STRESS SENSITIVE CAPACITIVE TRANSDUCERS TO VERIFY PACKAGE MODELS

Andrew McNeil and Gary Li

Freescall Semiconductor Inc., 2100 E. Elliot Rd, Tempe AZ 85254

ABSTRACT

This paper describes MEMS capacitive transducers modified to characterize package stress. Two transducer types were designed: one to measure uniform in-plane strain, the other to measure uniform z-axis bending ("curvature"). These package-stress transducers had the same sensing mechanism as the MEMS acceleration transducers (capacitive output), so they could be used in existing accelerometers to quantify package-induced deformation. These transducers were fabricated in a production MEMS process (Motorola/Freescale 3u thick polysilicon "two poly" flow) and were characterized with capacitive probe and in accelerometer packages. Test data from the two sensor types provided useful data for verifying package models.

INTRODUCTION

MEMS sensors must meet increasingly stringent accuracy requirements. Some low-cost, mass-market three-axis accelerometers specify typical thermal output changes of 9 milli-g or less [1,2] at specified temperature range. These stringent specifications require accurate modeling; using typical values for proof mass mass and spring constant shows that this corresponds to proof mass displacement of about one Angstrom (1E-10m).

Simulating parameters such as "TCO" (Temperature Coefficient of Offset) requires FEA modeling of package-MEMS interactions. FEA models are required for both package thermal-mechanical performance and MEMS electrostatic-mechanical performance. Often the package models and MEMS models can be run separately and then numerically linked [3,4]. Figure 1 shows a cross-section of a typical accelerometer. The package-induced effects are primarily determined by displacements on the "MEMS mounting surface", as this is where the MEMS structures are fabricated.

Figure 1: Simplified cross-section of typical MEMS sensor including CMOS die and MEMS die with cap. These die are over-molded with thermoset plastic. MEMS structures are much smaller scale than package features and located on "MEMS mounting surface".

Package FEA models require verification, but this verification can be difficult because the area of interest (displacements on the MEMS mounting surface) is not easily accessible in standard accelerometer packages. Usually the MEMS die is encapsulated by mold compound.

One approach is to use stress sensing silicon dice. An example is to fabricate piezoresistive stress sensors on silicon die

[5]. An array of piezo-resistive stress sensors can be used to estimate the stress state at a location on the stress sensing side.

When used to study capacitive-MEMS products piezoresistive sensors have several potential disadvantages. First they use a different sensing mechanism (piezoresistance vs. variable capacitance) so they can't be coupled with the standard CMOS control die for the accelerometer. A further challenge is that the stress sensing die should be the same physical dimension as the MEMS die, this is because the MEMS die design has the significant effect on the package thermal-mechanical response. It is difficult to achieve the same form factor because not only must the die size be the same, but most MEMS capacitive acceleration die have wafer-level "caps" attached that form a two-die stack as shown in figure 1 [3]. A final problem is that the piezo-resistive effect relies on resistors with fairly large temperature coefficients, and this can complicate multi-temperature testing of packaged devices.

In summary: for validating package stresses in production MEMS products the stress sensing die would have following characteristics:

- Same physical form factor and material as the actual MEMS sensor die
- Compatible with actual CMOS control die so product can be converted into deformation sensor (same sensing mechanism, compatible pin-out, appropriate sensitivity).

PROCEDURE

Two types of package deformation transducers were constructed: one to sense package-induced strain, the other to sense package induced uniform curvature.

Lateral Device: The lateral strain sensor is a modified version of the lateral acceleration transducer. First the operation of the lateral acceleration transducer will be described.

Figure 2: Typical x-axis lateral accelerometer uses proof mass mounted on springs and is symmetric about AA. This produces differential output ($\Delta C = C1 - C2$). Fixed electrodes x1, x2 form sense capacitors C1, C2.

An overview of a lateral capacitive acceleration transducer is shown in figure 2. This common type of acceleration transducer uses a proof mass mounted on spring compliant in a lateral (e.g. x)

direction. Acceleration causes proof mass displacement relative to fixed electrodes x_1 and x_2 . This causes differential capacitance change, with one sense capacitor increasing and the other sense capacitor decreasing. Typically acceleration output is proportional the difference of the two sense capacitors (C1-C2).

Often acceleration transducers are made with symmetric proof mass/spring design. This allows the transducer to reject a symmetric displacement field such as uniform strain. It can be shown that the differential output (C1-C2) of the transducer will not be affected by symmetric deformation.

Figure 3: Modified transducer adds anchor to asymmetric location. This anchor virtually eliminates acceleration sensitivity and causes the transducer to produce capacitance signal when subjected to uniform x strain.

Figure 3 shows how the lateral acceleration transducer was modified to convert it into a strain sensor. An extra anchor is attached to the proof mass at distance S from the proof mass center. Assuming a uniform strain ϵ_x with zero x -displacement $\Delta x=0$ at $x=0$, the displacement at location x will be:

$$\Delta x = \epsilon_x x \quad (1)$$

If the anchor is rigidly attached to the proof mass the proof mass displacement will be equal to the asymmetric anchor displacement. This displacement can be found by substituting S into eqn. 1 yielding $S \epsilon_x$. The average fixed electrode displacement will be zero because the average electrode location will be zero. T

Assuming the parallel plate equation with capacitor area A , and gap g_0 , the capacitance C can be expressed as:

$$C = \frac{\epsilon_0 A}{g_0} \quad (2)$$

Generally thermal-mechanical displacements are a small fraction of the sense gap, in this case the capacitance change can be approximated as linear expression:

$$\Delta C \approx \frac{-\Delta x}{g_0} C_0 = \frac{\epsilon_0 A \Delta x}{g_0^2} \quad (3)$$

Thus the average sense capacitor change can be approximated as average gap change, this can be use form the following expression for differential output ΔC :

$$\Delta C = \frac{2 \epsilon_x S C_0}{g_0} \quad (4)$$

Equation 4 is an approximation of the differential capacitance output of the lateral strain sensor. The parameter S can be used to modify the sensitivity of the strain sensor. The goal is to produce ΔC of desired level (high enough to achieve good SNR, low enough not to rail CMOS control die). In this case the sensor was made by simply adding an anchor to an existing acceleration transducer.

Curvature Sensor: The die curvature sensor is a modified version of the z -axis acceleration transducer. First the operation of the z -axis acceleration transducer will be described.

Figure 4 shows an overview of how a typical z -axis acceleration transducer works, this device will be referred to as a “teeter totter”. This design typically has symmetric design for sense electrodes and springs and an asymmetric portion (“heavy end”) to cause rotation under z -axis acceleration. Because of symmetric electrodes a symmetric deformation will cause no differential output ($\Delta C = C1-C2 = 0$ if two capacitors initially equal).

Figure 4: Typical z -axis “teeter totter” accelerometer uses proof mass mounted on torsional suspension and is symmetric about AA. Substrate is shown with uniform curvature such that $\Delta z = K_c X^2$. Symmetric design of electrodes and spring rejects simple, symmetric curvature.

For z -axis acceleration transducers one important type of deformation is bending of the MEMS die. One type of deformation is uniform, quadratic, x -axis bending,

$$\Delta z = K_c x^2 \quad (5)$$

Where K_c is the curvature constant with units m^{-1} and Δz is the z -displacement. Another common way of expressing curvature is with a “radius of curvature” R_c . ($R_c = 1/2 K_c$)

Figure 5 shows how the teeter totter was modified to form a curvature sensor. The heavy end has been removed, and sense electrodes have been modified such that in-board electrodes form one sense capacitor and out-board electrodes the other capacitor. This sensor now responds to curvature since the in-board gap changes less than the out-board gap.

Figure 5: Modified z-axis “teeter totter” accelerometer now functions as deformation sensor. Bottom sense electrodes have each been split into two sections, and re-arranged such that one electrode is in-board and the other electrode is out-board. This device will now respond to uniform substrate curvature. “d1” and “d2” are centroid locations of sense electrodes relative to center of transducer.

Using an analysis similar to the lateral device (parallel plate capacitance calculation, small displacement, long narrow proof mass) the following equation approximates the sensitivity of the simple curvature sensor.

$$\Delta C \approx \frac{K_c (d_1^2 - d_2^2) C_0}{g_0} \quad (6)$$

All stress sensor were manufactured in the standard production process (Motorola/Freescale “two poly” [6]). All stress sensors were virtual “drop in” replacements for the actual acceleration die, with same die size and same pin-out.

For characterization the stress sensors were tested in two ways:

1. Probe: Parts probed using a capacitive LCR meter. This was a room temperature probe to measure the differential capacitive output of bare (unpacked, un-sawn) MEMS wafer.
2. Sensors were package in standard packages with appropriate CMOS control die, and were testing over temperature (-40 to 105C) using accelerometer test systems. In this case the parts were tested in a constant acceleration state (1g) so parts have static output.

RESULTS AND DISCUSSION

A summary of probe data for two lateral stress sensing designs is shown in Figure 6, data is “delta capacitance” (C1-C2) in fF. This data is from about 600 parts from ten wafers. The two strain sensing designs have opposite location for added anchor, they should show opposite readings of equal magnitude. In this case the probe data is for the bare MEMS wafer so most of the normal package (mold compound, lead-frame, etc) is not present. The small amount of strain (about -4.8 μ strain) is from thermally dissimilar materials present in the MEMS wafer (glass frit for wafer level packaging, silicon oxide, silicon nitride).

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Quantiles

Level	Min	10%	Med	90%	Max
STRL	-5.94	-2.74	-0.76	0.53	3.82
STRR	-5.69	-0.83	0.80	3.02	5.15

Figure 6: Probe data for ~600 lateral strain sensors, unpackaged MEMS wafer. The value dC is the delta capacitance between sense electrodes as measured with an LCR meter (fF). The two devices “STRL” and “STRR” have anchors added to left and right side respectively so they should have opposite outputs. In the case the “STRL” has median output of -0.76 fF and STRR has median output of +0.80 fF

Figure 7: Plot shows output of 20 lateral strain sensing structures measured over temperature. These were used in standard accelerometer package with production control die. This is analog output (in mV) of accelerometers with accelerometer die replaced by strain sensing die. The average response was about 0.31 mV/C.

Figure 7 shows a plot of packaged lateral strain sensors measured over temperature. This data was collected with an analog output CMOS control die, so the output shows output in mV vs. test temperature. The 20 parts show a consistent trend, with about 0.31 mV/C slope. Using the CMOS control die calculation an estimate was made that this corresponded to approximately -0.005 μ strain/C. FEA simulations of this package were run and strain was extracted, this yielded thermal strain within 18% of this value.

Figure 8: Plot shows output of 12 curvature sensing structures measured over temperature. This is the analogue output (in mV) of accelerometers with accelerometer die replaced by strain sensing die. These parts show consistent behavior with about -0.41 mV/C .

Figure 8 shows a plot of packaged curvature sensors measured over temperature. This data was collected with an analog output CMOS control die, so the output shows output in mV vs. test temperature. The 12 parts show a consistent trend, with about -0.41 mV/C slope. Based on control die characteristics this yields a curvature coefficient K_c of about 0.085 m^{-1} . This was within about 20% of curvature from FEA modeling.

These test die were useful in establishing accuracy for an FEA models of a common package. The package used special stress isolating features and thus produced low levels of package stress, and these structures provided a very sensitive measurement of package displacement.

In the future these structures could be modified. These structures could be modified to measure package stress in newer, higher-stress sensor packages. They also could be design to sense

other deformation modes. Further multiple sensors could be placed in test die to get deformations in different locations.

SUMMARY AND CONCLUSIONS

Modified versions of MEMS acceleration transducers can act as displacement sensors, and these sensors can be used to sense several deformation modes (average in-plane strain, out of plane curvature). These sensors allow measurement in the actual MEMS mounting location and can be directly substituted in place of other transducers (e.g. acceleration transducers). These provide a useful method of verifying package models.

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CONTACT

*Andrew McNeil,
Andrew.mcneil@freescale.com

telephone: +1-480-413-8857;