Fabrication of piezoelectric thick-film bimorph micro-actuators from bulk ceramics using batch-scale methods

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Abstract

Piezoelectric ceramic films in the 20-60 micron thickness range are rarely employed today in commercial micro-mechanical devices, even though their expected force capability suggests that they are well suited to many micro-fluidic and micro-pneumatic applications. Some examples would be micro-scale fuel cells and micro-combustors. Head sliders, radio-frequency (RF) micro-switches and powered micro-optics are further potential application areas. These are only a few and the barriers in bringing them into reality are those of processing compatibility rather than commercial desirability. Such issues are being addressed in the EU Framework 6 Project ‘Q2M’, which focuses on batch-scale fabrication issues for high quality new micro-mechanical devices that are cost-effective and which have extended capabilities.

This paper discusses a potential batch-scale production route for piezoelectric thick-film bimorph micro-actuators that combines ultra-precision grinding of ceramics and femto-second laser machining, along with standard micro-fabrication techniques such as wafer bonding. This new method has the key advantage that many different shapes and thicknesses of actuator can be made with only minor process changes, meaning that actuators can be designed to suit their intended application. It contrasts with current practice whereby micro-actuators are often designed around a limited range of standard components, with consequent reduction in their achievable performance. The examples used are a 6mm diameter plane-spiral bimorph actuator for integration into a polymeric micro-valve and 2-5mm long bimorph cantilevers intended for use in a new type of silicon ‘house’ micro-valve, with pneumatic applications.

Keywords Bimorph, PZT, micro-actuator, wafer bonding, femto-second, ultra-precision grinding, MEMS

1. Introduction

Commercial manufacture of piezoelectric ceramic thick films in the thickness range 20-60 microns currently presents a significant technological challenge [1]. Traditional mixed-oxide, high temperature sintering routes tend to result in ceramics that are deformed or cracked at this level. Alternative bottom-up deposition methods involve spinning nanometre-scale layers of a sol-gel ceramic precursor onto a substrate, followed by rapid thermal annealing and sintering. Film thickness is increased by successive deposition, layer-by-layer. The resultant ceramic is effectively ‘clamped’ to its substrate preventing its free microstructural development. In practice the ceramic tends to evolve under tensile stress, which becomes more severe as layer thicknesses increase. The ceramic is then prone to cracking and the achievable electro-active properties are around 30-50% of the bulk values, when taking the example of the most commonly used lead zirconate titanate (PZT) family of ceramics. This is perfectly adequate for some applications, however the full potential of the materials is not realised using the bottom-up technique.

For improved performance bulk ceramics are sometimes thinned down to the required dimensions by lapping and polishing. This method can indeed produce higher performing thick films, but the procedure tends to be painstaking and slow. In this paper we describe a method that extends this basic idea, using ultra-precision grinding techniques to increase the material removal rate, and combines it with standard micro-fabrication procedures [2]. The new route is designed to produce actuators that can operate at their full potential and it provides the flexibility to design micro-actuators that are tailored to their intended application. In the opinion of the authors many designs of micro-fluidic actuators presented in literature are compromised in some way by the need to build around the availability of standard electro-ceramic components. Frequently these are thicker than required, precluding the optimum mechanical design solution from being achieved; and, significantly, failing to address the wider systems requirements, as relatively large electronic components must still be used. Typical drive voltages for bulk PZT ceramics are around 1V/µm. Hence, by adopting 20-60µm thick-film PZT micro-actuators, direct integration with CMOS electronics can be said to be achievable. Progress towards this goal is an objective of the EU ‘Q2M’ project consortium, our partners in this work [3-4].
2. Process

2.1 Assembly of the multi-material stacks

The key feature that distinguishes the new process from previous work is the adoption of ultra-precision grinding of bulk ceramics in combination with standard micro-fabrication procedures. This enables the PZT ceramic components to be fully integrated at the wafer scale with huge time savings over conventional lapping and polishing techniques and with excellent layer-thickness control [5-6].

Standard 50mm diameter PZ26 discs (Ferroperm Piezoceramics A/S, Kvistgard, DK) are first machined to ensure their flatness, nominally +/-1µm form, and surface roughness, nominally <30nm, using an 8-inch wafer face-grinder, designed and built by Cranfield Precision Ltd UK (Figure 1). Figure 2 illustrates the four major steps that follow. By first preparing the ceramic surfaces it is possible to achieve much thinner bonds than would normally be the case [7]. Adhesive (BCB) wafer-bonding the ceramic components together with a titanium shim, using a SUSS Substrate Bonder SB6 VAC/SKM, introduces a compressive stress to the ceramic in the multi-layer structure. This is a consequence of the thermal expansion mismatch in the metal and the ceramic components. In Stage 2 the structural layers remain flat and parallel owing to the stiffness of the stack. In Stage 3 a glass carrier wafer is introduced and temporarily bonded to the stack using a UV adhesive. The bond is quick to make at room temperature and robust. Importantly for complex applications such as this, it does not impart extra stress to the structure so that the devices can be released cleanly and without distortion. The UV curable adhesive is Delo-Photobond4464 (Delo Inset) spun at 2000rpm onto a glass wafer carrier at room temperature and exposed to 320-450nm wavelength light for 40s. The carrier wafer is required to maintain the parallelism of the layers during the second machining step, Stage 4.

Figure 3 shows the bonding set-up adopted. It was found that the PZT ceramic can be sensitive to a local temperature variation associated with the central push-down pin of the wafer bonder. This affects the bonding process, as revealed by the second machining step. In Figure 4 a very slight 'orange peel' effect can be seen which indicates an imperfect bond. The twin wafer stack configuration (schematic) in Figure 3 was used to avoid this issue. In Figure 5 the multi-material make-up of the wafer stack is shown. Polyimide (PI) layers have been used for planarization and to prevent surface defects such as pores and cracks from developing into sites for localised electrical breakdown when the ceramic is subsequently poled under a strong electric field.
2.2 Laser Machining

The multilayer sample was subsequently diced using a femto-second laser by Micreon GmbH Hannover, using a 30-micron diameter beam. Variations to the basic plane-spiral actuator designs were implemented at this stage and hence 9 different designs and 36 actuators were fabricated on a test wafer (Figure 5). The minimum width of cut was not fully explored in this test, however it is comfortably below 100µm. Some re-deposition of vaporised material onto the cut surface is to be expected using this technique. This is potentially harmful to the operation of the devices and it was removed using a nitric acid etch before the devices were poled. The versatility of the laser machining process (Figure 6) in producing complex designs is illustrated here and, in the opinion of the authors, its inclusion in this process is justified, despite its relatively high cost. Laser machining is a very gentle process in contrast to wafer saw-dicing, which could be viewed as a possible alternative, albeit with more limited scope for design variations. Saw-dicing trials revealed some cracking of the pre-stressed multi-layer structure and it may well prove to be unsuitable for these devices.

2.2 Electrode Design

Following successful fabrication of the multi-material stacks the attention has turned to device operation and integration with ancillary components. Three electrical connections are required in order to give the actuators bi-directional capability. Blanket electrodes to the top and bottom surfaces are insufficient to enable this to be achieved. Under high-field conditions, such as those applied during poling, it is possible for short circuiting to occur. This is most commonly initiated by surface inhomogeneity at the exposed edges. Patterned electrodes on the top and bottom surfaces have been used to increase the inter-electrode gaps substantially and this has resulted in consistently high impedances between the layers. Figure 7 shows a range of cantilevers of different lengths from a second test wafer. Figure 8 shows the 6mm spiral configuration redesign. The laser machining process has been exploited to create access holes for the centre electrode.
Conclusion

A range of pre-stressed PZT thick-film bimorph micro-actuators have been created that are suitable for a variety of micro-valve applications. The process sequence used has been demonstrated to provide more flexibility for device design than has previously been the case and the wafer-scale production route is compatible with selective transfer bonding methods for the creation of more complex micro-electromechanical systems. The actuators are intended to operate with a 30V drive signal, making integration with CMOS electronics a possibility.

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References


