

Executive Summary

The International Microsystems Roadmap Leadership Group

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Introduction

The fast growing "Small Tech" industry is an industry holding both promises and pitfalls for those firms supplying, manufacturing, funding, and using products made using the Small Tech technology base. This industry is in an early stage of rapid technological development, thereby

characterizing the industry as chaotic -- offering both opportunities for great profits and threats of failure for new and existing firms. Typical of a chaotic industry, there are dozens of new entrants every year. There are also numerous competing front-end and back-end technologies for every one of the many MEMS based products commercially available. Our roadmap separates front-end technologies into silicon-based IC like MEMS and non-IC like MEMS production. Manufacturers, however, almost always focus on a limited subset of the front-end manufacturing technologies available. The industry's growth is unmistakable; and where there is growth driven by new, early-stage technologies, there is opportunity.

There is also a tendency to either "Hype" the value of the underlying technology or to radically understate the nature of its value. This roadmap seeks to dispel some of the ambiguity centered on this emergent industry. The International Microsystems Roadmap (IMR) provides directions to firms for the commercialization of products and systems produced utilizing micron scale devices and structures for industrial, automotive, information technology, defense, life sciences, consumer applications and many others.

Who is this Document for?

Microsystems based technology is the second micro-manufacturing revolution and is poised to be every bit as universal as its cousin technology, semiconductors. The purpose of the International Microsystems Roadmap (IMR) is to assist in the understanding of an industry based on this revolutionary technology known alternatively as: Microsystems Technology (MST), MEMS (Micro Electro Mechanical Systems), Micro-Machining, or even Top-Down Micro-Nanotech.

This document is designed for those seeking to understand the industry and where future growth and profit opportunities lie, as well as for those intending to develop their own commercialization roadmaps for their products in specific industry segments. To that end, the roadmap provides general trends in 15 specific areas essential to the commercialization process of MST/MEMS/Micromachining-based products. This roadmap in particular aims:

- To "Speed-up" the process of commercialization of products based on microsystems technologies through the pre-competitive sharing of information between the firms and contributors involved in this road mapping process.

- To assist decision makers and their staff members to understand the industry, its technology, markets, and potential for future growth.
- To guide both technologists, investors, marketing professionals, and entrepreneurs in conceptualizing the reality of the technology and its potential applications, thereby providing value to the entire stakeholder community, operating in relation to this technology.
- Specifically those stakeholders include:
 - 1) MEMS/MST based product users and potential users (i.e. systems integrators, entrepreneurs, etc.)
 - 2) Suppliers to MEMS/MST manufacturers
 - 3) MST/MEMS manufacturers
 - 4) MST/MEMS researchers and research institutes
 - 5) Policy makers
 - 6) The capital investment communities (Angel, Venture, M&A, Investment Banking)
 - 7) Industrial and academic institutions
 - 8) All entities seeking to join this technology and its markets

Looking Back

While the chaotic nature of microsystems technologies appears to be new, this is far from the truth. Although there is currently a plethora of new developments in this technology, the current chaos really represents the emergence of a slow-to-mature technology dating back more than 50 years. To understand the emergence of this industry, it is useful to look back on its history.

The 1950's mark the beginnings of the commercial use of what we now call MEMS technologies. It was through gaining knowledge of the properties of silicon that MEMS found its first utilization. Silicon was found to have differing strain measurements along differing axes resulting in useful mechanical properties that could be used to make small, valuable, and acute pressure sensors and strain gauges. The resultant technology, called "silicon whisker" technology, was developed at Bell Labs, Honeywell, Allied Signal, and other firms by the mid 1950's. The first actual micro products were very small, very light pressure sensors for the aerospace industry. Among the first to produce such products were Honeywell, Kulite, Endevco,

Rosemont, Bell Labs, and IBM. However, throughout the 1950's and on through the 1970's, MEMS was considered merely a niche subset of the semiconductor technology.

Etching silicon, glass, and quartz structures became the dominant micro technology in the 1960's and 1970's. Jim Angel and others popularized the term micro-machining during this time. The United States Air force, National Institute of Health, and other US agencies pushed micro technology for aerospace and medical applications, resulting in the establishment of more microsystems firms working the niche applications of MEMS. Late in the 1970's US automotive regulation fueled auto industry acceptance of microsystem-based products, ultimately becoming the largest user of MEMS technology in such products as manifold pressure sensors and fuel injection nozzles.

What we now call MEMS, Microsystems, or Micro-machining initially did not have any unique nomenclature for thirty years. The next advancement of microsystems technologies first came in the 1980's when numerous individuals, most notably Steve Jacobson, initiated the term MEMS. Nomenclature arises as solutions provide commercial value to a user community and technology diffusion occurs. The second development was emergence of two new MEMS front-end technologies, LIGA and Sacrificial Surface Micro-Machining. Numerous new applications of these technologies opened potential markets for MEMS devices. MEMS devices were by now evolved enough that they acted, not only as sensors, but also, to a much larger degree, as actuators. This, in turn, further diffused the technology and initiated competing microsystems-specific nomenclature.

The 1990's gave rise to commercially successful devices that sensed, thought, and actuated. Integration as well became an extremely important part of microsystems technology. Technologists gradually came to realize that packaging solutions held as much as 70% of the value and cost of a MEMS device. They further learned that combining sensing, thinking, and actuation integrating into a single package system was possible. This movement to systemization was difficult because of the greater complexity in manufacturing MEMS devices. This was often as difficult as the physics and engineering required to develop the MEMS devices themselves.

The microsystems marketplace at the turn of the 21st century has greatly increased. Microsystems clusters, or areas of regional microsystems activity, are recognized around the world. Well over 600 firms now base their search for competitive market advantage on

microsystems technology. Some 21st century markets, like the airbag accelerometer market and the ink-jet printhead market, are dominated by MEMS devices, while others loom as large potentials for a variety of optical and bioMEMS devices. Because MEMS devices can provide an interface between the digital and real (analog) world, the MEMS devices of the 21st century will be tasked to increase functionality.

The remaining body of this Executive Summary details how the roadmap is structured, highlights the major findings of our contributors, and follows with a short summary of each chapter of the roadmap.

Structure of the International Microsystems Roadmap

The roadmap is organized into three sections with fifteen chapters. The sections and chapters are structured as follows:

Section One:

1. Introduction
2. Commercialization of Microsystems
3. Optical MEMS
4. BioMEMS
5. An Improved Method and Forecast for the World-Wide Market Growth of MEMS

Section Two:

6. IC Compatible and Potentially IC-Compatible Microsystems Manufacturing
7. Non-IC Compatible Microsystems Manufacturing
8. Design, Simulation, and Modeling
9. Microsystems Reliability, Testing, and Metrology
10. MEMS Packaging & Assembly

Section Three:

11. Status and Future of Microsystems/MEMS Foundries
12. MEMS/MST Cost Model
13. Standards, or Lack Thereof
14. Integration
15. Glossary

Major Findings

Our contributors have provided many salient conclusions throughout our chapters. Some of the roadmap information supports the current microsystems technologies as the potential next “Big Commercial Opportunity.” Others identify bottlenecks and roadblocks. The nature of a

roadmap is that all chapters are interdependent and many of the major findings are voiced in differing ways across the body of the work. We specifically highlight fifteen major conclusions our contributors have made in the IMR.

- 1) Our contributors see a compound annual growth rate (CAGR) for the microsystems industry in excess of 20% through 2010. Estimates of a CAGR of less than 20%, cited by numerous studies, are conservative.
- 2) Differing technology manufacturing paradigms in microsystems are becoming increasingly competitive with each other, rather than only complimentary.
- 3) Application spaces have started to self-select dominant front-end technology pathways.
- 4) The costs of firms switching front-end manufacturing are rising fast and will continue to do so.
- 5) The trend to add functionality to microsystems devices is inducing the development of microsystems-based products which sense, think, act, communicate, self-power, and navigate. Subsets of these will provide uniquely useful commercial solutions.
- 6) There is increasing potential competition between subsets of MEMS device types.
- 7) Microsystems will continue to grow in traditional markets, but the real fuel for a high CAGR lies in emerging markets, such as micro fluidics, bioMEMS, RFMEMS, micro-power, and security/defense.
- 8) Because there are very few existing microsystems standards, over the next decade as applications mature, standardization across all phases of microsystems manufacturing will be necessary for continued growth.
- 9) Basic efforts in reliability and understanding micro-scale failure mechanisms are imperative for continued growth over the next decade.
- 10) Packaging is emerging from a unique application-dependant process and accelerating toward more semi-custom efforts.
- 11) The trend in the number microsystems foundries is dramatically increasing. One explanation for this is the fervor of semiconductor foundries seeking to use

their excess capacity by adding MST foundry work. Many of our contributors see as inevitable a shakeout in the total number of foundries thus created.

- 12) There is a shift in bioMEMS from only actuators or sensors toward in- vitro and in-vivo devices that increasingly sense, think, act, self-power, navigate, and communicate.
- 13) A robust test process, testing functionality and reliability, has historically gone hand in hand in MEMS-based device commercialization and the future appears to want to follow this trend.
- 14) More accurate and interdependent toolsets are emerging in MEMS design, modeling and simulation. These tools are increasingly able to simulate yield and performance parameters on MEMS structures and systems.
- 15) Our glossary points to the fractional nature of microsystems, but also serves as a starting point for a unified “dictionary” for the industry.

Roadmap Chapters

Chapter 2: Commercialization of Microsystems

Industries based on novel technologies are bereft with impediments delaying their creation. Many times emerging technologies commercial development may be buried in a single firm’s pursuit of a singular solution for a specific customer. The creation of an initial product is not necessarily the harbinger of a dynamic industrial or market formation or even for that matter the birth of a new firm. In order for a technology to form the basis of a new industrial revolution, it must answer the question of an initial commercial application and follow that by demonstrating its ability to solve similar problems in a uniquely commercially valuable manner. Cadres of technology product platforms are being developed that are commercially effective across multiple technology product domains.

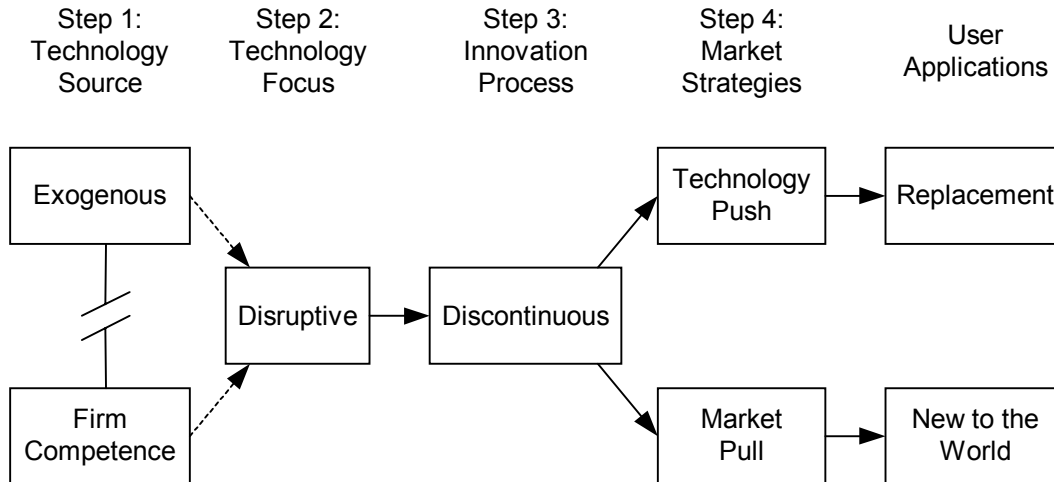


Figure 1. The Disruptive Technology Commercialization Model

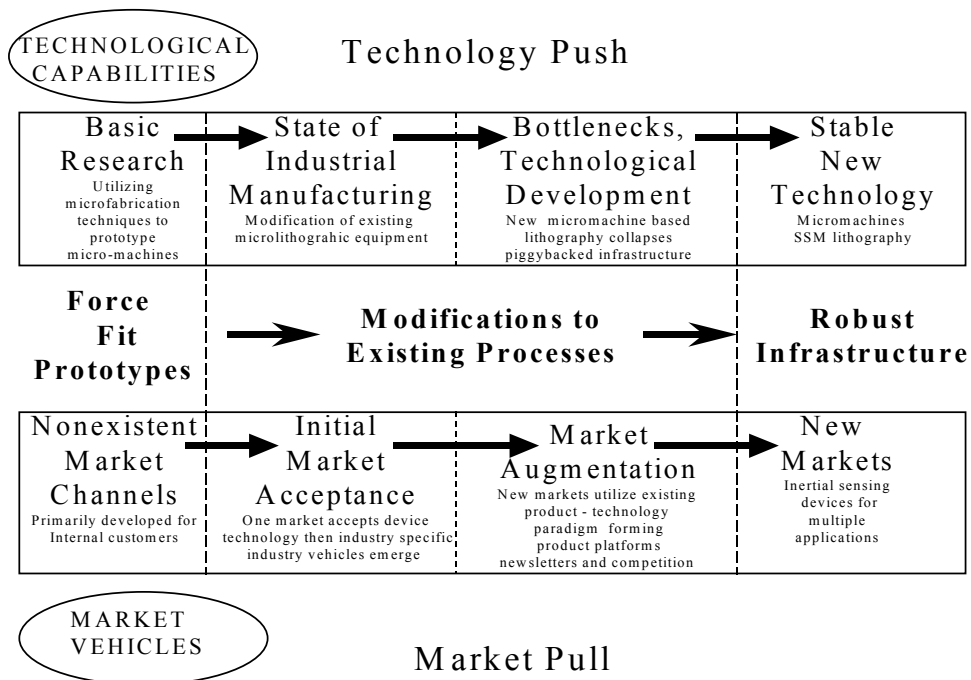


Figure 2. Infrastructure Model for Discontinuous Innovations

This chapter utilizes the historical data resident in the microsystems revolution modifying it through state-of-the-art technology commercialization methods to provide knowledge and wisdom to the reader while shedding light on the various aspects of the current and future state

of Microsystems, the Second Micro-Manufacturing Revolution. A complete, succinct overview of the current state of commercialization in the industry is provided through the use of a MEMS report card. Lastly, we provide models that illustrate the current state and the future promise of microsystems, as well as indicate the scope and future of Small Tech.

Chapter 3: Optical MEMS

Optical microsystems hold much of the same promise as all of the MEMS-based microsystems. Optical MEMS have made great strides in telecommunication, sensing, and projection applications. Contributors to the roadmap early on described an optical switch as a “Holy Grail” application with huge market potential. Our contributors envisioned Optical MEMS (also referred to as MOEMS) as a “Market Driver” for the optics and telecommunications industries. However, in recent years it has been observed that the first MEMS device to achieve widespread acceptance in telecom has been the optical attenuator. While these devices do not share the complexity of the high port-count switch, they have enabled the acceptance of MEMS as a “Real” technology. Telecom MEMS have evolved from an esoteric university research topic to real packaged products in the space of approximately 5 years. Outside of the technological achievement that this represents, it is a welcome sign that the industry is accepting micro-mechanical technology as an enabling technology for telecom.

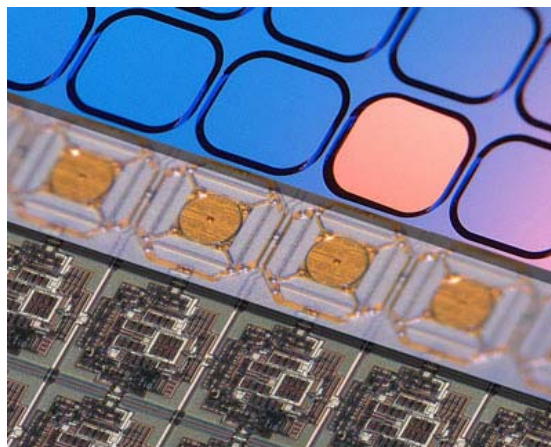


Figure 3. A Mirror Array from Transparent Networks

TI and others are famous for having initiated Optical MEMS with the Digital Micro-Mirror Device (DMD) on which TI's DLS technology is based. The potential of an all-optical switching

device for the telecommunications industry has greatly increased the interest in Optical MEMS and is poised to be one of microsystems' first "Killer Applications." Unfortunately, the equivalent of an economic winter has blanketed the telecommunications industry since 2000, lessening its desire for all optical switching solutions over the very near term. Most analysts feel that the demand for all optical switches is not over, but simply has been delayed by a few years. As well, it is important to note that even in the telecom downturn (and the associated cutbacks in new product development), MEMS are emerging in many important, but less "sexy", roles such as optical attenuation (Nortel, JDSU, LightConnect and others), small port switches (JDSU and Kymata) protection networks, tuneable RF (multiple firms such as Raytheon.), and integrated optics (Silex). However, telecommunication companies are failing daily and the negative impact on the Optical MEMS market is severe and profound.

Chapter 4: BioMEMS

MEMS in the medical-biochemical fields are presently poised to surpass MEMS applications in other areas, in terms of market revenue. Until the mid 1990's, MEMS techniques in the medical-biochemical fields were usually associated with blood pressure sensors. In the past 5 years, a host of other less-publicized bioMEMS based devices are being used in medical equipment or have been prototyped and are nearing entry into the market. Thus, estimates place the percentage occupied by bioMEMS in the total MEMS market at 40-45% of the total MEMS market in 2000 and see the total bioMEMS market rising to \$4-\$5 billion in the 2004 – 2005 timeframe.

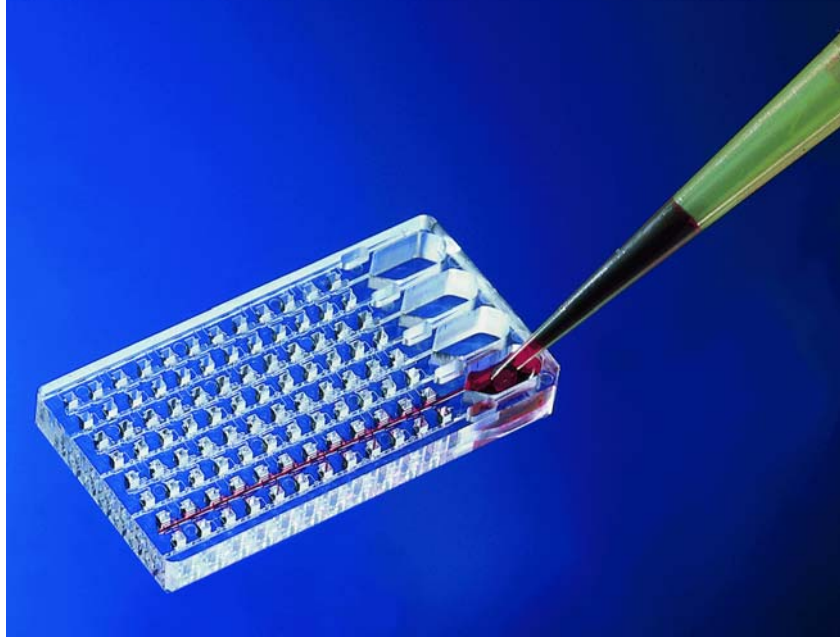


Figure 4. Micro Assay from *STEAG microParts GmbH*.

The bioMEMS market can be divided into in-vivo and in-vitro segments. The in-vivo or “inside-the human body” includes bioMEMS devices like micro motors, retinal implants, micro catheters, etc., and are significantly small compared to the in-vitro segment or “outside-the human body”. In-vitro devices range from body fluid microanalysis devices to microsurgical equipment and account for the bulk of the present bioMEMS market.

The only bioMEMS device that can be expected to have a billion dollar revenue is the bio-chip, an in-vitro device in which bio-molecules are chemically analyzed on a credit card sized chip as if it were a full-fledged laboratory. The value of the bio-chip market in 2000 was \$500 million, but is expected to be \$3 billion by 2004 or 2005. However, the subset of bioMEMS applications is large with several applications expected to surpass the \$500 million dollar mark by 2005 - 2006. The bioMEMS market is relatively new and has not reached maturity and there is still enough room for new players. The only bioMEMS product that has a significant number of competitive companies is DNA Array. The majority of most other bioMEMS device based companies have few market entries. Niche bioMEMS based markets that were not visualized before are being developed continuously.

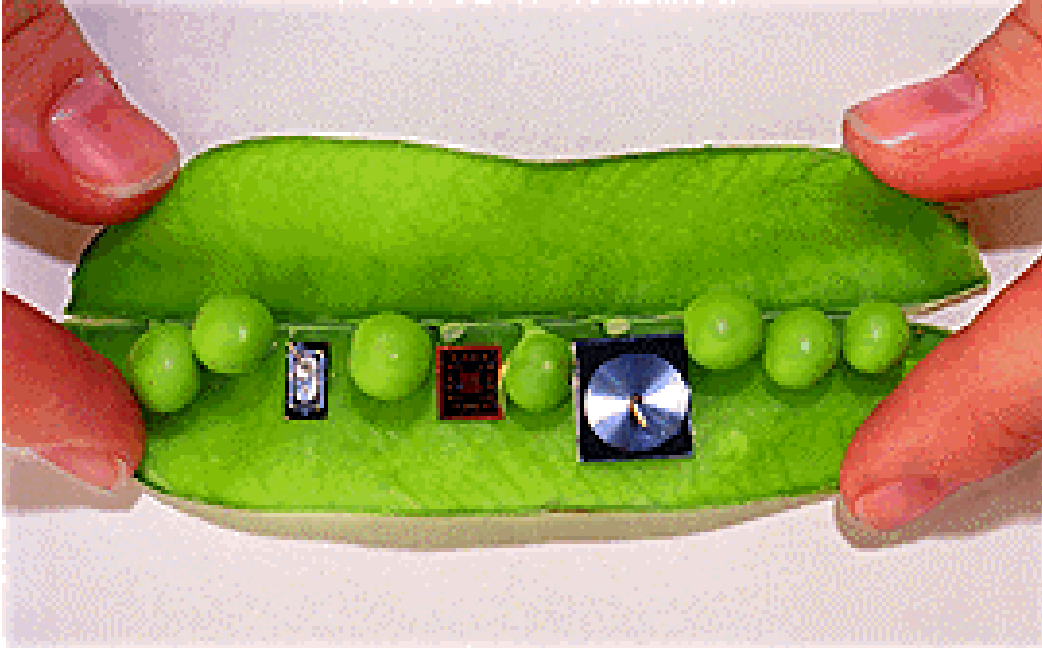


Figure 5. Chip-based Gas Chromatograph Components from Sandia National Laboratories

BioMEMS devices are increasingly acting as technological, as well as, market drivers for microsystems. The in-vivo and in-vitro applications that make up the bioMEMS family of products are currently utilizing considerably different front-end and packaging technologies. Material requirements suggest that this dynamically growing microsystems market area will use many differing technologies in the future. Unlike other MEMS markets that use silicon as the primary material, bioMEMS devices encompass both IC and Non-IC compatible technologies more broadly. Non-IC based technologies in bioMEMS have been developed in Europe, North America and Asia. LIGA and plastic extrusion technologies are led in Europe by institutes like Germany's Forschung Zentrum Karlsruhe (FZK) and in North American by leaders such as Sandia National Laboratories and the Center for Advanced Structures and Devices (CAMD) in Louisiana.

Chapter 5: An Improved Method and Forecast for the World-Wide Market Growth of MEMS

The roadmap provides a forecast based on expert opinions for figures representing the sum of the minima and maxima of the twenty-six major markets identified for MEMS. Current studies

show a tremendous variation in future sales and so do our experts opinions. This chapter provides a Monte Carlo simulation model to help determine ranges for the studies.

In the short run, maximum forecasts can diverge by a few hundred percent in each market. Whereas by 2025, the divergence between minimum and maximum forecasts are between one and two orders of magnitude for all applications considered. The forecast for current global sales ranges between \$600 million and \$31 billion. By 2025, the forecast for global sales of MEMS ranges between \$9 billion and \$360 billion!

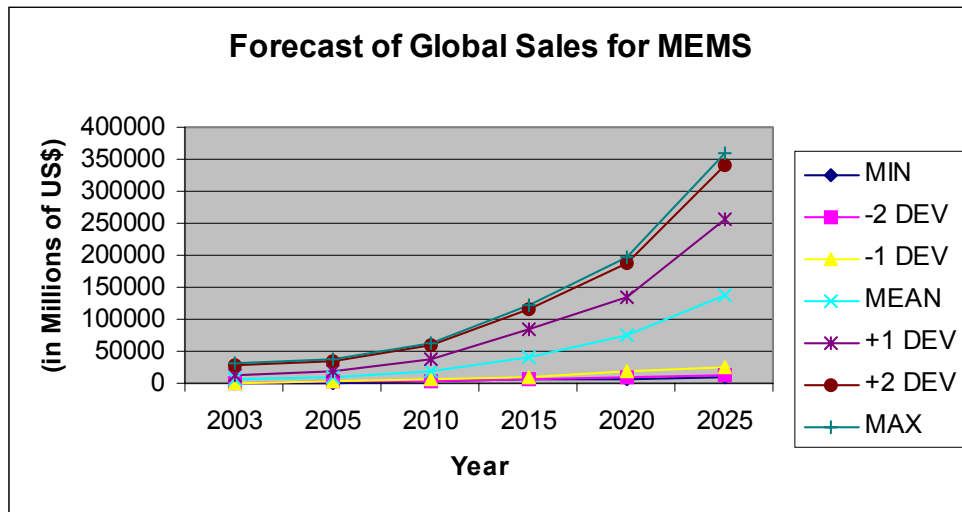


Figure 6. Forecast of Global Sales for MEMS

Section II Manufacturing Technologies

There are at least seven front-end manufacturing technologies falling into three classes: traditional bulk micromachining, sacrificial surface micromachining, and high-aspect ratio micromachining (HARM). The latter includes deep ultraviolet (DUV) lithography techniques and x-ray-based methods such as LIGA (from the German *Lithographie, Galvanoformung, Abformung*, meaning lithography, electroforming or plating, and molding).



Figure 7. MEMS Fabrication. Photo Courtesy of Sony Semiconductor

The MEMS roadmap divides these three classes of manufacturing technologies into two categories: IC and potentially “IC like” vs. non-IC like technologies. Non-IC like includes spark erosion, LIGA, silicon sculpting, and processes incorporating certain incompatible materials.

These manufacturing processes are complex, and the trend is toward increased complexity. By introducing substantially greater demands for fabrication with structural features in the third dimension, MEMS manufacturing technology will incorporate new capabilities, such as deep reactive-ion etching (DRIE), double-side aligners, stiction-abatement equipment, back-end flip-chip equipment, and bonded-wafer technology.

MEMS manufacturing process development will borrow from advances in IC fabrication, such as increased aspect ratios and reduced line widths, added metallization layer(s), chemical mechanical polishing (CMP), more sacrificial and structural layers, use of exotic materials and non-silicon based technologies, vastly more process steps, and increased wafer diameter.

Although the traditional approach in MEMS has been to develop application specific front-end manufacturing processes, the trend is reversing and contributors to the roadmap see a few dominant front-end process technologies emerging.

Chapter 6: IC Compatible and Potentially IC-Compatible Microsystems Manufacturing

Approximately fifty years ago, what is now known as Microsystems, MEMS or Micro machining was born of the use of semiconductor micro-fabrication techniques for mechanical applications. The first micro-manufacturing industrial revolution gave rise to the second while the first was still in its infancy. And thus was born the use of IC and IC-like manufacturing processes for microsystems. This has given rise to the axiom “if it isn’t going to be first manufactured using IC-related technologies in microsystems, it is likely not ever to be produced.” The majority of current MEMS based products are produced in this manner. The flagship of this technology segment is sacrificial surface micro machining which is directly discussed in the Integration chapter. The Analog Automotive Accelerometer, and the Digital Light Machine technology from TI are examples of IC like manufactured devices.



Figure 8: Silicon-based Micromachining (Courtesy of Sandia National Laboratories)

Chapter 7: Non-IC Compatible Microsystems Manufacturing

Non-IC like processes do not suffer the same barriers that IC like MEMS processes endure, but then neither do they benefit from the man-years of experience inherent in utilizing a semiconductor micro-fabrication based process. Nevertheless, these processes can be bifurcated between those, which are revolutionary in nature, and those, which are more evolutionary. Non-IC like processes can be split into four groups. They are those that utilize; a current process, evolutionarily (incrementally) improves an existing process, a new process centered on existing materials and a new process with new materials and tools required.

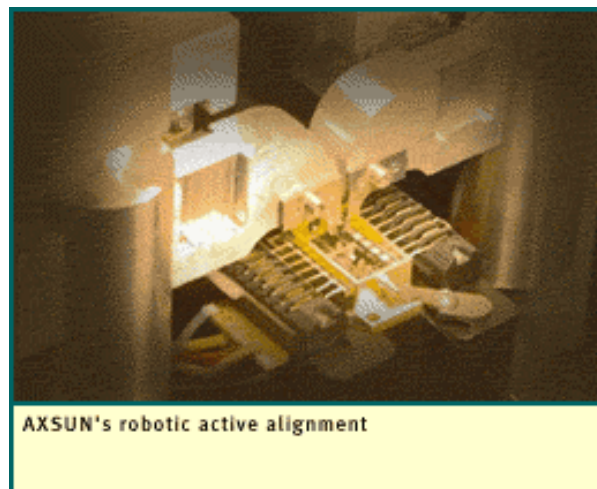


Figure 9: Robotic Alignment Fabrication (Courtesy of Axsun Technologies)

Non-IC compatible microsystems manufacturing systems cannot leverage or piggyback the semiconductor microsystems marketplace to the same extent that IC like MEMS technologies do. They can and do leverage knowledge in the plating arenas and plastic extrusion technologies, but in general they have a steeper learning curve than their IC –like MEMS manufacturing cousins. They do have some materials and structural advantages in the MEMS manufacturing world.

Non-IC like MEMS have the potential to build some of the most cost effective MEMS devices. Non-IC like MEMS processes make both the “Biggest Mass” small devices and can utilize the widest range of materials such as bio-compatible materials suitable for in-vivo manufacturing. A small but rapidly growing group of companies, provide, utilize or base their search for competitive advantage on these Non IC compatible and very promising processing steps. They include; Microparts (EU), QSI (NA) and Twente Microproducts (EU). Foundries

such as Axsun (see photo) and technology factor developers such as FZK are based on Non-IC like technologies. The Non IC compatible industry is developing its own support infrastructure with firms such as Jenoptik (EU). The health industry is the emergent industry for these technologies with firms like Mannesmann (EU), ISTAT (NA) and many other medical systems integrators purchasing and investigating products based on this technology

Chapter 8: Design, Simulation, and Modeling

Microsystems engineers are increasingly turning to commercial tools designed specifically for MEMS devices. Unlike microelectronic devices, MEMS are not laid out in street-grid geometry, so MEMS based tools allow the designers to work in either 2D or 3D and incorporate process information to convert between them. These tools provide a seamless path to 3D analysis tools and contain a robust library of standard parts and components. These tools build a visual model of the final product using process information and system definitions. The trend in tool development will increasingly be to provide both 3D representation and arbitrary cross-sectional capability.

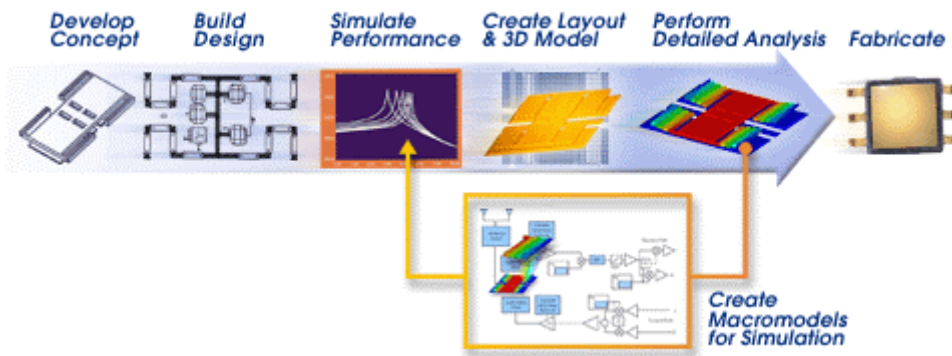


Figure 10: Design Process Flow (Courtesy of Coventor)

The performance of MEMS devices rely on complex interactive physical, fluidic, chemical, and other phenomena. There is more emphasis and focus on coupled modeling tools in MEMS today than ever before. Coupled tools will enable engineers to more effectively and efficiently model effects such as electro-mechanical, fluid-mechanical, chemo-mechanical, thermo-mechanical, and device/package interactions, which are critical to optimizing the MEMS device

performance. These tools will be instrumental in shortening MEMS product development cycles and in improving yield during the manufacturing phase.

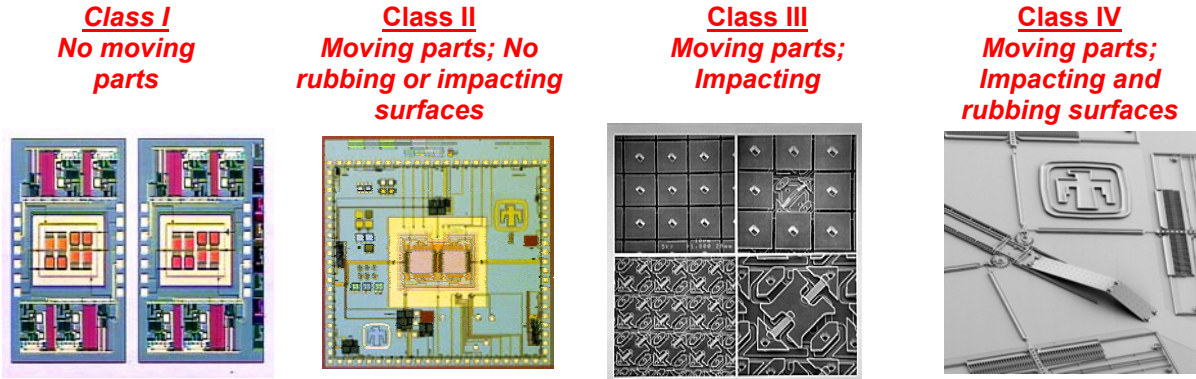
Design Rule Checkers (DRCs) will ensure that MEMS designs do not violate the foundry's fabrication rules. These tools will provide feedback about aspect ratios, etch release systems, side wall angles, process variability, mechanical tolerances, and material properties.

Chapter 9: Microsystems Reliability, Testing, and Metrology

MEMS reliability and device commercialization go hand-in-hand. MEMS devices, which have been successfully tested for functionality and reliability, provide the basis for microsystems commercial successes. Pressure sensors, optical switches, and other devices are examples of such commercial success. In-process reliability, in robust manufacturing processes, provides the basis for critical infrastructure in the future. Process quality and the manufacturing practice itself influence reliability. New standards and methods for long term reliability testing must be developed to bring MEMS process yields and reliability to the same levels enjoyed by IC product manufacturers.

The "In-use" reliability of current state-of-the-art MEMS devices demonstrates the clear need for defining such standard procedures for measurements of various parameters such as fracture strength and wear resistance. MEMS devices currently are able to sense, think, act, communicate, navigate and/or self-power many different energy domains and environmental conditions. Their ability to continue functioning in their designed manner for the designed lifetime when subjected to varying degrees of mechanical, thermal, chemical, electromagnetic, frictional, tribological, or other stress is the ultimate measure of reliability.

The smaller dimensionality and the multiple physical and energy domains of MEMS operations make reliability issues far more complex than for products like integrated circuits, which operate primarily in a single (electrical) domain. Furthermore, materials in the micro domain behave differently than their macroscopic counterparts. Material properties such as strength, stiffness, and wear are significantly impacted by scaling effects resulting in increased reliability issues and complexities of analysis.



Example MEMS Devices

**Some
Accelerometers
Pressure Sensors
Ink Jet Print
Heads
Strain Gauge**

**Gyros
Comb Drives
Resonators
Filters**

**Relays
Valves
Pumps**

**Optical Switches
Corner Cube Refl.
Shutters
Scanners**

Primary Failure Mechanisms

**Particle
contamination**

**Particle contamination
Shock-induced stiction
Mechanical fatigue**

**Particle contamination
Stiction
Shock-induced stiction
Mechanical fatigue
Impact damage**

**Particle contamination
Stiction
Shock-induced
stiction
Fatigue
Friction**

Figure 11. Taxonomy of Devices for assessing “in-use” MEMS/MST Reliability Issues According to Failure Mechanisms *Source: Sandia National Laboratories*

Chapter 10: MEMS Packaging and Assembly

Packaging constitutes the single largest element of cost and a major limitation to the miniaturization potential of MEMS devices. Effective packaging solutions remain a major obstacle to MEMS commercialization. Materials, design, assembly methods, encapsulation processes, environmental concerns, and functionality are the major challenges facing effective packaging solutions. MEMS applications frequently challenge packaging engineers to accommodate a variety of increasingly complex operating environments.

Major limitations of current MEMS packaging technology include the lack of standards or standardized packaging methods. Currently, few MEMS devices incorporate concurrent designs of the device and package, typically resulting in the use of retrofitted IC packaging solutions. The trend is towards increased use of a concurrent design. The trend among MEMS packaging engineers is moving beyond reliance on IC standards. MEMS packaging still needs to address

the traditional IC packaging problems, as well as the need to accommodate the mechanical extension of the MEMS device. MEMS packaging often plays the dominant role in determining the cost, reliability, and accuracy of the completed MEMS.



Figure 32: Modular Architecture Micro-Assembler (Courtesy of TNO Industries)

Chapter 11: Status and Future of Microsystems/MEMS Foundries

The challenge for MEMS manufacturing lies in cost-effective fabrication of small volumes, and the preparation for ramp-up to high volumes. MEMS is still an emerging and disruptive process technology that is not yet standardized to any great breadth or depth. Dominant MEMS manufacturing technologies in many application spaces are still to be determined. Therefore, MEMS manufacturers must be prepared to deal with multiple wafer materials, various shapes and sizes, as well as supporting multiple process technologies. Furthermore, the cost of any new MEMS foundry infrastructure is very high. Fortunately, last-generation IC foundries can be used for fabricating present-generation MEMS. However, as MEMS devices mature, becoming more complex, many contributors foresee more MEMS specific foundries offering unique process capabilities. The roadmap contributors suggest a model similar to the fabled semiconductor concept. Two scenarios will potentially evolve: (1) independent design/development companies will act as liaisons between the MEMS end users and the foundries and/or (2) foundries will

offer integrated product development services by providing turnkey design/development capability as part of the front-end process support, pushing the industry closer to standards.



Figure 13. Pattern Registration and Photolithography in Dalsa's Purpose-built Wafer Fab.

Expertise in front-end processing is not enough. Understanding and experiencing the back-end processing is also essential. Successful foundries of the future will move toward high volume or flex-volume high yield MEMS manufacturing. These will either be integrated front-end and back-end manufacturing foundries. Close and formal relationships will develop between front-end and back-end foundries. The focus will shift to providing microsystem, as opposed to micro-device, solutions from concept to volume.

Chapter 12: MEMS/MST Cost Model

The MEMS/MST Cost Model chapter contributors also contributed greatly to the foundry and the manufacturing technologies chapters. One of our contributors highlights the differences between capital and operating costs for different selections of front-end MEMS manufacturing technologies. The contributors to this chapter discuss both actual and option-based costs. The chapter points out the cost of choosing a non-dominate technological path or a pathway that may not be optimal for the given product technology paradigm or application space. In that vein, commercial foundries are likely to play an even more important role in the future because it is the foundry, and not the firm, that has to bear the burden of the technological pathway choice. Bulk, High Aspect Silicon Etching (HARSE) and SSM (Sacrificial Surface Micro-Machining) as shown in Figure 14 are all forms of MEMS front-end manufacturing technologies.

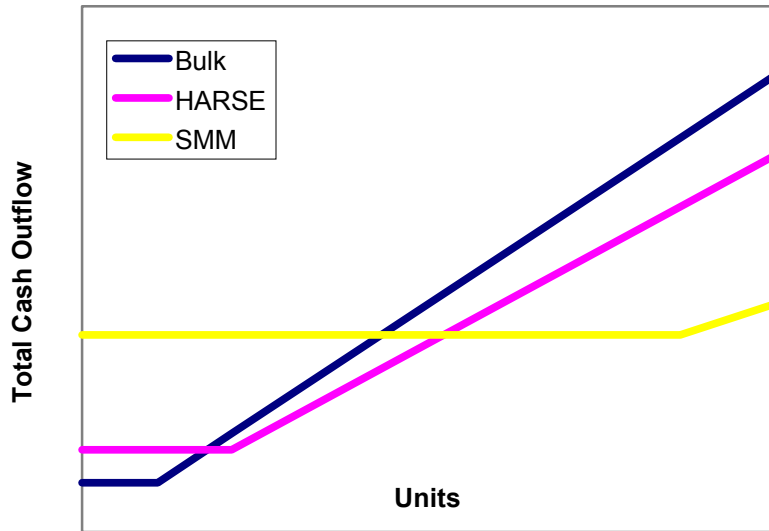


Figure 14. Hypothetical Total Cash Outflow at Different Production Levels using Different Manufacturing Methods

Chapter 13: Standards, or Lack Thereof

There are more norms than standards in the industry because it is still an emerging technology. The trend towards integrated MEMS systems suggests that the need for standards will grow as interconnections and complexity among systems becomes more important. Standardization in the MEMS field will accelerate as growth propels more applications into the billion-dollar orbit. Many user societies such as the SAE have form, power, fit and function standards to which MEMS devices already conform. Establishment of standards in all aspects of MEMS will accelerate development of new applications. Standards efforts face industry resistance as industry leaders hesitate to share their hard won knowledge that may constitute competitive advantage.

Active standardization committees already exist for materials, equipment, design, modeling, test, interconnections, processes, and packaging. Standards for materials and equipment have already started to appear; with design, modeling and test standards imminent; to be followed by interconnections, process and packaging standards. Semiconductor Equipment Manufacturing

International (SEMI) has long been a residual source for semiconductor-based standards reference, but is also emerging as an important standard-setting body for the MEMS industry.

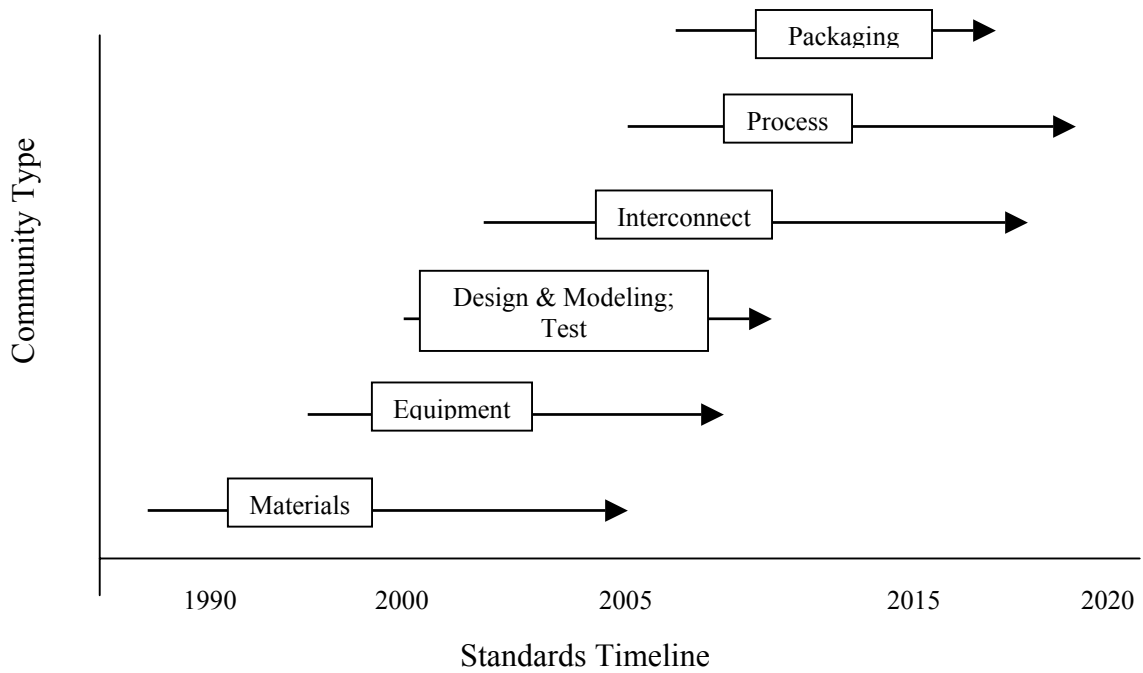


Figure 15 : Timeline to Standardization

The multitude of foundries demonstrates the need for standards. Standards unofficial or official already are being set at the process step level. Yet, there are still many ways to manufacture a MEMS device. Sacrificial surface micro machining has at least five different processes noted as initially MEMS in the middle, MEMS up front and MEMS at the end, with bonded wafer and silicon germanium alternatives. The CMOS standard for sacrificial surface micro-machining is still far off. However, efforts at Sandia National Laboratories and DARPA have initiated efforts along this path in IC like arenas with the SUMMIT and MUMPS processes and programs.

Chapter 14: Integration

Trends point toward more highly integrated system solutions. This trend is toward developing more complex devices that sense, think, act, communicate, and/or navigate, rather

than simple sensing or actuating. The choice of whether to integrate the control and signal conditioning electronics on the same chip, as the MEMS elements do (monolithic integration), or to use hybrid packaging technology is now one of the most contentious issues in MEMS technology. The ultimate decision will result from effective microsystems design balancing tradeoffs between device performance, manufacturing complexity, and yield.

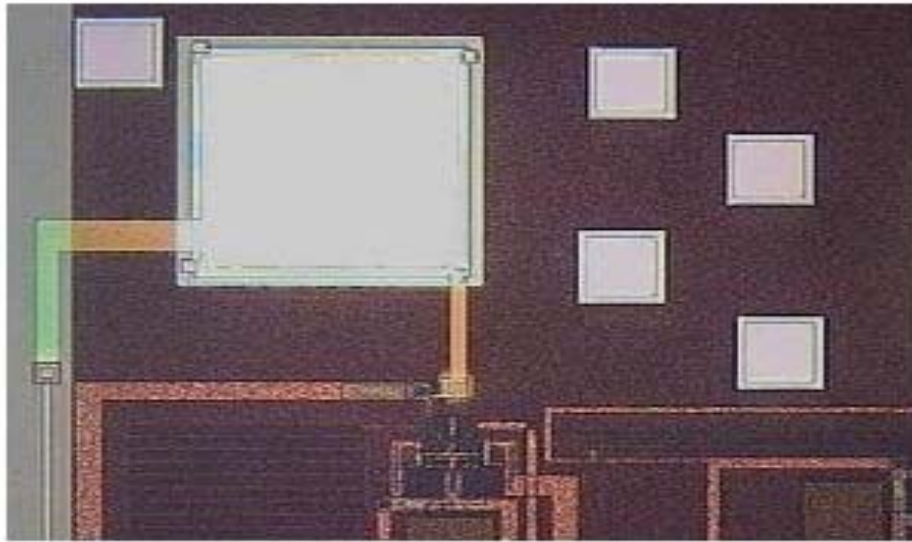


Figure 16. Fully Integrated Acoustic Micro Sensor Fabricated by Post-processing on a Standard 0.8µm CMOS Substrate. (Courtesy of QinetiQ)

Placing both the MEMS and the IC solutions on one chip approximately doubles the cost of silicon and limits manufacturing flexibility. But, integration reduces packaging costs while providing performance advantages. Sometimes monolithic integration is physically impossible due to the incompatibilities of IC fabrication technology and MEMS fabrication technology. When this occurs, hybrid solutions satisfy the requirements and/or provide superior design. Monolithic integration must overcome yield concerns and must be cheaper to produce or perform significantly better than hybrid solutions. Sometimes the application itself is not conducive to any integrated solution

Chapter 15: Glossary

One of the most difficult tasks in micro and nano technologies is to agree on a consistent use of terms. Indeed, a common vocabulary is often the first step in developing norms or standards in an industry. This is even true for the terms describing the field: MEMS, Microsystems, Micro-Machining, M3, and Top-Down Nanotech. Since they are defined differently depending on which continent one works, whether your emphasis is on micro versus nano. This is further complicated in the microsystems arena since devices function in many differing energy and environmental domains. Some symbols are used differently and mean different things in those domains, and a higher level of sophisticated understanding becomes involved in the field. These differences at basic levels reflect, in turn, differing industry scopes.

Difference in microsystems nomenclature can cause wide variation in the comprehension of the topic. The IMR Glossary is designed to provide a comprehensive, definitional effort for terms used in this emerging industry. We have provided operational terms, definitions used in differing application spaces, processing jargon, regional terms, management terminology, statistical terms, test, packaging and reliability terminology and many others.