Reliability assessment of a MEMS microphone under mixed flowing gas environment and shock impact loading

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ABSTRACT

In this work the reliability of a Micro-Electro-Mechanical Systems (MEMS) microphone is studied through two accelerated life tests, mixed flowing gas (MFG) testing and shock impact testing. The objective is to identify the associated failure mechanisms and improve the reliability of MEMS devices. Failure analyses are carried out by using various tools, such as optical microscopy, scanning electron microscopy (SEM), energy dispersive X-ray spectrometry (EDS). Finite element analysis is also conducted to study the complex contact behaviors among the MEMS elements during shock impact testing. The predicted failure sites are in agreement with the experimental findings.

1. Introduction

The applications of Micro-Electro-Mechanical Systems are increasing rapidly, especially in the consumer electronics. MEMS accelerometers, gyroscopes and microphones have already been used in various portable electronic products, such as mobile phones, tablets, cameras and game controllers [1–4]. MEMS microphones are widely used in portable electronic devices due to their small size, better acoustic performance, and compatibility with automated assembly process.

Some MEMS devices like gyroscopes need to be hermetically packaged and their reliability is highly dependent on the quality of hermetic bonding [5–8]. Different from hermetically packaged devices the sensing element of MEMS microphones are commonly exposed to temperature changes, humidity and corrosive gases during field use [9–11]. The humidity and corrosive gases usually cause wire bond corrosion and failures [12] and oxidation-induced stress corrosion in polycrystalline silicon thin film membranes [13,14]. To assess the reliability of electronics exposed to various environmental conditions mixed flowing gas tests are often used [15]. For instance, Zhang et al. studied the influence of H2S exposure on immersion-silver-finished PCBs via MFG testing [16]; Yang et al. used MFG tests to assess the reliability of land grid array sockets [17]; Zhao et al. investigated the reliability of Ni/Pd/Au–Ag pre-plated leadframe packages by using MFG tests [18]. So far, however, there have been no reports on the MFG tests of MEMS microphone or similar thin film structures.

In addition, MEMS microphones experience vibrations, shock impacts or occasional drops during normal operations. The shock impact reliability of MEMS microphones is crucial to the portable electronic devices. The acceleration experienced by a mobile phone during normal operating environment is around several g (g is the Earth’s gravitational acceleration). However, a mobile phone accidentally falling from a height of about 1.2 m can experience a roughly 500–5000g shock load as measured on the printed wiring board (PWB) [19,20]. The peak acceleration values vary with different impact surfaces, and orientations of collisions. Some recent investigations report that the maximum acceleration at the impact site of the secondary impacts can be much higher than those of the primary impact [21,22]. As a result, MEMS microphones mounted on the surfaces of PWBs need to be shock-resistant in order to ensure the expected lifetimes of the electronic products. Besides, the reliability studies should be extended to high shock levels for the sake of a sufficient margin of safety.

In this work the reliability of a MEMS microphone under harsh environment and shock impact loading is studied by experiments and simulations. The paper is organized as follows. Firstly, the details of the experimental setup, failure analysis, and finite element analysis are reported. Secondly, the observed failure modes are presented followed by simulation results and discussions of the failure mechanisms. Thirdly and finally, conclusions drawn from the reliability assessment are given.

2. Materials and methods

2.1. MEMS microphone

In the package of the MEMS microphone, the MEMS and the application specific integrated circuit (ASIC) are placed side by side on a laminate substrate, connected electrically with wire bonding and sealed under a metal lid. Fig. 1(a) shows an SEM image of the MEMS microphone with the lid removed. The MEMS microphone is based on a typical parallel capacitor membrane design...
chamber, aluminium jig, and pneumatic shock impact tester are presented in Fig. 2. The MFG test was carried out in the corrosion test chamber according to the Telcordia Technologies GR-63-CORE standard [25,26], an industrial standard for telecommunications equipment and systems. The volume exchange rate and the air flow rate were set to be 8 times per hour and 28.7 l per minute, respectively. The relatively humidity (RH) and concentration of gaseous pollutants were monitored at the inlet tubes. Table 1 gives the temperature, relative humidity, and concentration of gaseous pollutants used in MFG test. The MFG test is a highly accelerated test as the concentrations of gaseous pollutants in the test chamber are about 4–50 times higher than those in typical Nordic outdoor environments (presented in Table 1).

The MFG test setup and monitoring system are the same as what have been reported in Ref. [27]. As shown in Fig. 2(b), a loudspeaker is placed inside of the test chamber to monitor the health of the microphones. During the monitoring process, firstly a known acoustic stimulus (a logarithmic sine sweep over the specified frequency range of the microphone) is produced by the loudspeaker, secondly the microphone records the signal and the recorded signal is send back to the computer, and thirdly the control program compares the magnitude frequency response of measured signal with a reference sample. The similar monitoring system can also be used for other reliability tests.

For the shock impact tests, there were in total twenty-four samples tested in four different impact orientations (X, Y, Z+ and Z–), i.e. six samples for each orientation. The pneumatic shock impact tester shown in Fig. 2(d) is capable of producing shock impact levels up to 100,000g. The PWB (34 × 30 × 1.7 mm3) is made from aluminium alloy 7075 in order to minimize the influence of the PWB motion on dynamic response of the MEMS microphone under shock impacts. The test boards can be attached to the jig in different orientations, X, Y, Z+ and Z–. The finite element simulation was employed to help design the jig, which can survive shock impacts up to 65,000g with negligible plastic deformation. The MEMS microphones were in a power-off state during the shock impacts and their state of health was tested by a health monitoring system as previously discussed after every five impacts. During the shock impacts the acceleration histories were measured by a lightweight accelerometer mounted on the top of the jig. These measured acceleration pulses were used as the loading conditions in the finite element simulations.

2.3. Finite element model setup

The finite element analyses were conducted by employing the finite element software, ABAQUS v.6.9-EF. The structural details in the MEMS chip are much smaller in scale than the component board, and therefore, a submodeling approach was used in order to achieve both accuracy and efficiency. In the global model the component board with two MEMS microphones was considered (see Fig. 3). A cross-section view of the MEMS microphone in the global model is presented in Fig. 3(c) where most of the structural details in the MEMS chip are simplified and the wire bonds are not considered either. The focus of this simulation is on the reliability of the MEMS chip since the reliability of the wire bonds has been previously investigated [21,22].

As shown in Fig. 4, the submodel with fine mesh was established on the level of the MEMS chip to build a realistic representative of

Table 1

<table>
<thead>
<tr>
<th>Environment</th>
<th>°C</th>
<th>% RH</th>
<th>Cl₂ (µg/m³)</th>
<th>H₂S (µg/m³)</th>
<th>NO₂ (µg/m³)</th>
<th>SO₂ (µg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test chamber</td>
<td>30</td>
<td>70</td>
<td>19</td>
<td>262</td>
<td>188</td>
<td>136</td>
</tr>
<tr>
<td>Outdoor (Nordic)</td>
<td>5</td>
<td>78</td>
<td>0.9</td>
<td>4.6</td>
<td>28</td>
<td>30</td>
</tr>
</tbody>
</table>
the real structure. However, there are still some structural details that need to be simplified with special treatments before a sound finite element model can be built. As shown in Fig. 4(b) and (c), the challenges include the thickness changes of the porous backplate membrane, the distance stoppers, the large number of fingers, and the bowed edge of the backplate. The details of the modeling procedure are addressed as follows. Shell elements were used for meshing the backplate membrane and thickness changes were considered in the shell section definition. The distance stoppers designed on the fringe of the backplate membrane cannot be neglected as they are crucial for the interaction between the two membranes under shock impact. The geometric feature of the distance stoppers was simplified by the rectangular shell elements and the height of the distance stopper was included in the shell section definition (see Fig. 4(d)). The bowed edge is responsible for transferring boundary conditions from the base to the backplate membrane, and therefore this feather was included in the model and meshed with solid elements. Furthermore, the porous backplate membrane was modeled as a homogeneous material with calculated equivalent material properties. More details of the equivalent material properties calculation and the finite element model setup can be found in Ref. [28]. The calculated equivalent material properties as well as other material properties used in the simulation are listed in Table 2.

3. Results and discussion

The experimental and simulation results are presented in the following sections.

3.1. Mixed flowing gas test failures

The MEMS microphone samples were removed from the corrosion chamber after 90 days testing. No obvious failures were detected by the health monitoring system except for a slight decrease (about 0.5 decibel difference) in the magnitude frequency response. After careful sample preparation and failure analysis, two distinctive failure modes were observed, namely wire bond corrosion and membrane brittle fracture. Wire bond corrosion was found in every sample experienced 90 days MFG test. Six out of thirty-two samples showed membrane fracture after the metallic lid was removed for inspection.

3.1.1. Wire bond corrosion

First of all, the composition of the wire bond was investigated and found to be gold wire ball on top of gold, nickel and chromium. The composition of the wire bonds was measured with energy dispersive X-ray spectrometry as shown in Fig. 5. The Au/Au bonding interface and Ni/Au deposition interface can also be seen in the SEM micrograph.

Further investigation reveals that the wire bonds were detached from the pads and the corrosion products had grown at the Au/Au interface. Fig. 6(a) presents an SEM image of a detached wire bond as well as the corrosion products. In Fig. 6(b), the EDS analysis of a tested wire bond shows that the nickel had diffused vertically through the pad metallization and reacted with the gaseous pollutants in the corrosion chamber. The nickel diffusion and the growth of the corrosion products in volume are believed to be the reason causing the wire bond detaching. The composition of the corrosion products was found to be nickel, sulfur, and oxygen. Unfortunately, the accurate composition ratio cannot be measured as EDS is not accurate enough for detecting lighter elements such as oxygen. In order to improve the reliability, Ni/Au deposit should be replaced by Ni/Pd/Au deposit so that palladium can be the diffusion barrier for nickel.

3.1.2. Membrane brittle fracture

As shown in Fig. 7, cracks were observed in both diaphragm and backplate membranes after removing the metallic lid of the microphone samples, which had experienced 90 days MFG test. Since no significant electrical performance changes as monitored by the health monitoring system, the cracking of the membranes probably took place during the sample handling, e.g. taking the samples out of the test chamber or opening the lid for failure analysis. Membrane embrittlement is believed to be the cause of the cracking. The explanation of the observed fractures would be the stress corrosion cracking of surface thin film [5].
The embrittlement of the silicon membranes is probably associated with the growth of surface SiO$_2$ thin film. The surface of silicon is usually covered by a thin oxide layer, namely silicon dioxide (SiO$_2$) layer. The growth of the SiO$_2$ layer is highly dependent on the temperature and the exposure time to air as the process is diffusion controlled. The oxide growth can also be accelerated by the humid environments as reported in [24]. The membrane embrittlement might be caused by the environmentally-assisted oxide layer

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>Density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysilicon</td>
<td>158</td>
<td>0.22</td>
<td>2.33</td>
</tr>
<tr>
<td>Porous membrane (calculated)</td>
<td>48.93</td>
<td>0.33</td>
<td>1.39</td>
</tr>
<tr>
<td>Single-crystal silicon (orthotropic)</td>
<td>$E_1 = E_2 = 169$</td>
<td>$G_{13} = G_{23} = 79.6$</td>
<td>$\nu_{12} = 0.064$</td>
</tr>
<tr>
<td></td>
<td>$E_3 = 130$</td>
<td>$G_{12} = 50.9$</td>
<td>$\nu_{13} = 0.28$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\nu_{23} = 0.36$</td>
</tr>
<tr>
<td>SnAgCu</td>
<td>52.4</td>
<td>0.37</td>
<td>7.2</td>
</tr>
</tbody>
</table>

Table 2
Material properties used in the simulation [29,30].

Fig. 5. (a) SEM image of a virgin wire bond. (b) Composition of the wire bonds measured by EDS.

Fig. 6. (a) SEM image of a detached wire bond which had experienced 90 days mixed flowing gas test. (b) A cross-section image of a tested wire bond and EDS analysis.
growth and the segregation of impurities to the grain boundaries. Muhlstein et al. reported a failure mechanism of the surface oxide thin film (termed reaction-layer fatigue) in Ref. [13]. In their study, the endurance strength of their polycrystalline silicon samples was found to be around 2 GPa, i.e. roughly half of the fracture strength. However, the reaction-layer fatigue cannot be employed to explain the observed fractures in the current study since the stress level in the MEMS microphone during MFG testing or sample handling would never exceed 2 GPa. Compared to the test environment in [13], the situation in the mixed flowing gas test is more complicated as the combined effect of the humidity and the gaseous pollutants is still unclear.

3.2. Shock impact acceleration tolerance

The shock impact tests were carried out in all the impact orientations with peak accelerations up to 80,000 g. No failures were found in tests with X and Y impact orientations, and only failures in the Z+ and Z− orientations were detected under the acceleration level of about 65,000 g. All six samples were failed after the Z orientation shock impact tests and two failure modes were distinguished, the cracking of the diaphragm and the cracking of backplate and runner. Micrographs of three failed microphones are shown in Fig. 8. In Fig. 8(a) the diaphragm had completely disappeared after the shock impact. In the case of the second microphone, most of the diaphragm had disappeared and only a small fraction remained (see Fig. 8(b)). In the third microphone shown in Fig. 8(c), a corner of the cracked diaphragm remained after the shock impact, and in the same microphone the cracking of the backplate and runner was detected (see Fig. 8(d)).

3.3. Stress–strain analysis

The simulation results are used to explain the observed failure modes and predict potential failure locations. As shown in Fig. 9, six snapshots of the deformation and strain distribution of the diaphragm and diaphragm runner are presented. The calculation was conducted in the Z impact orientation with a peak acceleration level of 65,000 g. All the deformed shapes are related to the excited vibrational modes of the structure under the shock impact and the contact interaction between the diaphragm and the distance stoppers of the backplate (not shown in Fig. 9). The strain concentrations are located at the edge of the diaphragm as well as the vicinity of the connection between the diaphragm and the runner. Besides, the end of the runner is also found to be a critical part as it experienced cyclic bending during the shock impact.

In order to predict the potential failure locations in the MEMS structure, the stress concentrations are studied. As shown in Fig. 10, three potential failure locations are predicted. Fig. 10(a) presents the stress concentration at the edge of the diaphragm beneath the backplate runner. This is probably the location where the crack initiated and finally led to the cracked diaphragm as shown in Fig. 8(b). Another evidence is presented in Fig. 11(a) where the crack diaphragm is visible beneath the backplate and the predicted location of crack nucleation is indicated by an arrow. Fig. 10(b) presents the stress concentration near the connection between the diaphragm and runner. This location is in agreement with the observed diaphragm cracking shown in Fig. 11(b), in which the predicted location of crack nucleation is indicated by an arrow. The last potential failure location is at the end of the diaphragm runner (see Fig. 10(c)). However, no evidences of this failure mode have been found during the physical failure analysis in this study.

During shock impacts the central region of the backplate and diaphragm are prone to contact each other, which is a necessary...
condition for any stiction failures. The surface-to-surface contact between the membranes was considered in the finite element model. Two comparison cases were calculated, i.e. the $Z^+$ and $Z^-$-orientation shock impact with a peak acceleration level of 65,000g. The calculated time history of the distance between the backplate and diaphragm is shown in Fig. 12. The distance is derived from the center of the two membranes. As shown in the figure, the initial distance is 6 $\mu$m, and zero distance indicates the occurrence of contact. In the initial stage of the $Z^+$-orientation impact, both the backplate and diaphragm bent towards the PWB side. The displacement of the backplate was less than that of the diaphragm as the boundary of the backplate was constrained, resulting in an increasing distance between the two membranes. The first contact took place when the diaphragm bounced back from the lowest point and moved towards the backplate. In the case of the $Z^-$-orientation impact, the backplate and diaphragm bent towards the lid side right after the shock impact. Due to the boundary constraint, the backplate bent less than the diaphragm, which allowed the diaphragm to catch up with the backplate and led to the contact. This contact analysis can be employed for further stiction failure analysis in the future.

4. Conclusions

In this work the reliability of a MEMS microphone was studied by two accelerated tests, i.e. mixed flowing gas testing and shock impact testing. The concentrations of gaseous pollutants in the corrosion test chamber are about 4–50 times higher than those in typical Nordic outdoor environments. Wire bond corrosion and membrane embrittlement induced membrane cracking were detected after the 90 days mixed flowing gas test. The nickel diffusion through the pad metallization and the growth of the corrosion products are believed to be the reason causing the wire bond detaching. It is believed that using Ni/Pd/Au deposit instead of Ni/Au can improve the reliability as palladium prevents nickel from diffusing into gold.

The membrane embrittlement is found to be associated with the growth of surface silicon dioxide thin film as well as the complex interaction with the gaseous pollutants. This failure mechanism is different from the normal fatigue failure of polycrystalline silicon thin film. Further studies are required to investigate the mechanism of the membrane embrittlement.

The shock impact tests covered all three orthogonal axes as well as various shock levels ranging from 1500g to 80,000g. No failures were found in the tests with X and Y impact orientations, and only failures in the $Z^+$ and $Z^-$-orientations were detected under the acceleration level of 65,000g or higher (which was around ten times greater than the acceleration levels that were measured in field use for consumer electronics devices). The failure modes were found to be the cracking of the diaphragm and the cracking of backplate and runner. The finite element analysis predicted the
deformation and stress-strain state of the MEMS structure. The predicted locations of stress concentrations are in agreement with the observed failure modes. The simulation results help explain the complex interactions between the diaphragm and the backplate. Furthermore, the surface-to-surface contact at the central region of the membrane was predicted, which shows the existence of potential stiction failure.

The presented experimental and simulation results deepen our understanding of corrosion reliability and shock impact reliability of the MEMS microphone. The conclusions drawn from the shock impact testing are also applicable to other MEMS sensors with similar thin membrane structure.

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References