Inkjet Printing for Applications in Microfluidic Lab-on-Chip Systems

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Abstract

Inkjet printing is a digital printing technique that is capable of depositing various functional materials onto different substrates in an additive way. In this contribution, applications of inkjet printed structures for smart microfluidic lab-on-chip systems are discussed. Such systems can be used e.g. for different chemical or biochemical analysis tasks and are often fabricated from polymers. Inkjet-printed electrodes and electroactive polymer (EAP) actuators for use in microfluidic lab-on-chip systems are shown. Silver and gold electrodes are presented that are fabricated by printing metal nanoparticle inks onto polymer substrates. After printing the structures are sintered using low-pressure argon plasma sintering, a low-temperature sintering process that is compatible with polymer substrates with a low glass transition temperature T_G*. The structures consist of several electrodes and contact pads and feature minimum structure sizes of approximately 70 µm. These structures are in principle suitable for requirements in lab-on-chip systems. The use of all inkjet-printed EAP actuators in a polymer-based micropump is discussed. Cantilever-type bending actuators generate deflections of more than 190 µm when a voltage of 600 V is applied. Based on these results, performance characteristics of a micropump with printed actuators are estimated.*

Introduction

Microfluidic lab-on-chip systems are systems that can be used to control, mix and analyse small fluid volumes. In such systems, different biological and chemical analysis processes can be carried out [1]. Lab-on-chip systems can be fabricated from polymer materials and often consist of a substrate with fluid channels and a cover foil. For example, chip-based electrophoresis is used to separate different contents of test fluids by means of an electric field [2]. The electrode structures can be applied on the cover foil of the chip using standard thin film processes.

For the distribution of fluids across the channels of a chip, pumping and valve functions are required. Typically, external pumps are used and well-developed. A drawback of external devices is the need for an assembly process for the complete system. As an alternative, several types of micropumps have been investigated by different groups. The use of pumps that create a fluid flow based on a membrane that deflects above a pumping chamber is widespread. Piezoceramic actuators, often fabricated from lead-zirconate-titanate (PZT) can be used to drive the membranes [3]. The mechanical parts of the pumps are typically fabricated using mass-compatible processes, while the PZT element is fixed on the membranes by adhesives. Therefore, a separate joining step is necessary. To avoid this additional process step, electroactive polymer (EAP) foils [4] or screen-printed PZT layers [5] can be employed. With screen-printed PZT, a high-temperature sintering step above 900 °C is needed, which is not applicable to low-cost polymer materials.

Inkjet printing is a digital printing process by which different solutions or suspensions of functional materials ("inks") can be deposited. Different from lithography-based processing, no masking is required. Furthermore the process can run at room temperature and in ambient atmosphere, which makes is cost-efficient and flexible. Various devices have been manufactured using printing processes, examples of which are OLEDs [6], organic photovoltaic devices [7] and RFID antennas [8]. The electrical contacts needed are often printed using silver or gold nanoparticle suspensions. After printing, a sintering step is needed to generate a conductive structure. The sintering takes places at elevated temperatures, typically above 150 °C, which limits the use of polymer substrates. Alternatively, sintering can be achieved by local laser irradiation, plasma or microwave exposure, broadband light sources or electrical power [9]. These processes are compatible with low T_G polymer substrates.

In this contribution the use of drop-on-demand inkjet printing to generate electrode structures and piezoelectric polymer actuators for use in microfluidic lab-on-chip systems is discussed. Firstly, inkjet-printed gold and silver electrode structures on polymer substrates are presented. The structures are printed using commercially available nanoparticle inks and sintered using low-pressure argon plasma. Secondly, all inkjet-printed EAP actuators are presented. The concept of a micropump with printed EAP actuators is discussed.

Printed Electrodes for Lab-on-Chip Systems

Currently electrodes for microfluidic lab-on-chip systems are often fabricated using lithography-based patterning and thin film processes like sputtering or electron-beam evaporation. Especially for single-use devices these processes are relatively cost intensive. Therefore digital printing techniques represent a promising alternative to generate conductive structures. Figure 1 shows an electrode pattern on a polymer substrate that has been printed using a commercially available silver nanoparticle suspension in ethanol and ethylene glycol (CCI-300, Cabot Corp.). Industrial piezoelectric printheads with a droplet volume of 30 pL are used (Galaxy 256/30, Fujifilm Dimatix Inc.) and positioned with a six-axis robot (Kuka Robert GmbH). The electrode pattern includes lines with a width of 70 µm and several contact pads. The target application of the electrode pattern is chip-based electrophoresis.

As substrate material cyclo olefin polymer foils (Zeonor, T_G 136 °C) are used. In order not to damage the substrates, a low temperature sintering process using low-pressure argon plasma is employed. This transfers the printed features into conductive structures without damaging the substrate [10]. The sample presented here has been sintered at a relatively low RF power of 150 W for 15 min yielding a resistivity of approximately 40 times the bulk silver value ($\rho \approx 65\ \mu\Omega\,cm$). With higher powers or longer processing times the resistivity can be reduced.

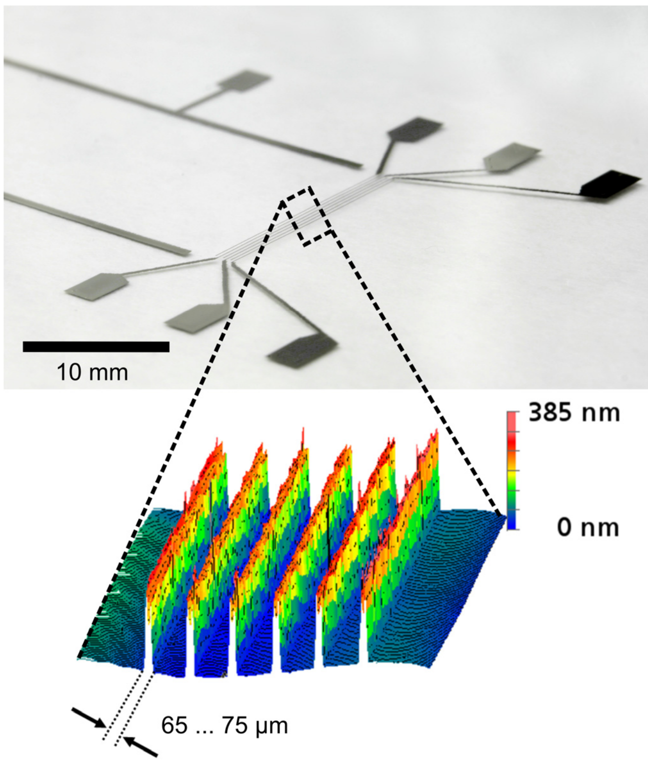

***Figure 1.** Inkjet-printed electrode layout for microfluidic applications, photograph (upper) and profile (lower).*

Due to its antibacterial behavior, silver is not compatible with specific biological or chemical analysis processes. Therefore printing of gold nanoparticle inks is under investigation; results of printed and plasma sintered gold conductors are shown in Figure **2**. A commercially available gold nanoparticle ink (NPG-J, Harima Chemicals Inc.) is printed on a PET substrate. Line widths of 70 to 100 µm are realized. The resistivity of these structures is relatively high ($\rho \approx 2700\ \mu\Omega\,cm$, corresponding to approximately 1100 times the bulk gold value). Optimization of the process concerning line formation and conductivity is ongoing, it is planned to investigate laser sintering to increase the conductivity.

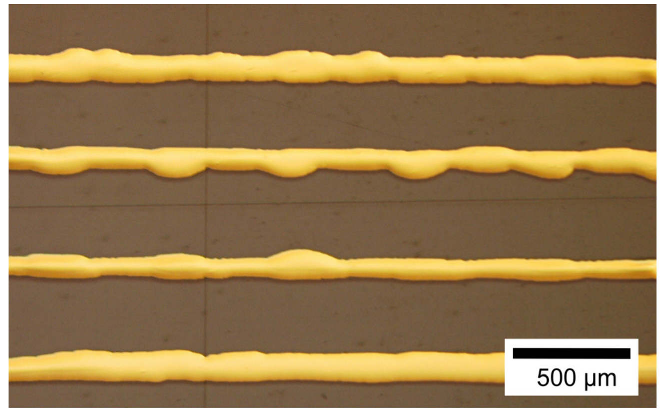

***Figure 2.** Inkjet-printed gold electrodes on PET substrate. Argon plasma sintering is used to render the structures conductive.*

Inkjet-Printed Electroactive Polymer Actuators

In almost all microfluidic systems a fluid needs to be distributed through the channels on the chip, thus a pumping function is required. In this section results on all inkjet-printed electroactive polymer (EAP) actuators that can be used to generate a pumping function are discussed. The actuators consist of an EAP layer that is sandwiched between two electrodes. All the active layers are inkjet printed onto polycarbonate substrates (PC, Makrofol, Bayer MaterialScience AG). The electrodes are printed using silver nanoparticle ink (CCI-300, Cabot Corp.) and sintered using argon plasma. For the EAP layers, a commercially available solution of piezoelectric polymers (solvene™, Solvay Solexis S.p.A.) is inkjet-printed. Printing is done in multiple layers; a final thickness of 10 to 15 µm is achieved. After printing, the polymer layers are cured at moderate temperatures of 130 °C to 140 °C. The samples are mounted as cantilever beams fixed mechanically at one end; a photograph is shown in Figure 3.

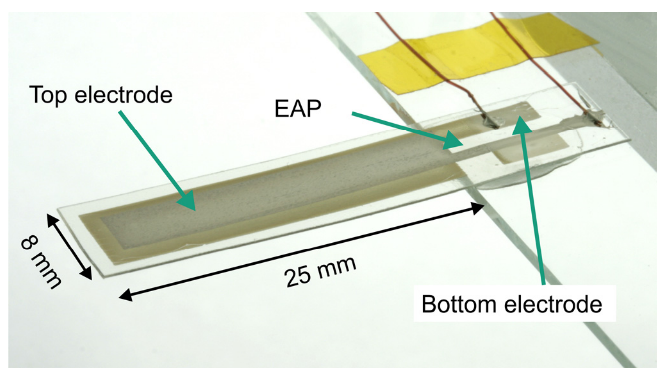

***Figure 3.** Inkjet-printed electrode polymer (EAP) actuator mounted as a cantilever bending beam. [11]*

Prior to use the actuators need to be poled electrically to invoke piezoelectric behavior. This is done by applying a voltage of several hundred volts for few minutes. When an electric field is applied across the EAP layer, piezoelectric strain is induced that leads to a bending motion of the structure, comparable to a bi-metallic beam. The static deflection of bending beams with lateral dimensions of 8 × 25 mm² has been measured using a laser triangulation sensor. Results are displayed in Figure 4. For driving voltages of 600 V, deflections of more than 190 µm can be achieved. The resonance frequency has been measured with a laser Doppler vibrometer; the first resonance frequency of the structures presented is approximately 100 Hz. These results are promising for application of such actuators in a membrane pump.

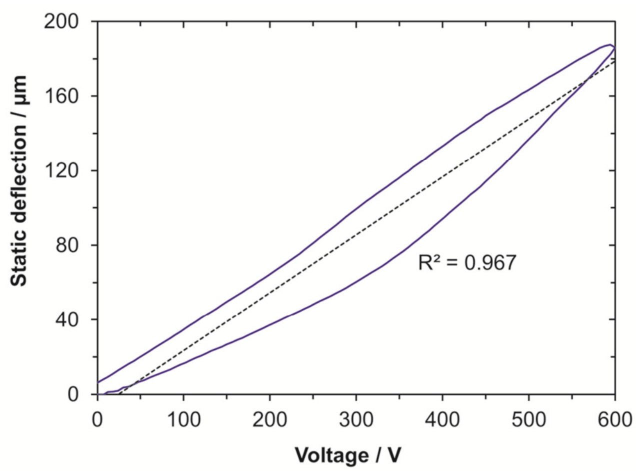

***Figure 4.** Static Deflection of an EAP actuator under static electric load. [11]*

A possible concept of a polymer-based membrane pump is depicted in Figure 5. The pump consists of a fluidic substrate made from polymer and a membrane with a printed EAP actuator. The substrate can be manufactured using standard polymer processing techniques like injection molding or hot embossing and features a pumping chamber, inlet and outlet channels and valve structures. These features are integrated in the mold. On top of the fluidic substrate, an actuator membrane with a circular inkjet-printed EAP actuator is mounted. When the EAP actuator is driven electrically, the membrane will deflect and the resulting volume change will lead to a pumping of the fluid from the inlet to the outlet channel.

Based on the measurement results of cantilever-type bending actuators mentioned above, the deflection behavior of membrane actuators for use in a micropump is estimated. An analytical model [13] is employed to calculate membrane shape and deflection. Assuming membrane diameters between 5 mm and 10 mm, the central membrane deflection is calculated to range between 5 µm and 20 µm. These results are used to estimate the volume change and thus the pump performance. When driven at resonance frequency, a pumping rate of several 100 µL min^{-1} can be expected.

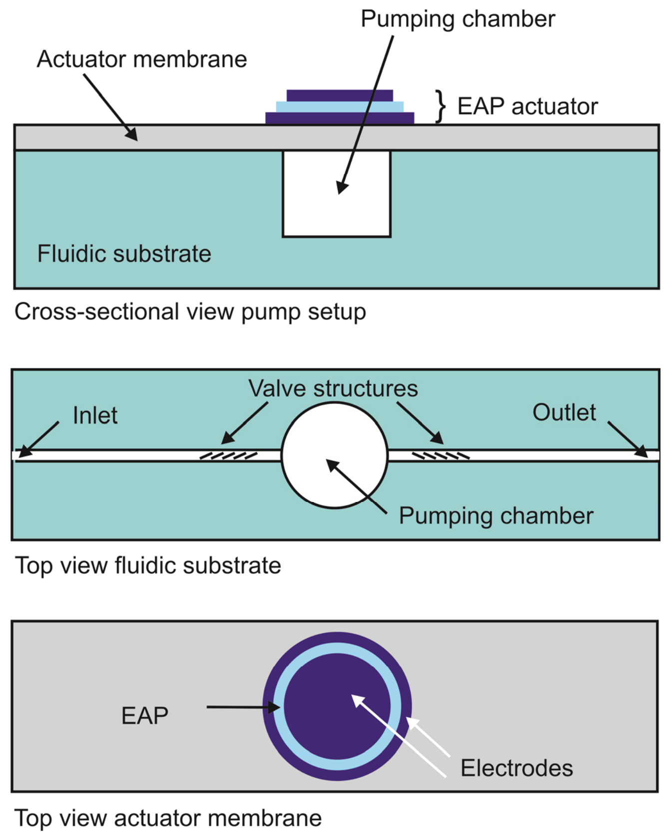

***Figure 5.** Principle of a polymer-based micropump with printed EAP membrane actuator. [12]*

Conclusion

The use of inkjet printing as a manufacturing tool for microfluidic lab-on-chip systems has been discussed. Results of inkjet-printed silver and gold metallization layers on polymer substrates are provided. A low-temperature argon plasma expose is employed to render the printed structures conductive. Furthermore, the use of all inkjet printed electroactive polymer actuators for use in a micro pump is suggested. Measurement results of cantilever bending beams are provided, test samples exhibit static deflections of more than 190 µm at 600 V driving voltage. Based on these results, a concept of a micropump with printed EAP actuators is presented.

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