Towards Batch Integration of SMA into Microsystems: An Actuator Prototype

D. Clausi, J. Peirs, D. Reynaerts

Katholieke Universiteit Leuven, Department of Mechanical Engineering, Division PMA

Abstract

Shape Memory Alloys have a considerable potential for integration into microsystems, where scaling down of their size allows favorable exploitation of the intrinsic adaptive capabilities, providing an actuation mechanism for applications (e.g. micropneumatics) requiring large force control and large actuator stroke. However, the implementation of these materials into actual structures is rather complex and mostly confined to depositing thin NiTi films onto certain target substrates, resulting in devices having a relatively high cost-per-piece.

This paper is aimed at investigating a novel approach for batch integration of SMA to microactuators, which might provide a cost-effective alternative to thin film technology while enhancing functional properties and design flexibility. Indicative requirements for the actuator design have been drawn from typical microvalve applications. In order to evaluate the actuator performance, brass microcantilevers have been produced, with prestrained SMA thin wires bonded on top of them, eccentrically with respect to the cantilever's neutral plane. The activation of SMA element is obtained by direct heating through electrical current. The bending actuation of the cantilever leads to large strokes, expected to match the requirements of a wide range of applications.

Keywords: SMA, actuator, Microsystems, Micro-electro-mechanical-system (MEMS), micro-fluidics, microvalves

1. Introduction

In the recent past, the field of Microsystems has been subjected to growing attention from both industry and research community. Microsystems have been recognized as having the potential to revolutionize the performance of a wide range of products by merging silicon-based microelectronics with micromachining technologies, thus enabling complete systems-on-a-chip to be realized and allowing novel functionalities at reduced costs.

Certain classes of applications, namely microvalves, have been found particularly attractive when produced with micromachining technologies, having the potential to achieve control of large gas flows at relatively large pressure differences, with the rapid response time and low power consumption offered by microsystems. Furthermore, the perspective of batch production promises a cost-efficient approach to the production of single microvalves and opens up the integration of many devices on a common fluidic plate, enabling a modular approach in designing microfluidic systems.

Several microvalves, using different actuation mechanisms, have been investigated by many research groups in the last years. Despite the wide variety of devices that have been built and tested, the basic configuration of microvalves can be divided in two main groups: seat valves an gate valves (Fig.1).

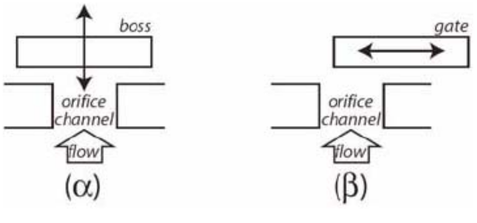

Fig.1: Working principle of seat valve (α) and gate valve (β)

Seat microvalves are also known as "membrane-type" and are characterized by an actuation mechanism that counteracts the large pressure forces controlled by the valve. In order to allow for a large gas flow, a large valve stroke is needed.

An interesting approach in designing such microvalves is presented in [1], where multiple circular nozzles are expected to increase the flow capacity when compared to a single orifice of the same area, while keeping the required actuation force constant.

In gate microvalves, the static pressure and valve actuation are perpendicular ("cross-flow") and therefore do not counteract each other. This valve design removes the requirement on the actuator's high force output. Nevertheless, large stroke actuators are needed to obtain large gas flows. This configuration lacks contact between gate and orifice, which means that some leakage cannot be avoided.

As clear from the above described basic valve configurations, a common requirement for effective control of gas flows at micro-level is a robust high force/high stroke actuation mechanism. Another crucial factor is the availability of such microactuators at low unit cost. For this reasons, gas microvalves have not fulfilled their maximum commercial potential yet, primarily for the cost-per-performance ratio of today's devices, whose miniaturization is limited by technological constraints and low energy densities of conventional actuation principles at small scale.

In this context, the application of shape memory alloys for actuation of micropneumatic devices might bring a relevant technological breakthrough.

SMA materials exhibit the highest energy density amongst current MEMS compatible materials and, importantly, as size is reduced towards the micro-scale, they benefit from improved heat transport, which increases their response speed. Other remarkable advantages of SMAs for micro-applications are their simplicity, clean operation and low voltage requirement, which make them suited for CMOS processing [2, 3, 4].

Most of the current efforts for the implementation of

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SMAs into microsystems are based on thin film technology [5,6]. Despite their attractiveness in terms of batch fabrication, the techniques used for depositing thin NiTi films onto target substrates (e.g. vacuum vapour deposition and sputtering) require expensive equipment and present several problems in terms of composition control and prestraining of the deposited material[3,6,7].

An alternative approach is based on cold-rolled SMA sheets, which has been proven successful to a certain extent and rather promising.

Kohl et al.[8] used SMA rolled sheets of 95μm thickness operated in bending mode to actuate microvalves, obtaining controlled pressure differences and gas flows respectively of 100kPa and 1200 Standard ccm.

More recently, S. Braun et al.[9] reported on the fabrication of a NiTi-SiO_2-gold trimorph microactuator. The NiTi was etched out of a cold-rolled sheet 20μm thick, pre-stressed by the dielectric layer consisting in 2μm thick SiO_2 PECVD deposited, and actuated by resistive heating through the 150nm thick gold layer evaporated on top of the structure. The observed stroke of the unloaded 3mm long actuator was about 730μm, with a power requirement of 20 mW.

One potential limit of rolled sheets is the detrimental effect of bending actuation on the efficiency of the actuator, being the energy efficiency of SMA in bending mode lower than the one in tension mode.

Cost-effective integration of SMAs into microsystems is believed to be viable by the authors by using prestrained thin fibres in combination with Si micro-cantilevers, which would serve the role of bias spring. With SMA wires placed eccentrically with respect to the neutral plane of each cantilever and fixed at their ends, the actuation mechanism could exploit the high recoverable strains of the SMA, while keeping the stresses into the Si cantilever well below the elastic limit of the material.

The approach envisioned to fabricate such actuators at wafer level starts from a SOI wafer and is based on standard IC processing for patterning of the Si structures: front side DRIE to fabricate the cantilevers and obtain the overlap for out-of-plane placement of SMA wires and back side DRIE to release the cantilevers. The actual integration of the active elements is achieved by spinning the adhesive that bonds the SMA fibers onto the Si substrate, deposit the prestrained fibers and finally cure the adhesive locally at the fixing points by exposing it with UV light. Contact pads ensure electrical contact between the active material and the power source via electrical wires contacted by conventional wire bonding.

As feasibility study for implementation of SMA fibers onto the cantilevers and in order to evaluate the performance of the actuators, some prototype structures have been fabricated. Conventional production techniques have been used in order to make the process easier and faster and avoid dealing with mask design and fabrication and with setting up of a complete photolithographic process, which at this stage would have been premature.

The fabrication process of the actuators and some preliminary results are reported in the next sections.

2. Fabrication of SMA microactuator prototype

The main effort required in the production of prototypes of SMA microactuators involves the fabrication of the cantilevers. Brass has been selected as substrate material for the production of these structures, in view of its easy machinability and favorable mechanical (E modulus fairly close to the one of Si) and electrical properties (good conductivity, favorable for the subsequent spark erosion process). A sheet of 600μm thickness was cut in rectangular shape of 60x30mm size by spark erosion and eventually machined by micro milling to obtain the desired thickness for the cantilever and the supports for the SMA wire. For this purpose, groups of 2 pockets (respectively $3x1x0.53mm^3$ and $1x2.5x0.53mm^3$ size) were milled into the brass sheet. Reference holes were also made, to serve as alignment marks for the SMA wire and starting holes for the subsequent sparking process.

A Φ37.5μm Flexinol™ wire, previously cleaned in Acetone, was clamped to a vertical support, with a mass of 17g crimped at its free end. Electrical contacts were made at the two ends of the wire and connected to a DC source. The actuator wire was subsequently cycled under constant load, with a resulting stress of 150MPa.

The brass plate was eventually positioned with respect to the SMA wire, using the holes previously machined as reference. Strain gauge glue (X60) was used to fix the wire onto the substrate at discrete locations (see Fig.2). UV curing glue was used in other samples instead of X60, displaying good bonding performance.

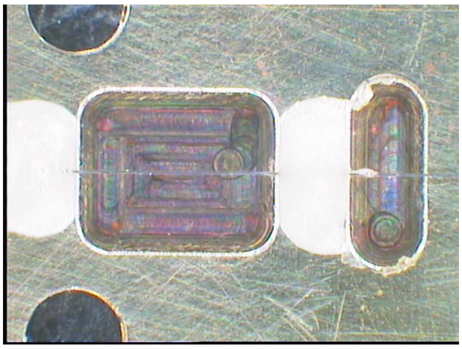

Fig.2. Detailed view of SMA wire glued onto brass substrate. It is possible to see the two reference holes and the pockets milled to provide out of plane placement of the SMA element.

The following step consisted in spark eroding the brass plate by wire EDM to fabricate and release the cantilever structures. The resulting actuators were 3mm long and 0.5mm wide between the droplets of glue, with an anchor of 2x2.5mm hosting the glue and providing room for one of the electrical contacts. The cantilever thickness was 70μm, according to design. The final configuration of the microactuator is depicted in Fig.3.

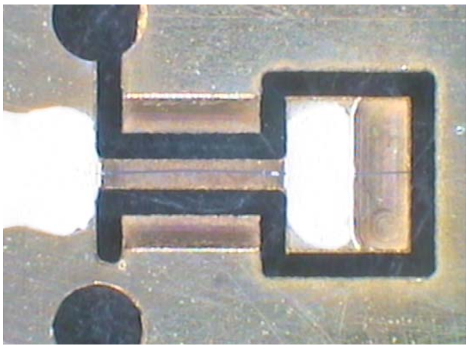

Fig.3. Microactuator released from substrate. The actuation length of the SMA wire, between the two fixed ends, is 3mm.

3. Testing procedure and results

Resistive heating was used to induce the phase transformation of the SMA material, for which reason electrical contacts were needed. Since the brass substrate has a much lower electrical resistance compared to the SMA wire, contacting the latter directly onto the cantilever would result in a parallel arrangement that would draw most of the current to the cantilever instead of the SMA wire, leading to highly inefficient actuation. For this reason, an open circuit has been made with respect to the brass cantilever: at its free end, the SMA fiber and the electrical wire were contacted directly onto the metal, while on the clamped side they were bonded onto the insulating layer of glue. The resulting electrical circuit was then connected to a DC source to provide current for resistive heating of the SMA element.

Objective of the testing phase has been the assessment of the general behavior of the fabricated device, leaving the thorough investigation of its performance to a later stage, when silicon microstructures designed for specific applications and with strictly defined requirements will be available.

Despite the non optimal design and production process used to fabricate the actuators, the observed performance under actuation featured a stroke in the order of 0.5mm (theoretical value) at a frequency of about 1.5Hz and power consumption of 120-140mW. In particular, the high stroke displayed is expected to match the requirements of knife gate valves, being the typical orifice high in the order of 250 – 300μm [10]. The actuator is shown in closed and open configuration in Fig.4

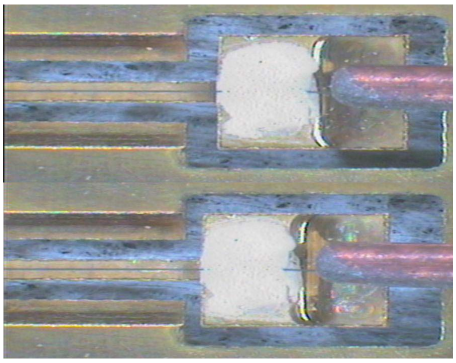

Fig.4. Actuator in rest position (upper image) and actuated configuration (lower image).

The measured values can be sensibly improved by reducing the droplet size of the glue and using electrical insulating material as substrate with contact pads patterned onto its surface. The actuator could then be contacted on the clamped side only, leaving the free end of the cantilever unloaded. Using silicon as structural material will also allow higher maximum stresses in the cantilevers, thus providing a more effective reset mechanism.

4. Conclusions

Integration of SMA material into microsystems has been pursued in the present work. Actuators based on thin SMA fibers bonded on cantilever structures were designed, produced and tested, showing attractive performances. The work has served the purpose of demonstrating the feasibility of this approach for applications where high work outputs are required.

The concept hereby described has several advantages when compared to conventional implementation strategies of SMA into microstructures: it is based on off-the-shelf components (SMA wires and commercial adhesives), therefore resulting into cheaper devices; It is readily implemented into Si microstructures, by depositing the wires automatically in place and selectively curing the adhesive; it allows a wide design flexibility, in terms of prestrain of SMA wire, number of wires on a single actuator, positioning with respect to the neutral plane of the cantilever. The latter point makes it possible to tailor the performance of the actuator, in terms of force-displacement characteristics, on the application's needs.

Future work will focus on fabrication of actuators on Si wafers, using conventional clean room technologies to etch the cantilevers and spinning or automatic dispensing techniques to deposit the glue for bonding the wires onto the substrate.

Acknowledgements

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