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MEMS-Micropumps: A Review

Microfluidics has emerged from the MEMS-technology as an important research field and a promising market. This paper gives an overview on one of the most important microfluidic components: the micropump. In the last decade, various micropumps have been developed. There are only a few review papers on microfluidic devices and none of them were dedicated only to micropumps. This review paper outlines systematically the pump principles and their realization with MEMS-technology. Comparisons regarding pump size, flow rate, and backpressure will help readers to decide their proper design before starting a microfluidics project. Different pump principles are compared graphically and discussed in terms of their advantages and disadvantages for particular applications. [DOI: 10.1115/1.1459075]

1 Introduction

Microelectromechanical systems (MEMS) have enabled a wide range of sensors and actuators to be realized by allowing nonelectrical devices onto microchips. In the early years of MEMS-development, fluidic components were among the first devices which were realized in microscale using silicon technology. The most common components were: flow sensors, microvalves and micropumps. With the growing importance of genomics, proteomics, and the discovery of new drugs, microfludic systems became hot research objects. The field of microfluidics expanded to the development of numerous micro devices: filters, mixers, reactors, separators. New effects such as electrokinetic effects, acoustic streaming, magnetohydrodynamic effect, electrochemical, and more, which previously were neglected in macroscopic applications, now gained their importance in microscale.

A recent report of System Planning Corporation [1] estimated a microfluidics market of 3 to 4.5 billions US$ and an annual growth rate for scales of 25 percent–35 percent. The report considered four types of microfluidic devices: fluid control devices, gas and liquid measurement devices, medical testing devices, and other devices. The report figured out that the most promising microfluidics products are devices for DNA, protein analysis, and drug discovery.

Since the establishment of the term "microfludics," several excellent review papers on microfluidic devices have been published. Gravesen et al. gave a general overview on fluidic problems in micro scale [2]. Shoji and Esashi discussed microfluidics from the device point of view and considered micropumps, microvalves and flow sensors [3]. Ho and Tai discussed the MEMS-applications for flow control in the macroscopic domain [4]. Elwenspoek et al. summarized their works on microfludics in [5]. Stemme discussed microfluidic devices under such categories: passive devices (channel, valves, filters), flow sensors, and diaphragm pumps [6]. Zengerle and Sandmaier concentrated on microvalves, micropumps and their commercialization strategy [7]. Since the field has been growing rapidly, it's very difficult to cover all kinds of microfluidic devices in a single review. In contrast to the previous reviews, this paper only deals with micropumps and discusses their design methodology as well as the development of pump designs in the published examples. The design methodology will cover two main aspects: the pump principles and their comparison. With this concept, the paper tries to give a general view on micropumps, and to help microfluidics designers making their development decision easily.

Using the micromachining technology, a wide range of microdevices has been realized. The most important micromachining techniques are bulk micromachining. surface micromachining, and LIGA technology. Bulk micromachining uses the starting substrate (a silicon wafer) as device material. Surface micromachining is performed on the surface of a substrate, the substrate itself usually doesn't have a function in devices. LIGA-technology (German acronym for Lithographie Galvanoformung Abformung) creates high aspect ratio structures using X-ray lithography and electroplating. A short description of these technologies was given in [4]. Many MEMS-devices combine two or more of the above techniques. A new trend, especially for microfluidic devices, uses plastic as device material. The common machining technologies for these devices are micro plastic molding or hot embossing. Combining with on-going investigation of polymer microelectronics, plastic microdevices promise a low-cost alternative to their silicon counterparts.

2 Pump Principles

In contrast to another MEMS-devices, micropumps are one of the components with a largest variety of operating principles. Like other MEMS-applications, the first approach made by researchers was the micromachining realization of well-known principles from the macroscale. Micropumps can be divided in two mean categories: mechanical pumps and nonmechanical pumps.

The first category usually utilizes moving parts such as check valves, oscillating membranes, or turbines for delivering a constant fluid volume in each pump cycle [8]. The second category adds momentum to the fluid for pumping effect by converting another energy form into the kinetic energy. While the first category was mostly used in macroscale pumps and micropumps with relatively large size and large flow rates, the second category discovers its advantages in the microscale. Since the viscous force in microchannels increases in the second order with the miniaturization, the first pump category cannot deliver enough power in order to overcome its high fluidic impedance.

For flow rates larger than 10 ml/min, miniature pumps or macroscale pumps are the most common solution. The typical operation range of positive displacement micropumps lies between 10 μl/min to several ml/min. For flow rates less than 10 μl/min, alternative dynamic pumps are needed for accurate control of these small fluid amounts. With these flow rates, most of the pumps are working in the range of Reynolds number from 1–100, and therefore in a laminar regime.

All the pump principles, which were realized recently in microscale, are discussed in details in the following subsections.

2.1 Mechanical Pumps. All mechanical pumps require a mechanical actuator, which generally converts electric energy into mechanical work. The comparison of mechanical works generated
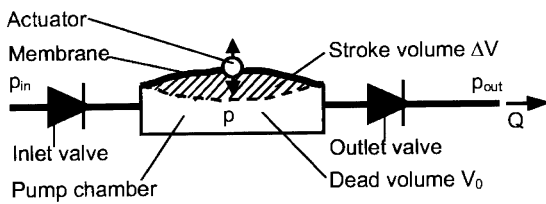
Fig. 1 General structure of a micro check-valve pump

by different pumps is discussed later in this paper. Shoji [3] divided actuators into two mean categories: external actuators and integrated actuators.

External actuators include: electromagnetic actuators with solenoid plunger and external magnetic field, disk type or cantilever type piezoelectric actuators, stack type piezoelectric actuators, pneumatic actuators, and shape memory actuators. The biggest drawback of external actuators is their large size, which restricts the size of the whole micro-pumps. The advantage is the relatively large force and displacement generated by external actuators.

Integrated actuators are micromachined with the pumps. Most common integrated actuators are electrostatic actuators, thermopneumatic actuators, electromagnetic actuators, and thermomechanic (bimetallic) actuators. Despite their fast response time and good reliability, electrostatic actuators cause small force and very small stroke. With special curved electrodes, electrostatic actuators are suitable for designing micropumps with very low power consumption. Thermopneumatic actuators generate large pressure and relatively large stroke. This actuator type was therefore often used for mechanical pumps. Thermopneumatic actuators and bimetallic actuators require a large amount of thermal energy for their operation, and consequently, consume a lot of electric power. High temperature and complicated thermal management are further drawbacks of these actuator types. Electromagnetic actuators require an external magnetic field, which also restricts the pump size. Their large electric current causes thermal problems and high electric energy consumption.

Check-Valve Pumps. Check-valve pump is the most common pump type in the macroscale. The first attempts in designing a micro pump were the realization of check-valve pumps. Figure 1 illustrates the general principle of a check-valve pump. The pump consists of:

- An actuator unit; a pump membrane that creates the stroke volume ΔV,
- A pump chamber with the dead volume V_0,
- Two check-valves, which start to be opened by the critical pressure difference Δp_{crit}.

Richter et al. [16] determined the operation conditions of a check-valve pump as:

- Small compression ratio ε which is the ratio between the stroke volume and the dead volume $\varepsilon = \Delta V/V0$,
- High pump pressure p ($|p - p_{out}| > p_{crit}, |p - p_{in}| > p_{crit}$).

Following design rules can be used in order to fulfill the above conditions:

- Minimize the critical pressure Δp_{crit} by using more flexural valve design or valve material with small Young's modulus,
- Maximize the stroke volume ΔV by using actuators with large stroke or more flexible pump membrane,
- Minimize the dead volume V_0 by using thinner spacer or wafer,
- Maximize the pump pressure p by using actuators with large forces.

The terms for passive microvalves used in this paper were defined by Shoji in [3]. One of the first micropumps made in silicon was presented by van Lintel [9]. The pump had check-valves in form of a ring diaphragm, which was relatively stiff and need a
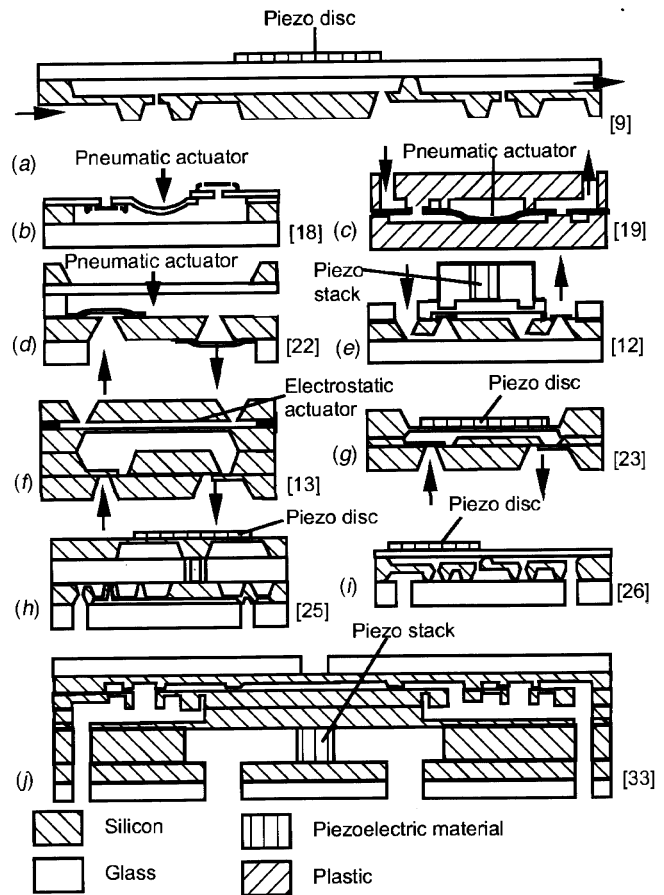

Fig. 2 Check-valve micropumps: (a) piezoelectric actuator with ring mesa valves; (b) pneumatic actuator with polyimide disk valves; (c) pneumatic actuator with membrane valves; (d) pneumatic actuator with rubber membrane and parylene disk valves; (e) piezoelectric actuator with polysilicon disk valves; (f) electrostatic actuator with silicon cantilever valves; (g) piezoelectric actuator silicon cantilever valves; (h, i, j) piezoelectric actuator with ring mesa valves.

large lateral area. That makes one valve consume a large silicon area, which has almost the same size of a pump chamber, Fig. 2(a). The same valves were also used in the pumps reported in [10] and [11], which had thermopneumatic actuators instead of piezodisks. The next improvement was the pump presented by Shoji [12], which had check-valves made of polysilicon by using surface micromachining. The valve is a disk supported by four thin polysilicon beams. This design allows small valves to be integrated under the pump chamber. Zengerle [13,14] presented another small and more flexible design. The valve has a form of a cantilever, Fig. 2(f). Koch et al. [15] and Wang et al. [16] proposed the same valve type in their micropumps.

Another way to make check-valve flexible is using material with smaller Yong's modulus. Table 1 compares the common materials used for check-valves in micro pumps. Polyimide, polyester, and parilene is one order more flexible than silicon. Pumps presented by Shomburg et al. [17,18] used polyimide as material for the disk valve (Fig. 2(b)). The pump reported in [19] and that presented by Kaemper et al. [20] had polyimide ring diaphragm valves (Fig. 2(c)). A similar design using polyester valve was reported by Boehm et al. [21]. In the pump presented by Meng et al. [22], the disk valve was realized in parylene (Fig. 2(d)).

The next optimization is to fabricate the pump membrane with flexural material like polyimide [19] (Fig. 2(c)) or silicone ruber [22] (Fig. 2(d)). These membranes require small actuating pres-

Table 1 Young's modulus of different materials

Material	Young's Modulus (GPa)
Stainless steel	~240
Silicon	~200
Silicon nitride	~300
Polyimide	~10
Parylene	~3
Silicone ruber	~0.0005

Table 3 Typical parameters of peristaltic micropumps (values for water)

Ref.	Author	Year	Chamber size (µm)	Chamber height (µm)	Max. Defl (µm)	Max. Flow Rate (µl/min)	Max. Back Pressure	Freq. (Hz)	Technology	Actuator
[34]	Smits	1988	5000	-		100	5880	15	Bulk micromach.	Piezoelectric
[35]	Shinoharal	2000	10000	400		40	2450	1	Bulk, anodic bonding	Piezoelectric
[36]	Judy	1992	400	4	4		-		Surface micromach.	Electrostatic
[37]	Folta	1992	1000	10	10	7		20		Thermopneumatic
[38]	Mizoguchil	1992	800	18	35	3	4822	3	Buk micromach.	Thermopneumatic
[39]	Grosjean	1999	500	60	60	4.2	3447	2	Bulk, Precision eng.	Thermopneumatic
[40]	Cabuz	1999	800	500	500	8000	-	100	Plastic Molding	Electrostatic

sure and have large deflection as well as large stroke volume. This type of membrane is suitable for pneumatic or thermopneumatic actuators.

Using thinner spacer or thinner wafer for the pump chamber can minimize the dead volume. The pump presented by Zengerle [13] (Fig. 2(f)) was in this way improved in the version presented by Linnemann et al. [23]. The middle wafer was polished and thined to 70 micron. As a result, the compression ratio increased from 0.002 to 0.085 [24]. The improved pump design was able to pump gas and was self-priming. The design of van Lintel [9] (Fig. 2(a)) was improved from the later version [25] (Fig. 2(b)) and had a compression ratio of 1.15. This pump was self-priming and insensitive to ambient pressure because of the implementation of a special pump membrane limiter. Another good design, which minimizes the dead volume in the Linnemann's pump, was combining the check-valve with the pump chamber realized by Gass et al. [26,27] (Fig. 2(i)).

Table 2 lists the most important parameters of the above check-vale pumps and those reported in [28–33]. The pump designs depicted in Fig. 2 also illustrate the "evolution" in designing check-valve micropumps. The development shows clearly how the pump chamber becomes smaller, and how the check-valves and the pump membrane become more flexible. Most of the developed micropumps tend to have a piezoelectric disk as actuator, which is reasonable for the performance and size needed for this pump type. ·

Peristaltic Pumps. As opposed to check-valve pumps, peristaltic pumps don't require passive valves for the flow rectification. The pump principle is based on the peristaltic motion of the pump chambers, which squeezes the fluid into the desired direction. Theoretically, peristaltic pumps need 3 or more pump chambers with reciprocating membrane. Most of the realized pumps have 3 chambers. Some pumps were designed with active valves, which in fact represent pump chambers, also belong to the category of peristaltic pumps. The optimization strategies are maximizing the compression ratio and increasing the number of pump chambers (Table 3).

Table 2 Typical parameters of check-valve micropumps (values for water, except [18] for air)

Ref.	Author	Year	Chamber size (µm)	Chamber height (µm)	Max. Deflection (µm)	Max. Flow Rate (µl/min)	Max. Back Pressure (Pa)	Typ. Frequency (Hz)	Technology	Actuator
[9]	van Linten	1988	12500	130	-	8	9800	1	Bulk, anodic bonding	Piezoelectric
[10]	van den Poll	1990	7500	273	23	30	4000	0.5	Bulk, anodic bonding	Thermopneumatic
[11]	Lammerink	1993	7500	261	23	58	2940	5	Bulk, anodic bonding	Thermopneumatic
[12]	Shoji	1990	5000	-	-	20	14700	40		Electrostatic
[13]	Zengerle	1992	4000	425	4	70	2500	25	Bulk, adhesive bonding	Electrostatic
[14]	Zengerle	1995	4000	425	5	850	31000	1000	Bulk, adhesive bonding	Electrostatic
[15]	Koch	1998	4000	380	1.7	150	2000	200	Bulk, adhesive bonding	Piezoelectric
[16]	Wang	1998	5000	370	-	365	2380	25	Bulk, adhesive bonding	Piezoelectric
[18]	Schomburg	1993	5000	100	100	44	3800	5	LIGA	Pneumatic
[20]	Kaemper	1998	10000	-	30	400	210000	50	LIGA	Piezoelectric
[21]	Boehm	199	10000	200	-	2100	11000	100	Plastic Molding	Piezoelectric, Electromagnetic
[22]	Meng	2000	7000	400	-	13000	5900	12	Bulk, Silicone	Pneumatic, Electromagnetic
[23]	Linneman	1998	5700	15	15	1300	90000	200	Bulk, direct bonding	Piezoelectric
[25]	Maillefer	1999	4000	-	-	4	35000	2	Bulk, anodic bonding	Piezoelectric
[26]	Gass	1994	14000	2.00E-04		100	9000	40	Bulk, anodic bonding	Piezoelectric
[28]	Dario	1996	10000	1500	-	780	5500	264	Plastic Molding	Electromagnetic
[29,30]	Guo	1996	6000	-	100	40		2	Precision Eng.	ICPF
[31]	Accoto	1998	10000	-	-	600	9800	2	Precision Eng.	Piezoelectric
[32]	Benard	1997	8400	450	-	50	519	1	Bulk, adhesive bonding	Shape-memory-alloy
[33]	Li	2000	3600	18	18	1400	300000	3500	Bulk, direct bonding	Piezoelectric

Since a peristaltic pump doesn't require high chamber pressure, the most important optimization factors are the large stroke volume and the large compression ratio. The first peristaltic micro pump presented by Smits [34] (Fig. 2(a)) had piezoelectric actuators and pump chambers etched in silicon. Shinohara et al. [35] presented a similar design with the same performance.

Judy [36] proposed a pump, which utilized surface micromachining and electrostatic actuators (Fig. 2(b)). The pump chamber, and consequently the dead volume, can be kept very small. No results for maximum flow rate and backpressure were reported for this pump.

The pump reported by Folta et al. [37] (Fig. 2(c)) used thermopneumatic actuators, the pump chamber height was 10 micron. However, the heat loss caused by the good thermal conductivity of silicon minimized the thermopneumatic effect and increased the power consumption.

Mizoguchi et al. [38] (Fig. 2(d)) also used thermopneumatic actuators for driving 4 pump chambers, the pump had external laser light as heat source. Similar to the methods discussed in the previous section, Grosjean et al. used silicone rubber in order to form the pump membrane [39] (Fig. 2(e)). With external pneumatic sources, the pump could generate a flow rate up to 120 µl/min. In thermopneumatic operation, the pump only delivered few µl/min like the similar designs in [37] and [38].

The pump presented by Cabuz et al. [40] increased the compression ratio to 10 by using curved pump chambers and flexible plastic pump membrane for electrostatic actuation. The numerous pump chambers were designed by using a three-dimensional array structure (Fig. 2(f)). With these optimization measures, the pump was able to deliver 8 ml/min with only 75 V drive voltage and 4 mW electrical power (Fig. 3).

Valveless Rectification Pumps. The structure of valveless rectification pumps is similar to those of check-valve pumps. The only difference is that instead of using check-valves the pumps use diffuser/nozzle or valvular conduit structures for flow rectification. Maximizing the stroke volume and minimizing the dead volume can optimize this pump type.

Stemme [41] presented the first pump with diffuser/nozzle structures. The pump was fabricated in brass using precision machining (Fig. 4(a)). Further development of this pump leads to the flat design in silicon [42–44] (Fig. 4(b)). Using small opening angles (7–15 deg), the flow is pumped out of the diffuser structure (Fig. 2(a)). With deep reactive ion etching (DRIE), small chamber height, and consequently small dead volume and large compression ratio were achieved.

The pump effect appears in the opposite direction if the opening angle is large. The pump presented by Gerlach had an opening of 70.5 deg, which is determined by the ⟨111⟩ surface freed with anisotropic wet etching [45–47] (Fig. 4(c)). This pump design was optimized in the work of Jeong and Yang [48]. The stroke volume was increased by using the thermopneumatic actuator and corrugated pump membrane. Ullman gave in [49] a theoretical analysis of diffuser/nozzle pumps.

Forster et al. [50,51] applied the valvular conduits structure which was first invented by Tesla [52] in micro scale. The inlet/outlet structures shown in Fig. 5 cause the rectification effect without check-valves. This pump type can be realized easily in silicon with DRIE-technology.
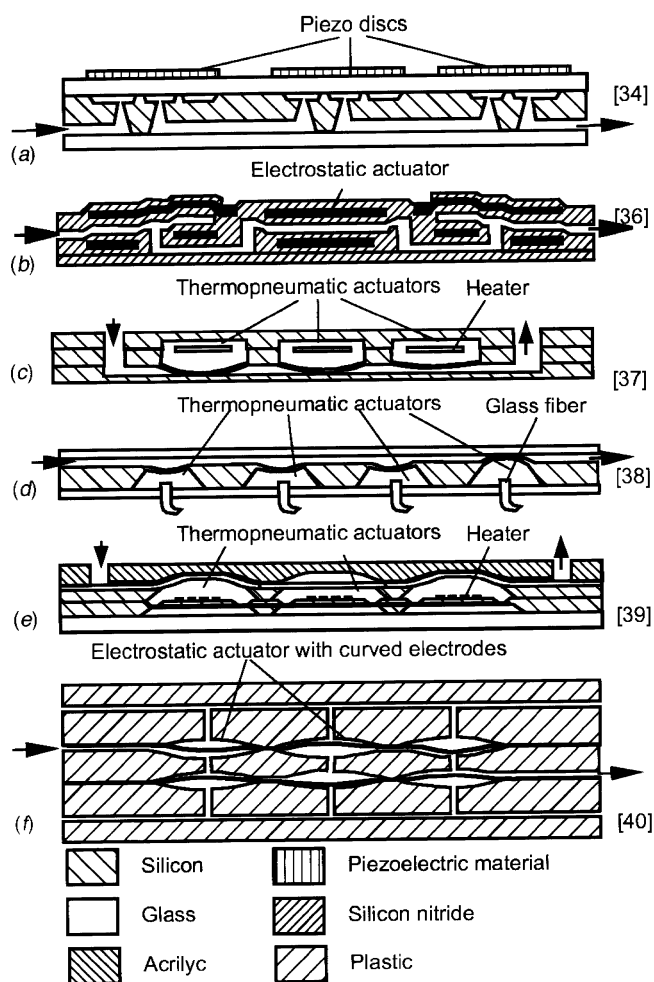
Fig. 3 Realization examples of peristaltic micropumps (not to scale): (a) piezoelectric actuators with glass membrane; (b) electrostatic actuators with polysilicon membrane; (c) thermopneumatic actuators with silicon membrane; (d) thermopneumatic actuators with silicon membrane and fiber guided laser as heat source; (e) thermopneumatic actuators with rubber membrane; (f) electrostatic actuators with curved electrodes.
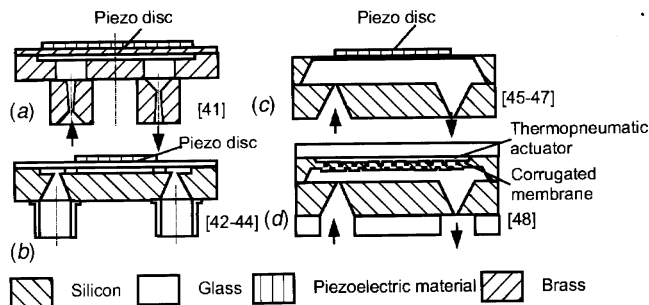

Fig. 4 Realization examples of valveless rectification micro pumps (not to scale): (a) piezoelectric actuator with external diffuser/nozzle elements; (b) piezoelectric actuator with planar integrated diffuser/nozzle elements; (c) piezoelectric actuator with vertical diffuser/nozzle elements; (d) thermoelectric actuators with corrugated membrane and vertical diffuser/nozzle elements.
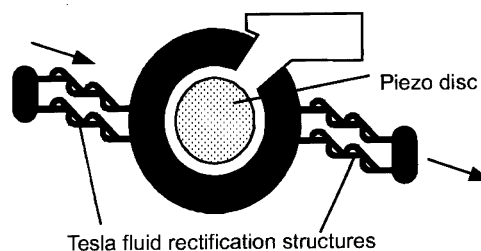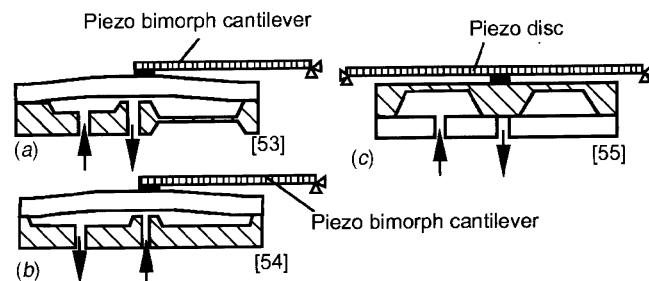

Fig. 5 Valvular conduit pump

Fig. 6 Other valveless pumps

Another approach of valve-less pumping was proposed by Stehr et al. [53,54]. The pump principles were called the elastic buffer mechanism (Fig. 6(a)) and the variable gap mechanism (Fig. 6(b)). This pump type is able to pump liquids in two directions depending on its drive frequency. Nguyen et al. also demonstrated the pump effects in a similar structure [55] (Fig. 6(c)).

Maysumoto et al. [56] presented another valveless concept by using the temperature dependency of water viscosity. The fluidic impedance at the outlet and the inlet are modulated by means of heat. The heating cycles were synchronized with the pump frequency. Table 4 lists the most important parameters of the discussed valveless rectification micro pumps.

Rotary Pumps. Another mechanical pump type, which can be realized with micro machining technique, is the rotary pump. The rotary pump has a big advantage of pumping highly viscous fluids (Table 5).

Ahn et al. [57] (Fig. 7(a)) presented a micropump with a microturbine as rotor in an integrated electromagnetic motor. The pump simply adds momentum to the fluid by means of fast moving blades. The rotor, stator, and coils are fabricated by electroplating of iron-nickel alloy. The high aspect ratio structures were fabricated at a low cost by using conventional photolithography of polyimide.

Table 4 Typical parameters of valveless rectification micro pumps

Ref.	Author	Year	Chamber size (μm)	Chamber height (μm)	Max. Deflection (μm)	Max. Flow Rate (μl/min)	Max. Back Pressure	Typ. Freq. (Hz)	Technology	Actuator
[41]	Stemme	1993	19000	-	13	16000	7840	110	Prezision eng.	Piezoelectric
[4-44]	Olsson	1995	5000	80	13	1200	16000	1400	Plastic Molding	Piezoelectric
[45-47]]	Gerlach	1995	5000	430	45	400	3200	3500	Bulk	Piezoelectric
[48]	Jeong	1999	4000	115	100	14		4	Bulk	Thermopneumatic
[50]	Forster	1995	6000	156		900	14700	3700	Bulk, deep RIE	Piezoelectric
[53, 54]	Stehr	1996	5300	425	40	900	6000	50	Bulk	Piezoelectric
[55]	Nguyen	1998	4500	425	15	80	5000	110	Bulk	Piezoelectric
[56]	Matsumoto	1999	5000	250		5.5		5	Bulk	Piezoelectric

Table 5 Typical parameters of rotary pumps (typical size is the size of the turbine or the gear wheel)

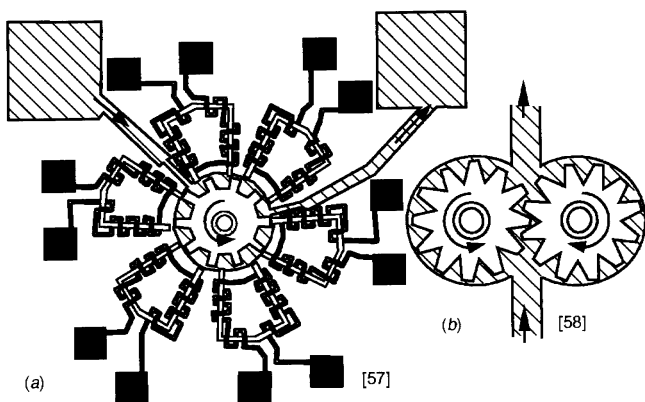| Ref.	Authors	Year	Typ. Size (μm)	Chamber height (μm)	Max. Flow Rate (μl/min)	Max. Back Pressure	Rotation speed (rpm)	Technology	Actuator
[57]	Ahn	1995	500	160	24	10000	5000	Bulk	External motor
[58]	Doepper	1997	596	500	55	12500	2250	LIGA	Integrated motor

Fig. 7 Rotary pumps

The micropump presented by Doepper et al. [58] (Fig. 7(b)) had two gear wheels made of iron-nickel alloy with LIGA-technique. An external motor drove the gear. The gears forced the fluid along by squeezing it to an outlet. Actuating by means of an external magnetic field is possible, but it is so far not reported. Mass production of this pump can be realized with plastic molding.

Ultrasonic Pump. Ultrasonic principle is a gentle pump principle with no moving parts, heat and strong electric field involved. The pump effect is caused by the acoustic streaming, which is induced by a mechanical traveling wave (Fig. 8(a)). The mechanical wave can be a flexural plate wave (FPW) [59,60] or a surface acoustic wave [61,62]. The mechanical waves are excited by interdigitated transducers (IDT, Fig. 8(b)) placed on a thin membrane coated with piezoelectric film [59,60] or on a piezoelectric bulk material [61,62]. The pumps have a thin flow layer of about 20 micron (for water) (Fig. 8(a)), and are therefore also suitable for particle separation applications. Using curved IDT, locally sample concentration can be achieved with this kind of pump.

2.2 Nonmechanical Pumps

Electrohydrodynamic Pumps. Electrohydrodynamic (EHD) pumps are based on electrostatic forces acting on dielectric fluids. The force density F acting a dielectric fluid with free space-charge density q_f in an inhomogeneous electric field E is given as [63]:
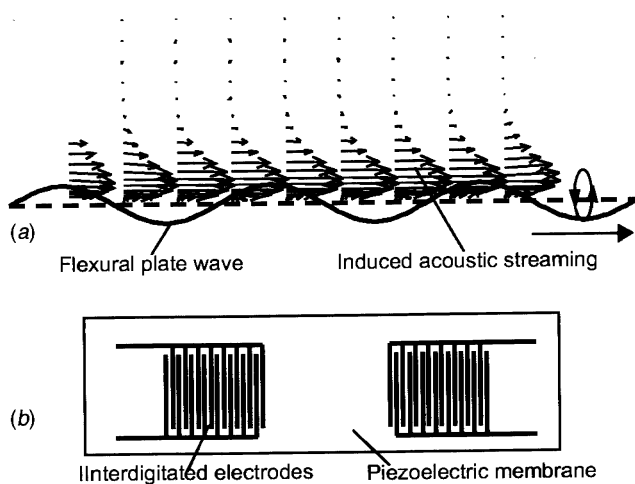

(a)

Flexural plate wave   Induced acoustic streaming

(b)

IInterdigitated electrodes   Piezoelectric membrane

Fig. 8 Ultrasonic pumps

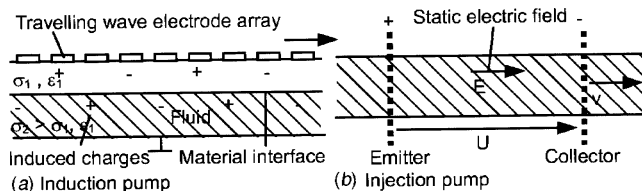(a) Induction pump   (b) Injection pump

Fig. 9 Principles of electrohydrodynamic pumps

$$F = \underbrace{q_f E}_{\text{Colomb force}} + \underbrace{P \cdot \nabla E}_{\text{Kelvin polarization force}} \underbrace{- \frac{1}{2} E^2 \nabla \varepsilon}_{\text{Dielectric force}} + \underbrace{\nabla \left(\frac{1}{2} \rho \frac{\partial \varepsilon}{\partial \rho} E^2 \right)}_{\text{Electrostrictive force}}$$

(1)

where ε is the fluid permittivity, P is the polarization vector, and ρ is the mass density. EHD pumps can be categorized into two main types: the EHD induction pump and the EHD injection pump.

The EHD induction pump is based on the induced charge at the material interface. A traveling wave of electric field drags and pulls the induced charges along the wave direction (Fig. 9(a)). The first micromachined EHD induction pump was presented by Bart et al. [63], similar designs were reported by Fuhr et al. [64–67] and Ahn et al. [68]. A fluid velocity of several hundred micron per second can be achieved with this pump type. For better pumping effect, a temperature gradient and consequently a conductivity gradient across the channel height was generated by an external heat source and heatsink (Peltier element) [67].

In the EHD injection pump, the Colomb force is responsible for moving ions injected from one or both electrodes by means of electrochemical reaction (Fig. 9(b)). Richter et al. demonstrated this pump principle with micromachined silicon electrodes [69,70]. The pressure gradient bults up in the electric field causes the pump effect. Furuya et al. used electrode grids, standing perpendicular to device surface, in order to increase the pressure gradient [71]. The pump can deliver 0.12 ml/min with a drive voltage of 200 V. Table 6 lists the most important parameters of the EHD-pumps discussed above.

Electrokinetic Pumps. In contrast to the EHD-pumps, electrokinetic pumps utilize the electrical field for pumping conductive fluid. The electrokinetic phenomenon can be divided into electrophoresis and electroosmosis.

Electrophoresis is the effect, by which charged species in a fluid are moved by an electrical field relative to the fluid molecules. The velocity of the charged species is proportional to the field strength E:

$$V = \mu_{ep} E$$

(2)

where μ_{ep} is the electrophoretic mobility of the species. Electrophoresis is used for separation of molecules like DNA molecules.

In contrast to electrophoresis, electroosmosis is the pumping effect of a fluid in a channel under the application of an electrical field. A surface charge exists on the channel wall. The surface charge comes either from the wall property or the adsorption of charges species in the fluid. In the presence of an electrolyte solution, the surface charge induces the formation of a double layer on the wall by attracting oppositely charged ions from the solution. An external electrical field forces the double layer to move.

Table 6 Typical parameters of electrohydrodynamic micropumps

Ref.	Authors	Year	Typ. Size (µm)	Channel height (µm)	Max. Flow Rate (µl/min)	Max. Back Pressure	Principle	Technology
[63]	Bart	1990	500	-			EHD-induction	Bulk
[64-67]	Fuhr	1992-1997	600	50	0.45		- EHD-induction	Bulk
[68]	Ahn	1998	3000	200	50	220	EHD injection	Bulk
[69, 70]	Richter	1990-1991	3000	-	15000	500	EHD-injecton	Bulk
[71]	Furuya	1996	400	100	0.12		EHDinjection	Bulk

Fig. 10 Phase transfer pumps

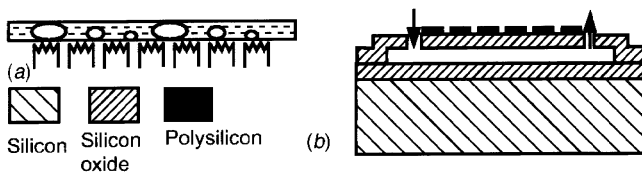Fig. 12 Magnetohydrodynamic pump: (a) schematic of concept, (b) design example, fluid flows out of page plane

Due to the viscous force of the fluid, the whole fluid in the channel moves with a flat velocity profile (plug flow):

$$V = \mu_{eo}E \qquad (3)$$

where μ_{eo} is the electroosmotic mobility of the fluid. Due to its nature, the electroosmosis effect was used for pumping fluid in small channels without applying a high external pressure. In micro analysis systems electroosmosis effect is used for delivering buffer solution, and in combination with the electrophoretic effect, for separating molecules. The most common application of electrokinetic pumps is the separation of large molecules like DNA or proteins. The device proposed by Harison et al. [72,73] could generate a fluid velocity of 100 μm/s with a field strength of 150 V/cm. Webster et al. [74,75] uses the gel electrophoresis for separating DNA-molecules in microchannel with relatively low field strength (5 to 10 V/cm).

Phase Transfer Pump. Beside the ultrasonic principle, electrohydrodynamic principle and electrokinetic principle, phase transfer is another principle for pumping fluid in small channels, in order to overcome the high fluidic impedance caused by viscous forces. This principle uses the pressure gradient between the gas phase and liquid phase of the same fluid for pumping it. The realization in microscale is simpler than in other pump types. Takagi et al. [76] presented the first phase transfer pump (Fig. 10(a)). The alternate phase change is generated by an array of 10 integrated heaters. The same pump principle was realized with stainless steel and 3 heaters in [77]. Jun and Kim [78,79] fabricated a much smaller pump based on surface micromachining. The pump had 6 integrated polysilicon heaters in a channel with 2 micron height and 30 micron width (Fig. 10(b)). The pump is capable to deliver a flow velocity of 160 μl/s or flow rates less than 1 nanoliter per minute.

Electro Wetting Pump. The electro-wetting pump was proposed by Matsumoto et al. [80]. The pump principle uses the dependence of the tension between solid/liquid interface on the charge of the surface. The principle can be used for direct pumping, but no example was reported. Lee and Kim [81] reported a micro actuator based on electro-wetting of mercury drop, which can be used for driving a mechanical pump with check valves as proposed in [80].

Electrochemical Pump. Electrochemical pumps use the pressure of gas bubbles generated by electrolysis water. Bi-directional pumping can be achieved by reserving the actuating current, which makes the hydrogen and oxygen bubbles reacting back to
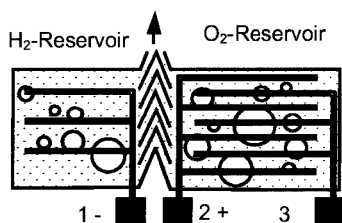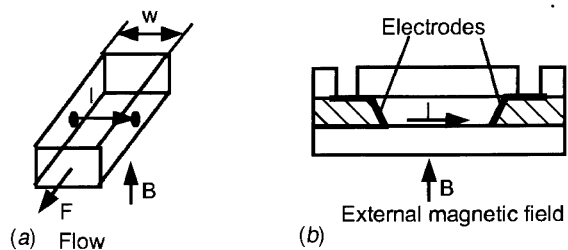
water [82]. The pumped fluid volume can be measured by estimating the gas volume with the measurement of the conductivity between electrodes 2 and 3 (Fig. 11).

Magnetohydrodynamic Pump. The pumping effect of a Magnetohydrodynamic (MHD) pump is based on the Lorentz force acted on a conducting solution:

$$F = I \times Bw, \qquad (4)$$

where I is the electric current across the pump channel, B the magnetic field strength and w the distance between the electrode (Fig. 12(a)). Lemoff et al. [83,84] realized this principle in silicon (Fig. 12(b)). The pump was able to generate a not-pulsatile flow like that of EHD-pumps and electrokinetic pumps. A maximum flow velocity of 1.5 mm/s can be achieved (1 M NaCl solution, 6, 6 V). MHD-pumps generate a parabolic velocity profile, similar to a pressure driven flow in channels.

3 Scaling Law for Micropumps

The first question, which arises in dealing with micropumps, is what kind of pump can be actually called a micropump? Is that the size of the pump itself or is that the fluid amount the pump can handle? Since the above question is still unanswered, Fig. 13 illustrates the typical sizes versus the maximum flow rates of the published micropumps listed as references. The pump chamber
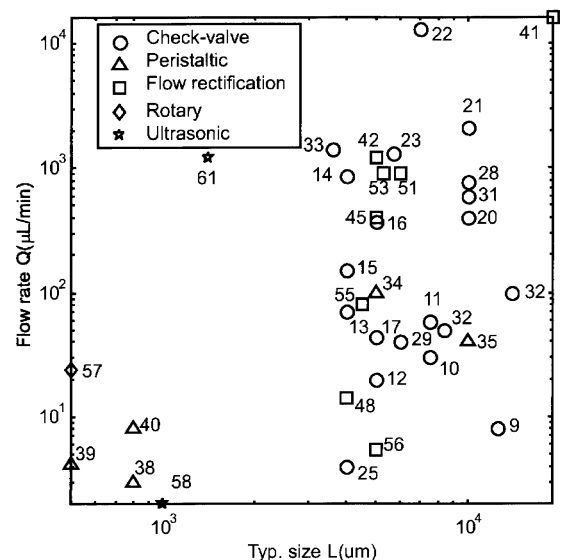

Fig. 13 Flow rate versus typical size for mechanical pumps (the numbers indicate the corresponding references)

Fig. 11 Electrochemical pump

Table 7 Typical parameters of phase transfer micropumps

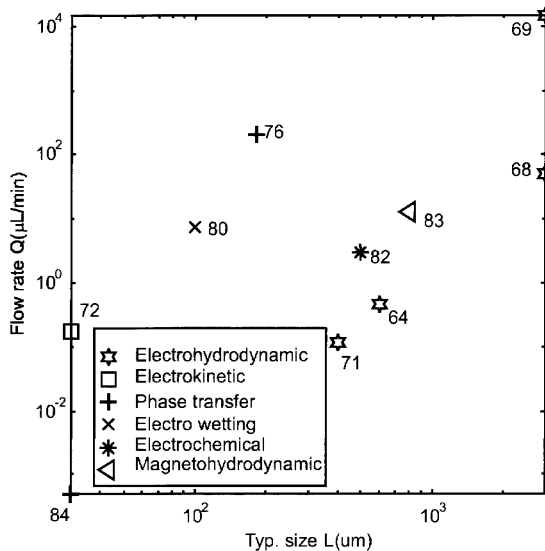| Ref.	Authors	Year	Typ. Size (μm)	Chamber height(μm)	Max. Flow Rate (μl/min)	Max. Back Pressure (Pa)	Typ. Frequency (Hz)	Technology
[76, 77]	Takagi	1994-1995	180	180	210	-		4 Bulk micromachining
[78, 79]	T. Jun	1996-1998	30	2	5.05	800		1 - 4 Surface micromachining

Fig. 14 Flow rate versus typical size for non-mechanical pumps (the numbers indicate the corresponding references)

Table 8 Maximum energy density of typical actuators in micropumps

Actuator	Maximum energy density	Parameters	Order (J/cm3)
Electrostatic	$\frac{1}{2}\epsilon E^2$	E: electric field strength ε: dielectric permittivity	0.1 - 1
Thermal	$\frac{1}{2}E(\alpha\Delta T)^2$	α: coefficient of thermal expansion ΔT: temperature difference E: Young's modulus	1 - 10
Magnetic	$\frac{1}{2}B^2/\mu$	B: magnetic field strength μ: magnetic permeability	1 - 10
Piezoelectric	$\frac{1}{2}E_Y(d_{33}E)^2$	E_Y: Young's modulus E: electric field strength d_{33}: piezoelectric coefficient	0.1 - 1

diameters of mechanical pumps are chosen as the typical sizes. Most of the mechanical pumps have a size between 5 mm and 1 cm, due to their relatively large piezoelectric actuator unit (Table 7). With the use of alternatives such as thermopneumatic actuators [10,19,37,39,48], electro-wetting actuators [80] or electrochemical actuators [82], the pump size can be reduced to less than 100 micron. No mechanical micropump was able to generate a flow rate less than 1 μl/min accurately, due to the large viscous forces and their relatively "large" size.

Figure 14 shows the flow rate-size characteristics of nonmechanical pumps. The channel widths are taken as typical sizes. With nonmechanical principle such as electrohydrodynamic, and electrokinetic pumping, micropumps can penetrate the 1 μl/min limit. Figure 15 depicts the estimated maximum Reynolds number
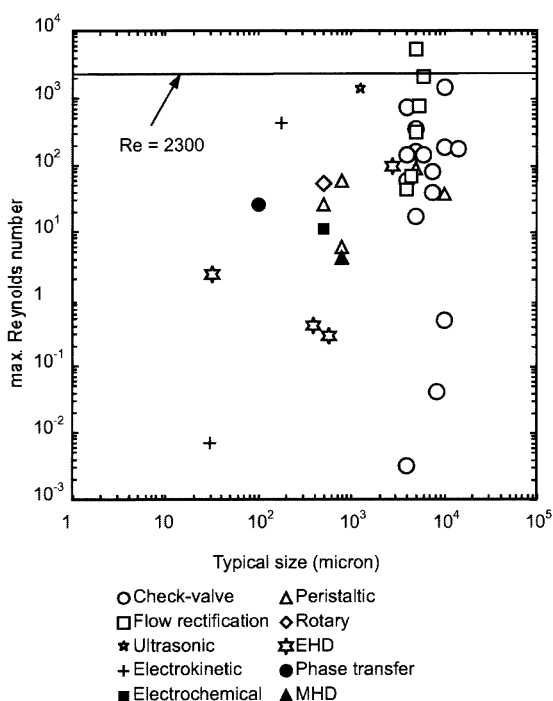
in the reviewed micropumps, it can be seen clearly that most of the pumps have laminar flow characteristics.

The next problem of scaling law is the relation between the pumped energy or the mechanical work and the pump size. Table 8 gives an overview about the energy density stored in actuators used for micropumps [85]. Assuming that the energy density in all actuator types doesn't change with the miniaturization, the energy stored in a micropump actuator decreases with three order of the miniaturization. The pumped energy per stroke is given by [41]:

$$E_{\max}=\frac{p_{\max}Q_{\max}}{4f} \qquad (5)$$

where $p_{\max}$ is the maximum back pressure and $Q_{\max}$ is the maximum flow rate for a given reciprocating frequency f. This equation can only be applied for mechanical pumps using reciprocating pump membrane. The energy efficiency of a pump is defined as the relation between the energy stored in the actuator and the pumped energy. Assuming that the energy efficiency of mechanical micropumps doesn't change compared to its macroscopic counterpart, the energy delivered by a micropump decreases with three orders of miniaturization.

Figure 16 evaluates the pumped energy of the check-valve pumps, the peristaltic pumps and the flow rectification pumps listed in the reference. The data show clearly that the pumped energy varies between 0.01 and 1 μJ while the pump size is restricted between 0.6 mm and 10 mm. The field figures indicated pumps with piezoelectric actuators. Most of the piezoelectric actuators are external, which leads to the size restriction mentioned above. Smaller thermopneumatic actuators (almost 10 time smaller than piezoelectric actuators) can be integrated in the
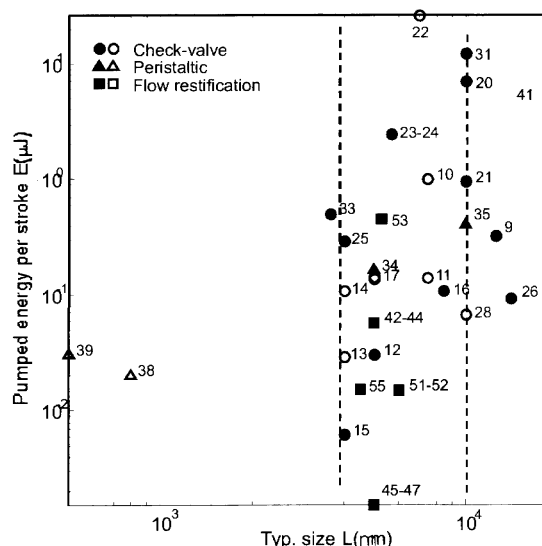

Fig. 15 Maximum Reynolds number versus typical size

Fig. 16 Pumped energy per stroke versus typical size (filled figures indicate that the pumps use piezoelectric actuators)
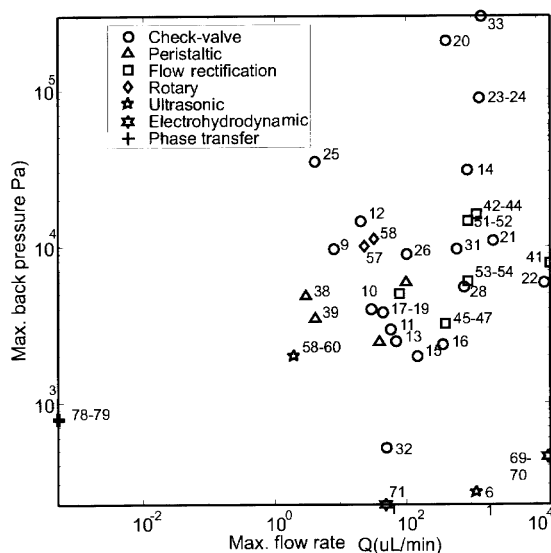
Fig. 17 Maximum back pressure versus maximum flow rate (the numbers indicate the corresponding references)

micromachining process [38,39], but their values of the pumped energy per stroke are also 10 times less than those of piezoelectric actuators. This observation leads to the conclusion that the pumped energy in mechanical pumps also decreases with the miniaturization.

Figure 17 plots the maximum back pressure versus the maximum flow rates. The flow rate is proportional to the average flow velocity, which in turn is proportional to the pressure loss. Figure 15 agrees with this general observation.

Concluding Remarks

The emerging MEMS technology opens new possibilities for fluid machinery in a very distinct length scale, the micron size. In this range, the surface to volume ratio is much larger than that in macro scale, which leads to high viscous forces and restricts down-scaling of well-known mechanical pump principles. Mechanical pumps fill the flow range gap between nonmechanical pumps and classical macro-scale pumps, which ranges between several microliter to several mililiter per minute. We need nonmechanical pumps for handling flow rates in nanoliter or picoliter per minute ranges. With the emerging biomedical technology, pumps for handling extremely small fluid amounts become more and more important. By integrating pumps with other microfluidic devices as well as sensors, the vision of a lab on chip for biomedical applications and drug discovery will be the reality in the near future. With this goal, the exploration of new pumping principles and their realization with MEMS-technology are and will be huge scientific and engineering challenges.

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