ITRS CHAPTER: MEMS

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MEMS are fabricated using techniques similar to those used for ICs to create micrometer-sized mechanical structures (suspended bridges, cantilevers, membranes, fluid channels, etc.) that are often integrated with analog and digital circuitry. MEMS can act as sensors, receiving information from their environment; or as actuators, responding to a decision from a control system to change the environment.

The ITRS has organized a MEMS Technology Working Group (TWG), which has developed a new chapter on MEMS for its 2011 report. The report focuses on MEMS technologies associated with mobile Internet devices, such as smartphones and tablet computers. These applications represent the fastest growing segment in MEMS manufacturing, according to 2011 market forecasts by iSuppli, Yole Développement and SEMI.

The report focuses on the leading MEMS devices used in mobile Internet applications: accelerometers and gyroscopes, microphones, and RF MEMS, including resonators, varactors and switches. The report also reviews emerging MEMS applications, including optical filters, picoprojectors, the electronic nose, microspeakers and ultrasound devices.

Difficult Challenges

The ITRS MEMS roadmap considered both the evolution of discrete MEMS devices and integrated MEMS technologies. Here, the term "discrete" MEMS is used to refer to devices that perform one function. For the purposes of this discussion, a three-axis accelerometer with an integrated ASIC is referred to as a discrete MEMS device. "Integrated" MEMS refers to the integration of multiple types of sensing functions, such as accelerometer and gyroscope, in the same package.

Discrete MEMS accelerometers, gyroscopes and microphones are expected to see continuous incremental improvement in performance. MEMS three-axis accelerometers are expected to see improvement in resolution, bias and drift, with resolutions improving by a factor of 2 from 1,000 µg to 500 µg by 2017. MEMS three-axis gyroscopes are expected to see a continuous increase in resolution from 100 µ°/s/fflHz to 50 µ°/s/fflHz. MEMS microphones are expected to see an improvement in sensitivity from -42 dB (V/Pa) to -38 dB (V/Pa) at 1 kHz.

The greatest challenge faced by manufacturers of discrete MEMS devices comes from the required cost and size reductions. The cost of MEMS accelerometers and gyroscopes is predicted to lower from 60 to 20 cents and $2.70 to $1.20 per die, respectively, by 2017, with no known solutions at the present time.

RF MEMS resonators, varactors and switches are also expected to see a continuous incremental improvement in performance. The greatest challenge that these devices face in order to penetrate into the mobile Internet market is increasing their reliability, driving the need for reliability simulation tools and methods for accelerated lifetime testing. RF MEMS also specifically call out requirements for inductors with Q>50 integrated at the package level and methods for minimizing package interconnect length and loading.

The greatest challenges by manufacturers of integrated MEMS technologies were in relation to their integration path toward the inertial measurement unit (IMU), a device that incorporates a three-axis accelerometer, three-axis gyroscope, three-axis magnetometer (compass) and a pressure sensor (altimeter). The IMU is also referred to as a 10 degree of freedom (DOF) multimode sensor. Multimode sensor technologies face challenges in assembly and packaging, but have known interim solutions over the near term. The greatest cause for concern for multimode sensor technologies relates to testing. The cost of testing has been continuously increasing, yet the price of the devices continues to fall—a trend that cannot be sustained. The challenges of testing are further compounded by the increasing complexity of the tests, which require testing the multiple functionalities (acceleration, angular rate, direction and elevation) of the IMU.

The trends of increasing device performance, reducing cost and size, and advancing integration path in turn drive the requirements for advances in design and simulation, packaging and integration, and testing.

Challenge	Need
Assembly and Packaging	• Standardization for MEMS packaging to support integration. • Packages are needed that reduce or eliminate mechanical stress and enhance hermeticity. • Package data that can be used to accurately predict the effect of the package on device performance.
Device Testing	• Move from testing at the device level toward more testing near the wafer level. • Validated tools to predict device performance from wafer tests. • Methodologies for design for test.
Reliability	• More knowledge of the physics of failure is required to develop accelerated life tests. • Need to share information. Individual solutions exist, but are not being generalized across the industry.

Table MEMS1. Summary of MEMS Difficult Challenges

Design and Simulation

Continuous improvement of simulation tools: MEMS devices are expected to see a continuous incremental improvement in performance metrics. The simulation tools must also continuously improve in their capacity to predict those performance improvements. This will require improved links between device and system simulation; more specifically, the integration of finite element modeling with electronic computer aided design (ECAD) tools. Fabrication process modeling should also advance so that material properties and process-induced surface characteristics and stress fields can be more accurately predicted from a process flow.

Design for testability: A critical challenge for MEMS devices is the cost of testing, which is already about one-third of the manufacturing cost and is continuing to rise, while the price of devices is expected to continue to drop. Furthermore, integrated 10 DOF multimode MEMS have no known solutions for testing. There has been a mantra in the MEMS community that designing a new device requires consideration of the package at the start of the process. Now, this mantra should expand to include the need for designing for test at the start. There are no formal algorithms to design MEMS for test, especially for integrated multimode MEMS sensors. The consensus opinion of the committee is that as much testing as possible should be moved upstream in the process. Design tools are needed to support this. There is also a call for "design for no test," where research could further enable techniques to design systems that are self-testing and self-calibrating.

Simulation tools for predicting packaged device performance from wafer-level testing: Manufacturers typically test their devices after they are fully assembled and packaged—referred to as device-level testing. An important piece of addressing testing challenges is moving as much of the testing as possible to the wafer level, simplifying and reducing the burden of testing at the end. This will require validated simulation tools and methodologies to predict the effects of assembly and packaging from wafer-level test data.

Reliability simulation: Accurate predictive models using information from the design and fabrication process are needed in order to predict and optimize the reliability of MEMS. These models may also prove useful in developing accelerated reliability test methods. Addressing this need requires research and the advancement of knowledge of the physics of failure, so that the models can be developed.

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Cost modeling for packaging and integration: Cost analysis is an important methodology for ensuring that future predictions of the price of a MEMS component are consistent with the resources and technology needed to deliver it to the marketplace. Currently, the methodology can be usefully employed to cost/price discrete MEMS devices and predict the production developments needed for the immediate future. Advancing predictive models of integration paths for MEMS could be useful for technology roadmapping over the long term.

Packaging and Integration

Cost reduction: MEMS devices are expected to see a continuous incremental improvement in performance while simultaneously requiring a reduction in package size and cost. The greatest challenges for discrete MEMS devices, with no known solutions, are in the latter: reduction in package size and cost. Advancement of assembly and packaging technologies and materials is required to meet these challenges.

Package standardization: MEMS technologies require some sort of packaging standardization so that costs can be lowered and the trend of a custom package for each MEMS device can be reversed. One suggestion, among many to consider, is a line of cavity-type packages starting at 3 x 3 mm and with 1 mm increments to 7 x 7 mm. Packages should include a data sheet with all parameters needed to accurately simulate the stress on the MEMS and predict the packaged device performance using wafer-level tests.

Package standardization of signal lines: As MEMS continue to advance in integration and functionalities of the ASIC, standardization of the signal lines and power handling will become increasingly desired. The pull for this is likely to come from the integrated multimode sensors and the advancement of the ASIC toward microcontrollers. RF MEMS also see a unique need for inductors integrated in the package with Q>50 and methods for minimizing interconnect length and loading.

Advancement of 3D packaging technologies (TSV): MEMS have 3D packaging requirements that surpass those for current ASICs and memories, especially with the regard to package-induced mechanical stress on device performance.

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Testing

Cost of test: The cost of testing continues to rise, yet the price of devices is expected to fall; this is not a sustainable situation. MEMS devices require not only electrical tests, but also need to be stimulated mechanically (i.e., shaken, rattled and rolled). These added requirements result in expensive handlers, which are the pieces of the automatic test equipment that provide stimulus and monitor responses of the devices. These handlers tend to be customized for each manufacturer. Standardizing the handlers and the test methods could lower costs considerably. The cost of testing is also influenced by the requirements for tests by the customer, which add expense but might not add any value. Standardizing tests on product performance, reliability and device data sheets can also significantly reduce the cost of testing.

Wafer-level testing: Testing of integrated 10 DOF multimode MEMS sensors has no known solutions, and it is not clear that solutions can be developed using the standard approach, which is to conduct the testing at the end of the manufacturing process (device-level testing). A possible solution could be to move as much of the testing as possible to the wafer level. This will require knowledge and predictive models of and/or the elimination of effects from assembly and packaging so that information from wafer-level testing can predict the final packaged device performance. The goal would be to make the final tests of the finished device a simple verification of the expected performance. Wafer-level testing should also be used to feed data forward in earlier stages in the process, including to the designer, to improve designs and product yields.

Design for test: This is also referred to as self-test/self-calibration. This topic is covered in the section on possible solutions for design and simulation. There is presently a lack of know-how for designing for testability and methods for self-test/self-calibration that can reduce the burden of test at the back end of manufacturing. Since design for test is very application-dependent, methodologies will need to be developed for each device technology.

Accelerated reliability test methods: There is a continuing need to extend knowledge of the physics of failure of MEMS devices. This is especially relevant for RF MEMS devices, where their adoption in many applications has been hindered due to reliability requirements. Extending knowledge of the physics of failure will enable methods to improve device reliability and to develop accelerated reliability test methods. Specific knowledge of reliability metrics and test methods resides in companies, but this information is not typically shared because it can be a commercial advantage to the company to keep it secret. Otherwise, the possible solution is to share the information that exists, evaluate gaps, and support R&D on developing knowledge for those areas that require it. Then this knowledge can be applied to the development of standardized accelerated reliability test methods.

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Update for 2012

The MEMS Technology Working Group focused this year on a complete rewrite of the iNEMI MEMS Chapter, which includes a new discussion on MEMS for consumer medical applications and proposes the idea of integration nodes as a path for MEMS sensor fusion modeled after the evolution of the IMU. The 2012 update to the MEMS technology roadmap leveraged this effort to update device performance metrics and a reorganization of the technology requirements tables.

Predicted cost metrics for devices have been dropped from the tables because of a variety of concerns from the manufacturers; instead, cost targets for testing are listed. The integration path for MEMS IMUs has been removed from the accelerometer and gyroscope tables and put into a new table. The integration path for IMUs has been accelerated by one year; the 9 DOF device integrated at the package level as well as the 6 DOF device integrated at the chip level were moved from 2013 to 2012. Finally, the RF MEMS tables have been combined into a single table.

Conclusion

The back end of MEMS manufacturing (packaging and testing) consumes two-thirds of the total manufacturing cost, yet virtually all R&D investment has been in the front end of manufacturing (device and process development). This unbalance can be attributed to a lack of articulation of the important problems at the back end.

The roadmapping efforts described in this report are the first steps in the long journey of communicating the industrial needs for MEMS technology to advance along its projected technology timeline. The development of a consensus opinion that documents the issues facing the industry, which is the primary output from technology roadmapping, can be used as a tool to optimize R&D investment that meets critical manufacturing needs in a timely manner.

About the Authors

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Michael Gaitan leads the Semiconductor and Dimensional Metrology Division's Microelectronics Device Integration Group at the National Institute of Standards and Technology (NIST). His group advances measurement science and standardization of test methods for MEMS device technologies. He chairs the iNEMI and ITRS MEMS Technology Working Groups.

Robert Tsai

Robert Tsai is the director of the MEMS program at TSMC, where he is spearheading the growth of the MEMS foundry business. Prior to joining TSMC, Tsai was a senior vice president and CTO of AOPC, a maskmaker for large TFT-LCD manufacturers in Taiwan. He has 30 years of experience in laser scanning, laser-related semiconductor processing and other cross-field electro-optical and MEMS technologies. He is Asian co-chair of the ITRS MEMS Technology Working Group.

Philippe Robert

Having worked in various positions in industry, Philippe Robert, Ph.D., is now manager of the MEMS Sensors group at CEA-Leti. He has authored or co-authored about 40 journal papers and conference contributions, and holds more than 40 patents dealing with MEMS and NEMS. He was member of the IEEE MEMS Technical Committee in 2007 and 2008. He is European co-chair of the ITRS MEMS Technology Working Group. ■

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