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Microprocessor implemented self-validation of thick-film PZT/silicon accelerometer

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Abstract

This paper describes a piezoelectric micromachined silicon accelerometer fabricated using a combination of thick-film printing and silicon micromachining and introduces a microprocessor implemented self-validation routine for the device. The thick-film printed PZT elements act as sensors detecting the deflections of the inertial mass and also as actuators capable of performing a self-test routine. The self-validation procedure is performed at resonance and therefore, a microprocessor is used to identify the resonant frequency associated with each device and confirm the operation of the PZT elements. Whilst, this approach is certainly feasible, its implementation can be simplified by reducing the cross-talk between drive and detection elements and altering the geometry of the accelerometer. The performance of the device demonstrates the suitability of thick-film printed piezoelectrics for this type of application. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Thick-film; PZT; Accelerometer

1. Introduction

The combination of thick-film printed piezoelectric layers based on lead zirconate titanate (PZT) and silicon micromachined structures was first developed in order to achieve a batch fabricated actuation mechanism capable of driving a micropump [1–3]. More recently, the combination of thick-film printed layers with silicon micromachining processes has been fully characterised [4]. The process developed has since been applied to the fabrication of an accelerometer [5] and a resonant beam. This paper briefly describes the application of the fabrication technology, the design of the accelerometer and explores the possibility of using the PZT elements as actuators to perform a self-test function. Self-validation is an obvious requirement in certain safety applications such as crash detection for airbag actuation.

Whilst, this device was fabricated to demonstrate the processing issues involved in combining thick-film printing and silicon micromachining, it has proved to function very well as a shock/vibration sensor. Employing the PZT in a self-test mechanism also presents a simple method for checking the operation of the sensor without complicating its design. This device is the first of its kind fabricated in this manner and demonstrates many of the fabrication issues addressed in [4].

The mechanical design of the device is shown in Fig. 1. The device is a deflection-based dynamic mechanical accelerometer with an inertial mass suspended by four beams, each located at a corner of the seismic mass. The deflection of the inertial mass relative to the chip frame due to applied accelerations is sensed using the thick-film printed PZT elements located on the supporting beams. The piezoelectric element is printed as a capacitor structure with the active layer being sandwiched between a top and bottom electrode. As the mass moves relative to the chip frame, the beams deflect causing the piezoelectric layer to deform and hence an electric charge is generated. The amount of charge generated depends upon the piezoelectric properties of the printed layer, its thickness and the magnitude of the deflection generated by applied accelerations. The overall sensitivity of the accelerometer depends upon the amount of charge generated in relation to the background noise associated with the sensor. Fig. 1 shows the device. The size and weight of the inertial mass is 4 mm^2 and 17 mg, respectively whilst, the silicon beams are 975 μm long, 750 μm wide and approximately 40 μm thick. The thick-film piezoelectric layer is located on the beams and is an additional 60 μm thick.

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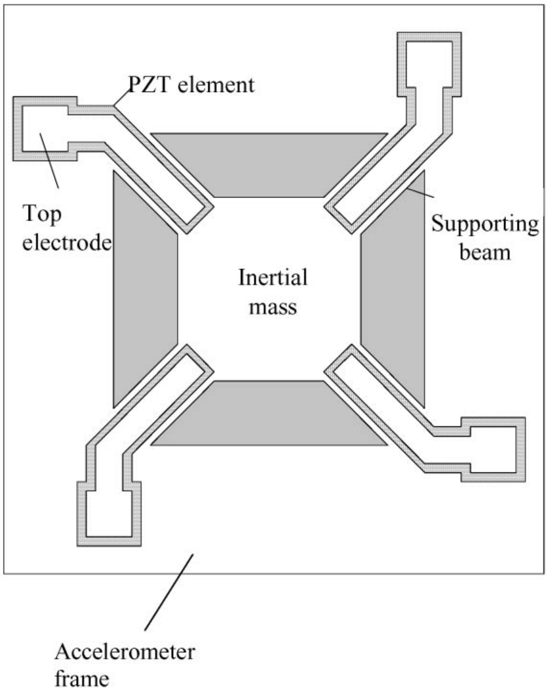

Fig. 1. Plan view of accelerometer layout.

The device was first modelled using the ANSYS finite element (FE) package in order to achieve suitable accelerometer characteristics and to optimise the position of the piezoelectric elements on each beam in order to achieve maximum sensitivity. Details of the FE modelling can be found in [6]. The FE calculated a voltage distribution along the top electrode surface of the piezoelectric element of 400 μV/g for a $9.8\ \mathrm{m/s^2}$ acceleration in the out of plane direction. The natural frequency of the accelerometer was also determined since this is the fundamental factor in defining the frequency range of operation for the device. The simulated resonant frequency for the fundamental mode of the structure was 9.5 kHz.

2. Fabrication

The combination of processes used in its fabrication, in particular the use of thick-film printed PZT elements to sense structural deflections, presents a lowcost technique for depositing piezoelectric material suitable for a wide range of piezoelectric microelectromechanical systems (MEMS). The mixture of silicon structures and micromachining processes with screen printed thick-films is not an obvious combination, but does offer some important advantages especially when depositing piezoelectric layers. Screen printing typically deposits layers of material 50–100 μm thick providing large actuating forces or sensing signals when compared to alternative techniques for depositing piezoelectric materials, e.g. sol–gel [7] or sputtered [8], since the magnitude of the charge output varies as a function of film thickness. In addition, the piezoelectric properties of the thick-film are typically improved over sol–gel or sputtered alternatives.

The combination of thick-film printing and silicon micromachining is not straightforward. During printing, the thick-film paste is deposited through a patterned screen by a squeegee that is drawn across the stencil. During deposition, the squeegee presses the screen down on to the substrate and this pressure has, until now, limited the use of screen printing to large robust structures capable of withstanding the squeegee pressure. The work presented in [4] has addressed this drawback by printing first and then micromachining. Using this approach, we have been able to combine thick-film printing processes with silicon micromachining for much finer structures.

The fabrication process is shown in Fig. 2 and described briefly here, a detailed description can be found in [6]. Firstly, double sided alignment marks, chip frame and thick-film printing alignment aids were plasma etched into the front surface of the 525 μm thick double side polished type <1 0 0> silicon wafers used for this batch. Next, a standard KOH etch was used to etch a trench in the back of the wafer defining the square inertial mass. The trench was 480 μm deep leaving a thin membrane 40 μm thick and 660 μm wide. The KOH etch has to be performed before printing since the PZT and electrodes cannot withstand the etch [4]. The bottom electrode (50 nm Ti + 500 nm Pt) was then e-beam evaporated onto the front surface of the wafer and patterned using an ion beam mill and resist mask.

The substrates were then prepared for the thick-film printing process. The PZT paste, made from 95% PZT-5H powder, 6 μm average grain size, 5% lead borosilicate powder and 5 ml ESL 400 organic vehicle, was printed through a stainless steel screen patterned with a 23 μm thick

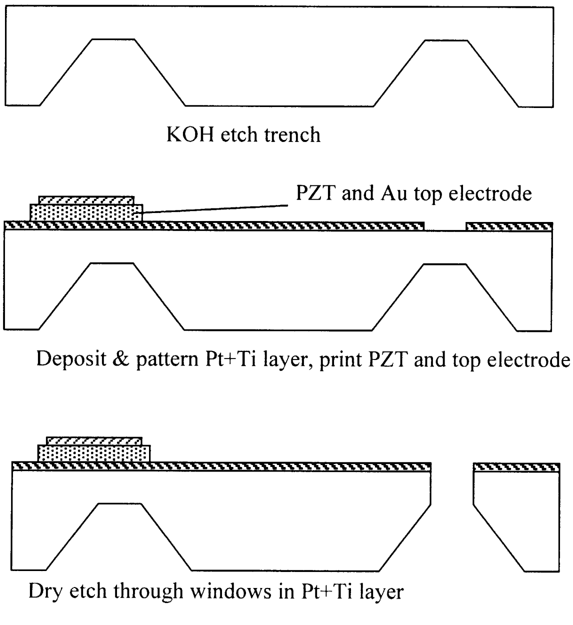

Fig. 2. Schematic of fabrication process.

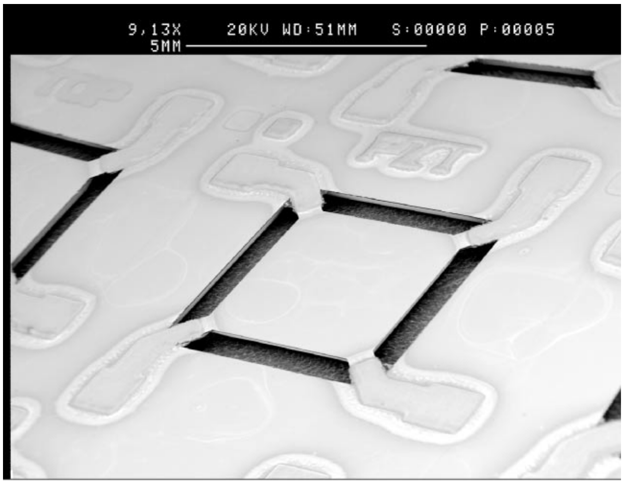

Fig. 3. SEM photo of accelerometer structure.

layer of emulsion thereby depositing the PZT ink on the bottom electrode only where required. Two print strokes yielded a thickness of approximately 60 μm after drying and firing. The film was fired at 890°C for 1 h which has been found to sinter the particles adequately without resulting in too much lead loss from the PZT. Also, the firing reaction that inhibited subsequent etches (described in [4,9]) was kept to acceptable levels. A gold cermet ink, ESL 8836, was deposited on top of the PZT with one print stroke leaving an approximate thickness of 10 μm. Accurate alignment between printed layer was essential since the PZT layer acts as the dielectric isolating both electrodes. The final process involves dry etching from the front of the wafer through the silicon membrane with the bottom electrode acting as a mask to define the final structure. An SEM photo of the etched devices is shown in Fig. 3.

The wafers were sawn into the individual chips and epoxy bonded to an alumina substrate for testing purposes. Contacts to the top and bottom electrodes were achieved using standard gold wire bonding. The yield of this process was excellent with 97% of devices in the first batch of this kind being successfully fabricated and sawn.

3. Accelerometer results

The full results for the device can be found in [6] and are summarised here. After poling the PZT elements for 1 h at 150°C with a field strength of 6.67 MV/m the accelerometer was connected to a Kistler 5001 Charge amplifier and placed on a shaker table in order to determine the fundamental sensitivity in terms of pC/m/s^2. The sensitivity of the device was found to be 16 pC/m/s^2 in the z-direction which is excellent especially when compared to other micromachined silicon accelerometers using thin-film piezoelectric sensing materials. For example, the device presented in [10] which consists of a sputtered zinc oxide (ZnO) piezoelectric film has a sensitivity of 0.15 pC/m/s^2. In this instance, the advantage of the thick-film piezoelectric layer is clear. The x- and y-axis acceleration cross-sensitivity was measured at 0.64 pC/m/s^2 for the accelerometer alone which represents a cross-sensitivity of 4%. The FE calculated cross-sensitivity was lower at 0.14%, but this is a reasonable difference given alignment inaccuracies setting up the experiment and variations in actual device geometry.

The observed resonant frequency was 7.55 kHz which was 26% below the FE predicted value of 9.5 kHz. This was due to the variations in the mechanical properties of the thick-film PZT layer, its deposited thickness and the thickness of the silicon supporting beams. The impact response of the accelerometer is shown in Fig. 4. This was as expected for an un-damped device. The accelerometer has been packaged in a straightforward manner to enable basic tests to be performed. As such, no over range protection or

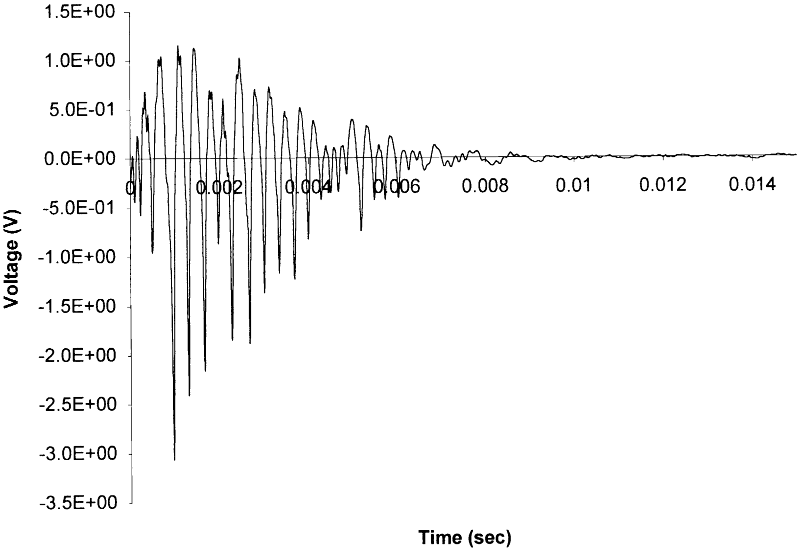

Fig. 4. Typical accelerometer impact response.

damping mechanisms have been incorporated into the package. These measures can be incorporated at a later stage and the behaviour of the device can be modified accordingly.

4. Self-validation

Piezoelectric materials are extremely useful in electromechanical applications since they can be used as both sensors and actuators. The proposed self-test mechanism uses the PZT elements as actuators to test the functionality of individual beams. In this manner, three beams are used to excite the inertial mass whilst, the vibrations are sensed by the remaining beam. The signal from each beam can be checked in sequence to ensure neither the beam or the PZT element has failed or deteriorated.

In order to explore the possibility of testing the accelerometer in this manner, an individual PZT element was connected to a charge amplifier circuit and the remaining three PZT elements were then connected to a signal generator with a 5 V peak to peak output. The output from the beam under test was initially observed on an oscilloscope and a signal at the drive frequency was detected. However, when the inertial mass was physically damped the detected signal did not change. The observed signal was, therefore, due to electrical cross-talk coupled between the drive and detection elements across the common ground plane. This coupled signal dominated any electrical signal occurring due to mechanical vibrations, and therefore, performing self-test on the accelerometer at any arbitrary frequency is not feasible. After performing a frequency sweep, however, the magnitude of the detected signal was observed to change at resonance. If the device is excited at resonance using just one PZT element to excite the vibrations, then the detected signal from the beam under test was observed to rise from 62 to 96 mV. The change in signal of 34 mV can be simply detected over the coupled cross-talk. This was confirmed by observing the response of the accelerometer on a spectrum analyser. The spectrum analyser output of the fundamental mode of the accelerometer is shown in Fig. 5. Again, the inertial mass was excited by just one PZT element and the vibrations sensed with another element. The peculiar frequency response of the detected signal, which falls approaching resonance before rising to a peak and then falling away again, is due to the interference between the coupled electrical and mechanical signals. This phenomena has been observed on thin-film piezoelectric/silicon resonators [11].

Since the mechanical signal is clearly visible over the coupled electrical signal, exciting the accelerometer at resonance is a possible method for performing a self-test function. Due to the tolerances associated with the fabrication process, however, no two structures will possess the same resonant frequency. Therefore, a microprocessor has been used to implement the self-validation routine that frequency sweeps, the accelerometer and monitors the response in order to detect the fundamental resonance. Microprocessors are widely used in many applications and are ideal for integrating with transducers to perform calibration and signal processing functions. A microprocessor offers a flexible solution capable of controlling all the functions required of the self-validation circuitry and determining the suitability of the accelerometer.

A schematic of the system developed for the self-validation routine is shown in Fig. 6. The configuration for both sensing and validation modes is shown. At the heart of the system is a PIC16F877 microprocessor which was chosen

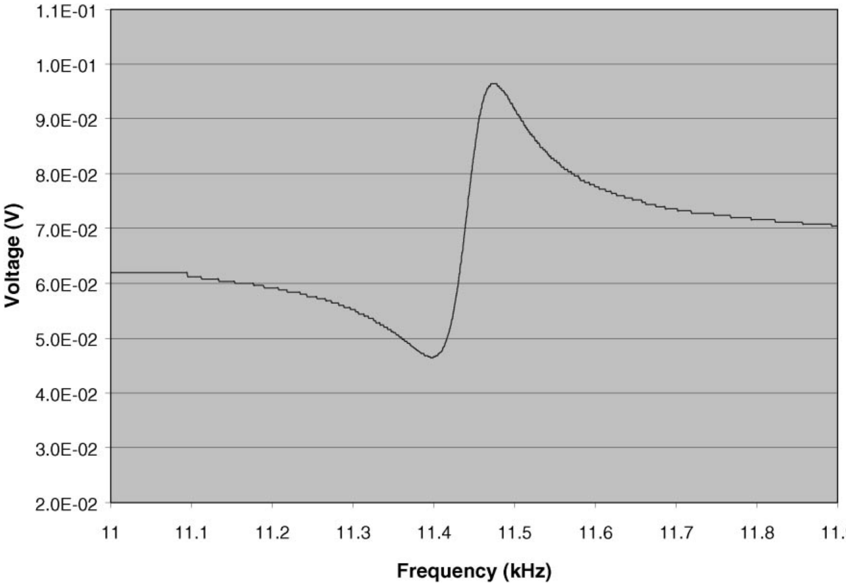

Fig. 5. Frequency response of accelerometer under self-test actuation.

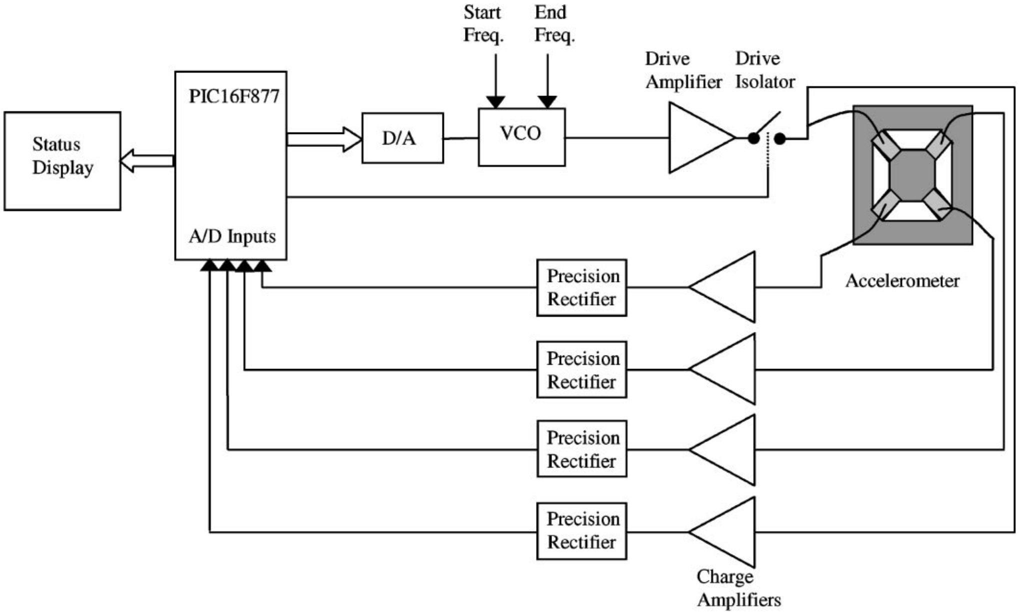

Fig. 6. Schematic of accelerometer self-validation circuitry.

because it includes an eight channel A/D converter in addition to a number of digital ports. The device has 8 kB of program memory which allows the incorporation of signal processing within the device, this memory is of the FLASH type, and thus, enables rapid reprogramming of the device for development purposes. The device can also be readily connected to external devices such as an LCD display for display of the accelerometer's status and can be connected to a PC via a serial connection to upload information from the accelerometer which could be used for data logging purposes. In the standard sensing mode, the microprocessor is not involved in this configuration since a standard analogue output is used. In this case, the output of each PZT element is simply fed through a charge amplifier and combined at a summing amplifier. Depending upon the application, the output could be fed through the microprocessor in which case signal processing could be performed for any given requirement.

When performing the self-validation, however, the output of each PZT element is fed, via each charge amplifier and a precision rectifier, to the microprocessor. The microprocessor controls a voltage controlled oscillator (VCO) through an analogue voltage produced using an 8-bit D/A circuit. The VCO then produces a sine wave at even frequency intervals between pre-set start and end frequencies which are chosen to enclose a range in which the resonance of the device should be found. The output of the VCO is amplified and then applied to one of the PZT elements of the accelerometer, this signal is isolated from the accelerometer in normal use. As the frequency applied to this leg is stepped through the range of frequencies the signal level on one of the other PZT elements is sampled using one of the internal A/D channels and numerical differentiation used to establish if a resonance has been detected. Numerical differentiation is required as the coupled signal level varies with drive frequency. To reduce the risk of incorrect identification of a resonant peak the signal level at the resonant frequency is compared with the level off resonance and must be greater by a predetermined factor. This process is then repeated for the remaining two PZT elements, using a further two separate A/D channels so that the response from each PZT element can be individually recorded. If a suitable resonance can be found for all three of the detecting PZT elements it can be concluded that all four PZT elements are functioning correctly. In the current demonstrator circuit, the pass/fail condition is simply indicated using a pair of LEDs which give a result for the accelerometer as a whole. The software to achieve the self-test operation is written using the C programming language and cross-compiled into assembly language suitable for running on the microprocessor.

5. Evaluation of self-validation

A series of accelerometers were tested on the system and this work has highlighted interesting characteristics of both to the accelerometer itself and also the thick-film PZT material. Whilst, the self-validation routine functioned correctly on all the devices tested, its implementation has been complicated by the electrical cross-talk between drive and detection elements. This cross-talk means self-validation must be performed at resonance and the physical amplitude of vibrations must exceed a given minimum in order for the mechanical resonant signal to be detected over the coupled cross-talk signal.

Further, complications that have been identified by this work is that the coupled electrical cross-talk signal is affected by the geometry of the device. It was found that the magnitude of the electrical cross-talk signal observed on any leg was affected by that legs physical proximity to driving leg. Hence, the observed electrical cross-talk was typically larger for the leg adjacent to the driving element.

In addition, the piezoelectric characteristics of individual PZT elements varies. When used in the sensing mode this is not a concern since the output of all four legs is combined. When used in the self-validation mode, however, this meant the observed mechanical resonance was often different for each leg tested. This variation in legs was also evident when actuating the accelerometer since some legs proved better at exciting the resonance than others. This variation is primarily due to misalignments in the positioning of the PZT which will lead to variations in the degree of mechanical coupling to the piezoelectric layer. In addition, the reaction material that forms around the PZT during firing and that subsequently inhibits the etching of the accelerometer will lead to variations in the geometry of each leg. Variations in the thick-film PZT material itself should be minimal since this is deposited on each leg simultaneously. There will, however, be small variations in PZT thickness and, since the PZT elements are poled simultaneously, this will lead to a small difference in the field strength applied across each PZT element. It is difficult at this stage to quantify the influence of each potential source of variation in the observed signal from each leg.

6. Conclusions

The device presented here is the first of its kind fabricated with thick-film printed PZT layers combined with silicon micromachining. The fabrication process is not complicated and these devices have been successfully realised with an excellent yield of 97% working devices from the first batch. The process is also very flexible and a wide range of structures and devices could be realised in this manner. The performance of the sensor also justifies the use of thick-film layers of PZT since the magnitude of the sensor output is 100 times that of alternative thin-film piezoelectric accelerometers of similar dimensions.

The self-test opportunity provided by the use of the PZT elements as actuators has also been explored. Self-validation has been shown to be feasible, but improvements in the fabrication tolerances of the device, measures to reduce cross-talk and possible alternative mechanical designs of accelerometer should be implemented in order to achieve a more reliable, robust and simple self-validation procedure. Work has been carried out in addressing these issues and, for example, titanium oxide has recently been identified as a suitable barrier layer capable of preventing the lead migration and the resulting reaction material. Work is currently underway in improving the minimum feature size and alignment accuracy of the thick-film PZT layer.

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Biographies

S.P. Beeby obtained his BEng (Honours) in mechanical engineering in 1992 and was awarded his PhD in 1998. He is currently, a research fellow in the Department of Electronics and Computer Science and is researching in the field of microelectromechanical systems (MEMS). He has been responsible for successfully combining thick-film printed piezoelectrics with micromachined silicon devices for MEMS applications and has also developed MEMS resonant and capacitive sensors. His interests include the finite element modelling and design of MEMS devices, silicon processing and MEMS packaging and testing. He currently has over 40 publications in the field.

N.J. Grabham received the degree of MEng in information engineering from the University of Southampton in 1998. He is currently, a full-time PhD student in the Department of Electronics and Computer Science and is working on the development of a thick-film magnetostrictive material for use as an actuator in MEMS devices. His interests include thick-film materials and the application of microprocessors to sensor applications.

N.M. White received the PhD degree from the University of Southampton, UK in 1988. He was appointed as lecturer in 1990 and is currently reader within the Department of Electronics and Computer Science, University of Southampton. He is also research director of the University of Southampton, Institute of Transducer Technology (USITT). He has published extensively in the areas of thick-film sensors and intelligent instrumentation and is author or co-author of over 70 academic publications, including the monograph 'Intelligent Sensor Systems'. Dr White is both a chartered engineer and chartered physicist in the UK, and is a past chairman of the Instrument Science and Technology Group (ISAT) of the Institute of Physics (IOP).