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A Low Power, Tight Seal, Polyimide Electrostatic Microvalve

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Abstract

An electrostatically-actuated polyimide microvalve is developed with sub-micron gaps between the electrodes to provide high force with low power consumption (<1mW). Built-in residual stress results in a curled bimorph cantilever which allows for a microactuator with large displacement. This microactuator is used to open and close a fluid path hole etched in silicon for a microvalve. The microactuator can be actuated with 25V for a displacement of 200 μm. The cantilever actuator is mainly composed of polyimide, which is flexible enough to conform over the flow hole, thereby eliminating the need for the design of a valve seat.

Introduction

Microvalves provide one of the most important links to a micro total analysis system by micro electromechanical systems (MEMS) [1]. Applications include fluid injection analysis [2], chemical processing/analysis stations[3], drug delivery[4], atmospheric and temperature control apparatus[5-6], and possibly many more. Among the commercially available microvalves, each has its strengths and weaknesses and to date no one microvalve can be applied to all situations[7]. One of the design concerns is the wear to the valve or valve seat since high pressure is applied to assure tight seals. Many designs of microvalves require a protruding valve seat for high pressure tight seal [8,9]. Futhermore, since semiconductor materials such as silicon, silicon dioxide, or silicon nitride are the choice of materials, even higher pressure is required to minimize leakage. Power consumption of thermally actuated microvalves typically require higher than 200 mW and high operation temperatures limits its use in many biomedical applications. In this paper, a polyimide, electrostatically-actuated microvalve is presented which is low power, low temperature, and does not require a valve seat design since polyimide is flexible enough to easily conform over the much harder silicon substrate on which the flow hole is generated. Polyimide can be spun on substrates to thicknesses less than 0.1 μm and the insulation is excellent with large dielectric constants. This provides the design freedom for small gap, high power density electrostatic actuators. The one set back of using polyimide is that the hysteresis will be much larger resulting in slower response times than stiffer material valves.

Principle of Operation and Design of Microvalve

The actuation principle is the same as previous electrostatic actuators [5,10-12]. Figure 1 illustrates the actuation principle of the microvalve with the cross-section of the device. Figure 1a is the cantilever that is curled upwards by residual stress intentionally built-in using two polyimide bimorph layers with different coefficients of thermal expansion. As voltage is applied bewteen the ground plane and the electrode sandwiched in the polyimide cantilever, electrostatic force flattens the cantilever onto the substrate, and the flow path hole is sealed up.

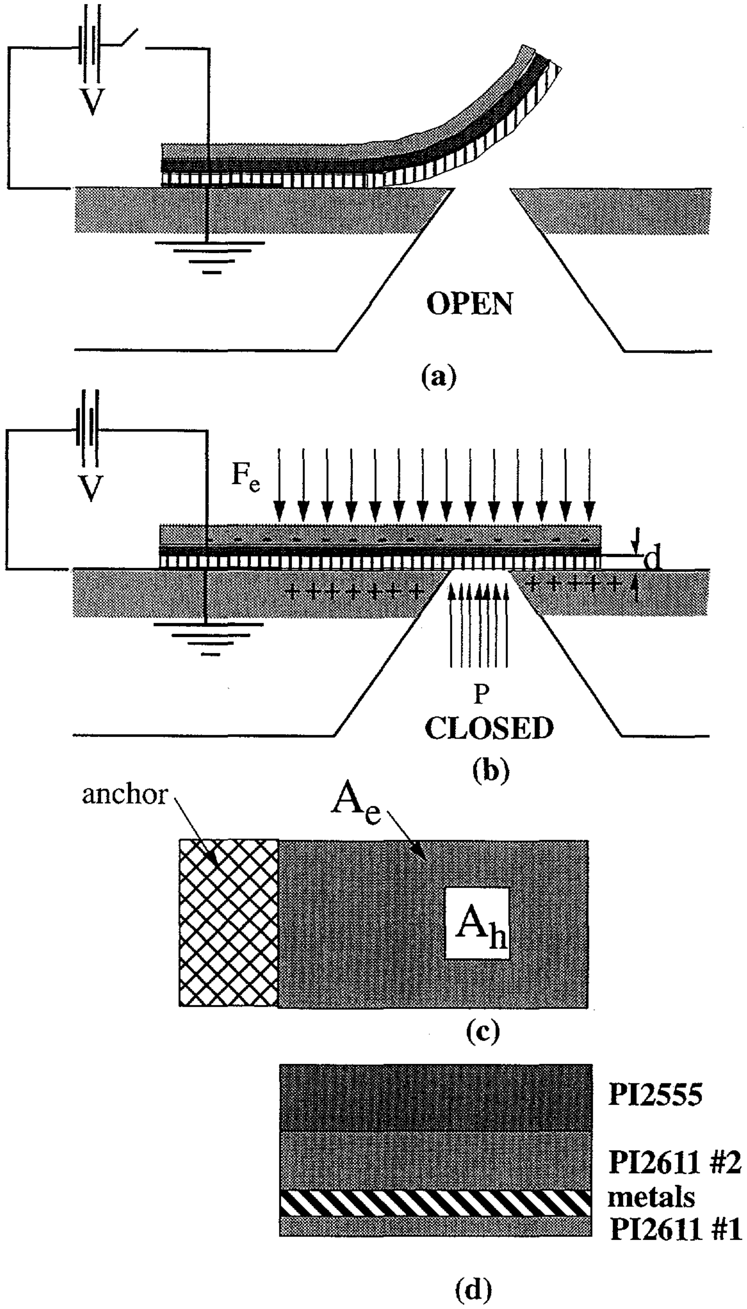

FIGURE 1. Schematic of operation principle of polyimide electrostatic microvalve (a) microvalve in open configuration with voltage supply open (b) microvalve closed by applying voltage to generate electrostatic attraction force. (c) top view illustrating areas for flow pressure through hole and area of electrostatic force. (d) layout of material layers.

The critical voltage that causes the cantilever to roll flat onto the substrate is derived in [12]:

$$V_c^2 = \frac{Eh^3}{12R^2}\left(\frac{d_p}{\varepsilon_0\varepsilon_p} + \frac{d_n}{\varepsilon_0\varepsilon_n}\right) \qquad \text{(EQ 1)}$$

where Vc is the critical voltage, E is the equivalent Youn'g modulus of the multilayer cantilever, h is the thickness, d and ε are the dielectric gap and dielectric constants of polyimide and silicon nitride, and R is the radius of curvature of the curled cantilever. For the microvalve, the thin film layers layers are illustrated in Fig.1(d). The bottom-most layer is du Pont polyimide PI2611 and the thickness is 0.08 μm, the metal layer Ti/Au is 0.15 μm, the second PI2611 is 1.5 μm, and the top-most layer is du Pont PI2555 with a thickness of 2.5 μm. The thickness of the insulating silicon nitride is 0.1 μm. The effective Young's modulus is 3GPa and the initial curvature is 294 μm. The dielectric constants of PI2611 and nitride are 3.3 and 8, respectively. With these dimensions, Eq(1) gives us a critical voltage $V_c = 35V$.

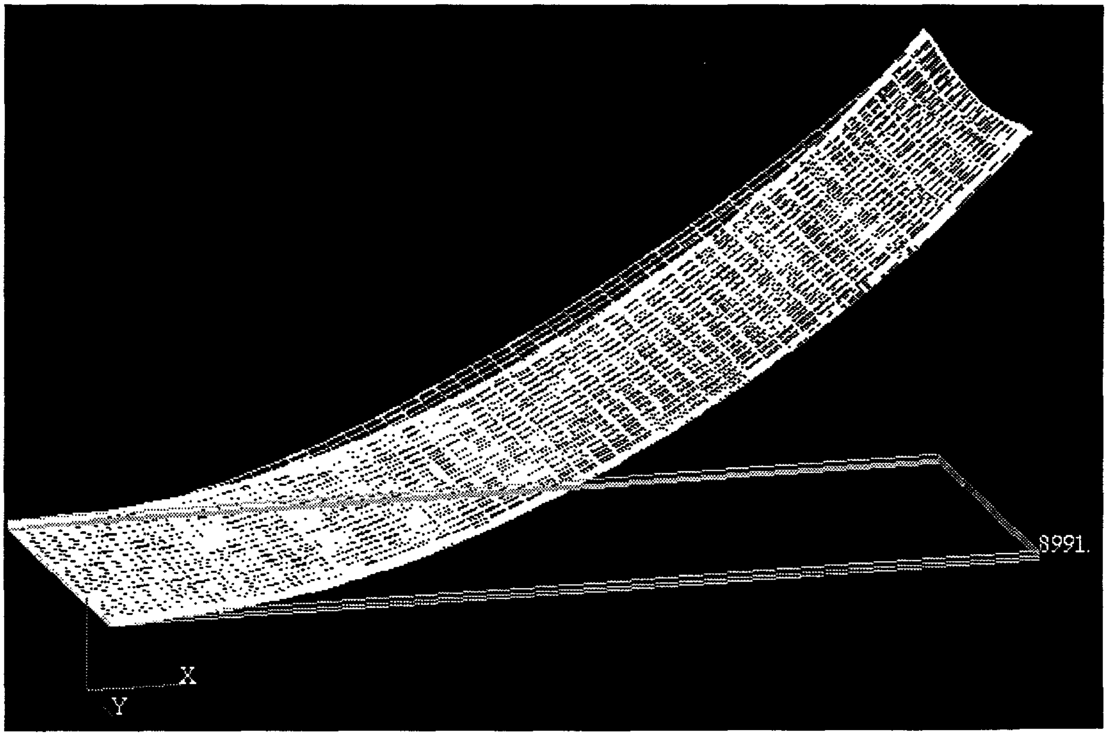

FIGURE 2. Finite element analysis of residual stress generated initial curvature. Cantilever beam is 500 μm long and 200 μm wide, with

The width and length of the cantilever was 200 μm and 500 μm, respectively. For the design of the initial curvature in the cantilever, since there are four layers in the cantilever and the width-to-length ration is much greater than 0.1, finite element analysis using Abaqus was used instead of deriving an analytical solution. Figure 2 shows the finite element analysis results of the multilayer indicating the resultant opening of the cantilever caused by the built-in residual stress in the polyimide/Au/Ti thin film design. The resulting curvature is 230 μm. There is also a curvature in the width direction of 311 μm.

The microvalve will be in equilibrium if the flow pressure is less than the exerted electrostatic force. In order for the microvalve to sustain a flow pressure P, the electrostatic force F_e must be greater or equal to $P \bullet A_e$, where A_h is the area of the flow hole. F_e can be represented by the electrostatic force formula and the following equation is the condition:

$$F_e \geq P \bullet A_h \Rightarrow \quad V^2 \frac{A_e}{A_h}\left(\frac{\varepsilon_p}{2d_p^2} + \frac{\varepsilon_p}{2d_p^2}\right) \geq P \qquad \text{(EQ 2)}$$

In order to sustain a higher voltage, the ratio A_e/A_h must be maximized and the dielectric gap must be minimized. For a 100 μm flow hole, with V = 50V, A_e = 90000 μm^2, A_h = 10000 μm^2, a maximum pressure of 130 MPa can be sustained. However, this formula does not take into account the the possibility of deformation at the valve seat that can cause an initial gap that can propagate along this interface between cantilever and ground plane, lowering the sustainable pressure along the way.

Fabrication of Microvalve

Figure 3 illustrates the fabrication sequence of the microvalve. The conductive ground plane is created by diffusing phosphorous into the surface of the wafer. LPCVD silicon nitride is then deposited and the fluid hole is patterned on the back side for 44% KOH etching (Fig.3a). The ground electrode is opened in the silicon nitride on the fron side as well. Then The next step is depositing 3000Å of PECVD oxide for a sacrificial layer and patterning only under the cantilevers. Figure 3b shows the cross-section of the next few layers that are deposited, 0.08 μm of PI2611 polyimide, 0.05 μm Ti, 0.1 μm gold, followed by 1.5 μm of PI2611 and 2.5 μm of PI2555 to provide the upward bending residual stress. At last a 200Å thick nickel layer is deposited as a mask for O_2 reactive ion etching (RIE) of polyimide. Polyimide films are all cured in 400°C nitrogen environment. During etching of the polyimide layers, the bias electrode pad will be exposed to serve as an etch mask for the bottommost polyimide layer (PI2611). After removal of the nickel mask, the nitride in the flow hole is etched away by CF_4/O_2 RIE. The last step is etching away the sacrificial silicon dioxide layer by 6:1 buffered hydrofluoric acid (BHF) for two minutes. Adhesion issues were the most critical to the process and a protection mask was designed to protect the anchor pad from excessive attack of the BHF. Figure 4a is the device before sacrificial release illustrating the top view where the two electrode positions, the sacrificial layer, and the flow hole underneath the cantilever. Figure 4b is a SEM of the polyimide microvalve with a 500 μm long, 200 μm wide cantilever and a 50 μm square flow hole. Devices were fabricated with flow hole sizes ranging from 25 μm to 100 μm. Slits were designed to slightly soften the cantilever for reduction of actuation voltage.

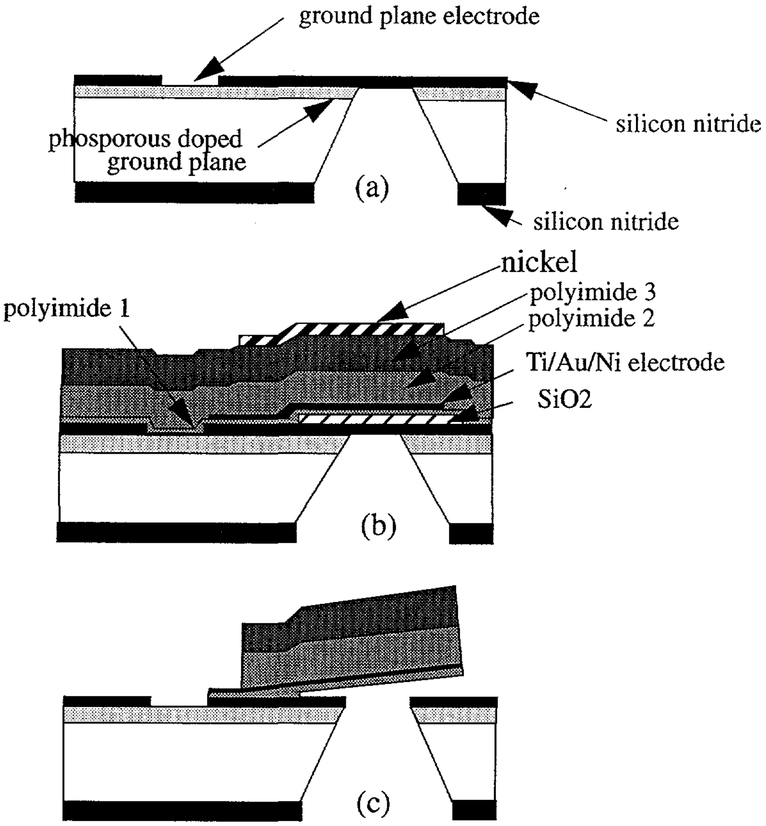

FIGURE 3. Process flow for Polyimide Electrostatic Microvalve

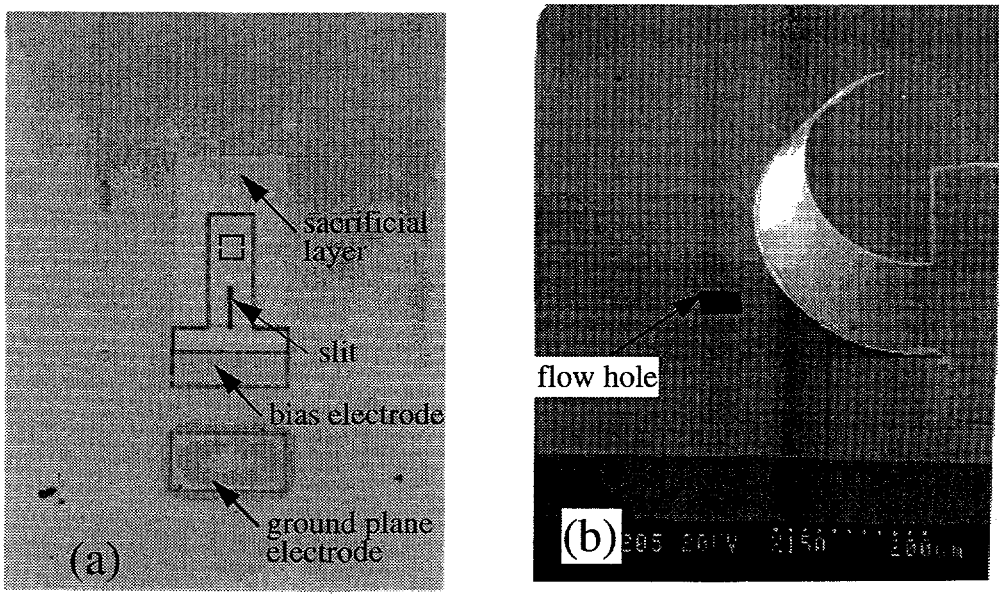

FIGURE 4. (a) Photograph of microvalve before release (b) SEM of microvalve after release showing the etched hole beneath it.

In this particular fabrication run, the phosphorous doped ground plane is etched through at the ground plane electrodes due to overetching of the silicon nitride. This causes the contact resistance to be very high that could lead to charge build up during actuation that could add to hysteresis of the response time.

Testing Results

Preliminary tests had the valves collapsing at 50V but staying closed while voltage is lowered to 25 V. Response frequencies were approximately 10 Hz. Initially the cantilever is curled upwards 200 μm to 300 μm, which match the simulations. Pressure standoff tests were performed and with 55V applied voltage, the 500 μm long, 200 μm wide cantilever microvalve could sustain up to 24 kPa applied through a 100 μm square flow hole, much lower than the calculated value of 130 MPa. The power required to statically actuate the microvalve was below 1 mW. It was observed that many times the microvalve cannot be closed twice in a row. However, upon reversing of the voltage, the microvalve could be actuated once again. This must be due to residual charge build-up in the dielectric layers. Also, electrical breakdowns causing short circuitry would occur at a relatively low voltage of 70V, indicating pinholes in the silicon nitride.

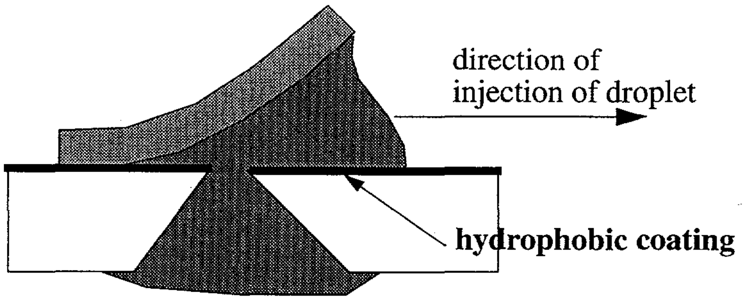

FIGURE 5. Illustration of liquid microvalve droplet injector

Discussion

A low power, tight seal, electrostatically-actuated microvalve is developed and demonstrated. This microvalve is suitable for pneumatic applications, however, liquid flow handling is possible with proper design. Since both of the electrodes are shielded by dielectric material (nitride and polyimide), there is no leakage current possible even in conductive solutions. Figure 5 illustrates a droplet injector application. With a proper hydrophobic coating the liquid can ooze out of the open flow hole by the enhancement of capillary adhesion forces. As the microvalve is closed, a droplet of liquid can be forced out of the hole for very small and precise amounts of liquid transport. Silicon nitride can serve as this hydrophillic coating.These polyimide microvalves can withstand temperatures up to 400°C and are suitable for biotechnology applications. A flow control system can be built by fabricating multiple microvalves on a chip and digitally operating the microvalves. Currently charge build-up is a problem and will be improved by better electrode contact resistance in future designs.

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