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Experimental study on the package of high-g accelerometer

Jun Liu, Yunbo Shi, Ping Li, Jun Tang*, Rui Zhao, He Zhang

Science and Technology on Electronic Test & Measurement Laboratory, North University of China, Taiyuan, Shanxi Province, China

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ABSTRACT

In this paper, the effect of the package die adhesive and package shell on the performances of silicon based MEMS high-g accelerometers was reported. Using Raman spectroscopy, the residual stress caused by different package die adhesive thickness and different package shell material was characterized. It can be concluded from the testing results that: with thicker die adhesive, the residual stress increment was much smaller; the piezoresistance variation caused by this residual stress was much smaller; and the temperature shift of the output voltage was much smaller. Comparing with the ceramic package, the stainless steel package has bigger sensitivity and bigger anti-overload ability.

1. Introduction

As one of the key components in the smart weapons and penetration weapons, MEMS high-g accelerometers need to work under extremely high impact conditions which may be up to 200,000 g. Due to the harsh environment, sensor failure caused by the package has become an important issue which should pay special attention. Shell fracture, cover dents, bonding failure, wire disconnection, etc. are all possible problems which may cause the sensor failure due to its package. It was reported that 50% of the total cost for the accelerometer fabrication was invested on the package process. So it is quite important to develop some reliable, low cost package techniques for the high-g accelerometers design [1–4].

Different package techniques and the key factors existed for the MEMS sensors were reported. Zarnik reported the process-induced residual stresses that adversely influence the pressure sensor's performance [5]. The preliminary finite element simulation (FEA) and DOE simulation was performed and it was concluded that thick adhesive layer together with the minimum sinking of the silicon die into the adhesive and minimum adhesive area around the die result in the minimum residual stress to the sensor. Mariani has studied the effect of packaging on the failure of a uni-axial polysilicon MEMS accelerometer available on the market [6]. They found that package is not always beneficial in enhancing the sensor impact-carrying capacity.

Considering the harsh environments of the high-g accelerometers, some research works on package effect to the reliability and performance of the MEMS high-g accelerometers have been performed. It can be concluded that, the residual stress, which is induced by the material property differences among the package shell, the seal adhesive and the MEMS structures, is one of the key factors. Cheng reported a FEA simulation in the frequency domain and time domain analysis for a packed accelerometer used under high-g environments. The simulation results show that the Young's Modulus of seal adhesive has important influences on the mode shapes and the sensor performances. Another important factor for the high-g accelerometer package is the package shell. Two different materials were mainly used for the high-g accelerometers: the first material is ceramic, which has already been commercially used in the accelerometers developed in Draper; the other material used was metal (mainly stainless steel), such as the 7270A developed by ENDVCO, the 3991A11 developed by PCB and the 8742A100 developed by KISTLER [7–12].

As one of the key techniques for the MEMS high-g accelerometers, the package process was widely researched to improve the reliability and the performances. But from the literatures reported, it is found that, most of the work was focused on the modeling and simulation. The experimental research is still far not enough. In this paper, we introduce an experimental study of the package effects on the sensor performances and reliability. By combining the Raman spectroscopy, we have quantitatively tested the residual stress with different quantity of seal adhesive and different package shell materials (ceramic and stainless steel). The accelerometer performance differences caused by them were also tested. Using Maste hammer and the Hopkinson bar, the sensitivity, anti-overload ability and the reliability with different package shell were tested. Finally, the packed high-g accelerometers were applied to the projectile launch experiment, and the performances with different package shell were tested.

* Corresponding author. Tel.: +86 351 3920397; fax: +86 351 3922131.
E-mail addresses: shiyunbo@nuc.edu.cn (Y. Shi), tangjun@nuc.edu.cn (J. Tang).

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Table 1
Material properties.

	Density (kg/m^3)	Young modulus (Gpa)	Possion ratio	Thermal conductivity (W/m °C)	Thermal expansion coefficient (ppm/°C)
Si	2330	190	0.3	100	3.1
EPO-TEK H70E	1500	3	0.3	0.9	186
Stainless steel	7900	200	0.3	25.96	16
Ceramic	3750	307	0.28	21.8	7.5

2. Experimental

2.1. High-g accelerometer design and fabrication

The silicon based piezoresistive MEMS high-g accelerometer was designed, which was based on a beam-mass structure, as it is shown in Fig. 1(a). The designed measure range of this accelerometer was 150,000 g, and the anti-overload ability was 200,000 g.

When there is an input acceleration in the sensing direction (*Z* direction), according to the FEA simulation, as it is shown in the inset image of Fig. 1(b), we can calculate the stress distribution on the structure surface:

- The maximum stress is 46.733 MPa under 200,000 g input in the sensing direction, which is far less than the allowable stress of the silicon.
- The stress distribution in *X* direction (SX) and in *Y* direction (SY) were calculated, and the regions for the piezoresistors fabrication were selected, as it is shown in Fig. 1(b).

Four piezoresistors were fabricated on the four cantilevers and a Wheatstone bridge was formed for the acceleration detection in *Z* direction.

Bulk silicon process was used for the accelerometer fabrication, which was described in detail in Refs. [13,14]. N type 4 in. double side polished Si wafers were used. The main processes were piezoresistor doping, backside etching (KOH wet etching), electrical connection (Al sputtering), ICP etching (structural release), and Si-glass bonding. And the fabricated sensor is shown in the Fig. 1(c).

2.2. High-g accelerometer package

During the package, the MEMS structures of the high-g accelerometers were bonded to the package shell, which were followed by a wire bonding process for the electrical interconnection between the MEMS structures and the electrical signal processing circuits. All the material properties used in this study were shown in Table 1.

EPO-TEK H70E was used as the die adhesive for the bonding of the MEMS structure to the package shell. EPO-TEK H70E is a two component, thermally conductive, electrically insulating epoxy which is designed for chip bonding in microelectronic and optoelectronics applications. Mix ratio of 1:1 between the two components was adopted in our study. And the bonded structures were baked under 85 °C for 90 min.

The wire bonding was performed by the ball–wedge wire bonder 7700E, which is a wire bonder produced by West Bond, and was made by the ball to wedge technique using ultrasonic energy and work piece heat. Au wires were used with a diameter of 50 μm.

Two different type of shell material were tested as the package shell: ceramic and stainless steel. The fabricated shell structures were shown in Fig. 2.

2.3. High-g accelerometer test and calibration

The effect of the die adhesive to the accelerometer performance was mainly characterized by the variations of the residual stress and the resistance before and after package process. Raman spectroscopy was used for the quantitative characterization of the residual stress variations before and after the package. Invia produced by Renishaw from England was used for the Raman measurement. The testing laser wavelength was 514.5 nm and the laser power was 5 mW. The detail experimental processes and stress calculation methods were described in our previous publications [15,16]. All the experiments here were performed under room temperature.

After the package, the sensitivity of the sensor was tested by Maste hammer, and the anti overload ability was analyzed using the Hopkinson bar. Finally, the sensor was tested by the projectile launch in order to analysis the sensor's performance with different package in the real application environment. All the electrical characterizations of the accelerometers were performed using HP4140B picoammeter.

3. Results and discussions

3.1. Effect of the die adhesive to the structure residual stress

Due to mechanical constraints and the coefficient of thermal expansion (CTE) mismatch among the die, die adhesive and the shell substrate, the thermal stress was generated after the package process. And then, the thermal stress was transferred into the residual stress to the MEMS structure. The effects of the die adhesive with different thickness to the sensor performances were studied. Stainless steel was used as the package shell material in this experiment. By controlling the quantity of the die adhesive, two different thicknesses were achieved: about 70 μm and 200 μm. For the thicker die adhesive, due to the bigger quantity, there was also some overflow of the die adhesive and the dies were immersed into the adhesive for about 150 μm.

The residual stress was measured using the Raman spectroscopy before and after the package. For each measurement, we selected 6 different points on the same piezoresistor, and finally the average value of the residual stress was calculated, which was shown in Fig. 3(a). Meanwhile, the static resistance of the piezoresistor was measured, which was shown in Fig. 3(b).

From the data presented in Fig. 3(a) and (b), it can be concluded that with smaller die adhesive thickness, the residual stress was increased from −41.5193 Mpa to 76.4925 Mpa, which lead to much bigger piezoresistance variation: from 2.755 KΩ to 2.781 KΩ. But for the thicker die adhesive with the overflow, the residual stress variation and the resistance variation before and after package was much smaller: from −34.503 Mpa to 4.4847 Mpa and from 2.848 KΩ to 2.857 KΩ respectively. We have done the similar experiments and got the three sets of data. When the die adhesive thickness was 70 μm and 200 μm separately, the variation of residual stress in the structure were 83.067 Mpa, 105.336 Mpa, 118.011 Mpa and 38.8473 Mpa, 42.587 Mpa, 56.962 Mpa respectively, and the variation of piezoresistance were 24 Ω, 25 Ω, 26 Ω