis in open microfluidics. After line generation a DNA sample is injected via non-contact dispensing into the channel and separated by an electrical field with a field strength of E = 200 V/cm. To prevent evaporation the channel is cooled and covered with an oil layer. Migrating DNA was point-detected via LIF near the cathode.

represents an example of an oil covered open microfluidic structure (c). After fabricating the microfluidic system an electrical field of 200 V/cm was applied along the separation channel and separated ssDNA-fragments were detected *via* end-point laser-induced fluorescence about 15 mm downstream the injection position (λ_{ex}= 635 nm, λ_{em}= 685 nm) (Fig. 4 b). Together, the process took about 5 min from fabricating the open microfluidic structure to signal detection.
Applying the SCW-method in open microfluidic gel electrophoresis is a fast, low cost, low volume consuming and on-demand method for conducting electrophoretic separations. The software based customized design implementation increases flexibility while multiplexing is enabled due to the modular setup.

CONCLUSION & OUTLOOK

The semi-contact writing method is a modification of existing direct ink writing technologies and was successfully transferred to a variety of applications, like fabrication of masters in conventional PDMS prototyping, conducting path and electrode fabrication or open microfluidic gel electrophoresis. SCW enables accurate fabrication of structures exhibiting semicircular cross sections in a fast, convenient and low-cost manner. All presented applications benefit from SCW by increased flexibility, decreased process time & costs as well as less required expertise. In future, the SCW application spectrum will be extended and presented applications will be studied in more detail.

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