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Manufacture of micro-sensors and actuators for flow control

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Abstract

The design, manufacture and testing of micro-sensors and -actuators for aerodynamic drag reduction by flow control is described. Key factors in the designs are discussed, for example, the type and shape of the actuator electrodes affect the critical parameters of frequency response and deflection amplitude. Some aspects of future work are also covered.

Keywords: MEMS; Airflow control; Electroactive polymers; EAPs; Pressure sensors; Micro-actuators

1. Introduction

There are many applications for micro-sensors and -actuators for flow control, including noise control, jet vectoring, separation control and heat transfer. Another is the reduction of aerodynamic drag, which tends to put the most stringent limitations on sensor and actuator size, but is one of the applications with the largest potential gain.

At typical flight conditions (300 m/s and 10 km altitude), it has been shown [1] that a sensor/actuator array which aims to control all turbulent events on the fuselage for skin friction reduction would require elements on the order of 25 μm in size and separations of 10–100 times that dimension. In laboratory experiments, the sensor size and spacing can be relaxed by approximately an order of magnitude, but micro-scale devices are still required to resolve fully the turbulence and should detect flow structures with dimensions <1000 μm, pressure variations of ~5 Pa, at frequencies in the kHz regime. This paper reports on some on-going work investigating the nature of turbulence close to a wall and concentrates on the design and fabrication of such sensors and actuators. Results from both experiments and computer simulations are presented.

2. Design

Micro-electro-mechanical systems (MEMS) offer a solution to these problems by virtue of their small size, low cost and their ability to be manufactured into the large arrays of sensors and actuators required. Pressure sensors were chosen as the fluctuations are about 10 times the wall shear stress in a turbulent boundary layer and offer a linear instrument – most thermal shear stress gauges are not. The rationale for the use of dimple actuators is given in some earlier work [2].

The pressure sensors are of a conventional concept but require careful design in order to offer the sensitivity and frequency response required. They consist of a square membrane with a piezo-resistor located on each side; one pair crossing opposite edges of the unsupported membrane, where the stress (and hence the sensitivity) is greatest, and the other pair on the rigid substrate and acting as a reference pair. When connected in a Wheatstone bridge arrangement, an output voltage proportional to the pressure is generated. Fig. 1 shows a computer simulation of the stress pattern on the membrane when pressure is applied.

Analysis [3] of the sensitivity and frequency response for the design shows that one of the critical parameters is the

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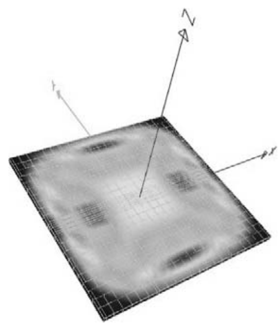

Fig. 1. Computer simulation of stress pattern on the membrane of a micro-sensor under pressure.

built-in stress of the membrane as it affects the sensitivity of the sensor. Tests showed that the stress in the silicon nitride was approximately 240 MP, which is generally defined as low but is still high enough to affect the device. Thermal oxide was found to have a stress of similar magnitude, but of the opposite sign and is used here, as a bi-layer with the nitride in an effort to achieve zero overall stress. However, this stress-cancelling effect is, at present, unconfirmed.

The actuators are active dimples and act as time-dependent surface depressions that modify the near-wall vorticity. Electroactive polymers (EAPs) are used as the actuating medium and lie flush with the surface but when actuated will deflect downwards only forming a dimple. Target specifications include a vertical displacement of 10% of their diameter and a frequency response in the kHz range.

The EAP material (NuSil MED10-6607) was tested in order to measure its physical properties, in particular the Young's modulus, Y. Samples were prepared by spin-coating as per those for the actual dimples and Y derived from digital speckle photometry of bulge tests. It was found to be different in magnitude to bulk samples and varied with the applied stress. However, over the range anticipated during operation of the dimples, Y is approximately constant.

In its simplest form, a dimple consists of the EAP sandwiched between compliant electrodes. Upon application of a voltage (typically 50 V/μm), the elastomer is subjected to compressive stress generated by the electrostatic attraction between the electrodes and expands laterally, as it is incompressible. This lateral movement is constrained at the edge of the dimple and the required out-of-plane motion occurs. The effective pressure, P, in the thickness direction is [4]

$$P = \varepsilon_0 \varepsilon_r E^2 = \varepsilon_0 \varepsilon_r \frac{V^2}{z_0^2}, \tag{1}$$

where E is the electric field in V/m, z_0 the initial EAP thickness, ε_r the relative dielectric constant of the elastomer and ε_0 the permittivity of free space. The value calculated here is double the electrostatic pressure of a conventional parallel plate capacitor and is attributed to the fact that the device has compliant electrodes which allow coupling of the attractive forces between the oppositely charged electrodes and the repulsive forces separating the charge on each electrode. Assuming fully compliant electrodes and using the Y derived earlier, the strain in the thickness direction, S_z, can be calculated by

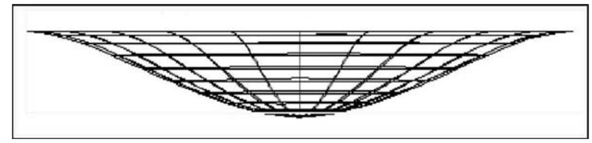

Fig. 2. Computer simulation of a dimple under deflection of 10% of its diameter. Note that the vertical scale is expanded for clarity.

$$S_z = -\frac{P}{Y} = -\frac{\varepsilon_0 \varepsilon_r}{Y} \frac{V^2}{((1+S_z)z_0)^2} \tag{2}$$

and the strain in the lateral direction can be calculated from the Poisson's ratio. If the dimples are approximated by spherical geometry, the out-of-plane displacement can be simply calculated and for a 20 μm film of MED10-6607 is 7.7% of dimple diameter per kV of applied voltage. Fig. 2 shows a computer simulation of such a dimple under deflection.

In practice, the electrodes are not fully compliant and restrict the movement of the elastomer, requiring more complicated analysis. Future options include compliant, conductive elastomer electrodes but, at present, they are made of gold and shaped into concentric rings to make the electrode more compliant. Current work will optimize the mark/space ratio of these rings and its correlation with finite element analysis (FEA). Currently the EAP is 20 μm thick, whilst the electrodes are 100 nm thick and have line/space widths from 5 to 20 μm.

3. Manufacturing technology

The manufacturing technologies used are adapted from standard semiconductor processes and, in brief, the steps are:

Pressure sensor

(i.) Grow thermal oxide on wafer.
(ii.) Deposit silicon nitride on upper surface.
(iii.) Pattern Pt resistors on upper surface.
(iv.) Pattern Au tracks on upper surface.
(v.) Deep reactive ion etch (DRIE) from lower surface to form cavities.
(vi.) Bond wafer into mounting annulus.
(vii.) Wire-bond between wafer and annulus.
(viii.) Attach electrical connections via underside of annulus.
(ix.) Wafer is ready to test.

Dimple actuator

(i.) Grow thermal oxide on wafer.
(ii.) Pattern lower electrode on upper surface.
(iii.) Spin-coat EAP on upper surface of wafer.
(iv.) Pattern upper electrode on EAP.
(v.) DRIE from lower surface to form cavities
(vi.) Etch oxide on underside of dimples.

(vii.) Bond wafer into mounting annulus.
(viii.) Wire-bond between wafer and annulus.
(ix.) Attach electrical connections.
(x.) Wafer is ready to test.

4. Results

Fig. 3 shows a 200 μm × 200 μm pressure sensor, whilst Fig. 4 shows a full wafer with a 3 × 3 array of sensors at its centre. The gold tracks lead from the sensors to the through-hole connections on the mounting annulus, thereby minimising disturbances to the airflow close to the sensors.

The sensitivity of the 400 μm × 400 μm sensors was found to be 0.007 μV/V/Pa, which is close to the 0.004 μV/V/Pa from the earlier analysis using a nitride-only membrane. Tests to establish frequency response are on-going.

Fig. 5 is a close-up of one of the dimple actuators and shows the concentric rings of the electrodes, whilst Fig. 6 shows a completed wafer with four dimples at the centre. Each dimple has a different electrode coverage ratio, thereby allowing the optimum design to be found.

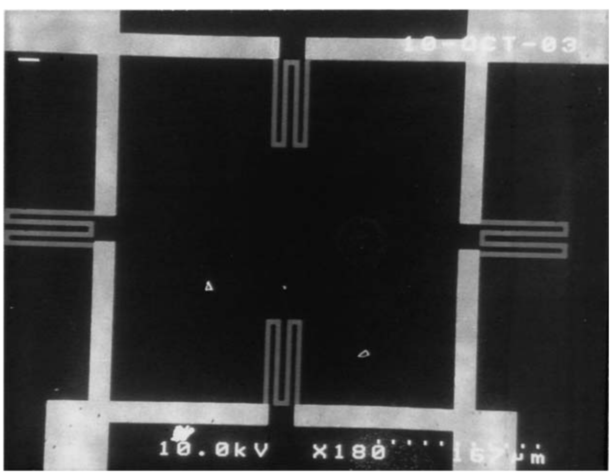

Fig. 3. SEM image of a pressure sensor. The 40 nm × 5 μm Pt resistor pairs and Au tracks can be seen.

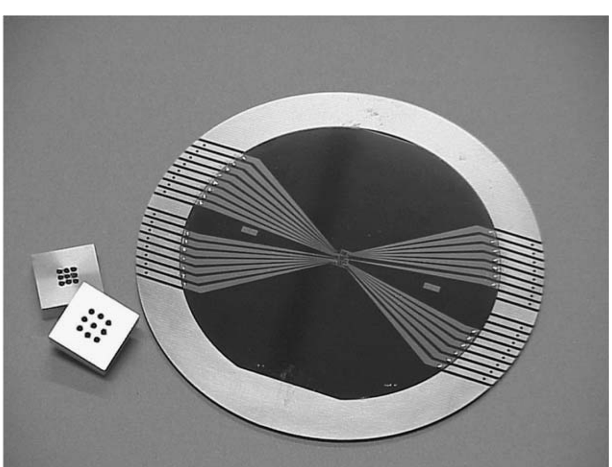

Fig. 4. A 100 mm wafer with a 3 × 3 array of 400 μm × 400 μm pressure sensors at the centre.

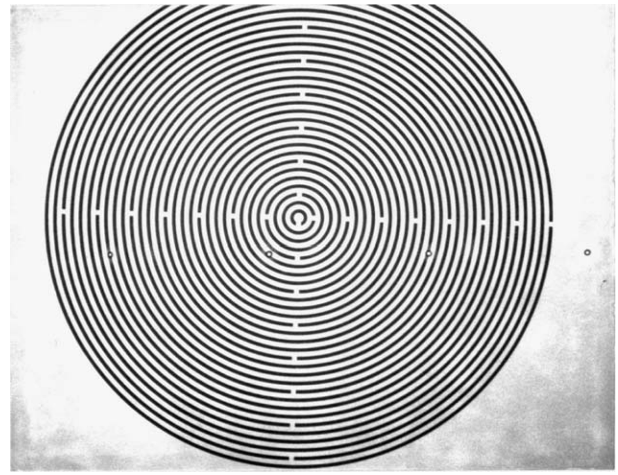

Fig. 5. Close-up of an active dimple showing the concentric ring design of the gold electrodes.

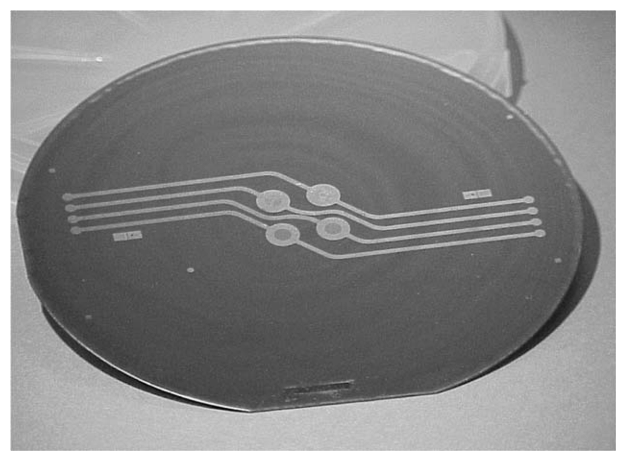

Fig. 6. A completed active dimple test wafer.

Test dimples, excited acoustically, show resonant frequencies of ~2.5 kHz using laser vibrometry. Each electrode design shifts the peak by about ±0.1 kHz.

5. Conclusions

Micro-sensors and -actuators have been designed and manufactured for use in flow control. The EAP material has been tested and the Young's modulus, Y, measured. It was found to be different to that of the bulk material. This is attributed to the preparation method (i.e., spin-coating). In addition, and unlike many materials, Y is non-constant. Both sensors and actuators are undergoing further tests but initial results show a sensitivity of 0.007 μV/V/Pa for the sensors and a resonant frequency of approximately 2.5 kHz for the dimples.

6. Future work

Future work for the sensors will include the investigation of EAPs as an alternative membrane material. This work should allow easier integration with the actuators on a single substrate which might itself be flexible and thus form a "smart skin".

For the actuators, alternative electrode materials will be investigated, in particular, compliant, conducting elastomers.

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