MEMS Manufacturing Testing: An Accelerometer Case Study

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Abstract
Electrical testing of MicroElectroMechanical Systems (MEMS) can take on many different forms including wafer probing, electrical trimming, final test at temperatures, engineering characterization, and reliability evaluations. MEMS testing has had limited visibility in literature from companies that have successfully industrialized applications such as pressure sensors and accelerometers. This limited visibility is not an indication of the importance of this topic that represents a significant portion of the overall cost, rather it is more likely and indication custom nature of test for MEMS. This paper presents a case study that addresses the issues associated with MEMS testing of accelerometer devices and an effective solution based on a system approach.

Keywords: Accelerometers, MEMS, Electrical Trim, Measurements.

1. INTRODUCTION

MEMS technology and the drive for cost reductions continue to evolve. Examples of cost reduction include die size reduction, yield improvement, and integration. The accelerometer that is the focus of this case study contains an interface IC and transducer die packaged in a Small Outline Integrated Circuit (SOIC) 16-lead package. The primary components of the device are shown in Figure 1. The g-cell transducer is constructed using surface micromachining techniques. The signal conditioning of the accelerometer channel begins with a capacitance-to-voltage conversion followed by a 2-stage switched capacitor amplifier. The 2-stage amplifier has adjustable offset and gain trimming.

The accelerometer device has a 4-pole, low-pass, switched capacitor Bessel filter with options for a cutoff frequency of 400 to 700 Hz. The output of the filter is amplified by the output stage, which buffers the signal to the external Vout pin and contains the temperature compensation for sensitivity. The EPROM trim state is valid from 4.4 to 5.5 V with 4.75 to 5.25 V considered the normal operation range for V_{DD}. A self-test voltage can be applied to the electrostatic deflection plate in the transducer resulting in a known output. The product has several fault checks for low voltage detection (LVD), clock and/or bias monitoring, and a check of the stored even parity of the EPROM trim register.

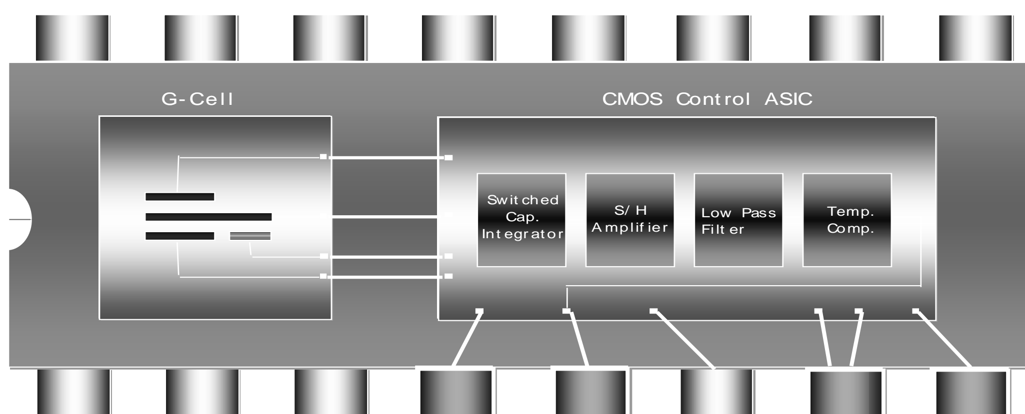

Figure 1. Two-chip accelerometer containing a g-cell transducer and CMOS interface IC.

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Serially accessed EPROM trim registers control the offset and gain of the interface IC. The roll-off frequency is trimmed by adjusting the frequency of an oscillator. The parity bit is used to obtain "even" parity for the trim bits. Even parity is obtained by programming the parity bit when "odd" parity exists on the trim bits. The lock bit is programmed separately as the final calibration operation. Once the lock bit is set, no changes can be made to the trim bits. Loading seed values for the oscillator, gain, offset, and self-test into the trim station setup file, starts the EPROM trim sequence. Convergence algorithms are utilized to determine the intermediate and final trim code values.

The initial MEMS electrical test occurs at the conclusion of the wafer fabrication. This probe test is performed on both the transducer and Application Specific Integrated Circuit (ASIC) wafers. The primary intent of probe is to validate the wafer fabrication and insure device functionality to justify the expense of back end manufacturing and test. MEMS test platforms for accelerometer testing can vary depending on the production model used in manufacturing. When producing MEMS devices in high volume, variations in the electrical parameters can occur from device to device [1] and require calibration trimming. The primary driver of the test flow is the type of signal conditioning employed for device calibration. MEMS trimming techniques includes laser trimming, zener zap, polysilicon resistor trimming, and E/EPROM methods. The baseline processes using a custom ATE and handler interface requiring updating were the back end trim and final test platform. The process was not obsolete but a new system was required which would adapt to new technology and be more cost effective.

In evaluating the changes required to the back end trim and final test platform, the starting point was cost. In an industrialized MEMS business the manufacturing cost is a principle component that drives growth. The cost components include: capital, contacts, maintenance, floor space, operators, engineering support, management, electricity, and liquid nitrogen for temperature control [2]. Of these cost components the primary considerations were capital, contacts, and maintenance. These three components drive over 50% of the overall test cost. The test system cost can be evaluated in terms of cost-per-second of its intended lifetime. Given this fixed rate the overall cost per device can be minimized by higher throughput both in terms of index and test time.

Intangible costs were also considered against the above factors. A primary intangible cost driver is the ability for a test system to adapt to new technology such as changes to the physical stimulus or the electrical interface. Changes to the physical stimulus may be an acceleration range change or an axis variation. Changes to the device could span the range from a simple trim word change to a completely new architecture. Consideration of the tangible and intangible costs drove the final solution utilizing principles of standardization and modularity.

2. TEST SYSTEM COMPONENTS

The first step in the drive towards equipment standardization was to divide a test system into the components required to create the test system. Dividing the system into components permitted focus on optimal solutions for the subset before considering the system as a whole. A test model for a MEMS platform is shown in Figure 2 [3]. The primary components of the MEMS test model that had some uniqueness when correlated to the typical semiconductor test were the Automatic Test Equipment (ATE), handler, nest, and physical stimulus. The temperature conditioning and electrical interface areas were strong candidates for reuse. The boundary conditions of each component were then analyzed with a special emphasis on modularity both in regards to the MEMS technology and intended lifetime.

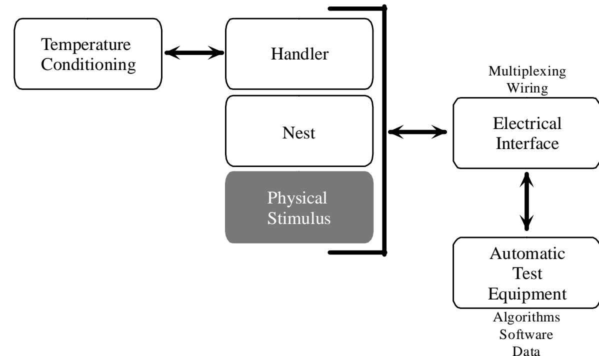

Figure 2. MEMS test system components.

3. AUTOMATIC TEST EQUIPMENT (ATE)

The ATE represents the heart of the test system. When asked what type of test system is in use, it is common to reply with information on the ATE. The ATE provides the electrical stimulus and signal acquisition for the testing process. The typical MEMS device has two functions that must be considered for the test system. The first is the transducer that is transforming one form of energy into another form of energy. For the application reported here the transducer is converting acceleration energy into electrical energy using surface

micromachined capacitors. The second function to consider involves the signal conditioning, signal shaping, and analog or digital data acquisition. This secondary ATE functionality is very comparable to an ATE used in the typical semiconductor industry. Selection of the ATE must take into account the various signals utilized during the calibration and functional testing of the MEMS device. The accelerometer requirements for an ATE include both analog and digital sourcing and measurements.

The physical stimulus associated with an accelerometer test system is considered a part of the electrical stimulus with a downstream conversion to physical motion. Physical stimulus is driven from within the ATE software on a classic MEMS accelerometer solution. This allows precise, cohesive synchronization of physical stimulus and capture of the associated response. Latency and phase relationships in the physical system typically have required special consideration. A classic solution would achieve this integration through close software control of the discrete components. Selection of a standard ATE hardware solution, which provided this same control, would require a careful examination of the intrinsic integration of the standard solution.

The stated capabilities of a standard ATE solution will not always define the suitability for the task. The designer must verify that the top-level control syntax for the standard ATE solution, that inevitably acquires a historical paradigm, can be abandoned when needed. The ATE software is then written to alternately use the best features of the standard solution, but revert to rudimentary control syntax when needed to maximize speed and accuracy.

The analog sourcing capability of the ATE is used to drive the shaker, which is providing the mechanical stimulus. The ATE must then be capable of simultaneous capture of the response of the device and the response of a calibrated reference accelerometer. The simultaneous capture of the device and the reference signals and the knowledge of the reference accelerometer's calibrated sensitivity allow the device sensitivity to be calculated without the precise control of the shaker stimulus. The analog capture capability of the ATE can be enhanced by signal processing capabilities. Hardware and software signal processing can extract the waveform or waveforms of concern from the captured signal. This processing filters the out of band noise and improves the repeatability of the measurements.

Typical MEMS ATE systems have been comprised of rack and stack components. These systems have performed the tasks but have required extensive resourcing to meet the demands of an ever-changing technology. The platform selected for the next generation system is a commercially available digital Very Large Scale Integrated (VLSI) test system with a mixed signal option. The system provides the intended function for MEMS in addition to microprocessors and other typical semiconductor applications. The flexibility for future MEMS systems is enhanced by the selection of this platform over rack and stack components.

4. HANDLER WITH TEMPERATURE CONDITIONING

The primary purposes of the handler for trim and final test are to transport the device to the test nest, temperature condition the device, secure the device for testing, and transport the device for binning based on the ATE results. The baseline handler for the accelerometer test process was a linked system with temperature capability that transported the devices in a carrier with a batch size of up to 16. A photograph of the baseline hander system is shown in Figure 3. The baseline process is a custom handler that is common to the MEMS industry [1].

Figure 3. Baseline accelerometer test cell with linked tri-temperature test capability.

Handlers in the general semiconductor business have evolved into two primary styles: gravity fed and pick & place. These systems have advanced to the point where index times with a test time of zero, are in the 25,000 unit per hour range [4, 5]. This throughput rate is based on a test time of zero. Typical MEMS throughput rates are at least one order of magnitude less than that industry. This reduction is attributed due to the physical stimulus. The handler system and physical stimulus were closely coupled in the selected design.

5. PHYSICAL STIMULUS

For MEMS accelerometer testing, applying a known acceleration into the device involves transferring a mechanical displacement or acceleration from an electrodynamic shaker through multiple mechanical interfaces into the MEMS device under test. Figure 4 shows a simple physical stimulus system for MEMS accelerometer trim and test. Even in its most simple form, the physical stimulus required for accelerometer trim and test is often a complex mechanical system that varies due to frequency *f*, temperature *T,* and device.

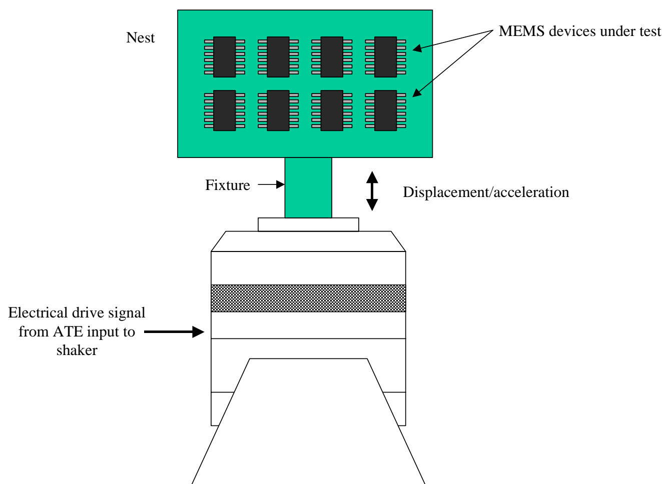

Figure 4. Physical stimulus and nest for baseline accelerometer trim and test process.

Previous test system implementations were large systems constructed around a specific MEMS accelerometer product as shown in Figure 5. Device packaging and axis orientation largely determined test system design. As a result, the baseline test systems were large and inflexible in terms of product changes.

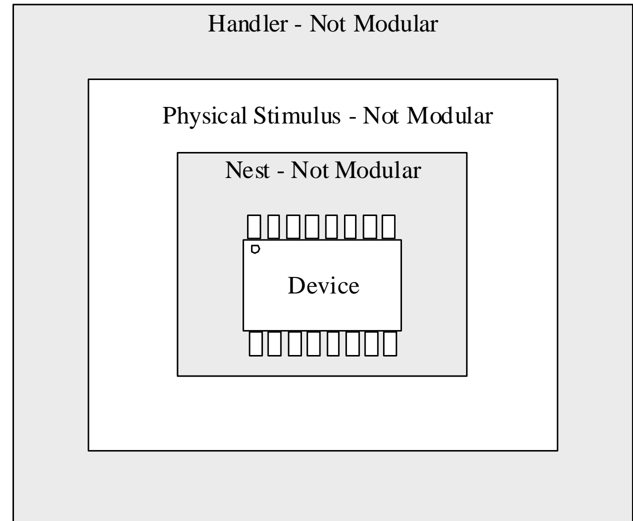

Figure 5. Previous test system implementation showing lack of modularity and thus flexibility to meet new demands.

If changes to the device were made using this baseline implementation, they would flow throughout the entire test system, from the nest system to the physical stimulus system to the handler system resulting in enormous costs in time, expenses, and effort to implement. Additionally, baseline handler systems were unique implementations specifically designed to the test system. There are several disadvantages to this approach:

- New techniques and implementations are required for each system resulting in little reuse of designs and parts.
- Handler and test systems are unique. A minimal amount of parts and subsystem are exchangeable resulting in higher maintenance and engineering support costs.
- Design and development costs are spread over fewer system implementations resulting in high cost to implement
- Due to system uniqueness and small user base, previous user experience is not folded into each design

To reduce these problems in implementing a new test system, a commercially available test handler with a proven history of operation and flexibility was chosen which now addresses the above key concerns as follows:

- The handler system is a mature, well-developed machine. Time and

effort are not spent on handler system design. A mature machine has lower down time resulting in higher Overall Equipment Efficiency (OEE) during trim and test.

- Handler and test systems are not unique. Parts and subsystems are exchangeable resulting in lower maintenance and engineering support costs.
- Design and development costs are spread over a larger commercial user base resulting in lower handler costs
- With a large commercial user base, a higher level of robustness is built into the system from other applications and previous user experience.
- Engineering resources can be implemented for system improvements on a more global level.
- Data handling efforts are minimized based on one system approach.

Modularity of the new test system was a paramount concern. From this handler platform, mechanical interfaces to the physical stimulus system are defined and fixed. This allows for greater flexibility in the implementation of the physical test system and in utilization of the handler with other devices. Even with changes made internal to the product, as long as packages remain the same, only nest connections and physical stimulus system changes need to be implemented. A graphical representation of the modular system is shown in Figure 6.

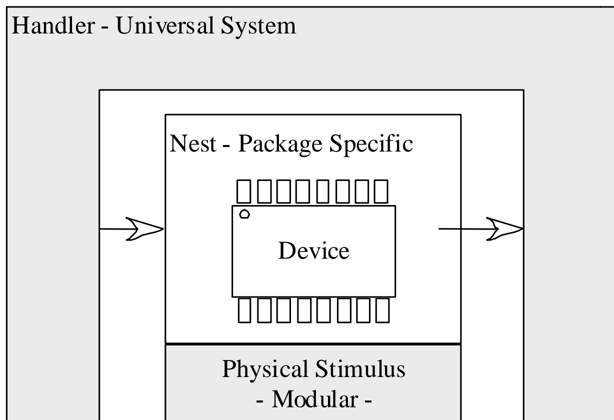

Figure 6. Modular test system implementation.

A significant aspect to this method is the required complexity of the physical stimulus system. Severe constraints are placed on the physical stimulus system geometry due to fixed handler geometry and interfacing. As a result, complex mechanical systems are often needed to conform to the handler geometry and interfaces. Physical stimulus system issues such as multiple system resonance, mechanical stability, thermal responses, and reliability due to increased system complexity become critical. A complex physical stimulus system design requires more design and test efforts to ensure proper and timely implementation. First, the principles of mechanical system modeling once considered unnecessary, are now required. In the past, trial and error methods were used to perform physical stimulus system design changes and evaluations. Now, due to complex design requirements, numerous design change iterations or large design of experiment matrices are required to optimize the mechanical systems and their interactions. Performing this analysis through trial and error is virtually impossible and would require large amounts of time. Computer analysis helps reduce the time and cost of the design development process. More sophisticated evaluation techniques are also required to evaluate and characterize system design and performance.

Many of the mechanical properties of the physical stimulus subsystems vary with frequency, time, temperature, and indexing. Depending on the system design and operation, some of these properties may be relatively constant. In past implementations, little variation was observed and the time invariant system was modeled as shown in Figure 7. This model was valid for the majority of test conditions previously in use. Physical stimulus systems were only one or two degrees of freedom mechanical devices in the operating region of interest with easily identifiable discrete operational modes and resonance frequencies. New complex designs are multiple degrees of freedom systems in the operating region. Additionally, the transfer functions and responses for these systems must be designed to be time invariant, again emphasizing sophisticated and thorough system analysis, and testing. Unlike previous test system designs, the new more complex mechanical systems can benefit significantly by implementing closed-loop control systems to reduce system and test variance.

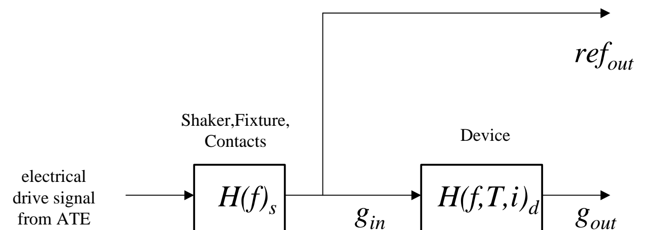

Figure 7. Previous physical stimulus system model.

Even in its most simple form, the physical stimulus system required for accelerometer trim and test is a closed-loop control system as shown in Figure 8. For this closed-loop system, *H* denotes the subsystem or interface transfer function. The closed loop feedback allows for system corrections due to variation. However, constraints in resources often lead to the implementation of a simplified open-loop physical stimulus system in place of a closed-loop system.

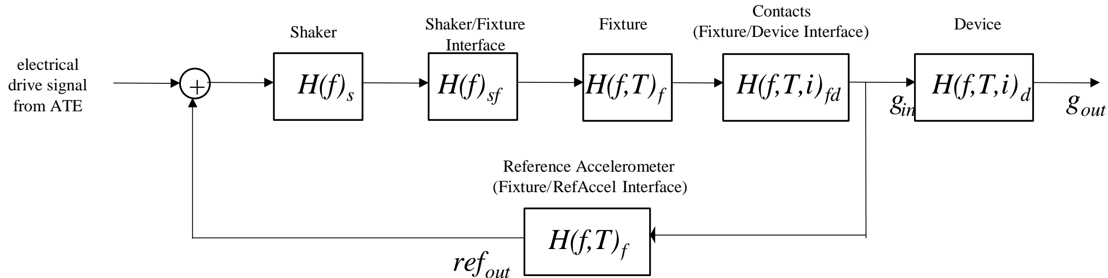

Figure 8. Simplified physical stimulus system block diagram

6. ELECTRICAL INTERFACE

The electrical interface provides the connection between the ATE and handler, nest, and physical stimulus. It is an essential element to insure the integrity for both sourcing and capturing of the signal. The electrical interface for the baseline trim and test operation was a custom design by the ATE and nest vendor. The primary design opportunities relating to the process baseline include modularity for different pin configurations, signal access ports, cable lengths, filtering components in close proximity to the device, and signal integrity.

Figure 9 shows the circuit elements required for the typical MEMS accelerometer. Passive components R_1 and C_1 provide an approximate 16 kHz low pass filter for the output signal and reject any clock noise that may be present. The C_2 bypass on the V_{DD} is also used for noise suppression. The test nest fixturing must provide space for these components as close to the device as possible. The test nest not only has to provide contact to the DUT for testing but also had to secure it sufficiently to withstand the rigors of the physical stimulus, in this case varying levels of acceleration, frequencies and temperature extremes.

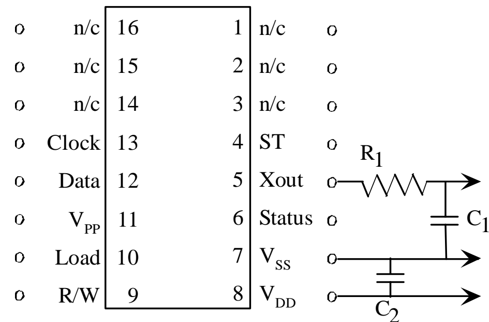

Figure 9. Device electrical interface connection showing passive components for noise suppression.

7. NEST

A MEMS test nest is a key design detail based on the combined electrical and physical stimulus that must be controlled to trim or test the device. In the case of accelerometer devices the physical stimulus used for device trim and test is a sinusoidal vibration in the audio range of frequency. A shaker exciter system and clamping mechanisms to hold the device typically have resonance peaks in the same frequency range [6]. The baseline process utilized an Unholtz-Dickie model SO92-HX SA30 shaker system rated at 1,000 lb_f. The greater the number of piece parts on the test nest directly correlated to an increase in resonance frequency concerns. A photograph of the test nest and carrier board on the baseline process is shown in Figure 10.

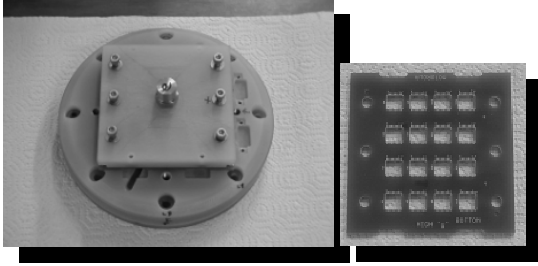

Figure 10. Left photograph shows the acceleometer test fixture on baseline process. Fixture contains 16 devices on the carrier board shown at the right.

The test case search for a new nest focused on the requirement to create a clamping means for one device. The contact spring lifetime had to be approached such that sufficient clamping force such that contact was not broken during testing. On the other hand the contact force could not be excessive such that the wear characteristics were affected. The nest also required space for the passive components described above. The contact system needs a high level of robustness to meet the millions of contact cycles over a testers lifetime. A contactor with marginal performance can cause devices under test to fail because of contact resistance is high, open, or shorted. In the case of an accelerometer device the contactor sees a great amount of physical stress induced from shaker system.

8. FUTURE MEMS TEST CHALLENGES

The future of MEMS testing will be two fold. The first challenge will involve the evolution to greater digital and more complex device functionality from the historic analog devices. MEMS are moving up the technology curve at a rapid pace and are requiring new features such as digital interfaces, RF communication, built-in self test (BIST), and scan testing. The other future push will be the continued pressure on the test cost. The test cost pressure is constantly present in any manufacturing operation and efficiency in the overall test strategy can provide a positive impact on the overall product revenue.

9. SUMMARY

The baseline trim and test process used for accelerometer testing had no modularity to meet the changing device platforms. A test system has been developed for accelerometer product electrical trimming and tri-temperature testing that meets the cost demands and provides modularity for future MEMS products. The division of the system into sections provided focusing of resources and solutions prior to the integration of the system. The ATE selection resulted in a standard VLSI platform with pin electronics. Modular components not only enhance the system design but also provide an improvement in overall equipment efficiency (OEE) during production. Standardization and modularity enhance the system cost. Spare parts can be stocked at a reduced level resulting in a lower operating cost.

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