Evaluation of Thermo-Mechanical Stability of COTS Dual-Axis MEMS Accelerometers for Space Applications

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Introduction

Microelectromechanical systems (MEMS) is one of the fastest growing technologies in microelectronics, and is of great interest for military and aerospace applications. Accelerometers are the earliest and most developed representatives of MEMS. First demonstrated in 1979, micromachined accelerometers were used in automobile industry for air bag crash-sensing applications since 1990. In 1999, MEMS accelerometers were used in NASA-JPL Mars Microprobe [1].

The most developed accelerometers for airbag crash-sensing are rated for a full range of ±50 G. The range of sensitivity for accelerometers required for military or aerospace applications is much larger, varying from 20,000 G (to measure acceleration during gun and ballistic munition launches), and to 10^{-6} G, when used as guidance sensors (to measure attitude and position of a spacecraft). The presence of moving parts on the surface of chip is specific to MEMS, and particularly, to accelerometers. This characteristic brings new reliability issues to micromachined accelerometers, including cyclic fatigue cracking of polysilicon cantilevers and springs, mechanical stresses that are caused by packaging and contamination in the internal cavity of the package. Studies of fatigue cracks initiation and growth in polysilicon [2, 3] showed that the fatigue damage may influence MEMS device performance, and the presence of water vapor significantly enhances crack initiation and growth.

Environmentally induced failures, particularly, failures due to thermal cycling and mechanical shock are considered as one of major reliability concerns in MEMS [1]. These environmental conditions are also critical for space applications of the parts. For example, the Mars pathfinder mission had experienced 80 mechanical shock events during the pyrotechnic separation processes [4].

In general, most of the analyses of the failure mechanisms in MEMS have been performed, using test structures. However, a comprehensive qualification of MEMS, requires experimental data obtained using real parts. In this respect, endurance characteristics of the accelerometers with respect to temperature cycling and mechanical shock is of great interest in their evaluation for space applications.

In the present study, thermo-mechanical stability of commercially available, mass production accelerometers (ADXL250) available from Analog Devices was evaluated, by subjecting them to multiple temperature cycles in the range from –65 °C to +150 °C and mechanical shocks of 2000 G in the X and Z directions.

Part Description

Analog Devices ADXL250 is a dual-axis, surface micromachined accelerometer rated for ± 50 G and packaged in a hermetic 14-lead surface mount cerpack. The operating temperature range of the part is from –55 °C to +125 °C and the storage temperature range is from –65 °C to +150 °C. The part can withstand acceleration up to 2000 G.

The device is fabricated using a proprietary surface micromachining process that has been in high volume production at Analog Devices, since 1993. The two sensitive axes of the ADXL250 are orthogonal (90°) to each other and in the same plane as the silicon chip. The differential capacitor sensor consists of fixed plates (stationary polysilicon fingers) and moving plates attached to the beam (inertial mass) that shifts in response to the acceleration. Movement of the beam changes the differential capacitance, which is measured by the on-chip circuitry (the clock frequency of the capacitance meter is 1 MHz). Figures 1 and 2 show overall views of the chip and the capacitive sensor. Figures 3 and 4 show close up views of the elements of the sensor, such as spring attachment and polysilicon finger attachment.

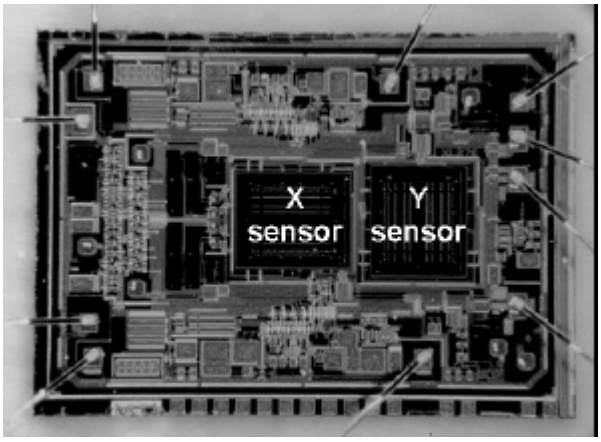

Figure 1. Overall view of the ADXL250 chip.

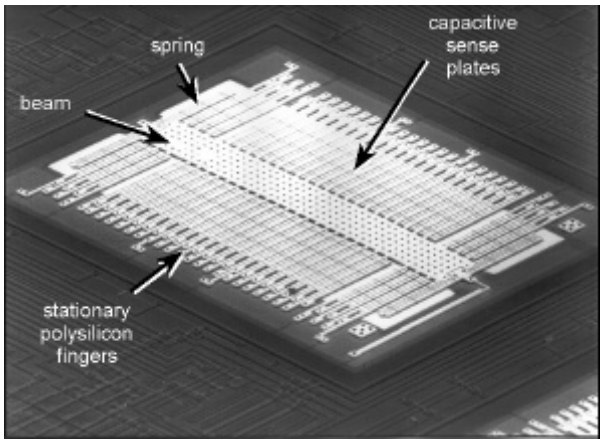

Figure 2. Overall view of the capacitive sensor.

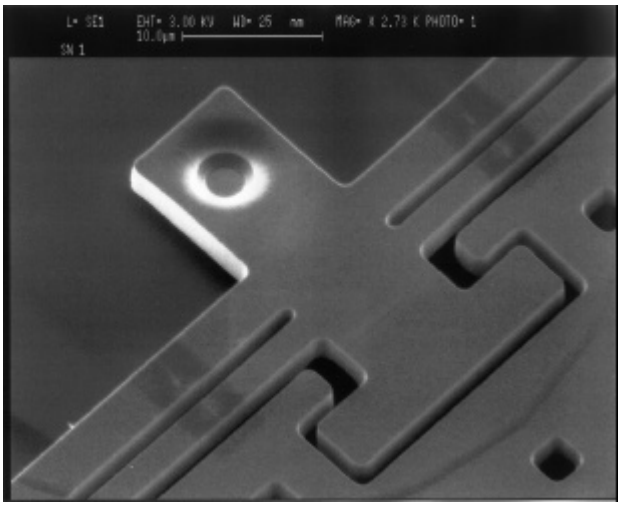

Figure 3. Close up of the spring attachment.

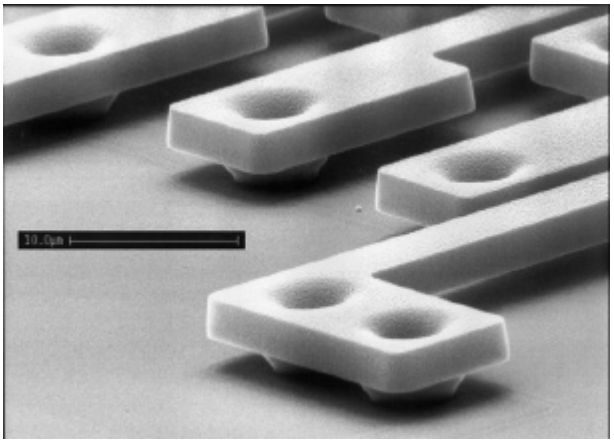

Figure 4. Close up of the stationary polysilicon finger attachment.

The sensor has 12-unit capacitance cells for electrostatically forcing the beam during a self-test. During a logic high on the self-test input pin, an electrostatic force acts on the beam equivalent to approximately 20% of the full-scale acceleration input, activating both the entire mechanical structure and the electrical circuitry. The polysilicon electrodes have a thickness of 2 μm and are suspended approximately 1 μm over the surface by means of two long and folded polysilicon beams, acting as suspension springs. The overall capacitance of the sensor is small, typically in the order of 0.1 pF and during acceleration, the capacitance variation, which is measured by the on-chip electronics, ranges from 0.001 to 0.01 pF [5].

Electrical Tests

The ADXL250 accelerometer has limited number of parameters specified, including sensitivity for X and Y channels (specified for 38 ±5 mV/G), self-test for X and Y channels measured as output voltage change ($0.25\ V < V_{out} < 0.6\ V$), and quiescent supply current, ICC (5 mA max). The sensitivity was calculated using a self-calibration technique, which is based on output measurements at four different orientations of the part in the gravity field of the Earth.

A resonant frequency of polysilicon stationary fingers and/or springs is sensitive to the presence of microcracks [3]. Therefore, changes in the resonant frequency caused by mechanical or thermal cycling could be used as a precursor of fatigue failures. For this reason, the resonant frequency of the capacitor sensor is determined using the self-test response at different self-test input frequencies.

The resonant frequency for a rectangular bar (of the length L, thickness h and width a), which is fixed at

one end and free at another end, can be calculated as follows:

$$f = \frac{0.559}{L^2}\sqrt{\frac{EJ}{rha}}$$

where E = 160 GPa is the Young's modulus of polysilicon;
r = 2400 kg/m^3 is the density of polysilicon;
J = ah^3/12 is the moment of inertia of the bar.

With the length of the stationary finger of 180 µm, thickness of 3 µm and width of 2 µm, the calculation yields, resonant frequency of 122 kHz in X/Y direction. Similar calculations for Z direction give resonant frequency of 81 kHz.

The resonant frequency of the moving core of the sensor (beam) can be estimated, using an equation for an undamped, spring-mass system:

$$f = \frac{1}{2p}\sqrt{\frac{K}{M}}$$

where M = 2.7 x 10^{-10} kg is the estimated mass of the beam;
K = 12EJ/A^3 is the spring ratio;
A = 230 µm is the effective length of one (out of four) springs holding the beam.

The calculation yields a resonant frequency for the beam of 6.2 kHz, which is lower than the resonant frequency of 24 kHz per manufacturer data.

A typical output response of the part when the self-test input frequency was swept from 0 to 27 kHz is shown in Figure 5a. Several sharp and reproducible resonant spikes were found in the range from 5 to 25 kHz. However, the resonant frequencies were shifting with changes of power supply voltages (see Figure 5b). Besides, direct measurements of the output buffer amplifier (when pulses of different frequency were applied to the offset null input), showed frequency response similar to the self-test experiments (see Figure 5c). These results suggest that the observed resonant-like spikes were caused by electronic circuits of the chip and were not related to the mechanical resonance of the sensor.

Temperature Cycling Test Results

Temperature cycling was performed on 10 parts in the range from – 65 °C to +150 °C, with 15 minutes dwell time at each temperature. Measurements were taken after 100, 200, 400, 700, and 1000 cycles. Figure 6 shows results of this test. No failures or any significant changes in parameters of the parts were observed.

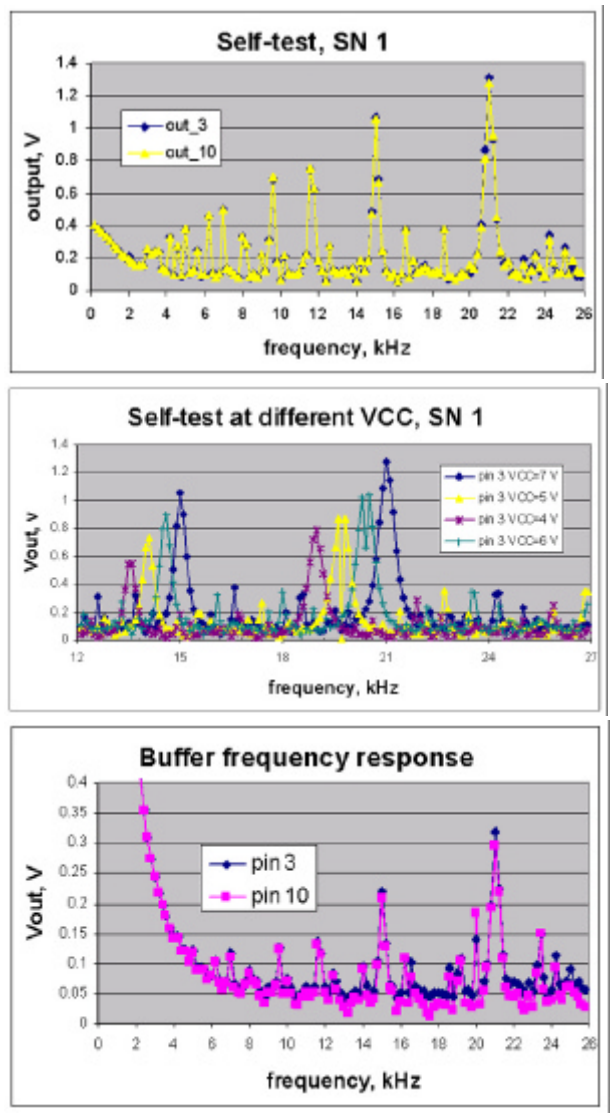

Figure 5. Self-test frequency response.

Mechanical Shock Test Results

Mechanical shock testing was performed on two groups of devices with ten samples in each group. The first group was subjected to 2000 G shocks in X-direction and the second group to 2000 G shocks in Z direction. Measurements were taken after 100, 300, 1000, 3,000, 10,000, and 30,000 shocks.

All parts in the second group withstood 30,000 shocks with only minor changes in their parameters (see Figure 7). One sample in the first group failed after 10,000 shocks with output Y stuck high (4.9 V). Parameters of samples in the first group also, did not

show any significant changes during this testing (see Figure 8).

All samples in both groups except for the failed one, passed PIND testing. The failed part exhibited permanent noise bursts indicating presence of free particles inside the cavity.

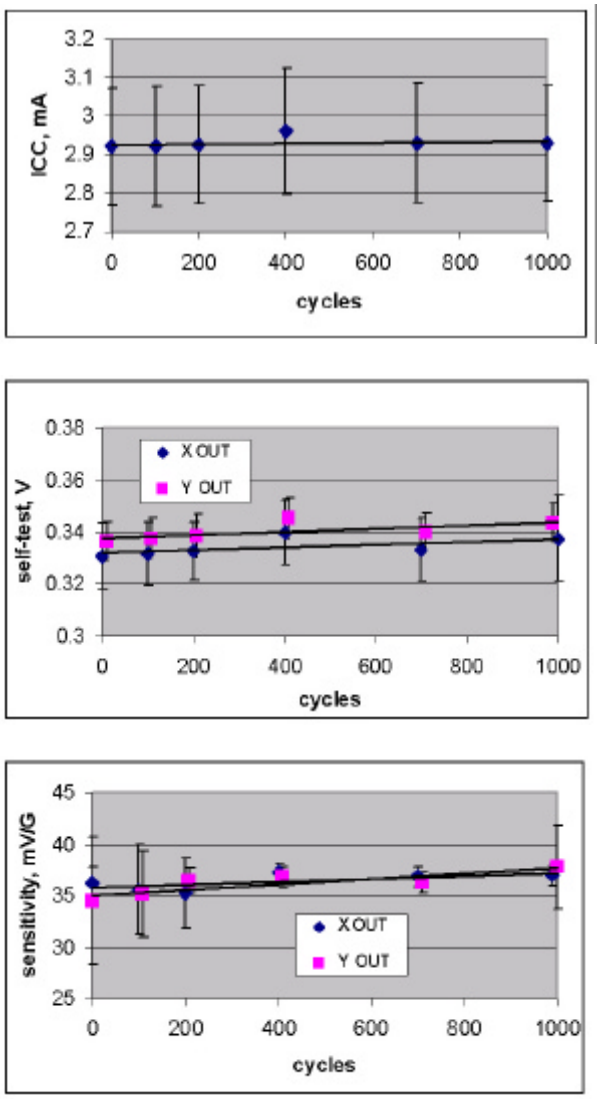

Figure 6. Temperature cycling effect on parameters of the accelerometer.

Internal Examination and Failure Analysis

The failed part and several good parts from different groups were decapsulated after testing and examined using optical and SEM microscopes. No microcracks or other defects, which would indicate fatigue-related damage in the sensors, were observed in any of the parts. Figure 9 shows typical close-up views of the polysilicon spring ends after temperature cycling and mechanical shock testing.

A site with a structural anomaly was found in the sealing glass of the failed device. This site had excessive voiding and porosity, which most likely was due to a contaminant embedded in the glass (see Figure 10).

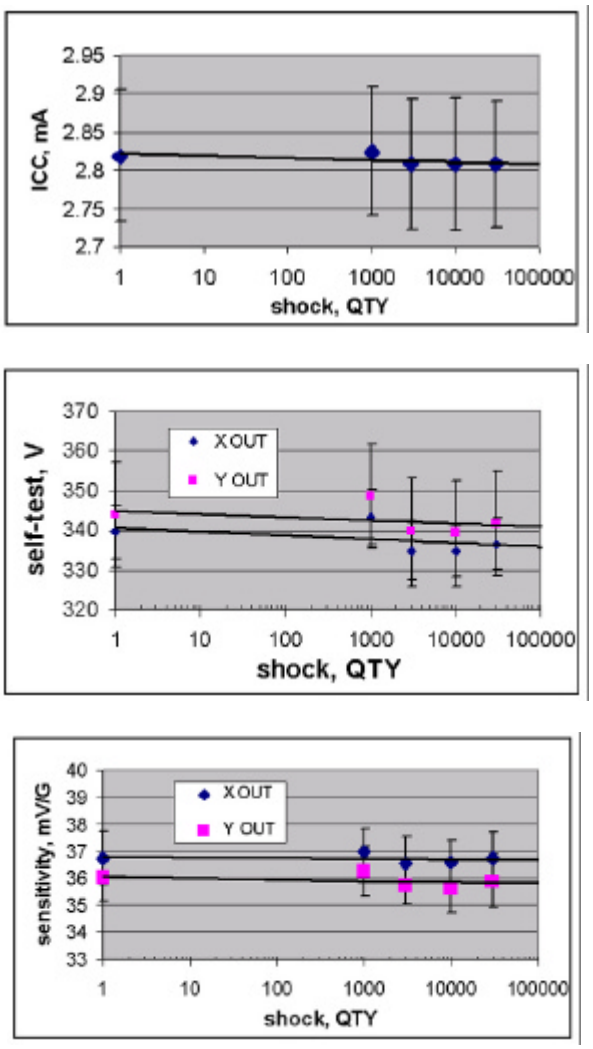

Figure 7. Z-direction mechanical shock effect on parameters of the accelerometer.

Electron beam induced current technique (EBIC) was used in attempt to find any anomaly in the failed Y-channel electronic circuit as compared to the X-channel. EBIC images of the two channels were similar, suggesting that no damage to electronics has occurred.

A small particle with a size of approximately 1 μm, which most likely chipped out from the package, was found jammed between the comb fingers in the Y-channel sensor in the failed part (see Figure 11). This particle appears to have wedged electrodes of the

capacitor sensor, causing the Y output to be stuck high.

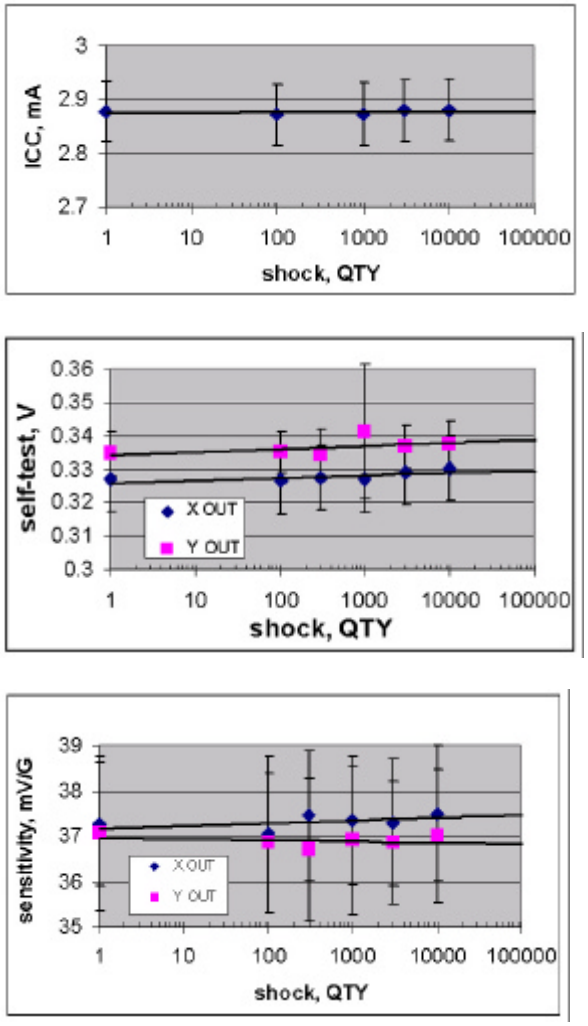

Figure 8. X-direction mechanical shock effect on parameters of the accelerometer.

Discussion

The process of decapsulation of ceramic packages, usually generates glass and/or ceramic particles, making it harder to identify the original particle, which was expected in the failed part. However, the following observations suggest that the failure was due to the packaging problem:

1. Only the failed part had loose particles inside the cavity, detected during PIND testing.

2. Sealing glass in the failed part had a site with excessive porosity and local mechanical stresses caused by the embedded foreign material (contaminant). This facilitated glass cracking during the mechanical shocks and resulted in chip-outs and generation of loose particles.

3. A particle jammed between the electrodes was found in the capacitor sensor of the stuck Y channel of the failed part.

4. No indication on possible damage to the polysilicon fingers and/or springs, or to the electronics was found.

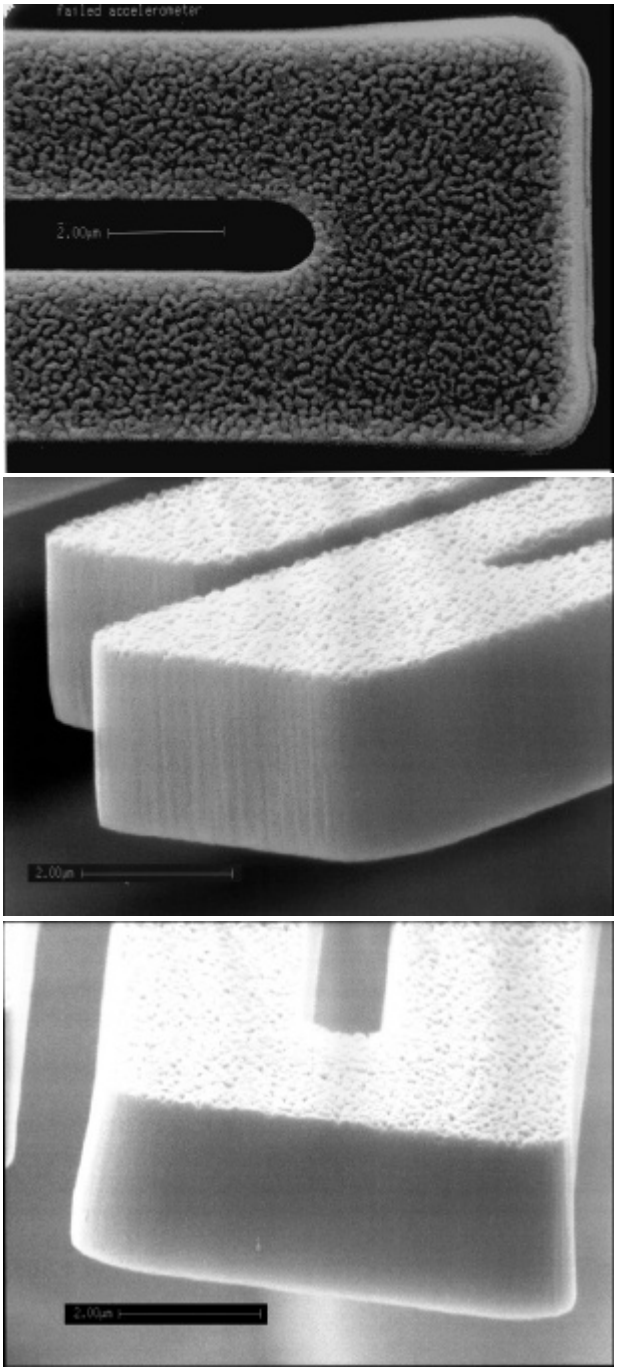

Figure 9. Typical close up views of the polysilicon spring ends after temperature cycling and mechanical shock testing.

The observed failure, stresses the need for thorough control of packaging materials and process for MEMS and for accelerometers, in particular. For example, the adaptation of new packaging solutions for MEMS, such as the use of cap-on-chip technology [6], would probably eliminate problems associated with loose particles in the package.

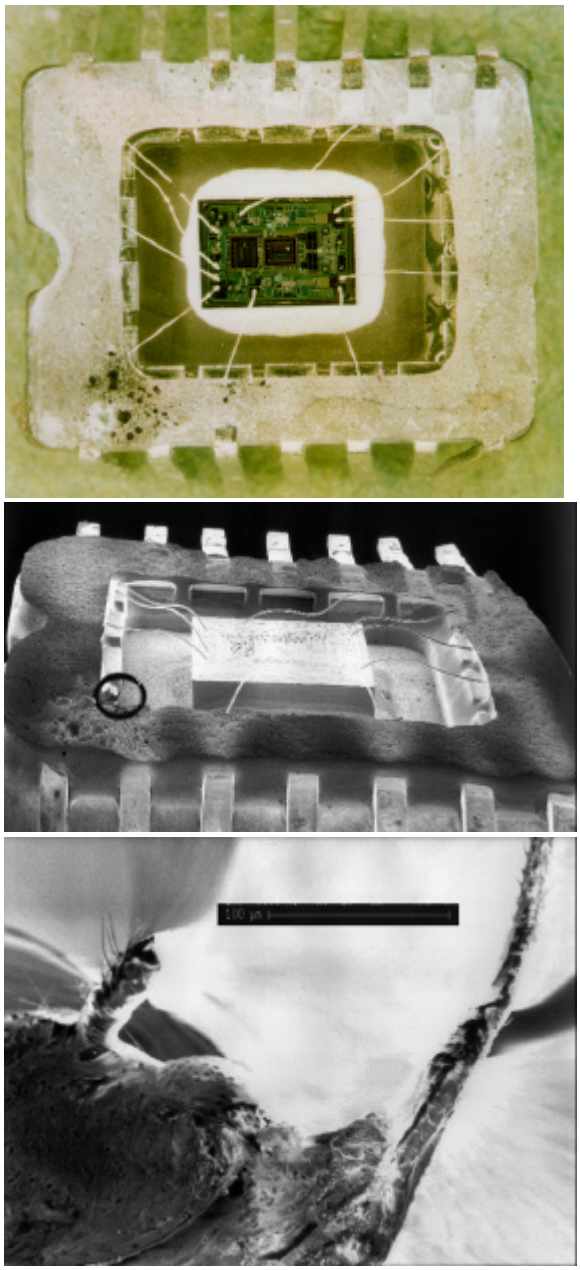

Figure 10. Structural anomaly in the sealing glass of the failed part (bug-in-the-glass).

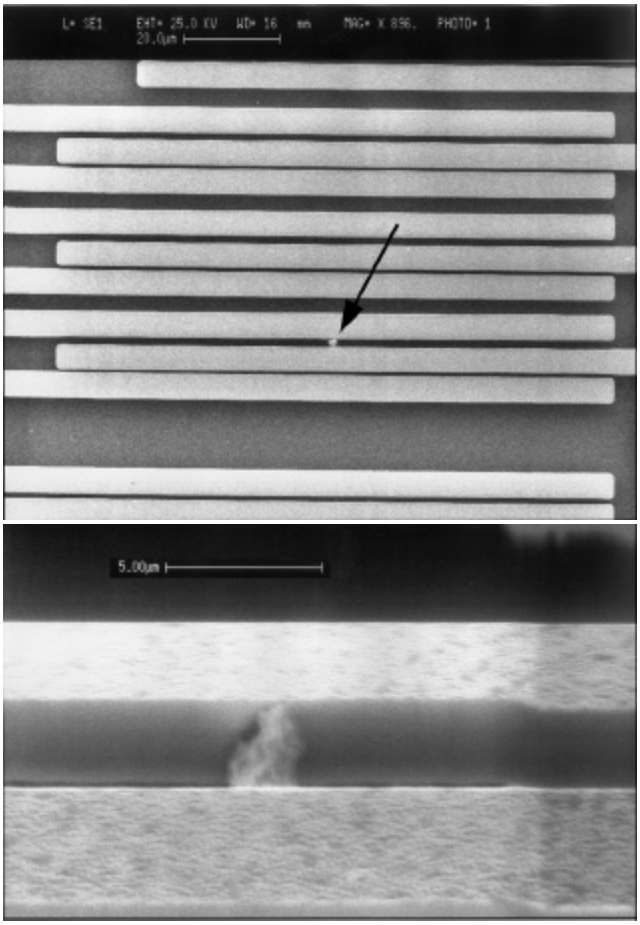

Figure 11. Overall and close up views of a particle jammed between the plates of the capacitive sensor in the failed part, channel Y.

Conclusions

Analog devices ADXL250 dual-axis accelerometers successfully withstood 1000 temperature cycles in the range from –65 °C to +150 °C, as well as 30,000 mechanical shocks of 2000 G in Z direction and 10,000 shocks in X-direction, with only minor parametric changes. No evidence of fatigue-related defects or microcracks in the stationary polysilicon fingers and/or springs were observed.

One part failed, with output Y stuck high after 10,000 shocks in the X-direction. The failure most likely was caused by a structural defect in a sealing glass (contaminant), which enhanced glass cracking and formation of loose particles. During the mechanical shocks, a small particle of submicrometer range size, appeared to have broken loose and lodged in space

between the capacitive sense plates, wedging the electrodes and causing failure of the device.

The results demonstrated that mechanical robustness of the micromachined accelerometers is adequate for most aerospace applications, provided a proper control and qualification of the packaging materials and processes is performed.

References

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