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A low-power high-flow shape memory alloy wire gas microvalve

Henrik Gradin¹, Donato Clausi², Stefan Braun¹, Göran Stemme¹,
Jan Peirs², Wouter van der Wijngaart¹ and Dominiek Reynaerts²

¹ Microsystem Technology Laboratory, School of Electrical Engineering, Royal Institute of Technology,
100 44 Stockholm, Sweden

² Department of Mechanical Engineering, Katholieke Universiteit Leuven, 3000 Leuven, Belgium

E-mail: hegra@ee.kth.se

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Abstract

In this paper the use of shape memory alloy (SMA) wire actuators for high gas flow control is investigated. A theoretical model for effective gas flow control is presented and gate microvalve prototypes are fabricated. The SMA wire actuator demonstrates the robust flow control of more than 1600 sccm at a pressure drop of 200 kPa. The valve can be successfully switched at over 10 Hz and at an actuation power of 90 mW. Compared to the current state-of-the-art high-flow microvalves, the proposed solution benefits from a low-voltage actuator with low overall power consumption. This paper demonstrate that SMA wire actuators are well suited for high-pressure-high-flow applications.

(Some figures may appear in colour only in the online journal)

1. Introduction

Gas valves are fundamental building blocks in the automation industry. Microelectromechanical systems (MEMS) can potentially enable microvalves with small size, rapid response time, low power consumption and cost-efficiency through batch fabrication. Over the years many different types of microvalves have been designed and fabricated [1, 2]. However, to gain a foothold in the market, MEMS microvalves have to compete effectively with the mature technology of conventional valves. Primarily due to a poor performance-to-cost relationship compared to traditional gas valves, microvalves are not yet used as standard components in industry.

This work proposes microvalves with an actuation mechanism that allows large gas flow control, batch manufacturing and a small footprint area to limit the unit cost.

The two main microfluidic designs for gas microvalves [3] are diaphragm valves (also known as seat valves) and gate valves. The majority of microvalves belong to the diaphragm-type valve design (figure 1(a)) where a boss or diaphragm moves towards or away from a flow orifice and thereby closes or opens the valve, respectively [4, 5]. In 'conventional' seat-type microvalves, the actuator counteracts the pneumatic force

of the gas, and despite suggested pressure balancing schemes [6] or nozzle/seat optimization [5, 7], such valves feature limited flow/pressure performance per footprint area, which results in a high fabrication cost per flow control.

Gate valves regulate the flow by a gate moving perpendicularly to the flow (figure 1(b)) [8–11]. In these types of microvalves, the actuator does not directly perform work against the gas pressure, which results in reduced demands on its force output. In addition, it is possible to control large gas flows by using actuators with high displacement.

Despite the potential for large flow control, an inherent limitation of this design is the considerable leakage in the closed state, which makes gate microvalves unsuited whenever an airtight environment is required. However, this design constraint is far less stringent for high-pressure and high-flow applications where limited leakage is allowed, such as 3/2 way pressure controllers for the automation industry [3].

The first gate microvalves [9, 10] featured an in-plane gate that was controlling an out-of-plane flow. The power consumption of these valves was high, more than 1 W. A low-power version also exists; however, it features an external magnetic actuation [8], and therefore it does not offer a complete on-chip solution.

Figure 1. Illustration of the working principle of a seat/diaphragm valve (a) the flow regulating boss moves against the flow/pressure and a gate valve (b) the gate moving perpendicular to the flow.

Gate microvalves with in-plane flow and out-of-plane gate movement have also been presented [3]. A considerable advantage of this type of microvalves is that a smaller actuator and less footprint area can be used compared to gate valves with in-plane gate movement. Use of a thermal bimorph actuator was attempted in previous out-of-plane actuated gate microvalves [3]. However, the actuator failed in stability and displacement, and an external manipulator was required to test the flow performance.

For gas microvalve applications, a robust actuator is needed to avoid mechanical instabilities and to allow reliable performance. Furthermore, gate-type microvalves require actuators with large strokes to enable large gas flow control. Shape memory alloy (SMA) is therefore a promising microactuator material, having a volumetric work density of at least one order of magnitude larger compared to other actuation mechanisms [12]. Thin SMA films can be directly deposited onto MEMS structures, but the complex control of the film deposition and the limited mechanical stability of the final devices hinder their application as valve actuators [13]. Alternatively, bulk SMA material can be used and integrated onto the MEMS structure. Compared to thin NiTi films, using bulk SMA has the advantage of enabling more robust devices that have a wider range of performance and a more stable shape memory behaviour. To allow cost-efficient fabrication of gate microvalves using bulk SMA, manufacturing schemes compatible with batch fabrication have to be utilized. Methods for the wafer-level integration of bulk SMA material onto silicon microstructures have recently been developed and can be readily implemented for low-cost manufacturing of microvalves. Integration of TiNi SMA sheets onto patterned silicon wafers utilizing either adhesive bonding [14] or eutectic bonding [11] has been presented. The eutectic bonding integration has also been applied for the fabrication of a gate microvalve with high-flow control [11]. However,

this design relied on the pressure of the gas medium to open the valve, and the valve suffered from uncontrolled heating because of an uneven heat distribution from the external gold heater to the SMA element. Furthermore, SMA sheets are subjected to bending actuation, which exploits the material in an inefficient manner and results in low energy efficiency compared to SMA in tension [15].

For operation in tensile mode, SMA wires are ideal since they can be strained in near perfect tension, which maximizes the efficiency of operation. Very promising integration processes of NiTi wires on silicon for the creation of robust actuators have been reported using adhesive bonding [16], electroplating [17] and wire bonding [18]. The initial material cost for SMA wires is very low, since commercially available actuator materials are used.

This work analyses the potential of SMA wire actuators for gate microvalve applications. The first working front gate valve and the first gas valve driven by SMA wires are fabricated and evaluated. The performance advantage of SMA-wire-actuated gate valves consists of high deflections and more work at lower power consumption than SMA sheet actuators and other thermal actuators presented in previous gate valve designs.

2. Design

An SMA-wire-actuated gate microvalve can be designed to either operate in plane or out of plane. To avoid the need for the additional footprint area for the gate movement, the out-of-plane gate design is mostly suited. Haasl *et al* [3] presented three out-of-plane gate microvalve designs, and the valve with a gate moving in front of the orifice channel had the lowest footprint area relative to the flow control. The main drawback of this design is that a minimum distance is needed between

Figure 2. Illustration of the working principle of (a) the original front gate valve by Haasl *et al* [3], where a minimum distance is needed between the gate, the flow channel orifice to avoid the gate touching the orifice and (b) the improved front gate valve design where the gate instead moves away from the flow channel orifice.

Figure 3. Illustration of an SMA wire microvalve in the closed state (a) and open state (b).

the gate and the flow orifice due to the rotation of the gate towards the flow orifice (figure 2(a)). By rotating the gate away from the flow orifice instead, this limitation is removed. The leakage gap is then limited only by the fabrication tolerances (figure 2(b)).

SMA wires can then be placed onto this gate and cantilever, resulting in a normally closed valve as illustrated in figure 3. In the closed state, the air flow is partially blocked by the gate. In the actuated state, the SMA wires are resistively heated and contract, thus deflecting the cantilevers and opening the valve (figure 3(b)). When the current to the SMA is removed, the wires cool and the cantilevers stretch the SMA wires again, thus closing the gate (figure 3(a)). The actuator retains a residual deflection in the cold state [17].

3. Theoretical model

A theoretical model of the valve was created to study the influence of different design parameters. Figure 4 depicts the model and table 1 overviews design parameters.

The flow model is adapted from [19] and presents two equations covering choked sonic flow and subsonic flow, respectively:

$$\dot{m}_{\text{sonic}} = C_d A_{\text{eff}} \alpha(\gamma) \cdot \frac{P_{\text{in}}}{\sqrt{RT}}, \quad (1)$$

$$\dot{m}_{\text{sub}} = C_d A_{\text{eff}} \delta(\gamma) \cdot \frac{P_{\text{in}}}{\sqrt{RT}} \cdot \left(\frac{P_{\text{out}}}{P_{\text{in}}} \right)^{\frac{\gamma+1}{2\gamma}} \cdot \sqrt{\left(\frac{P_{\text{in}}}{P_{\text{out}}} \right)^{\frac{\gamma-1}{\gamma}} - 1}, \quad (2)$$

where

$$\delta(\gamma) = \sqrt{\frac{2\gamma}{(\gamma-1)}} \quad (3)$$

$$\alpha(\gamma) = \sqrt{\gamma \cdot \left(\frac{2}{1+\gamma} \right)^{\frac{\gamma+1}{\gamma-1}}} \quad (4)$$

The coefficient of discharge C_d accounts for the non-idealities of the flow through the orifice, and it has shown an empirical dependence on pressure and temperature. For pressures in the range of interest, a value of approximately 0.84 has been empirically found [19]. $\alpha(\gamma)$ and $\delta(\gamma)$ are gas-dependent functions of the specific heat ratio γ and T is the static temperature at the inlet to the microvalve. P_{in} and P_{out} are the inlet and outlet pressures, respectively. A_{eff} represents the effective area of the orifice, and its value depends on the configuration of the valve, either open or closed. The gas flow in the closed state can be divided in two components: (1) the flow under the gate, which depends on the initial actuator deflection; (2) the flow that leaks through the gap between the orifice and the gate, which is proportional to the gap size g_0 .

The first component is proportional to the orifice area s_1 under the gate:

$$s_1 = (\delta_{\text{closed}} + t_{\text{adhesive}}) \cdot W_{\text{orifice}} - H_{\text{elev}} \cdot W_{\text{elev}} + H_{\text{elev}} \cdot (W_{\text{orifice}} - W_{\text{elev}}) \quad (5)$$

for $\delta_{\text{closed}} > (H_{\text{elev}} - t_{\text{adhesive}})$ and

$$s_1 = (W_{\text{orifice}} - W_{\text{elev}}) \cdot (\delta_{\text{closed}} + t_{\text{adhesive}}) \quad (6)$$

for $\delta_{\text{closed}} < (H_{\text{elev}} - t_{\text{adhesive}})$.

The second component (leakage flow) is a function of the coordinate g_θ , which in turn depends on the bending angle θ . The side area s_2 can be computed as the sum of the two lateral areas $s_{2\text{-side}}$ and the top ($s_{2\text{-top}}$) and bottom ($s_{2\text{-bottom}}$) areas:

$$g_\theta = H_{\text{gate}} \cdot \sin(\theta) - \delta_{\text{closed}} \cdot \tan(\theta), \quad (7)$$

$$s_{2\text{-side}} = (H_{\text{gate}} - \delta_{\text{closed}}) \cdot (g_0 + 0.5 \cdot g_\theta) \quad (8)$$

$$s_{2\text{-top}} = W_{\text{orifice}} \cdot (g_0 + g_\theta) \quad (9)$$

$$s_{2\text{-bottom}} = W_{\text{orifice}} \cdot g_0; \quad (10)$$

hence,

$$s_2 = 2 \cdot s_{2\text{-side}} + s_{2\text{-top}} + s_{2\text{-bottom}}. \quad (11)$$

The effective area in the closed state is obtained by summing the two components:

$$A_{\text{eff,closed}} = s_1 + s_2. \quad (12)$$

The sonic and subsonic flows in the closed state can be computed by introducing equation (13) in equations (1) and (2), respectively.

In the open state, the flow is orifice-controlled, and the effective area equals the orifice area:

$$A_{\text{eff,open}} = W_{\text{orifice}} \cdot (H_{\text{orifice}} + t_{\text{adhesive}} - H_{\text{elev}}) + H_{\text{elev}} \cdot (W_{\text{orifice}} - W_{\text{elev}}). \quad (13)$$

Figure 4. Illustration of the valve model and parameters.

Table 1. Definition of symbols.

Parameter	Explanation	Value	
		Prototype	Optimization
$\dot{m}_{sub}$	Mass flow rate in the subsonic regime		
$\dot{m}_{sonic}$	Mass flow rate in the choked/sonic regime		
C_d	Coefficient of discharge		0.84
P_{in}, P_{out}	Absolute inlet and outlet pressures		
R	Gas constant		286.9 J/(kg K)
T	Gas temperature in K		298 K
γ	Ratio of specific heats (c_p/c_v)		1.4
$W_{orifice}$	Orifice width	800 μm	1000 μm
W_{elev}	Width of elevation	600 μm	1000 μm
W_{gate}	Width of the gate	1600 μm	1600 μm
$H_{orifice}$	Orifice height	200 μm	450 μm
H_{elev}	Height of elevation	50 μm	80 μm
H_{gate}	Height of the gate	320 μm	525 μm
$t_{adhesive}$	Adhesive layer thickness	25 μm^a	0 μm
δ_{closed}	Deflection in the closed state	80 μm	80 μm
g_0	Manufactured gap between the orifice and the gate	25 μm	5 μm
g_θ	Extra gap on the upper part of the orifice due to bending		
θ	Bending angle		
s_1	Flow area under the gate in the closed state		
s_2	Flow area between orifice and gate in the closed state		
$A_{eff.}$	Effective flow area		

^a Estimated value.

The model also accounts for the adhesive layer thickness and for the elevation in the orifice.

The flow is modelled as subsonic flow for $P_{out}/P_{in} < 0.528$, i.e. 90 kPa differential pressure at atmospheric outlet pressure, and as choked sonic flow at higher relative pressures

[20]. The model can then be used to predict the flow conditions; a plot of flow as a function of pressure is shown in figure 5 for a valve prototype design with the parameters in table 1. An optimized design, demonstrating the valve design potential, is also plotted in the same figure.

Figure 5. Flow-pressure characteristics as predicted by the model for the prototype design and an optimized design.

4. Fabrication

The fabrication of the first microvalve prototype consists of two parts, the silicon processing and the aluminium holder machining. The silicon processing starts with forming an oxide mask on a 4" silicon wafer followed by a Bosch deep reactive ion etching (DRIE) on the bottom side to form a flow channel. Thereafter, a second Bosch DRIE is performed from the top side to form the silicon cantilevers, the gate and the gap between the gate and the flow orifice (figure 6(a)) [16]. Prestrained NiTi SMA wires (Dynalloy Flexinol HT, with a nominal A_f transformation temperature of 90 °C) are then transferred onto the silicon wafer (figure 6(b)) and both mechanical and electrical connections are formed by Ni-electroplating (figure 6(c)), as presented in [17]. Finally, the wafer is diced into individual chips. The top and bottom sides of the silicon chip are shown in figures 7(a) and (b), respectively.

The holder processing starts with drilling an inlet port in an aluminium block (figure 6(d)). Thereafter, an elevation for the reduction of the cold-state deflection leakage as well as alignment structures is milled in the aluminium substrate (figure 6(e)). A flow channel is then drilled to connect the inlet port to the silicon flow channel (figure 6(f)). The top side of the holder is shown in figure 7(c).

Lastly, the silicon chips are glued with two component epoxy (Biltema Snabb-epoxy) onto the aluminium substrate (figure 6(f)). The glue is applied manually with a needle, carefully avoiding glue on the cantilevers and orifices. The assembled microvalve is shown in 7(d).

5. Evaluation

The microvalve prototypes were evaluated in a measurement setup as illustrated in figure 8. The inlet pressure to the device was set by a pressure regulator, while the outlet was kept at atmospheric pressure. Both the flow rate and the pressure were

Figure 6. Fabrication of the microvalve prototype. ((a)–(c)) Process flow of silicon structures [17]. (a) Bottom and top side deep reactive ion etching to form the inlet channel and silicon cantilevers. (b) Wafer-level transfer of SMA wires to an 7×7 array of silicon structures. (c) Wafer-level mechanical and electrical connection of the SMA wires to the silicon structures. Dice the wafer into single chips. ((d)–(f)) Machining of an aluminium holder. (d) Drill inlet port on the sidewall of the aluminium block and planarize the top surface by micromilling. (e) Mill alignment structures and elevation. (f) Drill hole connecting the inlet port in the holder to the inlet channel in the silicon chip. (g) Align the silicon chip to the holder and bond the two parts.

continuously measured with a mass flow sensor (Honeywell AWM5102VN, accuracy ± 400 sccm) and a pressure sensor (Motorola MPX2200DP, accuracy ± 8 kPa), respectively, and recorded via a computer using National Instruments LabView. In addition, the deflection of the gate was measured with a displacement sensor (Keyence LK-G32, accuracy ± 3 μ m). The devices were tested at a maximum pressure difference of 200 kPa, which was the limit of the pressure sensor.

5.1. Pressure flow characteristics

Pressure flow characteristic curves of the valve in the open state and in the closed state are compared to the corresponding theoretical model in figure 9. The actuation of the SMA wires was performed at 150 mA and 0.6 V, i.e. 90 mW. A slight

Figure 7. Microscope pictures of (a) top view and (b) bottom view of the silicon chip before assembly and (c) the top view of the holder before assembly. A photograph of the assembled valve is displayed in (d).

Figure 8. Measurement setup.

Figure 9. Measured flow as a function of pressure for a typical valve prototype in the open state and in the closed state. As a comparison the corresponding theoretical model from figure 5 is also plotted.

increase of the flow in the closed state was observed after the first actuation, which is attributed to an increased cold-state

Figure 10. Flow control (open-state flow–closed-state flow) for three different evaluated devices and compared to the theoretical model.

deflection of the actuator after the first actuation cycle [17]. The net controlled flow (flow in the open state–flow in the closed state) is similar between different devices as shown in figure 10 and measures 1600 ± 100 scm at 200 kPa, which is near the theoretically predicted value of 2050 scm.

5.2. Valve switching

To evaluate the response time, stability and flow control during valve switching the dynamic performance of the valve was tested. Measurements were performed up to 10 Hz (limited by the flow sensor response time of 60 ms) at different pressures, using rectangular voltage profiles with a peak value of 0.6 V and a resulting peak current of 150 mA, corresponding to a maximum power of 90 mW. The measured deflection and flow at 1, 2, 6 and 10 Hz at the constant relative input pressure of 200 kPa are plotted in figure 11.

Figure 11. Flow and gate deflection versus time for a valve actuated at 1, 2, 6 and 10 Hz, respectively. The relative inlet pressure was kept constant at 200 kPa.

6. Discussion

The microvalve prototypes successfully control large flow at high pressure as illustrated in figure 9. The actuator enabled a stable flow control without any reliability problem, vibrations or instability of the gate as has been the case in previous works [3, 11]. The flow was controlled successfully up to a pressure of 200 kPa, which was the limit of the pressure sensor. In the tested configurations the relative leakage, i.e. the closed-state flow relative to the open-state flow, is high with a leakage between 50% and 70%, depending on the initial deflection value in the closed state and on the mounting tolerances of the measured sample.

The theoretical model, both in the open and the closed states of the valve, corresponds well to the flow measurements (figure 9). The coefficient of discharge C_d of 0.84 also fits well with the non-idealities of the flow behaviour of this gate valve design. The theoretical model can be used to provide realistic predictions on the flow performance for the optimization of the valve design.

Figure 12 illustrates how the valve can be further improved to both decrease the flow in the closed state of the valve and increase the flow in the open state. The high flow in the closed state is due to a high flow underneath the gate and a high flow between the gate and the orifice.

The flow underneath the gate is mainly determined by the cold-state deflection of the actuator. The cold-state deflection can be tuned by varying the cantilever thickness, width, length and the amount of prestrain for the wires before integration. When designing the valve, a trade-off is needed between the need of minimizing the cold state deflection to reduce the leakage and the desire to maximize the stroke to increase the flow in the open state [16]. Instead of, or as an addition

Figure 12. Schematic of the flow control in the prototype (a) compared to that in an optimized design (b). In the optimized design the closed-state flow is decreased by both reducing the leakage gap between the orifice and the gate and by matching the size of the elevation to the cold-state deflection and the reduced adhesive layer thickness. In the open state, the flow is maximized by increasing the size of the inlet orifice to match the height of the hot-state deflection.

to, lowering the cold-state deflection, the flow underneath the gate can be reduced by placing an elevation in the orifice that matches the cold-state deflection. However, in

the prototype design the elevation height was lower than the combined adhesive layer thickness and cold-state deflection. In addition, the elevation was designed to have 100 μm alignment tolerances towards the orifice side walls (figure 4) and towards the gate for manual assembly. In an optimized design, both the adhesive layer thickness and the alignment tolerances can be reduced by replacing the milling of the holder and manual alignment with MEMS processing and automated assembly or accurate wafer-level packaging, thus reducing the leakage underneath the gate.

The gap between the gate and the orifice, g_0 , also contributes to high leakage. For the prototypes, the gap between the gate and the orifice is 25 μm , since plastic foil masks with a limited resolution were used for the fabrication. However, by using quartz glass masks the resolution can be improved and the gap size would then only be limited to the etching process. A typical DRIE aspect ratio achievable is 30:1 [21], but the state-of-the-art machines can achieve more than 100:1 [22]. With a wafer thickness of 500 μm and etching performed from both sides, expected leakage gaps are 8 μm for typical etching systems but as low as 2 μm is achievable with the latest DRIE systems. The cold-state deflection also induces a tilt on the gate, θ , thus increasing the gap, g_θ , between the upper part of the gate and the orifice (figure 4). For a cold-state deflection of 50 μm and 3 mm long cantilevers, the extra gap distance at the bottom of the gate is negligible (since it approximately coincides with the neutral plane), and at the top it is 7 μm . This effect is hard to reduce, except by lowering the cold-state deflection as described above.

With a manufactured leakage gap of $g_0 = 5 \mu\text{m}$ and a cold-state deflection almost completely reduced by an elevation, flows in the closed state lower than 1000 sccm at 200 kPa can potentially be achieved as shown in figure 5.

The open-state flow is mainly determined by the actuators hot-state deflection and the flow orifice dimensions. The L-shaped flow channel in the holder, fabricated for easy assembly and to simplify measurements, was designed wider than the flow orifice to reduce the effect of turbulence and fluidic resistance. The lowest of the actuator deflection and orifice height therefore determines the open-state flow. For 3 mm long cantilever arms, a deflection of over 450 μm can be achieved [17], while the current orifice height is 200 μm . By increasing the height of the orifice channel to match the actuator deflection, the open-state flow can be doubled. For the prototype design, the orifice height was limited since a 300 μm thick wafer was used. In addition to increasing the orifice height, the orifice width can be increased to the full gate width. However, for the prototype valve the width was designed to only half of the maximum width to reduce the pressure drop over the cantilevers and reduce the risk of instability.

The above design improvements can be applied to achieve an open-state flow increase from 4600 sccm for the current prototype design to 13 000 sccm for an optimized design at 200 kPa, as demonstrated by the theoretical model and figure 5. Combining the open- and closed-state flow design improvements result in a relative leakage lower than 10% (figure 5).

The valve bandwidth was measured up to 10 Hz as displayed in figure 11. A flow switching of more than 1600 sccm at 200 kPa was successfully achieved up to 10 Hz. The valve control was stable with no vibrations or fluttering of the gate as seen from the deflection measurement. However, the measured flow after switching has shown a stabilization time, which is likely related to the flow sensor's response time of 60 ms. This stabilization time affects the flow measurement at 10 Hz to a large degree. It can also be noted from the deflection measurements that the cooling of the wires takes place faster than the heating, because of the increased heat transfer caused by the air flowing over the wires. An increased input power can therefore further increase the bandwidth of the actuator by allowing faster heating.

The temperature increase of the gas is low. If all input power to the actuator of less than 100 mW is assumed to be dissipated through heating only the air flow, then this heating effect results in a temperature increase of less than 4 $^\circ\text{C}$ for flows larger than 1000 sccm. The heating of the gas also decreases proportionally with the increase in the gas flow.

The results were repeatable between different devices and the flow regulation was stable. The double cantilever configuration of the silicon bias springs is beneficial for two reasons. Firstly, placing the bias cantilevers apart prevents the gas flow from impinging on them directly and therefore it drastically reduces instabilities, and secondly, the gas flow is directed towards the SMA wires, thus improving the cooling speed of wires through forced convection and making it possible to achieve a high bandwidth.

6.1. Comparison to previous work

Three aspects are of main importance for MEMS microvalves to be attractive for practical applications. (1) The valve should control high flows. (2) The valve should have low manufacturing cost, which can be achieved by having a small footprint area and batch manufacturing. (3) The power consumption should be as low as possible to allow powering by control signal standards in embedded systems. In addition, there are applications also demanding flow control at high pressures and/or low leakage. Since some of these aspects are contradictory, the ideal valve is difficult to build, and the most important factors for the intended application need to be chosen. The manufactured valve prototype performance and the potential improvement of the valve from the theoretical model presented are compared to existing the state-of-the-art high-flow microvalves with integrated actuation in table 2, figures 13 and 14. Considering flow control per footprint area, this work shows pneumatic performance that are among the highest current state-of-the-art devices, and by applying the design improvements previously discussed the flow control can be further increased. The SMA-wire-actuated microvalve also offers the lowest power consumption with respect to existing high-flow microvalves, and is only outperformed by PZT microvalves, which however provide an order of magnitude lower flow rate per footprint. The SMA wire actuator valve has more than one order of magnitude lower power consumption than the gate valves with in-plane actuation [9, 10] and has two

Table 2. Comparison of gas microvalves with high-flow control. (The footprint was selected as the batch manufacturable part of the valves, not including housing. n/a indicated that the data are not found in the literature.)

Design and type	Batch manufacturable footprint (mm × mm)	Relative leakage	Input power	Voltage	Response time
This work (out-of-plane gate, integrated SMA)	1.6 × 5	50%–70% (<10% possible)	90 mW	0.6 V	50 ms
Gradin <i>et al</i> (out-of-plane gate, integrated SMA) [11]	1 × 3.3	10%–30%	350 mW	1 V	300 ms
Walters <i>et al</i> (in-plane gate, integrated thermal) [9]	4 × 4	6%–10%	1.1 W	30 V	50 ms
Williams <i>et al</i> (in-plane gate, integrated thermal) [10]	2.5 × 5.0	~0%	1.4 W	20 V	500 ms
Zdeblick <i>et al</i> (seat valve, phase change) [4]	6.3 × 6.6	0%	0.8 W	n/a	n/a
Park <i>et al</i> (seat valve, PZT) [5]	10 × 10	0%	0.16 μ W	60 V	0.7 ms

Figure 13. Flow control/footprint comparison of this work and the theoretical model to the state-of-the-art high-flow microvalves.

Figure 14. Flow control/power comparison of this work and theoretical model to the state-of-the-art high-flow microvalves.

orders of magnitude lower voltage than the PZT microvalve [5]. The main drawback of the SMA wire valve compared to the other valves is the high relative leakage. However, this can be addressed by an improved design as discussed above (figure 5).

7. Conclusion

SMA wire actuators have been applied for the first time for the control of high gas flows in gate microvalves. A front gate microvalve prototype was fabricated and compared to the current state-of-the-art microvalves. The measured pressure-flow characteristics are very stable, and benefit from the robust actuator performance and its capability to withstand the forces generated by the gas. The SMA wire actuator was able to control flows of more than 1600 sccm at a pressure drop of 200 kPa. Over 10 Hz flow control was feasible with an actuation power of only 90 mW. The first prototype featured high relative leakage in the closed state, due to a non-optimized design and to fabrication constraints. However, the flow control, low power consumption and stability that this microvalve concept proved are very promising for the creation of record performing microvalves.

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