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Structure and characterization of a planar normally closed bulk-micromachined piezoelectric valve for fuel cell applications

Hengbing Zhao[a,*], Kevin Stanley[a], Q.M. Jonathan Wu[b], Eva Czyzewska[a]

[a] *Department of Microtechnology and Sensing, Institute for Fuel Cell Innovation, 3250 East Mall, Vancouver, BC, Canada V6T 1W5*
[b] *Department of Electrical and Computer Engineering, University of Windsor, 401 Sunset Avenue Windsor, ON, Canada N9B 3P4*

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Abstract

Microfuel cell systems require microvalves that are chemically tolerant of hydrogen, have thermally insensitive activation mechanisms, and tight geometric constraints. A planar bulk-micromachined piezoelectric valve for portable fuel cell system is proposed. The actuating diaphragm and the valve seat are etched on silicon wafers. A piezoelectric bimorph disc is glued to the actuating diaphragm to lift the diaphragm and open the valve. The pressure differential between the valve chamber and the outlet and the initial pressure caused by the deformed tethers are employed to increase the sealing force. The actuating device with four Z-tethers attached to the actuating diaphragm is thermally insensitive and can reduce thermally induced deflection at the center and avoid clamping effect at circumferential edge. The proposed actuating diaphragm with Z-tethers shows good thermal stability and excellent actuating performance through the finite element method (FEM) analyses. The prototype valve of 20 mm in diameter and 2 mm thick was fabricated and tested as a regulator. Using compressed air, the flow characteristics for the prototype valve were measured at different inlet pressure and elevated air temperature. The design, fabrication, simulation and characterization of the prototype valve are described.

Keywords: Fuel cell system; Piezoelectric; Bulk-micromachining; Microvalve

1. Introduction

Small fuel cell systems are becoming promising candidates for commercial applications due to potentially high energy density. Efficient operation of fuel cells depends on the fuel flow rate, pressure and concentration [1–6]. The relevant microfluidic control components must be small to reduce the impact of balance of plant on the microfuel cell gravimetric and volumetric energy density, and at the same time meet fuel cell application requirements such as hydrogen tolerance, thermally insensitive activation and geometric constraints. Our goal is to develop a planar proportional valve and put it on the fuel line of a 20 W fuel cell system to control the fuel flow rate. The requirements are that operating temperature range is 10–85 °C, humidity is 0 RH to saturation, maximum flow rate is 350 sccm and pressure drop across the valve is 0–44.1 psi.

Various active microvalves have been developed so far [7–20]. There are four principal means that have been commonly utilized for microvalve applications: electrostatic forces [7], piezoelectric forces [8–14], shape memory alloys [16,17], and thermal expansion forces [18–20]. The piezoelectric actuation of microvalve structure is attractive due to the relative simplicity of the actuator design, scalable geometry, lower power consumption in static operations, rapid response, and high work energy density. Based on the above advantages of piezoelectric actuation and the requirements of small fuel cells, a planar normally closed piezoelectric valve was proposed. The microvalve is fabricated on silicon wafers using bulk-micromachining techniques and actuated by piezoelectric bimorph disc. Both silicon and piezoelec-

* Corresponding author. Tel.: +1 6042213000x5594; fax: +1 6042213001.
E-mail addresses: hengbing.zhao@nrc.ca (H. Zhao), jwu@uwindsor.ca (Q.M. Jonathan Wu).

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tric ceramic are hydrogen compatible. With Z-tethers design, the valve is thermally insensitive and can operated within relatively large temperature range. This paper describes the structure and the fabrication process of the valve. The simulation and test of thermal deflection and the behavior of the piezoelectric actuating device are presented. The flow rate and leak characteristics of the prototype valve are obtained.

2. Microvalve structure, fabrication and operation

Almost all applications of piezoelectric actuators in the microvalve can be grouped into two major areas: one where actuators are bonded on structures for flexural control by using the transverse effect – d_{31} piezoelectric strain coefficient of the material [8,9], and another where actuators are directly used for micropositioning as linear actuators by using the longitudinal effect – d_{33} piezoelectric strain coefficient [10–13].

Longitudinal piezoelectric effect can generate tremendous force. However, the stroke permitted by induced strain levels is miniscule, and requires amplification of the stroke of piezoelectric actuators [11,12]. The requirement for fabrication is also critical [10,13]. In our application, large deflection is required and low force can be tolerated. Therefore, the bimorph PZT element—transverse effect is utilized.

2.1. Structure

A schematic of the microvalve is shown in Fig. 1. The stand-alone device has a square footprint of 25 mm on a side, and a height of less than 2 mm. The valve consists of four parts: seat plate, actuating diaphragm, piezoelectric disc and top cover. The seat plate is known as the base, which may be part of the chamber wall. It contains the outlet, seal rings, and support spokes around the outlet. These rings tend to increase the sealing area and decrease gas leaks. The middle layer is the actuating diaphragm, which is patterned and etched on a silicon wafer and is connected to the border by four flexible Z-tethers, covering the valve seat. The four Z-tethers at the circumference of the actuating diaphragm are used to support the actuating diaphragm, increasing the flexibility at the contact line to avoid clamping effects, and reducing the thermal deflection at the center. The detailed dimensions and material parameters are given in the next section. The piezoelectric bimorph disc actuator is glued to the top of the diaphragm, and the electrodes are routed through the conducting layers of the actuating diaphragm.

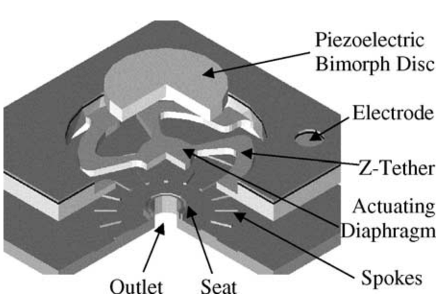

Fig. 1. Schematic view of the piezo valve without cover (not in scale).

For the prototype of the microvalve, a series bimorph with silver electrodes was employed. The bimorph element consists of two thin PZT plates (BM532, Sensor Tech.)—7 mm in radius and 0.25 mm thick, which were bonded together without internal shim. BM532 is a kind of PZT-5H materials from Sensor Technology Ltd. The electrode can be patterned and routed through different areas or layers of the actuating diaphragm and aligned with the wrap-around silver electrodes of the actuator. The disc bends out when a voltage is applied to the electrodes. If disc actuators are fixed at their circumferences, the center's motion can be used for actuating purposes.

2.2. Fabrication

A wet bulk-micromachining process is used to craft the structure on silicon wafer and simply explained here. First a thin oxide is thermally grown on the surface of silicon wafer. Then deposit positive/negative photoresist by spin coating or spraying. Expose to UV light by projection through film mask and immerse in an aqueous developer solution to dissolve exposed/unexposed resist. The pattern is transferred from film mask onto resist layer. Etch the exposed oxide to transfer the pattern to oxide layer and then remove the rest of resist. The patterned oxide is used as a mask against etching. Thus, etching can selectively remove material from a wafer.

Fig. 2 illustrates a schematic view of the fabrication process used for the prototype valve. The actuating diaphragm shown in Fig. 2a was made by patterning of the thermally grown oxide (1) on a double-sided polished 0.5 mm thick $\langle 1\,0\,0 \rangle$ p-type silicon wafer and etching of the cavity (2) and electrode hole (3) to the depth of 300 μm (tetraammoniumhydroxide (TMAH), 95 °C; 3 h 10 min). In the next step, boron was thermally diffused to form electrodes (4) (solid boron diffusion sources, 1000 °C; 45 min). Finally, supporting tether and boss (5) (details shown in Fig. 1) were etched through from the other side of the wafer (TMAH, 95 °C; 2 h 25 min).

The seat plate shown in Fig. 2b was fabricated using thermally oxidized single-sided polished $\langle 1\,0\,0 \rangle$ p-type silicon wafer. The first 20 μm deep alignment pattern (6) was etched using TMAH (95 °C; 30 min), followed by valve seat (o.d. 1.4 mm) etch (7) to the depth of 7.5 μm (TMAH 95 °C; 7 min). The wafer was then thermally oxidized to form a 0.5 μm thick SiO_2, that was next patterned and etched to form a 95 μm high spoke support (8) (TMAH 95 °C; 105 min). Final steps included etching sealing rings (9) (TMAH, standard conditions, 10 min), followed by laser drilling of 0.8 mm in diameter outlet (10) in the middle of the valve seat.