A Robust Normally-Closed Silicon Microvalve

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ABSTRACT
A nickel-silicon bimetallic microvalve intended for use in analytical instrumentation has been designed, fabricated, packaged, and tested. This valve's range of operation constitutes an order-of-magnitude increase in both pressure and flow as compared to the performance of previous bimetallically actuated valves. System requirements of 0-200 psi and 0-600 sccm have been met or exceeded with air, He, N_2, and H_2.

INTRODUCTION
The design of a robust gas-control valve is subject to a complex group of constraints. Proportional control of gas flow at moderately high pressures (5-200 psi) and moderately high flow rates (0.1-1000 sccm) requires significant mechanical motion and adequate stiffness in the mechanical structure used for flow control. For a poppet valve in which a flat valve face moves in opposition to an orifice surrounded by a seat, typical dimensions required are an orifice diameter on the order of 200-400 μm and total face motion (stroke) on the order of 50-100 μm. Control of low flows at the high end of the pressure range, where the valve face is nearly in contact with the valve seat, requires that the structure be stiff enough to resist closing as the face approaches the seat, and stiff enough in the opposite direction for insensitivity to environmental vibrations which would otherwise open the valve by the action of a mechano-pneumatic positive feedback loop. In many applications safety considerations dictate that a valve should go to a no-flow mode when power fails. For reliability the dirt-sensitive mating area between face and seat should be as small as possible, and reliability should be sufficient to permit millions of operating cycles. Finally, as in all engineering endeavors, the fabrication cost should be minimized within other constraints.

Historically such valves have been solenoid actuated and have been fabricated by traditional macro-scale manufacturing techniques. More recently several microvalves fabricated using MEMS techniques have been developed [1-7]. The valve presented in this work is a candidate for use in future gas chromatography systems and has generated considerable interest within Hewlett-Packard [8,9]. Its simplicity of fabrication and its rugged structure make it a strong contender for many gas-phase applications.

MICROVALVE DESCRIPTION
Figures 1 and 2 illustrate cross-sectional and top views of the valve. Figure 3 is a photograph of the bottom side of the actuator chip which comprises the top half of the valve, and Figure 4 shows a detail of the orifice and seat combination in the bottom orifice chip.

The actuator chip [10] comprises a central silicon boss surrounded by a radial array of bimetal legs of plated nickel 25-50 μm thick on single-crystal silicon also 25-50 μm thick. The "spider legs" of the actuator act to relieve hoop stress during actuation, so that a greater valve stroke is achieved than would otherwise be possible. Each leg connects at its peripheral end to a torsion-bar suspension of plated nickel, which in turn is attached to a silicon frame. The suspension allows rotation of the end of the leg while resisting vertical motion, in a manner which approximates a simply-supported boundary condition. The long, thin suspension arms also provide high thermal resistance between the legs and the frame for reduced power consumption.

In operation the actuator is heated by a thin-film nickel heater situated near the central ends of the spider legs. The heater sits on the silicon surface between areas of plated nickel, and comprises two resistors in a parallel electrical configuration. Contact to the ends of the resistors is made at points 180° apart by two electrically isolated plated nickel regions connected to bonding pads, and the resistor current splits from the contact points to flow both clockwise and counterclockwise along the meandering path. Although the resistor region is thinner than the plated nickel regions, the meander shape adds stiffness and prevents excessive bending in this region.

Because the actuator chip contains no diffusions or contact holes, its fabrication process uses only four photomasks in three photomasking steps. Actuators can be electrically tested and optically inspected in wafer form, minimizing testing costs.

A separate chip containing a square orifice framed by a square valve seat sits beneath the actuator chip. This chip requires two photomasks in its fabrication process. Like the actuator chips, orifice chips can be inspected and marked in wafer form.

The orifice chip consists of a square raised seat area which frames a central orifice. In contrast to previous orifice chips, the seat and orifice (patent pending) are formed in a self-aligned manner so that the inner perimeter of the seat exactly defines the minimum cross-sectional area of the orifice, maximizing the orifice area in relation to the seat area and providing several benefits. The small seat area relative to the orifice area maximizes the head pressure which the valve can open against for a given actuator force. Conversely, the large orifice area relative to the seat inner perimeter maximizes flow through the valve at a given head pressure and valve stroke. In addition, the small seat area relative to the orifice area minimizes heat flow from the actuator chip to the orifice chip when the valve face is in contact with the valve seat, minimizing the thermal power required to open the valve. This last consideration is especially important in a thermally actuated valve.

The two chips are separately fabricated and diced out of their wafers, and are placed together during packaging. While a hermetic seal is required between the bottom of the orifice chip and the package base, no hermetic seal is required between the actuator chip and the orifice chip. This characteristic provided much freedom in design and testing, since several variants of actuator and orifice chips could be mated to evaluate flow and pressure characteristics.

In production the chips can be packaged in a metal can suitable for manifold mounting, with an internal volume of 1.2 cm^3. To create a

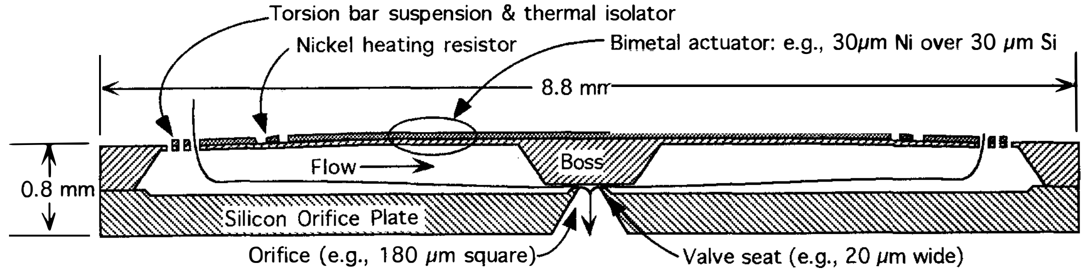

Figure 1. Cross section of silicon microvalve.

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packaged valve the actuator and orifice chips are stacked on top of one another on the package base and leads are attached, then a cap is welded on. Gas inlet and outlet are through the base of the package, as are electrical leads. The flow path occurs around the entire perimeter of the actuator chip's suspension area, which maximizes sweeping of the upstream volume of the package.

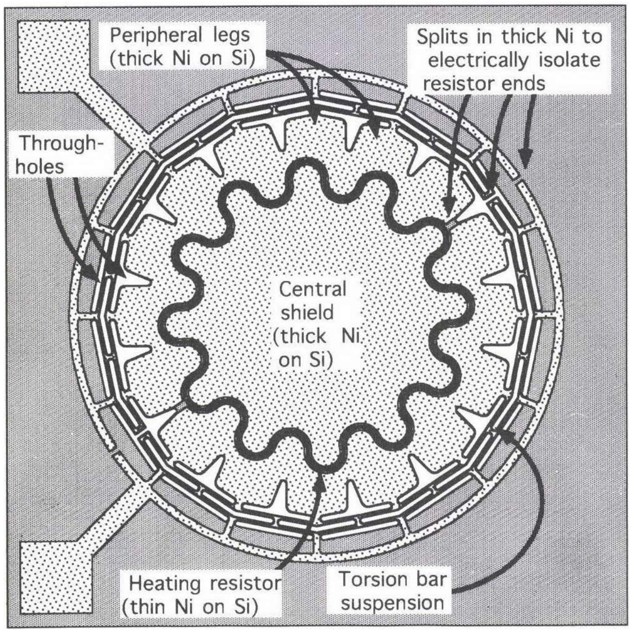

Figure 2. Simplified plan view of an actuator chip.

MODELLING, DESIGN, AND FABRICATION

The valve chip and orifice were designed by a combination of hand calculations, finite element simulations of both mechanical and thermal characteristics using ANSYS software from Swanson Associates on HP Unix systems, and equation-based computer models using TKSolver Plus. Layout was performed using DW2000 software from Design Workshop, and a combination of optically generated and electron-beam generated photomasks was used in contact and proximity lithography on a Karl Suss MA-25 double-sided mask aligner.

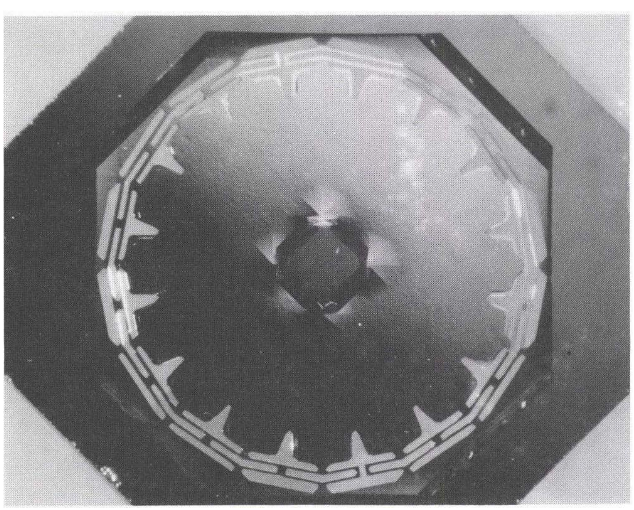

Figure 3. Photograph of the back surface of an actuator chip.

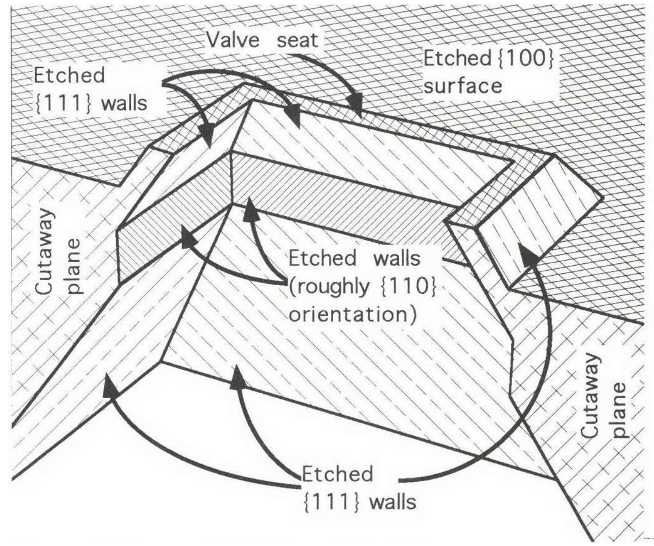

Figure 4. Cutaway detail of an orifice 200 μm square surrounded by a valve seat 20 μm wide.

OPERATION & PERFORMANCE

The valve operates in a normally-closed fashion. With no power applied, the central boss of the actuator covers the orifice and contacts the valve seat, preventing gas flow. When power is applied to the heating resistor the central boss rises as much as 100 μm out of contact with the valve seat, permitting gas flow.

Figure 5 is a set of experimental curves showing flow versus applied voltage at several different head pressures, with helium used as the flowing gas. Each curve shows roughness because voltage was controlled by manually turning a potentiometer. In addition, each curve shows hysteresis because it takes more power to open a cold valve than it does to hold a warm valve open. At higher pressures (e.g., 50 and 100 psi) a thermal feedback loop is evident on the right-hand side of the curves: as the valve face lifts off of the valve seat in a regime where pressure has held it closed until appreciable power is supplied, thermal conductance between the face and seat decreases rapidly. The decreased conductance causes the actuator to warm rapidly at an essentially constant input power, and the valve opens more quickly than it would in the absence of this rapid warming. This feedback effect operates slowly enough (transients on the order of 100 ms) to indicate that it is not a mechano-pneumatic feedback effect due to insufficient structural stiffness.

As with any thermal actuator, there is a tradeoff between actuation speed and power consumption, and speed is in any event slow compared to that of a solenoid actuator. By applying a large power pulse it is possible to move a thermal actuator rapidly in one direction, but the rate of movement in the opposite direction is limited by cooling through conduction and convection. Rapid cooling requires high thermal conductance, and high thermal conductance requires higher applied power to open the actuator. In the present valve the thermal conductance has been designed to limit the power requirement to 1 Watt for the desired pressure and flow ranges, and actuation time (full open to full closed) is thus several hundred milliseconds. This speed is not rate limiting in setting flows for gas-phase analysis systems, since compressible gases flowing through small-bore tubing result in pneumatic time constants on the order of hundreds of milliseconds to seconds.

Laser doppler velocimetry was used to characterize the mechanical resonances of the valve actuator as evidence of high structural stiffness. Figure 6 shows a plot of amplitude versus frequency for an actuator chip placed on a shaker table; the laser was focused on the top of the actuator at a point 1.9 mm from the center of the chip. The fundamental piston mode at 7.39 KHz is in fair agreement with ANSYS modelling which predicted a first resonance at 8 KHz; the lower experimental resonance frequency is thought to be due to thinner nickel and silicon in the fabricated device than in the ANSYS model. Modes 2 and 3 are rocking modes; their separation in frequency is thought to be caused by the slight asymmetry introduced by the suspension split used to isolate the two ends of the heating resistor. Additional characterization up to 50 KHz (not shown) revealed ten higher-order modes.

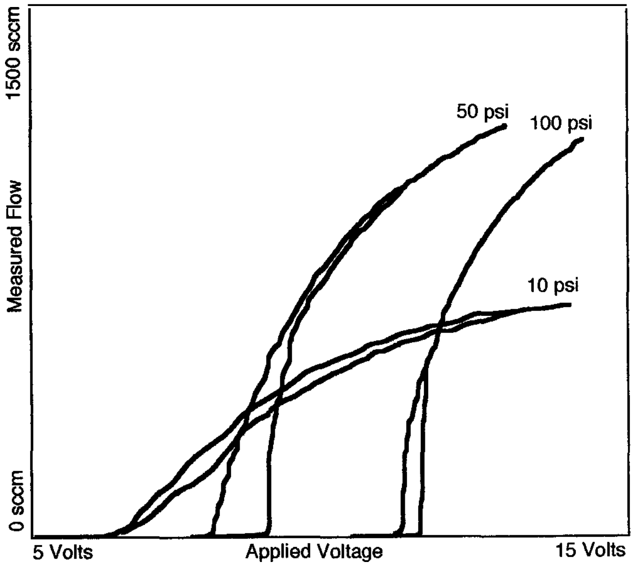

Figure 5. Flow versus applied voltage in helium at 10, 50, and 100 psi head pressures.

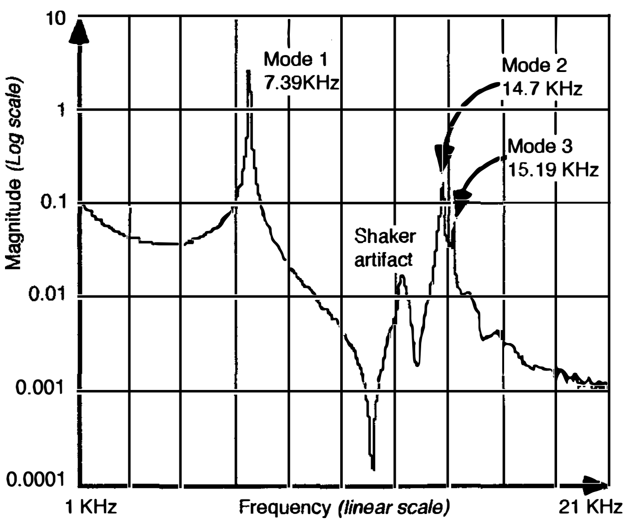

Figure 6. Experimental frequency response curve obtained using a laser doppler velocimeter focused on a valve actuator chip.

CONCLUSIONS

A robust silicon microvalve meeting the many criteria for use in gas phase analysis systems has been developed. This valve's range of operation constitutes an order-of-magnitude increase in both pressure and flow as compared to the performance of previous bimetallically actuated valves [3,4] and is in the same range as that of thermally actuated valves employing fluid expansion [1,5,7] or shape-memory alloy [2,6]. The improvement compared to previous bimetallic valves is made possible by an actuator using a torsion-bar suspension and a nickel-and-silicon bimetal combination, which allow larger valve dimensions and higher stress levels for consequent longer stroke and higher force. In addition, a novel orifice and seat configuration minimizes the requirements for force and power.

The authors believe that the simple fabrication process for this valve combined with its high reliability will provide a significant contribution to gas phase analysis systems.

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