Chapter 10

Electroosmotic Flow Pump

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Abstract

Electroosmotic flow (EOF) pumping has been widely used to manipulate fluids such as liquid sample reagents in microfluidic systems. In this chapter, we will introduce the research progress on EOF pumps in the fields of microfluidic science and technology and briefly present their microfluidic applications in recent years. The chapter focuses on pump channel materials, electrodes, and their fabrication techniques in microfluidics.

Keywords: Electroosmotic flow pump, Channel material, Pump electrode, Fabrication, Microfluidic applications

1. Introduction

Micropumps are the essential active components of fluid transport systems in microfluidics. They can manipulate small volumetric fluids on spatial scales, from several to a hundred microns [1-3]. Nowadays, they have been widely used in many scientific and technical fields of microfluidics, such as biological/chemical analysis and assays [4-7], liquid drug reagent injection/delivery [8-9], and microelectronic chip cooling [10].

With the rapid development of microfluidic technologies, great attention has been paid recently to miniature micropumps with compact design for microfluidic analysis and assays. Miniature micropumps can be easily integrated into microfluidic systems and enable users to achieve low-cost portable pumping devices such as disposable insulin infusion pumps. Miniaturization of pumping systems can simplify the operation of sample introduction and transport in the microfluidic platform with less manual intervention. Meanwhile, miniaturization can greatly reduce the quantities of sample reagents and achieve microfluidic analysis or assays efficiently.

Recently, electroosmotic flow (EOF) pumps [11-12] have received extensive attention because of their ability to drive a wide range of liquid fluids and generate high pumping pressures or flow rates with continuous pulse-free flows. Besides, the EOF pumps can exhibit precise control of small volumetric fluids in microfluidic systems under finely controlled electric fields. Compared with mechanical micropumps, EOF pumps do not require moving mechanical parts inside, which can be easily integrated into pumping platforms to achieve the miniaturization of microfluidic systems. Notably, by changing the strength and direction of the electric field through the pump channels, the EOF pumps can conveniently offer bidirectional fluid flows for microfluidic systems.

The pumping flows in EOF pumps are driven by the mechanism of electroosmotic flow phenomenon [13-15]. When in contact with an uncharged liquid fluid (e.g., deionized water, aqueous solution), channel wall surfaces of PDMS, glass, PMMA, or Si can carry electrostatic charges, forming an electrical double layer nearby. The electrical double layer has a compact layer (containing immobile ions) on the channel surface and a diffuse layer (containing mobile ions) in the liquid fluid. Once an electric field is applied through the pump channel, the mobile ions in the diffuse layer move under the electric field force. As a result of the viscous effect, the moving ions will drag their surrounding fluid molecules to the same speed, forming electroosmotic flow in the pump channel. In short, the electroosmotic pumping performance of EOF pumps is fundamentally dependent on the material property of the pump channel wall and electrical field applied to the pump electrodes. The fabrication of pump channels and electrode plays a vital role in cost control of the EOF pumps. The material and fabrication of the pump channel and electrode are also important considerations in the selection of EOF pumps for microfluidic applications.

Recently, the scientific and technical research of EOF pumping in microfluidics has often focused on the pump channel material, pump electrode, and their fabrication techniques. In this chapter, we will mainly present the research progress of EOF pumps in these aspects and briefly introduce new and recent applications of EOF pumps in microfluidics.

2. Channel material and fabrication

Generally, EOF pumps can roughly be divided into direct EOF pumps, porous membrane EOF pumps, and packed porous media EOF pumps, according to the type of EOF-generating pump channels.

2.1. Direct electroosmotic flow (EOF) pump

Direct electroosmotic flow (EOF) pumps utilize open pump channels to drive fluids inside. The pumping pressure or flow rate can be increased via enlarging the number of pump channels. Direct EOF pumps are extremely suitable for the introduction delivery of sample reagents containing cells, biomolecules, and larger particles.

Basically, the common direct EOF pumps are fabricated by capillaries (e.g., PMMA, fused silica capillaries), which are named open-capillary EOF pumps [16-20]. The open-capillary EOF pumps, compared with others, are simple, cheap, and easy to fabricate, because the capillaries

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are popular on the market. However, the capillary cannot offer high pumping pressure or flow rate for microfluidic systems. In the open-capillary EOF pump, inert solid-metal-based thin wires are often used to fabricate the pump electrodes. Normally, the outer diameter of thin wires is much larger than the inner diameter of the capillary channel. To generate electric field through the capillary channel, the thin wire electrodes have to be inserted and fastened into two fluid reservoirs connected with both ends of the capillary. The open-capillary EOF pumps are widely used as sample introduction devices to drive liquid reagents into microfluidic chip platforms.

The direct EOF pumps can also be constructed by open channels. These pumps can be described as direct open-channel EOF pumps [20-24], which are usually used to perform on-chip integratable control of sample reagents in microfluidic chip systems. The open channels in these pumps are usually fabricated with photolithographic microfabrication technologies. Figure 1 shows a widely used direct EOF pump using a PDMS microchannel as an open pump channel. Two inert solid-metal wires (platinum or gold) are inserted into both inlet and outlet fluid reservoirs of the PDMS microchannel as the pump electrodes. The PDMS microchannel in this pump can be fabricated with the standard soft lithography technology, which will facilitate the integration of this EOF pump microfluidic systems. To obtain high pumping pressure or flow-rate fluid flows, the direct open-channel EOF pumps can be usually designed and fabricated with a large number of open pump channels in parallel.

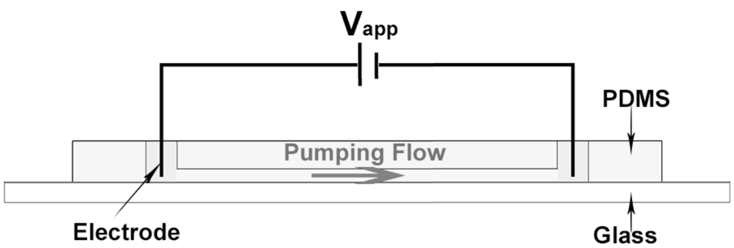

Figure 1. Open-channel EOF pump with metal wire electrodes.

2.2. Porous membrane electroosmotic flow (EOF) pump

Porous membrane EOF pumps [25-28] utilize a piece of porous membrane to construct sub-microscale or nanoscale pump channels within. They are miniaturized and highly integrated microfluidic pumping devices. Compared with the direct EOF pumps, the porous membrane EOF pumps under action of a large number of micro-/nanopump channels can offer high pumping pressure or flow-rate flows. The porous membranes are frequently made of glass, silica, alumina, or organic polymer (PC or PET) using the high-temperature sintering technique or etching technologies like chemical track etching, physical etching, and soft lithography. The drawback of the porous membrane EOF pump is that the sub-micro- or nanoscale pump channels in the pump cannot be used to transport cell, biochemical macromolecules, or large particle in aqueous suspensions.

Figure 2 shows a popular porous membrane EOF pump with mesh microelectrodes. In this EOF pump, the porous membrane is located between the inlet and outlet fluid reservoirs and vertically fastened to the macrofluid channel wall by both supporting frames. Two pieces of mesh microelectrodes are attached onto both sides of the membrane to reduce voltage drop and generate a high electric field through the pump channels. The pump channels embedded in the porous membrane are relatively short (from tens to several hundreds of μm). Hence, an electric field with high strength can be obtained when a low voltage is applied. In order to reduce fluid flow resistance, the micro-/nanopump channels embedded in membrane are often designed and fabricated straight from one side of the porous membrane to the other.

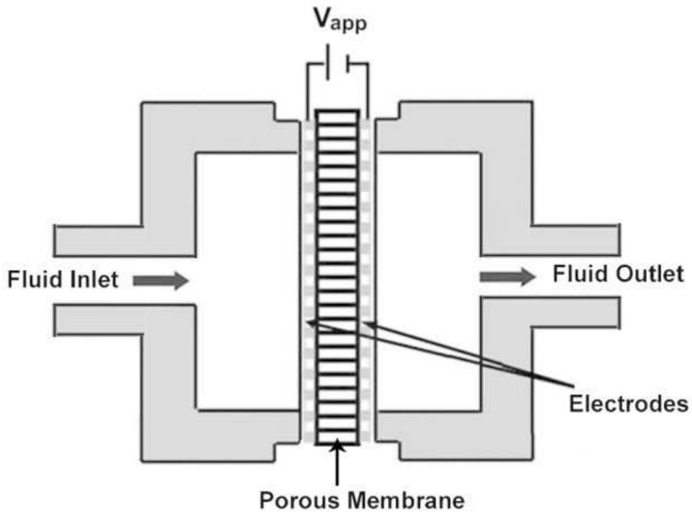

Figure 2. Porous membrane EOF pump with mesh microelectrodes.

2.3. Packed porous media electroosmotic flow (EOF) pump

Packed porous media EOF pumps [29-32], highly miniaturized and integrated microfluidic pumps, can drive high-pressure or flow-rate fluids. Similar to the porous membrane EOF pumps, the packed porous media EOF pumps have a large number of sub-micro- or nanopump channels inside. The sub-micro-/nanopump channels are usually prepared by packing sub-micro-/nanodielectric particles or columns into a mini-/microfluidic channel. These dielectric particles or columns can be made of fused silica, alumina, or organic polymer.

Figure 3 presents a typical example of packed porous media EOF pump with metal wire electrodes. In this EOF pump, a short mini-/microfluidic channel is used to build the pumping region with two pieces of porous membranes on both sides. The packed particles are held in place inside the fluid channel. Two metal wire electrodes are separately inserted into both inlet and outlet fluid reservoirs, paralleling to the fluid channel. Because the particles are randomly distributed inside the fluid channel, the fluid flow resistance in the pump will rise with pumping, thus leading to the reduction of pumping pressure or flow rate. To produce high flow rates or high pumping pressures, the EOF pump can be designed with a large number of

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parallel sub-micro-/nanopump channels. Alternatively, sub-micro-/nanodielectric columns can be introduced and packed into this pump (shown in Figure 3) to construct parallel sub-micro-/nanopump channels. For convenient fabrication purpose, the packed columns should be short in length compared with the fluid channel.

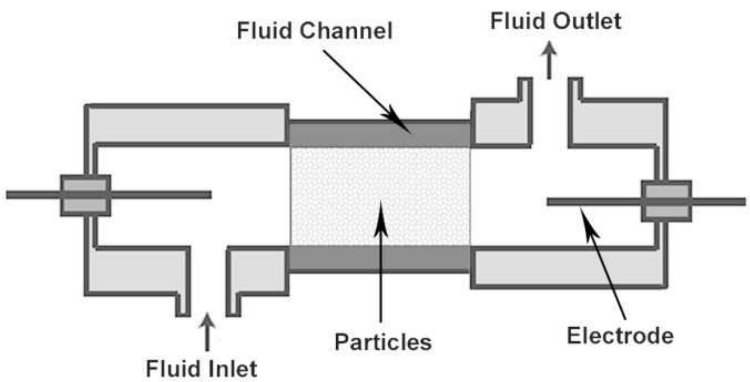

Figure 3. Packed porous media EOF pump with metal wire electrodes.

3. Electrode and fabrication

Electrodes, the key components of EOF pumps, can be used to induce the driving electric field through the pump channels with applied voltage. In EOF pumps, the material and fabrication of the electrodes are vital factors in pump performance and cost control. Basically, there are two electrode types. One is contact electrode exposed to the fluid and the other is noncontact electrode separated from the fluid. This section will show detailed description of them.

3.1. Contact electrode

Contact electrodes mainly made of solid metals are the most widely used electrodes in EOF pumps. The solid-metal-based contact electrodes are often divided into three groups, which are metal wire electrodes, membranous microelectrodes, and mesh microelectrodes.

Metal wire electrodes [33-36] are inserted into the inlet/outlet reservoirs of the pump channels in EOF pumps, as shown in Figure 13. These metal wire electrodes are the simplest type for EOF pumps, which can be bought easily. However, they are not suitable for the integration or miniaturization of the pumping devices in microfluidic systems. Due to the smaller size of metal wires as shown in Figure 3, the metal wire electrodes are not capable of generating a roughly uniform electric field throughout the whole pump channels with applied voltage. Therefore, the pump cannot offer steady flows with a uniform velocity field inside the channel.

Membranous microelectrodes [37-40] are often fabricated under the pump channel using sputtering or deposition techniques, as shown in Figure 4. They can be well miniaturized and

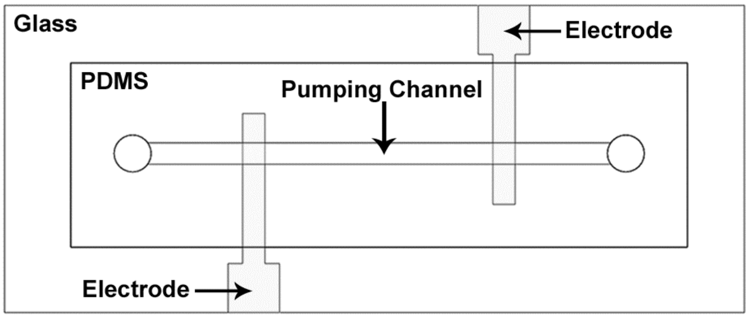

Figure 4. Membranous microelectrode used in open-channel EOF pump.

integrated into the on-chip pumping system. However, it is important to note that the membranous microelectrodes have to be fabricated separately with the pump microchannels, and they should be accurately aligned with the pump microchannels during bonding. The fabrication of these membranous microelectrodes is complex, expensive, and time-consuming.

Figure 5 presents the fabrication of the membranous microelectrodes together with the pump channels for the open-channel EOF pumps. The membranous microelectrodes are fabricated onto a glass substrate through techniques of sputtering and standard soft lithography (Figure 5 (a)), and the PDMS pump microchannel can be prepared by soft lithography technique (Figure 5 (b)). After fabrication, the PDMS pump microchannel is irreversibly bonded with the glass substrate. Since the membranous microelectrodes are located under the pump channel, the EOF pump cannot obtain a parallel electric field through the pump channel or drive uniform pumping flows. To achieve an almost uniformly distributed flow, the pump microchannel needs to be designed with a relatively low high-aspect-ratio section.

Similarly, mesh microelectrodes [41-43] are miniature and integratable ones for EOF pumps, as shown in Figure 2. They are very suitable for the porous media EOF pumps, which will strengthen the miniaturization and integration of the EOF pumps into microfluidic systems. In EOF pumps, the mesh microelectrodes are usually placed and fastened on both ends of the porous pump channels. During assembly, meshes of each electrode have to be aligned with the sub-micro-/nanopump channels. Different with the membranous microelectrodes, the mesh microelectrodes can induce a roughly uniform electric field in the pump channels. They can easily offer high flows at relatively low voltages. However, they do have the same characteristics that are extremely complex and expensive in fabrication.

The contact electrodes exposed to the fluid usually give rise to a serious problem of electrolysis during pumping. Bubbles or other electrolytic products can occur at the electrode surfaces, entering the pump channels and blocking the EOFs. What's more, the joule heat will be generated in the fluid. All bring a sharp decrease in electroosmotic mobility and flow rate. Even worse, the short circuit of high-voltage supply equipment happens sometimes. The use of inert solid-metal platinum (Pt) and gold (Au) electrodes can largely reduce the electrolysis in EOF pumps. The abovementioned problems can be eliminated if the solid-metal electrodes are separated from the aqueous reagents in the pump channels.

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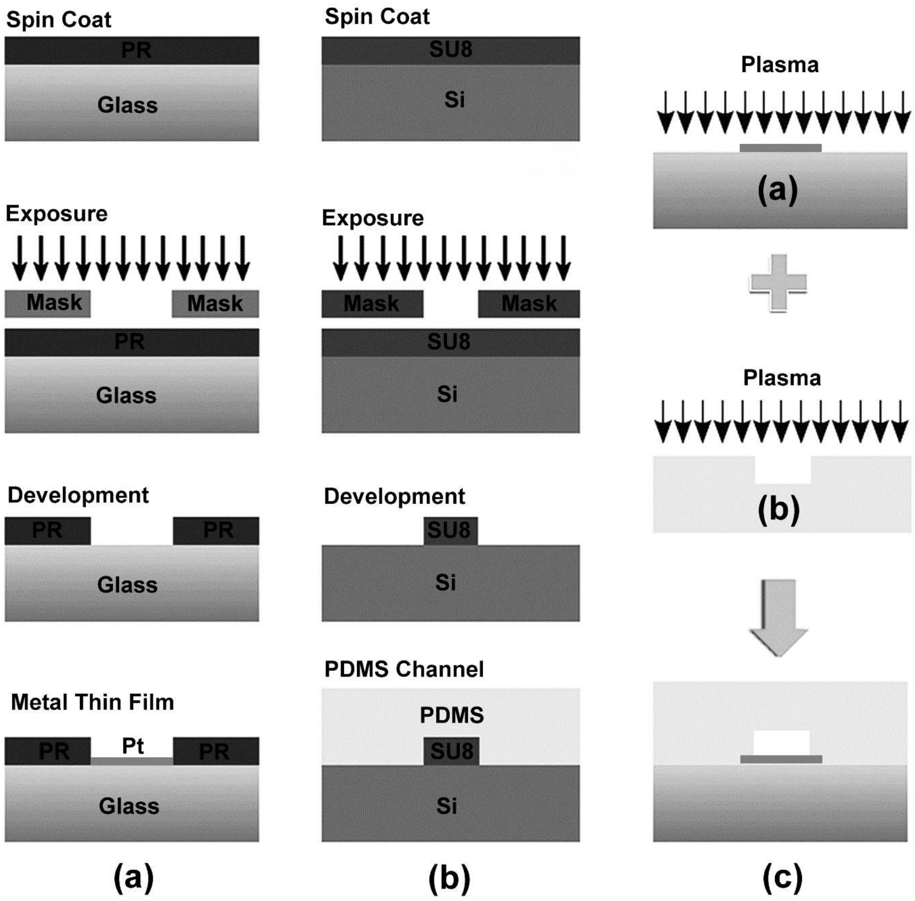

Figure 5. Fabrication of open-channel EOF pump with membranous microelectrodes and PDMS-based pumping microchannel.

3.2. Noncontact electrode

Noncontact electrodes have been developed to prevent the above problems. These noncontact electrodes often utilize nonmetal materials (e.g., polymer gel, silica, polyaniline, PDMS) as membrane layers to separate the solid-metal electrodes from the EOF pumping fluid. The membrane layers are capable of allowing ion charges to pass through but stopping water molecules, and thus bubbles and by-products from electrolysis at the electrode surfaces can be prevented from entering the EOF pump channels in these micropumps.

Gel-type salt-bridge electrode, a widely used noncontact electrode in the field of electrochemistry, has been successfully fabricated for EOF pumps with bubble-free formation [22, 33]. Figure 6 shows a typical bubble-free EOF pump with this gel-type salt-bridge electrode. As shown in Figure 6, this EOF pump employs a thin gel region to protect the solid-metal wire electrode from the fluid. The wire electrode is immersed in the electrode reservoir filled with a conductive aqueous solution. When a high voltage is applied to the pump, the electrolysis can still emerge inside the pump. But, bubbles can only be generated at the wire electrode

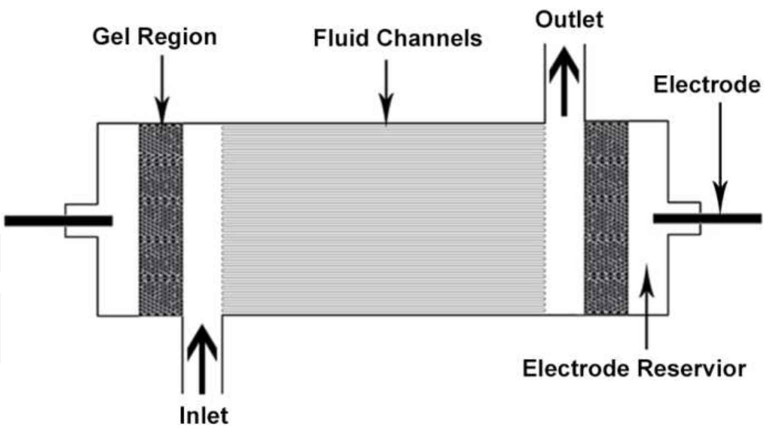

Figure 6. Gel-type salt-bridge microelectrode used in open-channel EOF pump.

surfaces in both electrode reservoirs, having no effect on the fluid flows in the pump channels. In this pump, both of the two gel regions are located in the electrode reservoirs between the metal wire electrodes and the parallel pump channels. The polymer gel, a sensitive polymer material, can be used for the microscale gel regions with the normal photolithography technique. During photolithographic fabrication, the mask for both two gel regions always has to be aligned costly and accurately. As a result, the fabrication of these gel-type salt-bridge electrodes requires a complex process. Another potential problem for this electrode is that the gel region can be easily collapsed due to the poor compatibility of gel material to the electrode reservoir wall. In the worst cases, electrolysis and bubbles will also be generated in the pump channels.

Other noncontact microelectrodes, such as fused silica capillary microelectrodes [31, 44], polyaniline-wrapped aminated graphene microelectrodes [45], and Ag/Ag2O microelectrodes [46], have been successfully fabricated to work as noncontact electrodes for bubble-free EOF pumps. In fabrication, three noncontact microelectrodes can be made from the chemical synthesis or assembly method in the laboratory. Compared with the gel-type salt-bridge microelectrodes, the three microelectrodes are robust in long-time running. However, the fabrication of this kind of electrodes is also a very complex, time-consuming, and expensive process. Now, the first challenge is to develop a new noncontact electrode with a simpler and cheaper fabrication technique.

Injecting wettable liquid metal into microchannels to make noncontact electrodes should be a simpler and cheaper method for bubble-free EOF pumps. Figure 7 shows a handy liquid-metal (GaInSn)-based EOF pump fabricated in a PDMS microfluidic chip [47]. In this pump, the liquid metal is a kind of metal alloy (GaInSn), which can be easily injected into microchannels by a simple syringe. The melting point of this liquid metal is only 10.6 °C below room temperature. As shown in Figure 7, two pairs of liquid-metal electrodes are fabricated parallel to each other and vertical to the pump channel in the same horizontal plane of the microfluidic chip. These two pairs of electrodes are also designed symmetrically to both sides of the pump channel. To induce high electric field strength in the pump channel when a relatively low

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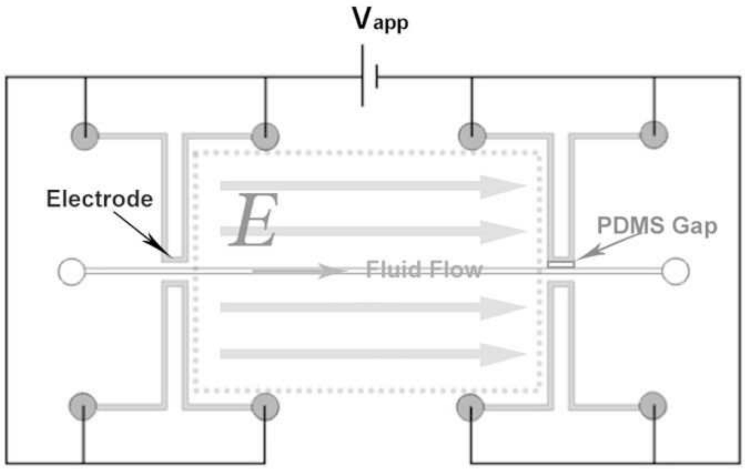

Figure 7. Handy liquid-metal microelectrode used in open-channel EOF pump.

voltage is applied, the electrodes are placed very close to but always not in contact with the pump channel. In this pump, the PDMS gaps are designed to be ≤ 40 μm between the liquid-metal electrode channels and the pump channel. For the convenience of liquid-metal injection, the liquid-metal electrode microchannels are all designed in the ohm shape.

Figure 8 depicts the typical fabrication of the liquid-metal noncontact electrodes for the open-channel EOF pump. Compared with membranous or mesh microelectrodes (shown in Figure 5), the liquid-metal electrode channels can be easily made just in one step together with the pump channel using the same fabrication technique. Furthermore, the liquid-metal electrodes can also be easily designed and fabricated in any shape and any location in the EOF pump. Using liquid-metal-filled microchannels as noncontact electrodes can provide an efficient approach to the miniaturization and integration of EOF pumps in microfluidic systems.

4. Applications

EOF pumps can offer a simple and cost-effective way to generate adequate pumping pressures and flow rates for microfluidic systems. They have been widely and successfully used in many areas of microfluidics. In this part, we will briefly introduce applications of EOF pumps in microfluidics. Based on the category of application areas, this section will be divided into 1) microfluidic delivery and actuation and 2) microelectronic thermal management.

4.1. Microfluidic delivery and actuation

Due to the simplicity of pumping components, EOF pumps have been widely used in microfluidic delivery of pure liquids or aqueous solutions. As a micrototal analysis pumping tool, the EOF pump is commonly fabricated to be disposable devices with a compact design. The online reduction of sample reagent quantities should be desirable. For microinjection delivery,

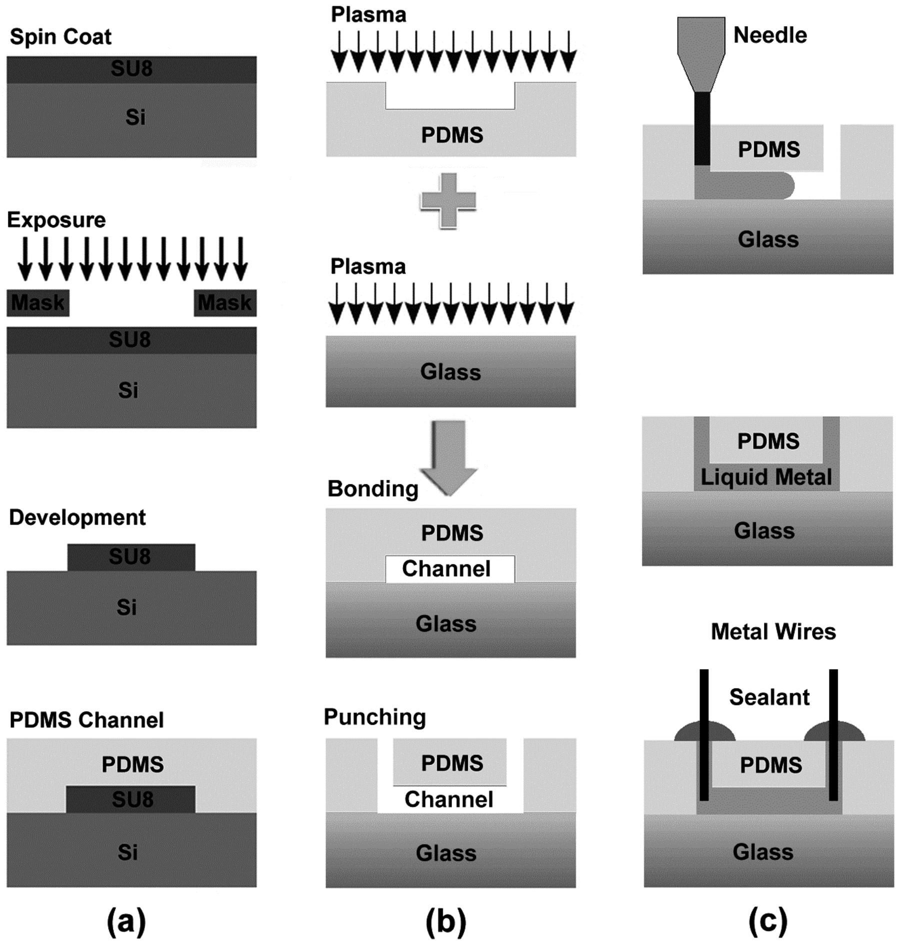

Figure 8. Fabrication of handy liquid-metal microelectrode for open-channel EOF pump.

in particular, the EOF pump is usually required to offer high flows. Preferentially, open-capillary EOF pumps [16-20] are used to perform the introduction of sample reagents into a microfluidic analysis or assay system. The open capillary has the ability to deliver a wide range of sample reagents such as pure liquid drug reagents and aqueous solutions containing cells, particles, or biochemical macromolecules. The porous media EOF pumps [25-32] can also be used to drive pure liquid sample reagents for the injection purpose. For on-chip microfluidic delivery, open-channel EOF pumps [20-24] are the most popular pumping devices. The reason is that the open pump channels and the pump electrodes can be easily and conveniently integrated into the microfluidic chip together with other functional components.

In most microfluidic systems, efficient mixing of sample reagents is extremely essential for improving the throughput of microfluidic assays and analysis. Many active mixing methods [48] using external actuation forces to perturb the sample reagents to enhance their diffusion have been recently developed to achieve a high mixing performance. Most of the external actuation forces are generated by mechanical moving, stirring, or vibrating. Owing to the fast electrical operation, the EOF pump has also been widely used to perform highly efficient active mixing in microfluidics. The EOF-actuated mixing utilizes electroosmotic driving forces to induce oscillatory, turbulent, or chaotic flows in the sample reagents, while a periodic electric field is applied simultaneously [49]. Several typical open-channel configurations, such as T-shaped, Y-shaped, and multi-shaped configurations, have been developed for the EOF-actuated mixing [50-56]. The use of EOF pump does not require mechanical moving components and hence brings cheaper and more reliable microfluidic mixers. Besides, the EOF pump can also be used as a microactuator for focusing and separation of droplets, particles, or cells in microfluidic systems [57-58].

4.2. Microelectronic thermal management

With the rapid development of MEMS technologies, the design of a miniature electronic chip with more and more functional components has become an essential demand in recent years. Consequently, power consumption is increased to maintain operation which generates great heat flux. Air-forced cooling cannot remove such high heat flux from the hot chip. Micro-pumping that drives liquid fluids through microchannels is an efficient approach to perform heat dissipation of electronic components [10-12].

EOF pumps have been considered in microchannel-based liquid cooling for electronic chips owing to their low power consumption and high pumping pressure. EOF pumps can work without any noise during liquid coolant pumping. Recently, a porous media-based EOF pump [59] has been successfully utilized for liquid cooling of microelectronic chips. In this micro-channel liquid cooling system, the pump works as an external device to drive water coolant to force thermal dissipation of the hot region in the microelectronic chip. To reduce the thermal resistance, the microchannels filled with liquid coolant are tightly attached to the hot surface of electronic chip. Since the microchannels have high surface-volume ratio available for thermal dissipation, the EOF pump is capable of removing the heat generation efficiently.

5. Future and prospect

This chapter has briefly reported recent research progress of EOF pumps with emphasis on channel materials, electrodes, and their fabrication and summarized pump applications in microfluidics.

EOF pumping is commonly used in many microfluidic devices. Nowadays, it has become an increasingly popular tool to manipulate such liquid sample reagents with electric fields. The number of microfluidic applications is growing fast, and certain EOF pumping devices, like porous membrane EOF pumps (Osmotex), have been already commercially available. However, the popular use of EOF pumps in microfluidics may be limited due to the lack of high-performance pumps with cost-effective characteristics.

The EOF pump continues to be improved, which shows stable performance, rapid operation, and compact design. EOF pumps with noncontact electrodes have generated robust pumping flows without bubble formation, but there is still a lot of work to be done for improving these pumps. Further research is required to understand the basic driving mechanism of gel, silica, or PDMS-based noncontact electrodes. Research on new material design and fabrication is also an urgent need for noncontact electrodes with low-cost and simple process. Another option of liquid metal, instead of solid metal and conductive aqueous solution in electrode reservoirs of noncontact electrodes, should be an alternative solution for the water electrolysis at the solid-metal electrode surfaces.

EOF pumps do not require mechanical moving components, and they can offer excellent miniaturization potential in integrated microfluidic applications. With applied electric fields, EOF pumps are capable of performing fine control of fluids fast. In the near future, the EOF pump should be an important element in promising implantable medical devices such as drug transport or infusion pumps.

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