A WAFER-LEVEL, HETEROGENEOUSLY INTEGRATED, HIGH FLOW SMA-SILICON GAS MICROVALVE

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ABSTRACT

This paper presents a novel gas microvalve design in which a flow control gate is opened by the pneumatic pressure and closed by a SMA actuator, allowing large flow control. The microvalves were fabricated using a novel wafer-level Au-Si eutectic bonding process for TiNi to silicon integration. The resulting microvalves demonstrate a record pneumatic performance per footprint area; a microvalve of only $1 \times 3.3 \text{ mm}^2$ footprint successfully controls 3000 sccm at a pressure drop of 130 kPa.

KEYWORDS

Microvalve, shape memory alloy, SMA, TiNi, eutectic bonding, wafer bonding, heterogeneous integration

INTRODUCTION

Over the years many different types of gas microvalves have been designed and fabricated [1]. So far, they have had a limited performance per footprint area ratio, resulting in a poor performance per cost compared to conventional gas valves. This work addresses this shortcoming by developing high-performance, large flow control valves with a small footprint area that can be manufactured batch-wise and therefore at potentially lower cost. There are two main designs for gas microvalves [2]. One is the diaphragm or seat valve design (Fig. 1(a)), where a boss or diaphragm moves towards or away from a flow orifice, and thereby closes or opens the valve, respectively [3]. Despite suggested pressure balancing schemes [4] or nozzle/seat optimization [5], such valves are inferior in terms of the absolute flow they can control compared to gate valve designs. Gate valves regulate the flow by a gate moving perpendicular to the flow (Fig. 1(b)) [2, 6, 7]. This type of design allows for gas flow control orders of magnitude larger than seat valves, but has the inherent limitation of considerable leakage flow in the closed state. However, the latter is acceptable in specific applications in the automation industry e.g. in IP converters [2].

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

Three fundamental gate valve configurations can be distinguished [2]. Designs with in-plane flow and out-of-plane gate actuation are the most promising for reducing the valve footprint area, because no footprint area needs to be reserved for the gate movement. All of the previous reported out-of-plane actuated gate microvalves featured external actuation. Attempts with integrated thermal bimorph actuators failed since the actuators were not strong enough to withstand vibration and forces caused by the high flow or pressure of the gas medium [2]. For gas microvalve applications, a strong and robust actuator solution is therefore needed. Shape Memory Alloy (SMA) is a promising actuator material because of its high work density [8]. SMA actuators have previously been used in seat valves [1], but not in gate microvalves. At low temperatures, the SMA material is easily deformable and stays deformed also after the deforming stress has been removed. Upon heating the material transforms to the initial shape. Despite the advantages of SMA, its use in MEMS has been limited mainly because of the difficulty of reliable and cost efficient integration [8]. A promising method for patterning of SMA TiNi-sheets and wafer-level adhesive bonding onto a patterned silicon wafer has recently been demonstrated [8]. The long term stability of the adhesive bond is potentially limited under high strain cycling actuation and has so far not been investigated. To avoid polymers in the process, this work introduces an alternative method for SMA-to-silicon bonding method based on Au-Si eutectic bonding [9]. To the author's knowledge, this is the first wafer-level eutectic bonding method for thermally mismatched metal sheets and silicon substrates, overcoming problems with large thermal stresses. Based on this novel SMA integration concept, this work presents a new design of highly miniaturised SMA microvalves that feature a record pneumatic performance.

MICROVALVE DESIGN

This work introduces a novel microvalve design (Fig. 3). The design features the main properties of a gate valve through the flow controlling element consisting of a gate moving perpendicular to the flow, which allows for controlling a large flow (Fig. 4(a) and (b)). The inherent gate valve leakage flow is guided from the inlet, via a narrow leakage gap, to the area underneath the SMA actuator and then sideways around the SMA to the outlet port. Similar as in seat valve designs, the valve is opened by using the pneumatic energy of the medium. Unlike in seat valve designs, where the entire inlet-outlet pressure drop acts over the entire area of the flow orifice, in this new

Figure 3: Novel SMA gate microvalve design.

(a) The pressure load $P_s - P_{out}$ acting on the SMA actuator in the cold state pushes the actuator and gate upwards and opens the valve.

(b) When the SMA actuator is heated the pressure load is counteracted by the SMA shape recovery and the valve closes.

Figure 4: Operation principle of the valve.

hybrid design, the leakage flow path generates a pressure P_s underneath the SMA actuator, with $P_{out} < P_s < P_{in}$. Hence, only a fraction of the inlet-outlet pressure drop acts on the actuator. The valve is closed by heating the SMA actuator (Fig. 4(b)), which triggers the SMA shape recovery and counteracts the pressure load, $P_s - P_{out}$. The valve actuator material is a cold-rolled TiNi SMA alloy sheet with the excellent characteristics of bulk TiNi material. This actuator material is more robust and able to counteract larger pressures than thermal bimorph actuators, as previously used in out-of-plane gate valves [2].

FABRICATION

The wafer-level fabrication process consist of three parts; the microstructuring of two 4 inch silicon substrates (Fig. 5.1), the SMA machining (Fig. 5.2) and the heterogeneous integration of the SMA and the Si substrates (Fig. 5.3). For the 320 μm thick top silicon wafer an oxide mask for the gate is defined on the backside and a recess is DRIE-ed on the frontside (Fig. 5a). The wafer backside is sputter-etched with Ar and a 400 nm Au layer is sputter deposited. The Au is patterned and the flow channel and gate are DRIE-ed (Fig. 5b). On the bottom 320 μm thick sili-

Figure 5: Process flow of the microvalves

Figure 6: Backside of the patterned TiNi sheet with integrated heaters before it is integrated onto the silicon.

Figure 7: The final fabricated wafer stack of SMA microvalves.

con wafer a 20/400 nm TiW/Au layer is sputter deposited and patterned to match the selective bonding region with the top silicon wafer. During the subsequent selective Au-Si eutectic bonding [9], in vacuum with a tool force of 3 kN and at 400 °C for 10 min, the absence of Au on the gate region prevents the bonding of the gate to the bottom wafer (Fig. 5c). Two DRIE steps are then performed to separate the gate from the flow channel on the top wafer and form an inlet port in the bottom wafer (Fig. 5d). The frontside is prepared for the SMA integration by HF removal of the native oxide, air exposure for 3 hours, and a 400 nm Au sputter deposition (Fig. 5e). This specific treatment ensures a higher bond yield as compared to Ar sputter etching and in-situ Au deposition. The SMA machining starts from a 10x10 cm², cold-rolled TiNi sheet ($A_f \sim 50\text{--}60\text{ }^\circ\text{C}$), commercially available from Johnson Matthey. For increased electrical insulation, a 100 nm PECVD SiO₂ layer is deposited on both sides. Thereafter, a 50/400 nm TiW/Au layer is sputter deposited on both sides. The SMA sheet is attached to a blue wafer dicing tape (Nito Denko) and a carrier wafer for easier handling [8]. The gold layers are patterned on the front side to form heaters, and on the backside as an etch mask for the subsequently HF/HNO₃ etching [8] to form the SMA cantilevers. The Au bond pads are defined from the Au mask. The patterned SMA sheet (Fig. 6) is removed from the temporary carrier and placed on a glass wafer for alignment to the Si wafer. The wafer stack is subsequent Au-Si eutectically bonded in vacuum at 2 kN and 400 °C for 10 min and the result is shown in Fig. 7. The typical yield of the SMA-to-Si eutectic bonding was between 50 and 70%. More recent tests on dummy wafers, using a thicker gold layer, showed a perfect bonding yield. As a last step, the wafer is diced, hereby removing the mechanical connection of the gate to the surrounding silicon wafer. Pictures of a resulting microvalve are shown in Fig. 8.

Figure 8: Top view and side view of a fabricated microvalve.

VALVE MEASUREMENTS

For the pressure-flow characterisation, the microvalves were epoxy glued onto a metal manifold and the inlet was coupled to an air compressor while the outlet was left open to the atmosphere (Fig. 9). The flow and pressure were continuously measured with a flow sensor (Honeywell

AWM5102VN) and a pressure sensor (Smartec SPD100G) and recorded via a computer using National Instrument's LabView. The input pressure to the valve was set by a pressure regulator on the air compressor. The upper pressure limit was 200 kPa due to the limitations of the tubings to the metal manifold.

Figure 9: Illustration of the measurement setup for the valve characterisation.

Because some devices had insufficient heater-to-SMA electrical insulation, the actuation characterisation was performed using a hotplate at 170 °C and at 20 °C to generate the hot and cold state, respectively. The open and closed state pressure-flow characteristics of a valve are shown in Fig. 10.

Figure 10: Measurements of the air flow plotted against an up-ramping and down-ramping inlet pressure in the open and closed state, respectively.

A flow difference of between 500 and 3500 sccm between closed and open state is achieved at 130 kPa relative valve inlet pressure, and this for a valve footprint area of only 1x3.3 mm². These values are for a valve with effective actuator length of 1.4 mm from the base to the gate.

Furthermore, there is a pressure-flow hysteresis for the cold, open valve state. This can be attributed to the plastic deformation of the SMA during the first pressure up-ramping, once the pressure P_s becomes high enough to plastically deform the SMA cantilever, which causes a large increase in flow. During subsequent down-ramping of the pressure, the SMA remains plastically deformed,

Table 1: Comparison of valve performance for gas microvalves.

Design and type	Flow switched (sccm)	Pressure drop (kPa)	Footprint (mm x mm)	Pneumatic performance/footprint (sccm/kPa/mm ²)	Relative pneumatic performance/footprint
This work (out of plane gate, integrated SMA)	3000	130	1 x 3.3	6.99	100%
Walters et al. (in plane gate, integrated thermal) [6]	5000	69	4 x 4	4.53	64.76%
Haasl et al. (out of plane gate, external actuation) [2]	3400	95	2.3 x 3.7	4.21	60.14%
Williams et al. (in plane gate, integrated thermal) [7]	900	50	2.5 x 5.0	1.44	20.59%
Zdeblick et al. (best seat valve, phase change) [3]	5000	140	6 x 6	0.99	14.19%

hence the flow does not decrease to its original value without heating the actuator. The relative leakage is $< 15\%$ beyond the inset of plastic deformation at 80 kPa inlet pressure.

In another experiment, flow switching was performed at a fixed relative inlet pressure of 130 kPa with an effective cantilever length of 2.25 mm. The switching performance is shown in Fig. 11. The valve successfully switches a flow difference of 2300 sccm at 130 kPa.

Figure 11: Switching of a valve at 130 kPa at 20 °C and hot-plate of 170 °C .

DISCUSSION

The amount of flow controllable by a microvalve is related to the pressure drop over the valve and also on the size of the microvalve. A relevant measure to compare different types of microvalves is the pneumatic performance normalized to the key cost controlling parameter, which is here defined as the controlled flow per the specific pressure drop, divided by the MEMS footprint area of the valve. With this measure a performance comparison of different microvalves can be made, as shown in Table 1. All gate microvalves show significantly higher performance compared to seat valves, and our novel design has the highest performance of all microvalves with integrated actuator reported this far.

CONCLUSION

This paper demonstrates the first wafer-level integration of SMA to silicon by Au-Si eutectic bonding, resulting in microvalves with a flow control of 3000 sccm at 130 kPa and an active MEMS footprint of only 3.3 mm². These valves have a performance/footprint of 6.99 sccm/kPa/mm², which is higher than previous microvalves with integrated actuators.

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