Executive Summary

The International Micro-Nano Roadmap Leadership Group

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Introduction

We are involved in three economic waves of small tech development. We are on the top semiconductor microfabrication wave in the middle of the MEMS wave and are on the cusp of the third wave, Nanotechnology. This roadmap focuses on the fast growing enabling Micro and Nano technologies which are on the upside of these economic waves and filled with opportunity, promise and pitfalls for those firms supplying, manufacturing, funding, and using products made using these two technology bases.

The emerging Micro and Nano technologies are enabling technologies that are not focused on any single market or application space. This is typical of a industry based on fast paced technology change. This roadmap seeks to dispel some of the ambiguity centered on these emergent, enabling and often disruptive Micro and Nano based product applications. There is a dual tendency to either "hype" the value of the underlying technology or to radically understate the nature of its value. The International Micro-

Nano Roadmap provides direction to firms for the commercialization of products and systems produced utilizing nanometer and micron scale devices and structures for industrial, automotive, information technology, defense, life sciences, consumer applications and many others.

Who is this document for?

The purpose of the second edition of the Micro / Nano Roadmap is to assist in the commercial development of products and systems based on the Micro and Nano enabling technology base. The roadmap is designed to assist governments, organizations and individuals in the Micro or Nano value chain to develop their own strategic roadmap to improve their own chances for competitive advantage.

The roadmap in particular aims:

1 To "speed-up" the process of commercialization of products based on Micro and Nano technologies through the pre-competitive sharing of information between the firms and contributors involved in this roadmapping process.

2 To assist decision makers and their staff members to understand the industry, its technology, markets, and potential for future growth.

3 To guide corporate strategists, technologists, investors, policy makers, 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.

4 To provide a roadmap that allows companies, regions and individuals to develop a roadmap suited to their own needs

5 To ensure representation by many stakeholders including:
   1) Micro and Nano based product users and potential users (i.e. systems integrators, entrepreneurs etc.)
   2) Micro and Nano Suppliers
   3) Micro and Nano manufacturers
   4) 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 these technology and its markets

Looking Back

While the chaotic nature of Micro and Nano technologies appears to be new, this is far from the truth. Although there is currently a plethora of new developments in these technologies, 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 the commercial history of Micro and Nano based commercialization history.

Micro

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 utility. 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 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 in a single package system was possible. This movement to systemization was difficult because of the greater complexity; manufacturing MEMS devices was often as difficult as the physics and engineering required to develop and the MEMS device itself.

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 700 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 print head market, are dominated by MEMS devices, while others loom as large potentials for a variety of RF MEMS, 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.

Nano

The current embrace of Nano technologies as the potential next “big commercial opportunity” is built on a history of technology much older than widely believed. Nano technologies have been in commercial use for centuries. Perhaps the first product based on “bottom-up” nano properties of a material was carbon black. Does this fact diminish or enhance this technology base as part of “The next Commercial wave of technologies’ and Why then do we see these technologies as “emergent?” If historical commercial activity is any indication of the future the roadmap committee argues that this history is positive but guarded for the commercialization of Nano systems.

Nano technology is the third Micro manufacturing revolution based distinct but related to the first two; Semiconductor Micro fabrication and Micro Electro Mechanical systems (MEMS). Micro fabrication leverages the skill set of electrical engineers and MEMS those of Mechanical engineers whereas Nanotechnology leverages the skill sets of Materials and chemical based engineering and physical sciences. Nano technologies have been bifurcated into “Top Down Nano” which is a direct extension of Microsystems lithographic systems into the Nano range and “Bottom-up” which is more of the atom-by-atom creation of materials based system. Further a finer distinction can be made between bulk version individually addressed nanotechnologies.

Nanotechnology caught the imagination of the world; it has been popularized through the Nobel winning ground braking efforts of Dr. Smalley and others. Yet in 1974 a giant name in technology commercialization defined the field as:

The production technology to get the extra high accuracy and ultra fine dimensions, i.e. the preciseness and fineness on the order of 1 nm (nanometer, 10^{-9} meter in length). The name of 'Nano-technology' originates from this nanometer. In the processing of materials, the smallest bit size of stock removal, accretion or flow of materials is probably of one atom or one molecule namely 0.1~0.2 nm in length.

Therefore, the expected limit size of fineness would be of the order of 1 nm. Accordingly, 'Nano-technology' mainly consists of the processing of separation, consolidation and deformation of materials by one atom or one molecule.' Taken from N. Taniguchi, "On the Basic Concept of 'Nano-Technology'," Proc. Intl. Conf. Prod. Eng. Tokyo, Part II, Japan Society of Precision Engineering, 1974.

People have been commercializing technology based on bulk Nano reaction for hundreds of years (steel) albeit passively. IBM in 1990 provided their LOGO a written effort with Xenon atoms spelling IBM. Technologists and firms were investigating nano reactions in custom catalysts and microbiology from the 1930's and intensifying in the 1950's and 1960's. Further Pioneering firms utilizing Nano based solutions simply did not enjoy a common vocabulary to describe themselves. For Example, Dr. Al Chorney, former Vice president of one of the first "Modern Day" Nano Technology based firms Ferrofluidics Inc., founded in the 1960's and now president of SC Fluids stated: "…We simply did not know or use the term (Nano technology) to describe how our firm's technology base that provided unique value to our customers … we just knew we built unique products based on a unique technology base…it is gratifying to have the popular press and others give firms like ours a name. …".

A deep and rich history of commercial efforts in Nanotechnology based business and serial entrepreneurs exist in the field. Tom Griegos is a serial Nano technology entrepreneur. Currently he is the founder of the Nano technologies firm Surfect and he previously initiated two nano materials based firms both in the US and in Asia. Today fortune 5 as well as firms with 5 people is trying to commercialize unique solutions based on Nanotechnologies. The quality of new entrepreneurial enterprises investigating this space with firms like Zyvex and the industrial giants like Intel speak of the depth of commercial interest and resolve on commercialization products and systems based on Nanotechnologies

Summary

Today we have commercial MEMS and Nano solutions that are increasingly expected to provide more value as they replace traditional commercial solutions. Whether it is Nanotubes based computers or MEMS devices that sense, think, act, communicate and/or navigate them are running into both technological nay-sayers and the resistance that is experienced by any product requiring end-user behavioral change. MEMS and Nano devices today are acting more and more to revolutionize the markets and industries in which they find applications. These technologies have passed through many of the steps and the time required of a technology base to emerge as an industrial base.

<u>Structure of the International Microsystems Roadmap</u>

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

New Section Four

New Chapters

1. New Introduction
2. RF MEMS
3.Nanotechnology
4 MEMS Patent Analysis
5. Process and Equipment for MST
6. Equipment and Tooling for MNT

The Revised chapters are:

7) Status and Future of Microsystems / MEMS Foundries
8) Packaging and Assembly

Section One:
1. Introduction
2. Commercialization
3. Optical Microsystems
4. BioMEMS
5. Market Forecasting

Section Two:
6. IC Compatible Manufacturing
7. Non-IC Compatible Manufacturing
8. Simulation, Modeling and Design
9. Reliability, Testing and Metrology
10. Packaging & Assembly

Section Three:
11. Microsystems Foundry
12. Cost Models
13. Standards
14. Integration
15. Glossary

Major Findings

Our contributors have provided many salient conclusions throughout our chapters. Some of the roadmap information supports the current Micros and Nano technologies as the economic engine that could drive the 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 provide new findings from our new and revised chapters in section 4.

1. There is a longer history than commonly thought of products based on Nano technology
2. There are exceptional ways to categorize nanotechnologies that make commercial success
3. We provide a timeline to atomically precise manufacture
4. Nano technology
5. RF MEMS is near commercial breakthrough on many arenas and we provide a timeline and a roadmap.
6. There is a rich and core patent history in Micro and Nano technologies that include “core” patents
7. There is an imitation of a standard MEMS tool set
8. The MEMS industry is in an era of fermentation and we have provided an analysis of the existing foundry base to

We specifically include highlight fifteen major conclusions our contributors have made in the from our first roadmap effort:

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 is 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, or subsets thereof, to 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 Microsystems foundries is fluxing with a dramatic increase in the number of foundries since 2000 as semiconductor foundries seek

to use excess capacity by adding MST foundry work, but also indicating a shakeout in the number of foundries is also on the horizon.

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 and functional test and reliability have historically gone hand in hand in MEMS-based device commercialization and the future appears to follow this trend.

14) More accurate and interdependent toolsets are emerging in MEMS design, modeling and simulation which are increasingly able to simulate yield and performance parameters on MEMS structures and systems.

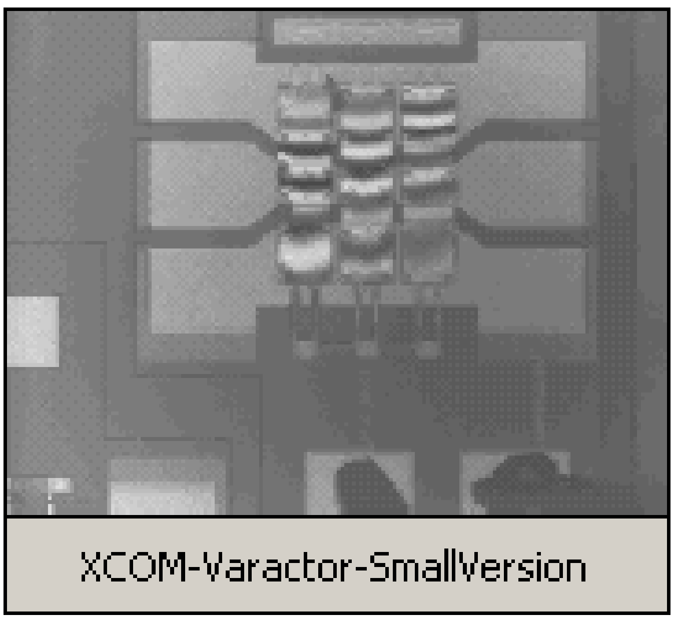
15) Our glossary points to the fractional nature of Microsystems, but also serves as a starting point for a unified "dictionary" for the industry.

Executive summaries of the second edition Roadmap Chapters

Chapters From Section Four

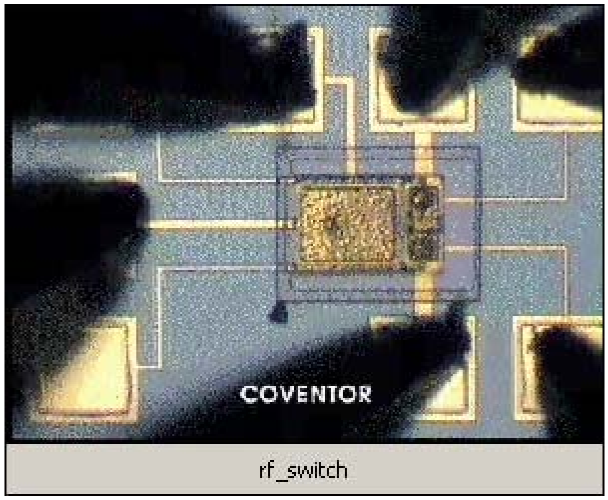
Second Edition Section 4 Chapter 2: RF MEMS

RF MEMS are a class of MEMS devices that mechanically manipulate Radio Frequency (RF), microwave, and/or millimeter-wave signals. The frequency range of interest for developers and users tends to be between 30 MHz and 100 GHz. At higher frequencies, systems tend to become quasi-optical, and the dividing line between RF MEMS and Optical MEMS begins to blur. RF MEMS have been in various stages of development since the late 1980's, with substantial breakthroughs and interest generated in the most recent five years. Many see RF MEMS as an enabling technology base that may provide the greater MEMS community with the next "Killer Application". This belief is largely based on the value of MEMS as replacements of present switching solutions in mobile telecommunications. Many firms are embracing RF MEMS not for consumer wireless markets, but for other communications applications. Still others see MEMS as a technology most suited for wireless sensors having wireless network protocols but that may or may not actually use RF MEMS antennas, switches and the like.



Movie 1. Varactor (courtesy; XCOM)

To view this movie, please go to **http://www.mancef.org/videos/varactor.avi**



Movie 2: RF Switch Coventor

To view this movie, please go to **http://www.mancef.org/videos/rf_switch.avi**

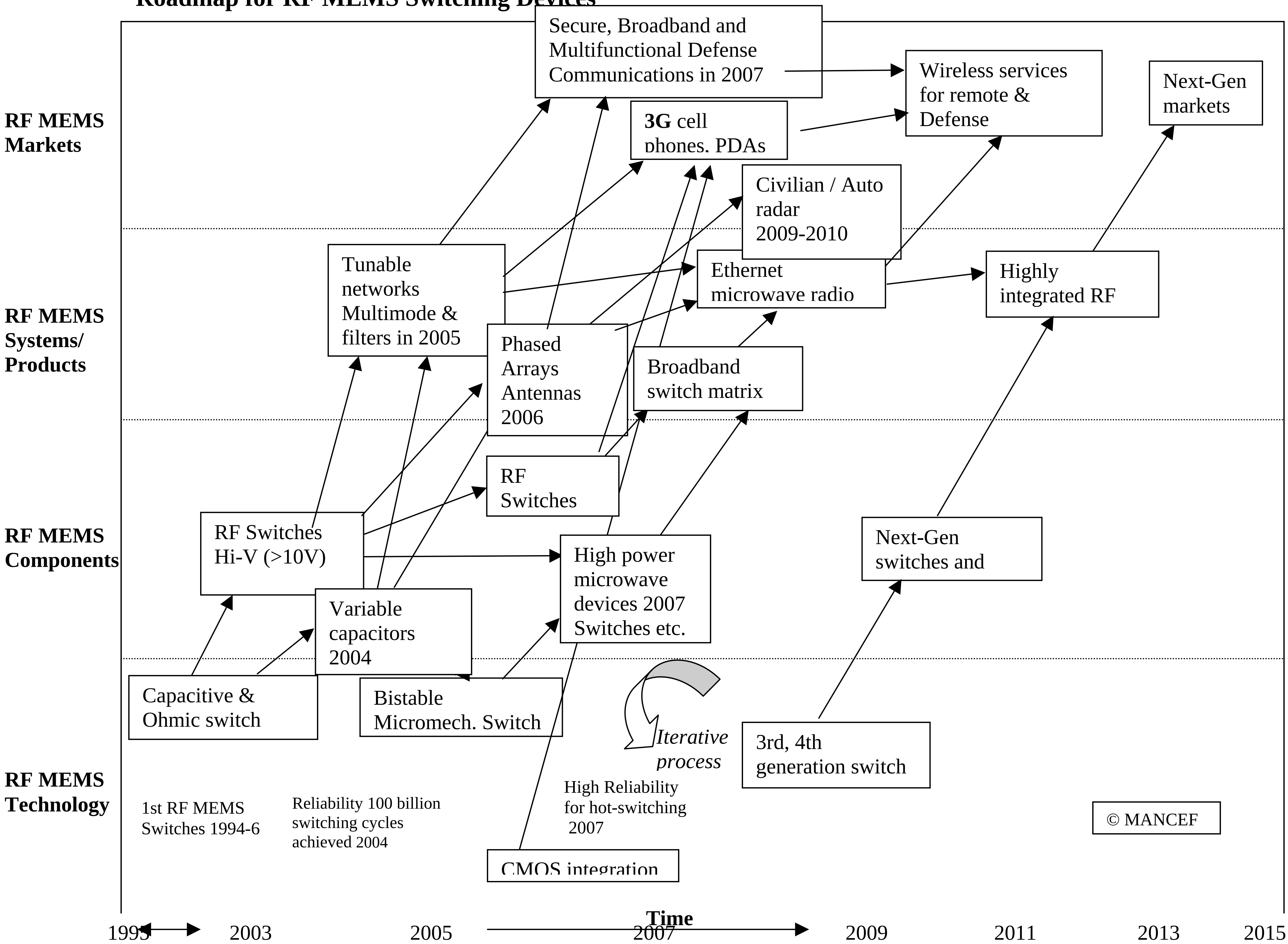
Many systems, subsystems, circuits, and components in the RF industry are presently based on transistors and diodes (traditional semiconductor devices), and on ferrites (bulky but high-performance microwave materials). The most common semiconductor devices used in RF systems include Field Effect Transistors (FETs), Pseudomorphic High-Electron Mobility Transistors (PHEMTs), Positive-Intrinsic-Negative (PIN) diodes, and varactor diode devices. The RF industry is large and healthy, spanning a wide range not only of technologies and products, but a wide range of applications as well, including telecommunications infrastructure, consumer devices, civilian radar and critical services, aerospace, and (largest of all) defense. The range of products available is staggering, with a highly fragmented market and customer space, each offering or requiring products that vary wildly in cost, size, and performance.

The conventional semiconductor technologies dominate the industry because of their small size and generally low cost. The large, expensive waveguide and ferrite-based products, by contrast, are used primarily for infrastructure, critical systems, and defense applications where high performance brings operational cost savings or safety returns. RF MEMS, by contrast, appears to offer many of the performance advantages of high-end components, yet promises the small size and low cost enjoyed by semiconductor devices. Performance advantages in RF circuitry are particularly valuable in applications close to the antenna, also called the “front-end” of an RF system. There is a significant performance and cost impact of using traditional high loss semiconductor technologies in front-end applications, because there are typically many such diodes or transistors that operate on an RF signal in any given design. As multi-frequency systems become commonplace, this performance penalty increases, and system designers are seeking new technologies that can solve their front-end problems.

RF MEMS switching devices and variable capacitors (varactors) may be the solution. These devices have demonstrated wide bandwidth, low loss, high isolation, unmatched linearity, unmatched power consumption, and (recently) high lifetimes in excess of 100 billion cycles. In this chapter, we show there are many enterprises enjoying success in the marketplace by leveraging the performance of RF MEMS. The original suppositions that RF MEMS are direct replacements for conventional RF ICs have not proven to be entirely correct. Instead, RF MEMS have been selected in specific applications because of a revised architecture, a reduced component count, as well as the improved performance. The cost of RF MEMS solutions remains high, however, so commercialization has been restricted to niche opportunities.

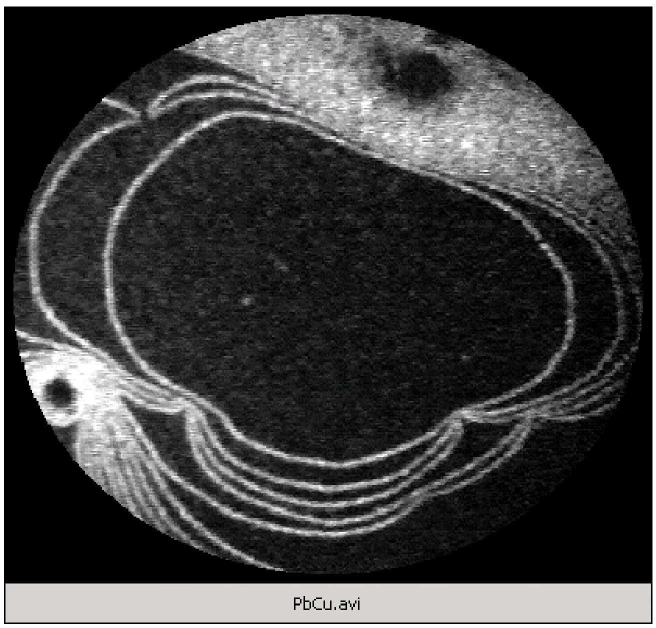
This chapter provides a technology product roadmap for RF MEMS with the market drivers that influence customers towards embracing this new technology. The chapter contributors often agree that RF MEMS is a product platform that can serve many differing market spaces, and recognize that there are "holy grail" applications with huge market potential. Some microsystems, MEMS, and nanosystems-based products are commercially maturing to the point of becoming dominant paradigms, but even despite its "age", RF MEMS is not considered a mature technology by nearly any metric. In this chapter, we define RF MEMS as a key disruptive technology and a market driver for the telecommunications industries. Some RF MEMS products are already available, but each developer is forced to carefully earn acceptance for each niche application. We provide in this chapter a partial list of existing and near-future products and applications with their timelines. We further provide a short review of the existing corporate interest, coupled with a history and short discussion of RF MEMS-based patents. Finally we review the obstacles inhibiting RF MEMS development. We provide a RF MEMS switch roadmap chart below

Roadmap for RF MEMS Switching Devices



Second Edition Section 4 Chapter 3: Nanotechnology

The term "nanotechnology" has captured the technological interest and excited the economic spirit of many people during the past decade. The commercial interest in nanotechnology has skyrocketed as the term has been popularized. The popularity of the phrase is such that it is currently used ubiquitously. This imprecise language, and overuse of the word, has made the term fuzzy, all-encompassing and trendier than many imagined possible. This is especially evident in nanotechnology market projections, which have risen dramatically over the past 5 to 10 years as more and more traditional "product families" are engulfed by the diffuse terminology and then included in these projections. This has led to many instances of "over-hype" as experienced in the "dot com" burn and subsequent demise. Movie 1 below provide a view of inorganic self assembly of atoms



Movie 3: Pb/Cu Atomic Mono layer Formation
(courtesy Sandia National Laboratories)
To view this movie, please go to http://www.mancef.org/videos/pbcu.avi

This chapter is designed to provide some structure to this rapidly emerging field. We will provide:

1) A group of definitions and categorizations
2) A discussion of funding sources and their investments
3) A discussion of the patent landscape
4) A discussion of traditional, existing and potential nanotech markets
5) A discussion of nanotech industries and products
6) A discussion of products
7) A discussion of particular companies within particular industries

Because of the meta-status of the term, nanotechnology is becoming an all-encompassing field. In reality it is currently an enabling technology that provides foundational elements to many industries or markets rather than a stand-alone industry of its own. This status may change over time. Nanotechnology is new and attracting attention, a darling of Wall Street. The current overarching use of the term has created a two-fold problem for those who collect data on nanotechnology and its uses. The first challenge is the "problem of plenty". There is currently a plethora of data easily retrieved by the simplest data search engines (there will likely be well over 3 million hits on any search engine on the web you choose by the time you read this document). The second challenge is the "problem of time". The term Nanotechnology or Nano was simply not used by the early Nano systems firms. For example, neither Ferrofluidics in the 1960's nor the large numbers of microbiology based biomolecule production companies of the 1970;s and 1980's used this terminology in descriptions of their development or their products. In this document we have developed a roadmap based on a clean dataset.

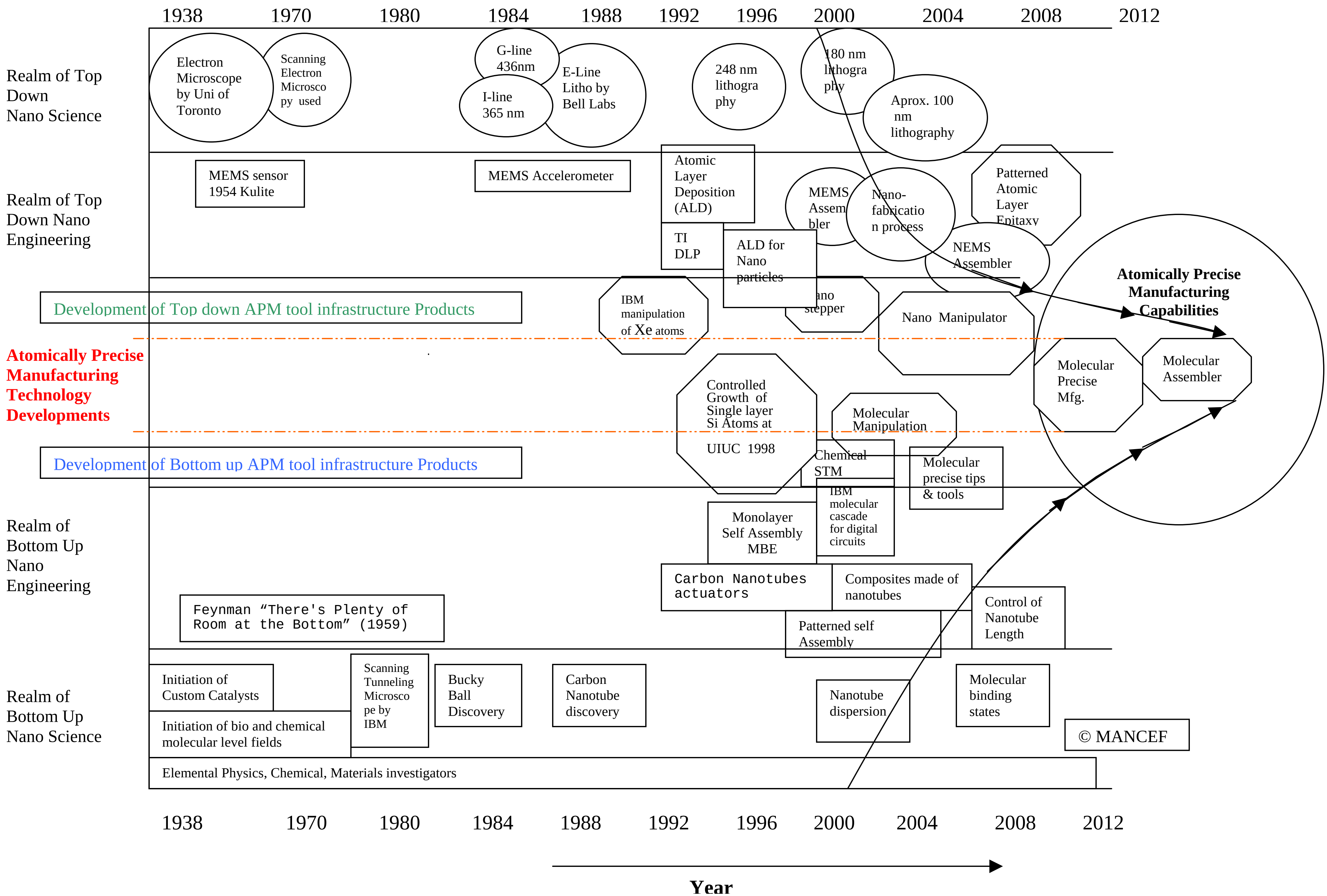
Patents and patent applications were gathered by our members using many sources. A key source was Aurigin, a web-based intellectual property (IP) management program for which Sandia IPMG has a license; Aurigin's patents are taken from databases maintained by the World Intellectual Property Organization (WIPO).

Populist thought and Impact

One problem with the field is that the term Nano has come be associated with almost anything new, small, molecular, atomic, trendy, ominous, or eye catching. Major Motion pictures, with movies such as Stepford Wives, Spiderman, and others, and books such as "Prey" have linked the technology to "hyper hype" in order to sell entertainment. The fascination with the term nano has elicited instances of unquestioning support by investors and cases of unreasoning fear by the general public; neither benefits the technology. Any new technology will (and should) get a critical review. This is particularly so especially when the technology under scrutiny is as far reaching and as broad in potential impact as nanotechnology. Stakeholders are beginning to understand the multi-various attractive features nanotechnology offers. The less desirable attributes are poorly understood by both participants in the nano-explosion and the population as a whole.

Numerous web sites have material available on that alternatively revel or revile the Nanotechnology's social impact. As always with new pioneering science the pace of social understanding lags technological progress. There is a fermentation that must take place which will force people to become aware or learn about nanotechnologies. Learning is change and people do not embrace change in the main but out of this we think two things will occur. First, there is and will continue to be an open and frank discussion of the subject. Second, and more importantly there must be accessible and easily understood material to educate ones self about the science. This effort seeks to assist this process in many ways. For example at the end of this chapter we list several companies that are developing products containing Nanotechnology. Further we offer several web pages in which to explore and learn more about Nanotechnology. Finally, we try to develop knowledge which will alleviate at least one source of concern: fear of the unknown.

Firms in the value chain of nanotechnology commerce are starting to provide similar information. For example some pioneering companies have provided white papers to explain the fundamentals of technology and answer questions concerning the critical implications of its use. One source for such documents is available at www.zyvex.com. Only by dealing head-on with these issues will the general public be empowered to make an informed decision. In the figure below we provide a roadmap for Atomically Precise Manufacturing



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Realm of Top Down Nano Science
Electron Microscope by Uni of Toronto
Scanning Electron Microscopy used
G-line 436nm
I-line 365 nm
E-Line Litho by Bell Labs
248 nm lithography
180 nm lithography
Aprox. 100 nm lithography
Realm of Top Down Nano Engineering
MEMS sensor 1954 Kulite
MEMS Accelerometer
Atomic Layer Deposition (ALD)
TI DLP
ALD for Nano particles
MEMS Assembler
Nano-fabrication process
Patterned Atomic Layer Epitaxy
NEMS Assembler
Atomically Precise Manufacturing Capabilities
Development of Top down APM tool infrastructure Products
IBM manipulation of Xe atoms
Nano stepper
Nano Manipulator
Atomically Precise Manufacturing Technology Developments
Controlled Growth of Single layer Si Atoms at UIUC 1998
Molecular Manipulation
Molecular Precise Mfg.
Molecular Assembler
Development of Bottom up APM tool infrastructure Products
Chemical STM
Molecular precise tips & tools
IBM molecular cascade for digital circuits
Realm of Bottom Up Nano Engineering
Monolayer Self Assembly MBE
Carbon Nanotubes actuators
Composites made of nanotubes
Feynman "There's Plenty of Room at the Bottom" (1959)
Patterned self Assembly
Control of Nanotube Length
Realm of Bottom Up Nano Science
Initiation of Custom Catalysts
Initiation of bio and chemical molecular level fields
Scanning Tunneling Microscope by IBM
Bucky Ball Discovery
Carbon Nanotube discovery
Nanotube dispersion
Molecular binding states
© MANCEF
Elemental Physics, Chemical, Materials investigators
1938
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Second Edition Section 4 Chapter 4: MEMS Patent Analysis

This chapter is a response to roadmap users that have requested a more in-depth knowledge of MEMS based patents. Roadmap users' questions were basically set in two groups. The first group of questions concerned the content of MEMS patents (content). The second group was focused on the patenting process (process) or questions about the process and pitfalls of IP management in general and patents in particular.

Specifics requests were as generic in the content grouping as:

1) Is there a great deal of MEMS patent activity?
2) What types of things are patented?
3) Are their clusters of patents?

Or as specific as;

1) What was the MEMS patent landscape for 1993?
2) Who were the major patent MEMS patent holders (assignees)?

Specific questions in the Process group included

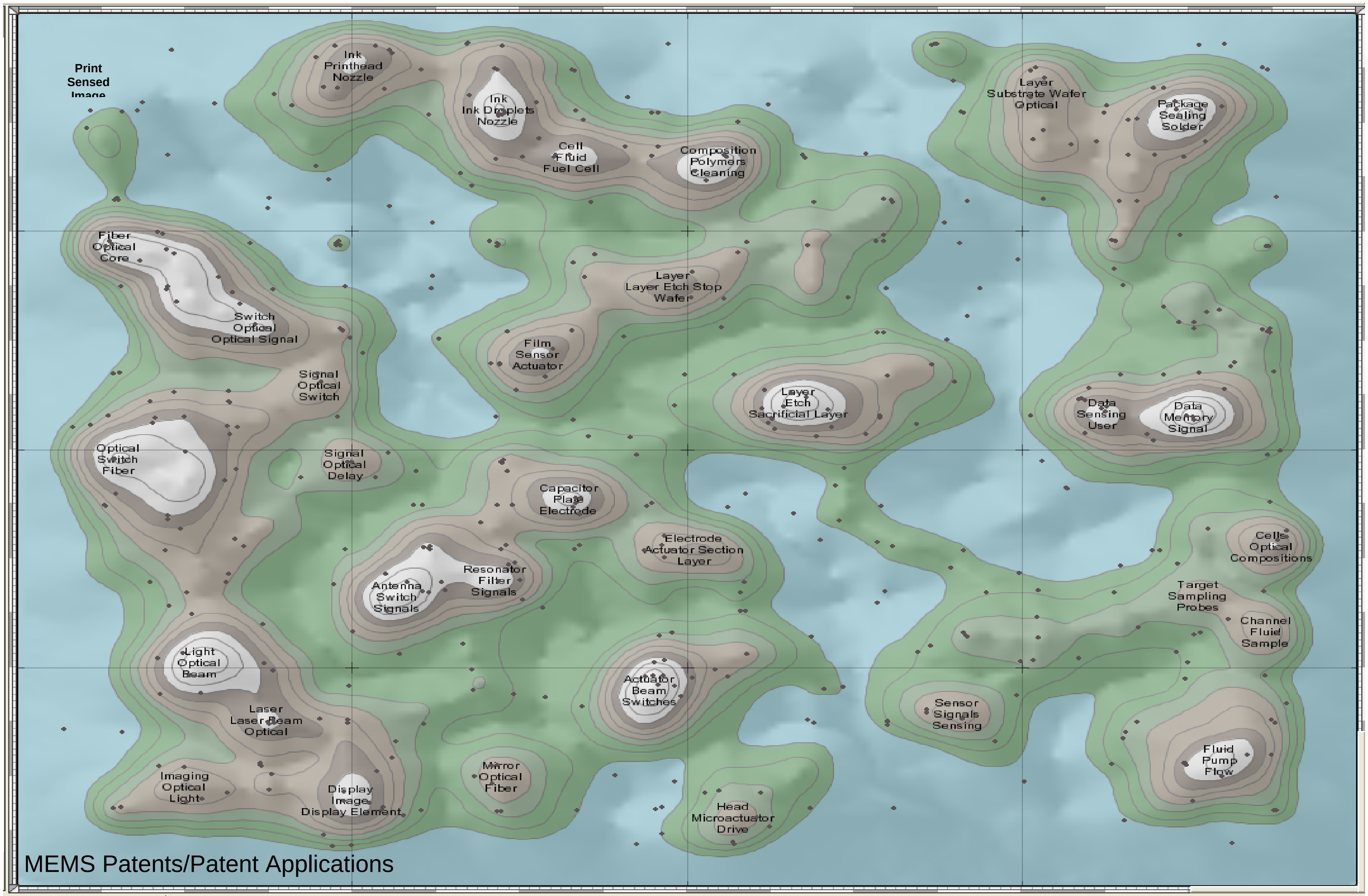
1) What should I patent?
2) What can I patent?
3) What type of patent should I get?

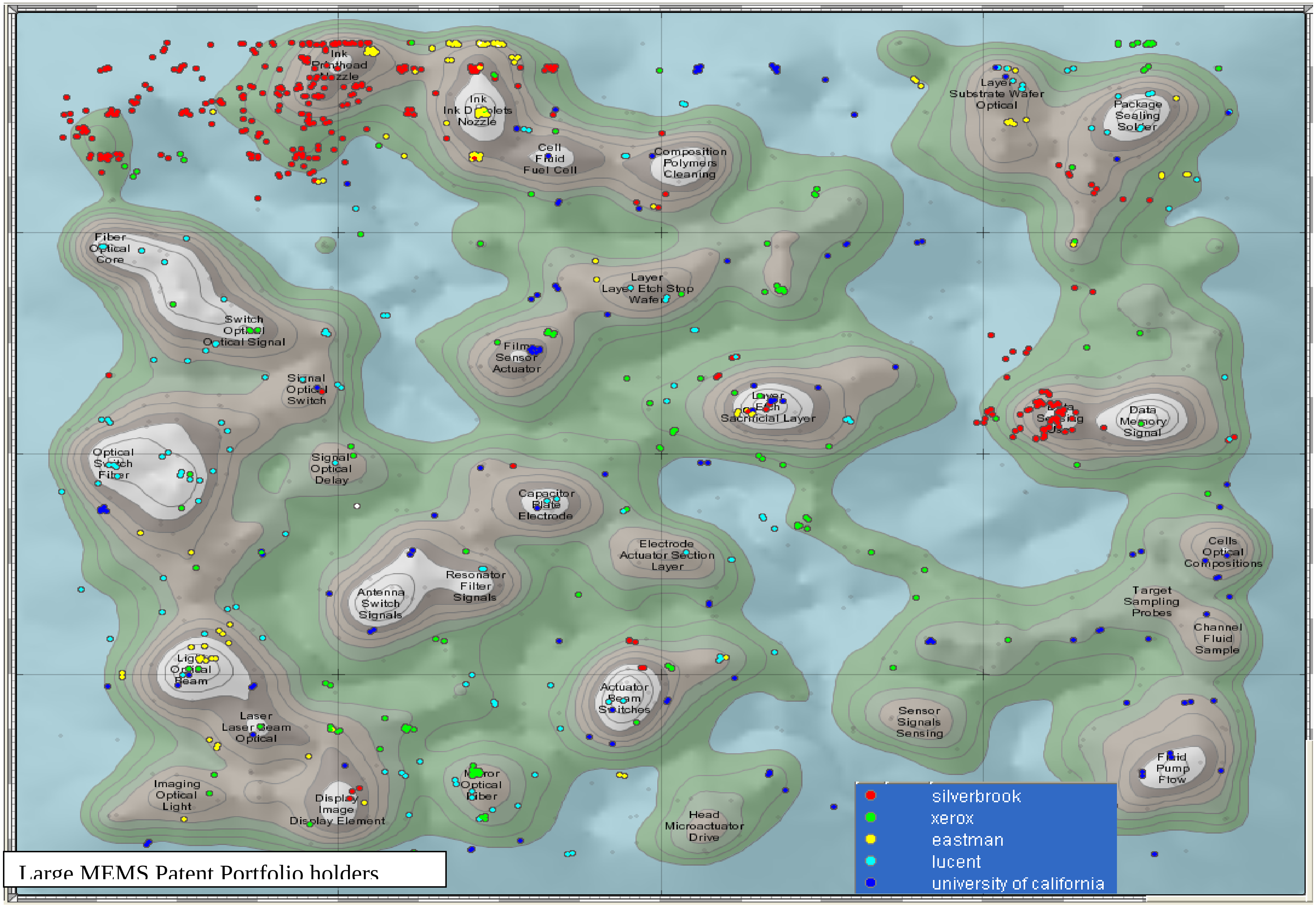
Or as specific as;

1) Should I apply for a patent myself?
2) Does this particular patent increase the value of my patent portfolio?

This chapter seeks to provide some information for all of these questions but we acknowledge our role as Conscious Incompetents suggesting experts where appropriate. We have chosen to base this analysis on data available from the US patent office to restrict our scope of analysis. We provide much of the content questions requested of us by our roadmap users. We utilize the most used patent system. Specifically we provide the identified clusters of MEMS patents over the past 10 years. Further in other chapters RF MEMS; and Nano technologies , we provide a detailed patent analysis of those activities. Finally we identify the top patent assignees from 1994-2004.

The second portion of this chapter provides some process knowledge and questions that one should ask when involved in the patent portion of your IP Management strategy. We emphasize a proactive rather than a reactive approach. See figure below for patent maps of terrain and key patent holders.


Print
Sensed
Ink Printhead Nozzle
Ink Ink Droplets Nozzle
Cell Fluid Fuel Cell
Composition Polymers Cleaning
Layer Substrate Wafer Optical
Package Sealing Solder
Fiber Optical Core
Switch Optical Optical Signal
Layer Layer Etch Stop Wafer
Film Sensor Actuator
Signal Optical Switch
Layer Etch Sacrificial Layer
Data Sensing User
Data Memory Signal
Optical Switch Fiber
Signal Optical Delay
Capacitor Plate Electrode
Electrode Actuator Section Layer
Cells Optical Compositions
Antenna Switch Signals
Resonator Filter Signals
Target Sampling Probes
Channel Fluid Sample
Light Optical Beam
Actuator Beam Switches
Laser Laser Beam Optical
Sensor Signals Sensing
Fluid Pump Flow
Imaging Optical Light
Display Image Display Element
Mirror Optical Fiber
Head Microactuator Drive
MEMS Patents/Patent Applications



Large MEMS Patent Portfolio holders

Second Edition Section 4 Chapter 5: Process and Equipment for MST

Although MST/MEMS is characterized by diversity this chapter managed to define 10 standard processes by which a majority of bulk and surface micromachining devices can be made. The toolset needed for that is relative limited in number, it is a mix of general thin film equipment like CVD equipment, lithography tools etc. and specific MST/MEMS equipment like Deep Reactive Ion Etchers and backside aligners. Those tools are discussed in more detail in the equipment chapter of this roadmap. In this chapter the defined general processes are described supplemented by examples of products made by these processes. A listing of principle equipment is included needed to run the basic processes of bulk and surface micromachining. It is based on the data of 37 micromachining factories in the world. The analyses of the data has demonstrated that the micromachining processes can be structured into 10 different processes, i.e. 10 process flows are able to serve far over 95% of the bulk and surface micromachining products. The 10 different process flow share close to 90% of the same equipment set, and differentiate from each other by mostly 2 to 3 additional processes. The figures below associate differing process with MEMS based product typologies and an example of a process stream.

	Surface micro-machining	**Bulk micro-machining** **(+ bonding, electro-plating,)**
Description	Structuring of thin layers at the surface of the wafer front side	Structuring and building-up in the thickness direction of the wafer
Typical product examples	Surface optical moveable mirrors	Pressure sensor
	Low sensitivity acceleration sensor	High sensitivity acceleration sensor
	Gyroscope	Flowsensors
	Optical waveguides	Micro filters
	Micro switches	Fluidic mixer
		Micro pump
		Etc.
Processing technology	Multi-layer polysilicon process	Anisotropic KOH wet etching
	Thin layer patterning of SiN, SiO2 and polysilicon	Deep Reactive Ion Etching of silicon
	Thin layer patterning of metal layers	Silicon on Insulator (SOI) etching
	Sacrificial layer etching	Anodic and Fusion wafer bonding
		High aspect ratio electro-plating

Process stream 1

Product group: **Thermal sensors, micro sieves, and other KOH etched structures**

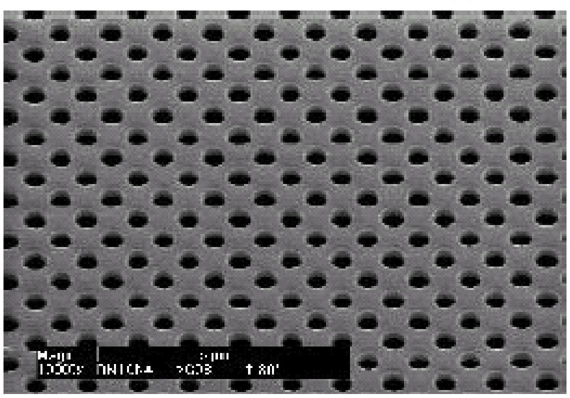
Physical description: **Silicon Nitride Membrane devices**

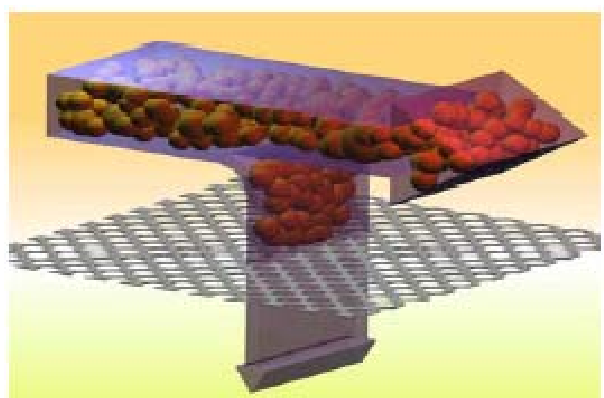
This process stream enables the manufacture of many types of devices with different functionality. All related devices contain patterned silicon nitride layers, membranes, or bridges, and wet anisotropically etched (KOH) cavities. Metal deposits on the front and or backside are another option. The equipment for this stream is from the basic set of equipment, as displayed in Appendix B. Some devices in this process stream are well known and still commercially interesting.

Key Equipment: **LPCVD and PECVD nitride, KOH, metal deposition and etching, RIE**

Products:

- Thermal Conductivity Device (TCD)
- Thermal gas flowsensor
- Thermal fluid flowsensor
- Thin membranes for TEM equipment
- Micro fluidic sieves and other perforated thin membranes
- V-groove glass fiber connector
- Micro needles for medical applications





Micro sieve by Aquamarijn and Fluxxion. This micro sieve is a perforated silicon nitride

Second Edition Section 4 Chapter 6: <u>Equipment and Tooling for MNT</u>

The emerging markets for MST/MEMS (Micro Systems Technologies / Micro-Electro-Mechanical Systems) products have created a demand for specialized equipment. The first to fulfill that demand where suppliers of dedicated MST/MEMS tools including Deep Reactive Ion Etchers (DRIE), waferbonders and backside aligners. Those companies (STS, Alcatel, EV Group and Suss Microtec) are still in the forefront of this market. Spin-offs from universities were started to fulfill (niche) demands, whilst established companies entered this arena at a later stage, offering adapted processing tools developed for other industries, such as, those specializing in thin film processing. More interestingly, even the (large) semiconductor equipment manufacturers have begun to show an interest. Within this context, there is now available a mixture of general equipment facilities, designed and developed for other applications such as semiconductors and also equipment adapted or specially tailored for Micro-Nano Technologies (MNT) production.

This chapter categorizes the equipment market into the following, general, areas:

- Front end equipment
- Back end equipment
- Nanotechnology equipment
- Test and measurement equipment

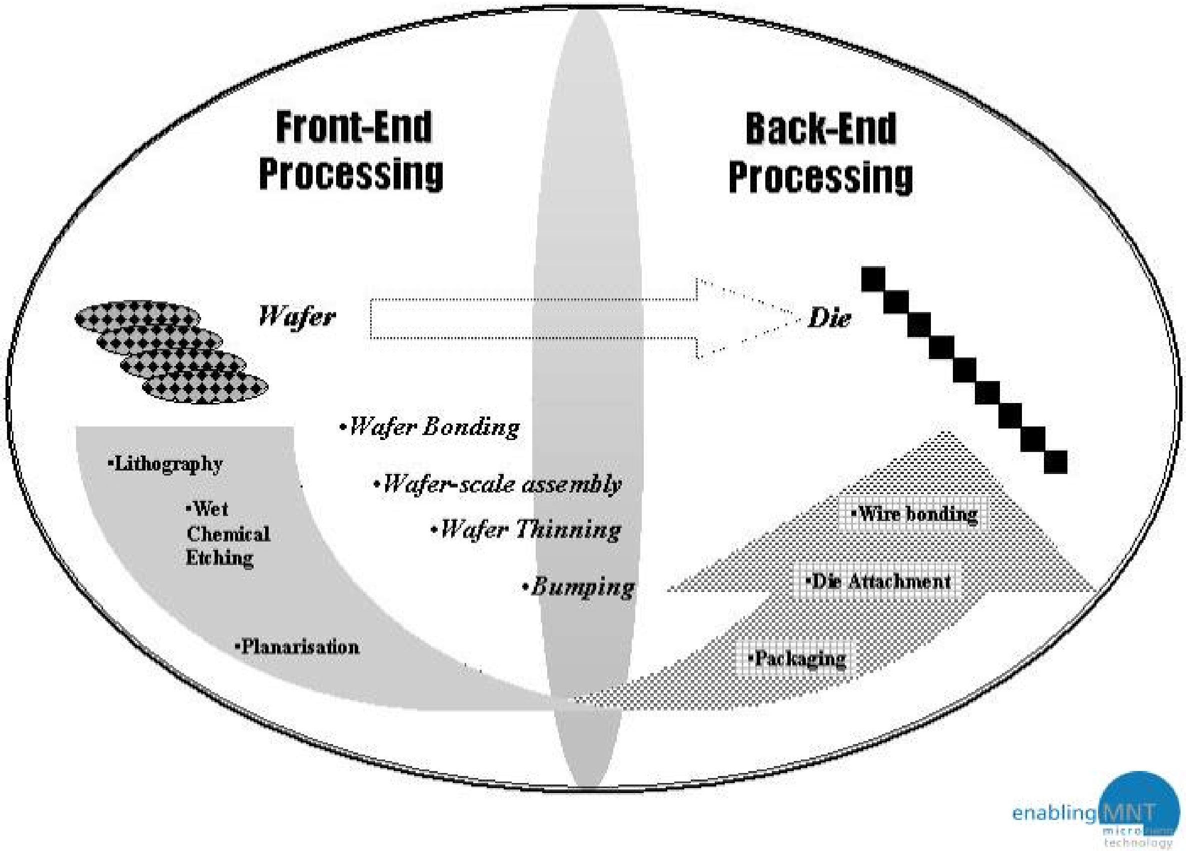
Front end equipment as a term, generally, refers to equipment used to process wafers within a waferfab facility. Test and measurement equipment, on the other hand, combines the collection of instrumentation used to control and maintain the product's quality. The definition of the back end equipment group is taken rather broadly as it covers equipment for assembly, packaging, material processing, molding and other similar capabilities.

We investigated the market status of equipment suppliers servicing the nanotechnology industry in terms of production and fabrication from an MST/MNT perspective. This review invariably addresses the pre-production and experimental / trial plants claiming a capability in nanotechnology. Although equipment for nanotechnology, dedicated to research applications, is already on the market, it can be stated that the market for nanotechnology production equipment is still at the beginning of its lifecycle.

For the purposes of this review, nanotechnology is defined as a set of capabilities directed towards the development and manipulation of structures at the atomic scale (100 nm or less). Important developments in areas that either overlap with and/or influence the progress of nanotechnology, such as semiconductor lithography and direct writing, are also discussed in this chapter.

Unlike electronic devices, where only electrical parameters need to be tested, MNT devices require precise measurement of multi domain parameters. In the case of mechanical microsystems, the static and dynamic behavior must be investigated in such a way that the measurement does not interfere with the performance of the device. The two most critical area in testing of micro and nanotechnology are: identification of the Known

Good Dies and measurement of material properties. Figure below provide the direction of the chapter



Processes crossing the borders between front end and back end processing

Second Edition Section 4 Chapter 7: *Status and Future of Microsystems / MEMS Foundries*

This chapter provides management of Microsystems foundries as well as their users assistance in their decision making process. We aim to assist designers in finding appropriate "Fabs" early in their device development phase, help foundries understand the direction of technology, and provide trends in fab construction and conversion. For example, it is comparatively easy for the MEMS designers to find prototypical foundry services. But, there remain prerequisites to finding a reliable path from product concept to commercializable volume.

The contributors to this chapter recognize that the cost involved in changing fabs or processes (see MEMS/MST Cost Modeling chapter), in both time and money, is enormous. A barrier for MEMS manufacturing is the difficulty of creating and maintaining cost-effective fabrication facilities for low volumes that can facilitate also high volumes. Another barrier is time needed to transform university developed processes into industrial ones. The drive to design for performance instead of design for manufacturability is helping to get customers interested, but is also delaying industrialization.

MEMS is still an emerging and disruptive process technology with many application specific technology choices. However, as discussed in both the Non-IC and the IC-like processing chapters the trend is toward concentration on fewer but more robust manufacturing. Further, dominant MEMS manufacturing technologies, in many application spaces, are still to be determined. If not the full process, some process steps are becoming more standard. Yet standardization does not exist to any great breadth or depth (Standards chapter). Therefore, MEMS manufacturers must be prepared to deal with multiple substrate materials of various shapes and sizes, as well as supporting multiple process technologies, some of which have little or nothing to do with traditional semiconductor technologies.

Here we also state that the cost of any new MEMS foundry infrastructure is very high and the trend is for that cost to continue to increase. Fortunately, last-generation IC foundries can be used for fabricating present-generation MEMS for IC like process technologies and this has contributed to a larger trend for existing semiconductor fabrication facilities to move to MEMS facilities or dual facilities providing both semiconductor and MEMS based processes for commercial and internal customers. 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 its standards. In the Design Simulation and Modeling (DSM) chapter, contributors provide a short discussion on methods that current foundries and MEMS DSM suppliers are using and suggest future trends.

However, this is still not the case, and many examples show that the foundry customer relation is still more a partnership relation then a straightforward customer-supplier relation. The contributors to the Foundry chapter also have recognized a number of trends. First, there has been a continuous growth of companies offering foundry services in MST/MEMS for the last 5 years. Of the MST/MEMS foundries identified in 1999, only half of them are currently offering similar services. Half of the ex-foundries however are still in existence today, but concentrate don other activities. The gap has been filled by new entrances, partly by the conversion of semiconductor to MEMS foundries, attracted by the increase of volumes transferred to reaming foundries and partly driven by demand from their customer base. Finally, there is a large trend to embrace some sort of quality standards. This is a natural outgrowth, in that there is a rush to embrace quality standards for MEMS manufacturing facilities. Practically all foundries already having some sort of ISO 900X certification or are in the certification process.

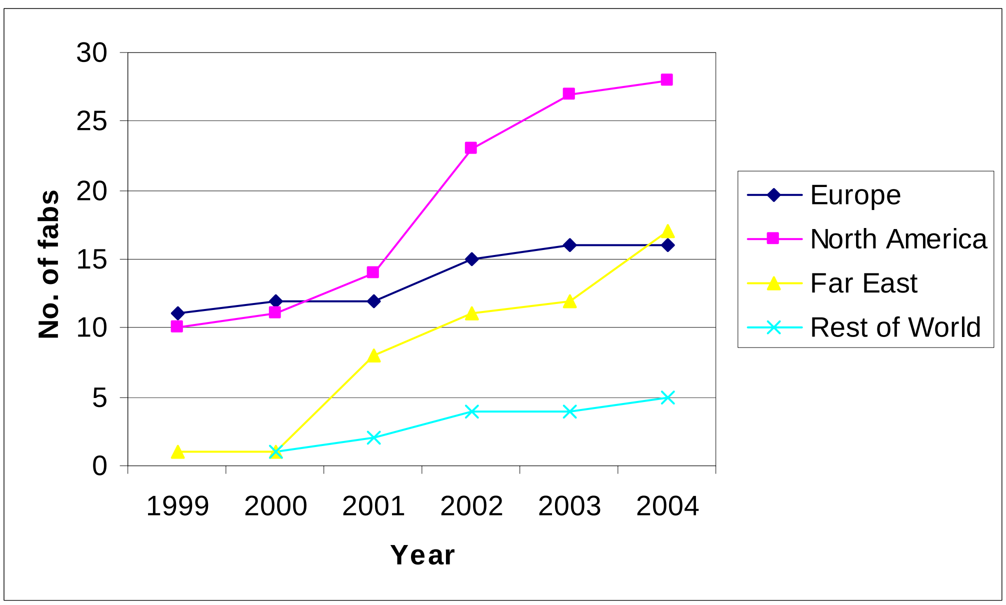
In the early days of MST, the foundry concept came up as a way to lower the barriers of bringing a design to market. This is still a viable concept. The market is dynamic, as can be expected in this fast growing segment, and there are forces pulling foundries into the captive market; i.e., the success of their own products or the "IP Hunger" of larger companies. However, now interesting commercial opportunities are bringing new players into the field. The number of foundries is growing, especially in the Far East.

There are 5 categories of foundries:

1) University originated, mostly research oriented and/or SME
2) Smaller semiconductor companies offering MST service for balancing the capacity
3) Larger semiconductor companies offering MST to protect the customer base
4) Smaller non-semiconductor companies offering MST service for balancing the capacity
5) Pure foundries

In particular it is categories 2 and 3, semiconductor companies, which are growing in number.

There are other signs of maturation of this industry. There is now much more attention to quality and production professionalism compared to the early days of MST. The foundries are also concentrating more on smaller areas of technology and marketing. This focus will deepen and improve the technology base of the foundries. This trend is supported by the rising attention of the larger equipment suppliers to the needs of the MEMS market. We provide a chart of the number of MEMS foundries worldwide below



Trend and number of foundries worldwide

Second Edition Section 4 Chapter 8: Packaging and Assembly

There are many references by MEMS experts as to the high percentage of the product cost attributed to the "Back end" (i.e., package and test). This percentage has been cited as high as 70% of the total cost. Packaging has not until recently received the research and development attention it deserves as a key enabler for microsystems commercialization. Packaging has often been referred to as the "Achilles Heel of MEMS Manufacturing" and a key "Bottleneck" in the process of MEMS commercialization.

A significant amount of attention is now being directed at packaging concerns. Packaging was an afterthought for most MEMS designers and manufacturers only a few years ago. Now it is part of the initial design process as mentioned by many notables such as Dr. Steven Senturia (see the Design, Simulation, and Modeling chapter for further insight). It is this second question that will dominate packaging and assembly over the next 5 years in order to make the majority of MEMS devices cost-effective and more ubiquitous in the marketplace. Therefore, a chapter in this MST Roadmap has been dedicated to the challenges of packaging.

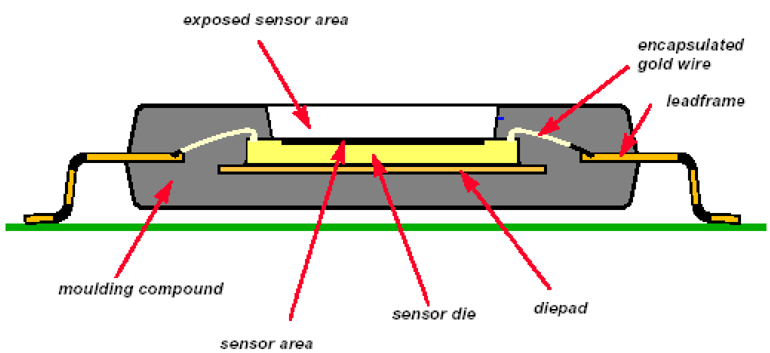
Assembly of MEMS devices utilizes many engineering and design tools and supporting infrastructure for microsystems. There is a trend for MEMS specific packaging and assembly tools from EVG, Karl Suss, MA3 Solutions and many others, although Cost of Ownership in relation to the often relative small production volumes can be a problem. But, to date, many MEMS devices are developed using equipment not specifically MEMS-oriented, but more likely standard semiconductor industry equipment that has been modified somewhat ("Force-fit Prototyping" see the Introduction chapter). As discussed in both the IC and Non-IC related chapters, there are many application specific processes in MEMS. Nowhere is this more apparent than in MEMS packaging. More often than not, this application specific approach leads to a trial-and-error approach to packaging design and implementation. However there is a growing attention to more generic approaches of which waferscale packaging and modification of standard IC packaging concepts to enable MEMS packaging are the most striking examples.

There is a trend toward the "Product Family" concept in Microsystems. This occurs when the same core MEMS device is utilized in several applications causing the manufacturer to package the device in several different ways, depending on the environment where the device will finally be used. For example, *in vivo*, bioMEMS devices have to be encapsulated so that they are truly non-invasive. MEMS devices used in engine performance sensing must be temperature resistant, while other MEMS devices used in space applications will have to be radiation hardened. Thus, since there are so many different types of MEMS devices being developed for use in nearly every conceivable market, there are at least double the amounts of packaging methods that have to be considered.

Often, the MEMS industry is likened to the semiconductor industry in its nascent days. At that time, the semiconductor industry faced many of the same issues with packaging ICs because the expensive packaging was often considered an afterthought.

Over time, the semiconductor industry separated into two completely different fields with very little overlap: front-end and back-end (packaging). Lately the borderline is becoming vague with the introduction of wafer bonding (a wafer scale packaging technology) and the decreasing features sizes in back end processing. It is quite possible that the MEMS industry can learn lessons from their semiconductor counterparts and design-in manufacturability and packaging concerns starting with the early prototype concepts.

This chapter focuses on the recent developments in MEMS packaging, as well as discusses the future of this sub-industry. One of the more promising approaches to MEMS packaging appears to be the "Supply Chain Method" and this process is discussed We provide below in figures a plastic package with an optical-lid for MEMS.



Cross section of a moulded cavity package (courtesy Eurasem BV)

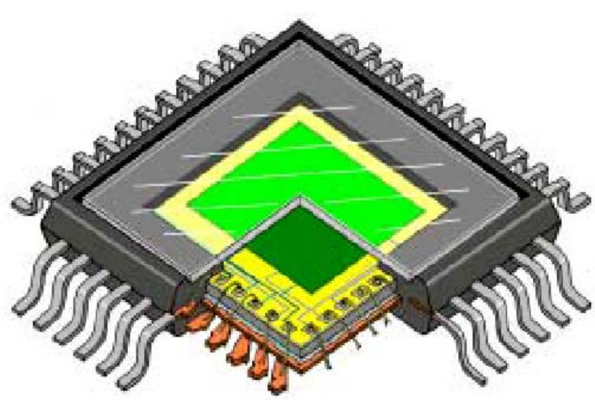


Figure 16: Plastic package with optical lid (Courtesy Eurasem BV)