THICK-FILM ACTUATION TECHNOLOGIES FOR MEMS APPLICATIONS

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Abstract — *This paper compares two thick-film actuation technologies and assesses their suitability for use within micromachined devices. The materials are a piezoelectric composition, which exhibits a d_{33} coefficient of the order of 130pC/N, and a magnetostrictive material which possess a magnetostriction of 4.4ppm at a magnetic field of 11.5kA/m. Examples of their application in micromachined devices are also given.*
Key Words: *Thick-Film, Piezoelectric, Magnetostrictive*

I INTRODUCTION

This paper discusses two types of thick-film actuation material that have been developed at the University of Southampton. These materials are a piezoelectric type, based on lead zirconate titanate (PZT) and a magnetostrictive composition based upon the giant magnetostrictive material Terfenol-D. The two materials have differing fabrication and operational methods. This paper will illustrate these and also describe the benefits of both solutions when combined with micromachined devices.

II OPERATIONAL MODES

Piezoelectric and magnetostrictive materials are actuated in different manners; the methods and some of the basic material properties are described in the following sections.

II.1 PIEZOELECTRIC MATERIALS

Piezoelectric materials, when used as actuators, require the application of an electric field across the material. With bulk materials this is usually achieved by depositing a metallic layer on two opposing faces and applying a voltage to these, thus generating the required field. The activity of piezoelectric materials can be described using the d_{33} constant of the material; this relates the applied electric field to the resulting mechanical strain in the direction of the applied field whilst being driven as an actuator. Piezoelectric materials can also be used to sense applied force, in which case the d_{33} constant relates the applied force to the charge produced by the material.

II.2 MAGNETOSTRICTIVE MATERIALS

Magnetostrictive materials are actuated by the application of a magnetic field in the direction of desired movement. The actuation field can be provided using a solenoid coil to contain the material. The magnetostriction of a material is usually specified in terms of the extension of the material per unit length of material measured in the direction of applied field, for a given magnetic field strength.

Piezoelectric materials require the direct application of a voltage to generate the required electric field. This is typically of the order of 1MV/m requiring a voltage of the region of 100V. In the case of the magnetostrictive material, the magnetic field can be external to the device, often using a coil at a lower voltage but potentially requiring more current. The advantages and disadvantages of direct and external actuation fields will be discussed later.

III THICK-FILM FABRICATION TECHNIQUE

The processes used to produce piezoelectric and magnetostrictive thick-film materials consists of a number of stages. The first stage is to prepare a paste containing the desired active material in powdered form; this paste also needs to contain a suitable substance to allow the active material to bind together. In both the piezoelectric and magnetostrictive thick-film materials developed at the University of Southampton this is a devitrifying lead borosilicate glass. To form the dry powders into a paste, a commercially available organic vehicle (ESL 400 series) is used. This organic vehicle gives the paste the desired thixotropic properties required for the printing process. It is removed by drying before the paste forms into a fired, composite thick-film.

As part of the optimization process undertaken during the development of the materials, the required proportions of the materials in the paste have been studied. In the case of the piezoelectric thick-film material, a blend of different size particles of PZT has been found to increase the d_{33} value of the paste. Details of this optimization process have been reported previously [1].

For the magnetostrictive material a different route has been taken, due to the shape of the particles and a need to keep them as large as possible [2]. To improve the magnetostrictive properties an inert filler material has been added to improve the structure of the thick-film. The inert filler material used is an alumina powder with a particle size of the order of a tenth of the magnetostrictive ones. The effect of this filler material on the mechanical and electromechanical properties of the thick-film has been previously reported [3].

The second stage in the fabrication process is to print the paste through a patterned stencil onto a suitable substrate to define the areas that are to have the active material deposited on them. The printing is accomplished with a screen printer designed to give highly repeatable deposition characteristics. Traditionally alumina (AlO_2) tiles have been used as substrates for thick-film devices and circuits, but thick-films can also be deposited onto steel and silicon substrates. If a flexible substrate is required polymer based pastes with lower temperature processing requirements can be used in place of the glass based cermet type pastes.

The third stage is to take the wet print from the printing stage and to remove some of the organic vehicle by heating; this drying process leaves the paste in a dry state but still held together by the residual vehicle.

The final fabrication stage is to fire the paste in a thick-film furnace, typically at temperatures in the region of 900°C. In the firing process initially the remaining components of the organic vehicle are burnt off, as the temperature of the thick-film paste continues to rise the glass will flow and adhere to the active material and to the substrate. On cooling, the glass will set into a solid form binding the components of the paste together and also to the substrate. Owing to the devitrifying nature of the glasses used, further heating cycles will not cause the glass to reflow.

Depending on the materials being combined in the thick-film, some changes may be made required to the fabrication process. For example, the magnetostrictive material used is pyrophoric and degrades on oxidization; this requires processing in a nitrogen atmosphere at a reduced temperature, which necessitates selection of a glass frit that will flow at the reduced temperature and does not require the presence of oxygen to devitrify.

IV COMBINING THICK-FILM MATERIALS AND MICROMACHINED SILICON

Both the piezoelectric and magnetostrictive thick-films developed at the University of Southampton were initially developed for use on alumina substrates as the bonding of the glass binder to the alumina was already established. Transferring of the technology from alumina substrates to silicon has required some further research, due to different material properties and interactions. When migrating onto silicon substrates different thick-film materials will present different problems.

In the case of the piezoelectric thick-film, the main problem has been the migration of lead from the PZT into the surrounding silicon during the firing process, causing changes in conductivity within the silicon. One solution to this problem is to use a barrier layer between the PZT and the silicon [4], if a metallic layer is used this can also double as one of the electrode layers.

With the magnetostrictive thick-film material, diffusion was not found to be a problem, possibly due in part to the lower firing temperatures. The reduced processing temperature, however, caused poor adhesion between the thick-film and the host silicon. To solve this issue a number of interface layers were investigated to improve the bonding [5], resulting in the use of a silicon dioxide layer being applied to the silicon prior to the printing of the thick-film.

V PROPERTIES OF THICK-FILM MATERIALS

The key properties of the piezoelectric and magnetostrictive thick-film materials are summarized in the following sections.

V.1 PIEZOELECTRIC

The most common piezoelectric thick-films are fabricated using a combination of PZT and a devitrifying glass. The optimum piezoelectric properties are achieved when the crystal phase lies on the morphotropic phase boundary. This optimum position can be achieved either by adjusting the stoichiometry of the material or most commonly by adjusting the furnace firing profile. A typical thick-film PZT furnace profile will have a peak temperature of 900°C and achieve piezoelectric activity levels of ~130pC/N [1].

V.2 MAGNETOSTRICTIVE

The magnetostrictive thick-film material requires processing at a peak temperature of 550°C in a nitrogen atmosphere; therefore any other materials used in a micromachined device in which it is incorporated must be capable of withstanding this temperature. The magnetostrictive thick-film possess a magnetostriction of 4.4ppm at a magnetic field strength of 11.5kA/m. Increasing the applied magnetic field will increase the magnetostriction in a non-linear manner up to the point of magnetic saturation, which typically occurs at the order of 300kA/m for bulk Terfenol[6].

VI MICROMACHINED DEVICES WITH THICK-FILM ACTUATORS

Both the piezoelectric and magnetostrictive materials have been used with micromachined silicon devices, some examples of which are described briefly here.

VI.1 PIEZOELECTRIC

An example application of the piezoelectric thick-film material is in the ultrasonic separator described by Harris *et al* in [7]. In this application a multi-layer approach was taken to provide a greater actuation force, this structure can be seen in figure 1. In this approach a two layer transducer was fabricated with gold electrodes top, bottom and in the middle. The silicon layer to the base of the picture is chemically etched to provide inlet and outlet ports for the fluids in the system. The chamber is provided by an etched anodic bonded glass layer not visible in the figure. The layered PZT is used to generate ultrasonic waves within the chamber, which are used to manipulate particles in suspension. This type of transducer compares well to bulk PZT for transducing electrical energy into acoustic energy due to the lower mechanical impedance of the thick-film solution compared with bulk PZT [7].

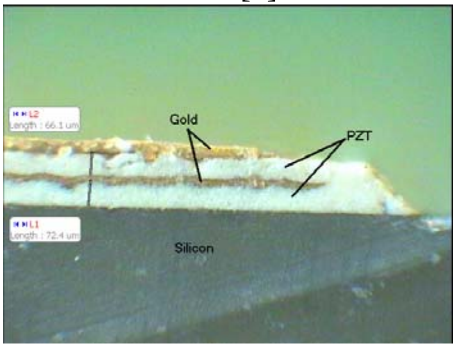

Figure 1. Cross-Section of 2 Layer PZT Actuator

VI.2 MAGNETOSTRICTIVE

An example application of the magnetostrictive thick-film material to a micromachined device is a diaphragm pump, which was fabricated with a two-layer integrated coil in the surface of the diaphragm [8]. The magnetostrictive thick-film was then deposited onto a silicon dioxide insulating layer over the surface of the coil layers. When a current is passed through the coil windings a field is produced which passes through the magnetostrictive thick-film, causing a bimorph type deflection to deflect the diaphragm and operate the pump. A photograph of the micromachined diaphragms with integrated actuation coils, prior to the deposition of the magnetostrictive thick-film onto the surface of the coils is shown in figure 2.

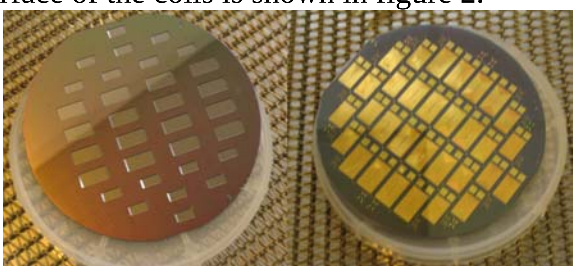

Figure 2. Diaphragms with Integrated Coils

VII SELECTION OF APPROPRIATE THICK-FILM ACTUATION TECHNOLOGY

The differing operational methods of piezoelectric and magnetostrictive thick-film materials permit a number of different situations to be addressed using the appropriate actuation technology.

Currently, the piezoelectric material can provide a greater strain than the magnetostrictive but it does require a direct contact to the material to provide the required actuation electric field. The presence of potentially high voltages to generate the electric field could limit the application of piezoelectric in areas where they may be volatile substances present, for example in micro-fluidic systems if solvents are present. Magnetostrictive materials solve this problem as the magnetic actuation field can be applied externally, allowing the device containing the magnetostrictive thick-film to be sealed. In the micro-fluidic example this would allow the drive power and the fluids to be totally independent.

Whilst the remote operation of the magnetostrictive thick-film can prove an advantage in some situations it can prove less advantageous, as for example in the case where a number of devices are to be located in close proximity. With the magnetic field driven magnetostrictive material selection of just one device can prove problematic due to leakage of magnetic field to adjacent devices, however with the direct application of the electric field to piezoelectric devices independent operation of closely located devices is a lesser problem.

VIII ONGOING RESEARCH

Current ongoing work at the University of Southampton in the area of thick-film materials includes continued development of the piezoelectric material through improved paste composition. Work is also ongoing on improving the finite element modeling of the piezoelectric thick-film material, which is an important part of the design process for many MEMS devices. Steps are also being taken to address some of the issues with the structure of the magnetostrictive thick-film to improve the coupling of the magnetostriction from the active material into the thick-film as a whole. Future work in the area of thick-film materials for actuation will also be investigating the development of a shape memory alloy (SMA) based thick-film.

IX CONCLUSIONS

Both piezoelectric and magnetostrictive thick-film materials have been developed at the University of Southampton. Both materials have been tested with micromachined devices for use as actuators. Thick-film technology can be applied to a wide variety of actuation tasks within the area of micromachined devices. It offers a choice of either a directly- applied, voltage-driven material (piezoelectric), or a remotely actuated, current-driven material (magnetostrictive). Selection of the most appropriate thick-film actuation technology depends, to a large extent, on the applications being considered.

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