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STANDARDS, OR LACK THEREOF

Chapter Leaders

Arturo Ayon
Sony Semiconductor
arturo_ayon@ssa-sa.sel.sony.com

Joe Brown
Karl Suss America, Inc.
jbrown@suss.com

Scott Bryant
International Technology & Trade Ventures
sbryant@ittventures.com

Janusz Bryzek
Transparent Networks, Inc.
jbryzek@sinewave.com

Job Elders
C2V
Job.Elders@C2V.nl

Andrew McQuarrie
Surface Technology Systems
100655.737@Compuserve.com

Christian Schaefer
EV Group
c.schaefer@EVGroup.at

Steven T. Walsh
University of New Mexico
Walsh@unm.edu

Executive Summary

Where are standards in the emerging MEMS/microsystems marketplace? As more companies seek to base their value proposition around MEMS/MST, standardization plays an increasingly important role in the further emergence of the microsystems industry. Therefore, the crux of the problem with the standardization process in microsystems today is not that participants do not agree that standardization may be necessary and, on the whole, beneficial. Rather, due to diverse market applications and process technologies, not every segment is ready for them.

For example, many of the IC-like processes (see chapter on IC manufacturing) have piggybacked on the long history of semiconductor micro fabrication. These manufacturers and suppliers are more accustomed to standards and have already adopted some of the SEMI Industry standards. Other processes, most notably non-IC-like manufacturing, do not benefit from such a history. Therefore, non-IC-like and IC-like MEMS manufacturing technologies are at different stages on this continuum.

Most IC-like manufacturing processes were at stage 1 (basic research) in the 1960s, 1970s, and even in the 1980s as the chart below suggests. Many of these processes progressed to stage 2, or a state of industrial manufacturing, in the 1980s and 1990s. Many people believe that some of the IC-like processes are now in stage 3 or perhaps even stage 4, or the initiation of robust infrastructure. Most non-IC-related technologies trail IC-related technologies by at least 10 years on this chart, making IC related technologies the most fertile ground for standards efforts at the process level.

The contributors to this chapter present the status of relevant MEMS standards and the direction they are likely to proceed. Each specific MEMS market segment or application area has its own particular requirements. Yet, the contributors feel that many of the process steps—especially IC-like silicon processes—are at the point where standards can play an important role for further commercialization, and many of the suppliers, manufacturers, and users are discussing them seriously. The process of standards development for microsystems is emerging, but mainly focused on the IC-based silicon substrate portion of MEMS at this time.

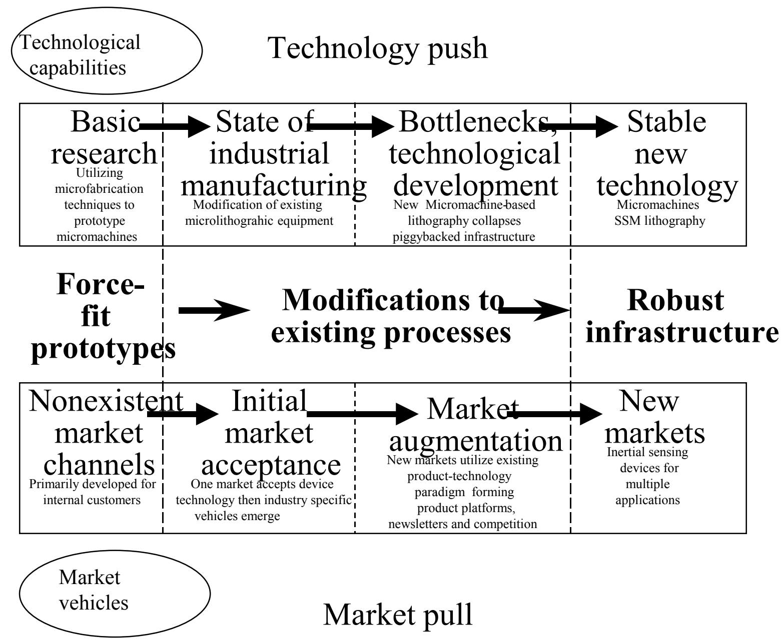

Figure ES-1. Technology Push versus Market Pull Commercialization.

There are two camps of thought regarding standards. Many within the industry feel that the premature institution of standards will hinder, rather than help, the commercialization process of MEMS technologies. Yet, the advent of a large number of MEMS-focused foundries and the many years of process knowledge behind the MUMPS and SUMMIT processes, along with captive manufacturing facilities, such as Independent Devices Manufactures (IDMs), suggest that the time for standards in IC-like processes is nearing. This group feels that the industry cannot reach its broad-based application potential until some standards are set.

Yet other firms, both large and small, see standard-setting as something more beneficial to other segments of the industry value chain, rather than their own. They argue that standards require them to prematurely share IP that was hard-won, and that standard-setting at this time will stifle creativity. Both camps seek growth and broad-based diffusion, but predict different futures over the near-term.

If there is such a division about the standards issue, where is much of the push for standards coming from? It's coming mainly from the systems integrators (users). In short, systems integrators in any industrial setting are a huge driving force behind the evolution of standards. Yet, despite the best efforts of various international organizations to create such standard-setting conditions (IME, 2001), they do not now extensively exist, even though many of the initiatives and organizations have been pursuing standards since 1993.

This chapter details the activities and organizations centered on the question of systems standardization. These include the European Committee for Electrotechnical Standardization, the German Institute for Standardization, the Institute of Electrical and Electronics Engineers, the Japanese Micromachine Center (JMMC) initiative on standardization, the Presidential Advisory Committee on Technologies (PACT) under the auspices of the International Electrotechnical Commission (IEC), as well as European Union and American initiatives on MEMS standardization by government and professional bodies, such as the National Institute for Standards and Technology (NIST), and Europractice or NEXUS. These efforts center on establishing a standard language (glossary), an inventory of existing processes, and suggestions regarding interconnecting various microsystem technologies and their interactions with the environment, as well as testing. There are also movements centered on creating preferred specifications of device sizes, element sizes, interconnect technologies, and electrical operating parameters. Currently, all of these activities are driven by the companies involved in the process and by government agencies.

The contributors also briefly present areas that appear ripe for future development, as well as offer a consensus opinion on a likely timeline for the development of standards within the MEMS industry. Further, the chapter discusses some of the bottlenecks to standardization and offers suggestions for overcoming these bottlenecks.

1.0 Introduction

Standards provide a method for communicating agreed-upon technical norms across an industry. It can also be considered a form of technology transfer. The directions of standards for MEMS systems in this chapter can be captured in the following diagram (modified from Cook, 1998):

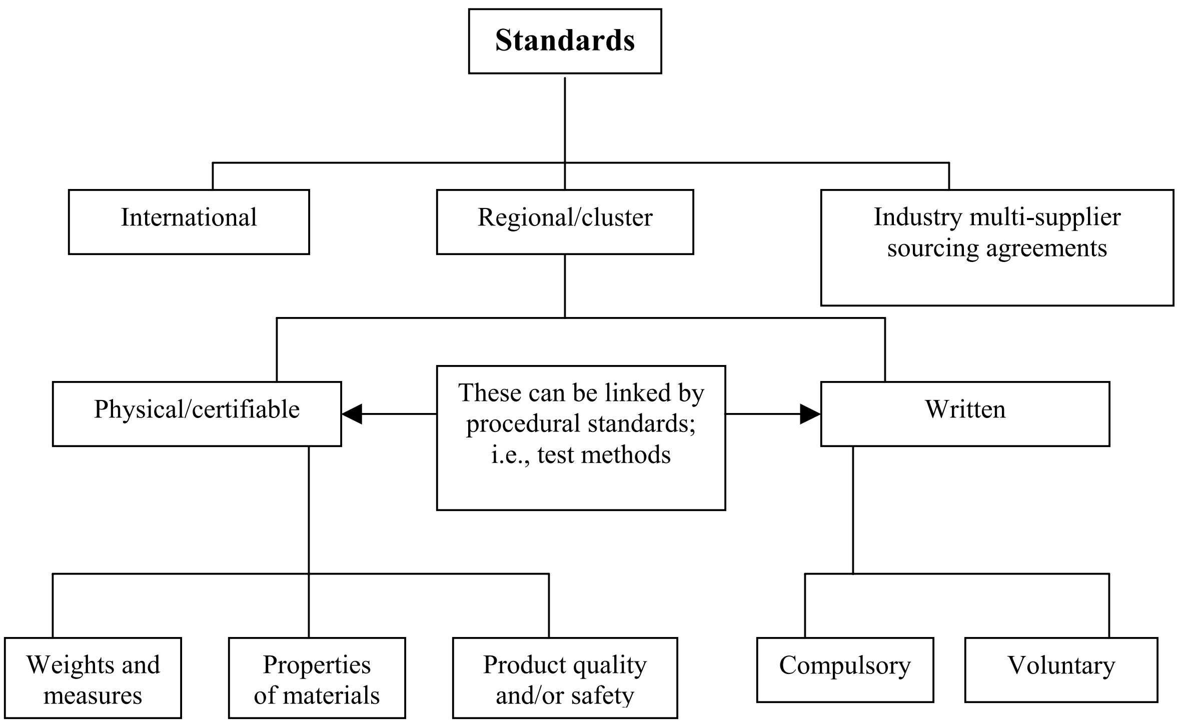

Figure 1. Direction of MEMS Standards.

The process of standards development for MEMS remains in its infancy. Microsystem technologies as a whole are in an "Era of Ferment," meaning it is a time when few, if any, dominant designs, dominant processes, or dominant packaging methodologies have emerged (Anderson & Tushman, 1990). To that end, an earlier conclusion, by industry experts arguing that competing manufacturing technologies, differing design modalities, and seemingly infinite packaging techniques have inherently limited the path to standardization in MEMS-based industries, (Bryzek, 1996) continues to hold true.

This is not to say, however, that there are not defined processes and process steps. Companies like Karl Suss and EV Group, for example, have built flexible tool sets around a subset of highly defined wafer bonding steps, while other suppliers, such as STS, have brought deep reactive ion-etching processes to a competency level bordering on standardization. This underpins the fact that the industry is still experiencing great variance in the depth, length, and duration of processes. So while the overall processes continue to differ widely, the process steps are often very well defined.

The discussion above highlights the difference between the standardization of process steps emphasizing equipment and the standardization of fabrication processes. As we have highlighted in the Executive Summary, some are near term, while others remain farther off and are being addressed by initiatives such as SEMI's Integrated Project. Many firms have developed in–house methods suitable for specific requirements, but unfortunately—as we highlight in the Foundry and Commercialization chapters—these are not currently transferable throughout the industry. This has the effect of making standards applicable to a subset (such as telecommunications or automobiles), rather than the whole emergent industry.

Materials play an important role in microsystems. Yet few, other than silicon, have any real standards. Some alumina and germanium substrates have standards, but plastics and extruded materials at this point do not. Further, new materials are de facto void of any but the commercializing firm's standard.

Standards are generally driven by the needs of high-volume applications. Because microsystem technologies are relatively young, there are few commercial devices. The majority of these are based on silicon micromachining. The MEMS industry has no identified broad-based, multi-market need to generate the volumes necessary to span the potential myriad of market and application areas possible for microsystem technologies. Therefore, current MEMS companies are unwilling to risk eroding the rich niche of intellectual and experiential leads, as well as large profit margins they developed in custom foundry operations, to join any standardization effort. Yet, without standards, the industry struggles to reach the level of reliability and manufacturing cost needed to diffuse the technology base into high-volume products. For almost ten years now (since 1993), generating standards for performance and production technology has remained one of the major technology management challenges faced by the MEMS industry (Carr, 1996).

There are various barriers to the emergence of standards in microsystems. According to business researchers Gulliksen, Gaboriault, and Aylward (2000), barriers to emergence over and above the capital-intensive and risky nature of the MEMS industry itself include:

- The "Disruptive" nature of the technology must be able to demonstrate several significant advantages over current technology to induce an OEM to invest in costly new designs, new tooling, new training, and new suppliers.
- The "Invisible" nature of the technology does not compel awareness among end-users about MEMS and thus, except in specific niches, there is little marketplace "Pull."
- The "Complexity" of the technology (an OEM may be required to develop its own drivers or other ancillary circuitry).
- The "Apathy" on the part of both OEMs and end users (adoption in and of itself will not enable an OEM to sell more product, nor does a mainstream end user perceive much tangible benefit) (Gulliksen, Gaboriault, and Aylward, 2000).

The situation is exacerbated by the fact that large-market OEMs are extremely reluctant to allow themselves to become dependent upon a single source for a critical component. Many simply will not put themselves in such a position, regardless of the possible benefits (Gulliksen, Gaboriault, and Aylward, 2000). Besides all of these considerations for or against standards, experienced industrial players understand that the process of standardization is always a political struggle, with winners and losers (Surowiecki, 2002), and, therefore, not always in their individual favor.

2.0 The Case against Standards

Companies that embrace microsystems have taken large risks and deserve to obtain economic rent for their successful efforts. An early move towards standards in an emergent industry does not allow pioneers to recoup their R&D investment and garner profit, unless provided with a royalty for their hard-won intellectual property. If not handled carefully, standards can also be used as a non-tariff trade barrier or for the monopolization of a technology among a set of companies (DIN, 2000). Under these circumstances, a standard becomes an impediment to the diffusion of innovation, hampering macro-economic growth.

In an "Era of Ferment," putting standards too early in the process of innovation discourages competing innovations in manufacturing, packaging, and product technologies. Currently, every segment in the microsystems value chain wants the segment before them to provide standards. Designers want the foundries processes to be standardized, users want the designers to standardize, and systems integrators want interconnects to be standardized. Yet none seem to want to be the first. This results in the point of view arguing that: "Standards will occur in their own time. No single group needs to push." Or the View "intellectual property will serve their originators for at least seventeen years. Why hurry a patent?"

Another rationale against standards is the unique and complex nature of microsystems. Microsystems companies, as a whole, focus specifically on the technology-product paradigm. The variety of microsystem applications currently challenge, and yet also provide for, unique solutions to even the most sophisticated and technologically advanced manufacturing line (Markus, 1996). Moreover, there is a trend toward increasing complexity of device applications and their solutions.

Finally, the trend towards specialized processes generates a divergence, where many of the current microsystem processes are no longer compatible with each other or with conventional processes. This has come about because of the following factors:

- A need for 3D rather than 2D structures.
- A need for multiple, novel materials for optical, magnetic, biological, and thermal sensors in various shape and sizes.
- A need for unique lithography requirements for critical-dimension control in large die or target alignments.
- A need for specialized packaging for non-electrical transducers in optical, mechanical, magnetic, chemical, biological or other domains.

This has created a problem for the emerging microsystem markets because there are very few applications with large enough volumes to fully utilize a dedicated production line—hence achieving the best economy of scale. Also, because new process development costs are very expensive, especially when new equipment has to be developed, small- and medium-sized volumes of microsystems will not be able to support the development of new processes unless there is very high "Added Value." Consequently, the uniqueness of almost every application and customer need requires equipment that is flexible within a large process latitude (Consentino, 2002).

3.0 The Case for Standards

Microsystems have the potential to be ubiquitous in our daily lives. For microsystems to meet this future, microsystem devices will have to be cheap, interconnectable, and easy to integrate into any system, which to this point has not occurred. Standardization in the MEMS field will accelerate as the growth of markets propels more applications into the billion-dollar orbit. There are, in fact, many standards in existence, which are transferable to microsystems, if the industry so desired. For example, the MEMS standardization effort has already benefited from the standards established for the IC industry. When transferable, they are the *de facto* standards for the microsystems industry today. The establishment of new standards is in turn expected to accelerate the development of new applications, thus bringing the benefits to the MEMS community (Bryzek, 1996).

In a macro sense, the "Purpose of having standards is to reduce the impediment to free trade." between foundries, designers, equipment makers, and end-users across the globe (Turner, 1999). For instance, traditionally there has been a lack of a clear interface between microsystems designers and manufacturers. Companies such as Coventor, MEMScap, Analog Devices, and others are changing that paradigm. Even though a dominant manufacturing paradigm has not yet emerged, many of the world's MEMS foundries are sharing their processes with companies to accelerate the design process. It has been demonstrated that businesses are also able to lower trading costs, simplify international contractual agreements and lower trade barriers behind an agreed upon international standard (DIN, 2000). At the macro-economic level, efficient dissemination of innovation via standards has been shown to be a precondition for economic growth (*ibid*, 2000).

Because microsystems is an emergent manufacturing technology, there is a need for multi-disciplinary skills at the manufacturer and user site. The specification and design interface between user and manufacturer is complicated by the multi-domain nature of microsystems (electrical, optical, magnetic, mechanical, etc.); the lack of simple design rules or cell libraries; and the special packaging and test requirements involved. This is very much an issue of technological maturity, and is compounded by the lack of standardized CAD tools. Standardization would allow for more microsystem products to be conceived by allowing designers to be somewhat unlinked to the specific manufacturing foundry.

It can also be argued that the lack of standardization must, by its very nature, increase complexity, which in turn is an impediment to free trade, user selection, and industry acceleration. For example, at the beginning of the design process, it is impossible to predict the design of the microsystems or even the software implemented. That means standards for interfaces are becoming more and more important.

For engineers, this translates into the ability to deal with rapidly changing products and finding the right answer for their implementation so they can speed their product to market (Krueger and Grace, 2001). For users, complexity translates into a bewildering array of technology offers from a large number of well-entrenched suppliers. In most cases, suppliers are not able to offer all the technologies. Also, offers from different suppliers are not in a form that can easily be compared. For manufacturers, where new processes are required, the development costs are too high even for many larger companies. Standardization would help to reduce the high costs surrounding MEMS product development that arise from the complexity of the design (Wilkinson, 1996). Reduced costs and ease of implementation would then feed the acceleration/adoption cycle of microsystem applications and designs, ultimately growing the MEMS market.

To be truly effective, standardization must address the single-source issue as well. Any supplier would like to be the sole source of a product. However, no customer wants to feel that he can be held hostage, therefore, trying to establish oneself as the only provider is likely to be counter-productive. An OEM needs to know that there is a fallback position in case a problem arises with a primary supplier (Gulliksen, Gaboriault, and Aylward, 2000). Standards can help with this predicament by allowing clusters of several suppliers to operate in a market, as recent multi-source agreements between Alcatel, JDS Uniphase Corp., and Kamelian exemplify. More broadly, the market increases its confidence in the quality and reliability of suppliers, where standards are in effect (DIN, 2000).

4.0 Microsystems Standardization Status

The following section tries to briefly highlight the status of standardization efforts by various industry and governmental groups around the world. Where actual standards have been produced, we try to capture the gist of the standardization activities along with the actual standard. Where standardization efforts have been under discussion but no definitive standards have emerged, we simply describe the organization's aims related to standardization.

4.1 Existing and Emerging Standards

4.1.1 European Committee for Electrotechnical Standardization (CENELEC)

The European Committee for Electrotechnical Standardization was set up in 1973 as a non-profit organization under Belgian law and is officially recognized as the European Standards Organization in its field by the European Commission. CENELEC works with 35,000 technical experts from 19 European countries to publish standards for the European market.

CENELEC also coordinates its activities with the International Electrotechnical Commission (IEC). Cooperation between CENELEC and the IEC aims to:

- Expedite the publication and common adoption of International Standards.
- Ensure rational use of available resources and, therefore, full technical consideration of the content of the standard should preferably take place at the international level.
- Accelerate the standards preparation process in response to market demands.

In 1999, CENELEC produced a MEMS-relevant standard: Data Requirements for Semiconductor Die (or Bare Die), called **ES 59008-1**.

4.1.2 German Institute for Standardization

The German Institute for Standardization (DIN from the German Deutsches Institut für Normung) is a registered association, founded in 1917 and based in Berlin. Since 1975, it has been recognized by the German government as the national standards body and represents German interests at the international and European levels. DIN has long been active in developing standards for the microsystems area. DIN's electrotechnical workgroup also works closely with the IEC and CENELEC. To date, DIN has produced three standards relevant to the MEMS industry:

- DIN 1495-3 Bearings for small electric motors and micromotors.
- DIN IEO 47 (sec.) 1299 and 1300 (pressure sensors).
- DIN 32561 Components tray interfaces and tolerances.

Other draft standards are also being developed through DIN, specifically:

- Draft 32563 Production equipment for microsystems, and a system for the classification of microsystem components.
- Draft 32564 Parts 1-3 terminology.
- Draft 32565 Interface between equipment and end-effectors.

4.1.3 Institute of Electrical and Electronics Engineers (IEEE)

One of the areas where standards have been developed early is the sensor's output signal format and control network communication (Bryzek, 1996). Selected state-of-the-art sensor systems are already network capable. However, due to the lack of a standard interface for connecting sensors to microprocessors and field networks, it is prohibitively expensive for sensor producers to develop custom interfaces to support the multitude of proprietary networks and protocols in the marketplace. Thus, sensor manufacturers are seeking to standardize interfaces for sensors.

In September 1993, the proposal to develop a smart sensor communication interface standard was accepted by IEEE-TC9. In March 1994, the National Institute of Standards and Technology and the Institute of Electrical and Electronics Engineers, hosted the first workshop to discuss smart sensor interfaces and the possibility of developing a standard interface that would simplify connectivity of smart transducers to networks. Subsequently, a series of workshops have been held, and technical working groups formed in February, 1995, and have developed the following standards proposals:

- The P1451.1 working group is concentrated on a common object model for smart transducers along with interface specifications to the model.
- The P1451.2 working group is concentrated on defining the Transducer Electronic Data Sheet (TEDS), the Smart Transducer Interface Module (STIM), and the

digital interface including connector pin allocation and a communication protocol between the STIM and the Network Capable Application Processor (NCAP).

- P1451.3: Digital communication and TEDS formats for distributed multidrop systems.
- P1451.4: Mixed-mode communication protocols and TEDS format.

By September 1998, the smart transducer interface specification was adopted and published by the IEEE as an industry standard, IEEE Std. 1451.2-1997, today referred to as IEEE 1451.12345, the Smart Sensor Communication Interface Standard. It should be noted that these industry standards are meant not only to solve the sensor incompatibility problem, but will also:

- Minimize the risk of technology investment.
- Accelerate the development of smart sensor technology.
- Provide opportunities for interoperability among sensors and control networks,
- Provide enabling technology for easing the integration and networking of sensors and actuators into distributed measurement and control systems used in manufacturing.

4.1.4 International Electrotechnical Commission (IEC)

The International Electrotechnical Commission initiated a broad effort in 1995 to create microsystem standards through the MEMS Standardization Initiative 2. However, it was not until 1999 before an IEC meeting discussed MEMS standards explicitly. The group designated to do this work was TC47 (Semiconductor Devices), Working Group 4 or TC47-WG4. The aim was to make the scope of TC47-WG4 as wide as possible, and to include passive components. Another group, namely, TC47-WG1, is concerned with microengineered components and devices at the wafer and chip level. Additionally, other IEC groups such as SC47E-WG1 are concerned with the specification of the finished device from the customer's point of view (IEC, 2000). Both EUROPRACTICE and NEXUS are active in the area of standards through national representation at the IEC. To date, the IEC has produced the IEC 62258 standard for Die Procurement and User Requirements.

4.1.5 Multi-Supplier Sourcing Agreements

Multi-supplier sourcing agreements represent an example of market-force-driven standards—i.e., customer pull is the drive for the development and enforcement of standards. This customer pull can be manifested in several ways:

- A demand for component price reduction by virtue of standards.
- A demand for improved margins via reduction in final product manufacturing cost (adoption of MEMS/MST technologies requires consideration of total cost of implementation rather than individual device costs).
- Increased served available market by adoption of standards (some markets will remain unavailable unless basic "Standards" such as those facilitated by multi-supplier sourcing agreements are established).

Multiple sourcing and interchangeability of products from different suppliers is anathema to most vendors, since this inevitably leads to price sensitivity and reduced margins, but it is key to acceptance and wide-scale adoption (Gulliksen, Gaboriault, and Aylward, 2000). However, the harmonization of technical rules can help businesses cooperate and create strategic alliances, as well as reduce costs and increase profits (DIN, 2000). Recently announced multi-source agreements within the telecommunications industry for Semiconductor Optical Amplifiers (SOAs) and for Wave Dense Multiplexing (WDM) source lasers bode well for pushing an important MEMS market towards greater standardization, and, therefore, volume and profits.

SOAs can be deployed in a wide variety of applications in metro and long-haul networks. These include amplification, regeneration, wavelength conversion, and switching. Alcatel Optronics, JDS Uniphase, and Kamelian Ltd., have recently announced a multi-source agreement for SOAs to define common mechanical and optical performance specifications. The mechanical interface covered by the agreement uses the same configuration for pin functions as industry standard pump lasers. This enables system manufacturers to more easily incorporate SOAs into their systems. Other mechanical factors described by the standard include hole position and overall module dimensions. The standard also defines minimal levels of optical performance required for pre-amplification and booster applications. For each application, a different class of SOA has been defined.

JDS Uniphase and Alcatel have also agreed to participate in an agreement that defines a consistent standard for the form, footprint, and electrical specifications of an internally wavelength-locked WDM source laser. The two companies believe that a common standard will make it easier for system manufacturers to move to the new device. As the bandwidth required of WDM systems increases and they become more complex, system manufacturers are demanding more integration and more functionality from each component and module. These manufacturers must not only seek ways to reduce the footprints of their devices, but also provide increased functionality within a smaller volume as well. This new integrated device is intended to enable system integrators to save space on each transmitter card, while maintaining individual channel integrity down to 50-GHz spacing between two adjacent channels. The package and pin-out of the new products remain compatible with previous source laser modules from each company. This consistent design is expected to allow customers to increase the functionality of an existing board design without a complete redesign, thereby reducing cost and time-to-market.

4.2 Emerging Standards

4.2.1 NIST: The MEMS Project

The MEMS Project within NIST provides the U.S. domestic industry with microsystem-based standardized test structures and test methods for characterizing the thermo-electro-mechanical properties of materials and thin films used in IC and MEMS technologies. The NIST MEMS Project has two research thrusts:

(1) To develop and provide the domestic industry with MEMS test structures, test methods, measurement standards, and standard manufacturing practices.

(2) To develop new MEMS-based micro-metrology tools and integrated measurement systems that improve measurements or create new innovation in measurement science.

4.2.1.1 MEMS Test Structure Standardization

The MEMS industry requires standardized tools such as test methods, standard reference materials, and test structures to manufacture their products. To date, the NIST MEMS Project has generated two new test structures. One structure measures mechanical stress/strain of interconnects in fully fabricated ICs, while the second was optimized to measure appropriate tensile strain in Analog Devices' commercial MEMS process and to measure compressive strain.

The first new structures were fabricated on a test chip containing the new test structure designs based on 1.2-µm CMOS processes by the commercial foundry MOSIS. These test chips contained test structures to measure the longitudinal stress component in IC interconnects. New designs are being developed to measure the lateral and normal components of stress as well. The second new test structures used a new "Folded Beam Micro Strain Gauge" with a venire resolution of 0.1 µm. Even though this was fabricated using Analog Devices' process other processes are also appropriate.

4.2.1.2 The MEMS Project and the American Society for Testing and Materials (ASTM) Task Group

The MEMS Project also plays an active role in the new ASTM Task Group E08.05.03 on "Structural Films for MEMS and Electronic Applications," which is developing standards for electronic and microsystem applications.

The MEMS Project's ASTM Task Group stated deliverables are:

- 2001: Develop a standard test method for measurement of MEMS test-structure length required by the MEMS industry for measurements of residual stress and elastic modulus.
- 2002: Develop a standard test method for measurement of residual stress in MEMS devices.
- 2003: Develop a standard test method for measurement of elastic modulus in MEMS devices (MEMS Project, 2001).

4.2.1.3 The MEMS Project and IC Interconnect Characterization

The MEMS Project is also pursuing the characterization of micromachining techniques. Test structures and test methods are being developed to characterize the stress, elastic modulus, and adhesion properties in IC interconnects.

The MEMS Project's IC Interconnect Characterization deliverable is:

- 2001: Develop a test method for elastic modulus of a CMOS IC's dielectric and interconnect layers based on mechanical resonant test structures (ibid, 2001).

4.2.1.4 The MEMS Project and the Manufacturing Engineering Laboratory

The MEMS Project is also working with other NIST groups and divisions furthering standardization efforts in U.S. MEMS industries. Among them is the Manufacturing Engineering Laboratory (MEL) at NIST, currently working to revolutionize the connectivity and utilization of sensors in metrology, manufacturing, and conditioned-based maintenance to enhance industrial capability and manufactured quality. This is achieved through workshops and working group meetings to identify common issues for the standardization of sensor interfaces.

The MEL has set the following standardization goals spanning the next seven years:

Smart Sensor Interfaces and Standards

- 2004: Provide leadership in voluntary standardization organizations for sensor interfaces for the proposed IEEE P1451.3 and P1451.4 standards and for sensor network capability relevant to manufacturing equipment. Provide facilities for demonstration, promotion, conformance testing, and validation of the emerging standards. Develop techniques for real-time processing of sensor data using embedded systems (*ibid*, 2001).

Smart Sensor Interface Development and Implementation

- 2004: Develop transducer interface standard reference implementations in support of the IEEE 1451 standard development and draft specification verification/validation (NIST, 2001).

Remote Calibration and Metrology

- 2005: Research and develop standard networks for remote calibration and metrology applications to lead industry and government in the use of standardized sensor, networking, intranet, and Internet technologies for remote metrology and tele-calibration such as SIMNet, MeasureNet, and WorldNet, and conditioned-based maintenance (MEMS Project, 2001).

Sensors and Sensor Integration for Condition-Based Maintenance (CBM)

- 2005: Develop sensor and networking systems, connectivity strategy, and algorithm for condition-based maintenance of machines. Integrate new sensor technologies for application to mechanical metrology, machine tools, and conditioned-based maintenance systems.
- 2008: Develop measurement methods and parameters for the performance characterization of machine tools and their subsystems under loaded and unloaded conditions. Provide leadership to facilitate the development of the respective national and international standards (MEL-NIST, 2001).

4.2.2 American Society for Testing and Materials

The industry requires standards for measuring the mechanical properties of thin films used in the manufacture of MEMS. Standard techniques for assessing the failure modes and mechanical properties of the materials from which MEMS are made are not yet available. To this end, the ASTM Task Group E08.05.03 on Mechanical Properties of Structural Films for MEMS and Electronic Applications is pioneering the development of mechanical property test techniques for the MEMS industry. The ASTM Task Group is under Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation in Committee E-8 on Fatigue and Fracture.

This task group has undertaken sponsorship of a series of round-robin testing of residual stress and elastic modulus in test structures on a die passed among participating laboratories. These parameters are important to the fabrication of MEMS devices. The first series of tests for this round robin emphasized the metrology of the structures required for the calculations of residual stress.

The task group is pursuing two MEMS metrology standards, one on linear metrology and one on out-of-plane curvature measurements and analyses. A 3-point method is used to analyze the out-of-plane curvature of fixed-fixed beam and cantilever test structures. To date, this task group has not produced a distinct test technique standard for structural films.

4.2.3 The Japanese Micromachine Center

The Japanese Micromachine Center (JMMC) has publicized the importance of standardization for the growth of micromachine technology for a long time. At the Third

Micromachine Summit held in Canada in April 1997, countries reached an agreement to hold the first standardization international workshop, which six months later became the Micromachine Standardization International Workshop held in Tokyo on October 28, 1997.

The JMMC has to date focused its standardization activities on:

- The translation of micromachine-related terms into English. It has generated an extensive glossary of terms, which may eventually become the de facto standard of MEMS terms (IME, 2001).
- The study of essential features of standardization (shape, size, power, torque, fluidic related) in the MEMS/MST field.
- The development of secondary equipment for observation and measurement and the standardization of such devices (Hirono, 1996).
- Cooperation with international standardization activities.

4.2.4 NEXUS

As NEXUS moved for an industrial driven activity, one main goal was to pass from Technology Push to the Market or Products Pull" and in this way, User Supplier Clubs were established as the most important basic activity. The idea of these clubs is for each application area of MST to bring together MST suppliers, MST users focused on that application, and related R&D institutes. There are the following five groups: Automotive, Medical & Biomedical, Aerospace & Geophysics, Instrumentation & Process Control, and Peripherals & Multimedia. Each club has members from 15 to 30 companies and institutes, organizes three to four meetings per year and workshops. Market analysis, technology needs, products performances and standards are analyzed by each of them (Menozzi, 1998). NEXUS is a powerhouse in the EMS/MST industry and seeks to encourage the setting of standards. It is an active participant of international standard-setting bodies, such as the ISO and the IEC.

4.2.5 Society of Automotive Engineers

By the year 2002, automotive applications of MEMS are expected to constitute a significant segment of the microsystems market. Automobiles provide an excellent application opportunity for MEMS devices because of their low cost, high volume, and high reliability.

As the need for multiplexed bus communications and shared measurement data by different vehicle systems increases, the need for vertical integration will also grow. Implementation of a Controller-Area Networking (CAN) bus by European auto manufacturers in 1988 and Chrysler's Collision Detection (C2D) bus in 1989 mark the shift in communications requirements. Industry experts expect the U.S. SAE J1850 communications protocol to migrate from its present electronic control unit location to remote locations that contain MEMS devices, allowing for enhanced distributed control (Grace, 1999).

Further, the auto industry agrees that the right power network solution for the future is a 42-volt system. This area does represent a strong possibility for standardization for MEMS devices, especially sensors, because the industry has already agreed on the goal and MEMS offers the cheapest, most reliable solutions. Beside customer requests, governmental regulations are forcing functions in the areas of economy, environment, and safety. "One of the big benefits of 42 volts is that there have been standards developed for it" points out Remy Kaiser, European director of Technology, Environment and Quality at Delphi Automotive Systems. "We don't have standards for the current voltages" (from Kaiser, 2000). However, the complete adoption of a 42-volt mono voltage storage system is expected to take more than 10 years (Krueger and Grace, 2001).

5.0 Bottlenecks to Standardization

MEMS technologies solve numerous commercial problems in nearly all industrial settings. This is an immense challenge for any process of standardization since all applications have unique characteristics. The situation is further complicated by the fact that MEMS/MST technologies are comprised of at least four semi-competing and semi-compatible processes which have dramatically improved over time. This multiplicity in applications and means to deliver a product create huge barriers to any process of standards development.

5.1 Secrecy

MEMS comprises an organic industry, in that its growth pattern is evolutionary rather than planned, and direction is determined by survival; industry participants, particularly in the U.S, are largely secretive, preferring to disclose as little as possible about their programs or business activities. At present, the industry lacks a worldwide infrastructure, and thus has no official vehicle for the ready sharing of technical and other information, promotion of the technology, or the establishment of industry wide standards and protocols for the common good of participants (Gulliksen, Gaboriault, and Aylward, 2000), although conferences and Web-based efforts, such as MEMSExchange, offer partial vehicles for this information sharing. Furthermore, in the area of packaging, much of the microsystems work is reputed to be based on company- and application-specific approaches, and is often treated as a proprietary competitive advantage in the marketplace. However, the lack of standard and the use of open packaging may retard the commercial acceptance of MEMS by the user community (ITRI, 2000).

A more open forum for sharing standard-setting approaches should help alleviate a form of secrecy that inhibits the industry from developing overall. The MEMS industry may also benefit from the national and international debates about intellectual property protection arising from the computer industry's experience. Reformists advocate new thinking and new legislation regarding intellectual property definitions to induce more creativity, competition, choice, and to improve the rates of adoption for innovations (Seymour, 2002). These types of changes would also conceivably make it easier for the industry to share more information without losing any competitive edge. However, this must be accomplished without further complications to the cost and procurement times of patents and patent law.

5.2 Global Industry Association versus the Market

There are industry players who feel strongly that standardization progress can only be made via the international standardization structure. One distinct advantage of using such official bodies is that the cost of developing standards is shared among participants or borne by the public through a government program. Participant at the Workshop on Standardization have most recently reaffirmed this view for MEMS in March 2001 (IME, 2001).

It has been recommended from numerous quarters that a worldwide MEMS industry association be formed, with membership open to any legitimate industry participant, including device vendors, foundries, OEM users, R&D houses, universities, consultants, manufacturers' representatives, equipment and materials suppliers, etc. Needed is an improved dialogue and partnership between device manufacturers, equipment vendors, and material suppliers to take the industry to the next level of standards (Consentino, 2002). This organization's charges may include, but would not necessarily be limited to:

- The promotion of the MEMS industry as a whole.

- The provision of a ready vehicle for the exchange of information, and a forum for technical issues.
- The establishment and maintenance of device standards and registration.
- The collection of industry statistics (Gulliksen, Gaboriault, and Aylward, 2000).

While some argue for a new association, others argue for leveraging existing organizations that have proven organizational capacity, international acceptance, and have a strong affinity with the MEMS industry. To that end, SEMI has already begun down this path since the semiconductor industry has existing standards that can be integrated to the microsystems industry. SEMI is poised to add MEMS standardization to the SEMI international standards effort. In November 2001 and March 2002, a MEMS-specific industry standardization effort in Munich, Germany was held under SEMI's auspices. Should SEMI become intimately involved with the MEMS industry, this bottleneck may be alleviated much sooner.

There is, however, a strong argument that only a messy market-based process is capable of handling the creativity and innovation of the "Era of Ferment" in a revolutionary industry. It is argued that while official bodies have the advantage of experience and authority, they tend to be rather slow-moving (Surowiecki, 2002). Such official standards also favor those businesses able to participate fully in the formation of standards, which can influence the shape of the standards in their favor, and gain insider knowledge (DIN, 2000). Furthermore, companies report that company wide or multi-supplier standards have more of a positive effect on their competitive position than do industry-wide standards (*ibid*, 2000). Thus, any global organization moving too slowly may not meet the timeline and agenda of some markets, such as the telecom industry, and face irrelevance among those market players.

A further lesson from the market is that the suppliers of the novel microsystems technologies being brought to the various markets are adopting the market standards established by the technologies previously available. It is anticipated that once MEMS/microsystems devices have achieved market entry and acceptance, these standards will then be modified to maximize the benefit of the new device types (both in terms of cost and performance). This overall "Flow" is common and should not be considered as a basis for the elimination of "External Drivers" such as standards groups or authorities, as these provide the "Checks and Balances" necessary. It is further argued by some that it is the process of open discussion about an individual standard itself that is the key item of value, as it is this process that acts as a disseminator of information and helps define the market pull for device designers.

5.3 Process of Proposing Standards

As dominant manufacturing technology and dominant device designs are selected for specific applications, standards will emerge for specific product-technology paradigms. One approach proposes handling standards in a more open registration format, suggesting that the specific, critical parameters (maximum dimensions, connection layout, minimum performance criteria, operating range, etc.) of submitted devices could be used as templates, and registration numbers assigned accordingly (Gulliksen, Gaboriault, and Aylward, 2000). These parameters would then become the standard for that device registration number. Other applicants who submitted devices that met the same specification could be granted use of the same registration number, thus enhancing interchangeability. Should a later applicant submit a device whose performance exceeds the standard, he could either be granted use of the same registration number or, at the option of the applicant, be assigned a new one, with its characteristics becoming the standard for the new number (*ibid*, 2000). However, there is no industry consensus about how to propose standards and use them.

At any rate, standards should reflect the minimum requirement and should take the form of preferred options rather than mandatory requirements. This arises from the need to find a compromise between necessary variety and design flexibility on the one hand, and clearness and completeness on the other. At a minimum, proposed standards must not hamper the development of existing or future microsystem technologies, components, or applications. Under all circumstances, however, proposed competing standards must be avoided (Scheunemann and Leutenbauer, 1998).

6.0 Consensus Timeline for Standardization

There is no true industry consensus for standardization to date. Many want it as soon as possible, as long as it does not include the segment where they compete. Figure 2 attempts to capture a forward-looking timeline of the standardization activities of the differing stakeholder communities involved in the MEMS industry. Here we look at materials, equipment, design and modeling, test, interconnect, process, and packaging.

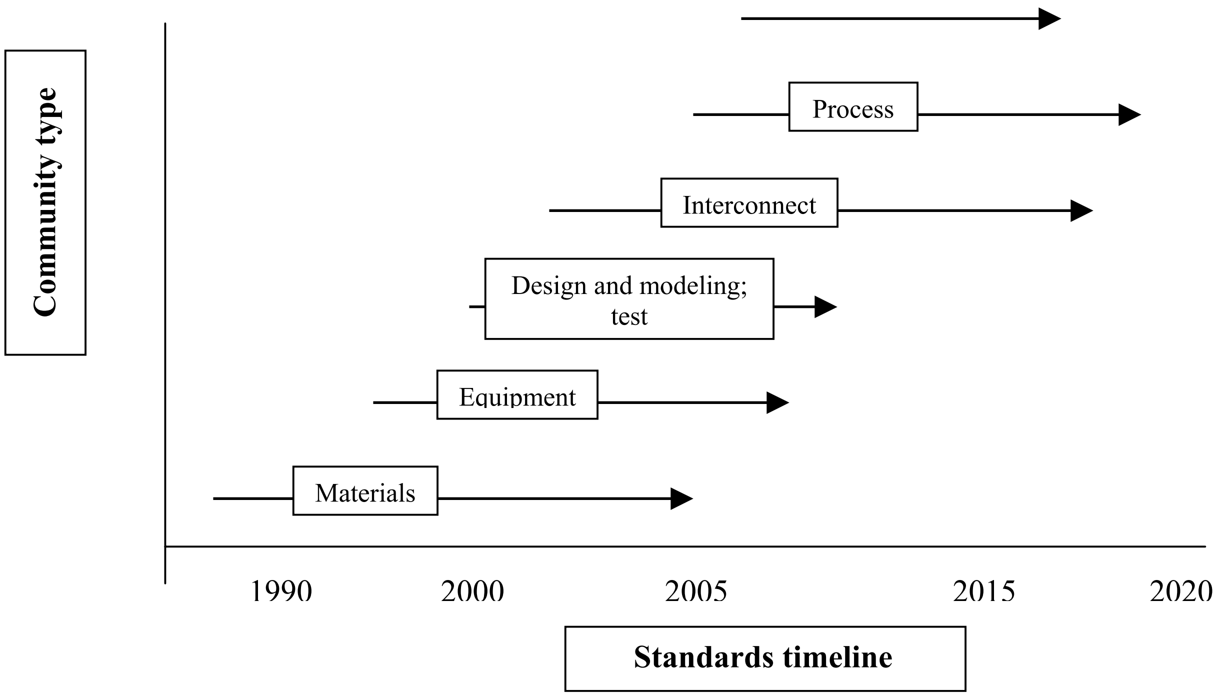

Figure 2. Timeline to Standardization.

As in all industries, it is not anticipated (or proposed) that the standards process will (or should) have a finite deadline. However, because the issue is a bottleneck for the industry, continuous adaptation, and evolution is expected—the timelines proposed are reference points for when a category should reach a "Significant Majority" status.

7.0 Areas for Standards Development

Several areas of microtechnology are in need of standards development, and some will experience this process faster than others. Here's a rundown:

Certain Devices: MEMS devices having wide "Off-the shelf" application are good candidates for the establishment and adoption of a standard. These include: micro-relays, micro-arrays, micro-optical switches, certain micro-fluidic devices, and sensors of various types (Gulliksen, Gaboriault, and Aylward, 2000).

Design Aids: These tools are only starting to be developed for commercial activities, and exist as discrete, stand-alone programs relevant to only a small piece of the design-simulate-fabricate-validate cycle. One of the most challenging aspects for CAD for MEMS is the multi-domain nature of the devices: thermal, fluidics, electrical, mechanical, magnetics, and optics. MEMS' need for coupled solutions over several domains challenges the state-of-the-art in CAD.

Equipment: The vast majority of companies currently involved in MEMS fabrication are performing their processing in facilities previously fitted-up for IC processing, and on equipment that the fast-growing IC industry has outgrown. The downside to this situation is the limited influence MEMS technologists have on semiconductor processing equipment manufacturers to develop innovative manufacturing solutions. However, the semiconductor industry association, SEMI, has already provided chemical, materials, reticle standards for LIGA, and certain parameters for equipment. These are the only internationally recognized standards in the industry. It is also argued that MEMS specific standards for new metrology methods should be identified (Westkaemper , 2000).

Packaging: Currently, packaging is the Achilles heel of MEMS manufacturing. Unlike ICs, MEMS packaging is an application-specific task and can completely destroy a potential product's ability to reach the marketplace. Generic methodologies for the packaging of classes of MEMS structures do not currently exist, yet are essential to the continued growth of the field. Every company, large or small, that emerges in the field, cannot recreate the long route of learning that some of the early MEMS product pioneers have had to traverse (ITRI, 2000).

Parametric Testing: A regular, well-characterized set of parametric test structures designed to screen the health of the integrated process both during fabrication and as a pre-functional testing screen is sorely needed. Such a set of parametric test structures has yet to be developed, characterized, and implemented in most of the critical MEMS processes (*ibid,* 2000).

8.0 The Simplest Solution is the Best One

This chapter considers standards, or the lack thereof, to be an industrial scenario of Occam's Razor. Occam's razor is a logical principle attributed to the mediaeval philosopher William of Occam. The principle states that one should not make more assumptions than the minimum needed. It admonishes us to choose the simplest model from a set of otherwise equivalent models of a given phenomenon. In any given model, Occam's razor helps us to "Shave Off" those concepts, variables, or constructs—in this case standards and proposals for standards—that are not really needed. By doing that, developing the model will become much easier, and there is less chance of introducing inconsistencies, ambiguities and redundancies (Heylighen, 1997). One can argue that the simplest solution will yield the best solution to the standards question for the MEMS industry.

Choosing the simplest solution doesn't necessarily mean choking off innovation too early in a technology development cycle, or giving away economic rent or the firm's secrets. It means doing whatever you can to make the adoption of designs, process, and packaging simplest for stakeholders. It means more vertical foundries, more foundries talking to developers. It means working to form some standards in *at least those industry areas where the Era of Ferment is past*.

For example, initial microsystems product applications centered on pressure sensing. These applications have matured their intellectual property span. Pressure sensors, therefore, represent a good place to initiate MEMS standards. As another example, the automobile industry's vision in setting standards for the 42-volt electric-voltage model and its long-standing use of sensors indicate that the auto industry is near-term market ripe for standardization. In this vein, standards are now implemented (to a varying degree) in the higher-volume markets such as thin-film heads and ink-jet printer cartridges (albeit these being default standards initially imposed by large suppliers by virtue of market share). These standards represent a basis for adaptation to serve other MEMS devices, but only where practical (for instance, the 42-volt automotive standard is not particularly applicable to the majority of hand-held devices).

The crux of the matter is often that the term "Microsystems" is too broad in of itself—there are very few "Transportation" standards for instance, but a vast number for the sub-categories such as aircraft and automobiles (even then, these are divided into sub-categories in each of the overall markets). It is these individual markets, therefore, that will determine the standards required—albeit this determination predominantly being a default decision for the lowest-price part or device that meets the demands of the technology node required.

Ironically, the recent economic downturn has become a standards-forcing event for certain industries. Direly affected by the downtown, the telecommunications industry has accepted the challenge to reduce industry costs throughout the value chain by focusing on industry cost-sharing achievable only through shared standards for important components. The recent announcements of multiple-source agreements in the telecommunications industry demonstrate how industry users can foment MEMS standard-setting through internal and internal/external consortia. These types of multiple-source agreements will benefit system manufacturers by giving them the confidence to take advantage of cost-effective components in their systems, knowing they are working with a standard design. Industry multiple-source agreements provide a pathway to a rapid evolution of the all-optical network by reducing design concept, cost-to-design, integration, and price barriers to adopt MEMS solutions. As such, economic realities have forced Occam's Razor into play by forcing industry-wide simplification as the best solution to achieving industry goals, while simultaneously confronting high-supplier costs and supplier lock-in.

9.0 Conclusion

MEMS is characterized as an enabling technology, one that allows the fabrication of devices to perform functions that have never been done before or in a manner that is unprecedented. As such, it has the potential to change the world as we know it. These words could have been written more than twenty years ago, and would have had every bit as much relevance then as they do now. The world has changed, clearly, but very little of this change was enabled by MEMS. It is evident that steps must be taken to energize this enabling technology. One of the important methods to energize the MEMS industry is to generate standards, which decisively diffuse MEMS innovations.

To date, most of the problems to industry growth highlighted in the 1990s are now being addressed on some level. Citing from Roger Grace's 2000 Report Card, "Design automation activities continue to be in high gear with companies such as Intellisense, Microcosm, and MEMScap developing new products to cut design iterations, lower development costs, and reduce time-to-market. Significant investments by companies, including Alcatel, Electronic Visions Group, Karl Suss, STS, and Unaxis in equipment specifically designed to meet the requirements of MEMS/MST designers and manufacturers are helping to overcome the 'Home Brew' approach previously used to create equipment solutions. Test and measurement activities for MEMS are being pursued by major producers of MEMS, e.g., Analog Devices, and by companies specifically established to provide this service and related equipment, e.g., ETEC and Exponent."

Another major promise of good news is the creation of a number of MEMS "Vertical Foundries" such as Standard MEMS, to help support mid to large-scale production programs. Coventor, through its expansive strategic partnering program, serves complete design-to-delivery plans to companies requiring MEMS solutions—or provides whatever pieces of the plan are needed. Therefore, it's no longer necessary to create an elaborate and costly semiconductor facility to be a MEMS producer. Exponent and Sandia National Laboratories are helping MEMS companies better understand the reliability issues associated with MEMS development and production (Grace, 2001).

The microsystems industry needs a supportive environment for R&D, production, and testing (Carr, 1996). Standards will help make this a functional reality. Early efforts in the 1990s to build a support structure were not directed at supporting or generating the manufacturing infrastructure necessary for companies to go beyond advanced prototyping stages. The uniqueness of some of the key steps of MEMS technology challenge the existing manufacturing technology infrastructure and place challenges and potential limitations on the development of a comparable support structure for MEMS (Markus, 1996). However, microsystems industry efforts to form a global industry association, as well as MEMS user initiatives to create *de facto* industry standards through multiple-source agreements, will help create the supportive environment envisioned by industry players.

This overview captures the various starting points from which the infrastructure for standardization and simplifying some things in the MEMS industry will occur. We have demonstrated that, whether near or far on the time horizon, the microsystems community agrees that standards are a critical success factor to the diffusion of the technology and to the growth of potential and existing markets. However, the issue of standards remains as a thorn in the foot of the MEMS community, affecting its ability to run the fastest race to billion-dollar applications and multi-billion dollar markets. Yet, ushering the current world of MEMS craftsmen and customized production toward standardized mass-assembly and production means inherently creating a whole group of specialist losers and a whole other group of mass-production winners.

The crux of the problem with the standardization process in the MEMS industry today is not that participants do not agree that standardization may be necessary and, on the whole, beneficial, but rather that the process is not innocent nor necessarily beneficial for individual industry players and investments (Surowiecki, 2002). This has the effect of slowing down the timeline for standardization, while offering creative ferment in the industry's nascent problem-solving abilities. However, somewhere in the messy and lumbering story of MEMS standardization, a tipping point exists, whereby gathering enough weight behind a standard will force everybody else to fall in line. The industry continues to await the scale to tip in any direction, but benefits from the discussion itself in the meantime. This is a natural process during an "Era of Ferment"—there are "Some" markets and "Some" standards. A couple of decades from now, this will be a "Chicken and Egg" argument, the reality being that the markets and standards emerged hand in hand.

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