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A flip–chip encapsulation method for packaging of MEMS actuators using surface micromachined polysilicon caps for BioMEMS applications

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Abstract

In this paper, we present a novel technique for encapsulation of MEMS devices. The technique is demonstrated to address two issues related to the use of in-plane thermal actuators for BioMEMS applications. First, an encapsulation process is described to provide protection to a MEMS actuator from debris and other particulate matter when deployed in a biological environment. The encapsulation structure consists of a multilayer wall around the actuator and a surface micromachined polysilicon cap. A small clearance is provided around a piston that transmits motion from the actuator to the external world. In air, the packaged actuator performance is comparable to that of an unpackaged actuator, thus indicating successful encapsulation without any damage to the actuator. Second, this packaging approach is used to address the issue of reduction in efficiency of the thermal actuator in liquids by coating the packaged actuator with a thin conformal hydrophobic layer. This prevents liquid from entering the encapsulation, thus isolating the hot actuator components from the liquid. Experimental results show that efficiency of the packaged actuator in water improved giving a performance similar to that observed in air, suggesting an isolation of the hot actuator components from the liquid. Although the technique is demonstrated for thermal actuators, it is also applicable to other MEMS devices and in-plane actuators such as electrostatic comb drives for engineering as well as biological applications.

Keywords: Thermal actuator; Tether; Liquid; Hydrophobic; Atomic layer deposition

1. Introduction

BioMEMS and "lab-on-a-chip" microfluidic devices are finding increasing applications in the life sciences [1–7]. These include *in vivo* pressure sensors, implantable microelectrode arrays, drug delivery systems, biochemical sensors, sensors for measurement of local tissue properties, microsurgical tools, DNA sequencing chips, micro-assays, and many others. These devices use MEMS transducers for physical and chemical sensing. Many BioMEMS devices also employ micromachined actuators to provide precise motion because they offer advantages of miniaturization, electronic control, repeatability, fast response and batch manufacturing. In microfluidic systems, micro-actuators are used as pumps, valves, and micro-mixers [8,9]. There is also interest in using MEMS actuators to develop micro-surgical tools [10,11] for precision surgery with minimum damage to surrounding tissue. Micro-grippers based on electrostatic [12] and thermal [13] actuation developed to manipulate micron-size objects are also envisioned for manipulating small chunks of biological tissue or single cells [14]. Micro-actuators are also used as resonator structures for bio-chemical sensing [15].

With these applications in mind, it is clear that there is a need for integration of microactuators in BioMEMS devices. A number of choices are available for actuation at the microscale including those based on electrostatics, thermal expansion, piezoelectric effect, magnetism and smart materials [16]. The use of electrostatic and thermal actuators is desirable in many BioMEMS applications as these are used regularly in engineering MEMS applications and a body of knowledge on design,

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fabrication processes and materials already exists for these actuators. These actuators are compatible with the standard IC fabrication techniques and are easy to integrate with the electronics circuitry. Additional advantages particularly for the electrostatic actuators include a fast response and low power consumption. These actuators have a displacement range on the order of several micrometers. As the size of the biological cells and sub-cellular organelles is also in the same range, these actuators make good candidates for cell manipulation. For example, one particular application of interest for the current authors is to develop a BioMEMS platform to apply controlled strain to single cells and study the corresponding mechanical, genetic and biochemical response [17–19]. This device requires actuators that can provide in-plane displacements greater than 10 μm and forces on the order of a few μN. This range of displacement and force makes electrostatic comb-drives and in-plane thermal actuators attractive choices for this application.

However, there are a number of issues that need to be addressed for successful integration of MEMS actuators for such applications. Many of these issues arise from the fact that the MEMS actuators are required to operate in relatively complex environments such as the phosphate buffered saline (PBS) solution, *in vitro* cell culture media and that present *in vivo*. This is a very harsh environment for MEMS devices, which are typically operated in vacuum or gases. For example, the typical *in vitro* cell culture medium is an ionic aqueous solution containing many supplements and growth factors necessary for cell vitality and growth. This chemically and biologically active nature of the environment is a main concern in operating MEMS actuators in these solutions. The challenges include electrolysis, polarization, particulate contamination, corrosion, capillary forces, stiction, excessive heat dissipation associated with thermal actuators, and unintended dielectrophoretic effects in the case of the electrostatic actuators. The problems related to electrolysis and polarization have been addressed, enabling the use of MEMS actuators in partially conducting liquids using high-frequency actuation signals [20,21]. In many cases, however, additional packaging is necessary to protect the MEMS structures from biological debris, particles, and cells that may be present in the surrounding environment since such contamination can cause stiction or blocking of the actuator. Okandan et al. [22], have demonstrated a custom surface micromachining process for encapsulation and sealing of electrostatic comb-drive actuator from biological media. We recently presented an alternative technique for encapsulation that uses a standard multi-user MEMS fabrication process and flip–chip bonding [23]. This paper further extends that work on packaging of MEMS devices for BioMEMS applications. The technique is demonstrated for encapsulation of in-plane thermal actuators.

An important advantage of the thermal actuators over the electrostatic actuators for deployment in biological media is their ability to work in ionic solutions without need for very high drive frequencies [18]. However, the main challenge in using a thermal actuator for BioMEMS applications is the cooling of the thermal actuator by the surrounding liquid environment, which subsequently restricts displacement [20]. The maximum displacement of the thermal actuator is also limited by the maximum temperature, which cannot exceed the boiling temperature of the surrounding medium. Finally, the power consumption of thermal actuators in an aqueous environment is increased by an order of magnitude when compared to that used in air. Such heating can adversely affect the cells or the biological tissue in the vicinity of the actuator. The encapsulation technique presented in this paper resolves these issues by separating the actuator from the liquid and biological medium.

The problem concerning deployment of electrostatic actuators in ionic solutions is the electric field generated by the high-frequency actuation signal, which can result in unintended dielectrophoretic forces [4,8] on the cells in the vicinity. To avoid this problem, it is desirable to isolate the electric field from the biological environment using a conductive shield around the in-plane electrostatic actuator. The proposed encapsulation technique has potential to provide just such a conductive shield around the actuator.

2. Design and fabrication

The basic idea behind the encapsulation technique is schematically shown in Fig. 1. A “wall” structure is built around the MEMS device to be encapsulated using the different layers available in a typical MEMS surface micromachining process. A polysilicon “cap” structure suspended by tethers is also fabricated using a similar process. The cap is transferred onto the wall structure using a flip–chip bonding technique [24,25], thus encapsulating the MEMS device.

2.1. Actuator and wall design

A commercially available multi-user polysilicon surface micromachining MEMS process [26] was used for fabrication of the actuator and the encapsulation structures. Three polysilicon layers (Poly0, Poly1, and Poly2), two oxide layers (Oxide1 and Oxide2), a metal layer (Au with Cr adhesion layer) and a nitride isolation layer are available for the process. The nominal thicknesses of these layers are listed in Fig. 1. It has been previously shown that structures of various heights can be fabricated by using different combinations of these layers [27]. These stacked layers were used to provide a uniform gap between the MEMS structure and an encapsulating cap. In Fig. 1(a), the MEMS device to be encapsulated is represented by stacked Poly1 and Poly2 layers. A multilayer wall structure was built around the MEMS device. The wall was designed to be taller than the actuator structure by stacking all the polysilicon layers and trapping both the oxide layers. For example, by stacking all the available layers to make a wall structure, a gap of 1.75 μm above the stacked Poly1 and Poly2 layers is achieved. The stacking of layers also assists in the flip–chip process by absorbing additional compressive stress. Gaps were provided in the wall structure for the piston to transfer motion externally. Additional gaps can also be provided for electrical traces if necessary.

The actuators used for this demonstration were thermomechanical in-plane micro-actuators (TIMs) [28,29], which are also known as bent-beam or chevron thermal actuators. The actuator structure consisted of ten bent-beam elements formed by stacked