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Four-electrode micropump with peristaltic motion

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ABSTRACT

We present an electrostatically driven four-electrode micropump that operates with peristaltic motion. The working fluid is gas. In particular, we focus on the characteristics of the micropump as a function of the various actuating signals for four flexible electrodes. The micropump operated between 60 V and 120 V with a customized pulse signal. Whereas the maximum flow rate using a basic actuating signal was approximately 38 μl/min at 90 V and 15 Hz, the maximum flow rate using an optimized actuating signal was approximately 136 μl/min at 90 V and 15 Hz. This is an increase of approximately 3.6 times the minimum flow rate. Various actuating signals were generated from a microcontroller unit (MCU) equipped with a logic circuit and a high-voltage DC power supply and function generator. The minimum flow rate occurs with a four pumping sequence with three electrodes. However, the maximum flow rate occurs when these four electrodes participate sequentially. The proposed micropump consists of only a single chamber and a flexible membrane with four electrodes. The chamber is divided into smaller cells with the embedded electrodes controlled by a custom-made logic circuit that generates various phase-sequencing actuation signals. This micropump is applicable for gas chromatography.

1. Introduction

Microfluidics emerged in the beginning of the 1980s and have been used in the development of inkjet print heads, DNA chips, lab-on-a-chip technology, micro-propulsion, and micro-thermal technologies [1]. Microfluidic systems with functions such as electrophoretic separations and fluidic manipulations (i.e., mixing, reacting, injection, and separating) have been developed to move fluids using a micropump [2,3].

Micropumps can be categorized as mechanical or non-mechanical [1–4]. Mechanical systems contain moving parts, usually the actuation and valve membranes or flaps. The driving force can be generated by utilizing piezoelectric, electrostatic, thermo-pneumatic, pneumatic, or magnetic effects. Non-mechanical pumps function via electro-hydrodynamic, electro-osmotic, electrochemical [5], or ultrasonic flow generation. We previously proposed a high-performance electrostatically driven peristaltic bidirectional micropump [6–9]. In general, the advantages of electrostatically driven pumps include a rapid response time and high stroke volume. However, electrostatically driven designs require a high operating voltage [2–4,10–12]. Therefore, a combination of the peristaltic principle with electrostatic actuation is a reasonable tradeoff [10–12]. Several peristaltic micropumps have been proposed to solve many of the problems with micropumps. Recently, Kim et al. reported an electrostatic peristaltic 18-stage gas micropump with active microvalves. Although the maximum flow rate was approximately 4 ml/min, their micropump contained valves, with a complicated and difficult fabrication process and operation sequence [13]. Chia et al. reported a thermo-pneumatic peristaltic micropump [14]. Their pump had three chambers consisting of air-heating and fluid-squeezing zones. The maximum flow rate was 20 μl/min at 9 V and 1.2 Hz. Although the operating voltage was low, the maximum flow rate was also low. Chan et al. reported a bubble-actuated micropump with high-frequency flow reversal [15]. However, this micropump also has a low flow rate (37.8 μl/min at 5 V).

As previously reported, our proposed device does not use physically separated chambers. Rather, it uses only one chamber with four electrodes that can divide the chamber into four virtual chambers [6–9,16,17], as shown in Fig. 1. In this paper, we focus on the behavior of these four electrodes with different sequencing actuating signals. We tested the performance of the micropump under

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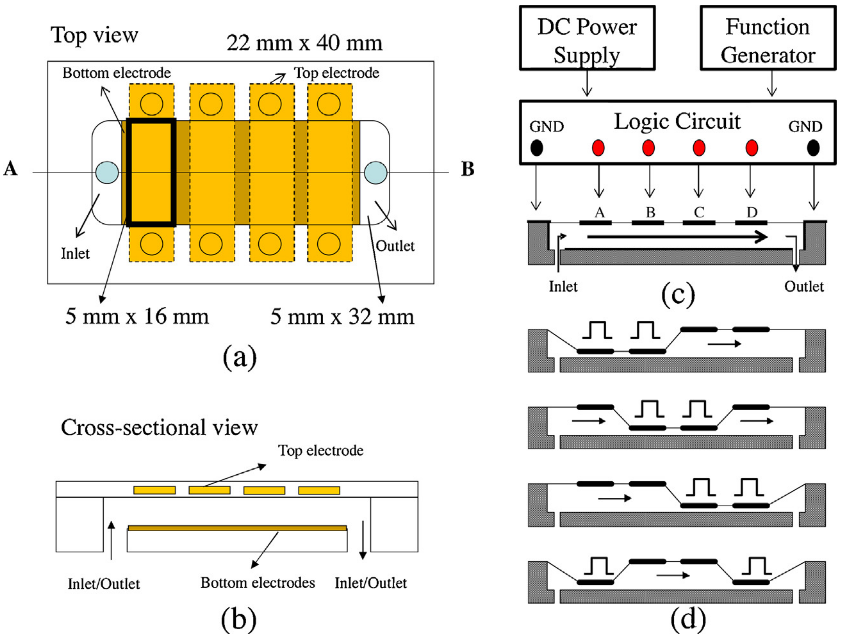

Fig. 1. Concept for the bidirectional multi-electrode micropump operating with peristaltic motion: (a) top view of the proposed micropump, (b) cross-sectional view, (c) customized logic circuit, and (d) actuating signals.

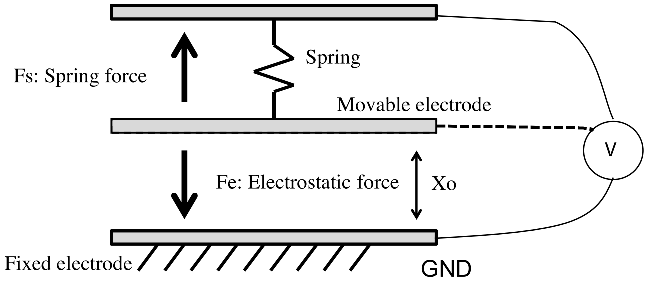

Fig. 2. Basic structure of the parallel plate actuator.

various phase sequencing actuation signals to reduce the operation voltage and to increase the flow rate.

2. Experiments

2.1. Operating principle

Electrostatic force is the force between particles caused by their electric charges. An interesting characteristic of electrostatic force is that it can be either attractive or repulsive—unlike gravitational force, which is exclusively attractive. Peristaltic motion can eliminate the need for valves and a nozzle/diffuser design for flow control, and it can also reduce dead volume, which can be a critical problem for the performance of micropumps [6–9]. As shown in Fig. 1, the proposed micropump is driven by electrostatic force with bidirectional peristaltic motion. The concept of the proposed micropump is to use only a single chamber with four moving electrodes, with polyimide as the base material of the moving electrodes. The electrodes are embedded in a polyimide membrane (see Fig. 1(a) and Fig. 1(b)). Using various actuation signals from the DC power supply, function generator, and logic circuit, the electrodes can divide the chamber into two, three, or four chambers (see Fig. 1(c) and Fig. 1(d)).

In order to measure the operating voltage of the micropump, we calculated the pull-in voltage between a flexible electrode and a movable electrode [18–21]. Fig. 2 shows the basic structure of

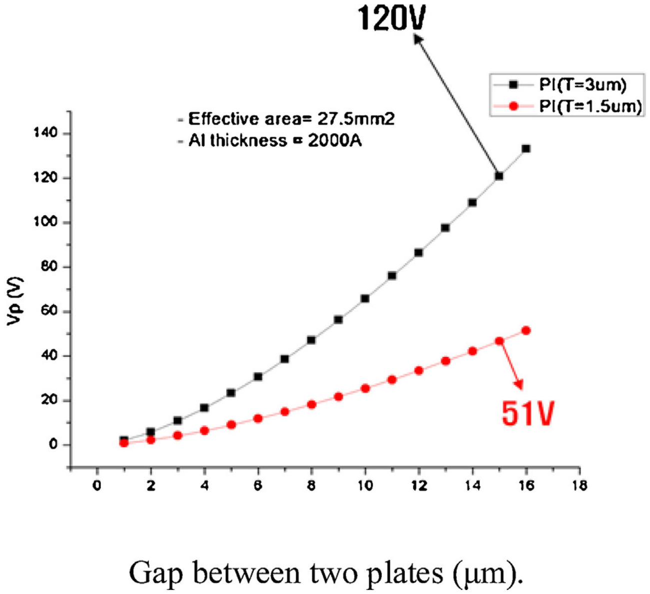

Fig. 3. Pull-in voltage changes to the micropump under polyimide thickness as a function of distance.

the two parallel plate actuators. Kaajakari [20] and Teymoori and Abbaspour-Sani [21] describe a method for calculating the pull-in voltage in electrostatic microactuators between two electrodes when the first is fixed and the other is a thin and flexible film.

Let d be the distance between the two plates ($d = x_o + x$), A be the area of the plates, and C be the capacitance ($C = \varepsilon_0\varepsilon_r/x_o$), where $\varepsilon_0\varepsilon_r$ is the multiplication of the permittivity of air and material. The total potential energy of the system is:

$$E = -\frac{1}{2}\frac{\varepsilon_0\varepsilon_r A V_s^2}{d-x} + \frac{1}{2}kx^2 \quad (1)$$