2

COMMERCIALIZATION OF MICROSYSTEMS

Chapter Leaders

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

Christian Schaefer
EV Group
c.schaefer@EVGroup.at

Inderpreet S. Thukral
IBM
ithukral@vnet.ibm.com

Roger Grace
Roger Grace & Associates
RGrace@rgrace.com

Murkuu Tilli
Okmetic
makuu.tilli@okmetic.com

1.0 Introduction....35
2.0 The Microsystems Commercialization Process....35
3.0 Impediments to MST Commercialization..44
4.0 Commercialization Status of MST Applications....52
5.0 A Report Card On Overall MST Commercialization....60
6.0 Conclusions....64
7.0 References....66

Executive Summary

Industries based on emergent or disruptive technologies are characterized by impediments delaying their creation. Many times, the commercial development of an emerging competitive technology is the act of a single firm's pursuit of a solution for a specific customer. The creation of this initial product is not necessarily the harbinger for an industrial dynamic or market formation or even for that matter the birth of a firm. However, in the case of an emergent technology like MEMS, this hurdle has been crossed. For a technology to form the basis of a new industrial revolution, it must answer the question for an initial commercial application and follow that by demonstrating its ability to solve similar problems in a uniquely commercially valuable manner. MEMS manufacturing has achieved this level of activity. From this, a cadre of technology product platforms is developed that is commercially effective across multiple technology product domains, as microsystems are doing, as this document is written.

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 for through the use of a MEMS report card. Finally, we provide models that illustrate the current state and the future promise of microsystems, as well as indicating the scope and future of "Small Tech."

1.0 Introduction

Following in the Footsteps of Microelectronics Technology

MEMS/MST technologies are just beginning to start a micro manufacturing revolution comparable to the microelectronics technology. Just as it took over 20 years for semiconductor microfabrication-based microprocessors, memory devices, and other "Killer Apps" to develop, similar innovations from microsystems will revitalize existing industries and generate new markets.

MEMS/MST: The Rising "Winds of Creative Destruction"

In the last five years, there has been an unprecedented growth of interest in microsystems technologies. An estimated 900+ companies, research institutes, and universities are currently involved with microsystems. Commercial and industrial microsystems users are growing exponentially. Yet, there are serious issues and barriers impeding microsystems commercialization.

The Goal of this Chapter

In this chapter, we will discuss the issues behind the commercialization of this diverse and challenging field, along with the following:

- We provide models that will help stakeholder groups take advantage of their commercialization or public policy efforts.
- We list some emerging products and the time it takes to reach full commercialization.
- We list some current and future markets based on the technology/product paradigm.
- We provide an overall measurement of commercialization status.

2.0 The Microsystems Commercialization Process

Microsystems form a disruptive technology manufacturing base. They are the second micro manufacturing revolution and leverage engineering skills across several domains. These technologies are the basis for discontinuous innovations that provide unique solutions to customer-based problems. MEMS companies are characterized by making devices such as pressure sensors that then can be applied to many different markets. This means that disruptive technology solutions initially largely exist in the technology-product paradigm, rather than in the product-market paradigm. The microsystems arena is in an “Era of Ferment” (Anderson & Tushman, 1990) without dominant designs/processes in most application areas. This drives the direction of any technology roadmap to focus on the technology-product interface, rather than on the technology-market interface.

2.1 Sustaining Technology versus Disruptive and Discontinuous Innovations

Over the past 75 years, new technology commercialization has divided into *traditional* branches that produce products and services, and *disruptive* branches in which new technologies produce new product and service milestones. Yet another way of describing technology commercialization is that new technologies (Bower & Christiansen, 1995) either s*ustain* current manufacturing practices, or *disrupt* existing manufacturing processes by introducing something new and different, eventually rendering the sustaining practices and capabilities obsolete.

Disruptive technologies are often associated with discontinuous innovations. This term may be applied to either:

- Step-function improvements in current product-market paradigms, or
- Physical and service products representing new industries or markets.

Discontinuous innovations:

- Can be the products of current sustaining technologies that produce a higher-value proposition.
- Can redefine an industrial value chain or create a new value chain and/or market proposition.
- Change existing product-technology paradigms, often replacing them with manufacturing models requiring new technology capabilities.
- Are new and differing product platforms which ultimately generate a normal progression of incremental innovations.
- Often change the way customers use products.
- Are increasingly important to individual firms.
- Are no longer the sole domains of entrepreneurial firms.

- Launch new products and create nascent industries.
- Stimulate the development of new firm-based competencies, while generating future sustaining technologies

2.2 Technology-Product versus Product-Market Paradigm

Microsystems devices, despite their near half century of commercial utility, have not yet graduated from an era of ferment. Up to this point, a dominant design/process has not emerged for the industry or for many of the applications areas derived from this technology base. Without a well-known design/process path, companies must often develop or improve on current processes to produce their own MST-based devices. The resulting innovations will then focus their competitive advantage at the interface where the technology and a potential product could meet. The resulting MST-based products from such companies can then go on to compete in numerous market and industrial spaces. The efficiencies and performance generated at the technology-product interface defines the competitive winners at the product-market interface. For example, pressure sensor companies produced products for the aerospace industry and then produced them for the medical industry, displacing traditional macro-technologies in both cases. The real competitive advantage, in both cases, lies in the efficiencies and performances generated by the MST manufacturers at the technology-product interface.

This causes problems for business professionals, who have been taught to be market-focused. This leads to a condition known as marketing myopia, where one allows oneself to be defined by the market or industry being sold to. Only of late have business professionals been exposed to the idea of expeditionary marketing, which suggests that a firm should be defined not by the market space that it inhabits, but rather by the technological competencies and solutions sets that it renders to multiple industry settings. MEMS is an exogenous technology base seeking to dislodge traditional solution sets in every industry in which it seeks to become the dominant solution.

MST by its very nature is a solution set to multiple industries rather than a single, market-driven application. MEMS companies generate products to fit a specific application space, but have to have other application spaces to capitalize on first-mover advantage. MST devices are poised to play an important role in more than sixty industries. The exact timing of microsystems acceleration into those industries is unknown, precisely because they remain, again, at the juncture between the dominant design/process and the "Era of Ferment".

2.3 Learning from Past Disruptive Technologies

Microsystems advances represent the early phases of disruptive technology. Disruptive technologies promise strong and early market entry for products, but are risky ventures. In terms of commercialization, how can microsystems potentially be made profitable? How can commercialization deliver appropriate payoffs to investors?

Replace Existing Products First

Firms that have been most successful with disruptive technologies have first used the technology to replace existing products. Many firms turn their replacement product into a springboard for more aggressive, more valuable, more promising innovation platforms with a greater impact on the corporate bottom line. They then use their increased value to add value to the industry itself. This approach (Lynn, Morone, Paulson, 1996) has been described frequently in the managerial literature since 1950.

Firms commercializing innovations based on disruptive technologies face enormous internal and market-related problems. These are manifested as:

- External and internal skepticism regarding the value of the technology.
- Difficulty with manufacturing processes.
- Resistance from marketing managers regarding product promotion.
- Potential users may resist adopting the products and the behavioral changes necessary for broader technology implementation.

The More People Like What the Technology Can Do, the Easier It Is To Market

Market acceptance is a critical element in the commercialization of disruptive technologies. Marketing theorists (Von Hipple 1978, 1988, 1986, and Veryzer 1998) have codified the connection between innovation and market acceptance. In general, as the commercial significance of an innovation increases, the difficulty and duration of its implementation increases.

Size Of Firm Makes a Difference

One might expect small firms to be more seriously impacted by such difficulties, but, in fact, experience shows that small firms seem to handle them more successfully. Advances and commercialization of microsystems technologies affect small and large firms differently:

- In large firms, disruptive technologies have traditionally been the responsibility of R&D departments.
- In startup high-tech firms, they are everyone's responsibility, particularly the firms' founders.

What to Watch for When the Disruptive Nature of Innovation Works Against Itself

- **New products may disrupt existing products**

Firms with broad product lines may find that new products or innovative new manufacturing methods, "Disrupts" their existing product structure. Rather than cannibalize the company's existing profits, management may choose to suppress or ignore innovations.

- **Difficult to accurately predict financial outcomes**

Because disruptive technologies are unstructured and have uncertain technological outcomes, commercialization is hard to quantify and difficult to justify financially. MEMS has taken a long time for marketable and concrete applications to emerge. Commercializing incremental evolutionary or sustaining technologies, on the other hand, may find widespread application within months. Incremental steps are easier for managers to understand and incorporate into existing infrastructure, processes, cost assumptions, and stakeholder expectations.

Ignore Disruptive Technologies "At Your Own Peril"

Nonetheless, technology-based firms must continue to identify and develop strategically important disruptive technologies because they will be central to developing:

- New corporate technological competencies.
- Evolving and distinctive corporate identities.
- Generations of improvements in corporate competencies.

2.4 A Model for Understanding MST Commercialization

The model presented in Figure 1 (adapted from Walsh and Kirchhoff, 1998) for the commercialization of products based on microsystems disruptive technologies begins with a choice of technology type and ends with a user application. (This model was influenced by the works of Utterback 1994, Twiss 1980, Frohman 1980, 1981, Marquis1969, Rosenbloom 1978, Abernathy & Clark 1985, Bower and Christenson1995, and others.)

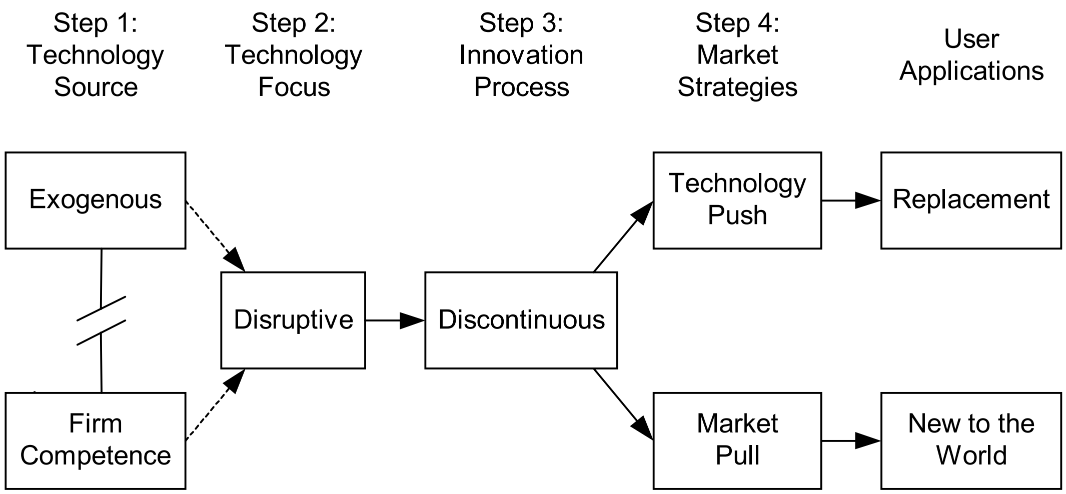

Figure 1. The Disruptive Technology Commercialization Model.

Figure 1 provides a view of major factors affecting the innovation process. The top of the figure identifies "Technology-push" associated with specific state-of-the-art technology and manufacturing processes. In the other part of the figure, "Market-pull" stems from a demand for capabilities not yet available in existing products.

In advanced technologies, market-pull is commonly initially generated by:

- Defense requirements.
- Government regulatory pressures (e.g., environmental, safety, and health).
- Explicit commercial needs (e.g., advanced wireless telecommunications).
- Unfulfilled market opportunities.

Technology-push, on the other hand, can result in major innovations that often piggyback on technologies in existing markets (Walsh, Boylan, Paulson, and Marone, 1996), decreasing the effort required to produce a novel product. For example, the early semiconductor silicon industry borrowed the technology for producing silane-based polysilicon feedstock from the silicones industry. MEMS technologies have borrowed from semiconductor microfabrication, using the knowledge base to broaden its applications and market potential.

2.4.1 The Role of Government Policy and Internal Product Champions

According to much of the literature on commercialization, a major change agent is one of the most important things to have when facing radical commercialization challenges. These agents are powerful because they can decrease risk. For MEMS these are:

- External agent: A proactive government policy, such as funding of a selected proposal.
- Internal agent: A product champion, who can overcome corporate roadblocks that would otherwise inhibit commercialization of a particular product.

Who are the Product Champions?

Within corporations, product champions:

- Are often regarded as visionaries.
- Are sometimes feared.
- Are moderate risk takers.
- Are not prone to backing bold, high-risk projects (Madique, 1969, Madique & Hayes, 1984).
- Often obtain higher-than-average returns on new product opportunities.
- Rarely experience dire consequences if their attempts fail.

Dr. Richard Payne is an example of a product champion for the development of the accelerometer device for air bag deployment at Analog Devices Inc.

Until recently, microsystems commercialization has progressed slowly. The model in Figure 1 is useful for identifying causative complications. Many researchers (Mansfield, 1968, and Enos, 1967) have found that it takes an average of 11-18 years to go from invention to business innovation. This period for radical innovation has been remarkably consistent in the twentieth century. To overcome buyer/user resistance to disruptive technologies, you must demonstrate significant cost reductions and/or performance improvements. These, in turn, induce customers to accept the risks of newness (Mansfield, 1968). Interestingly, this occurs in single-product/single-industry markets, as well as "Lead User" groups in many different markets (Von Hipple, 1986).

The "Winds of Creative Destruction" (Schumpeter, 1934) have traditionally moved slowly but have redefined the way industries conduct business. Schumpeter describes capitalism as an economic system that finds its competitive strength in innovation. His "Innovative Activity" (creative destruction) is clearly driven by what today we call disruptive technologies. Abernathy and Utterback (1988) emphasize this in describing disruptive technologies as those that generate entirely new technology-product-market paradigms that in turn create new markets that initially may be opaque to customers. Opaqueness, they note, constrains customer enthusiasm for varying established behavioral habits. But such enthusiasm is needed if disruptive products are to be accepted and utilized.

To understand the commercial innovation process, one must recognize that in a business sense, innovation is aligned with use. It is not simply technological change. An innovation in a business sense is a new product, process, or service, which gains commercial viability and produces revenue. For this discussion, there is a difference between a technological innovation and a commercial innovation. In discussing commercialization, we use the business sense of the term innovation.

2.4.2 MST Commercialization Steps 1 & 2: Choosing And Sourcing A Technological Platform

Disruptive technologies not only create sustainable competitive advantages, they provide proprietary markets for evolutionary technologies. This is why the choice of the technological platform is so important for the firm's direction. That's because discontinuous innovations lead to changed customer behavior once the customer accepts the advantages of the new disruptive technologies. As users identify new needs, evolutionary technologies emerge from core competence research to create continuous innovations to satisfy these users. In this way, a technology that was initially disruptive eventually leads to a stream of evolutionary technologies. Evolutionary technologies produce continuous innovations capable of constantly updating and improving current customer-based products. Companies building on disruptive technologies remain competitive in rapidly changing markets.

Basically, there are three disruptive technology choices for firms embracing microsystems concepts: traditional bulk micromachining, sacrificial surface micromachining, and high-aspect-ratio micromachining (HARM). The oldest—traditional bulk micromachining—has been the dominant production technology for pressure sensors since such sensors were introduced in the 1950s (Grace, Battelle Institute, 1992). Many firms have based products on bulk micromachining. Included among these are the early startups such as Rosemont, Kulite, National Semiconductor, Fairchild, and divisions of large corporations such as General Motors.

HARM technologies such as LIGA, deep UV (laser LIGA), and microplating are becoming more commercially viable. They were developed for the fabrication of high-aspect-ratio plating molds and provide radical new ways to produce micromachined parts at relatively low cost. The German firm, MicroParts GmbH, is the world's largest producer of HARM-based products, but the technology is moving to the Pacific Rim. Taiwan's National Science Council is currently funding a National Light Source Project chartered to develop HARM-based products. In Japan, a MITI-supported effort called the Micromachine Center has a concentrated program to investigate HARM technologies for its twenty-eight sponsor firms.

Sacrificial surface micromachining was introduced in the 1980's and is the newest microsystems technology. It is the base process for Analog Devices' automotive air-bag accelerometers and Texas Instruments' digital light processing (micromirror) technology as well as a number of other significant commercialization thrusts.

2.4.3 MST Commercialization Steps 3 & 4: Innovation And Market Strategies For Microsystems

By definition, according to Schumpeter, innovation implies the commercialization of invention or technological change. Commercialization is widely perceived as the process of bringing a product or service into working applications. This is heavily dependent on marketing. The models depicted in Figures 1 and 2 explore discontinuous market-pull innovations and discontinuous technology-push innovations.

Discontinuous Market-Pull

This combination of disruptive technology and market strategy may be the lifeblood of true "creative destruction" as described by Schumpeter. The combination is not itself the basis for creative destruction, but it does provide a bridge between the old and the new. Disruptive technologies need to evolve over time so that inventions can gradually acquire a production infrastructure, i.e., raw material suppliers, process methods, etc. One way to accomplish this is to launch the technology by manufacturing replacements and substitutes for preexisting customer applications. Such replacements are usually easy to sell and require minimal changes in customer behavior. Early applications of microsystems technologies were in products that replaced large and expensive sensing devices. Microsystems devices offered equal or better sensing, smaller and more reliable designs, and lower cost. The previously mentioned automotive airbag triggering accelerometer is a good example of a traditional MEMS device, now costing less than $3 that replaced a mechanical device costing far more.

Discontinuous Technology-Push

While users can be relied upon to pull replacement and/or substitute innovations into the market, they rarely pull major discontinuous innovations into any market. The behavioral changes required by the application of discontinuous innovations invariably create trauma for users even if the innovation greatly improves performance and/or efficiency. Since customers resist self-imposed trauma, they do not ask suppliers to create discontinuous innovations for them. Discontinuous innovations need to be pushed into markets by technology.

Numerous small new firms are appearing in the microsystems industry as the technology evolves and expands. Microsystems will create major disruptions as these and many other firms push the technology in the future.

3.0 Impediments to MST Commercialization

Impediments to the commercialization of microsystems include:

- Industry-wide nomenclature differences affecting market analysis.
- Manufacturing and marketing infrastructure deficiencies.
- Stakeholder intransigence or conflicting goals among stakeholders.
- Customer acceptance.
- Lack of market pull.

3.1 Disparate Nomenclature And Accurate Market Analysis

Because microsystems technologies are so new, the terms behind the technologies differ among the various stakeholder groups and even between geographic regions. For instance, although we have been using the term microsystems for convenience, readers should be reminded that the terms "MEMS," "MST," and "Micromachines" are not always directly interchangeable; and hence, the scopes of the studies that use these terms can vary greatly.

Ink-jet printheads provide perhaps the best illustration of how and where MEMS "Component" purists and MST "System" proponents differ. The latter regard the entire ink-jet cartridge delivery system as a microsystem, whereas the former group counters that only the nozzle of the device is micromachined. Both are correct by their own definitions. However, the definition that one accepts substantially changes the expected market valuation and impedes a unified description of the market or of products. Figure 2, which shows a compilation of different microsystems market studies, attests to this problem.

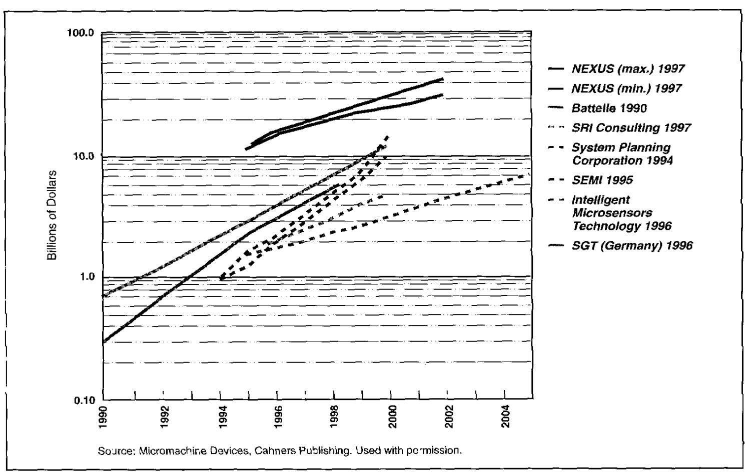

Figure 2. Microsystems Market Projections.

Some of the difficulty in evaluating these numbers resides in the differences between the definitions of the markets being studied as MEMS or MST, and the fact that some studies choose to count the value of the entire subsystem in which the component resides, rather than merely the

MST component value. For example, the Network of Excellence in Multifunctional Microsystems (Nexus) estimated the 2000 MST market to have been about $31 billion. Compare the Nexus numbers with the year 2000 microsystems market estimates from other studies. Estimates ranged from $8 billion (Battelle Institute, 1992) to $14 billion (Systems Planning Corp., 1994) and back to $7 billion (Venture Development Corp., 2000). Projections from newer studies have even wider variations. While this is not the only cause for variation in the available studies these studies all have at least one thing in common: the suggestion of double-digit growth over many years, as captured by their estimates in Figure 2.

The roadmap group tried to find support or evidence to the contrary about these market reports, without performing yet another market study. We found a study that reported the number of patent applications by U.S. and non-U.S. firms over a twenty-year period. Figure 3 lends credence to bold market projections for MST by showing the amount of research activity increasing at a rate similar to the market estimates, but pre-dating the commercial rise of MST sales.

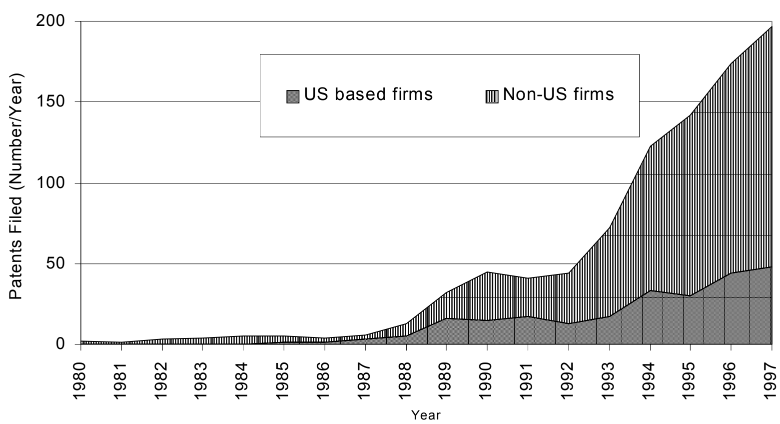

Figure 3. Worldwide Microsystems Patent Activity.

Nevertheless, taken together, we derive the following truths from these disparate studies. First, those using market analyses of the MEMS/MST market must use them prudently and with insight. Second, since the annual market for microsystems products prior to 1995 was less than $1 billion, these studies universally predict one thing accurately: a significant rate of growth in the MEMS area has occurred and continues to occur. For instance, nearly all existing studies and expert opinions depict an industry with a compound annual growth rate (CAGR) around 20%, while some have predicted as high as 60% for specific market segments. For this roadmap, our contributors estimate the CAGR to be about 20% in the near-term and in the high single-digit range after the year 2013.

3.2 Manufacturing Choice

The Foundry chapter (11) in this roadmap discusses efforts to set tolerances, ISO certification, and reproducibility. However, there are no microsystems processing standards yet. As a result, firms using microsystems technologies must choose manufacturing technologies based on other criteria. Companies naturally want to capitalize on their strengths, and their choice of product design, application, and manufacturing technology is often linked to their historic capabilities. In the case of entrepreneurial firms, the choice may be guided by the background of the founders or by a new manufacturing path. However, not being able to rely on an industry standard involves risks, which are discussed further in the Cost chapter (12).

In the microsystems industry, no single manufacturing technology dominates in the way, for example, that CMOS for semiconductor manufacturing does. Rather, there are at least seven microsystems technologies, falling into one of three categories:

1. Traditional bulk micromachining.
2. Sacrificial surface micromachining.
3. High-aspect-ratio micromachining (HARM), including:
    - Deep ultraviolet (DUV) lithography techniques.
    - X-ray-based methods such as LIGA (*Lithographie, Galvanoformung, Ab formung,* or lithography, electroforming/plating, and molding).

These categories are similar to those used for chip manufacturing, but there are many differences. In this roadmap, MEMS/MST manufacturing technologies are divided into two categories: Integrated circuitry (IC) and potentially IC versus non–integrated circuitry. Non-IC means any technology base which cannot be processed in an IC fabrication facility, such as spark erosion, LIGA, and some form of silicon sculpting (see chapter 4, section 4.0). At any rate, the lack of a dominant manufacturing process is both good and bad, but certainly represents an impediment to commercialization of microsystems technologies.

3.3 Infrastructure

Because microsystems technologies are still so new, they continue to frustrate suppliers, manufacturers, and users, and are slowing commercialization. To better understand the problem, an infrastructure model (see Figure 4) has been generated that takes the three MEMS production technology groups (bulk, sacrificial, HARM) through a four-stage development process. The model reflects the actual historical growth of MEMS technology.

During *stage 1*—the stage of basic research and nonexistent market channels—managers and technologists who initially investigated MEMS technologies typically forced a fit between manufacturing and market channels. In lithography, for example, MEMS technologists were required to utilize existing lithographic techniques that were optimized for microelectronics fabrication.

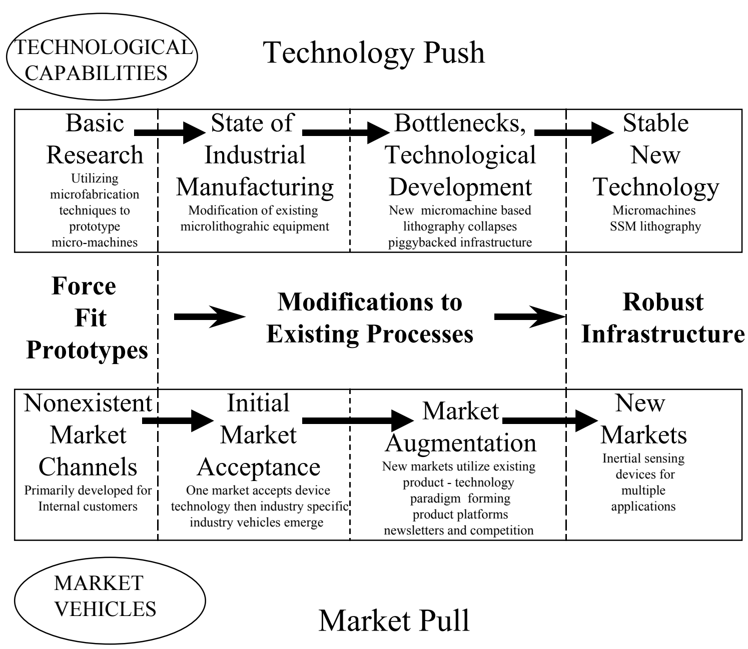

Figure 4. Infrastructure Model for Discontinuous Innovations.

At *Stage 2*—the initial market acceptance of MEMS products, the technology-market-product paradigm shifts, has begun. At this point, market channels are beginning to widen because high-technology entrepreneurs are entering the industry. Also, at this point historically, firms generate highly specific products for special market niches and convince OEMs to use MEMS-based sensors for a variety of applications. Concurrently, modifications to existing manufacturing equipment begin to appear. An example would be MEMS lithography, whereby double-sided lithographic aligners constructed from obsolescent electronics microfabrication tools emerged to support the manufacture of MEMS products.

At *Stage 3*—bottlenecks, technological development and market augmentation—market channels widen still further and awareness of field-tested MEMS products is growing so that OEMs can begin to approach MEMS firms with suggestions for new products. MEMS production begins to be supported by the entry of capital equipment and consumables suppliers.

By *Stage 4*—the stable new technology and new markets stage—we see a robust infrastructure emerging for some competing techniques. Typically, MEMS production firms are now larger corporations, in contrast to small, high-tech entrepreneurial start-ups. In the field, the salesman-entrepreneur is being replaced by the sales-engineer and the use of strategic market partners to obtain market leverage is becoming common. At this point, a mature infrastructure exists and the behavior of manufacturers, customers, and suppliers is similar to that in many other mature markets.

In other types of infrastructure building, the microsystems industry has experienced fewer impediments. Efforts to raise awareness and involvement in emerging markets, like those based on MEMS production technologies, also encourages infrastructure development by increasing customer awareness and acceptance, as well as supplier interest and involvement. In this area, an industry infrastructure is well established. Information exchanges focused on encouraging the development of MEMS have a history extending back to the early nineties. The number of regional and international cross-disciplinary technical and professional meetings having an MEMS orientation or at least having MEMS special sessions has also grown rapidly since 1997. Surprisingly, in MEMS production technologies, pioneering firms gain by sharing some proprietary information due to the positive effects that shared technical and market information have on the development of infrastructure.

Agencies from the European Union, U.S., Japan, as well as regional and state agencies are attempting to accelerate microsystems diffusion as a next-generation economic initiative. The

European Union through Nexus, IVAM and other organizations, has set up regional economic development areas and user groups to accelerate microsystems proliferation. The European Commission's five regional Europractice MEMS fabrication service centers facilitate the development of MEMS-based devices and markets in Europe. In Japan, the Micromachine Center has over thirty-one corporate members plus university research center involvement. Taiwan, Korea, Australia, Singapore, and China have begun to organize, fund, and implement their foray into "Small Tech". In the U.S., efforts like the Advanced Technology Program (ATP) of the National Institute of Standards and Technology (NIST) and Department of Energy initiatives at locations such as Sandia National Laboratories and several high-energy synchrotron storage ring locations promote MEMS applications development, technology transfer, and concurrent commercial development for bulk, surface, and LIGA micro-fabrication. Like Europe, the U.S. also has thriving clusters of MST business and research activity; at least six have been identified in the U.S. by Ardesta's Small Times magazine in 2002.

3.4 User Behavior

All microsystems technologies and microelectronics have the potential to have a profound impact on many people and the potential to change people's lives in the future. Yet the fact that users must change their way of life to use microsystems-based products is a major impediment to the commercialization of MST.

Many MST devices today are competing at the core product level as a "Golden Screw" in the customer's unique, total solution. These solutions replace existing technologies and many times do not directly interface with the end-user, meaning their invisibility to the user does not require any behavioral changes from the user. Today and in the future, MST devices will be called on to provide more and more value to customers, and that value will be expressed in the form of a discontinuous innovation requiring customer change.

The essential consideration in customer acceptance is that when you ask people to change, they resist it. This suggests an extremely compelling value statement must exist to initiate consumer behavioral change. Next-generation MST devices must incorporate more value and complexity in their solutions than they now provide. These devices are functioning not as replacement products, but as discontinuous innovations that are closer to the end-user and require them to change. MST devices must have an exceptional value proposition on more than one critical dimension to overcome consumer resistance. Anything less will not accelerate the technology's diffusion.

3.5 Stakeholder Groups

Government, academia, and industry worldwide are involved in the commercialization of microsystems technology. Governmental and academic activities are often concerned with technological research and manufacturing infrastructure requirements, whereas industry is usually more focused on product development. This can lead to incompatible goals and aspirations between stakeholders. These incompatible goals generate business models that often are not viable for one or the other stakeholder groups and, therefore, are not pursued. Many times technologists want to develop technology for technology's sake, while commercializers of technologies are interested in technology only as a tool if it generates higher-than-average rates of return.

This is seen again in firm-based decisions to commercialize disruptive technologies. MEMS is an exogenous technology and so challenges the stakeholder infrastructure of an established business wishing to commercialize the technology. Due to ingrained resistance by managerial stakeholders, this is often not accomplished within the current divisions of such a firm. Rarely will firms try to cannibalize their own products with an MST-based solution. Furthermore, when established firms do embrace disruptive technologies, it is accomplished when parachuting to a new competency base as well as to a new market space. The resulting paradigm means that MST solution sets have to be introduced by small firms in their industry or by skunkwork-like divisions within established firms, whose product development focus does not currently challenge the firm's core products. This means that rather than replacing an existing market share in a company, a new market share must be generated by these firms, a much more lengthy process, which may not be supported by shareholders.

3.6 Market-Pull versus Technology Push

Most microsystems-based products have been developed by a technology push, rather than a market pull. A technology push requires a customer education component and, therefore, takes longer than market-pull commercialization. Presently, the market pull is starting to become more prevalent in some application spaces. As more market action for MST-based solutions is generated, less technology-push education will be required (see also Sections 2.3, 2.4, and 3.4.)

4.0 Commercialization Status of MST Applications

Many aspects of microsystems differ significantly from the counterparts they are replacing, specifically in the areas of design, materials, and fabrication processes. New designs are relatively easy to commercialize. A new material requires a much higher degree of technology complexity, slowing the commercialization process. A compelling commercial opportunity that is uninhibited by time constraints must be present to warrant the development of a new fabrication process. There are over ten, and, as some of our contributors have suggested, as many as fourteen, front-end MST manufacturing processes that already exist.

Rather than try to report the status of fourteen fluxing technologies, this report divides MEMS manufacturing technologies into two categories: Integrated circuitry (IC) and potentially IC, versus non –integrated circuitry. Non-IC means any technology base which cannot be processed in an IC fabrication facility. In the tables following, we rate the leading technologies' market position, or in the case of emerging products, the number of companies basing their offering on a specific product-technology paradigm. These analyses are relative, rather than absolute, to the technology-market situation. When neither technology dominated a product, we classified both as leaders.

Table 1. Positioning of IC versus Non-IC Manufacturing for Existing Products

Existing technology products	Integrated circuitry and potential IC	Non-integrated circuitry
Hard-disk driveheads	Lead	Close follower
Ink-jet printheads	Lead	Distant
Heart pacemakers	Lead	Lead
In-vitro diagnostics	Follow	Lead
Hearing aids	Lead	Lead
Pressure sensors	Lead	Lead
Chemical sensors	Follow	Lead
Infrared imagers	Follow	Lead
Accelerometers	Lead	Follow
Gyroscopes	Follow	Lead
Magnetorestive sensors	Follow	Lead
Micro spectrometers	Lead	Follow
Optical displays	Lead	Follow

Table 2. Positioning of IC versus Non-IC Manufacturing for Emerging Products

Emerging products	Integrated circuitry and potential IC	Non-integrated circuitry
Drug-delivery systems	Lead	Lead
Optical switches	Lead	Follow
Lab on a chip	Follow	Lead
Magneto-optical heads	Follow	Lead
Projection valves	Follow	Lead
Coil on chips	Lead	Follow
Microrelays	Lead	Follow
Micromotors	Follow	Lead
Inclinometers	Lead	Follow
Injection nozzles	Follow	Lead
Anti-collision sensors	Lead	Follow
RF devices	Lead	Lead
Electronic noses	Lead	Lead

4.1 Full Commercialization Evolution

Commercialization takes time. As Table 3 shows, full commercialization of microsystems technologies has taken decades.

Table 3. Product Evolution Timetable

Product	Discovery	Product evolution	Cost reduction and application expansion	Full commercialization
Pressure sensors	1954-1960	1960-	1975-1990	1990-present
Accelerometers	1974-1985	1985-	1990-1998	1998
Gas sensors	1986-1994	1994-	1998-2005	2005
Valves	1980-1988	1988-	1996-2002	2002
Nozzles	1972-1984	1984-	1990-1998	1998
Photonics/displays	1980-1986	1986-	1998-2004	2004
Bio/chemical sensors	1980-1994	1994-	1999-2004	2004
RF switches	1994-1998	1998-	2001-2005	2005
Rate sensors	1982-1990	1990-	1996-2002	2002
Chromatography	1975-1980	1980-	1990-2000	2001
Microrelays	1977-1982	1993-	1998-2006	2006

4.2 The Nexus Estimate of MEMS/MST Systems Commercialization

The 2002 Nexus report projected a growth in the world microsystems market from a 1996 estimate of $13 billion to $68 billion by the year 2005 with an annual growth rate of 20%. This forecast has a much greater valuation than other studies due primarily to a systems-based outlook, which counts all microstructure products (monolithic and hybrid). Current principal products and market volumes are listed in Table 4.

Table 4. Nexus' Near-term Commercialization Estimates for Existing Products

Existing products	1996 Report I		2000 Report II		2002 Report I & II	
	Units (millions)	US$ (millions)	Units (millions)	US$ (millions)	Units (millions)	US$ (millions)
Ink-jet printheads	100	4,400	375	11,200	600	16,300
Read/write (HDD and TP heads)			1,330	8,260		
Hard-disk drive heads	530	4,500			1,760	9,800
In-vitro diagnostics	700	450	?	1,250	4,000	2,300
Heart pacemakers	0.2	1,000	0.7	3,100	0.8	3,700
Bio-chips			30	645		
Optical mouse			30	750		
Hearing aids	4	1,150	650	2,140	7	2,500
Pressure sensors	115	600	130	1,050	190	1,400
Chemical sensors	100	300			400	800
Infrared imagers	0.01	220			0.4	800
Gyroscopes	6	150	13	340	21	540
Accelerometers	24	240	100	470	136	580
Magnetoresistive sensors	15	20			60	60
Flow sensors			11	230		
Infrared sensors			7	19	11	40
Inclinometers	1	10	9	54		
Micromotors	0.1	5	0.01	2	2	80
Microspectrometers	0.006	3	0.03	8	0.06	12
Magneto-optical heads	0.01	1	2	20		
Totals		**13,049**		**29,538**		**38,912**

Developmental products that have a high probability of being on the market by 2002 are listed in Table 5. Products emerging from development between 2000 and 2005 will contribute an additional $6 billion to the overall MST market size. The rapid progress of microsystems technology makes it likely that several totally new products will appear over the next five years.

The Nexus Task Force concluded that keeping up with these developments will require continuous monitoring, and their newly released 2002 report now has projections through 2005.

Table 5. Nexus' Near-term Commercialization Estimates for Emerging Products

Emerging products	1996 Report I		2000 Report II		2002 Report I	
	Units (millions)	US$ (millions)	Units (millions)	US$ (millions)	Units (millions)	US$ (millions)
Microdisplays			----	150		
Fingerprint sensors			13	520		
Drug-delivery systems	1	10			100	1,000
Optical switches	1	50			40	1,000
Lab-on-a-chip (DNA)	0	0			100	1,000
RF MEMS			----	-----		
Nebulizers			1	30		
Needleless injectors			1	30		
Projection valves	0.1	10			1	300
Coil-on-chips	20	10			600	100
Microrelays	0	0.1			50	100
Optical MEMS			16	100		
Implantable micro pumps			0.06	200		
Injection nozzles	10	10			30	30
Anti-collision sensors	0.01	0.5			2	20
Electronic noses	0	0.1	0.002	8		
HVAC (automotive)			1	15		
Totals		**90.7**		**1,053**		**3,550**

4.3 Strategic Market Insights for Established MST Applications

The tables presented here are meant to offer commercially useful strategic insight. In the examples that follow, microsystems applications are specifically defined in the fields of information technology, aerospace, automotive manufacturing, and medicine and biology. They combine available market study information with many currently existing expert opinions. For simplicity, we use only one comprehensive example of an "Emerged Product" and one best-guess example of a PMT paradigm to illustrate each area. Each table lists numbers (all based on worldwide production) for six variables in two years: the data point year (1996) and the forecast year (2002). The variables examined are:

1. The volume range in units of the product application, as determined by various MEMS studies and expert opinions.

2. A best-guess MEMS device price (retail) for the product under review.
3. An associated MST systems price.
4. An indication of whether the MEMS application represents totally new technology or a replacement technology.
5. Cost drivers if any.
6. Performance advantages if any.

Readers are cautioned against trying to estimate the total size of a particular market segment simply by multiplying the price and volume figures presented here. If this erroneous procedure is used, for example, then the lowest price (variable No. 2) × lowest volume, and the highest price (variable No. 3) × highest volume, will provide grossly exaggerated, unrealistic, and rather meaningless market value ranges.

4.3.1 Information Technology (IT)

In IT, the two examples of MEMS product applications are "Already-emerged" MEMS-based ink-jet printheads and "Now-emerging" MEMS-based data storage devices. Both aim at replacing existing PMT paradigms, and both are making inroads in established markets. The MEMS/MST-based products either already show better performance, lower cost, and a steeper and more accelerated learning curve than the products being replaced, or at least possess the potential to do so.

Ink-jet printheads are made by more than eight companies worldwide including multinational firms such as Canon, Hewlett Packard and Lexmark. MST now dominates ink-jet printhead manufacturing. MST ink-jet printheads outperform those made with earlier vintage technologies and printers that use MST ink-jet printheads now compete directly with laser printers on performance, but at a substantially reduced cost. Printhead sales in 1996 have been placed at 50 million to 100 million units. Some estimates suggest they will reach 500 million units by 2002. Others predict just half that. Volume notwithstanding, what is likely is that up to 95% of future ink-jet printheads will be produced by MEMS/MST methods. Table 6 describes the printhead market.

Table 6. Ink-jet printheads

Variable	1996	2002
Units (millions)	500-100	250-500
MEMS price (US$)	1-4	1
MST price (US$)	50-60	25-50
Technology replaced	Piezo	Laser
Cost advantage	<20%	20%-200%
Performance advantage	near 10×	1.2× to 10×

The second IT example involves hard-disk drives (HDDs) for data storage. Here, head positioning and accelerometer devices are the specific microsystem items referenced. Head positioning is an emerging application of MEMS technology. The economic potential is significant due to the ultimate replenishment needs of a large installed equipment base. MEMS-based products offer specific advantages in size, speed and weight, but in HDDs, competing technologies do exist. With HDDs accelerating along the cost/performance curve, the cost per gigabyte of disk memory is rapidly decreasing. Recent street pricing was about $30 to $45/Gbyte for IDE drives, well ahead of one previous market forecast in 1996 that projected a cost of $50/Gbyte by 2002. Data access speed has also increased but at a slightly slower pace. Drive manufacturers are beginning to use MEMS/MST methods. Early applications were directed at the lightweight portable computing market. Table 7 reflects MEMS-based HDD market trends.

Table 7. Hard-disk Drives

Variable	1996	2002
Units (millions)	100-700	400-2000
MEMS price (US$)	1-10	1-5
MST price (US$)	1-20	1-10
Technology replaced	Macro	Laser
Cost advantage	<20%	20%-200%
Performance advantage	near 10×	10×

4.3.2 Aerospace

The aerospace industry was the first to use MST since it was an enabling technology. One early application was for aircraft cabin-pressure sensors. Factors driving the replacement of aerospace macrosystems with MST are clearly weight, performance, reliability, and cost. A key distinction between the Lunar Rover of the 1970s and the current NASA/JPL Mars Rover is enhanced MST utilization in the latter. Table 8 defines the established market in just one aerospace product area, pressure sensors. Many corporations produce these systems including Honeywell, Kulite, and Rosemont.

Table 8. Aerospace Pressure Sensors

Variable	1996	2002
Units (millions)	1-3	1-3
MEMS price (US$)	5-200	4-180
MST price (US$)	5-2000	4-800
Technology replaced	Macro	Macro
Cost advantage	10×	10×
Performance advantage	10×	10×

4.3.3 Automotive

The automotive industry was the second to widely utilize MEMS to solve technical problems. Initial applications included the manifold absolute-pressure sensors (MAPS) and MST-based nozzles for fuel systems. Today, one of the most widely used automotive MEMS systems is the airbag-triggering accelerometer. Other automotive systems now under development include gyros for rollover sensing, vehicle dynamic control (e.g. ABS), and GPS navigation. Both accelerometers and gyros are discussed below. Accelerometer use in automobiles resulted from legislation that initiated an innovation "Express." An instant market was created, and with the arrival of MST, macromechanical airbag triggers disappeared almost overnight.

Many companies compete in the accelerometer niche market. Among the most prominent are Analog Devices, Bosch, Breed, EGG, Motorola, Rockwell, Sensonor, Siemens, and TRW. Table 9 shows an assessment and forward projection for this segment.

Table 9. Airbag Accelerometers

Variable	1996	2002
Units (millions)	20-30	80-150
MEMS price (US$)	5-7	2-3
MST price (US$)	5-15	2-5
Technology replaced	Macro	Macro
Cost advantage	10×	10×
Performance Advantage	10×	10×

MST-based, two-axis accelerometers (i.e., gyros) are not truly a replacement for conventional gyroscopes. The latter never caught on for automotive applications due to their cost and size. On the other hand, MST-based gyros have a significant future in automotive technology with at least three applications per vehicle now envisioned. Table 10 shows projections in this area.

Table 10. Automotive Gyroscopes

Variable	1996	2002
Units (millions)	0.15-	5-40
MEMS price (US$)	25-35	10-20
MST price (US$)	25-35	10-20
Technology replaced	Macro	Macro
Cost advantage	10×	10×
Performance advantage	10×	10×

4.3.4 Medicine And Biology

The field of medicine has numerous applications for MEMS products. Among them are body fluid flowmeters, invasive and noninvasive pressure monitors, patient point-of-care chemical diagnostic and drug-delivery devices, a very large market for medical instrumentation and drug discovery, and a host of other bio applications including those in genomic science, engineering and forensics. Among the many manufacturers in these areas are Hewlett-Packard, i-Stat, IC Sensors, Lucas Novasensor, Perkin-Elmer, and Sentir. Table 11 illustrates the blood-pressure device market, initiated by Novasensor.

Table 11. Medical Blood-pressure Sensors

Variable	1996	2002
Units (millions)	16-20	20-30
MEMS price (US$)	1-10	1-10
MST price (US$)	1-10	1-10
Technology replaced	Macro	Macro
Cost advantage	10×	10×
Performance Advantage	Disposable 1.2-10×	Disposable

This section has illustrated how a marketing professional might obtain values inherent in current microsystems market forecasts. To illustrate certain points, we used data represented in current market studies and in expert opinions. We emphasize again that our use of the data does not represent an endorsement. We acknowledge the difficult problem faced by market researchers trying to accurately forecast microsystems markets formed by discontinuous innovations.

5.0 A Report Card on Overall MST Commercialization

Industry consultant Roger Grace recently compiled a microsystems "Report Card" to assess industry performance regarding commercialization. Here we use the concept, with additions, to display the trend in the industry's commercialization in 1999 and 2001. Certain aspects of the report card are stellar or exceptional, such as R&D, and the creation of wealth. Most others show a need for improvement. A single dominant manufacturing solution, for example, is elusive. But even here there is progress. Most categories, for example pressure sensors, have at least some dominant manufacturing technologies.

Table 12. Microsystems Commercialization Trend Report Card (1999 –2001)

1999-2001 Report Card on MEMS commercialization			
	1999-2000		2000-2001
Subject	**Grade**		**Grade 2001**
Research and development	A		A
Start-up funding attraction	B		A
Public relations	B		B+
Established infrastructure	B		B+
Creation of wealth	B-		A-
Design for manufacturing	B-		B

Market research	B-		B+
Industry roadmap	B-		B+
User acceptance of microsystems	C		B
Management expertise	C		B+
Marketing	C-		B
Profitability	C-		B
Universal nomenclature	D		C+
Trend to a dominant manufacturing solution	D		C
Industry association	INC		INC
Industrial standards	INC		INC
Overall grade	**B-**		**B+**

Research and Development (A, A)

Microsystems R&D activities began in the 1970s and 1980s in the U.S. by the National Institute of Health (NIH) and NASA.

Worldwide microsystems R&D is currently well funded by a variety of agencies and countries. These include:

- The U.S. Defense Advanced Research Projects Agency (DARPA).
- The U.S. Department of Energy (DOE).
- The European Commission's Nexus organization.
- Agencies in Korea and Taiwan.
- The Micromachines Center and the Ministry of International Trade and Industry (MITI) in Japan.
- Other governmental agencies and various private companies worldwide

Start Up Funding Attraction (B, A)

Starting with the first foundry funded by a venture capitalist in 1996, the trend has been great. Optics has had a problem in the last half of 2001, but there is increased activity. BioMEMS applications are still attracting large sums of funding.

Public Relations (B, B+)

The microsystems industry has received considerable coverage in the academic press. That coverage is now extending to the popular, technical, and business publications sector. The word "Hype" is now being used in connection with microsystems public relations. We are entering a period of having microsystems in an "Oversold" status.

Established Infrastructure (B, B+)

Firms providing infrastructure equipment for MEMS technologies have made major investments recently. Companies including Karl Suss, Electronic Visions, STS, PlasmaTherm, and Alcatel produce equipment specifically designed to meet the requirements of MEMS manufacturers. Design automation activities are also high. Companies such as Coventor, Intellisense, Tanner, CFDRC, Coyote Systems, and Memscap / Mentor are developing new software aimed at reducing design iterations, lowering development costs, and reducing time-to-market.

Test and measurement activities for microsystems are being pursued by major producers and research groups, including Analog Devices and Sandia National Laboratories, and by companies specifically established to provide this service and related equipment, such as ETEC (Mukai, 1998). Ubiquitous MEMS processes like Sandia's IMEMS and Summit IV, and MCNC's MUMPS are beginning to be well utilized. MEMS foundries and specialty fabricators (e.g., Cronos, Sentir, CSEM-LETI, Tronics, MEMS Inc., and others) are making it possible for designers and systems manufacturers to put their creations into production and to support mid-to-large-scale production programs. This fabless supplier model enables small to medium size enterprises to become microsystems providers. The recent establishment of capabilities at the Jet Propulsion Laboratory (NASA), and Sandia National Laboratories help MEMS companies better understand emerging reliability issues associated with product development and production (Miller, 1997).

Creation of Wealth (B-, A-)

Many MEMS millionaires have been created.

Design for Manufacturing (B-, B)

More emphasis on the systems approach, instead of design, for MEMS devices and microsystems, is yielding results. Packaging for microsystems technologies lags behind device development. Major problems with interconnectivity and packaging exist that translate directly into cost. It is said that 80% of the cost and value of a current MEMS device resides in the packaging. Packaging papers are beginning to appear regularly at MEMS technology conferences (Oh and Ahn, 1998), suggesting an increase in research efforts in the packaging area. One potential solution is the co-development of devices and packages. With some exceptions, interdisciplinary and interdepartmental approaches to packaging are nonexistent.

Market Research (B-, B+)

Certifiable, current market data is unavailable, but there is a plethora of market studies, many with different definitions of microsystems or MEMS.

Industry Association (Incomplete); Industry Standards (Incomplete)

An industry organization could greatly accelerate the commercialization of MEMS technologies. Activity is beginning that could result in the creation of a MEMS industry organization:

- **In the U.S.**, the MEMS Industry Group and SEMI have taken the lead.
- **In Europe**, IVAM and Europractice have promoted MST activities and development.
- **The Nexus program** and its user groups have brought some 300 private companies, universities, and research organizations under one umbrella.
- **Globally-focused industry groups** such as MANCEF are also making an impact.

Chief among the benefits offered by an industry association would be:

- Formal efforts on standards development.
- An international technology roadmap development.
- The collection of reliable market data.

The trend in nomenclature and user acceptance is becoming more positive and universal.

Marketing (C-, B)

Marketing trends are excellent. The last two years have shown great strides in marketing efforts, bringing more professionalism to the industry.

6.0 Conclusions

Where is the Microsystems Industry going from here? Microsystems technologies will be pushed from below by nanotechnologies. Yet, top-down nanotechnologies will be dominated by MST. Concurrently, nanotechnology will be pushed from below by femto and other small technologies. We have seen industry nomenclature, initiated as a segment of the semiconductor technologies in the 1950's, utilized only in sensor technologies. The term micromachining was first used in the 1960's, most notably by Jim Angel's group at Stanford University. The term MEMS was first utilized in the late 1980's and popularized by Jacobsen and Wood. Microsystems technology was first utilized in corporate settings and has been popularized in Europe throughout the 1990's. Nanotechnologies started to be used in nomenclature in the early 1990's. A new, more comprehensive term, "Small Tech", has emerged, which includes rather than excludes all other "Small" technologies. Figure 5, adapted from a figure in the Nexus 2002 Report II, explains this migration in technological scale and domain.

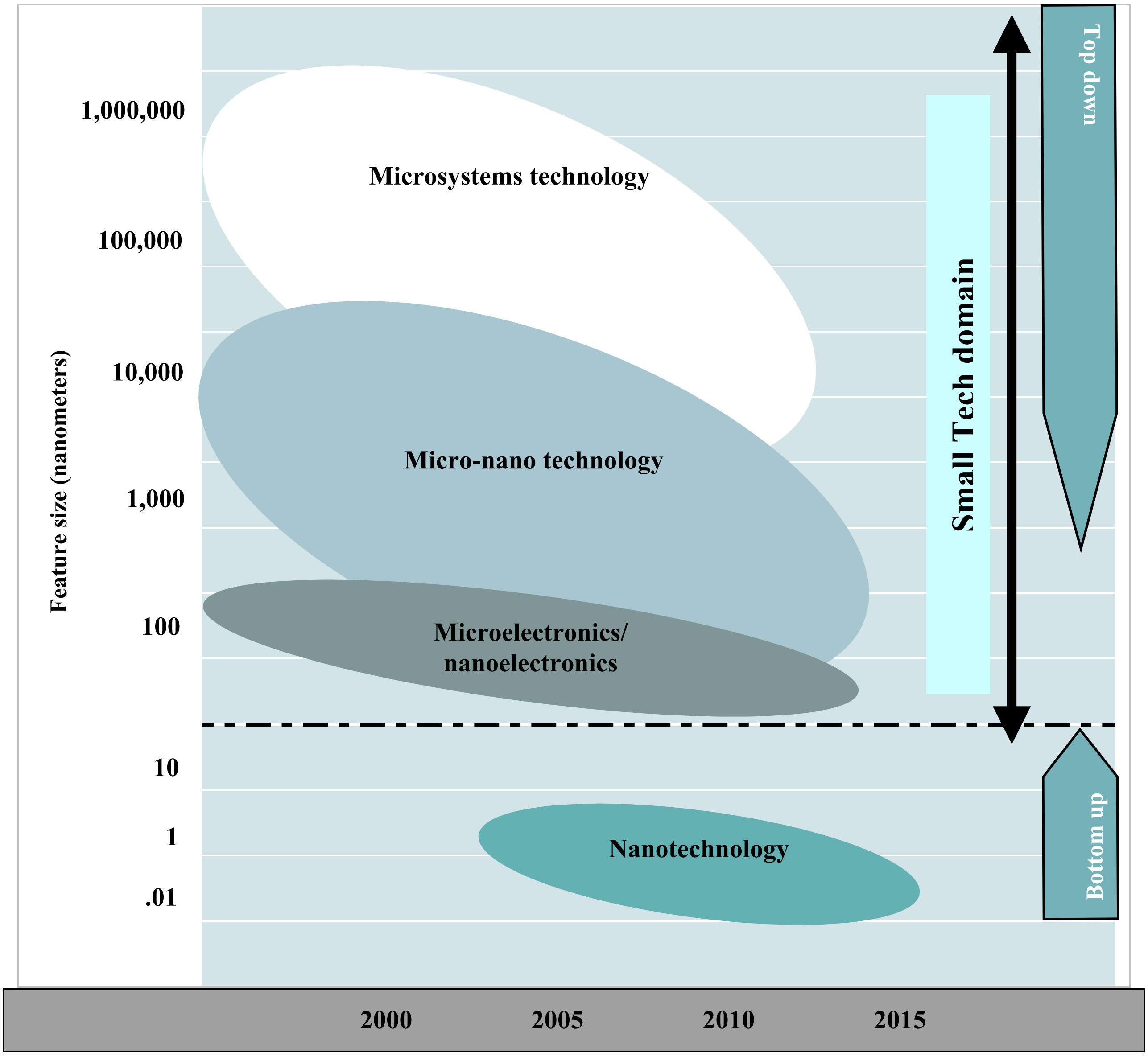

Figure 5. The Evolutionary Path of Small Tech.

7.0 References

Abernathy, W. J. and J. M. Utterback, "Patterns of Industrial Innovation," from "Readings in the Management of Innovation," eds., M.L. Tushman and W. Moore. Second Ed. Ballinger, Harper Business Press, a division of Harper Collins Publishers, New York, pp.25-36, 1988.

Abernathy, W. J. and K. B. Clark, "Innovation: Mapping The Winds of Creative Destruction," Research Policy, Vol.14, pp.3-22,1985.

Anderson, P. and M. Tushman, "Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change," Administrative Science Quarterly 35, pp. 604-633, 1990.

Batelle Institute, "Micromechanics: Multi-Client Study," Frankfurt, Germany, July 1992.

Bitindo, D. and A. Frohman, "Linking Technological and Business Planning," Research Management, Vol.11, pp.19-23, Nov.1981.

Bower, J.L. and C. M. Christensen, "Disruptive Technologies: Catching the Wave," Harvard Business Review, pp.43-53, Jan.-Feb. 1995.

Clark, K. B. and R. M. Henderson, "Generational Innovation—Architectural Innovation, the Reconfiguration of Existing Product Technologies and Failures of Established Firms," (WP3027-89-BPS) Administrative Science Quarterly, Vol. 35, 1990.

Enos, *J. ,* "Petroleum Progress and Profits," MIT Press, Cambridge, Mass., 1967.

Frohman, *A. L.,* "Managing the Company's Technological Assets," Research Management, Vol. 9, pp.20-24, Sept.1980.

Grace R., "Making Money with MEMS: How to Become A MEMS Millionaire," Solid State Sensor and Actuator Conference, Hilton Head Island, SC, June 10, 1998, (www.rgraceassoc.com).

Lynn, G., J. Morone, and A. Paulson, "Marketing and Discontinuous Innovation: The Probe and Learn Process," California Management Review, Vol. 38 (3) , pp.8-37, Spring 1996.

Lynn, G., J. Morone, and A. Paulson, "Emerging Technologies in Emerging Markets: Challenges for New Product Professionals" EMJ, Vol.8 (3), pp. 23–31, Sept.1996.

Lynn, G. and S. Walsh, "Radical Innovation: Challenges and Insights," Proceedings Annual Meeting of the Product Innovation Management Society 1991.

Madique, *M. A.,* "Entrepreneurs, Champions, and Technology," from "Readings in the Management of Innovation", ed. M.L. Tushman and W. Moore, Second Ed., Ballinger, Harper Collins, New York, pp.79-87, 1984.

Madique, M. A. and R.H. Hayes, "The Art of High-Technology Management," from "Readings in the Management of Innovation," eds. M.L. Tushman and W. Moore. Second Ed. Ballinger, Harper Business Press, a division of Harper Collins Publishers, New York, 1984.

Mansfield, *E.,* "The Economics of Technology," W.W. Norton, New York, 1968.

Marquis, *D.,* "The Anatomy of Successful Innovations," Managing Advancing Technology, Vol.1, pp.35–48, 1969.

Menozzi, G., "The Role of Nexus in European MEMS/MST Development, Parts 1 and 2, Micromachine Devices, pp.1-5, Sept.1998 and pp.10-13, Oct.1998. (Excerpted with permission, R&D Magazine, Cahners Business Information.)

Miller W.H., "Reliability: A Hidden Barrier To Successful Commercialization of MEMS?" Micromachine Devices, pp.1-4, Dec.1997.

Moore, *G.,* "Crossing the Chasm," Harper Business Press, Harper Collins Publishing, New York, 1991.

Morone, J., "Winning in High Tech Markets," Harvard Business School Press, Boston, 1993.

Mukai P., "Test Strategy Development for MEMS Devices," Proceedings Sensors Expo, San Jose, Calif. , pp.487-490, May19-21,1998.

Nexus, "Nexus Market Analysis Taskforce Issues Market Study Report on MEMS/MST," Micromachine Devices, pp.1-5, Oct. 1998. (Excerpted with permission, R&D Magazine, Cahners Business Information.)

Nexus, "Market Analysis for Microsystems 1996-2002," A Nexus Taskforce Report, 1998.

Nexus, "Market Analysis for Microsystems II 2000-2005," A Nexus Task Force Report, Feb. 2002.

Oh, K.W. and C. H. Ahn, "Development of an Innovative Flip-Chip Bonding Technique Using Micromachined Conductive Polymer Bumps," Solid State Sensors and Actuators Workshop, Hilton Head Island, SC, pp.170-173, June 8-11,1998.

Rosenbloom, *R. S.,* "Technological Innovation in Firms and Industries: An Assessment of the State of the Art in Technological Innovation," from "A Critical Review of Current Knowledge," ds. P. Kelly and M. Kranzberg, San Francisco Press, San Francisco, 1978.

Schumpeter, *J. A.,* "The Theory of Economic Development," Harvard University Press, Cambridge, Mass., 1934.

Stuart, C., “Small tech’s hot spots,” Small Times Media, Vol. 2, No. 2, pp. 28-29, March/April 2002.

Systems Planning Corporation, “Microelectromechanical Systems (MEMS), an SPC Market Study,” July 1994.

Twiss, *B. C.,* “Managing Technological Innovation,” Logman, London, 1980.

Utterback, *J. M.,* “Mastering the Dynamics of Innovation,” Harvard Business School Press, Boston, 1994.

Veryzer, *R.,* “Discontinuous Innovation and The New Product Development Process,” The Journal of Product Innovation Management*,* Vol. 15 (4), pp.304-321, 1998.

Von Hippel, *E.,* “Lead users: A Source of Novel Product Concepts,” Management Science, Vol.32 7), 1986.

Von Hippel, *E.,* “Sources of Innovation,” Oxford University Press, New York, 1986.

Von Hippel, *E.,* “Users As Innovators,” Technology Review, pp.30-39*,* Jan. 1978.

Von Hippel, *E.,* “Lead Users: A Source of Novel Product Concepts,” (1986) from “Readings in the Management of Innovation,” eds., M.L. Tushman and W. Moore. Second Ed. Ballinger, Harper Business Press, a division of Harper Collins Publishers, New York, pp.352-366, 1988.

Walsh, S. and B. Kirchhoff, “Strategies for HTSFs Embracing Autonomous Disruptive Technologies,” presented at the High Technology Small Firms Conference, University of Twente, June, 1998.

Walsh, S., R. Boylan, A. Paulson, and J. Morone, “Core Capabilities and Strategy: Evidence from the Semiconductor Silicon Industry,” from “Strategic Integration,” eds., Howard Thomas and Don O’Neal, John Wiley & Son Ltd., Cambridge, England, pp.149-165, 1996.

Walsh, S. and J. Linton, “Infrastructure for Emerging Markets Based on Discontinuous Innovations: Implications for Strategy and Policymakers,” submitted to Long Range Planning, 1999.

Wilkinson, J. M., “Medical Applications for MST,” presented at Commercialization of Microsystems ’99, Dortmund, Germany, (www.tfi-ltd.co.uk), July 7-10,1999.

Wise, *T. A.,* “IBM’s $5,000,000,000 Gamble,” from “Readings in the Management of Innovation,” eds., M.L. Tushman and W. Moore. Second Ed. Ballinger, Harper Business Press, a division of Harper Collins Publishers, New York, 1988.