Electro-Hydro-Dynamic (EHD) Micropumps with Electrode Protection by Parylene and Gelatin

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Abstract

This paper describes an ejection-type electro-hydro-dynamic (EHD) micropump using various types of polymers to protect the electrodes. The polymer layers of parylene and crosslinked gelatin were shown to protect the gold electrodes from electrolytic aging. The pump chip is packaged by the polydimethylsiloxane (PDMS) bonding technique. The results show that the polymer protection layers are successful in prolonging the operation lifetime. They can also provide the inner walls of channels with different surface properties for the working liquid to be driven through.

Key Words: Parylene, Gelatin, Surface Modification, Electro-Hydro-Dynamic (EHD)

1. Introduction

Micropumps have many applications that include the transport of reagents, delivering of pulsatile flows, generating pressure differences, moving cooling fluids, transporting suspended particles or cells. For many proposed microfluidic systems, the micromachined pump is a critical component. However it is not a mature component. In micro-electromechanical systems (MEMS), micropump can be classified into two categories. One category utilizes mechanical pumping principle that includes bubble pump, membrane pump, diffuser pump and rotary pump. The other category includes EHD pump, electroosmotic pump, electrophoretic pump and electro-wetting pump. These pumps are generally operated via electric field or electrochemical effect and have no moving parts [1].

The first EHD micropump was made by the silicon bulk micromachining and wafer bonding in 1990 [2]. It pumps ethyl alcohol with the flow rate of 14 mL/min and with the pressure difference of 420 Pa by applying a DC

voltage of 700 V. There is a modified EHD pump which replaces the silicon-mesh electrode with co-planar comb-shaped electrodes in 1998 [3]. It demonstrated the bi-directional pumping capability with simpler fabrication process. The electrodes' width and gap are 100 μm. The distance between electrode pairs is 200 μm. The dimension of channel is 3 mm wide, 30 mm long with a height of 100–200 μm. It also drives the ethyl alcohol at a flow rate of 40–60 μL/min by applying DC voltage of 40–100 V. The use of indium-tin-oxide (ITO) electrodes to resist aging was reported in 2003 [4]. The pumping flow rate of the ethyl alcohol is 365 nL/min by applying a DC voltage of 61V. However, both of the Cr/Au and the ITO electrodes have a working lifetime of less than 20 minutes. Moreover, the packaging is achieved using anodic bonding, and its bonding temperature is too high to ensure the property stability of the driving electrodes.

2. Pumping Principle of EHD Flow

In EHD pumping, the fluid force is generated by the interaction of the electric field and the mobile charges in

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the fluid. These pumps have interdigital comb-shaped electrodes, which are regularly spaced along a micro channel and require no moving parts like impellers, bellows or valves. The electrical charges generated from the electrodes will mobilize according to the direction of the electric field built-up by the electrodes, and tract the surrounding liquid molecules to move together by the ion dragging force [5].

The maximum velocity u of the laminar flow increases with the square of electric field E in the EHD pump as shown in Eq. (1).

$$u \approx \frac{\varepsilon E^2 D_h^2}{16\mu L} \tag{1}$$

L is the lateral gap between two interdigital electrodes; E is the electric field density of parallel-plate electrode pairs; D_h is the hydraulic diameter; ε and μ are the permittivity and viscosity of the working liquid, respectively.

The cross-section of the microchannel is rectangular in this EHD pump shown in Figure 1. Then, the hydraulic diameter D_h can be written as Eq. (2).

$$D_h = \frac{4wd}{2(w+d)} \tag{2}$$

where w and d are the width and depth of the microchannel.

In this study the microchannel width w is 150 μm and depth d is 30 μm. D_h is calculated as 50 μm by Eq. (2). The maximum velocity therefore can be calculated as Eq. (3).

$$u \approx \frac{25\varepsilon E^2}{16\mu L} \times 10^{-10} \quad (m/\sec) \tag{3}$$

The ultimate flow rate and velocity of an EHD pump with given length and depth are determined by the material properties (ε, μ) of the working liquid. In other words, by using the working liquid of high dielectric constant and low viscosity, the EHD pumps will have high flow velocities consequently [6].
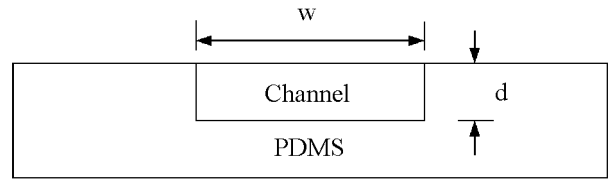
Figure 1. The cross-section of PDMS microchannel. The w and d are the width and depth of PDMS microchannel.

## 3. Device Fabrication

There are two major improvements by using polymer material in this work. First, the material of microchannel for the EHD pump is changed from silicon to PDMS [7]. Therefore, the good bonding between PDMS microchannels and glass substrates can be achieved after the hydrophilic treatment of PDMS at room temperature, and it has no negative influence of the bonding temperature on the driving electrodes. The PDMS packaging process herein could guarantee the continuous lifetime of the pump longer than 1 hour at least in the revised manuscript.

Second, this work used parylene [8] and crosslinked gelatin [9] to protect the edges of the driving electrodes from electrolytic aging. Water electrolysis happens frequently in EHD pumping for organic liquids due to little dissolved water. This phenomenon causes Cr/Au electrodes to fail. The polymer films covering the edges of electrodes will shield the adhesive Cr. Parylene and crosslinked gelatin are coated under the temperature below 60 °C and causes no damage to the device.

The processing sequence for fabricating the EHD pump with electrode protection by polymers is shown in Figure 2. We evaporated and patterned the 20 pairs Cr/Au electrodes on the glass substrates. The thickness of the Cr and Au are 200 Å and 1000 Å, respectively. Different polymers are used to coat and windows are selectively opened on the polymer coating to permit contact between the electrode and the working liquid in the microchannel. The polymer also protects the edge of the electrodes.
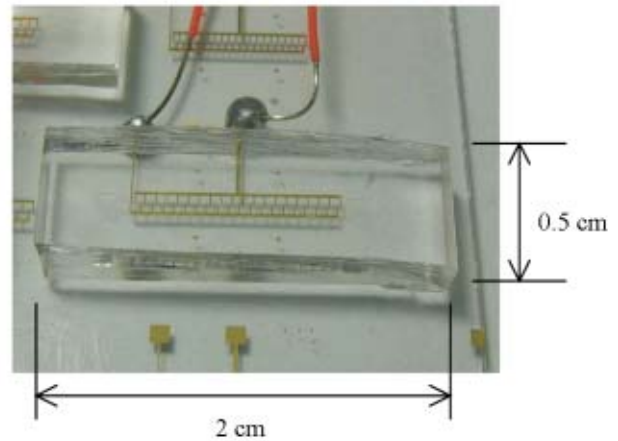
The parylene of 1 μm thick is etched by O_2 plasma using AZ4620 as the masking photoresist. The gelatin
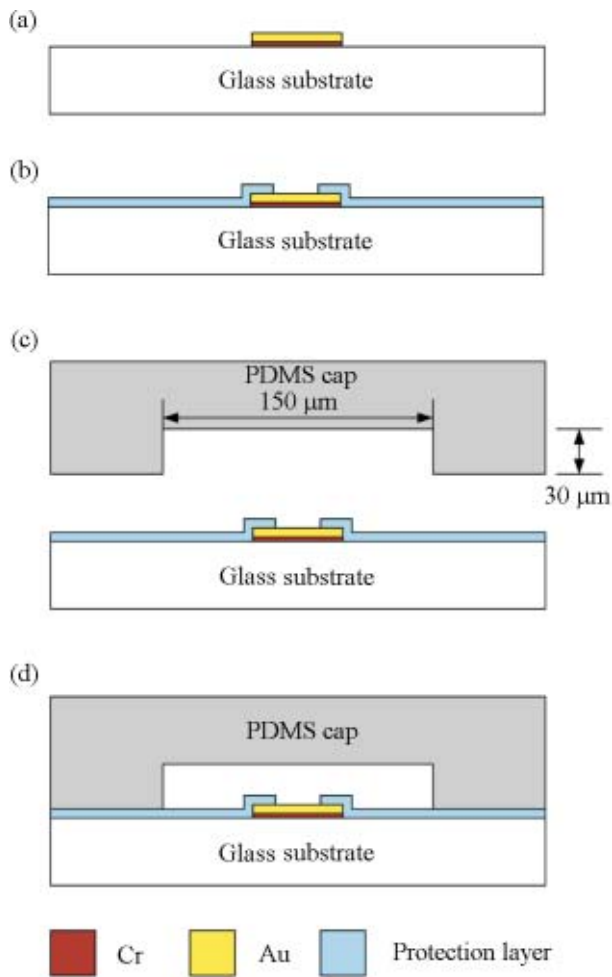
Figure 2. Fabrication process of the modified EHD pumps: (a) Cr/Au electrodes pattern (b) protection layer pattern (c) RIE clean electrodes and PDMS microchannel (d) electrodes bonded with PDMS microchannel.

Figure 3. The fabricated chip of the EHD pump with the size of 2 cm long and 0.5 cm wide.

can be treated as a negative photoresist by the addition of potassium dichromate ($K_2Cr_2O_7$). UV light is used to crosslink the gelatin resists and used warm water (about 50 °C) to develop the gelatin micro patterns [9]. The final thickness of crosslinked gelatin is measured as 1000 Å.

Meanwhile, the microchannels are made using PDMS. A curing agent and PDMS prepolymer (Sylgard 184 Silicone Elastomer Kit, Dow Corning, Midland, MI) is mixed in a 1:10 weight ratio for mixing. Then the prepolymer mixture was degassed in a vacuum chamber for one hour to remove air bubble from the mixture and to ensure complete mixing between the two components. After placing a 4-inch silicon wafer with original SU-8 mould

pattern in a 5-inch Petri dish, the prepolymer mixture solution was poured onto the silicon wafer. The entire stack was then cured for 20 minutes at 120 °C in an oven. After curing, the PDMS layer was peeled off from the silicon substrate. Finally, the PDMS layer was cut into an appropriate size, treated with oxygen plasma to adjust the PDMS surface so that it becomes hydrophilic. This will also promote good bonding with the electrodes chips. The completed EHD micropump is shown in Figure 3.

4. Results and Discussion

CCD image-capturing unit is used to record the EHD pumping velocity of the moving front of gas bubbles in the ethyl alcohol channel-flow through an optical microscope. Figure 4 shows the operation of this modified pump and the denotative diagram of pumping test. Figure 5 summarized the pumping velocities with different polymers as the electrode protection. Although the preliminary data in Figure 5 have large extent of variation, the pumping flow rate actually has the quadratic relation with applied voltage, similar to the qualitative trend predicted by Eqs. (1) and (3).

It can be also observed from Figure 5 that the pumping of ethyl alcohol is strongly influenced by the surface property of microchannel walls. For figuring out the wetting properties of the microchannels wall with different electrode protections, qualitative studies is per-
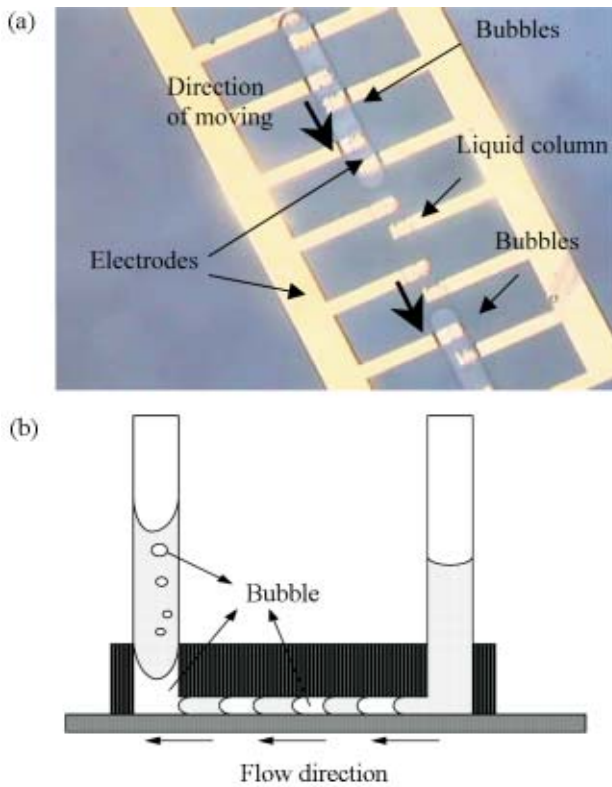
Figure 4. The operation of the modified EHD pumps: (a) captured image of EHD pumping flow; (b) denotative diagram of flow-rate measurement.
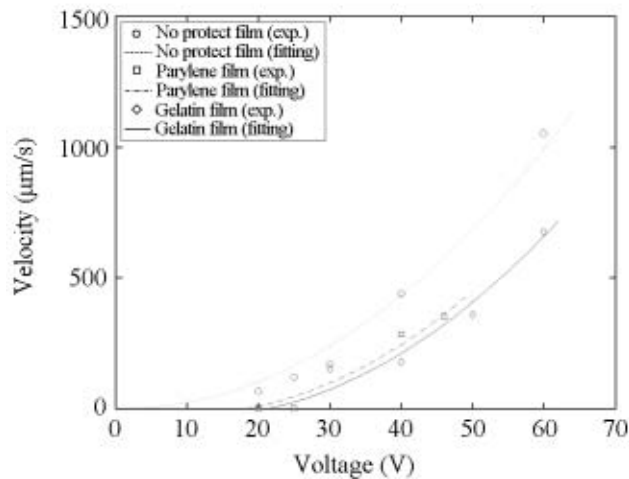
Figure 5. The pumping velocities of EHD pumps with different ways of electrode protection (working liquid: alcohol).

formed on the identical wall surfaces for pumping test via the contact angle measurement (KLA−125) by using DI water instead of alcohol temporarily. The contact angles in Table 1 show the wetting behaviors of several polymer surfaces as the referred data. The PDMS channel surface is originally hydrophobic and cannot conduct liquids automatically without the pretreatment of oxygen plasma. The channel wall with the gelatin protection layer has high surface energies and extremely hydrophilic, whereas the channel wall with the parylene protection layer tends to be lightly hydrophilic. With the sweeping of oxygen plasma for the fabricated EHD pump, the working liquid of alcohol can be drawn into the surface-modified PDMS microchannel automatically to be driven.

Electroosmosis effects also influence the velocity of EHD pumps. The fluid column moves from the anode to the cathode in the electroosmosis flow by applying an electric field. It is in the reverse direction to the EHD flow, therefore its velocity has an inverse response to the EHD pumping strength.

The electroosmosis velocity is given as Eq. (4) [10]:

$$u_{EO} = \frac{\varepsilon \zeta}{4\pi\mu} E \tag{4}$$

ζ is the electrokinetic potential or zeta potential.
Then the actual velocity of this EHD pump will be as Eq. (5)

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\begin{aligned}
u &= u_{EHD} - u_{EO} \\
&= \frac{\varepsilon E^2 D_h^2}{16\mu L} - \frac{\varepsilon \zeta}{4\pi\mu} E
\end{aligned}
\tag{5}
$$

The permittivity and viscosity of working liquid (ethyl alcohol) are 18.3×10^{-12} (F/m) and 2.431×10^{-3} (Pa·s), respectively. The lateral gap between two interdigital electrodes is 160 µm. Then it can be curve fitting to ac-

Table 1. The contact angles of different polymer surfaces, measured by KLA−125 (liquid droplet: DI water)

Surface	PDMS	Parylene	Gelatin
Contact angle (deg)	108 (decrease to 30 after O_2 plasma sweeping)	80−95	60
Wetting behavior	Hydrophobic	Lightly hydrophilic	Hydrophilic

cord as Eq. (5) by using experimental data and calculate the zeta potential of the pump microchannel with applying an electric field. The zeta potentials of three different surfaces (glass, gelatin and parylene) in the EHD microchannel are −181 mV, −1.67 V and −1.44 V, respectively. The zeta potential of the EHD pump microchannel with no protection film is close to the values of glass (about −80 mV) and PDMS (about −85 mV)[11]. However, the working liquid is not ethyl alcohol and the dimension of microchannel is not equal to this EHD pump in Reference [11]. The zeta potentials of gelatin film and parylene film are as well as the valuable reference message. It also can use the curves to deduce the cut-in voltage of the EHD pumps with different protect films. The cut-in voltages are 2.5 V, 22 V and 19 V for no protect film (glass), gelatin film and parylene film.

5. Conclusion

This paper demonstrated an EHD micropump with electrode protection by parylene and gelatin. Although these EHD micropumps still need improvements on the pumping efficiency and on the long-term stability during operation, they can drive the ethyl alcohol for longer than 1 hour without failure. It is observed that different polymer materials changes the surface properties and therefore greatly influence the driving velocity of the EHD flow. Finally, this study calculates the zeta potential and cut-in voltages of the EHD pumps with different protect films. This interesting result can be regarded as useful information for applying theses modified EHD micropumps to evaporative coolers, active mixers or other devices in microfluidics.

Acknowledgement

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