A NOVEL FABRICATION PROCESS TO REALISE A VALVELESS MICROPUMP ON A FLEXIBLE SUBSTRATE

Yang Wei, Russel Torah, Kai Yang, Steve Beeby, and John Tudor*
Electronics and Computer Science,
University of Southampton,
Southampton, United Kingdom

ABSTRACT

This paper reports, for the first time, the design, fabrication and testing of a valveless micropump, entirely screen printed onto a flexible polyimide (Kapton) substrate by using sacrificial, polymer-structural and piezoelectric layers. The sacrificial layer, used to achieve a pump chamber and inlet/outlet channels, is thermally removed, analogous to a standard MEMS sacrificial process. Applying a sinusoidal AC voltage to the piezoelectric layer drives a flexible membrane which pumps liquid through the chamber. A maximum flow rate of 67μL/min can be achieved using a drive frequency of 600 kHz.

KEYWORDS

Screen printing, sacrificial technology, smart fabrics, micropump.

INTRODUCTION

Micropumps are used for the transportation of fluids based on a variety of actuation elements to control the pumped volume from several microliters to several milliliters per minute [1].

Micropump fabrication using MEMS processes provides the advantages of high precision, small size, and high integration. Silicon and glass are usually used as substrates on which the pump geometry is formed. Photolithography and etching processes define the dimensions of the pump components, such as the chamber. These provide rigid, non-bendable solutions. Moulding provides an alternative fabrication route using polymeric materials, such as Polydimethylsiloxane (PDMS) [2] and Poly (methyl methacrylate) (PMMA) [3]. The pump geometry is transferred to the polymer layer through a mould which is defined by conventional photolithography and etching processes. However, moulding requires a bonding process to form a chamber at the end of the fabrication stage, thereby increasing the complexity of the fabrication process.

Screen printing provides an alternative solution for fabricating free standing structures on fabrics using a patterned screen to deposit functional materials onto substrates [4], the placement and orientation of which is defined solely by the pattern. In addition, screen printing is an industry standard for creating coloured artwork and in printed electronics thus providing potential compatible markets for this new sacrificial technology.

This paper demonstrates the feasibility of using screen printable sacrificial material for the fabrication of micropumps on a flexible Kapton substrate. Valveless micropumps have a simple mechanical structure decreasing the fabrication complexity. By printing an additional piezoelectric-electrode layers sandwich structure actuator on top of the membrane, the chamber volume can be changed, thereby driving the liquid. Printed pumps on flexible substrates have potential use in wearable smart fabric actuator applications such as drug or bactericide delivery and the release of deodorant or perfume.

BACKGROUND

Mechanical pumps use movable parts, such as valves and oscillating membranes, to deliver a constant fluid volume in each pumping cycle. Most mechanical pumps have a movable membrane to change the chamber pressure therefore driving the liquid. To ensure the pump flows in one direction, several configurations are used. Check valve pumps use two valves located at the inlet and outlet to stop reverse flow but the problems of these valves are the wear, fatigue, and blockage. Valveless pumps use fixed geometric valves to rectify the fluid so flow rates are different from two opposite sides of the diffuser and the fabrication process is less complicated than check valve pumps. Peristaltic pumps typically use at least three chambers to generate a directional flow but the driving frequency is normally low due to the nature of the heating and cooling cycles. Rotary pumps are advantageous for pumping viscous liquid but have a complicated mechanical structure and also require an external motor as the driving source. In contrast, non-mechanical pumps do not require movable parts or use mechanical forces to obtain the fluid movement. These pumps use an energy conversion between external energy, such as electrical and magnetic field, and kinetic energy in the liquid. The external energy provides a steady flow by continuously dragging the fluidic ions. In electrochemical pumps, gas bubbles generated from the electrolysis of water physically push the liquid to in the desired direction. However, these pumps strongly rely on the kinds of the driving liquids thus limiting the applications of these pumps.

Of the mechanical pumps, a valveless micropump has the simplest mechanical structure. It only requires a diffuser and nozzle to rectify the fluid flow and a movable membrane to change the chamber pressure, thereby reducing the risk of mechanical failures. Conversely, check-valve pumps need two small movable valves to rectify the flow; peristaltic pumps require at least three chambers connected in series to provide a directional flow, thereby potentially increasing the fabrication complexity and rotary pumps are difficult to achieve with printing due to the small gap between two gears. Even though non-mechanical pumps have less complicated structures and do not need any moving parts for pumping, these pumping mechanisms require high voltage, high magnetic field, or liquid environment (Electrolysis). Therefore, they are difficult to achieve using printing and used for wearable applications. In this research, a valveless pump is selected for the design based on the requirements of screen printing and the simplicity of the structure. A piezoelectric actuation mechanism is more advantageous than electrostatic and thermo-pneumatic mechanisms as it has a fast response speed, relatively low driving voltage, and is simple to fabricate/operate in both micro/macro scales.

DESIGN AND FABRICATION

Pump geometry

Fig 1 shows a schematic diagram of a valveless micropump. To print a pump structure, the structure must be split into planar layers. The order of these layers is determined by the printing sequence, namely a bottom-up process. The dimensions of the pump were theoretically determined using Comsol Multiphysics finite element modeling. The dimensions of the pump are given in Table 1.

Material selection

To achieve a screen printed pump the materials must be in a paste form and deposited through a screen; these pastes are solidified by heat or UV radiation.

The sacrificial material is essential to fabricate the pump chamber and channels because the pump geometry is determined by the dimensions of the sacrificial layer. A Trimethylolethane (TME) based screen printable sacrificial paste has been previously formulated by the author [4] and been demonstrated to be removable through sublimation. TME begins to sublimate at a relatively low temperature (~87°C) and is completely removed at 160°C for 30 minutes.

The structural layer can be printed using either thermally or UV curable polymer pastes. However, thermally curable pastes typically require curing temperatures from 100 to 200 °C which are in excess of the transition temperature of TME. Therefore, there is a risk of partial or complete material removal during the curing process of the structural layer. UV curable polymers, since they cure at room temperature, avoid the risk of mass loss from the sacrificial layer and the associated volume shrinkage compared with thermally curable polymer pastes. ElectraPolymers EFV4 screen printable UV curable dielectric polymer paste was therefore selected for the sidewall and the membrane of the pump. This paste is compatible with the sacrificial material with no chemical reaction between the two. It has a Young's modulus of 0.5 GPa after curing which is sufficient for this work but could be replaced by stiffer or softer materials depending on the application.

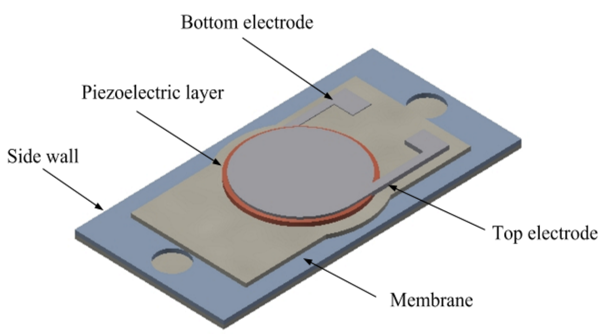

Figure 1: Schematic diagram of a valveless micropump.

Table 1: Dimension of a printed pump.

Parameter	Value
Chamber diameter (mm)	15
Diffuser length (mm)	15
Diffuser angle (^{o})	9.8
Inlet width (mm)	2

Johnson Matthey S-20 thermally curable silver conductive polymer paste was selected for the two electrodes since no suitable UV curable conductors were identified. This paste can be cured at 80 ^{o}C for 5 minutes providing a compromise between sufficient conductivity and low mass loss from the sacrificial layer.

To achieve a material with a low curing temperature and also a higher piezoelectric coefficient compared to piezoelectric polymeric materials, a screen printable piezoelectric polymer was obtained from Meggitt A/S [5]. This paste combines the advantages of ceramic PZT (i.e. high piezoelectric coefficient d_{33}) with those of a polymer (i.e. low curing temperature and flexible) and it can be cured at a relatively low temperature of 100 ^{o}C for 5 minutes.

Printing and removal processes

Kapton is initially used instead of fabric directly because fabrication processes and the material compatibility need to be identified prior to migrating to highly flexible fabrics. Kapton is a flexible substrate with a smooth surface, thus the challenges caused by the roughness of the fabric can be avoided at this initial stage. The Kapton sheet must be cleaned before use because any

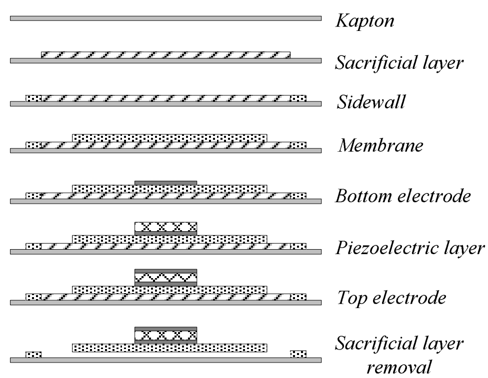

Figure 2: Cross-sectional diagram of the printing sequence.

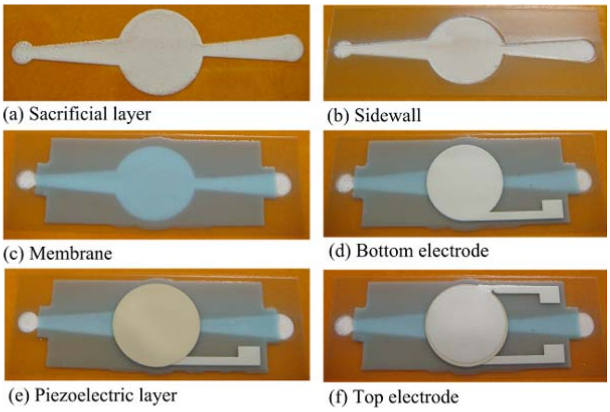

Figure 3: Individual printing steps of a pump structure.

contamination will result in poor adhesion of the printed layers to the substrate. Before printing, the Kapton sheet was temporally mounted onto an alumina tile which provided rigidity and support during the printing process. The alumina was removed after fabrication. Figure 2 shows a cross-sectional diagram of the printing sequence.

The sacrificial layer was printed and dried at 80 ^{o}C for 5 minutes. Five prints were necessary to achieve a suitable chamber thickness of 100 um. The sidewall layer was then printed to the same thickness as the sacrificial layer. Next, a membrane layer, of the same material as the sidewall, was printed on top. The membrane layer was printed to sufficient thickness to maintain its shape during the removal process without structural deformations. Bottom silver, piezoelectric layer and top silver layer were individually printed in this order and dried at 80 ^{o}C, 100 ^{o}C, and 80 ^{o}C, respectively. The curing period of these layers is 5 minutes which was enough to solidify the materials. Finally, the sacrificial layer was removed by placing the sample in a box oven at 160 ^{o}C for 30 minutes to achieve complete removal. Figure 3 shows a photograph of each fabrication step.

REMOVAL RESULTS EVALUATION

To examine the removal result, a sample was cleaved in half; a cross-sectional image is shown in figure 4.

Figure 4 shows that the membrane was completely separated by the sacrificial process and is free standing on the Kapton. No significant deformations, such as bending or sagging, were observed.

Further images were obtained using a Zeiss scanning electron microscope (SEM). Due to the size of the pump, the SEM was unable to produce a single image covering all areas of the pump sample, thus the images taken at left, middle and right of the cross section are shown in Figure 5. These images show that the sacrificial layer was entirely removed leaving a cavity.

PUMP TESTING

Wires were attached to each pump electrode and the samples were polarized using a bespoke polarization station at 100 ^{o}C for 20 minutes. After piezoelectric layer polarization, two plastic tubes with a diameter of 7 mm were attached onto the inlet and outlet using an adhesive, shown in Figure 6. Testing equipment was a power amplifier (HD17142, HD Communications Corp.), a TTi TGA1241 signal generator, and a timer. Figure 7 shows the equipment setup and connections of each component. Due to the properties of the adhesive, IPA and acetone

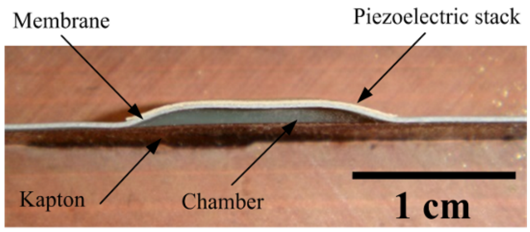

Figure 4: Cross sectional images of pumps printed on Kapton sheet.

were avoided for the pumping liquid even though they have a low surface tension. The actual pumping liquid was prepared by mixing a pinch of Sodium dodecyl sulfate (SDS) surfactant with water to provide a liquid mixture with sufficiently low surface tension.

The pumping liquid was syringed into the chamber and channels. To begin with, the height of the liquid in the inlet tube was 20 mm, with no liquid in the outlet tube. A driving sinusoidal signal with amplitude of 100 V_{pp} was applied to the piezoelectric layer and a frequency sweep from 100 kHz to 1000 kHz was performed to measure the flow rate of the pump. The average flow rate at each

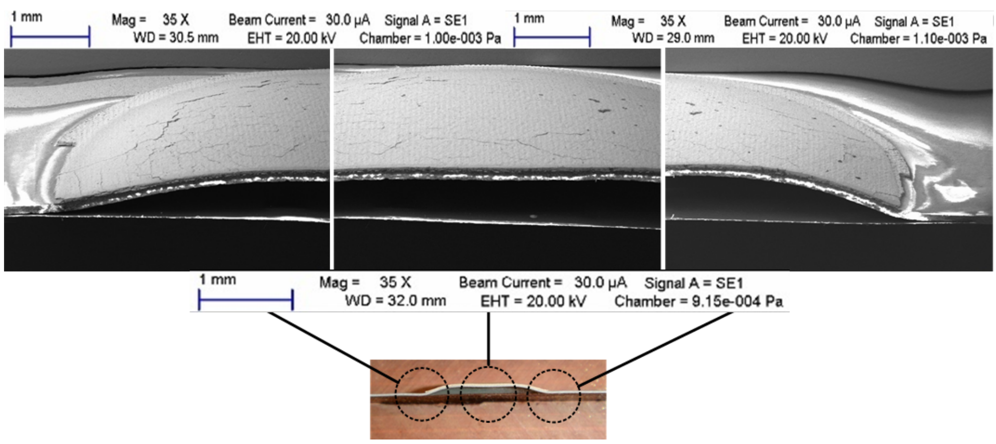

Figure 5: SEM images of a printed pump.

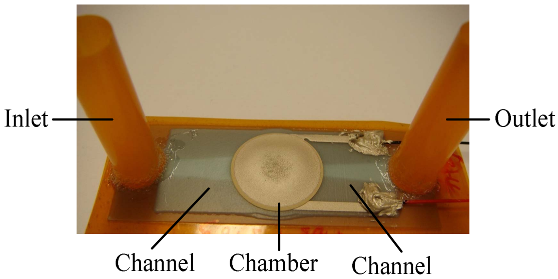

Figure 6: Pump with two tubes as inlet/outlet.

frequency was measured by the volume difference between the two tubes during a certain pumping period. Four tests were performed at each test frequency to extract the average flow rate. Figure 8 shows the pumping rate obtained at a fixed supply voltage. The flow rate gradually increases with increasing frequency and a maximum flow rate of 67µL/min was obtained at a frequency of 600 kHz. This frequency dependence is expected to be caused by mechanical resonances in the structure and further modeling is needed to identify the precise mechanism. Above this frequency, the flow rate gradually decreased.

CONCLUSIONS AND FUTURE WORK

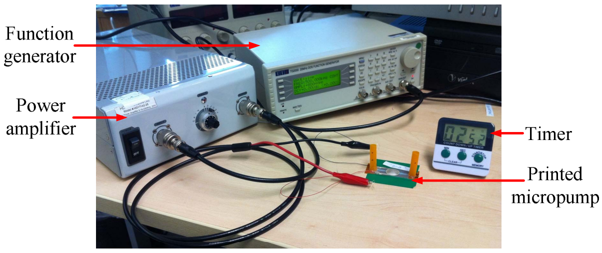

Figure 7: Testing equipment setup.

This paper has successfully demonstrated the feasibility of using a low temperature thermally removable sacrificial material TME and a piezoelectric polymer to fabricate valveless micropumps on Kapton. The sacrificial material can be screen printed and cured at 80 ^{o}C. This material can also be completely removed in an oven at 160 ^{o}C for 30 minutes. In this way, the chamber and channels are created. Visual analysis also shows that TME is fully released from a complex structure therefore confirming that TME is a suitable sacrificial material for

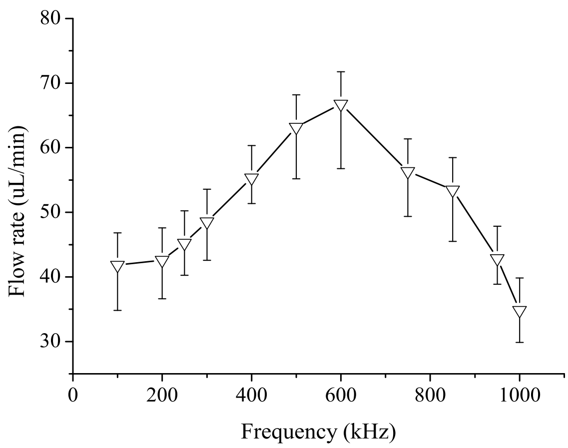

Figure 8: Flow rate vs frequency.

the fabrication of complex mechanical structures. Pump testing results show that a maximum flow rate of 67µL/min was obtained at a frequency of 600 kHz but the driving voltage of 100 V_{pp} is too high to use for wearable applications.

Having established a suitable print and processing procedure, future work will see the migration of the pump structure onto fabrics and also reduce the driving voltage.

ACKNOWLEDGEMENTS

The authors would like to acknowledge funding from the EU for the smart fabrics research project MICROFLEX (microflex.ecs.soton.ac.uk) from which this work was funded. In addition, we would like to thank Klopman International for supplying the fabric and MEGGITT A/S for supplying the screen printable piezoelectric polymer.

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CONTACT

*Y. Wei, Tel: +44 (0)23 8059 3234;
yw6g08@ecs.soton.ac.uk