Fluid Micropumps Based on Rotary Magnetic Actuators

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ABSTRACT

A jet-type magnetically driven fluid micropump to drive conductive fluids has been designed, fabricated, and tested. The pump actuation is based on a rotary magnetic micromotor with fully integrated stator and coils operating with the rotor immersed in the fluid to be pumped, thereby driving the fluid from a inlet flow reservoir through integrated flow channels to an outlet flow reservoir. The micropump has been successfully driven using standard diabetic-prescription insulin in saline buffer (Novo Nordisk, Regular Insulin) as a working fluid, demonstrating the feasibility of a rotary micropump for pumping and injecting fluids in drug delivery or chemical flow systems. The attained flow rate varies monotonically with motor speed. In the realized micropump, the fluid flow rate achieved is up to 24 $\mu\ell / min$ at a rotor speed of 5000 rpm. The operating voltage is less than 3 V and the power consumption is approximately 0.5 W. The differential pressure is expected to be approximately 100 hPa.

INTRODUCTION

In biomedical, biological, or chemical fluid system applications, there have been a large demand for a micro fluid control system which has fluid driving as well as flow sensing functions, allowing control of small amounts of fluid. Micropumps are an essential component in constructing the total fluid control system. Recently, specific applications such as drug delivery systems require sophisticate fluid control; i.e., a smooth fluid flow as well as a fast response time. Mechanisms widely used for conventional fluid pumps include reciprocating-type, centrifugal-type, propeller-type, and rotary-type [1]. In this study, a planar rotary fluid micropump which has a similar operation mechanism to the conventional rotary pump has been designed, fabricated, and tested.

To date, few fluid micropumps have been demonstrated using a membrane which is driven by various actuation schemes, including piezo actuation [2] or thermopneumatic actuation [3]. These deflecting-type micropumps usually are comprised of three parts: an inlet valve, an outlet valve, and a pump chamber. For a pumping action, these components are sequentially controlled, causing the micropump to intake and expel the pumped fluid. The output flow rate of this micropump is proportional to the actuation frequency of the pump chamber. In order to achieve an extremely precise and smooth flow, high actuation frequencies are preferred, but the achievable maximum actuation frequencies are usually limited by the required pumping actuation sequences as well as the limited response time of a deflecting membrane. Although the pump works in a steady state operation with an optimized high frequency, a fluctuation of flow rate can be observed because of its operation characteristics.

A basic concept of micromachined microturbine was introduced and fabricated earlier using a polysilicon on a silicon wafer [4]. The recently developed planar magnetic micromotor [5] allows that the concept of the microturbine to be reversed; i.e., to realize a rotary fluid micropump by driving the rotor in a fluid. As shown in Figure 1, a

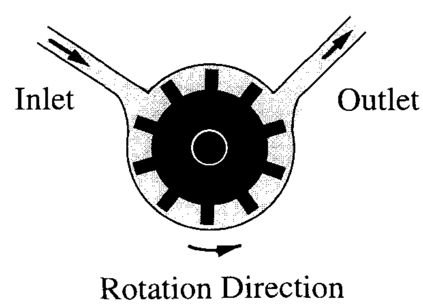


Figure 1. Basic concept of a jet-type rotary micropump.

rotary micropump traps the liquid in the spaces between the gear teeth, pushing it around the closed casing. It is then carried around by the rotation of the rotor and squeezed out through the outlet. This operation mechanism has the potential for very smooth fluid delivery. Since this micropump is driven by magnetic micromotor, the rotor speed in this pump can be widely and continuously controlled by adjusting the excitation frequency of the stator coils. Since the magnetic micromotor can provide functional actions such as stepping, continuous, forward, and backward operations, a fluid jet-injection by forward driving as well as an abrupt stopping of jet-injection by backward driving can be easily achieved. Thus, these functional jet actions will provide a favorable dynamic fluid control for a ink jet printer as well. Of course, fluid flow can be produced in either forward or backward direction depending on the rotation direction of the rotor, which also allows a micropump which produces bi-directional fluid flows.

Many biomedical, biological, and chemical fluids are conductive, which limits the driving principles available to drive the fluids. Magnetic drive allows the pumping of conductive fluids without inducing any electrical breakdown, if the conductor lines used to generate magnetic flux are properly insulated from the exposed fluid. One advantage of the magnetic micromotor in [5] is that due to the nature of the fabrication process, the conductor lines are buried in insulating polymer layer, thus realizing the required insulation.

In practical fluid control systems, response time of the system is one of the critical issues. The overall response time of a microactuator or a pump can be governed by both the inherent response characteristics of driving principle and the mechanical response time of moving parts themselves in the actuators. Magnetic driving forces produce no response delay, and thus the actuator response time is only subjected to its geometry, achieving relatively fast response. In addition, its driving voltage is compatible to CMOS integrated circuit power source, which gives magnetic microactuators to have an excellent feasibility to integrate with CMOS circuits, envisaging the development of implantable micropump and drug delivery system.

MICROPUMP DESCRIPTION AND THEORY

The pump actuator is based on the variable reluctance magnetic micromotor with fully integrated stator coils [5] which has 12 stator poles in three phase and 10 rotor poles. The stator coils arranged in one or more sets and phases should be excited individually or in pairs to produce torque for rotor rotation. Planar integrated meander-type inductive components [6] are used in this pump as the integrated stator coils. As shown in Figure 2.(a), two stator pole pairs in the same phase are located directly opposite each other and each stator pole pair contains 7 turns of toroidal-meander coil. When a phase coil is excited, the rotor poles that are located nearest to the excited stator poles are

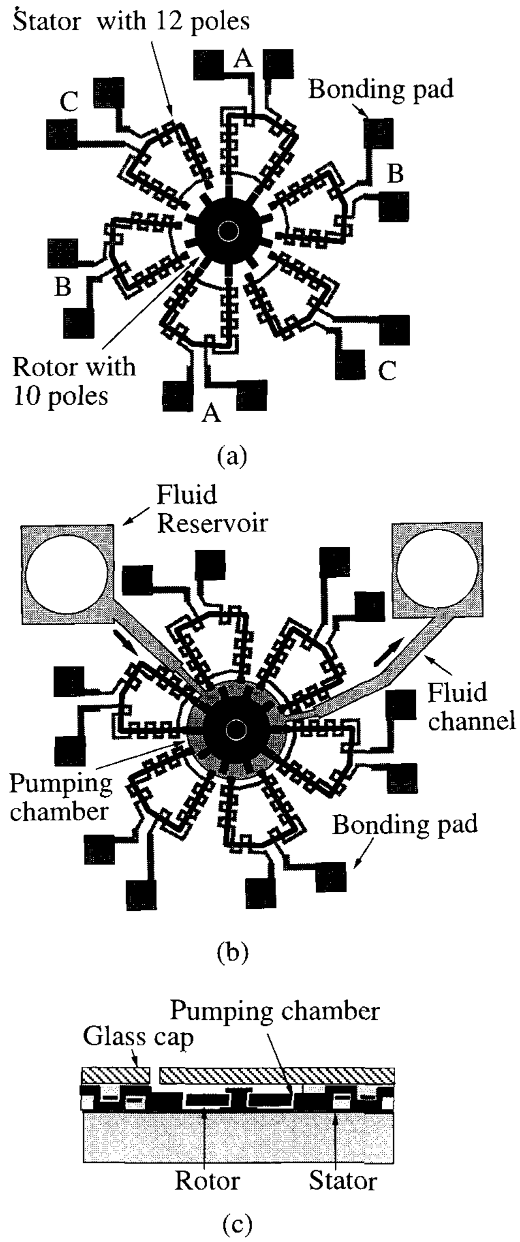


Figure 2. Schematic diagrams of a magnetic micromotor and a rotary micropump: (a) planar magnetic micromotor in [5]; (b) rotary micropump including a pumping chamber and channels; (c) cut view of the micropump.

attracted to the stator poles. When the rotor poles are aligned with the excited stator poles, the excited phase is switched off and the next phase is then excited to maintain continuous rotor rotation. The wound poles of all phases are arranged in pairs of opposite polarity to achieve adjacent pole paths of short lengths. The stator poles are positioned so as to greatly shorten the magnetic flux paths and to provide an isolated magnetic core for the flux path of each phase. In the present work, by introducing fluid channels and reservoirs into the magnetic micromotor as shown in Figure 2.(b), a rotary micropump can be demonstrated using the conventional rotary pump concept described in Figure 1. In this pump, the rotor will play two roles: a magnetic component for the motor as well as a mechanical component for the pump. Similarly, the salient poles of the rotor not only provide the required variable reluctances, but also generate fluid flow as a mechanical 'bucket' for the rotary micropump. In this pump, rectangular-type salient poles in the rotor are adopted for the bi-directional flow driving, but a curved shape or a bucket shape salient pole can also be used for a better performance as a pump, depending on the application.

As described earlier, the rotary micropump combines the constant discharge characteristic of the centrifugal-type with the positive discharge feature of the reciprocating-type pump. As the rotor turns, fluid trapped between the rotor poles (or teeth) and the housing is carried from the inlet to the outlet. Hence, a variable-delivery pump is considered, since the fluid volume displacement depends on the revolution of the rotor. Pumping operating speeds are increasing as the pressure ratings go up and the volumetric capacities decrease. As shown in Figure 1, when the rotor rotates with N (rpm), then the fluid displacement is expressed as

$$V_d = q V_1 N, \qquad (1)$$

where q is total trap number exist at the rotor and V_1 is the fluid volume trapped between a rotor pole pair and housing. When the motor is driven in 5,000 rpm, the attainable flow rate is approximately 24 $\mu\ell/min$. If the torque generated from the motor is keeping in a constant value during pumping, the developed pressure [1] at the out let gives

$$P_a = C\frac{T_q N}{V_d}, \qquad (2)$$

where C is a constant, T_q is the motor torque, and the pump overall efficiency is assumed 100 %. The achievable differential pressure between the inlet and the outlet is expected approximately 100 hPa.

FABRICATION

The process started with 3-inch <100> silicon wafers as a substrate, onto which 0.6 μm of PECVD silicon nitride was deposited. The fabrication steps of the micropump are described in Figure 3. Stators with fully integrated coils and rotors were fabricated separately on a 3-inch wafer, and then assembled to build the micropump as in [5]. The stators are composed of three phases and 12 stator poles, constructing isolated magnetic circuits to reduce magnetic reluctances. In order to increase the fluid drive, 50 μm thick nickel-iron rotors with high respect ratio were fabricated using conventional photolithography techniques. The stator and pin were fabricated using a polyimide multilevel metal interconnection technique, in which an electroplated high permeability nickel(81%)-iron(19%) permalloy [7] was used as the magnetic material.

Planar surfaces in a multilevel process are very important to obtain high aspect ratio patterns using conventional photolithography. It is not easy to attain a perfectly planar surface after a multilevel coil process without using mechanical or chemical polishing

(a)

(b)

(c)

(d)

(e)

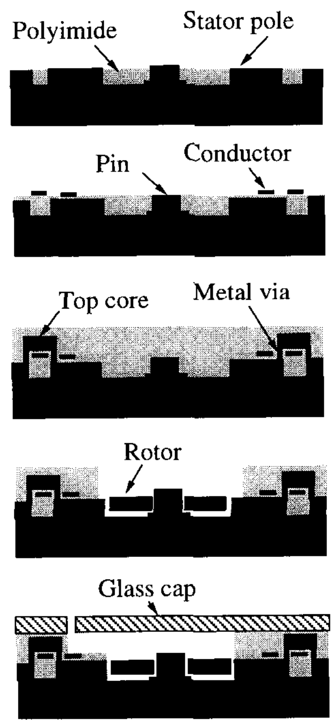


Figure 3. Fabrication steps: (a) deposit bottom cores and planarizing; (b) pattern conductors; (c) deposit metal vias and top cores; (d) dry etch fluid chamber and channel, and assemble rotors and stators; (e) seal fluid chamber and channel using pyrex glass.

techniques. The precision high aspect ratio patterns are usually required at the moving or contacting parts such as rotors and pins, but not at the inductive components. In order to address this issue, in present work, pins and stator poles are fabricated first on the planar surface of a silicon wafer before constructing inductive components, in contrast to the fabrication processes used in [5].

To obtain high aspect ratio patterns, photosensitive polyimide was used as a plating mold for the patterns of both stators and rotors. Photosensitive polyimide processing [8,9] has already been demonstrated to construct a 100 μm thick structure with a high aspect ratio of 8 (structure height/width) using conventional photolithography techniques. Plating molds 60 μm in depth were obtained using a photosensitive polyimide (Probimide 349, OCG Microelectronic Materials). The bottom magnetic cores and structures were then plated. Upon completion of the bottom core electroplating, the photosensitive polyimide and seed layer were removed. The surface was then replanarized with polymer dielectric. The rest of micropump fabrication processes is similar to the processes described in [5]. Upon completion of the stator and pin fabrication, the pumping chamber and the fluid channel were then dry etched through the insulating polymer layer to the substrate using an aluminum hard mask. The final thickness of the chamber and channel relative to the substrate was approximately 160 μm. The dimension of the fluid channel was 200 μm x 160 μm.

In a separate process, 50 μm thick nickel-iron rotors 500 μm in diameter were plated separately using the same photosensitive process described earlier.

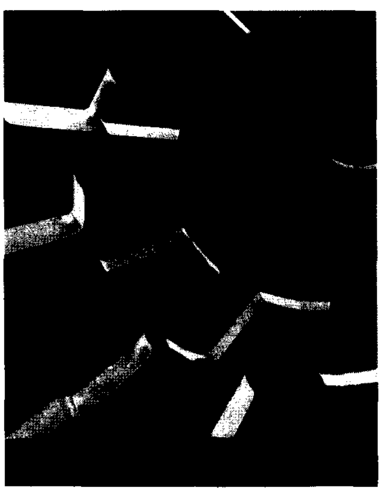
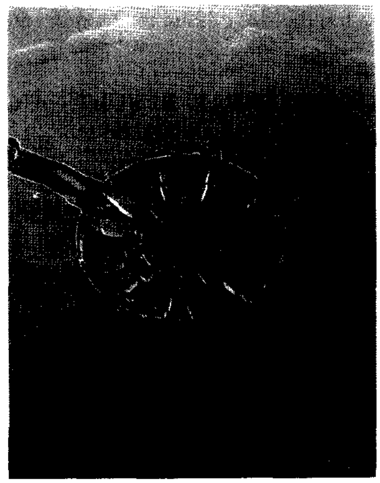
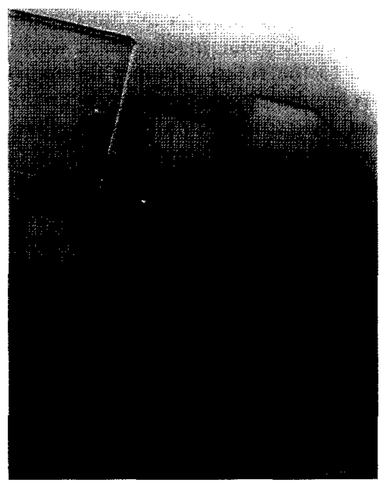


Figure 4. Scanning electron micrograph of the assembled rotor and stator. A uniform gap of 5 -10 um is shown.



(a)



(b)

Figure 5. Scanning electron micrographs: (a) pump part (where the diameter of the rotor is 500 μm); (b) magnified channel and rotor (where the channel is 200 μm x 160 μm)

These rotors were released from the substrate and assembled with stators. A uniform gap separation of approximately 5-10 μm between the rotor and the stator is shown in Figure 4. To ensure the rotation of rotor without touching on the stator poles, the gap separation between the rotor and the pin should be smaller than the gap separation between the rotor and the stator. Upon completion of the assembly, the flow channels and rotary element were optionally sealed with a pyrex glass plate. SEM photographs of the micropump (with no upper plate) are shown in Figure 5. The fabricated micropump has the size of 2 mm x 2 mm x 160 μm.

EXPERIMENTAL RESULTS AND DISCUSSION

The fabricated micropump was diced, mounted on a chip carrier, and tested. The stator coils were excited in phase series to rotate the rotor. The three phase square waves were applied to the corresponding stator windings. Applied currents of 200-500 mA with a driving voltage less than 3 V were sufficient to initiate motion from rest. Either by changing the phase firing order and keeping the micromotor connections constant, or by exchanging two of the phase connections of the micromotor and keeping the phase firing order constant, the direction of rotation of the magnetic micromotor could be changed reversibly.

First, the rotor of the micromotor was functionally driven without fluid. The stator coils were excited in phase series to rotate the rotor, while a standard diabetic-prescription insulin in saline buffer (Novo Nordisk, Regular Insulin) as a working fluid was applied to the rotary element through the inlet channel. As the rotor starts to rotate in the fluid, it was observed that magnetic flux passes through conductive fluids and then exerts sufficient magnetic force on the rotor to induce rotation and subsequent fluid flow. The flow rate in this micropump was proportional to the rotor speed and driving forces. The rotor of the micropump was successfully driven in the standard insulin in saline buffer, generating fluid flow through the channel. The attainable flow rate was approximately 24 $\mu\ell/min$ at 5000 rpm. Flow rate, developed pressure, and power consumption as a function of the rotation speed of the rotor are currently being investigated.

CONCLUSIONS

A jet-type rotary micropump to drive conductive fluids has been demonstrated on a silicon wafer. The pump actuation is based on a rotary magnetic micromotor with fully integrated stator and coils operating with the rotor immersed in the fluid to be pumped, thereby driving the fluid from a inlet flow reservoir through integrated flow channels to an outlet flow reservoir. Since the driving principle is magnetic, the pump can be used for conductive fluids. The micropump has been successfully pumped standard diabetic-prescription insulin in saline buffer as a working fluid, demonstrating the feasibility of this approach for pumping and injection of fluids in drug delivery or chemical flow systems. Applied current of 200 mA -500 mA with a driving voltage less than 3 V are sufficient to initiate motion from rest in a regular insulin fluid, and consequently generating fluid flow through the channels. The attainable flow rate is approximately 24 $\mu\ell/min$ in 5000 rpm, and the achievable differential pressure is approximately 100 hPa.

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REFERENCES

[1] T. G. Hicks, Pump Selection and Application, McGraw-Hill, pp. 27-157, 1957.

[2] V. Gass, B.H. van der Schoot, S. Jeanneret, and N.F. de Rooij, "Integrated Flow-regulated silicon Micropump", Sensors and Actuators A, Vol. 43, pp. 335-338, 1994.

[3] B. Bustgens, W. Batcher, W. Menz, and W. K. Schomburg, "Micropump Manufactured by Thermoplastic Molding", Proc. IEEE MEMS Workshop, pp. 18-21, 1994.

[4] M. Mehregany, K. J. Gabriel, and W. S. N. Trimmer, "Integrated Fabrication of Polysilicon Mechanisms", IEEE Transactions on Electron Devices, Vol. 35, No. 6, pp. 719-723, 1988.

[5] C. H. Ahn, Y. J. Kim, and M. G. Allen, "A Planar Variable Reluctance Magnetic Micromotor with Fully Integrated Stators", Journal of Microelectromechanical Systems, Vol. 2, No. 4, pp. 165-173, 1993.

[6] C. H. Ahn and M. G. Allen, " A New Toroidal-Meander Type Integrated Inductor with Multilevel Meander Magnetic Core", IEEE Transactions on Magnetics, Vol. 30, No. 1, pp. 73-79, 1994.

[7] I. W. Wolf, "Electrodeposition of Magnetic Materials", Journal of Applied Physics, Vol. 33, No. 3, pp. 1152-1159, 1962.

[8] A. B. Frazier and M. G. Allen, "Metallic Microstructures Fabricated Using Photosensitive Polyimide Electroplating Molds', Journal of Microelectromechanical Systems, Vol. 2, No. 2, pp. 87-94, 1993.

[9] A. B. Frazier, C. H. Ahn, and M. G. Allen, "Development of Micromachined Devices Using Polyimide-Based Processes", Sensors and Actuators A, Vol. 45, pp. 47-55, 1994.