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Assembling the Future

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MEMS, Or System Design Is More Than Building An IC

Gabe Moretti

NOTICE: this issue of Assembling The Future is late because my thirteen years old niece was visiting from Italy. I had forgotten how much time a young teenager can absorb from an old man like me. We had a lot of fun, unfortunately at the expenses of my work, but her goal of getting even better at speaking English has been achieved. She is fluent in Italian, French, and English and in October she will start learning German. There are, of course, more languages in her future, including Chinese and Arabic.

If it sound like I am proud of her is because I am.

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Exploring a complete electronic product one can quickly realize how limited the concept of "System" really is in the EDA industry. In most cases my discussion with EDA vendors regarding system is limited to "Electronic systems" where the term "electronics" means the hardware component that is destined to be implemented on a silicon device.

Micro-Electro-Mechanical Systems, or MEMS, is a technology that in its most general form can be defined as miniaturized mechanical and electro-mechanical elements (i.e., devices and structures) that are made using the techniques of microfabrication. The critical physical dimensions of MEMS devices can vary from well below one micron on the lower end of the dimensional spectrum, all the way to several millimeters. Likewise, the types of MEMS devices can vary from relatively simple structures having no moving elements, to extremely complex electromechanical systems with multiple moving elements under the control of integrated microelectronics. The one main criterion of MEMS is that there are at least some elements having some sort of mechanical functionality whether or not these elements can move. The term used to define MEMS varies in different parts of the world. In the United States they are predominantly called MEMS, while in some other parts of the world they are called “Microsystems Technology” or “micromachined devices”.

While the functional elements of MEMS are miniaturized structures, sensors, actuators, and microelectronics, the most notable (and perhaps most interesting) elements are the microsensors and microactuators. Microsensors and microactuators are appropriately categorized as “transducers”, which are defined as devices that convert energy from one form to another. In the case of microsensors, the device typically converts a measured mechanical signal into an electrical signal.

Many experts have concluded that MEMS and nanotechnology are two different labels for what is essentially a technology encompassing highly miniaturized things that cannot be seen with the human eye. Whether or not MEMS and nanotechnology are one in the same, it is unquestioned that there are overwhelming mutual dependencies between these two technologies that will only increase in time. Perhaps what is most important are the common benefits afforded by these technologies, including: increased information capabilities; miniaturization of systems; new materials resulting from new science at miniature dimensional scales; and increased functionality and autonomy for systems.

The use of MEMS in electronic systems as varied as cell phones and planes has increased every year. The need for as tight integration as possible between these devices and electronics components is also increasing. Unfortunately the tools required to support such integration are few.

The article "New MEMS design ecosystem evolving to meet changing market demands" by Mike Jamiolkowski, CEO of Coventor, provides a good profile of the state of the MEMS industry and the integration with the rest of the electronic system.

The article "Integrating MEMS into the IC design flow" by Claudia Relyea and Khaled AbouZeid of Mentor Graphics describes a way to integrate MEMS design directly into existing CMOS design flow.

New MEMS design ecosystem evolving to meet changing market demands

Mike Jamiolkowski, CEO, Coventor, Inc.

The MEMS market is exploding as smart phones, tablets, games and other mobile devices swallow billions of components. Motion processing and location sensing technologies are central to the functionality of today's handheld products that most of us find indispensable. Indeed, the merging of sensing with computing power and communications is transforming the MEMS market. But if it is to meet consumer demand for the fastest growing products, the MEMS industry will need to see the design ecosystem supporting it evolve.

For starters, pure-play foundries will need to offer standardized MEMS processes and collaborate with fabless MEMS makers to meet fast time-to-market and high-volume demands. Next, the design flow will need to combine MEMS and traditional IC technology, bringing together MEMS and analog/mixed-signal design in a single toolset and design flow. To complete a new MEMS design ecosystem, designers will also need process design kits, MEMS IP libraries, and reference flows from foundries. In short, the changing MEMS market calls for nothing short of a new silicon and software ecosystem – much of it based on the fabless model familiar to IC design companies - to enable designers to turn out products for the cost-driven, high-volume consumer market.

MEMS industry outpacing semi industry growth

The MEMS market will continue to see double-digit growth for the next six years with 20% compound average annual growth rate in units and 13% growth in revenues to become a $21 billion market by 2017, reports Laurent Robin, Activity Leader, Inertial MEMS Devices and Technologies at Yole Development (Lyon, France). MEMS market analyst Yole expects motion sensing and microfluidics to make up almost half the overall market by 2017, with accelerometers, gyroscopes, magnetometers and combos making up about 25% market share and microfluidics 23%. Yole predicts the growth for inertial combo solutions to be huge.

The promise of the MEMS market goes far beyond today's growth as impressive as that is. The Hewlett-Packard project Central Nervous System of the Earth, appropriately dubbed CeNSE, will eventually include a trillion tiny sensors installed globally to collect data about the world around us. Ten years from now, reports Peter Hartwell, nanotechnology researcher at HP, the company will have a single sensor the size of a pushpin to measure sound, vibration and temperature. Built into this device will be a processor, storage, radio, battery and energy scavenging technology. To sense the vibration of a bridge structure, HP already has a new MEMS accelerometer that's 1,000 times more sensitive than devices used in airbags and game controllers. HP will first deploy CeNSE to help Shell drill for oil.

Moving beyond "one process, one product" and enabling MEMS+ design

Up until now, IDMs have dominated the MEMS industry. Their huge investments in proprietary processes plus long R&D and production cycles have led to the "one process, one product" adage descriptive of the MEMS industry. To move beyond these dedicated MEMS fabrication lines toward standardized MEMS processes, the industry can leverage excess available capacity in many 8 inch wafer fabs. They can also put to use equipment still needing to be amortized. Pure-play foundries, MEMS makers and design tool suppliers can work together to attain today's market goals. Such collaboration has paid off for fabless InvenSense which has experienced a 67% growth rate to $144 million after working in a familiar fabless model to bring to market its gyroscope and motion sensing MEMS.

Design and integration innovation will, of course, be central to fulfill the promise of the MEMS market. As MEMS makers increasingly integrate multiple sensors like the combo accelerometers/magnetometers and accelerometers/gyros that shipped in volume last year, they'll require new design software and methodologies. These software tools will simplify the integration of MEMS into larger systems and modules. Combining the two very different disciplines of multi-physics, MEMS-specific design with anaog/mixed-signal IC development will go a long way to accelerate design cycles. Although MEMS are almost always on the same substrate or in the same package as the electronics, the two components have been developed separately. The cost and lagging time-to-market of this ad-hoc approach is no longer viable.

Models that encompass the complex physical behavior of MEMS-based inertial devices, resonators, microphones, optical MEMS devices, etc. will replace the Spice and/or FEA-based models that MEMS specialists have hand-crafted in a build-and-test design approach. Non-MEMS specialists will be able to use these models without a steep learning curve, considerably speeding the design cycle. These models will simulate MEMS plus electronics, thus avoiding errors likely to occur with manual handoff of a design from MEMS to IC designers.

Integrating the design flow for MEMS designers and their analog/mixed-signal IC colleagues all the way through to tape-out is a major strategy of Coventor. At each stage of its design flow—through simulation, functional verification, layout, physical verification and parasitic extraction---MEMS and electronic designers can work with tools from Coventor and its partners in the electronic design worlds – such as Cadence and The MathWorks. At every level of design, simulation compresses the design cycle. What needs to fall into place now is for pure-play foundries to offer process design kits, MEMS IP libraries and reference flows for developers to use throughout the design flow.

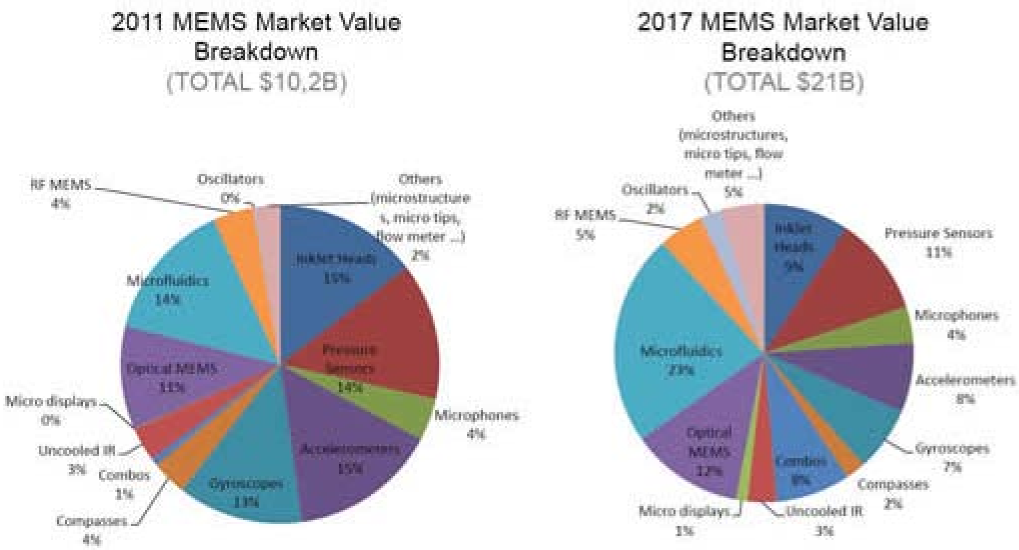
In the meantime, we can look forward to HP's CeNSE to "get at the heartbeat of the earth." CeNSE looks at the climate, shows how things are moving, where people are going and what they're doing. Its brainpower can be used to do something as simple as turn off the lights in a room where nobody is, reveals HP's Hartwell. We can also look forward to emerging MEMS-based personal medical devices that have already begun to be integrated or plugged into mobile devices. Wearable health monitors are also on the horizon. An ecosystem that unites the design of MEMS and ICs will accelerate time to market for these and other innovative MEMS products.

Integrating MEMS into the IC Design Flow

Claudia Relyea and Khaled AbouZeid, Mentor Graphics Corp.

Introduction

The Micro-Electro-Mechanical Systems (MEMS) market is experiencing unprecedented growth driven by high-volume consumer applications such as smart phones, tablets, digital cameras, automobile safety and control systems, and many others. While the highest volume today is in motion sensors, pressure sensors and inkjet heads, many other applications, such as RF, optical, and biomedical, are rapidly emerging.

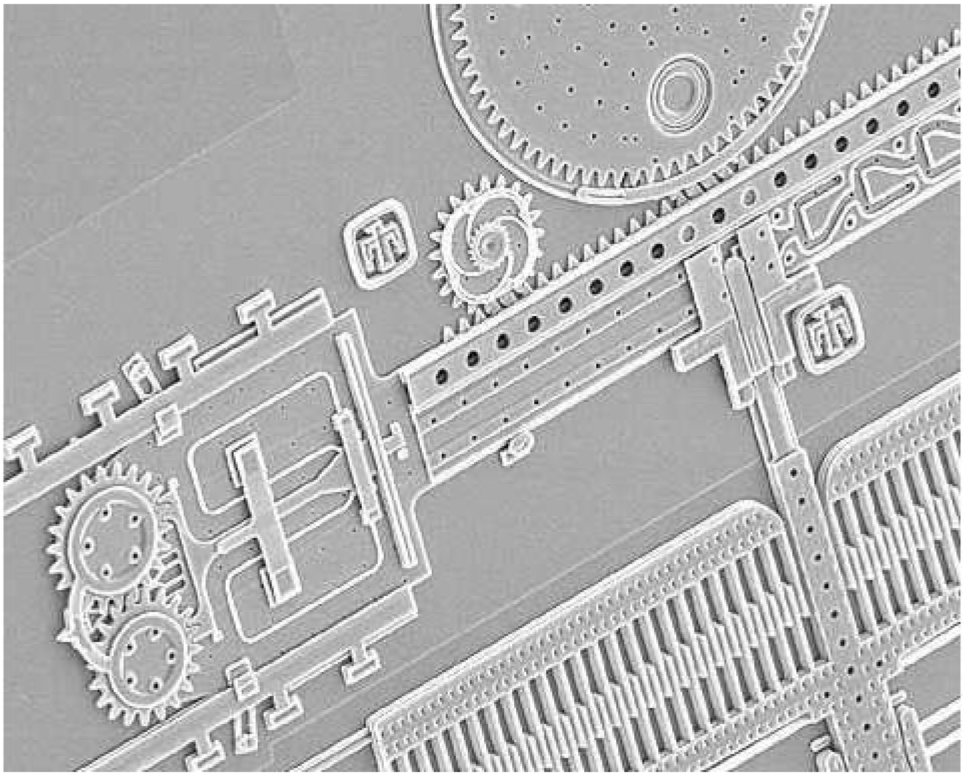


[Figure 1. The MEMS market continues to grow as new innovations and applications emerge. Source: Yole Development]

As MEMS moves from early adopters to mainstream, the technology is facing increasing market pressure to shorten development time, while simultaneously reducing cost and meeting performance and reliability requirements. MEMS is essentially a variation of the technology used to design and manufacture traditional ICs, and so the world is moving toward physical integration of MEMS into the high-volume CMOS IC manufacturing process, whether in a form of monolithic integration, or hybrid integration based on 3D-IC packaging technology. Consequently, one of the best opportunities to reduce development time is to incorporate MEMS design directly into the existing CMOS design flow that has worked so well to drive Moore's Law over many generations of IC technology.

A Tool Flow for Back-end MEMS-IC Co-Design

What would an integrated MEMS/IC design flow look like? Let's look at the basic elements of the flow, beginning with the physical layout. Of course, the best place to start any design is a library of existing proven components. A MEMS library includes parameterized primitives at the physical level that are fabrication-ready, such as beams, plates, springs, or even complete comb drives. Users select a primitive from the library and define parameters, such as length, radius, thickness, etc., to instantiate a particular component in the design layout.



[Figure 2. Each of the basic elements of this electromechanical lock could be stored in a MEMS library to enable rapid reuse and design variations. Source: Sandia National Laboratories.]

Obviously designers need a drawing tool that provides a graphical user interface for instantiating library primitives, creating new blocks, connecting components, and adding unique, application-specific structures and modifications. A layout view shows the resulting MEMS design and generates 3D views, while the library supplies the relevant material properties, such as mechanical, electrical, thermal and other properties, needed for subsequent simulations.

Once a design prototype is created, it can be fed to a process simulation tool, which models how the device will be manufactured using a specified manufacturing recipe (i.e., the process steps and characteristics specific to the target foundry and manufacturing line). This is similar to IC litho checking tools that predict how the shapes in an IC mask will be rendered on the silicon wafer. MEMS process simulation tools can refine the device behavioral models and identify design errors before test fabrication, saving overall design cycle time. Finally, designers often need to perform simulations of the MEMS devices using multi-physics simulators, which conduct simultaneous simulations of the device in different domains (e.g., mechanical and electrical domains).

MEMS productivity tools can include automatic layout generation tools, which take abstract MEMS system descriptions and generate detailed multi-component physical layouts, and a macro model generator, which converts detailed physical verification results into compact models for later analysis and system level verification.

The MEMS-IC Data Challenge

The above overview highlights the data interface issues in today's MEMs flow. MEMS devices typically exist in an electromechanical environment, that is, they are driven by, or provide input to an electrical circuit. For example, the simulation and verification of a MEMS actuator is dependent on the electrical input signal as well as the materials properties and mechanical dimensions. Combining mechanical and electrical elements on a die brings together new tool domains, so it's not surprising that the vendors of EDA and mechanical CAD tools face some data integration challenges.

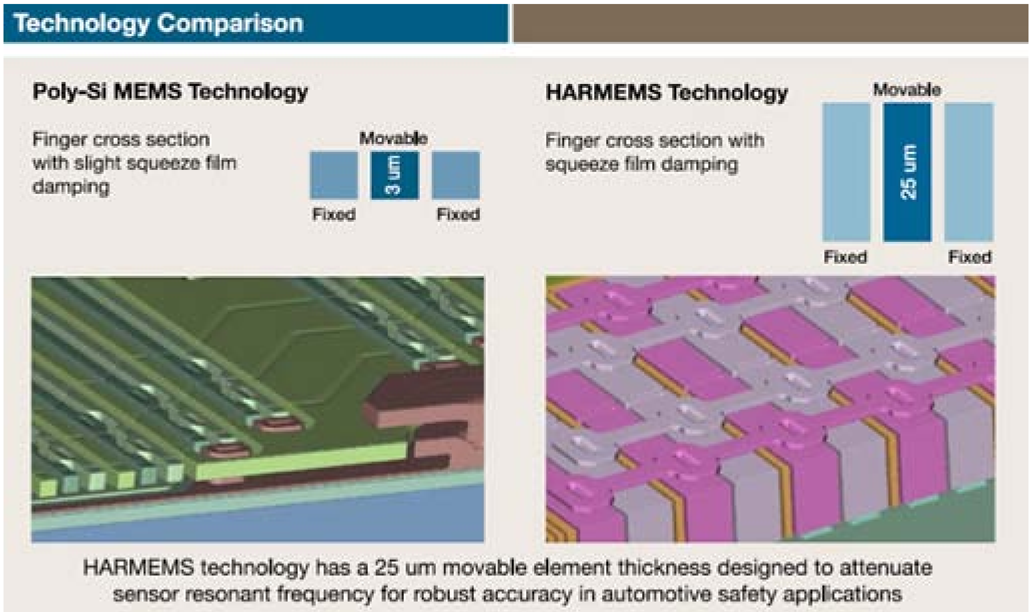
While we expect vendors to continue development within their own areas of expertise, and designers to remain specialized along mechanical and electrical disciplines, vendor collaboration and tool interoperability can enable a seamless environment in the critical areas where design teams must verify electromechanical interactions, and correct overall system behavior. Some of the most critical needs are interfaces between various types of layout tools (e.g., mechanical layout/CAD tools and IC circuit layout tools) to be able to share and integrate physical design data. Designers also need interfaces from the layout tools and libraries to multi-physics simulators and to electrical field solvers to validate electrical behavior.

Required Extensions to IC Tools

Once a layout is created, the design must be verified in a manner analogous to traditional IC designs. It must be checked to ensure that it meets all foundry design rules for manufacturing (DRC tool). The electrical portion must be checked to ensure that the physical layout accurately reflects the schematic description (LVS tool). Finally, extraction tools convert the layout specifications into electrical parameters that are fed back into simulation tools to verify that the design will function as intended, both in terms of functionality and performance. Here is where various parasitic effects (i.e., variances between the ideal and actual manufactured product) are accounted for. To illustrate some of the modifications that the standard IC tools will require to handle MEMS structures, let's take a closer look at the extraction step, since this is where the difference between MEMS and IC physical designs has a significant impact on tooling.

High Aspect Ratios

MEMS devices use different types of processing than integrated circuits to achieve the required physical dimensions. These techniques, such as surface micromachining, bulk micromachining, and molding processes, result in much higher aspect ratios than is typical for traditional devices (transistors). To address stiction (static friction that needs to be overcome to enable relative motion of stationary objects in contact) or adhesion problems, stacked layers can have very thin layers on top of very thick layers, or thin layers sandwiched between two thick layers, making extraction more difficult.



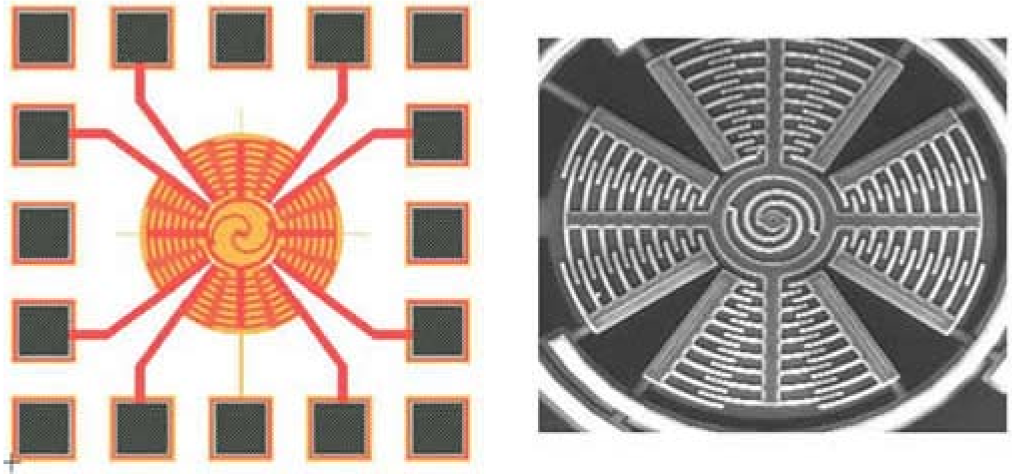
[Figure 3. IC designs tend to be regular, planar and relatively flat (low aspect ratio). MEMS devices, on the other hand, have more irregular topologies, varying stack thicknesses, and potentially much higher aspect rations. Combining these two types of elements on a wafer can raise new challenges for EDA tools.] Source: www.low-powerdesign.com/article_mems_032711.html

This is because traditional IC electrical extraction tools are based on calibrated capacitance models optimized for regular CMOS processes that are planar with relatively thin conductor layers, and hence very low aspect ratios. Because they're rule based, they're fast, but unfortunately they don't work well for the MEMS electrical interface. This is because the calibration process requires detailed curve-fitting analysis to optimize rule decks that were not designed with MEMS in mind.

The most flexible and accurate way to solve this problem is to use an extraction tool that is not dependent on calibration at all, but rather computes values based on the detailed underlying physics. Such a tool is called a field solver, since it directly computes the solution to Maxwell's Equation. Certain field solvers have been used for MEMS mechanical analysis and process characterization, and for calibrating rule-based IC extraction tools, but they were too slow for full chip extraction of a large device mixing an array of MEMS components and a complex IC circuit. However, a new generation of tools has been able to deliver both accuracy and speed, and is well suited for MEMS electromechanical design extraction going forward.

Complex Geometries

If you've ever looked at a magnified IC mask, perhaps you've noticed that the layout is extremely regular in the sense that all the lines and shapes are rectangular and at right angles to each other. The so-called "Manhattan" layout is a constraint and simplification that makes it easier to route and analyze IC designs. Unfortunately, the Manhattan constraint cannot be applied to MEMS devices, which have lots of curves and non-orthogonal angles (see Figure 4). Going from rectilinear to curved shapes is like stepping up from high school geometry to 3D calculus—the computations are much more difficult.



[Figure 4. Unlike IC layouts, which are rectilinear (Manhattan topology), MEMS devices have many curves and non-orthogonal angles. This makes the extraction task much more difficult. Newer field solver extraction tools, such as Mentor's Calibre xACT 3D, are key to addressing large, complex mixed MEMS-IC designs.] Source: http://jasonscarlett.com/_ucalgary/Gyro_Web/4.3.htm

As discussed above, traditional production extraction tools are rule based, so they take advantage of rectilinear simplifications in their models. Some can approximate rounded edges and 45 degree angles with sets of polygons with multiple vertices, i.e., stair-steps, but most don't and even the ones that do are not very accurate.

To improve accuracy, special mathematical approaches, such as complex fracturing, are needed. Field solvers already have these kinds of capabilities as a consequence of solving Maxwell's Equation, which is a multi-dimensional differential equation. Advanced field solvers apply a mesh to the design to deal with non-rectilinear shapes. The meshing scheme must be adaptive, that is, it must become denser where needed to maintain the best balance between speed and accuracy.

For very small designs, a designer might use a slow (but accurate) field solver extraction tool for the individual MEMS component, and a fast IC extraction tool for the drive circuit and interconnects, and then try to put the results together. This becomes too tedious and time consuming in a large electromechanical chip design. Using a high-performance field solver, either alone or in a hybrid integrated solution with a rule-based tool, allows the user to extract both the MEMS component and the interfacing IC design together with sufficient flexibility and accuracy to drive a very accurate system simulation. For example, MEMS motion sensors are custom designs characterized by very complex geometries: both wide and narrow wires with non-90 degree edges, large plates, holes, etc. These sensors need to be integrated with the ASICs that interact with them.

As such systems grow in complexity, having tools that span the requirements of both MEMS and IC domains will become more important for dealing with inherent complexity and reducing time to market. CAD/EDA vendors need to work on building the bridges between the MEMS layout tools and libraries, the IC layout tools and libraries, and the full-chip extraction tools to enable this to happen.

Conclusions

The worlds of multi-discipline systems and electronics are coming together on the silicon wafer. As the MEMS market has been developing, the designs were exploratory and small in scale. With the expected explosive growth in applications, we will see a corresponding growth in scale and complexity of designs, and increasing demand for on-chip integration.

Design automation tools for MEMS and IC development will need to expand and merge to provide design teams with the kinds of productivity and interoperability they demand to meet ever-present competitive forces.