PIEZOELECTRIC FILMS IN SILICON-BASED MICROACTUATION STRUCTURES

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Introduction

The mechanisms for micromechanical actuation that are most practical, and have been the most applied, are electrostatic attraction and piezoelectric effect. Both scale well into micro-dimensions, are relatively compatible with microfabrication processes, and are also suitable for displacement sensing. Of the two, piezoelectric devices are much better able to provide strong forces, and while electrostatic devices require no special material, their geometrical requirements are much less compatible with planar processing. For these reasons, piezoelectric actuation is very attractive for many applications in microsystems. The primary difficulties in developing micro-actuators based on piezoelectric effect lie in depositing or attaching an appropriate material to the mechanical, typically silicon, parts of the structure, and in developing compatible processes for machining these structures. In most actuators demonstrated to date, the approach has been to bond a micromachined silicon structure to a piece of bulk piezoelectric ceramic1. This eliminates the need for a suitable deposition process, but imposes severe restrictions on the size, geometry and position of the active element, and is not well suited to integration.

A far more flexible approach is to deposit piezoelectric material as a film onto a substrate suitable for further micromachining. The most attractive materials for this technique are in fact the same as are used in the bulk bonded approach, the perovskite ceramics; in particular, lead zirconate titanate (PZT), which gives a very high electromechanical coupling coefficient. PZT, and other lead titanates, are of interest in film form for a variety of applications: capacitative and ferroelectric high-density memory, piezoelectric motion sensing and actuation, pyroelectric detection, and electro-optic devices. Within this wide range of applications, a wide range of deposition techniques have been investigated, including electron-beam evaporation, sputtering, electrochemical reduction, chemical vapour deposition and the sol-gel process2. Of these, the sol-gel process offers particular advantages of film homogeneity, large area coverage, relatively low cost, and good compositional control. This latter point is of particular importance given the complex structure of PZT and the strong dependence of its properties on stoichiometry3.4. Stoichiometric deposition of oxide films using vacuum techniques usually requires high substrate temperatures5, and the composition is highly dependent on a number of process parameters.

For many applications of ceramic thin films, layer thicknesses of a few hundred nm are sufficient, but for actuation, multi-micron layers are needed to obtain high forces and mechanical strength. Such thicknesses are difficult to obtain by any technique; in sol-gel, the high degree of shrinkage during annealing causes large tensile stresses to form, and these will usually cause severe cracking once the total deposited thickness extends beyond about one micron. The actuator applications reported so far have been based on sub-micron films6, and a primary goal of this work is to overcome this limitation.

Film Deposition and Characterisation

The sol-gel technique involves the formation of oxide glasses and ceramics by hydrolysis and polycondensation of metal alkoxide precursors in solution, using an acid or base catalyst. For multi-component oxides such as PZT, the desired composition is obtained simply by mixing precursors in the appropriate molar ratio. This technique has been extensively used for the preparation of PZT and similar ceramics in powder form, from which bulk pieces are sintered; in such applications stress is generally not an important consideration. To obtain a film, a suspension of oxide nanoparticles is formed by the hydrolysis/condensation reactions in an appropriate solvent; this is then spin or dip coated onto a substrate, and heat treated to complete the condensation, remove residual solvents and react away remaining organic ligands. Stoichiometry can be affected by the formation and loss of relatively volatile PbO; this can be precompensated in the initial solution7; in our case up to 60% excess lead was used.

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Most reported techniques for sol-gel PZT coatings are variations of that of Budd et al.\textsuperscript{8} using methoxyethanol as the main solvent. To reduce toxicity we have developed a technique based on that of Yi et al. using acetic acid\textsuperscript{2}. In our method, lead acid trihydrate is mixed with acetic anhydride; this removes the water of hydration, as required, to produce anhydrous lead acetate in acetic acid after refluxing. This solution is then reacted first with zirconium propoxide, and then with titanium isopropoxide, using appropriate amounts of water and solvent. The resulting sol is applied by spin coating followed by rapid thermal annealing at high temperature. As reported previously for glass layers\textsuperscript{9}, we have found that iteration of this process can give thick, stress-free films, up to at least 3 microns.

Figure 1. SIMS (a) and X-ray diffraction (b) analyses of heat-treated PZT films on Si.

The as-deposited films are amorphous, so a further heat treatment is required to perform transformation into the polycrystalline perovskite phase. The orientation of this phase can be controlled by seeding the crystal grains from the substrate surface or an appropriate inter-layer\textsuperscript{3}. Figure 1(b) shows the dependence of crystalline structure on heat treatment. For sample 1, where strong peaks indicative of perovskite PZT are present, the final film was heated for one hour at 600°C in air. For sample 2 the final heat treatment was 6 hours, and sample 3 had no final heat treatment.

Figure 1(a) shows the compositional uniformity of the films; periodicity in the lead content indicates some loss at each layer deposition, and the film/substrate boundary is seen to be indistinct. Because of the very high permittivity of the ferroelectric film, it is important to avoid the formation of a dielectric layer between it and the electrode, as this would take up much of the applied field. Such a layer can be formed either by oxidation of the electrode surface or by interdiffusion between the substrate, electrode and film\textsuperscript{5}. We are currently investigating use of a metallic electrode interlayer to reduce this problem.

**Actuator Fabrication and Characterisation**

Fabrication of actuator structures is based on silicon sacrificial processing. Heavily doped p\textsuperscript{+} layers are formed in the surface of (100) p-type wafers, by ion implantation of boron followed by thermal diffusion; these are about 7 \(\mu\)m deep and act both as etch stops and lower electrodes. Typically 1 - 3 \(\mu\)m of PZT are then deposited and heat treated, then sputter coated with a top electrode of Cr. This is patterned to act as a mask for reactive ion etching, by which the beam and pillar structures are defined. Anisotropic wet etching is then carried out using EDP (ethylenediamine pyrocatechol) to undercut and free the actuating beams. This structure is illustrated in figure 2. Actuation of the structures is then evaluated by applying a sinusoidal drive voltage of varying frequency, and measuring the deflection of the beam tip by optical interferometry. The cantilevers are mechanically highly resonant, and this is reflected in their response. For the structure as illustrated, resonant vibration occurs at about 20 kHz. Off-resonance, displacements of only about 0.25 \(\mu\)m were obtained at peak-to-peak drive voltages of 50V. This is much less than can be predicted using electro-mechanical analysis of the structure and assuming the PZT to have the characteristics of typical bulk materials. The difference is probably caused by an interfacial oxide layer reducing the effective drive voltage, and poor crystallinity and orientation of the film. This is borne out by capacitance measurements, which indicate an effective permittivity of typically 30; much less than the values of bulk materials, often 800-1000. Also, large amplitude displacements (5 \(\mu\)m) are obtained at the resonant frequency with a driving signal at half this frequency, probably as a result of thermal excitation.

Figure 2. Structure of cantilever beam actuator. Base pillar is about 1.5 x 1.5 mm, and the beam width about 60 μm.

Conclusions

We have established a process for the deposition of multi-micron piezoelectric films which is compatible with fabrication of micro-mechanical actuator structures, and have fabricated such actuators, and demonstrated their operation. While some of these accomplishments have been reported by other groups, we know of none that have achieved all of them in an integrated fabrication process. However, considerable work is still required to optimise the material performance and fabrication processes, as well as to investigate specific applications. The industrial interest in micro-actuation based on piezoelectric material is very considerable; this is the most promising material and fabrication system for micro-positioning, micro-fluidics, and micro-manipulation devices, with applications in medicine, machine tools, optics, and many other fields.

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References