Thin film electro-osmotic pumps for biomicrofluidic applications

John M. Edwards IV

*Department of Chemistry and Biochemistry, Brigham Young University,
Provo, Utah 84602*

Mark N. Hamblin

*Department of Electrical and Computer Engineering, Brigham Young University,
Provo, Utah 84602*

Hernan V. Fuentes, Bridget A. Peeni, Milton L. Lee, and Adam T. Woolley

*Department of Chemistry and Biochemistry, Brigham Young University,
Provo, Utah 84602*

Aaron R. Hawkins^{a)}

*Department of Electrical and Computer Engineering, Brigham Young University,
Provo, Utah 84602*

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Electro-osmotic flow (EOF) pumps are attractive for fluid manipulation in microfluidic channels. Open channel EOF pumps can produce high pressures and flow rates, and are relatively easy to fabricate on-chip or integrate with other microfluidic or electrical components. An EOF pump design that is conducive to on-chip fabrication consists of multiple small channel arms feeding into a larger flow channel. We have fabricated this type of pump design using a thin film deposition process that avoids wafer bonding. We have evaluated pumps fabricated on both silicon and glass substrates. Consistent flow rate versus electric field were obtained. For the range of 40–400 V, flow rates of 0.19–2.30 $\mu\text{L}/\text{min}$ were measured. Theoretical calculations of pump efficiency were made, as well as calculations of the mechanical power generated by various pump shapes, to investigate design parameters that should improve future pumps. © 2006 American Institute of Physics. [DOI: [10.1063/1.2372215](https://doi.org/10.1063/1.2372215)]

I. INTRODUCTION

With the continued application of micro-electromechanical systems (MEMS) in microfluidic applications, the demand for small, efficient, and easily fabricated fluid pumps is apparent. Micropumps fall into two general categories: reciprocating pumps and continuous flow pumps. Reciprocating pumps consist of an actuator, an inlet and outlet valve, and a pump chamber. Pressure is generated by moving surfaces in the pump that compress and expand periodically on a fluid. Common reciprocating micropumps include electromagnetic, thermopneumatic, piezoelectric, and electrostatic pumps. Reciprocating pumps are capable of high pressures, but are complex to build, and provide pulse-like fluid flows.¹ The second class of pumps, dynamic pumps, includes electro-osmotic, electrokinetic, ultrasonic, and magnetohydrodynamic pumps. Pressure is generated in dynamic pumps from the momentum of a fluid as it moves through the pump. This type of pump provides constant, pulseless flow, requires fewer parts and can be made much smaller than recip-

^{a)} Author to whom correspondence should be addressed: Phone: (801) 422-8693; Fax: (801) 422-0201; Electronic mail: hawkins@ee.byu.edu

reciprocating pumps.¹ For these reasons, dynamic pumps are the most desirable for microfluidic devices, even though they cannot generate pressures as high as reciprocating pumps. This article describes a new electro-osmosis-based dynamic pump.

Electro-osmotic flow (EOF) is the flow of fluid over immobile surface charges induced by an electric field.^{2,3} EOF starts with the formation of an electric double layer (EDL), which results as counterions are attracted to charges on a surface. The EDL thickness is determined by electrostatic interactions and thermal diffusion, and approximates to the Debye length in the solution.⁴ Once an electric field is applied to the solution, ions move with respect to the field, dragging the surrounding solution with them. EOF pumps take advantage of this fluid movement to induce pressure and total fluid movement for distribution to other locations in a fluidic network.

Electro-osmosis as a pumping technique has been known for several decades.⁵ Early on, research on EOF pumps was limited primarily to theoretical models. However, with increasing interest in small pumps for small volume fluidic manipulations, experiments involving EOF have greatly increased in number. Beginning with work done by Pretorius *et al.*⁵ using packed silica particles in capillary columns, EOF pumps were shown to be adequate as pumps in fluid injection analysis systems. Other types of EOF pumps have been created in silicon and glass substrates either packed with silica or borosilicate glass particles,^{6–10} or left open without any packing materials.¹¹

EOF pumps are particularly attractive as alternatives to conventional pumping systems because of their small size and absence of moving mechanical parts. Small EOF pumps are desirable for fluid delivery for flow injection analysis, capillary electrochromatography, lab-on-a-chip, etc.^{12–14} EOF pumps fabricated directly on microchips instead of on bonded substrates decrease the overall size of the microfluidic system, are easier to integrate, and provide superior performance because of the reduction in connection fittings. Electrically driven pumps are also advantageous because they provide pulse-free, plug-like profiles, eliminating any velocity differential that is created as the fluid approaches the channel walls^{2,4} until after the flow leaves the pump. Previously fabricated EOF pumps have been shown to be capable of generating very high pressures.¹⁵ EOF pumps that are most commonly used in microchip separations are created by chemically etching channels in a glass substrate followed by thermally bonding a coverplate with access holes over the etched channel pattern.

Packed channel EOF pumps have been shown to produce higher pressures than open channel EOF pumps at lower currents due to their increased surface area.^{9,16,17} In experiments done by Tripp *et al.*¹⁵ using polymer monoliths, their EOF pumps were capable of producing pressures of 55.1 psi and flow rates of 41 mL/min at 50 V. Other experiments done by Chen *et al.*¹⁴ using silica particles in EOF pumps produced pump pressures of 2895 psi with flow rates of 1.6 μ L/min at 28 kV. However, packing channels on a microchip is much more difficult than packing capillary columns. Packed and monolithic columns have the disadvantage that there are inconsistencies in particle diameter, monolith structure, and packing density.^{9,16,17} These inconsistencies affect the local fluid velocities at specific locations in the column/channel.⁹ Overlapping electric double layers also contribute to a reduction in the surrounding fluid velocity. Open tubular capillary pumps are simpler to fabricate and give more reproducible results.¹¹

In this article, we investigate the flow and pressure characteristics of open channel EOF pumps produced by thin film fabrication. From experimental flow rates, we determined the pressures that were generated. Theoretical calculations of pump efficiency were made to determine the optimum number of pump channels required to minimize chip space and electrical power.

II. OPEN CHANNEL PUMP DESIGN

The open channel pump design consisted of multiple small channels connected to a large channel (Fig. 1), as previously demonstrated by Lazar and Karger.¹¹ Our system setup differs from that employed by Lazar *et al.* in that we have connected the electrodes to the ends of the multiple channel pump and single channel via two Teflon capillaries to facilitate ease of electrode connection (see Fig. 5). This induces an EOF flow in the Teflon capillaries and in the single channel,

FIG. 1. Illustrations of EOF pumps consisting of (top) a single channel and (bottom) a single channel with multiple pump arms. Both have equal total cross-sectional areas.

although their contribution to the overall EOF flow is negligible when compared to that of the multichannel pump. Therefore, we will approximate our system to the same open capillary case presented by Lazar *et al.*

To further demonstrate the reasoning behind using multiple small channels versus a single large channel, we examined the fluid flow and pressure generating properties of such configurations. Lazar *et al.* demonstrates the relationships shown in Eqs. (1) and (2) for the EOF fluid flow in an open capillary system¹¹

$$F_{\text{EOF}} = \frac{\pi \epsilon_o \epsilon_r \zeta n d_1^2 E}{4 \nu}, \quad (1)$$

$$F_{\text{max}} = \frac{F_{\text{eof}} \frac{L_1}{L_2}}{\frac{L_1}{L_2} + n \left(\frac{d_1}{d_2} \right)^4}, \quad (2)$$

where n is the number of pump arms, ϵ_o is the electric permittivity of free space, ϵ_r is the relative permittivity of the fluid in the channels, ζ is the zeta potential of the channel walls, E is the electric field applied across the pump, L_1 is the length of the multichannel pump segment, L_2 is the length of the microchannel attached to the EOF pump, d_1 is the equivalent diameter of one of the EOF pump arms, d_2 is the equivalent diameter of the microchannel attached to the EOF pump, and ν is the buffer viscosity.^{11,18}

Maximum achievable flow is found by substituting Eq. (1) into Eq. (2) to produce Eq. (3). Maximum achievable pressure is governed by Eq. (4) as a function of the electric field (see also Ref. 11):

$$F_{\text{max}} = \frac{\pi n \epsilon_o \epsilon_r \zeta E L_1 d_1^2 d_2^4}{4 \nu (L_1 d_2^4 + n L_2 d_1^4)}, \quad (3)$$

$$\Delta P_{\text{max}} = \frac{32 n \epsilon_o \epsilon_r \zeta E L_1 L_2 d_1^2}{L_1 d_2^4 + n L_2 d_1^4}. \quad (4)$$

In this analysis, it was assumed that the sum of the cross-sectional areas of the EOF pump channels was equal to the cross-sectional area of the larger single channel. The length of the small channels in the multichannel EOF pump were designated L_1 , and the larger channel was designated L_2 . The single channel EOF pump, therefore, had a length of $L_1 + L_2$. Equation (5) gives the

FIG. 2. Plot of the ratio of fluid flows of multiple channel EOF pump to single channel EOF pump of equal cross-sectional area, as a function of pump segment length L_1 . The total length $L_1 + L_2 = 100$ mm, such that as L_1 becomes longer, L_2 becomes shorter. This ratio is shown for several numbers of pump arms.

ratio of theoretical maximum flow rate generated by the multichannel EOF pump to the maximum flow rate generated by a single channel EOF pump of equal cross-sectional area.^{11,18}

$$\frac{F_{\text{multiple}}}{F_{\text{single}}} = \frac{n(L_1 + L_2)}{(nL_1 + L_2)}. \quad (5)$$

Figure 2 shows plots of Eq. (5) as a function of small channel length (i.e., L_1) for different numbers of pump arms. The highest flow rates were found for short EOF pump lengths and high numbers of pump channels. This led to the EOF pump design shown in Fig. 1.

III. THIN FILM EOF PUMP FABRICATION

EOF pumps were fabricated using standard thin film lithography on silicon and glass wafers (Fig. 3), in an adaptation of earlier work.^{19–21} To prevent electrical breakdown when using silicon wafers, a $2.5 \mu\text{m}$ layer of thermal silicon dioxide was grown on each wafer followed by a 200 nm layer of silicon nitride deposited by plasma enhanced chemical vapor deposition (PECVD). This was followed by an additional 300 nm silicon dioxide layer deposited by PECVD. This oxide layer was also applied over the top of the glass to ensure the pump's channel walls consisted of the same material. Next, 300 nm of aluminum was evaporated on the wafer followed by a spin coating of $3 \mu\text{m}$ of AZ3330 photoresist. The photoresist was then patterned and developed. To give the channels a rounded shape, the photoresist was re-flown at 250°C . Next, the aluminum was etched in an aluminum etchant (Transene, Danvers, MA), and $3 \mu\text{m}$ of silicon dioxide were deposited on top of the wafer using PECVD. To open the channels, channel ends were etched with buffered hydrofluoric acid (Transene) and then submerged in 2:1 HCl/HNO₃ and Nanostrip (Cyantek, Fremont, CA) to remove the sacrificial core consisting of aluminum and photoresist. After core removal, the smaller pump channels were $5 \mu\text{m}$ wide and 4 mm long, and the larger channel was $50 \mu\text{m}$ wide and 5 mm long. SEM images of various EOF pump features are shown in Fig. 4.

IV. MEASUREMENT OF PUMP FLOW CHARACTERISTICS

A schematic overview of the experimental setup for measuring pump flows is shown in Fig. 5. Reservoirs to hold solutions over openings at the ends of the microchannels were prepared from laser-cut tube-like pieces of poly(methylmethacrylate) (PMMA) with two 10-cm lengths of $750 \mu\text{m}$ i.d. Teflon capillary tubing epoxied into the reservoir. PMMA reservoir material could be

FIG. 3. Fabrication process for creating thin film microchannels.

easily made into various reservoir sizes using a laser cutter. The large i.d. of the Teflon tubing was selected because its effect on the overall EOF was insignificant. Short lengths of Teflon tubing were used so that buffer solutions could easily be purged from the apparatus, reducing the time between experiments. A carbonate buffer solution (10 mM, pH 9.2) was prepared from sodium bicarbonate and sodium carbonate. To accurately measure flow volumes generated by the EOF pumps, each test was run long enough to easily measure solution displacements in the Teflon tubing. Hydroquinone and *p*-benzoquinone were added to the buffer solution to decrease electrolysis gas generation. Palladium wire was inserted into the top of the capillary tubing to serve as an electrode.^{22,23} Palladium was chosen to further decrease the effects of electrolysis by absorbing any hydrogen gas produced.

With each flow-rate experiment, pressurized injections of carbonate solution were made to ensure complete removal of air in the device to prevent blocking of the channel. The current measured when all small channels were working was used for determining whether or not all channels in the other pumps were working.

EOF pumps on both silicon and glass substrates were tested. Graphs of flow rate versus electric field are shown in Figs. 6 and 7. Figure 7 shows plots on an expanded scale for the results obtained using single large channels. The flow rate was calculated by measuring the change in volume in the Teflon capillary and dividing by the change in time. As our results indicate, the values for flow rate versus electric field match very closely for the devices built both on silicon and glass substrates. This outcome was expected because the walls of the channels for both substrates were formed from the same type of PECVD-deposited oxide.

V. DESIGN OPTIMIZATION

EOF pump efficiency can be expressed as the ratio of usable mechanical work produced per unit time to the applied electrical power.²⁴ The flow created in an EOF pump attached to a load results in a backpressure which changes the EOF plug-like profile to assume a parabolic shape,

(a)

(b)

(c)

FIG. 4. SEM images of EOF pump features. (a) Cross-sectional view of a 5- μ m EOF channel. (b) Cross-sectional view of a 50 μ m flow channel. (c) Top view of the pump channels interfaced with the flow channel.

FIG. 5. Schematic of the experimental setup for testing thin film EOF pumps.

which is referred to as the pump curve.²⁵ If we assume that the pump curve closely approximates linear behavior over a wide range of applied electric fields, the relationship in Eq. (6) is produced:²⁵

$$\frac{\Delta P}{\Delta P_{\max}} + \frac{F}{F_{\max}} = 1. \quad (6)$$

The linear relationship shown in Eq. (6) then leads to the maximum mechanical power that can be produced by the pump,

FIG. 6. Plot of flow rate vs applied electric field for multiple channel EOF pumps and single channel EOF pumps fabricated on silicon and glass substrates.

FIG. 7. Expanded view of the flow rates generated in single 50- μm channel EOF pumps.

$$Q_{\max} = \frac{\Delta P_{\max}}{2} \cdot \frac{F_{\max}}{2} = \frac{1}{4} \Delta P_{\max} F_{\max}.$$

The electrical power being applied to the EOF pump can be expressed as $IV = EL_1 I$, where I is the current in the system. It is now possible to express the maximum possible EOF pump efficiency with Eq. (7). (See also Ref. 26.)

$$\eta = \frac{\Delta P_{\max} F_{\max}}{4EL_1 I}. \quad (7)$$

As applications of the EOF pump vary, the corresponding microchannel system can become very complex, leading to difficult theoretical analysis. Fortunately, such a potentially complex arrangement can be combined together into a lumped backpressure system consisting of a single equivalent channel for efficiency calculation purposes. For our treatment of EOF pump efficiency, we will pursue the simplest case of a single channel.

In order to more fully expand the efficiency equation represented in Eq. (7), it is necessary to introduce a relationship for electric power that is dependent on the resistivity of the buffer

$$EL_1 I = \frac{nA_1 E^2 L_1^2}{L_1 \rho}, \quad (8)$$

where ρ is the resistivity of the buffer. Now, if we substitute Eqs. (3), (4), and (8) into Eq. (7), we obtain the following generalized efficiency equation for an EOF pump system

$$\eta = \frac{2\pi n \epsilon_o^2 \epsilon_r^2 L_1 L_2 d_1^4 d_2^4 \rho}{v A_1 (L_1 d_2^4 + n L_2 d_1^4)^2}. \quad (9)$$

To use this efficiency equation for the thin film fabricated EOF pumps presented in this article, the equivalent diameter (d) for our devices must be calculated from the following equation

$$d = 4A/P \quad (10)$$

where A is the cross-sectional area of the microchannel, and P is its perimeter. We can express area by Eq. (11), and perimeter by Eq. (12)

FIG. 8. Plot of efficiency of an EOF pump system having EOF pump channels that are 4 mm long. The pump channels are attached to a 5 mm long, 50 μm wide single channel.

$$A = \frac{\pi ab}{2} + 2bm, \quad (11)$$

$$P = \frac{\pi[3(a+b) - \sqrt{(3a+b)(a+3b)}]}{2} + 2m + 2b, \quad (12)$$

where a is the height of the channel core, b is the channel half-width, and m is the height of the evaporated aluminum layer. These equations were generated assuming an approximate half-elliptical shape of the core plus the area contributed by the aluminum layer. Due to the fabrication techniques employed, $m=300$ nm, $a_1=2.2$ μm , $a_2=3.5$ μm , and $b_2=25$ μm .

Figure 8 demonstrates EOF pump efficiencies for 10, 100, and 1000 pump arms over a range of equivalent pump arm diameters. This figure shows that efficiency increases with an increasing number of pump arms and decreasing equivalent pump arm diameter. It can also be inferred from Fig. 8 that it is possible to select an equivalent diameter to maximize the efficiency of an EOF pump system for a given number of pump arms.

For microfabricated systems, a central aim is to minimize the total device size. Therefore, maximizing the use of the area on the chip is of great importance. EOF pumps can be designed for the most efficient use of space and, therefore, the maximum power for fixed chip area. The maximum mechanical power that an EOF pump system produces can be expressed as the product of the pressure generated in the system [Eq. (3)] times the flow rate [Eq. (4)]. This leads to

$$Q_{\text{mechanical}} = \frac{2\pi n \epsilon_o^2 \epsilon_r^2 \xi^2 d_1^4 d_2^4 L_2 V^2}{v L_1 (L_1 d_2^4 + n L_2 d_1^4)^2}, \quad (13)$$

where V is the voltage drop across the pump. As an example of the use of Eq. (13), we compare three different EOF pump shapes that occupy an equal chip area. Assuming that all three designs have the same spacing between pump arms and the same pump arm diameter, the on-chip area is $2nwL_1$, where w is the width of one pump arm. For a square design, the total width and length of the pump are equal, leading to $L_1=2nw$. A rectangular shape that is four times as long as it is wide leads to $L_1=8nw$. A rectangle, which is four times as wide as it is long, leads to $L_1=\frac{1}{2}nw$. Given an on-chip area of 1 cm^2 , and typical values for channel lengths and diameters ($L_2=5$ mm, $w_1=5$ μm , $w_2=50$ μm , $a_1=2.2$ μm , and $a_2=3.5$ μm), Eq. (13) leads to the results shown in Fig. 9.

FIG. 9. Schematic of three different pump configurations of equal area. The configurations differ by length-to-width ratios of 1:1, 4:1, and 1:4. Mechanical power ($P_{\text{mechanical}}$) increases with pump width. For these calculations, the pump arms were $2.5 \mu\text{m}$ tall and $5 \mu\text{m}$ wide.

The greatest mechanical power is generated by the short EOF pump with many pump arms at $(4.1 \times 10^{-15})V^2$ W, while the least efficient is the long EOF pump with fewer pump arms at $(3.4 \times 10^{-15})V^2$ W. If possible, using a short, wide design would be preferable from a chip area efficiency standpoint.

VI. CONCLUSIONS

Electro-osmotic flow pumps have found increased utility in recent years due to their ease of fabrication and implementation. This article describes the development and characterization of EOF pumps fabricated using standard thin film deposition and patterning. Due to the multiple-channel structure of the EOF pump, much higher pressures and flow rates can be achieved compared to a single microchannel of equal cross-sectional area. The measured flow rates agree well with EOF pump theory, and also demonstrate the reproducibility of EOF pump performance. Highest pump efficiency is achieved using very small-diameter pump arms. For a given total chip area, EOF pump power is maximized using many short pump arms rather than fewer long pump arms. The implementation of EOF pumps in microfluidic systems can be greatly facilitated through the ease and precision of thin film fabrication techniques, as well as through on-chip integration. For example, EOF pumps can be integrated on-chip with other microfluidic systems as the driving force for liquid chromatography with monolith and gel packed channels, or as a microelectronic cooling pump.

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