Wafer-scale manufacturing of robust trimorph bulk SMA microactuators

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Abstract

This paper demonstrates the concept of wafer-level fabrication and integration of robust bulk SMA microactuators based on adhesive bonding of cold-rolled SMA sheets to silicon wafers. Contact printing of an adhesive polymer ensures a selective bonding when transferring full SMA sheets to silicon structures on a patterned wafer. The induced stress of a thin dielectric film deposited on top of the SMA sheet ensures a stable and built-in reset mechanism of the actuators. The trimorph microactuators can be actuated by indirect resistive heating through a thin metal film. We report on the successful wafer-scale fabrication of actuator cantilevers and their characteristics. First test cantilevers show a cold-state deflection of 300 µm which, however, is limited by the silicon substrate. Upon heating, the cantilever shows a stroke of approx. 80 µm.

Keywords: SMA, microactuators, wafer-level integration, adhesive bonding

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1. Introduction

Shape Memory Alloy (SMA) materials can be easily pseudo-plastically deformed at temperatures below the transformation temperature. Upon heating above the transformation temperature, the material recovers the initial shape and when hindering the recovery, the material generates high forces with the energy density exceeding that of other actuation principles by at least one order of magnitude [1].

In most cases, the SMA is heated by electrical resistive heating – however, the necessary electrical contacting is difficult because of the stable native oxide of the SMA. Furthermore, the power consumption is relatively high [1].

To obtain an actuator structure, the SMA material must be deformed after the heating cycle at temperatures below the transformation temperature by an external bias spring (cold-state reset).

Basically, there are two different approaches to integrate SMA material in microelectromechanical system (MEMS) devices. One method is to fabricate the SMA actuator structure and the MEMS structure separately from each other and integrate them subsequently in a per-component assembly [2]. The cold-state reset is provided by a mechanical obstruction that pre-stresses the SMA component during the assembly. However, the per-component assembly is not batch compatible and therefore results in unacceptable high costs, which outbalances the featured advantages such as the availability of NiTi-foils in a wide thickness range and with reproducible bulk material characteristics.

Another method is to directly sputter deposit SMA material onto the MEMS structures [3]. However, sputter deposition of SMA is complicated and a subsequent annealing at high temperatures is necessary, which potentially causes problems with interdiffusion of SMA into the substrate as well as incompatibility issues with other processing steps. Furthermore, the film thickness and therewith the mechanical performance of the SMA is limited. However, this approach features an integrated cold state reset mechanism by built-in film stresses.

Previously, the authors of the present paper reported on a concept for batch manufacturing of robust trimorph bulk SMA microactuators [4], which allows for a novel integration method circumventing the limitations of the previous methods. In this concept, we utilized thin cold-rolled TiNi foil as the bulk material and added a dielectric layer at an elevated temperature which provides the cold-state reset in form of a stress induced deflection of the actuator in the cold state due to the different thermal expansion coefficients of the TiNi foil and the dielectric layer. Finally a thin metal layer is added to be operated as a thermal resistor to indirectly heat the SMA through the dielectric layer and thereby actuate the structure. However, this concept was realized on a per device level, only.

In the present work we report on a concept for both the wafer-level manufacturing and integration of robust trimorph bulk SMA microactuators into silicon structures.

2. Wafer-scale manufacturing of SMA microactuators

2.1. Principle of trimorph SMA actuators

There are two main technical challenges to be addressed to allow for batch integration of bulk SMA microactuators. The first is to provide a batch manufacturing compatible cold-state reset mechanism; the second is to allow batch manufacturing compatible electrical contacting.

Multi-Material Micro Manufacture
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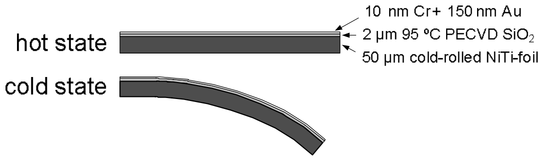


Figure 1: The trimorph microactuator is deformed in the cold state due to the induced stress of the dielectric layer. Upon actuation, which can be accomplished by resistive heating through the top gold layer, the SMA sheet regains its flat shape in the hot state.

In this study, our previously developed actuation concept using a trimorph SMA/dielectric/metal structure [4] was realized on a wafer-scale level. The dielectric layer stress deforms the actuator in the cold-state, see Figure 1. This built-in cold-state reset eliminates the need for mechanical pre-tensioning or additional microsprings. The choice of dielectric material, deposition conditions, layer thickness and thermal treatment [5] allows for tuning the actuator characteristics.

Actuation can be accomplished by an indirect heating scheme, in which the thin metal layer is deposited on top of the oxide. The heater is electrically isolated from the SMA and allows for easy electrical contacting and low actuation current. Moreover, the heater can be patterned prior to the etching of the SMA for optimized heat transfer, reducing thermal gradients along the beam and reducing power consumption. However, for certain geometries of the SMA structures, e.g. u-shaped beams, patterning of the metal layer is not required.

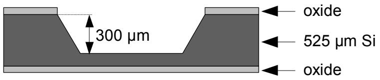
The electrical contacting and the intrinsic cold state reset are the key enablers for batch processing. Three key actuator performance factors, i.e. the shape memory effect, the cold-state reset and the electrical heating, can be optimized independently by each respective layer of the trimorph.

2.2. Principle of wafer-scale integration of SMA actuator structures

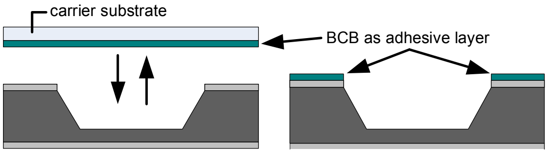
To allow for wafer-scale fabrication of the trimorph SMA actuators two key issues must be solved. One is to selectively bond SMA foils to a silicon substrate and the other is to then pattern the foil into desired actuator shapes. Adhesive bonding allows for good adhesion between many materials and can be done in low-temperature conditions in inert atmosphere [6] not risking devastating side effects such as substantial oxidation of the SMA.

Here we present a method to integrate SMA microstructures to silicon on a wafer-level by adhesive bonding followed by patterning into actuator structures. Contact printing of the adhesive to a silicon wafer with topographical structures results in a transferred adhesive layer only on the top surfaces of the silicon. SMA foil covering the whole wafer is applied above the conversion temperature to ensure a flat shape of the foil which enables good conformal contact to the silicon. During curing of the adhesive, the SMA is selectively bonded only to the regions of the silicon to which contact was made with the intermediate adhesive, defined by the topographical pattern on the wafer.

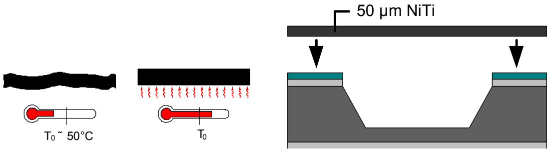
After bonding of the SMA foil to the silicon wafer, actuator structures can be patterned by lithography and standard wet chemical etching of NiTi. However, the adhesive must be carefully selected to not risk delamination upon exposure to the etchant. A possible way to circumvent this problem is to first pattern the SMA, which is temporarily bonded to a carrier wafer, and subsequently transfer bond the SMA from the carrier to the target silicon wafer. However, this introduces an additional and complicated alignment step of the SMA structures to the silicon during assembly of the two layers.



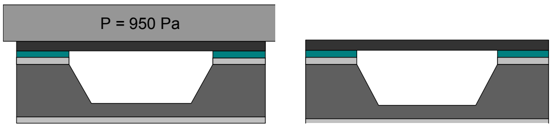
1) KOH-etching of 300 µm deep wells in 525 µm thick oxidized Si-wafer



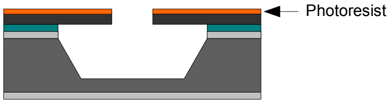
2) Stamping of adhesive layer (BCB) on non-etched top surface, resulting in a patterned adhesive layer.



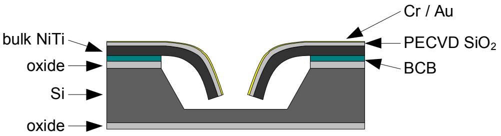
3) Flattening of a 50 µm thick TiNi-foil by heating above the conversion temperature T_0 and then applying the foil on the adhesive layer.



4) Loading the stack with a weight to ensure a uniform bond and hardcure the adhesive layer at 250°C in a nitrogen atmosphere.



5) Patterning the NiTi foil using lithography and wet etching.



6) PECVD of 2 µm SiO_2 at 300°C and evaporation of 10/150 nm Cr/Au. Finally the cantilevers are bending down into the KOH etched well due to compressive stress in the PECVD oxide.

Figure 2: Cross sectional drawings illustrating the steps (1-6) of the wafer-scale manufacturing of robust trimorph bulk SMA microactuators.

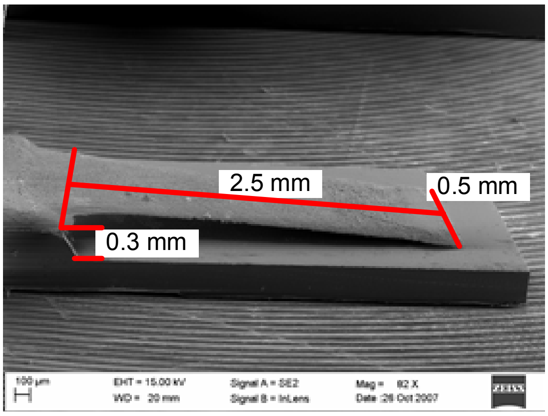


Figure 3: SEM-Picture of a wafer-scale manufactured trimorph microactuator, bending downwards due to the compressive stress in the PECVD oxide, which forms the built-in bias spring.

2.3. Fabrication

Figure 2 illustrates the process flow for the first test structures. We KOH-etched 300 µm deep wells in an oxidized Si-Wafer which define the maximum deflection of the cantilevers during operation (a). Then, we stamped a layer of Benzocyclobutene (BCB) on the unetched parts of the substrate, resulting in a self-aligned adhesive layer pattern (b). Next, we flattened a 50 µm thick commercially available TiNi foil (Johnson-Matthey, USA) by heating above the transition temperature, T_0, and applied it onto the adhesive layer (c). The wafer-SMA-stack was compressed to ensure a uniform bond and the bonding process was subsequently completed by hard-curing the BCB in a nitrogen atmosphere (d). Then, the SMA was patterned using lithography and wet etching (e). Finally, we PECVD deposited 2 µm of SiO_2 at 300 °C, which also further cures the BCB, and evaporated 10/150 nm Cr/Au (f). The resulting actuators are bending downwards into the wells due to the compressive stress in the oxide layer. The thin metal layer is electrically isolated from the SMA and can potentially be used as an electric resistor to heat the actuator with an electrical current, but it must then be deposited and patterned prior to the etching of the SMA or be used on other geometries of the cantilevers.

3. Results and discussion

3.1. Evaluation with cantilever test structures

Test cantilever structures with a width of 0.5 mm and a length of 2.5 mm were fabricated and diced from the wafer into single pieces for evaluation. Figure 3 shows a SEM-picture of a single cantilever and its dimensions.

The current SMA etch procedure results in an unacceptable underetch rate, as can be seen in Figure 4, and is therefore currently being improved.

3.2. Measurements

Figure 4 shows photographs of a single cantilever during operation. In the cold state the compressive stress in the oxide, forming the built-in bias spring, deflects the cantilever-tip downwards until it touches the bottom of the well. In the hot state, the SMA works against the bias spring and lifts the cantilever-tip up from the substrate.

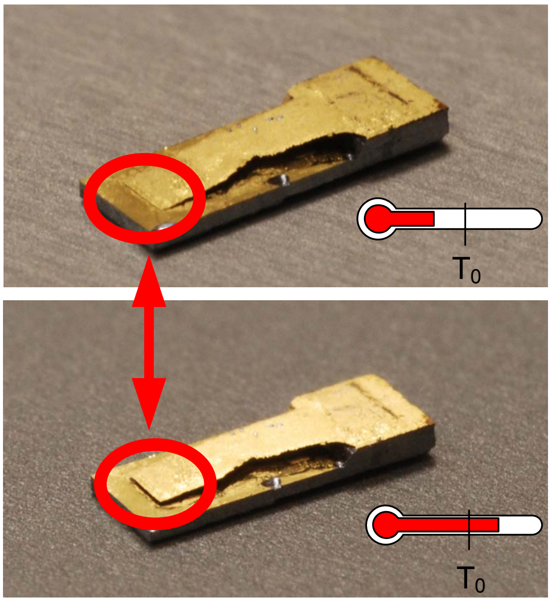
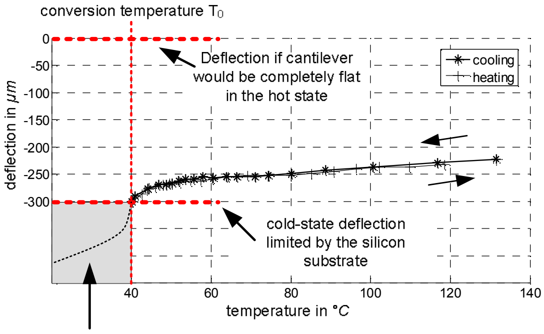


Figure 4: Pictures of a sample taken in the cold state (top) and in the hot state (bottom), showing the stroke range of the cantilever tip. In the cold state the cantilever deflects downwards due to the PECVD SiO2 layer which acts as bias spring. In the hot state the SMA works against the SiO2 bias spring and lifts up the cantilever.

Temperature-deflection measurements at quasi-static equilibrium conditions using a thermostat are shown in Figure 5. Starting at temperatures above T_0, the actuator shows simple bimorph behaviour. After decreasing the temperature to the transformation temperature between 60 and 40 °C the SMA phase-change decreases the SMA stiffness and allows for a considerable quasi-plastic deformation, resulting in a rapid deflection of the cantilever. The latter is mechanically limited at 300 µm by the silicon substrate. Hence, the maximal deflection in the cold state is equal to the depth of the silicon well, which is 300 µm.



Expected shape of the deflection curve without deflection limitation (in accordance to previous similar work [5]).
Note: the scaling in this regime is unknown.

Figure 5: Temperature–deflection measurement of a first test actuator. In the cold state, the measurements show a large deflection of 300 µm. Heating the actuator results in stroke of max. ~80 µm. The dotted line shows the expected shape of the deflection curve without the limitation, in accordance to previous similar work [4].

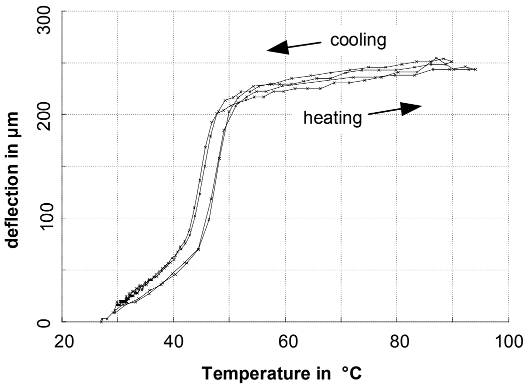


Figure 6: Temperature–deflection measurement of an earlier, similar actuator [4]. The deflection of the cantilever was not mechanically limited and showed a stroke of approx. 250 µm. This device, however, was fabricated on a per-device level.

Heating the actuator results in a relatively small stroke of max. ~80 µm. The actuators in this first batch run cannot completely recover the flat shape due to the high compressive stress in the oxide. However, earlier work of the authors [4] indicates, that the overall deflection and the resulting stroke would be much larger without the deflection-limiting substrate. Figure 6 illustrates the deflection of an earlier presented trimorph cantilever actuator [4], which was not mechanically limited and showed a stroke of approx. 250 µm.

In this work, we incorporated a limit to the deflection stroke due to two advantages: the bias spring is never fully relaxed, which potentially increases the stability of the actuator, and the risk for plastic deformation of both the SMA and the oxide is considerably reduced.

4. Conclusions

We successfully developed and demonstrated a process for the wafer-level integration of SMA actuators to silicon microstructures. The process adapts well to batch fabrication and allows for patterning of the SMA either prior or after the transfer bonding.

The processed materials are only exposed to low-temperature treatment and bonding pressures below 1 kPa which allows for the integration of sensitive components. The concept was demonstrated by the wafer-level fabrication of bulk trimorph SMA microactuators showing a working deflection range of approx. 80 µm.

Acknowledgements

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