Note: A low leakage liquid seal for micromachined gas valves

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(Received 16 November 2009; accepted 3 May 2010; published online 24 June 2010)

We report a method for addressing gas leakage in micromachined valves. The valves used for evaluating the proposed concept utilize a silicon valve seat that is bonded to a glass substrate and actuated by a piezoelectric stack, all of which are assembled within a ceramic package. The sealing method uses the capillary forces of a liquid sealant on the valve seat to reduce gas leakage below measurable limits. The gas leak rates are compared in valves with and without the seal enhancement. For example, a valve closes against 13.5 kPa with 10 V actuation, compared to 40 V required without the enhancement. Leakage is also evaluated for liquid flow. © *2010 American Institute of Physics.* [doi:10.1063/1.3436642]

Micromachined valves are attractive for a variety of systems with applications ranging from biological analysis to orbital propulsion. Performance metrics such as dynamic range, permitted leakage, response time, maximum pressure, power consumption, size, and material composition are generally determined by the target application.[1–3] For example, a Joule–Thompson cooler requires high pressure operation and high flow rates for successful operation.[4] Conversely, a microgas chromatograph favors valves with a rapid response time to properly determine the chemical composition of an input.[5,6] Valve performance is dependent upon several factors that include fabrication methods, material composition, and actuation mechanism. For any set valve fabrication and assembly, there are design compromises that allow valve parameters to be adjusted to meet the needs of a specific application.

For many systems, an ideal valve would not limit the flow rate when fully open and would also have no leakage when fully closed. Eliminating leakage in micromachined gas valves has been a major challenge; nonuniformities in the valve seat or the presence of even minute particulates can prevent complete sealing. This problem is further exacerbated by the use of valve actuation mechanisms that provide relatively modest sealing force. In order to address this issue, researchers have explored the use of soft sealing materials for the valve seat.[7,8] While such polymeric seals are suitable for a variety of valves and applications, the incorporation of such materials can be a significant challenge for other valves. The operating conditions and environments for certain valves may also limit the use of polymeric valve seats. In such cases, a wet valve seat may provide a solution that is both simple and effective.

Surface tension at solid-liquid interfaces has been exploited for controlling flow within microchannels.[9] For example, hydrophilic and hydrophobic regions along flow channels have been used to modulate pressure driven flow.[10,11] Capillary forces can dominate other forces at typical microchannel dimensions.[12]

In this note, we explore how capillary force can be used to prevent gas leakage in a valve that operates by moving a valve seat against a plate to modulate the height of a flow channel. The valve is similar to one reported by Park *et al.*,[13,14] but it utilizes a more elongated valve seat (Fig. 1). The valve seat is microfabricated on a silicon-on-insulator wafer and suspended above a glass substrate that has perforations for the flow inlet and outlet. The separation between the silicon valve seat and the glass plate is modulated by a piezoelectric stack mounted on the back side of the valve membrane and enclosed within the same package. As the actuator expands, it closes the valve by pressing the valve seat against the glass, and when it contracts it opens the valve.

The valve seat is designed in a starburst pattern that is axisymmetric with the gas inlet below it and the piezoelectric actuator above it. The elongated valve seat creates a wide flow channel even at a relatively small separation from the substrate, thereby compensating for actuation distances that are typically much less than 10 μm. This reduces flow resistance, but also permits higher leakage if a particle or structural nonuniformity occurs at any point along its 81 mm long serpentine perimeter.

For the purpose of this study, valves were fabricated by a process similar to one previously reported.[14] The silicon valve seat was spaced 1.3–1.4 μm from the glass substrate. This is a partially open state; the gap is increased or decreased by the polarity and amplitude of the actuation voltage.

A capillary seal for gas flow is formed by introducing liquid—water—into the region between the valve seat and substrate and then draining or evaporating it away from the other regions. The liquid-gas interface formed in this gap provides a capillary force that seals the valve from gas flow when it is closed [Fig. 2(a)]. When the valve is opened [Fig. 2(b)], surface tension and capillary forces drive the liquid toward places in the channel that have smaller gaps. This permits retention of the liquid on the valve seat. The axisymmetric actuation of the valve seat opens the inner points of the starburst pattern sooner than the outer edges. This tends

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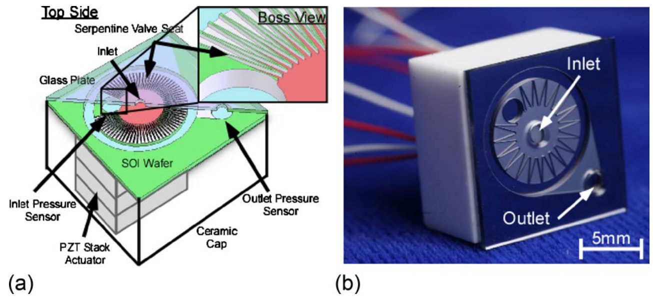

FIG. 1. (Color online) (a) The microvalve plate is designed from silicon and glass with a serpentine valve seat in a starburst pattern. The valve membrane is pressed against the glass plate by the piezoelectric stack to close the valve. The valve regulates gas, but because it utilizes membrane suspension, a sealant can be introduced into the valve channel without leaking into the package cavity. The valve also has embedded pressure sensors at the inlet and outlet. (b) A photograph of the top surface of the silicon microvalve assembled with a piezoelectric stack actuator inside a ceramic housing. Gas flows from the interior of the starburst across the valve seat to the exterior of the starburst pattern and exhausts from the outlet.

to drive the sealant from the center of the valve seat to the edges when it is opened [Fig. 2(c)].

The effectiveness of the capillary seal formed by the liquid in the flow channel is dependent upon both the liquid-solid and liquid-gas interfaces. The seal pressure can be estimated from the liquid meniscus. Using the Young–Laplace equation, the pressure drop across the meniscus (ΔP) can be determined from the liquid surface free energy (γ) and the vertical and parallel radii of curvature (R_1 and R_2),[15]

$$\Delta P = \gamma \times \left(\frac{1}{R_1} + \frac{1}{R_2} \right). \tag{1}$$

For a long serpentine valve seat, R_2 is essentially infinite. With a contact angle of 20° between water and glass, and a valve channel height of 1.4 μm (R_1=0.74 μm; γ=7.35 $\times 10^{-2}$ N/m), the differential pressure that the liquid seal should be able withstand at room temperature is approximately 98 kPa.

The presence of a liquid seal has an effect on flow characteristics when the valve is opened. Over the short term, it can be assumed that the liquid volume on the valve seat is constant as it migrates toward the outer points of the starburst valve seat when the valve is opened. The hydraulic resistance (H) of the valve and test setup can be approximated using the following equations:

$$H_{\text{rectangle}} = \left[\frac{12 \times \eta \times L}{g^3 \times (W - 0.5 \times g)} \right], \tag{2}$$

$$H_{\text{circle}} = \left(\frac{8 \times \eta \times L}{\pi \times \text{radius}^4} \right), \tag{3}$$

where the variables include height (g), channel length (L), viscosity (η), channel width (W), and radius. Equations (2) and (3) provide an estimate of the hydraulic resistance in channels with rectangular and circular cross sections, respectively. An analytical approximation of the flow modulation is plotted in Fig. 3, along with measured experimental results. The analytical model assumes an initial gap of 1.3 μm, a linear actuation approximation of 0.06 μm/V, and a closing voltage of 15 V. This model provides an equivalent resistance that is adequate for illustrating the basic operating concept. However, a more refined model that accommodates the presence of droplets on the valve seat may provide superior accuracy for conditions in which the valve is nearly closed, or other conditions with low gas flow rates. Over time, partial evaporation reduces the total liquid volume, thereby requiring a narrower channel to achieve the same capillary seal, but this does not necessarily result in a failure of the seal. Once a valve seat dries out, it can be easily rewetted. For some applications, a nonvolatile liquid such as oil may be more appropriate.

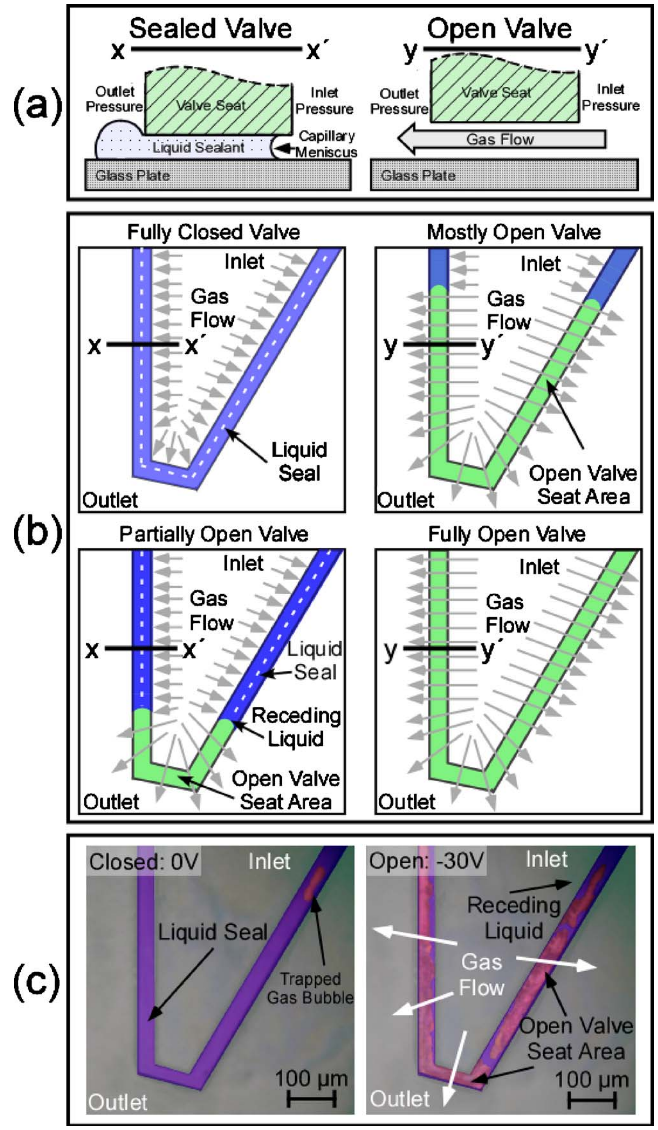

FIG. 2. (Color online) (a) Cross-sectional view of the flow channel: liquid sealant is in the channel between the valve seat and the glass plate. When the valve is opened, the liquid recedes and a gas channel is created across the valve seat. (b) Top view of the flow channel: when the valve is closed, flow from the interior of the starburst (inlet) is prevented by the liquid seal. As the valve is opened, the liquid recedes toward the interior of the starburst. This results in a partially to fully open valve that allows gas to flow from the interior of the starburst to the exterior across the valve seat. (c) Color enhanced photographs of the wet valve seat, showing the meniscus receding from the inner starburst points that are closer to the actuator, when the valve is opened. Prior to testing the valve for gas flow, the introduction and removal of liquid from the valve leave a wet seat. Trapped gas bubbles or coalescing droplets do not measurably impact valve performance.

The experimental results were obtained using nitrogen gas to generate differential pressures ranging from 4.1 to

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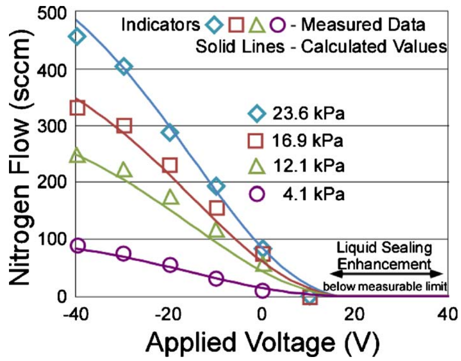

FIG. 3. (Color online) Nitrogen flow through valves assembled with a water seal. Gas pressures varied from 4.1 to 23.6 kPa and flow ranged from 400 ml/min down to below the measurable limit (<1 ml/min) when the valve was closed. The liquid seal prevented pressure flow from generating significant leakage for gas flow. Gas flow rates are compared to analytical flow calculations assuming a constant liquid volume and valve geometry.

23.6 kPa between the inlet and outlet while repeatedly actuating from −30 to 60 V, upward of 100 times (Fig. 3). Dry valves remained open until they were actuated with at least 40 V (Fig. 4). In contrast, the seal enhanced valves remained closed over an actuation range of 10–60 V for the entire range of tested pressures. Flow rates ranged from 403 ml/min down to flow rates below the measurable range of the test setup (i.e., less than 1 ml/min). These results were

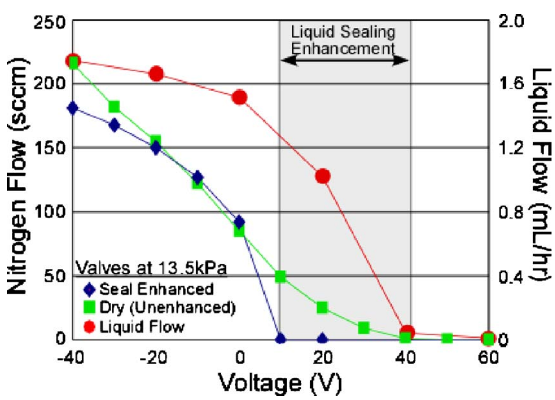

FIG. 4. (Color online) Nitrogen and isopropyl alcohol flow through valves assembled with and without a water seal. Gas pressures were maintained between 13.4 and 13.6 kPa and nitrogen flow ranged from 216 ml/min down to below the measurable limit (<1 ml/min) when the valve was closed. The liquid seal prevented pressure flow from generating significant leakage for gas flow, but it did not affect sealing for liquid flow. Liquid sealing enhancement can be clearly seen as both a closing voltage difference and a leakage difference for gas and liquid flow through an unenhanced valve.

obtained as long as 50 days after the introduction of the water sealant.

The ratio of the maximum gas flow rate to the leakage rate was at least 322 with a liquid seal while the ratio for a dry valve was 216. This shows that the liquid in the valve is effective at improving the seal and reducing leakage. Additionally, the difference in closing voltages (10 V for a wet valve seat, 40 V when dry) suggests that the capillary seals when the channel gap is approximately 1.4 μm, which is consistent with the gap distance targeted during fabrication.

The same valves were also tested with isopropyl alcohol flow to determine the closing point and leakage rates for liquid media, which also do not benefit from a capillary seal. Alcohol flow rates for the valves at 13.3 kPa differential pressure ranged from 1.767 to 0.06 m/h across the same voltage range. The valves required 40 V actuation to close against liquid flow; the leakage rate was 0.0283 ml/h (Fig. 4). This reconfirms that in the absence of a capillary seal, the valve permits more leakage.

These results indicate the effectiveness of capillary forces in providing a seal against inadvertent gas flow in a closed microvalve. This technique is easy to implement and is potentially useful with a variety of liquids, materials, and pressures.

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