An Electrohydrodynamic Micropump for On-Chip Fluid Pumping on a Flexible Parylene Substrate

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***Abstract*—We present the first design, fabrication and testing results from an Electrohydrodynamic (EHD) micropump on a flexible Parylene-C substrate. Parylene-C membranes with their excellent properties are rarely used yet are very promising candidates as flexible substrates. Low power on-chip micropumps are needed in various fields including biotechnology and cryogenic cooling. Furthermore, being fabricated on a flexible Parylene substrate, they can be utilized in commercial applications including wearable textiles. Pumping pressures of up to 490Pa (@30 Volts) with a flow velocity of 190mm/min (@20 Volts) is measured using Isopropanol (IPA) fluid. The micropump has no moving parts and occupies a volume of only 5mmx7mmx80µm. This is the first instance of a low power EHD micropump fabricated on a flexible Parylene-C substrate.**

Keywords-Electrohydrodynamic (EHD), micropump, flexible substrates, Parylene-C, Microfluidics

I. INTRODUCTION

Microfluidics technology has been attracting significant interest due to its vast potential to create miniature tools for life sciences [1-2]. One of the most important components of a microfluidics device is a micropump which has been investigated for several years. Micropumps can be categorized into 2 groups, one type is the mechanical micropumps and the other is the non-mechanical micropumps [3-4]. The former, which includes moving parts such as check valves, oscillating membranes or turbines, is mostly used for large-scale applications and can provide high flow rates. Check-valve pumps, peristaltic pumps, and rotary pumps belong to the category of mechanical pumps. Non-mechanical micropumps, have no moving parts and add momentum to the fluid by converting potential energy into the kinetic energy, and have advantages for micro scale applications. The examples for non-mechanical pumps include electrohydrodynamic (EHD) pumps, electro-kinetic pumps and magneto-hydrodynamic (MHD) pumps.

Despite the effort invested in micropumps, there is still a need for a low power, simple, and inexpensive micropump that fulfills the demands for lab on a chip devices that require moving fluids of small volume. Even though discovered in the 60's, on chip applications of electrohydrodynamic (EHD) pumping has not been fully explored at the micro scale mainly due to the requirement of large operating voltages. By utilizing microfabrication, one can reduce the operating voltages to values acceptable for most commercial applications, including cryogenic cooling [5-6]. Furthermore, a simple micropump with no moving parts and in essence without any vibration and noise would provide an ideal solution for on-chip applications such as miniaturized bioreactors.

The main thrust of flextronics or flexible electronics is to fabricate organic field effect transistors and display panels directly on flexible substrates. Polymers are routinely used as the substrate materials for most of the current flexible devices. These polymers include Polyethylene Terephthalate (PET) and polymethyl-methacrylate (PMMA). PET and PMMA are often used for optoelectronic devices because they are optically transparent with a high glass transition temperature [7-8]. Parylene, even though rarely explored, has attractive properties to be a competing technology as a substrate for flexible devices. Deposited at room temperature, parylene is a lightweight, transparent, mechanically strong and stress-free material which is compatible with integrated circuit fabrication processes. Rodger et al [9] used Parylene-C as a substrate to make flexible multi-electrode arrays for functional electrical stimulation in retinal prostheses. Furthermore, the biocompatible property of Parylene-C makes it a very attractive material for biological applications.

The applications for lab-on-a-chip devices are an emerging fieldand enabling users of technologies to experiment with miniature micro-fluidics systems. In this paper, we present a low power Electrohydrodynamic (EHD) micropump (shown in Fig.1 below) on a flexible Parylene substrate to allow on-chip fluid pumping.

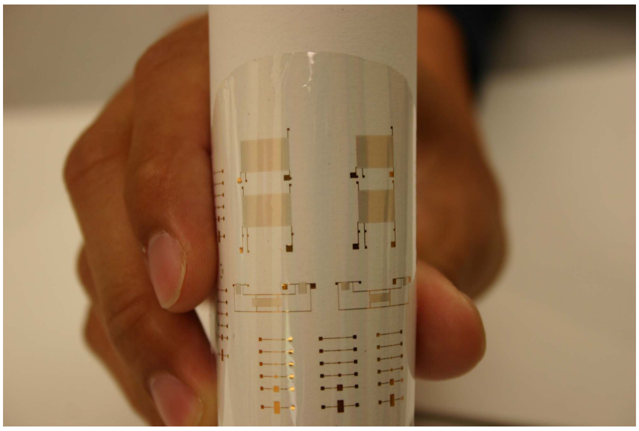

Fig.1: Optical photograph of the EHD micropumps fabricated on a flexible Parylene-C substrate

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II. EHD MICROPUMP ON A PARYLENE-C SUBSTRATE

A. Electro Hydro Dynamic (EHD) Micropump

The operation of Electrohydrodynamic (EHD) based micropumps is based on the interaction between electrostatic forces and ions in dielectric fluids. When electric field is applied to the sample, the net force, F, acting on the working dielectric fluids is given as [4]:

$$F = qE + P\cdot\nabla E - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left(E^2\rho\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\right) \qquad (1)$$

where q is the free space charge density, P is the polarization vector, ε is the permittivity of the fluid and ρ is the mass density [4]. Coulomb forces, the most important term acting on free charges, is presented in the first term of equation (1). The remaining terms present Kelvin polarization force, Dielectric force and Electrostrictive force in consecutive order. Free space charge, which can be produced due to inhomogeneities in the fluid, or through dissociation or direct charge injection, is needed in the dielectric fluid for the successful operation of these micropumps. Three kinds of pumping mechanisms have been developed based on the Coulomb force: induction pumping, conduction pumping, and ion-drag pumping.

The EHD induction pumping relies on the generation of induced charges at the material interface. Charge induction arises from the non-uniformity in the electrical conductivity of the fluid, which can be caused by the non-uniform temperature distribution or inhomogeneity of the fluid [10-11]. Conduction EHD pump relies on ion drag associated with the heterocharge layers of finite thickness in the vicinity of electrodes. The conduction term represents a mechanism for electric current flow in which charged carriers are produced by dissociation of molecules within the fluid [12-13].

In the EHD injection pumps (utilizing ion-drag pumping), the ions are injected from one or both electrodes into the fluid by electrochemical reactions. This requires two permeable electrodes (emitter and collector) in direct contact with the fluid to be pumped. The ions or electrons are injected from a sharp electrode into the liquid by an applied electric field though field emission, field ionization, and corona discharge [14-17]. Energy transfer between neutral molecules and ions causes the flow due to the frictional force. The direction of the flow is determined by the electrical properties of the charged molecule or ion. These types of EHD pumps heavily rely on electrical properties of the fluid pumped. Only fluids with specific permittivity and conductivity can be utilized in these pumps.

B. Properties of Flexible Parylene-C

Parylene, poly-para-xylylene, is the generic name for members of a unique polymer series with more than 20 variations, yet only 3 of them are widely used, Parylene N, C and D. All of these parylenes are produced from the same monomer modified, and a chlorine atom is substituted to one of the aromatic hydrogens for Parylene-C and two of the aromatic hydrogens for Parylene-D, as shown in Fig.2 [18]. Parylene-C, known to provide very low permeability to moisture and corrosive gases, is the material of choice for coating critical electronic assemblies. Along with its ability to create a true pinhole free insulation, the high resistivity, $6\times10^{16}\Omega$-cm, and high breakdown voltage (300Volts/μm), indicate that Parylene-C has excellent dielectric properties. The physical properties such as its high tensile strength (10,000psi) and mechanical strength (Young's modulus of 400Kpsi) [19] show that it is a very promising candidate amongst materials for flexible substrates.

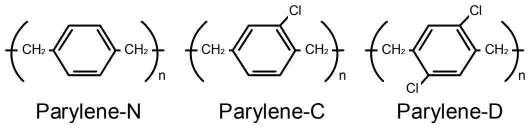

Fig.2: Different types of parylene

The conventional methods for forming the polymer such as extrusion or molding cannot be applied to Parylene due to its high molecular weight and its high melting temperatures. Similar to vacuum metallization, Parylene polymers are deposited from the vapor phase. In contrast to the high vacuum deposition processes, the Parylene is formed at around 0.1Torr with mean free path on the order of ~100μm. Thus, a substrate in the Parylene deposition chamber will be uniformly impinged by the gaseous monomer, which in turn obtains a truly conformal coating. Furthermore, the deposition rates of Parylene-C are fast compared to vacuum metallization. The deposition thickness can be increased by increasing the amount of dimer placed inside the evaporation chamber and thicknesses of up to 50μm are readily achievable.

III. FABRICATION

Parylene coatings are commercially available and widely used in the electronics and medical industries. Furthermore, due to its attractive properties, Parylene is also increasingly being explored in the MEMS community. To leverage the latest developments in the emerging field of flextronics, we have demonstrated an EHD based micropump on a flexible substrate. The fabrication process, which is illustrated in Fig.3, starts with depositing a thin (10μm) layer of Parylene-C (PDS 2010) on to silicon wafers at room temperature.

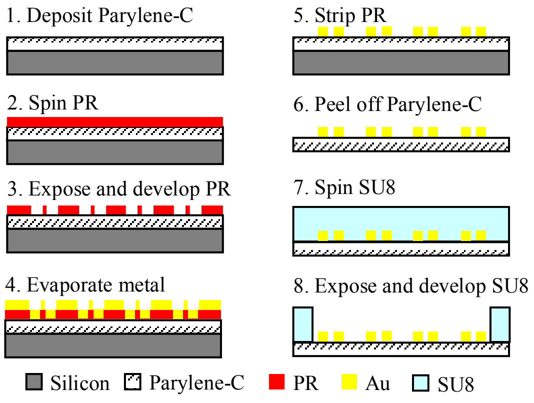

Fig.3: Fabrication process for EHD micropump on a flexible Parylene-C substrate

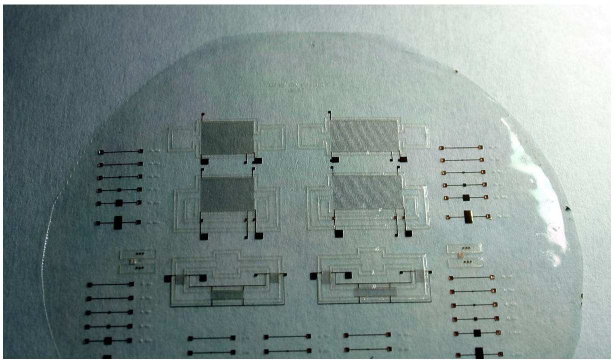

Fig.4 Optical photograph of the micropumps with SU8

This Parylene layer will form the flexible substrate. Next, we pattern the metal (Au-1500Å) layer using a lift-off process which forms the electrodes on the Parylene-C substrate. The SU-8 channels (SU-8 2075, MicroChem Corp., height of 80μm) are next patterned which form the channel walls for the reactor and guiding walls for performing flow measurements (Fig. 4).

After fabrication, the devices are easily peeled off the wafer and are shown in Fig.4. We have noticed that in order to successfully peel off the Parylene, one cannot utilize the routinely used silane adhesion promoter (adhesion is too strong and the films do not peel rather tear off) before depositing parylene instead need to use other promoters such as HMDS or NUBS. Furthermore, through experiments, we have found out that the parylene-C films with thicknesses of more than 5μm are quite robust and easy to peel; yet thinner films are hard to handle and tear quite easily.

There are 2 major factors that influence the operation of an ion-drag type EHD micropump, one, which is mentioned already, is the type of liquid and the other is the design of the electrodes. Darabi et al [20] through modeling and experiments has found out that saw-tooth electrodes perform the best for ion-drag pumping. In our micropump, we have selected saw-tooth electrodes with spacings (distance between collector and emitters) to be 20μm. The electrode widths are kept as 10μm. We selected the number of stages (a stage is a pair of saw-tooth emitter and flat collector pair with a picture shown in the inset of Fig.5) to be 75 and 200. The distance between two stages was kept at 80μm. The pumping grid was 5mm by 7mm and the height of the fluid can be up to 80μm.

Using our micropump fabricated on Parylene-C substrate, we successfully demonstrated fluid pumping with liquids including 2-(2-butoxyethoxy) ethyl acetate (BCRA), acetone, and isopropanol (IPA), moreover other fluids including Ethanol, Ethyl alcohol and 3M HFE-7100 [3] are also usable in EHD type micropumps.

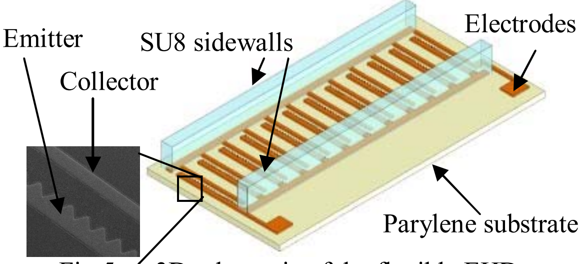

Fig.5: A 3D schematic of the flexible EHD micropump

IV. TEST RESULTS

A. *Flow velocity mesurements*

For the flow velocity measurements, we first fabricated the micropump on the Parylene-C substrate, and then patterned the SU-8 channels on top to guide the liquid flow. SU-8 channels confine the direction of liquid flow and prevent the formation of vortices, which are readily observed while pumping liquids without channels. In these experiments, we used commercially available 25μm florescent beads (Duke Scientific, CA). The application of a dc voltage to the emitter collector electrode pair (with emitter being the negative end) creates a field which forces the beads to flow from emitter to collector and the image is recorded by a CCD camera (Moticam 1000, MCCamera) for flow velocity measurements. We measured a flow velocity of about 190mm/min at an applied voltage of 20Volts, which is found to be the threshold voltage for the micropump with 75-electrode pairs.

B. *Pumping pressure mesurements*

To measure the pumping pressure, one requires a closed cavity in order to observe the rise in the liquid level. Polydimethylsiloxane (PDMS) is chosen as a cover for our test setup since it is readily available and ease to use. PDMS, widely used in microfluidics devices, is a popular material for soft lithography due to its low-cost, easy and reproducible fabrication process [21]. Moreover, we found out that PDMS did not bond to Parylene substrates, yet it bonds very well to Silicon dioxide layers. Accordingly, to measure the pumping pressure of the micropump, we fabricated the micropump on an oxidized silicon wafer. Using an SU-8 mold, we created a PDMS cover for our micropump. Before bonding PDMS to SiO_2, inlet and outlet holes were made using a needle; these holes are needed for liquid flow into the pumping area. To bond the PDMS cap onto the SiO_2 layer, first, the PDMS cover is treated with oxygen plasma in order to change its surface behavior from hydrophobic (as fabricated) to hydrophilic. Next, PDMS covers are placed on top of the SiO_2 layer and then put on top of a hot plate at a temperature of 150ºC with a small amount of de-ionized water used for precise alignment. Within 15 minutes, the DI water dries out and PDMS and SiO_2 are bonded to each other.

After attaching the PDMS cover, the micropump is placed in a Petri dish containing isopropanol (IPA). While measuring the pumping pressure, the inlet hole was left open and a glass tube was mounted to the outlet hole on the PDMS cover. Furthermore, due to capillary forces, we also observed that the liquid levels rise in the glass tube connected to the outlet hole. Thus, we have to take into account capillary forces when measuring the pumping pressure. To operate the micropump, the collector electrode is grounded and a negative DC voltage is applied to the emitter electrode. The measured pumping pressure of the device is shown in Fig.6. We get a maximum

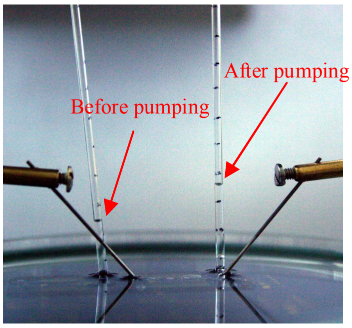

Fig.6: Optical photograph of pumping pressure set-up

pumping pressure of 490Pa at an applied voltage of 30Volts for IPA as displayed in Fig.7 (200-electrode stage pump).

Using a microfabricated EHD micropump on a flexible Parylene substrate, we have successfully demonstrated pumping of BCRA, acetone, and IPA fluids. BCRA fluid has a dielectric constant (k~ 7.7) and a relatively high viscosity (η~ 3.1mPas) hence during pumping the liquid inside the small (1mm) wide channels preferentially travels along the sidewalls. On the other hand, IPA has a relatively good dielectric constant (k~ 18.6) and a relatively low viscosity (η~ 2.43mPas) as a result, a good pumping effect has been observed. To achieve higher flow velocities, a high permittivity and a low viscosity fluid is recommended.

V. CONCLUSIONS

We demonstrated the first EHD micropump on a flexible (10µm) Parylene-C substrate. The flow velocity is measured as ~190mm/min at 20Volts and the pumping pressure is 490Pa at 30Volts for pumping Isopropanol. Pumping of other fluids is also demonstrated including BCRA and acetone. Parylene-C substrates are not only mechanically strong and IC compatible, yet are also biocompatible and hence we expect this technology combined with organic electronics to open new opportunities for on-chip liquid pumping for biomedical applications.

ACKNOWLEDGMENTS

This research was supported by funding from the Office of the Provost at Northeastern University. The microfabrication was carried out in the Kostas Nanomanufacturing Center. The authors would like to thank to Dr. Ahmet Umit Coskun for his assistance in fluidics.

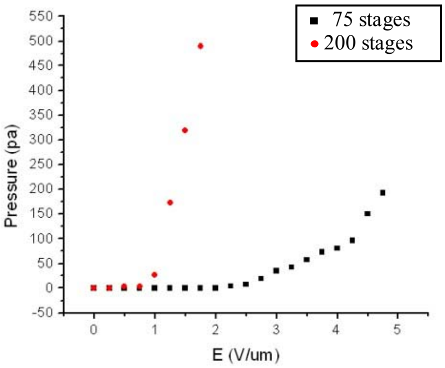

Fig.7: Measured pumping pressure versus electric

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