Modular Silicon Micropump

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ABSTRACT

A pump/valve modular system capable of micro-dosing small aliquots of solutions in the micro- nano- picoliter range is presented. The system consists of two micro machined buckled membranes actuated pneumatically to function as a bi-stable diaphragm mechanism that opens and closes a conduit and actively uptakes and delivers a specified volume of fluid. The module is micro fabricated on a silicon wafer that confers to the system broad substance compatibility and makes possible miniaturization to a few millimeters. A titanium nickel actuator could be used to electrically actuate the pump/valve. The large elastic modulus of the silicon oxide membrane allow operation at pressures from a few psi to 200 psi. Prototype devices have been constructed that deliver 1 to 10 nanoliters per stroke.

Background

The Human Genome Project and the Department of Health and Human Services (DHHS) Protein Structural Initiative have stimulated rapid growth in genomics and proteomics research. High-throughput systems for drug discovery and DNA analysis employ parallel channels to increase the number of experiments done simultaneously. There is a growing need for dispensing systems capable of micro-dosing small aliquots of aqueous solutions. Sample size must become smaller because DNA is expensive. The internal dead volume of the entire system is critical because a small sample is lost in a large volume and surface effects predominate. Further, samples must be of uniform volume, all wetted surfaces must be resistant to aqueous fluids and cleaning reagents, and temperatures and electrical potentials are limited.

In a wide variety of genomics and proteomics analysis systems it is necessary to convey nanoliter and picoliter samples from a supply reservoir to a test apparatus. In some systems, samples are transferred from the reservoir to a flat surface by means of capillary tubes that are used to 'print' on a flat surface. In others, the fluid is ejected from nozzles into reaction chambers. In both cases, a method of micro-dosing is required that can move fixed volumes of sample from reservoir to reaction site in a repeatable manner.

Conventional valves, based on solenoid actuation are large compared to the samples to be transferred, are difficult to 'tune' so that uniform samples are transferred; sample sizes vary randomly from nozzle to nozzle and from pulse to pulse within the same nozzle. Assembly of more than a few channels using discrete components becomes prohibitively labor intensive and expensive. Newer methods such as microfabrication techniques are increasingly seen as cost effective technologies for development and manufacture of integrated microsystems.[1],[2]

Modular Micropump Description

The modular silicon micropump is a two stage pulsatile peristaltic pump with two chambers (Figure 1). The chambers are formed in the surfaces of two silicon dies by back etching to form thin buckled diaphragms (Figure 2). When these thin membranes are oxidized, compressive stress develops and they form domes. The diaphragms are approximately 3 mm^2 and the domes are a few microns high. These domes are flexible and change shape if sufficient pressure is applied. This is the origin of the pumping action.

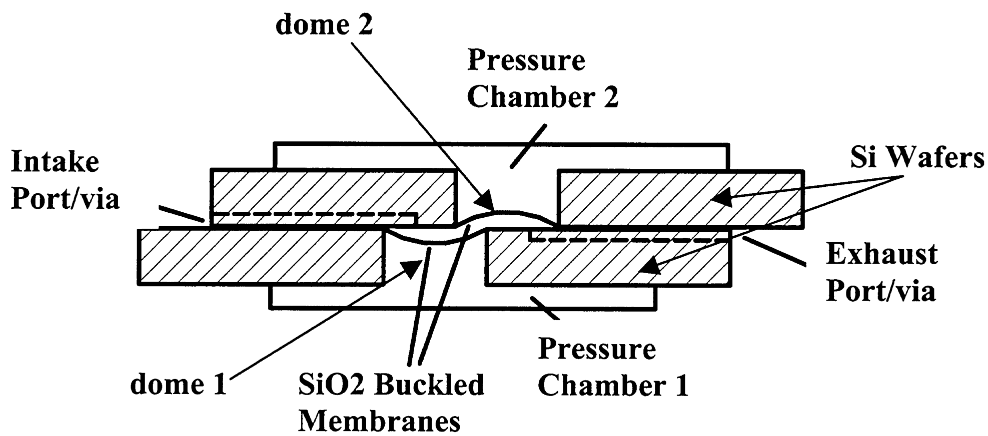

Figure 1: Single module micro pump. In the first stage of a cycle, the first chamber is filled from its reservoir. In the second stage of the cycle, the contents of the first chamber are transferred to the second chamber. The second chamber is then emptied into an outlet capillary tube.

The main components of the micropump are two silicon dies with buckled membranes that are bonded face-to-face and positioned to form pairs of chambers that partially overlap (Figures 1and 2). When the first chamber of a pair is changed from flat shape to dome shape, liquid is drawn into it. When the first chamber is flattened while the second is domed, its contents are transferred to the other member of the pair. If both diaphragms of a pair are flattened in sequence, the contents are forced out through an exit port into a capillary tube. Cycling is accomplished by sequentially changing pressures on opposing sides of the dies sandwich by means of valved enclosures.

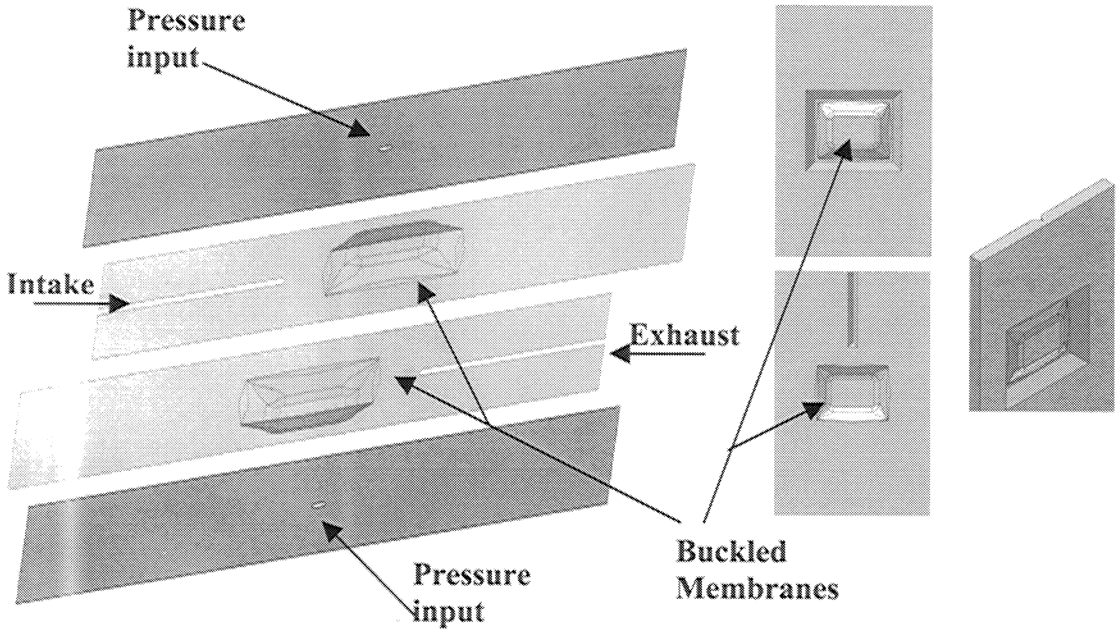

Figure 2: Silicon pump module that consists of four layers. (a) The two outer layers are plain and have an orifice to introduce pneumatic pressure into the volumes behind the membranes. The two inner layers have oxide membranes that change from buckled to flat (pumping action) and have etched inlet and outlet vias. (b) Drawings of back etched silicon dies showing a buckled silicon oxide on silicon membrane from three different view angles.

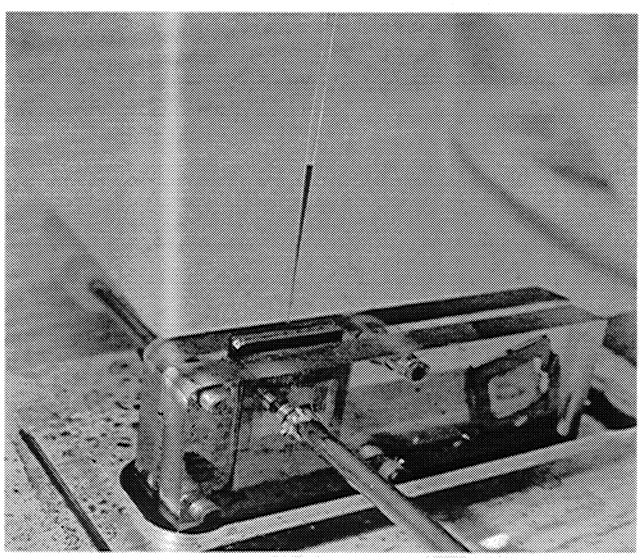

Figure 3: A prototype individual micropumps is shown at (a). Each pump module consists of a pair of dark-colored silicon dies approximately 10 mm by 15 mm secured between two transparent plastic blocks. Steel tubes are affixed to the plastic blocks to supply air pressure for controlling the shape of the silicon/silicon oxide membrane to provide a pumping action.

Initial Results

Using dies similar to those shown in Figure 3, functional prototype devices have been made that deliver 1-10 nanoliters per stroke. The micropump shown in Figure 3, is constructed of individual silicon dies with plastic enclosures as a proof of concept. To demonstrate pumping, one edge of the silicon die pair is dipped in blue water as shown in Figure 3. In this view, a capillary tube has been inserted in one end of the silicon die module to show the colored liquid that is being pumped. Air pressure is supplied from a compressor and controlled by a pair of pneumatic solenoid valves. These valves are turned on and off by a microprocessor controller that supplies pulses of electrical power. The pumping action is reversible: the direction and amount of liquid pumped is controlled by varying the duration and sequence of the pulses.

These examples illustrate one application for micropumps, but the configuration shown may not be optimum for other uses. Since several hundred membranes can be formed on a 10-cm diameter silicon wafer in a single etch operation, it will be economical to make arrays of pumps for a variety of microdosing operations. One of our research objectives will be to make and test a variety of rectangular arrays of pumps.

Pump Actuation and Configurations

The silicon micropumps described here can be used singly or in multiple arrays. Since several hundred membranes can be formed on a 10cm diameter silicon wafer in a single etch operation, it will be economical to use arrays of pumps for many different micro dosing operations. A variety of rectangular arrays are currently in development.

These silicon micropumps can also be operated electrically using a titanium-nickel thin film actuator and a bias spring instead of pneumatic pressure. Thin film micro actuators have been used for the past 10 years in micro valves, micropumps, and flow regulators and are commercially available from TiNi Alloy Co. A standard actuator is built on a 5.1 x 8.1mm silicon chip and has eight ribbons of thin film 4 microns thick, 250 microns wide and 2.15mm long. When the actuator opens a valve or a pump, it lifts a weight of 30-40 grams imposed by a bias spring for a distance of 100 to 400 microns. Only 60-80 mA (~2.4volts) are necessary to operate these devices.

Both the silicon buckled membranes and the titanium-nickel thin film actuators can be greatly miniaturized. The shape memory properties of nitinol operate down to the nano-scale and thin film microfabrication techniques allow features and devices of a few microns. A thin film actuator 1 millimeter on each side and 10 microns thick (vol.=10^{-6} cm^3) weighs approximately 0.1 micrograms and produces 64 microjoules of work per cycle (5). In addition, reducing the size of the micropump buckled membrane mechanism to one or two microns will reduce the volume or fluid per stroke to the picoliter range.

References:

[1] W.S. Trimmer, Micromechanics and MEMS classic and seminal papers to 1990,IEEE Press, isbn 0-7803-1085-3, IEEE Order Number PC4390 (1997)

[2] M. Madou, Fundamentals of Microfabrication,CRC Press, ISBN0-8493-9451-1 (1997)