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STRESS-MINIMIZED PACKAGING OF INERTIAL SENSORS USING WIRE BONDING

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ABSTRACT

This paper presents a packaging approach for inertial sensors using wire bonding technology. The die is mounted exclusively by bond wires on the front- and backside to the package. Conventional single-side die attach to substrates, such as gluing, is abandoned. The approach is characterized by its novel and symmetric die attach concept as well as its simplicity of applying a standard wire bonding process. The wire bond attachment facilitates significant reduction of thermally induced mechanical stresses. The attachment concept is characterized in terms of attachment stiffness and potential die resonances using Laser Doppler Vibrometry (LDV). White-light interferometry is used to investigate stress related warping that is induced by the die attachment process.

KEYWORDS

Low-stress, die attach, wire bonding, inertial sensors, Laser Doppler Vibrometry, white-light interferometry, packaging

INTRODUCTION

Packaging of MEMS-based inertial sensors, e.g. gyroscopes or accelerometers, remains a critical challenge. Often, package-induced stresses are not sufficiently enough taken into account in the design phase of novel MEMS-based devices. Especially, packages for inertial sensors do not only serve as a protective housing and enable improved heat dissipation, but must also ensure a rigid attachment of the MEMS die and avoid package-induced stresses. This is because displacement sensing devices are known to be sensitive to package-induced stresses [1].

Most MEMS packaging approaches rely on conventional die attach, where the die is fixated to a lead-frame using an epoxy-based adhesive that ensures a rigid bond between the die and the lead-frame. After curing, electrical interconnections are established and the plastic package mold encapsulates the entire component. Substantial differences of the Coefficient of Thermal Expansion (CTE) of the involved parts, e.g. silicon die, metal lead-frame and the adhesive as well as the molding compound causes differential shrinkage, while exposing the composition of materials to elevated temperatures during curing processes. This results in complex stress gradients across the attached die, often referred to package-induced thermo-mechanical stresses [2]. Also, chemical shrinkage of adhesives and mold compound need to be taken into account [3]. These stresses often significantly affect device performance, such as sensitivity, reduction of the resonance Q-factor or

resonance frequency shift, as well as long-term stability and reliability [4-6].

Figure 1: Illustration of the symmetrical die attach for inertial sensors, using exclusively bond wires, to minimize attachment stresses. This approach separates the attachment area (red) from stress sensitive detection and actuation elements located in the center of the die.

In order to overcome these thermo-mechanical stresses, various approaches have been reported in literature, e.g. implementing stress-relief structures, which compensate die attach stresses. However, such stress-relief structures can potentially affect attachment stiffness and increase fabrication complexity [7]. Walwadkar et al. have shown that an optimization of the adhesive thickness can reduce stress but does not offer a solution for package mold induced stresses [8]. Another approach relies on reducing the contact area between the die and adhesive underneath the stress-sensitive area of the MEMS die. Therefore, four dots of adhesive are dispensed at the corners of the die. This approach suffers from an additional dispensing step of a coating gel, which is difficult to control [9]. Additional approaches like CTE-matched materials and ductile adhesives have also been reported [10]. These approaches can significantly reduce package-induced stresses. However, they are often application-specific and do not fulfill the needs of demanding inertial sensor packaging. Therefore, packaging of high-performance inertial sensors can further benefit from improved packaging approaches.

We present a novel low-stress attachment method for inertial sensors based on wire bonding thus avoiding conventional high-temperature attachment processes and thereby significantly reducing stresses. This approach is characterized by its simplicity and flexibility and may be viable for a broad range of MEMS devices. Conventional die attach techniques utilize the entire backside surface of the MEMS die for the attachment. This single-side attachment approach causes an overlapping of the stress-sensitive part of the MEMS die and the attachment area.

Figure 2: a) The gyroscope die and the package frame are centered and mounted on a vacuum wire bonding chuck. 56 standard ball stitch bonds are performed to attach the die to the ceramic package front-side.

b) The package with the top attached die is turned and the bottom side of the die is attached with another 56 bond wire connections.

ATTACHMENT CONCEPT

We propose a symmetric die attach concept using both sides of the die. Figure 1 depicts the novel double-sided die attach approach using wire bonding. The stress-sensitive part of the die area is highlighted in red and the die attach area is marked in blue. This approach addresses three problematic aspects of die attach induced stresses and overcomes those by eliminating the origin of the stress generation:

1. Symmetry of package and MEMS die design
2. Separation of attachment area and active MEMS area
3. Reduction of thermally induced loads and chemical shrinkage

First, in the design phase of the MEMS-based inertial sensor, the symmetry aspect was taken into account and both the device and the package are designed in conjunction to achieve the highest possible symmetry. Thus, the symmetric attachment on the front- and backside minimizes mechanical attachment stresses, due to counteracting attachment loads.

Second, the attachment approach separates the die attach area and stress-sensitive device areas, where mechanical resonating elements as well as actuation and detection electrodes are located. The attachment excludes any overlapping with the stress-sensitive device area and is limited to the outer periphery of the die.

Third, the die attach, exclusively using bond wires, reduces thermally induced mechanical stresses by excluding cure shrinkage of the adhesive. Wire bonding is by far the most dominating electrical interconnection method and is characterized by its high throughput and placement accuracy [11]. Wire bonding has enabled various sophisticated MEMS integration approaches [12]. In addition, if room temperature wire bonding technique is used, the thermally induced mechanical stresses can be avoided. However, the characterized prototypes in this study were wire bonded at elevated temperatures. The bond wire connections serve simultaneously two purposes; electrical die to package interconnection and mechanical attachment. The final sensor housing is realized by low temperature capping process of the entire

package frame with a top and bottom lid. This eliminates package mold and post package cure. Addressing all of the above mentioned aspects results in a package that can reduce die attach stresses. Die attach using double-sided wire bonding is not limited to inertial sensors packaging. This approach is a feasible and promising packaging method and offers besides the low-stress packaging additional features, such as the possibility to electrically connect the die from the top and the bottom and thus avoiding additional fabrication of costly and complex Through Silicon Vias (TSVs).

FABRICATION

For evaluation of the new die attach process, a high performance MEMS SW610 Butterfly Gyroscope from Sensoror AS, Norway was used. The package consists of a custom-made ceramic package frame, as shown in Figure 3 [13].

Figure 3: Photo of the double-sided attached gyroscope die using wire bonding to the package frame. The top lid of the custom-made ceramic package is removed and the package is mounted on top of the package containing the Application Specific Integrated Circuit (ASIC).

The die is placed in the center of a custom-made chuck for the wire bonding process. Vacuum is used to ensure a

rigid fixation of the die during the wire bonding process. The package frame is centered around the die. First, the wire bonding process is performed on the frontside using a standard ball stitch wire bonding process with optimized looping parameters to achieve a stable and reliable attachment. The die is attached with 56 bond wire connections on the frontside. Then the package frame including the die is turned around to access the backside of the die. Second, the wire bonding process on the backside is performed to attach the die by 56 additional bond wire connections in the same way. For the final device, the package frame is encapsulated with a top and a bottom lid to ensure hermetic encapsulation and then mounted on a second package containing the Application Specific Integrated Circuit (ASIC). The characterization of the wire bond attachment method is performed directly after the wire bonding without lid sealing.

CHARACTERIZATION

The wire bonded gyroscope die is characterized in terms of attachment stiffness to verify the rigidity of the die attach. In addition, the attached die is inspected for stress-induced warpage or bow.

Laser Doppler Vibrometry Measurement

Sufficient mechanical attachment stiffness of the die to the package of the gyroscope is an essential requirement to ensure the proper operation of the device and is therefore characterized. However, this attachment approach does not allow standardized characterization methods of the attached die, such as die shearing, due to the centered position of the die in the package frame. Laser Doppler Vibrometry offers non-contact measurements over the frequency range of interest. Laser Doppler Vibrometry is utilized to investigate vibration, damping of resonating systems as well as resonance mode visualization on structures, such as the double-sided attached die in the package. Laser Doppler Vibrometry measurements are capable of providing displacement information by decoding velocity and phase shift from the frequency shift [14]. However, utilizing this measurement principle is limited to visualize the resonance modes of the attached die, which have an out-of-plane motion component. Figure 4 depicts the Laser Doppler Vibrometry measurement of the attached die velocity in dB versus the frequency from 5 kHz to 30 kHz.

Figure 4: Diagram of the LDV measurement shows the velocity spectrum over the frequency range of interest. The red graph shows five resonance peaks, two of the shaker and three of the die. The blue graph shows two resonance peaks of the shaker.

In particular, resonance modes of the attached die close to the frequencies of excitation and detection of the gyroscope, at 9 kHz and 9.3 kHz, would affect the operation of the gyroscope and should be therefore avoided [15]. The red graph in Figure 4 represents the velocity spectrum of the attached die and the blue graph shows the velocity spectrum of the package. Two strong peaks at 5.2 kHz and 20.5 kHz can be observed in both graphs and identified as resonance modes of the shaker. Three peaks at 18.48 kHz, 18.80 kHz and 26.46 kHz are identified as die resonance modes by visualizing the resonance pattern of the die. Table 1 lists the details of the identified resonance modes of the attached die. The displacement amplitude is well below the nanometer range, which is an indication of the stiffness of the wire bond attached die.

Table 1: Identified resonance modes of the double-sided attached die.

Die Mode No.	Resonance Frequency [kHz]	Disp. Ampl. [pm]	Velocity Ampl. [$\mu\text{m}\cdot\text{s}^{-1}$]	Accel. Ampl. [$\text{m}\cdot\text{s}^{-2}$]
1	18.48	248	31	3.34
2	18.80	228	25	3.15
3	26.46	55	11	1.51

White-light Interferometry

A conventional one-sided die attach experiences high stresses due to volume shrinkage of the epoxy and the mismatch due to differences in CTE of the involved materials. This results in die warping, which can in particular affect the functional integrity of inertial sensors. Therefore, the dies attached by double-sided wire bonding were investigated using white-light interferometry to visualize the warping. The measurements were performed using an optical profilometer, type Wyko NT 9300, Veeco Instruments Inc., USA. First, the surface topography of the attached die was measured. In a second, step the bond wires between the die and the package were removed. Finally, the surface topography was measured again. Both measurements were aligned and subtracted from each other, resulting in a differential height topography measurement, which visualizes the warping induced by the die attachment.

Figure 5: Differential surface topography measurement of the bond wire attached die revealing a cylindrical centered positive bow.

Figure 5 illustrates the surface topography of the differential measurement of the attached die versus the bare die. The die experiences a centered cylindrical bow

along the y axis, caused by the attachment. A maximum bow of 253 nm is measured over the die area of 65 mm x 55 mm.

Figure 6: Diagram of the differential measurement cross-section in the center of the die along the y-axis. The green and red graphs show the differential measurement of two different dies.

Figure 6 illustrates the differential bow of two double-sided wire bond attached gyroscope dies (green and red), before and after the removal of the bond wires, measured at the center of the die along the y-axis. The quadratic fitting (black dashed) shows a symmetrical difference of the bow with a maximum displacement at the center of 203 nm and 190 nm over a measured die length of 5 mm. The peaks in both graphs result from misalignment. It is believed that the warpage of the die is caused by remaining elastic stress in the bent wires and by the wire bonding that was not performed in room temperature.

CONCLUSION

We present a novel die attachment concept for inertial sensors using double-side wire bonding. The low-stress approach features a symmetric die attach, while separating the die attach area and the stress-sensitive functional die area. The wire bond attachment concept, characterized by its simplicity and flexibility, minimizes the thermal and mechanical packaging stresses. The attachment method is investigated in terms of attachment stiffness and attachment-induced warping using Laser Doppler Vibrometry and white-light interferometry. It was found that the double-sided attachment by bond wires had sufficient stiffness and that the attached die experienced three resonance modes, all at a sufficient distance from the excitation and detection mode of a gyroscope test device. This approach is a promising attachment method for various MEMS applications and is not only limited to inertial sensors. The attachment approach needs to be matched against conventional die attachment methods. The separation of die attach and stress-sensitive die area as well as symmetric front- and backside attachment offers accessibility of large die surfaces areas, which can be utilized for functional purposes, such as biomedical applications for surface modified sensing and detection or surface micro machined flow sensors.

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