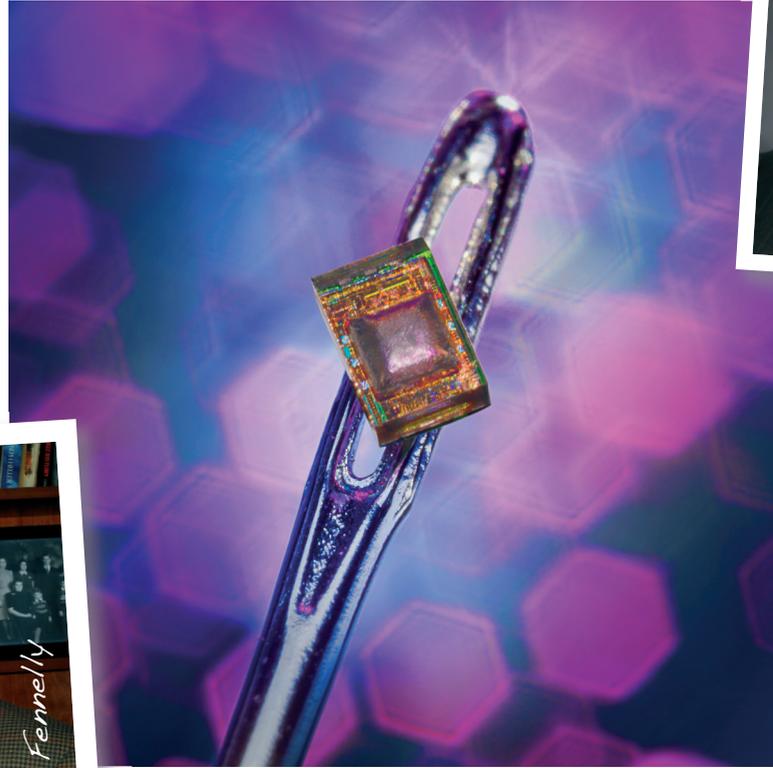


THERMALLY-BASED MEMS SENSORS

Measure Acceleration and Gas Flow

<< **Figure 1:** The MSC6226Xc Heated Gas accelerometer uses monolithic integration to combine the thermal sensing elements and the signal conditioning functions on the same chip. Its size is 1.7 x 1.2 x 1.0 mm and uses wafer level packaging (WLP). It is shown in size comparison to the head of a common sewing needle. Courtesy: MEMSIC Inc. >>



Part 1

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Introduction

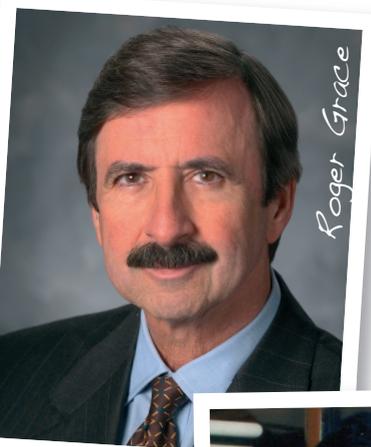
The electronic system designer is truly fortunate when it comes to specifying a sensor to optimally satisfy a specific system function. This results from the myriad of sensor technologies that currently exist to measure the various parameters to meet the system's design requirements. This applies to accelerometer and gas flow sensors. This article will address the topic of acceleration. The gas flow sensing article will appear in the next edition of this publication. The ability to make a measurement of shock, vibration and tilt can be accomplished by several sensor types including capacitive, piezoresistive, piezoelectric and last, but not least, heated gas (thermal). All of these sensor types can be designed and manufactured using MEMS technologies.

When it comes to gas flow measurements, the same situation exists. Popular gas flow sensing types include differential pressure, vortex, ultrasonic, Rotometers, hotwire anemometer. Again, gas flow meters that operate on the thermal principle are popular. Differential pressure, ultrasonic and hotwire anemometer as well as thermal types can be realised using a MEMS approach.

The advantages of using a MEMS-based approach to sensing are many and include enhanced reliability due to the fact that there are no moving parts, small size, high volume manufacturing capable, low cost, high reliability and high reproducibility due to their batch mode processing. Their ability to be integrated monolithically with other circuit functions including signal compensation/calibration and processing and their ability to be produced in low cost and miniature wafer level packaging formats make them the technology of choice for many applications (figure 1). Finally, the choice of the specific type of accelerometer and/or gas sensor can provide the designer with the optimum solution for their design based on the fact that various types of sensors tend to have their optimum performance in measuring different parameters due to the inherent nature of the technology used to create the sensor.

Accelerometers: Theory of Operation

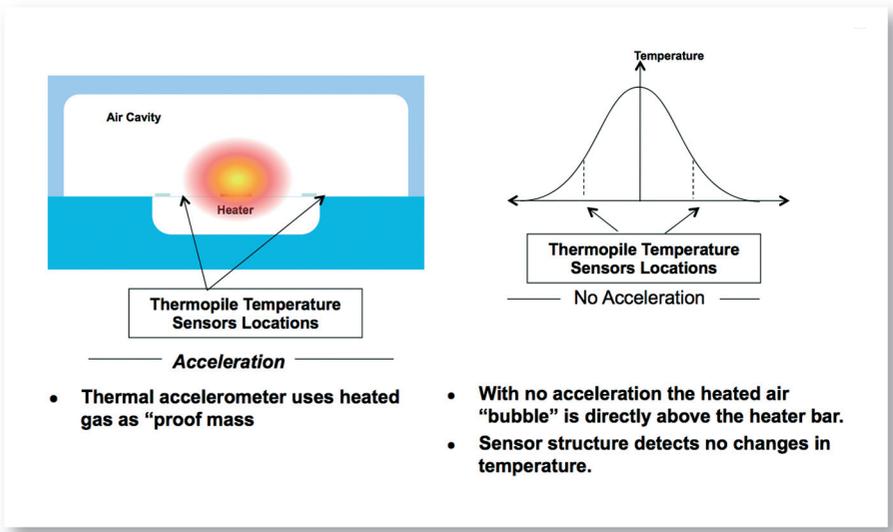
In a capacitance MEMS accelerometer, the proof mass is usually an inter-digitated cantilever beam mechanical structure. This structure consists of a set of fixed plates, configured as 'fingers' attached to the MEMS substrate. The movable proof mass also



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<< ABOVE | Figure 2a: Under zero input excitation, the heated gas accelerometer’s heated air ‘bubble’ is directly above the heater bar and the sensor structure detects no change in temperature. Courtesy: MEMSIC Inc. >>

consists of a set of finger plates attached through a mechanical suspension system to a reference frame. Both the fixed and movable frame fingers are connected in parallel. The deflection of the proof mass caused by acceleration is measured using the capacitance difference value between both sets of plates. MEMSIC’s heated-gas (thermal) approach for measuring acceleration is unique and operates on a totally different principle that involves no moving parts. It uses heated-gas molecules to detect acceleration using thermocouples. This technique is unique and patented by MEMSIC Inc.

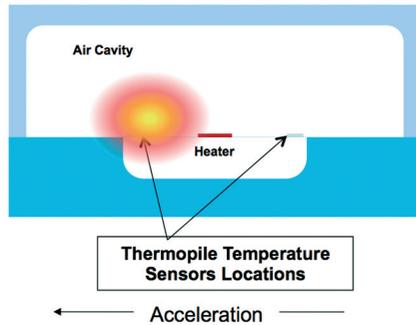
Unlike capacitance type MEMS accelerometers which use a solid mass structure, using heated gas and thermocouples as performed by MEMSIC is altogether different. This approach makes use of a centrally located resistive heating element to heat the gas molecules and temperature sensors such as thermocouples to measure the temperature difference between the time when there is no acceleration and when acceleration is applied (figure 2). It is also amenable to monolithic manufacturing to include all the necessary signal conditioning, interface and embedded algorithm circuitry on a single chip with wafer level packaging to finish (figure 3). When subjected to acceleration, the less dense air molecules in the heated gas move in the direction of acceleration and the cool and denser molecules move in the opposite direction, creating a temperature difference. The temperature from one side of the MEMS structure to the other is proportional to acceleration.

Technical Comparison

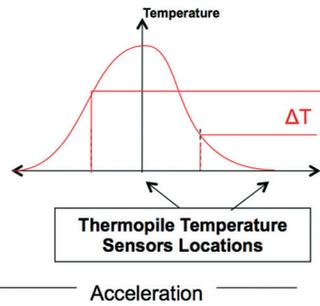
Capacitive MEMS accelerometers are the most popular devices in the market today when it comes to high volume/low cost devices, however, it does not have the best performance in many parameters versus the heated gas variety. We will compare from an overview perspective the performance of this type of accelerometer as well as with the piezoresistive and piezoelectric types with the performance of the thermal type as offered by MEMSIC (figure 4). Additionally, we will provide a detailed comparison between the heated gas (thermal) and capacitive approaches. The differences between the operating principles of both capacitance and the heated-gas MEMS accelerometers are profound and have important benefits to the end user. Moreover, the latter method allows for proprietary monolithic manufacturing. The latter method produces the smallest, lowest-cost and highest shock survivability MEMS accelerometers compared to the capacitance method.

For one thing, the absence of moving parts in the heated gas sensor makes it inherently more reliable. On average, failure rates achieved of 10 ppm for heated-gas accelerometers compare very favourably with capacitance MEMS accelerometer failure rates of 100 to 4000 ppm. Capacitance types are prone to failure due to ‘stiction’, a condition where the moving proof mass fingers stick to each other and render the accelerometer inoperable. They’re also susceptible to electromagnetic interference (EMI) since their sensing node has high impedance. This may be dealt with by proper shielding and packaging of the accelerometer and its interface circuit, but that also means more processing complexity and higher end user costs.

Capacitance MEMS accelerometers also suffer from mechanical ringing. This requires damping. They also have hysteresis. All of this translates into custom fabrication processing and higher costs.



- Thermal accelerometer uses heated gas as “proof mass”

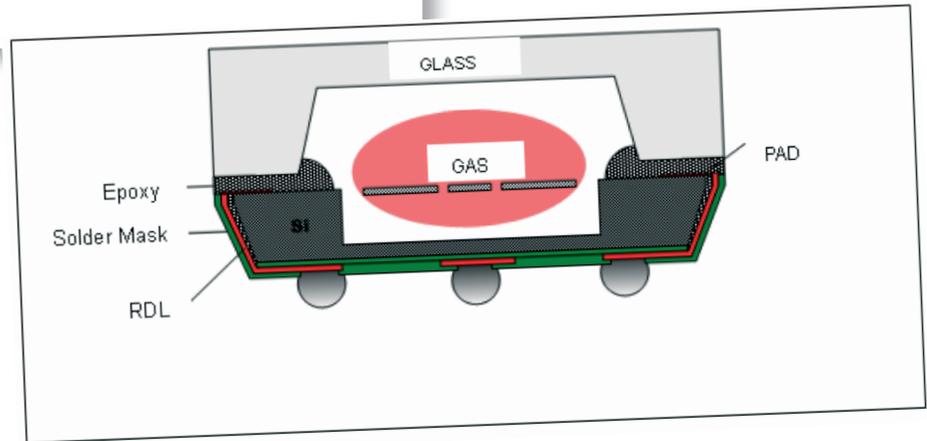


- With acceleration the heated air “bubble” moves in direction of the acceleration.
- Sensor structure detects a change in temperature.

<< LEFT | Figure 2b: For the heated gas accelerometer under excitation, the heated gas ‘bubble’ is used as a proof mass and moves in the direction of the acceleration. The sensor structure detects the change in temperature proportional to the acceleration. Courtesy: MEMSIC Inc. >>

<< RIGHT | Figure 4: Parametric performance comparison of Heated Gas Accelerometer versus alternative technologies. Courtesy: MEMSIC Inc. >>

<< RIGHT | Figure 3: The ability of the heated gas accelerometer to integrate the sensing element with the signal conditioning circuit on the same chip (monolithic) provides the opportunity to use Wafer Level Packaging technology where a ‘capping’ wafer is used to hermetically seal the system. This results in maximizing the reliability and reducing size and cost. Courtesy: MEMSIC Inc. >>



They also require more complex readout circuitry than heated-gas types. One area where heated-gas MEMS accelerometers don't fare as well is in frequency response. However, for many applications like a toy being thrown against the wall or a mobile phone being dropped, this is not much of an issue since the lower frequency response is more than adequate. The heated-gas MEMS have a maximum un-amplified frequency response of ~30Hz. Frequency extension circuits have pushed this out to >100Hz. Also, capacitance type MEMS accelerometers generally have lower noise densities than heat-gas types. The latter types, though, can alleviate this by using filtering or averaging to reduce noise-density to acceptable levels. A major differentiating factor between capacitance-type and heated-gas accelerometers is the manufacturing process. The former requires integrating the sensing element with signal-conditioning electronics, interface circuitry, and embedded algorithms on two or more chips thus resulting in higher costs, larger package sizes and lower reliability levels.

MEMSIC has created a patented monolithic process where the same chip holds the acceleration element as well as all the additional circuitry needed including embedded micro controller-based algorithms. Algorithms are the necessary elements that create an optimal system solution for the end user, and are often

the means by which MEMS accelerometer manufacturers can distinguish their products from their competitors' offerings.

Application Trade-offs

For automotive applications, the heated-gas approach is not as suitable as the capacitance method because it is bandwidth-limited and thermal noise can be a problem. It does not have the high-speed (300-Hz) and high-g (100 g to 500 g) full scale range of capacitance types. On the other hand, the heated-gas approach is more suited to electronic stability control (ESC), hill-start assist and rollover automotive applications due to its natural low-pass frequency response providing insensitivity to out-of-band accelerations in the vehicle caused by gravel striking the frame or other common vibrations.

For some home-appliance applications like washing machines, the regular, inexpensive and low-mass nitrogen gas normally used in a heated-gas MEMS accelerometer is not sensitive enough to detect washer imbalances due to unevenly distributed loads. This gas can be readily changed to a heavier mass gas for greater sensitivity. Toys are another example where the heated-gas approach is superior not the least reason being low cost. We all know that children handle toys very roughly. A toy withstanding a shock of 50,000 g's when a toy is angrily thrown at a wall is well within the

Parameter	Heated gas	Capacitance	Piezoelectric	Piezoresistive
Cost	Very low (cents in OEM lots)	Low to moderately high (cents to dollars in OEM lots)	Moderately high (cents to dollars in OEM lots)	Moderately high (cents to dollars in OEM lots)
Packaged IC size	Very small	Small to moderately high	High	High
Reliability	Extremely high	Moderately high	Extremely high	Moderately high
Sensitivity	Very high	High	High	High
Survivability to shock	Very high	High	High	High
Power dissipation level	Medium	Low to medium	Medium	High
Mechanical shock limit	>50,000 g	About 10,000 g	50,000 g	About 10,000 g
Failure rate	<10 ppm	100-4000 ppm	100-4000 ppm	100-4000 ppm
Resonance error	Undetectable	High	High	High
Hysteresis	Undetectable	High	High	High
Offset temperature coefficient	Highest	Fair	Fair	Fair
Offset drift	Lowest	Fair	Fair	Fair

capability of a heated-gas MEMS accelerometer. As a point of reference, a 10,000-g shock can be generated simply by banging a toy or any other product on a desktop.

Conclusions

The availability of heated gas (thermal) MEMS-based accelerometers provides the system design engineer with a valuable tool for the measurement of shock, vibration and tilt in many demanding applications. When compared to the popular MEMS capacitive accelerometers, they provide exceptional performance advantages over capacitive as well as piezoresistive and piezoelectric approaches. However, the system design engineer must be judicious in evaluating all of the system requirements before the selection of the accelerometer sensor technology that optimises the system's performance. We look forward to you returning to the next issue of this publication for a detailed analysis of MEMS gas flow sensors.

James Fennelly is the Business Development Manager for Automotive and Industrial Sensing at MEMSIC Inc., leading manufacturer of advanced MEMS accelerometer, magnetometer, flow and inertial measurement components and systems. He has over 10 years of experience in MEMS product definition and product line management. He holds a patent for a programmable temperature compensated tilt switch. He has published numerous MEMS focused articles in the US and Germany. He received his B.S.E.E.T. from the University of Massachusetts – Lowell.

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principle designer of MEMSIC's award winning AMR-based magnetic sensors. He is currently responsible for MEMSIC's sensor R&D activities including identifying and developing technology partnership with external partners, designing and developing MEMS-based sensors, design and process development for the magnetic sensor product line, ASIC development and foundry management activities. He received his B.S.E.E. from Huazhong University of Science and Technology (China) and his M.S.E.E. from the Ohio State University.

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