

# WIRELESS INTEGRATED MICRO SYSTEMS (WIMS): PAST, PRESENT, FUTURE

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## ABSTRACT

Wireless integrated microsystems (WIMS), also referred to with many names such as IoT/IoE, sensor nodes/motes, or smart nodes, represent portable and stand-alone devices that contain sensors, actuators, signal processing electronics, communication electronics, packaging, and power sources. During the past few years they have become an instrumental part of extending the microelectronics revolution that started many decades ago with the advent of integrated circuits. This paper reviews the past achievements in sensors/actuators, low-power electronics, wireless interfaces, packaging, and provides a perspective on the future trends in both technology and applications for these sensing microsystems and high-performance micro-instruments.

## INTRODUCTION

Wireless integrated microsystems (WIMS), also referred to with many names such as IoT/IoE, sensor nodes/motes, or smart nodes, represent portable and stand-alone devices that contain sensors, actuators, signal processing electronics, communication electronics, packaging, and power sources. During the past few years they have become an integral part of many emerging applications and are considered instrumental in achieving the ultimate goal of connecting the world through sensors that can continuously monitor the world around us.

Work on multi-sensor micro-instrumentation systems combining sensors and electronics and wireless interfaces started at Michigan in the early 1990s and led to the demonstration of some of the earliest miniature, low-power, wireless sensor modules [1,2]. The WIMS Center was launched in 2000 at the University of Michigan with funding from the US National Science Foundation to conduct basic research and development of all the critical components of microsystems in areas of sensors/actuators, low-power circuits for signal processing, innovative technologies including RF MEMS for low-power wireless links, new hermetic/vacuum packaging techniques, and active and passive power sources and energy harvesting from the environment [3]. During the past two decades, impressive progress has been made in all these areas. MEMS sensors now provide unprecedented performance at low cost, with performance improvements expected to continue. Extremely low-power circuits for sensor interfaces and signal processing have been demonstrated with nano-watt power levels [4]. New approaches to developing next-generation low-power wireless links based on RF MEMS and low-power micromechanical resonators and circuit techniques have been developed [5-7]. Hermetic and vacuum packaging techniques for MEMS and microsystems have been demonstrated for a number of different microsystems [8]. Low-power sensors from pressure sensors to accelerometers are now available at low-cost and have found many applications. What made this tremendous progress possible, and should we expect this progress to continue? Are there obstacles, and if so what are they? What will be the future trends and applications? This paper will provide a historical perspective of the development of sensors and actuators and their performance trends, fabrication technologies, interface circuits and packaging technologies.

## WIRELESS SENSING MICROSYSTEMS

### Architecture

Wireless integrated microsystems (WIMS) represent devices that contain sensors, actuators, signal processing electronics, communication electronics, packaging, and power sources, as illustrated in Figure 1 [1,9,10]. Significant progress has been made in each of these areas, and ongoing research promises to produce further significant improvements in each of these areas. It is worth reviewing past and recent progress and discussing future trends in each of these areas.

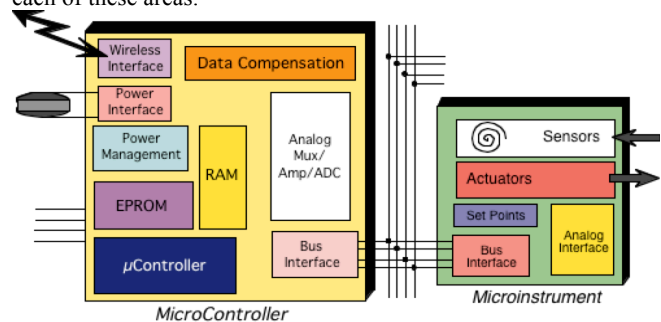


Figure 1: Architecture of a typical sensing microsystem, consisting of front-end sensors/actuators, interface electronics, micro-controller for signal and data processing, a low-power wireless interface, appropriate power source, and packaging suitable for the intended environment (not shown) [1,9,10].

### Sensors

Progress in all areas of sensor design, materials, integration, and fabrication technologies has been impressive. MEMS sensors started on the back of silicon-based integrated circuits technologies and have seen the same level of progress in microelectronics.

### Performance:

Sensor performance is measured in terms of its resolution (noise) and stability (drift). These and many other performance parameters have seen incredible improvement over time, often much better than those of integrated circuits (IC) as best described by Moore's law. Pressure sensors, inertial sensors, flow sensors, and fluidic components, and many others have improved by more 1.5x per year. An example that the Michigan group has tracked for many years is the performance of inertial sensors [11]. A graph showing performance improvement of MEMS gyroscope was reported in 1998 by the author [11], which illustrated performance improvement of 2x over a period of 10 years up to that time. An updated graph showing an impressive improvement of 1.6x/year over a period of 30 years is shown in Figure 2. The noise in these sensors has improved by a factor of almost 1 million over this period! Although we are approaching the fundamental noise level, further improvements are expected, as our understanding of material properties, device structure and modeling, and circuit readout techniques continue to improve and expand. This continuous improvement is indeed one of the greatest accomplishments of the MEMS and sensor community.

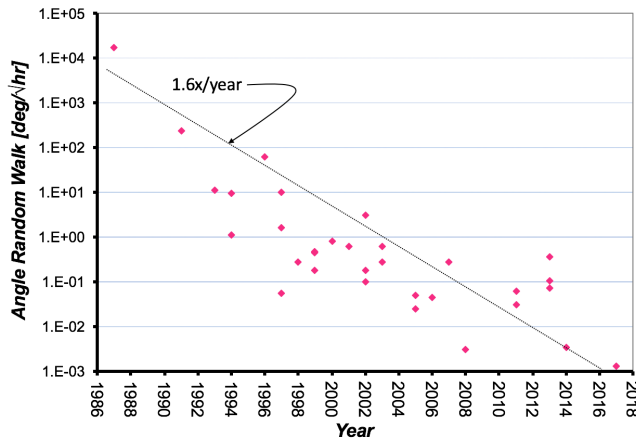


Figure 2: MEMS inertial sensors, such as gyroscopes, have demonstrated at least a factor of 1.6x improvement in their noise over a period of almost 30 years [11].

#### Materials:

Single-crystal silicon was, and continues to be, the material of choice for MEMS sensors. It is perhaps the best material providing excellent mechanical, thermal, and electronic properties as discussed by Petersen in his seminal paper [12]. Polycrystalline and epi-Si films paved the way for the commercialization of many sensor devices such as accelerometers. Silicon film properties and thickness can now be routinely controlled and reproduced. Other materials such as piezoelectrics (AlN, PZT, ZnO), metals, dielectrics, and polymers are also now routinely utilized in the production of many MEMS components despite early doubts that these materials could be reproducibly utilized in a production environment. Other materials are also finding their way into MEMS devices, including fused-silica [13] and GaN. Although compatibility, ease of deposition, stability, and cost will continue to be issues of concern for these and other new materials, past experience and the need for extending microelectronics beyond the limits of Moore's law clearly indicate that future microsystems will utilize many more materials to realize new functions, improve performance per function, and reduce cost.

#### Integrate or Not Integrate:

In the early days of MEMS and sensor development, the MEMS community debated whether future commercial sensors needed to monolithically incorporate interface electronics on the sensor chip to further improve performance. Some thought that due to the small sensor signal, and as sensors reduced in size, circuit integration was necessary. Often it was argued that the cost of manufacturing a hybrid system of sensor and circuit chips would be prohibitive. It is clear now that monolithic integration, although preferred, has not been an absolute necessity for either performance or cost. Indeed, this issue has been put to rest for many years with the commercialization of multi-axis inertial sensors, the majority of which are not monolithically integrated. A hybrid system of two separate sensor and circuit chips has been made possible by several factors, including new sensor designs, improved manufacturing techniques, improved readout circuit techniques and technologies, and improved testing and self-calibration approaches.

Heterogeneous integration of silicon ICs with a variety of materials to develop new classes of sensors and microsystems has already started and will certainly continue. These microsystems will advance the state-of-the-art and will help extend

microelectronics into many new applications at very low cost and extremely low power.

#### Three-Dimensional (3D) and Thick Structures:

Early MEMS sensors utilized the entire thickness of a silicon wafer, around 500 $\mu$ m using bulk micromachining [12]. The challenges posed by wet etching techniques limited the range of shapes and dimensions, and led researchers to utilize thin-film polycrystalline silicon on top of a silicon wafer to produce the microstructures needed for a given MEMS function. Polysilicon surface micromachining was indeed a significant advance that liberated the MEMS designer from the limits posed by the crystalline silicon properties and led to the commercialization of the first inertial sensors. However, the limited thickness of polysilicon introduced many other challenges, including limited sensor performance, higher noise, and lower signal. However, these limitations have been largely overcome with the use of SOI and deep RIE etching (DRIE). Figure 3 illustrates the progression of sensor materials used for building truly three-dimensional (3D) silicon MEMS [14]. DRIE silicon etching developed by Laermer and Urban has been an immense capability that had not been imagined until it was introduced in the early 1990 [14]. It has indeed changed the landscape of MEMS, and its impact on MEMS and the IC industry has been impressive. Silicon structures never before imaginable can now be routinely fabricated. This technology has been improved and ultra-deep RIE (UDRIE) is now capable of etching ultra-thick silicon structures with a thickness of 1mm [16]. It is worth noting that by the late 1980s the LIGA process was also introduced and used polymer molds and thick metal electroplating to produce truly 3D and thick MEMS structures [17]. This technology has been widely used to produce many sensor and actuator parts and components.

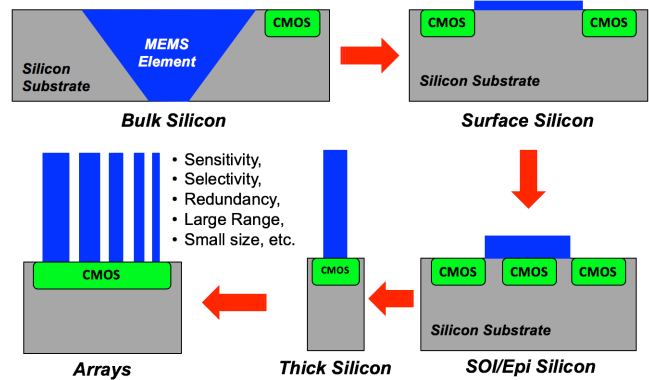


Figure 3: Evolution of silicon MEMS sensors and actuators, from bulk silicon, to thin-film polysilicon, medium thickness SOI silicon, and to very thick DRIE etched bulk silicon [14].

Beyond these wafer-level processes, the MEMS community has also seen impressive growth of a variety of precision mechanical machining techniques, utilizing a variety of approaches such as laser machining, micro electro-discharge machining ( $\mu$ EDM), and ultrasonic machining (USM) [17]. One recent technique used by the author for forming 3D structures from fused-silica is the very old technology of glass blow torching [13]. Extremely high-quality and smooth fused-silica 3D wine-glass resonant structures are fabricated and demonstrated a high quality-factor of almost 10 million [19]. Figure 4 shows the photograph of two fused-silica birdbath resonators with diameters of 2.5 and 5mm, and a thickness in the range of 10-80  $\mu$ m. Such elegant structures will become more commonplace in the MEMS industry, despite their unconventional materials and fabrication technology.

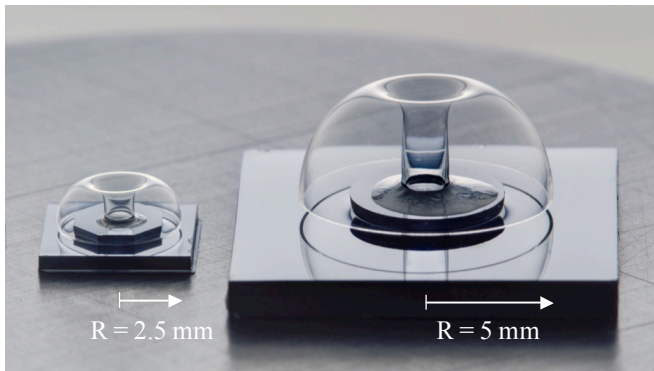


Figure 4: 3D Fused silica micro resonators for use in high-performance gyroscopes fabricated using blow torching [19].

### Interface and Signal Processing Electronics

MEMS and microsystems progress would not have been achieved at this level with such speed without the tremendous advancements in integrated electronics. One of the main motivations of developing silicon-based sensors was the potential of interfacing them with electronics. Electronics provide important functions of amplification, filtering, multiplexing, and processing of the acquired data. The IC community has not only realized the predictions provided through Moore's law in terms of density and cost, it has also improved performance. CMOS ICs can achieve low noise, high-speed, and low-power. One of the goals of our program at Michigan from the early days was to demonstrate that future wireless sensor nodes can perform many functions at extremely low power. Millimeter-scale sensor nodes can now provide significant functionality at nano-watt power levels [4,20]. This trend of extremely low-power electronics will continue in the future. There have been several programs aimed at taking advantage of the convergence of extremely high-performance sensors and low-power electronics to develop sensor nodes with near-zero power dissipation, thus enabling continuous sensing and monitoring of specific signals [21].

### Wireless Interfaces

RF communication and wireless interfaces have also seen tremendous progress in the past two decades, primarily driven by the mobile phone industry. A variety of protocols from Bluetooth to Zigbee and others have been developed for some sensing applications. For these applications limited range is needed, but power dissipation is critical and needs to be as low as possible. One of the early motivations of RF MEMS was the potential of developing extremely low-power radios by utilizing the high quality mechanical resonance characteristics of micromachined resonators, which are superior to their electronic counterparts by orders of magnitude. The  $fxQ$  product for MEMS resonators has continued to improve [5], and nowadays MEMS resonators are used in commercial applications, primarily as timing units, and increasingly in other communication functions [22]. The high  $Q$  is a clear advantage for reducing power dissipation. Several different versions of RF MEMS devices have been utilized in the zero-power sensor devices reported by several groups [21]. Extremely low-power radios have been developed for sensor nodes. Nanowatt transceivers with reasonable range have been demonstrated by several groups, including Wentzloff's at Michigan [23]. Figure 6 shows the tradeoff between power and sensitivity. Radios with nano-watt power dissipation and reasonable sensitivity have been demonstrated and are made practical through circuit techniques, IC technologies, use of MEMS timing units, and improved antenna designs.

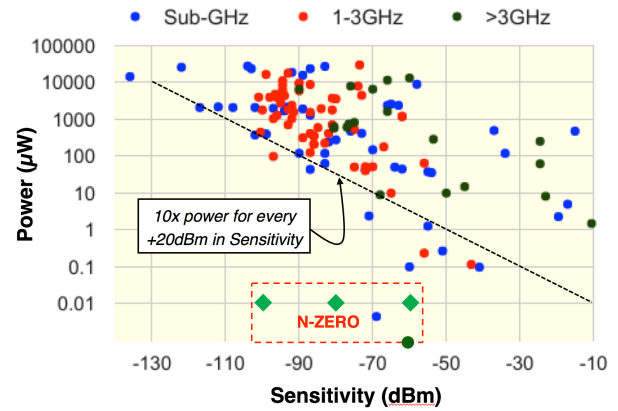


Figure 5: Power dissipation and sensitivity of wireless links [23].

### Packaging

Packaging and assembly techniques for MEMS and microsystems have been developed for some applications and being developed for others. There are several key technological challenges in packaging of microsystems. These can be categorized under three general topics of: transducer encapsulation (protection), connection, and assembly as illustrated in Figure 6. MEMS require direct interaction with their surrounding environment. As a result, the device cannot be physically isolated from the surrounding environment and selective access needs to be provided to the sensing/actuating part of the MEMS device. This creates a significant problem for the package. As a result, a lot of effort has been expended on developing the proper protection/encapsulation medium for MEMS. Two general approaches have been taken: the first depends on a package in the form of a shell or capsule that can be bonded to the device substrate as shown in Figure 6; and the second relies on using a thin film material that protects the regions that need protection, while providing access to those that need to interact with the external environment. In either case, the package has to satisfy certain requirements, such as hermeticity, vacuum encapsulation for some applications, ability to provide interconnections to the rest of the system, and ability to protect against harsh environment conditions such as shock, vibration and temperature. Great progress has been made in wafer-level packaging, in sealed feedthroughs and interconnections, and in selective encapsulation. Two challenging areas of stable vacuum packaging and protection against harsh environmental conditions remain. A stable vacuum environment is needed for many devices such as inertial sensors and although a variety of techniques have been demonstrated in research, more work is needed for low-cost vacuum packaging of commercial devices.

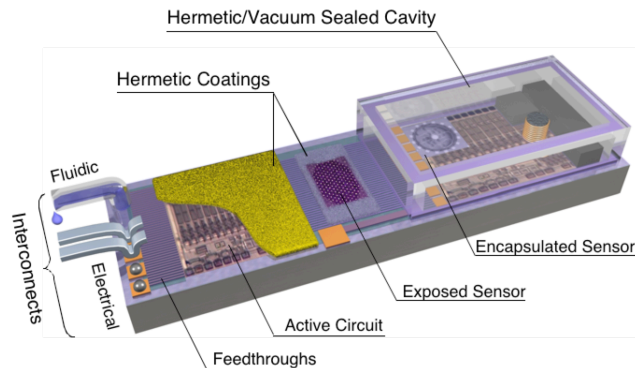


Figure 6: Packaging needs of MEMS/microsystems [8].

## FUTURE TRENDS AND CONCLUSIONS

Wireless integrated microsystems (WIMS) have become pervasive in many applications, and will continue to transform many applications ranging from healthcare to environmental monitoring and homeland security. They will help extend connectivity between personal communication devices and the internet to connectivity between us and the environment directly. MEMS sensors provide excellent performance, and undoubtedly sensors and micro-instruments with better performance will be developed and incorporated into more personal electronic devices from cell phones to wearables to home monitoring systems. The improved performance and enhanced functionality will be made possible through ongoing research on improved understanding of and controlling material properties, heterogeneous integration of sensing with electronics, utilization of integrated and distributed arrays of sensors, and improved design and modeling. Arrays of sensors, integrated on one substrate or distributed over a large area, will be utilized to expand functionality, performance, and stability. Sensing nodes will expand beyond just data gathering and signal processing to information processing and decision making by using machine learning techniques. These techniques can be utilized to generate very accurate information through the use of thousands or millions of medium performance sensors (now routinely available in cell phones and wearables) distributed over a large area. Precision, portable, and low-cost micro-instruments for monitoring chemical, biological, radiological, and physical parameters with performance paralleling bench-top instruments will certainly become available and cost-effective. These chip-scale micro-instruments (CSI) will make enable more applications and will further change the way we interact with our own bodies, the environment around us, and the tools and systems we use to augment many human functions. Past history has taught us that prediction of the future is unreliable. What is certain is that if there is a “pain”, researchers and innovators will find an affordable technological remedy. This has been true for MEMS and microsystems. When two decades ago many said that MEMS could not be manufactured and deliver the needed performance, today we have commercial sensors that perform much better than anticipated, and available at much lower cost than predicted. *Smart minds always find smart and simple solutions!*

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