Standard semiconductor packaging for high reliability low cost MEMS applications

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ABSTRACT

Microelectronic packaging technology has evolved over the years in response to the needs of IC technology. The fundamental purpose of the package is to provide protection for the silicon chip and to provide electrical connection to the circuit board. Major change has been witnessed in packaging and today wafer level packaging technology has further revolutionized the industry. MEMS (Micro Electro Mechanical Systems) technology has created new challenges for packaging that do not exist in standard ICs. However, the fundamental objective of MEMS packaging is the same as traditional ICs, the low cost and reliable presentation of the MEMS chip to the next level interconnect. Inertial MEMS is one of the best examples of the successful commercialization of MEMS technology. The adoption of MEMS accelerometers for automotive airbag applications has created a high volume market that demands the highest reliability at low cost. The suppliers to these markets have responded by exploiting standard semiconductor packaging infrastructures. However, there are special packaging needs for MEMS that cannot be ignored. New applications for inertial MEMS devices are emerging in the consumer space that adds the imperative of small size to the need for reliability and low cost. These trends are not unique to MEMS accelerometers. For any MEMS technology to be successful the packaging must provide the basic reliability and interconnection functions, adding the least possible cost to the product. This paper will discuss the evolution of MEMS packaging in the accelerometer industry and identify the main issues that needed to be addressed to enable the successful commercialization of the technology in the automotive and consumer markets.

Keywords: MEMS, micromachining, accelerometer, packaging, silicon sensor, reliability

1. INTRODUCTION

The adoption of air bag technology as a standard feature in automobiles has been the single largest driver of the inertial MEMS industry to date. This started in 1991 when the ADXL50 was introduced as the world's first integrated MEMS accelerometer in a TO5 metal can package[1]. Since then accelerometer technology has evolved significantly with two fundamental approaches, integrated single chip solutions and two chip accelerometer products. In 1995, Schemansky et al[2] described a two chip accelerometer system aimed primarily at the automotive airbag market. In either case, the microelectronic package must provide a) electronic interconnection, b) mechanical protection, c) environmental protection and where power is a consideration d) heat dissipation. The choice of a metal can package for the ADXL50

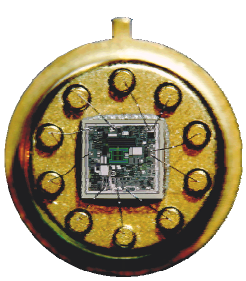

Fig 1. ADXL50 integrated MEMS single chip accelerometer

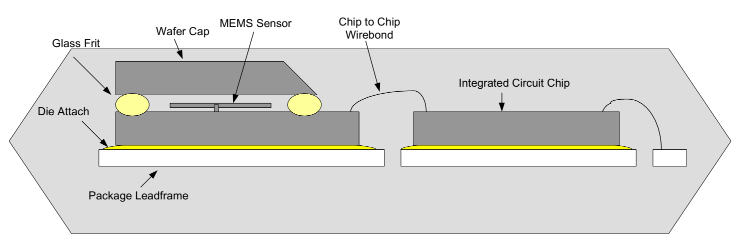

Fig 2. Cross-section of a two chip MEMS Accelerometer package

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was based on the reliability of this packaging solution in high reliability markets, essentially since the beginning of the semiconductor industry. The exposed MEMS structure requires the protection of the hermetic package environment. The use of a cavity hermetic package eliminates the high stress effects of plastic molding which can be detrimental to the performance of a sensitive MEMS device. In contrast, two chip solutions use a capped bulk micromachined MEMS structure and a standard silicon integrated circuit chip in the same package. The capping provides a hermetic protection for the MEMS and the two chips are typically subsequently packaged in a plastic package[3]. These two fundamentally different approaches to MEMS implementation, namely two chip or integrated, generate very different challenges for the manufacturers and inherently lead to different packaging approaches. In either case, the dominant market that drove the technology innovation, namely automotive, brought with it the highest quality and reliability expectations and aggressive cost curve expectations. Today, the inertial MEMS market is growing rapidly and it is estimated that the shipments of MEMS Inertial Sensors in 2004 are in the order of 300 million units[4]. While there is a growing market for MEMS accelerometers in consumer markets, the dominant market is still automotive. Single chip and two chip solutions have both found success and there are pros and cons to either approach. This paper describes the fundamentals of a single chip MEMS accelerometer and the evolution of packaging technology to meet low cost while maintaining high reliability.

2. FABRICATION TECHNOLOGY

The first element of the overall accelerometer system is the *i*MEMS® process that Analog Devices has developed and applied to the fabrication of accelerometers and gyroscopes. The defining feature of this process is that the MEMS sensor is fabricated on the same die as the signal process circuitry. Core, et. al, have described the process[5]. A very mature and well characterized BiCMOS fabrication circuit process is used to provide the signal processing circuitry. The circuit process also includes laser trimmable thin-film resistors. This circuit process has been integrated with a surface micromachined MEMS process. The MEMS process uses in-situ doped poly-silicon as the device material and silicon dioxide as the sacrificial layer. Figure 3 is a cross section showing the circuit and MEMS portions of a wafer as well as the interconnection between the two.

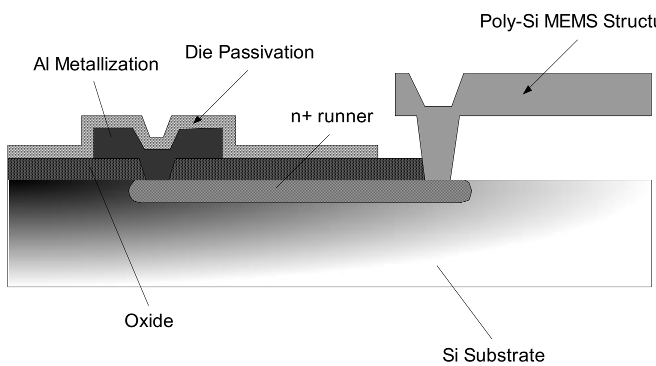
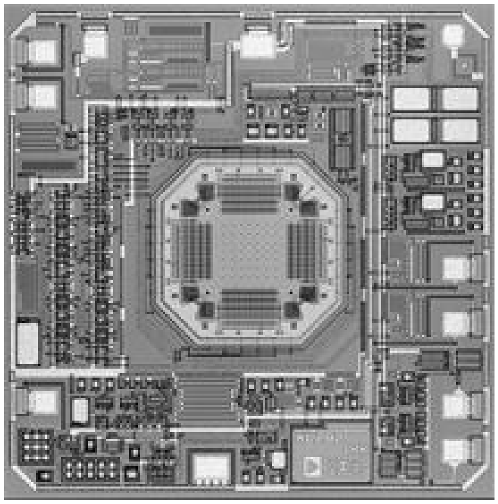


Figure 3. Cross section showing interconnection between MEMS and circuit in *i*MEMS®

The early development of the integrated MEMS process primarily focused on automotive reliability requirements. The reliability requirements encompassed both the mechanical behaviors of the sensor and the electrical characteristics of the overall electronic component. Offset (the sensor output voltage when no acceleration is applied) and sensitivity (the change in output due to acceleration) have been identified as the two most critical parameters used to measure product reliability[6]. It is these two parameters that are most closely monitored throughout a reliability qualification program. While the MEMS accelerometer is a sensor product the reliability tests that have evolved for the sensor are based on the very stringent reliability requirements of semiconductor IC packaging including MIL-STD-883. This trend has continued and the end users today tend to look at MEMS accelerometers as IC devices and expect the same level of reliability. The sensors are handled using standard automated insertion equipment and are expected to survive the most harsh board solder reflow processes. Extensive early development focused on the poly-silicon MEMS beam structure and the interconnection between the beams and the on chip BiCMOS circuitry.

Figure 4 is a photograph of the XL202, a two axis, low g accelerometer fabricated with the *i*MEMS® process. Note that the MEMS sensor is in the middle of the die, surrounded by the signal processing circuitry. The bond pads for the device are distributed around the periphery of the die, as is typical for an analog circuit.



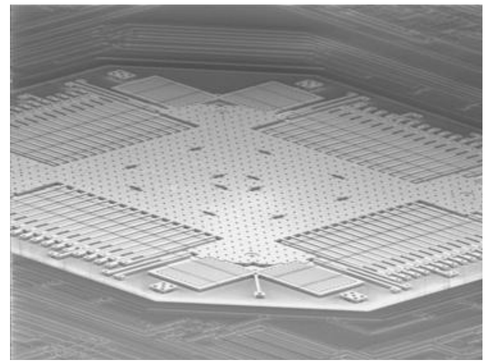
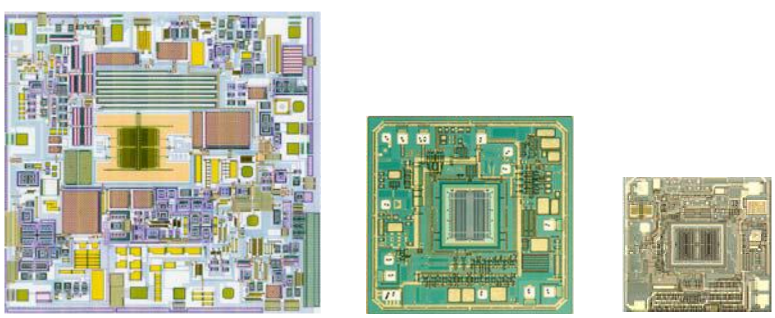


Figure 4. (a) Photograph of ADXL202 die, which is fabricated in the *i*MEMS® process (b) SEM photo of MEMS Sensor Area

Over the last 10 years the integrated MEMS fabrication and design processes have evolved together facilitating the continued shrinking of the MEMS sensor. Figure 5 shows the evolution of the 50g single axis family of MEMS accelerometers. The design of the MEMS beam structures have evolved to continuously improve the reliability of the end product. For example, simply shrinking the size of the MEMS structure reduces the probability of random defects in the wafer fabrication or packaging processes. While MEMS sensors have reliability performance which is on par with standard IC reliability FIT rates, the end markets expect a constant drive towards zero defects.



ADXL50 (1991) **ADXL76** (1996) **ADXL78** (2001)

Figure 5. Single chip MEMS accelerometer die size evolution

3. PACKAGING TECHNOLOGY

There are significant challenges associated with the packaging of MEMS accelerometers. The main driving issue is the moving MEMS elements that need to be carefully handled and protected through the assembly process. In the case of two chip approaches the MEMS sensor is packaged in a wafer level package and subsequently packaged in the outer plastic package. While the MEMS structure is protected there can be significant interaction between the molded package and the MEMS system creating performance and reliability challenges that need attention in the design of the assembly process. In the case of integrated MEMS approaches the challenges of handling moving MEMS structures through the assembly process are considerable. Some special processes have evolved to meet these needs and have been combined with standard high volume hermetic assembly processes to meet the needs of low cost manufacturing. Stiction, the propensity for micromachined silicon beams to stick when they come into contact, is one a failure mechanism in silicon micromachined structures. Analog Devices has developed a patented anti-stiction coating that was originally applied as part of the assembly process. This has been replaced by a wafer level coating that is deposited as part of the wafer fabrication process. This anti-stiction coating has eliminated the problem of stiction in these very small geometry MEMS structures.

Dicing of "open MEMS" structures is another very significant challenge for the industry. A patented dicing process is used to singulate MEMS accelerometers using standard assembly wafer saw equipment[7]. Figure 6(a) shows a MEMS wafer mounted to a wafer saw mounting tape that has been processed such that multiple holes are formed on the tape to correspond with the MEMS sensor at the center of each silicon chip. A cover tape is applied, Figure 6(b) and the wafer is then diced from the back side on a standard wafer dicing saw, Figure 6(c). The MEMS die is subsequently picked and assembled into a package using standard die attach equipment.

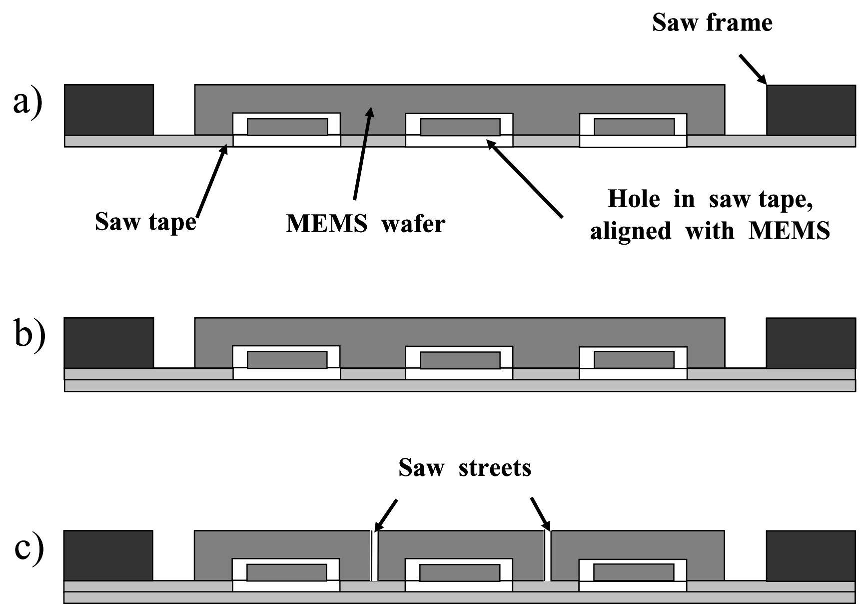


Figure 6. Description of Patented MEMS Wafer Dicing Process[7]

Die attach materials are carefully selected to minimize stress between the package base and the MEMS die. The thermal stability of the die attach material is also critical. Subsequent thermal exposure of an unsuitable die attach material can cause organic material to outgas which can deposit on the MEMS structure and cause reliability issues.

In the mid 1990's the ADXL76 family of products was released in a 14ld 300mil standard SOIC outline surface mount Cerdip configuration to meet the demands of customers for SMD technology. More recently a 5mm x 5mm x 2mm 8ld LCC was introduced. This package, while continuing to drive cost reduction, yielded the world's smallest accelerometer as the package size was optimized for the single chip MEMS die. Figure 7 shows the evolution of package size for single chip integrated MEMS accelerometers.

	Header	Cerdip/Cerpak	LCC
Xmm	**10**	**10**	**5**
Ymm	**10**	**10**	**5**
Zmm	**7**	**5**	**2**

Figure 7. Early generation packages for *i*MEMS® accelerometers

4. WAFER LEVEL CAPPING AND PLASTIC PACKAGING

The packaging of MEMS accelerometers in hermetic cavity packages has been very attractive to the automotive industry because of the fundamental reliability of the approach. However, there is a continued need to drive towards lower cost to meet the needs of the automotive market as well as bring the technology into the reach of high volume consumer applications. For these reasons a wafer level capping process has been developed for integrated MEMS accelerometers which allows the packaging of the device in very small and thin standard plastic IC packages[8]. The main objective in the development of this process was to reproduce the outstanding reliability of the traditional hermetic packaging process. The result of the development was a truly hermetic silicon cap mounted on the circuit area of the MEMS chip. Figure 8 shows a SEM photograph of a capped *i*MEMS® accelerometer.

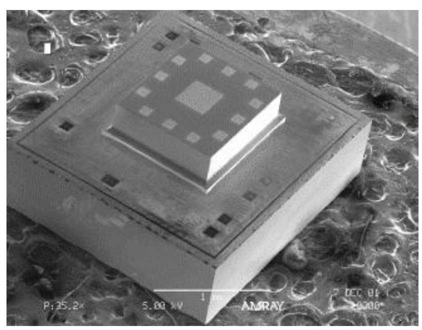


Figure 8. SEM Image of Capped *i*MEMS® accelerometer

The capped MEMS die is then packaged in 1.45mm thick 4mm x 4mm LFCSP (Lead Frame Chip Scale Package) [*]. The assembly process is a standard high volume transfer molded matrix leadframe based process described in Felton et al[9]. Fig, 9(a) shows a cross sectional view of the plastic MEMS accelerometer and Fig 9(b) is a photograph of the packaged product. The package takes full advantage of the size of the single chip MEMS die creating a very small and cost effective packaging solution. Again, reliability was the primary metric of success for the development of the

* LFCSP (Lead Frame Chip Scale Package) is known by several different acronyms including MLF®, QFN and MLP®.

plastic packaging technology and the end result is a product with comparable reliability performance to the ceramic hermetic package.

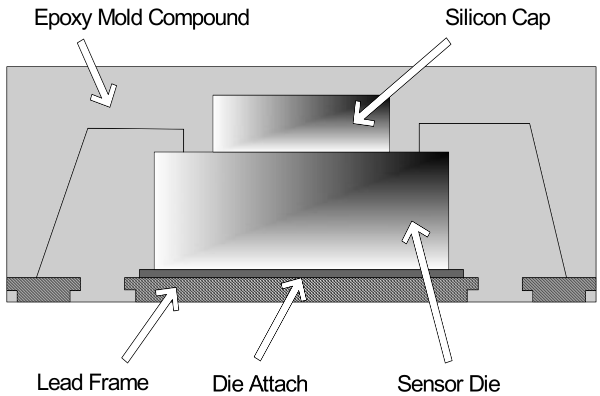


Figure 9 (a) Schematic cross section of capped *i*MEMS® accelerometer in a plastic LFCSP Package (b) Photograph of a 2 Axis Accelerometer in 4mm x 4mm x 1.45mm LFCSP Package

5. SINGLE CHIP MEMS RELIABILITY

The development of a plastic packaging solution for a single chip integrated MEMS accelerometer has been aimed at meeting the high reliability demands and continued need for cost reduction of the automotive industry. Success towards this goal would produce a product with a cost attractive to broader markets with the added advantage of zero defect quality levels. The packaged MEMS accelerometer was subjected to a series of stringent reliability tests. After reliability testing the products were required to meet the data sheet requirements and particular attention was paid to the stability of offset and sensitivity of the sensor. Table 1 shows the results of reliability testing of the plastic packaged accelerometer compared to reliability data for the same family of product in a hermetic LCC package. While the wafer level capping affords full hermetic protection of the MEMS element, the package itself is not hermetic. For this reason moisture testing must be added to the qualification test portfolio. The package was characterized to JEDEC MSL Level 3 with a 260 C solder reflow. Of special note is the excellent performance of the plastic package in temperature cycle and thermal shock at MIL-STD-883 Condition C (-65 C to 150 C). This is a particularly stringent test for a MEMS accelerometer in a plastic package.

Table 1. (a) Preliminary Reliability data for MEMS accelerometer in 4mm x 4mm x 1.5mm LFCSP package (b) ADXL78 Family Qualification data in 8ld LCC

Stress Test	**Conditions**	**Sample Size**	**Result** Fail/ Sample
HTOL 150°C 500 hrs	Mil Std 883, Method 1005	3 lots, 77 pcs	0 / 231
HTS 150°C 168 hrs	Mil Std 883, Method 1008	3 lots, 77 pcs	0 / 231
LTS -40°C 168 hrs	Mil Std 883, Method 1008	3 lots, 77 pcs	0 / 231
HAST 96 hrs	JEDEC STD-22, Method A110 130°C 85%RH Bias	3 lots, 77 pcs	0 / 231
Temp Cycle 500 cycles	JEDEC STD-22, Method A104 -65°C to 150°C	3 lots, 77 pcs	0 / 231
Thermal Sck 500 cycles	JEDEC STD-22, Method A106 -65°C to 150°C	3 lots, 77 pcs	0 / 231
Grp D, Sub 4	Mil Std 883, Method 5005 Group D, Subgroup 4	3 lots, 20 pcs	0 / 60

Stress Test	**Conditions**	**Sample Size**	**Result** Fail/ Sample
HTOL 150°C 1000 hrs	Mil Std 883, Method 1005	3 lots, 77 pcs	0 / 231
HTS 150°C 1000 hrs	Mil Std 883, Method 1008	2 lots, 77 pcs	0 / 154
LTS -40°C 1000 hrs	Mil Std 883, Method 1008	3 lots, 77 pcs	0 / 231
Temp Cycle 1000 cycles	Mil Std 883, Method 1010 Cond B -55°C to 125°C	4 lots, 77 pcs	0 / 308
Grp D, Sub 4	Mil Std 883, Method 5005 Group D, Subgroup 4	3 lots, 20 pcs	0 / 60

The reliability data presented here is gathered through rigorous reliability testing and analysis on large qualification samples. Ongoing reliability monitoring programs confirm the reliability of the product. But the ultimate measure of reliability is the end customer. Reliability or quality over time has become a major selling point in the semiconductor industry, especially in the automotive sector. Even with the level of complexity of a fully integrated MEMS sensor and integrated circuit on one chip, World-Class reliability is achievable. The OEMs have driven reliability requirements into the sub-FIT (< 1 FIT) level. A FIT (Failure in Time) is a metric derived from the number of failures from a population of devices operating for a given time period. Specifically it is the number of failures per 1 billion operating hours. The data in Figure 10 represents field reliability performance over a 3 year period from a population of greater than 100 million single chip MEMS accelerometers packaged in hermetic packages with anywhere between 700 and 3,000 operating hours (assuming 2 hours operation per day).

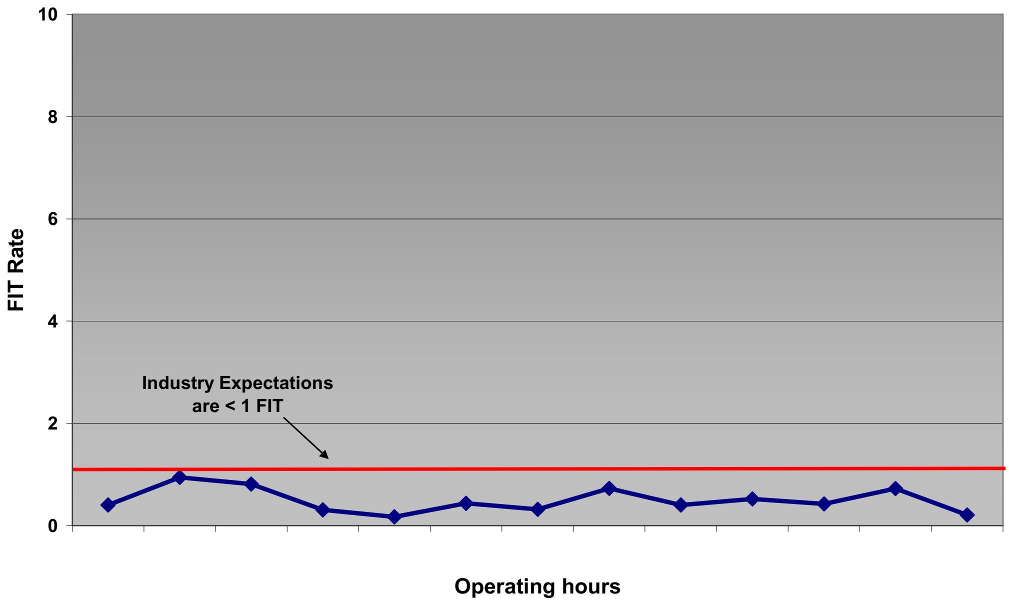


Figure 10. Field reliability data for single chip MEMS accelerometers

Board level solder reliability is a major concern in the automotive market, especially for devices to be deployed under hood or in other hazardous environments. Extensive modeling and empirical analysis has been carried out to predict the performance of surface mount MEMS accelerometers in such environments. Samples prepared in accordance with IPC-SM-782 were subjected to different board level solder reliability testing. Conditions of -40 C to 105 C (30 min / 30 min cycles) and -40 C to 125 C (10 min / 10 min cycles) on FR4 were tested to 1000 cycles with no failures .

6. SUMMARY

MEMS accelerometers are one of the best examples of the commercial success of a new technology. Surface micromachined single chip solutions and bulk micromachined two chip technology are used effectively to support the market. The reliability performance of MEMS accelerometers today is excellent, as it must be to support the safety critical air bag sensor market. The single chip solution has evolved to the point where it is now possible to make a 4 mm x 4 mm x 1.45 plastic package with development activity towards a 0.9 mm thick product. Continued development will lead to a single chip wafer scale packaged accelerometer that will provide the lowest cost possible. Many new applications of MEMS accelerometers have emerged in recent years as the price point of the technology has made the economics of high reliability sensors in consumer markets attractive. For many of these applications, price and size are equally important and new applications will emerge as size continues to reduce. Standardization of packaging for MEMS accelerometers, as well as for other MEMS sensors, is really not feasible as the wafer fabrication technologies are so diverse. When MEMS accelerometers are soldered to PC boards they are indistinguishable from other IC products on the board. For this reason, end users have begun to expect the same reliability performance from the sensor as they do of other components on the PCB. The MEMS accelerometers available today have risen to this challenge. New MEMS technologies continue to develop and the expectation is that they will evolve in a similar fashion to accelerometers. Packaging challenges will remain high on the list of issues to be resolved for these new technologies.

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