Breaking the barriers to commercialization of MEMS: a firm's search for Competitive advantage

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ABSTRACT

A model of infrastructure development for MEMS manufacturing Technologies is offered. The role of discontinuous innovation in achieving competitive advantage is briefly reviewed. This is followed by the development of a model that describes the stages in the growth of an infrastructure to support Micro-Electro-Mechanical-Systems (MEMS) infrastructure. We briefly describe how an infrastructure gradually grows to support a new industry, resulting from discontinuous innovation. The model indicates the evolving nature of the actions and investments that firms and governments need to make to support the growth of an immature industry. Consequently, we aim to not only offer a descriptive model, but offer guidance to firms on whether their intentions and resources fit with the state of the industry and to offer policy makers guidance on the timing of different types of support.

INTRODUCTION

The MEMS manufacturing platform, the emerging markets based on them and their associated discontinuous innovation are critical for the growth of economies and necessary for firms to obtain and maintain competitive advantage. But how might we foster them? How to encourage and assist the development and market penetration of these innovations is critical to both policy makers and corporate strategists.
First we must understand the more basic question:
"How does infrastructure develop for an emerging industry that is based on discontinuous and disruptive technology?"
Herein we address this question. First, the role of discontinuous innovation in achieving competitive advantage is briefly reviewed. This is followed by the development of a model that describes the stages in the growth of an infrastructure to support the new innovations or industry. Micro-Electro-Mechanical-Systems (MEMS) is then used to demonstrate how an infrastructure gradually grows to support a new industry, resulting from discontinuous innovation. This model, coupled with the example, indicates the evolving nature of the actions and investments that firms and governments need to make to support the growth of an immature manufacturing based industry which is based on discontinuous innovation. We hope to provides insight as to when a firm should and should not enter an emerging market. Consequently, this article aims to not only offer a descriptive model, but to offer guidance to firms on whether their intentions and resources fit with the current state of the industry and to offer policy makers guidance on the timing of different types of infrastructure building activities.

EMERGING MARKETS AND DISCONTINUOUS INNOVATION

Management and academic emphasis has shifted from radical (Lynn and Walsh, 1991), architectural or revolutionary (Abernathy and Clark, 1985) or discontinuous innovation to continuous or incremental innovation since the early 1980's. Currently, most American firms neglect radical innovations and focus their resources on incremental change or continuous improvement. However, incremental innovation is insufficient for sustained competitive advantage. Evidence that firms require more than continuous improvement as a design and manufacturing strategy is offered by Morone (1993). He found that successful Japanese and US firms in different industries were more similar to each other than to unsuccessful firms in the same industry. The successful firms, regardless of country of origin, achieved competitive advantage over rival firms based on a combination of incremental and discontinuous innovation.

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Continuous improvement and discontinuous innovation used together offer the potential for sustained competitive advantage. Since continuous improvement has been the subject of so much attention over the last two decades, we focus on discontinuous innovation. Furthermore, in many technology intensive industries, competitive advantage is built and renewed by discontinuous innovation which creates new families of products and business (Foster, 1986). Consequently, discontinuous innovation offers the potential for competitive advantage and requires greater attention by management practitioners and academe.

One disadvantage that discontinuous innovations have is they lack a supporting infrastructure, this is due to the relative novelty of discontinuous innovation. Consequently, we will consider the development of infrastructure. Historically, infrastructure for discontinuous innovations has often been provided by Government funded research programs, like the Strategic Defense Initiative and the development of nuclear technologies. However, the intervention of government is not necessary for the emergence of infrastructure for discontinuous innovation. Managing a discontinuous innovation often requires substantial capital investment in unproven technologies for a market that is ill defined. Furthermore, suppliers may be non-existent and government policy may discourage the development of the technologies and market. However, as unpredictable as the commercialization process for discontinuous innovation can be discontinuous innovation provides the greatest economic rent and most sustainable competitive advantage. Discontinuous innovation can result in a new "product-technology- market" paradigm placing the firm's product offering into a new and higher customer value plane (Bower and Christiansen, 1995, p. 45). Firms successful with this approach can pursue continuous improvement, while reaping the rewards of a unique product offering.

To understand how to develop an industry based on discontinuous innovation the question *How does infrastructure develop for an emerging industry that is based on disruptive technology?* must be answered. Consequently, a model of infrastructure development will be presented. Next, infrastructure status and development activity in MEMS will be considered to demonstrate the use of the model.

THE NEED FOR INFRASTRUCTURE AND AN INFRASTRUCTURE MODEL

Infrastructure is necessary for the development of radical products. Because the innovation is radical, it is very new. Consequently, the infrastructure needed to support the innovation(s) has not been established yet. For example, when electrical lighting was first introduced it lacked a supporting infrastructure. Gas lighting had been in use for many years and a gas delivery system existed in all major cities (see Utterback, 1994). But electricity was not as easily obtained as gas, since the use of electricity as a source of power was a radical innovation. The potential for the success of electric lighting, and other electric apparatus, relied on the availability of electricity. Radical innovations experience a lack of some of the desired infrastructure. Depending on the magnitude of the difference between the innovation(s) and pre-existing technology the extent of the infrastructure gap will differ. In most cases, the lack of infrastructure is not as intuitively obvious as in the electricity example. Infrastructure does not necessarily involve the establishment of physical structures, like electric transmission lines or roads. Infrastructure also implies a pool of knowledge and technical abilities—upstream infrastructure—and customer knowledge and marketing channels—downstream infrastructure. No matter how large or small the gaps in the required infrastructure are a model of infrastructure is of value, since it will help firm strategists and policy makers decide whether an emerging market currently has a good fit with a firm's capabilities, competencies and strategy. A description and explanation of the model is followed by the application of the model to an emerging industry based on discontinuous innovation—MEMS.

THE INFRASTRUCTURE MODEL

The infrastructure model is depicted in Exhibit 1. The model considers infrastructure as consisting of downstream and upstream components. Upstream infrastructure addresses the technical novelty of the discontinuous innovation(s). Downstream infrastructure is the identification and development of a customer base. These two infrastructure components can be considered independently, but must be considered together to evaluate the current status of the infrastructure of the industry that is emerging from the radical innovation. Consequently, we will now further consider the upstream capabilities, downstream capabilities, and the overall infrastructure.

The upstream infrastructure can also be expressed as "technology push" or the development of technological competencies. The nature of technical competence, or the level and type of knowledge that is possessed about the technology, changes with time and experience with discontinuous innovation. This growth in technological knowledge and competence results in a four-stage progression: basic research; state of industrial manufacturing; bottlenecks, technological development and stable new technology. *Basic research* is the scientific base or principles that the innovation(s) are based on. As knowledge about the science and ability to work with the science grows, it is possible to use the techniques in manufacturing—*state of industrial manufacturing*. Bottlenecks or constraints are encountered which hinder use or production. Encountering and overcoming these technological bottlenecks is the *bottlenecks, technological development* stage. Once these bottlenecks to production and/or use are addressed the innovation becomes a *stable new technology*.

Downstream infrastructure relates to the demand side or "market pull" for the products that develop as a result of the discontinuous innovation. In an emerging market based on discontinuous innovation, the market passes through a series of phases: non-existent market channels, initial market acceptance, market augmentation, and new markets. Initially these markets are faced with *non-existent market channels*, not only are there no distribution channels for new products, but potential customers are not even aware of the existence of the technology. Firms that utilize MEMS at this time must realize that they must make an effort to develop infrastructure, since potential customers need to be made aware of the technologies and time and effort will be required before the customers are prepared to accept the new products (Moore, 1991). If MEMS advocates do not focus on raising the awareness and acceptance of potential customer groups, the eventual acceptance of products by customers will be delayed—perhaps indefinitely. Eventually, there is *initial market acceptance* of one product. The product that is accepted or chosen by the marketplace typically offers an improvement of at least an order of (Walsh 1996). Order of magnitude improvements are so attractive that even a resistant market place is willing to undergo the learning, risk, and other disruptions associated with change. Frequently, managers and analysts will not realize the significance of an initial market acceptance. Many will still consider the technology to only have value in a limited number of applications, the transistor was initially perceived as just a vacuum tube alternative. However, the initial market acceptance of a product allows the market to test a product. In the *market augmentation* stage, the one product having entered the market has reduced potential user's perception of newness and the associated risk. Consequently, the users that already have applied the technology to solve one problem are receptive to modifications of the existing product or alternative applications that allow for the technology to be used better in their market. Furthermore, other markets become receptive to using the initial product in applications in their industry (that are similar to the initial application of the product). For example, high-speed valves developed for the aerospace industry have been applied to laboratory fumehood ventilation that also requires fast response to changes in user demands. Finally, completely *new markets* accept the discontinuous innovation as customers either actively seek solutions for their problems or customers are familiar enough with the technology to accept it without reservation.

Having considered the upstream "technological" and downstream "market" components of infrastructure development, the interaction of the two are discussed. The interaction is examined from the perspective of the firms that use the discontinuous innovations to produce new innovative products. These interactions consist of three stages: force fit of prototypes, modifications to existing processes, and robust infrastructure. Initially, there is a *force fit of prototypes*. Prototype products and processes are developed with production equipment and/or consumables already developed by the manufacturer. As market interest (market pull) and technological competence (technology push) increase *modifications to existing processes* and equipment occurs allowing for large scale production of product. Finally, the market is of significant size and the technical competence is distributed widely enough to support a *robust infrastructure*. At the *robust infrastructure* stage, suppliers are able to provide needed production equipment, raw materials and consumables. The model is important because it helps a firm determine at what time they should enter the emerging market. By examining the status of the supporting infrastructure, a company is forewarned about what infrastructure must be developed internally to enter early. A company can determine how far the infrastructure must develop before they can enter the market based on their intended strategy. Based on a firm's capabilities and the infrastructure requirements the management team may decide that late entry is the most suitable timing strategy. This model assists a firm in determining what entry time will offer advantage to the organization, based on the resources that the firm has upon entering the emerging industry. Having described the infrastructure model, a description of MEMS and the application of the infrastructure model follows.

MEMS: AN EMERGING INDUSTRY WITH AN INCOMPLETE INFRASTRUCTURE

MEMS has great potential for future growth and importance and we apply this model for validation and application of the infrastructure model. However, prior to discussing MEMS in terms of its developing infrastructure some background information about the industry is needed. Micro-Electro-Mechanical-Systems (MEMS) are also referred to as micromechanical systems, micro machines or Micro Systems Technology (MST). This manufacturing approach enables the development and production of many new products. MEMS manufacturing technologies are an example of discontinuous innovations that can replace some industries, revitalize other industries and create new markets. MEMS are the set of manufacturing technologies that are used to produce miniscule physical parts, like micro-gears. The total market for products produced through the use of MEMS technologies in 1994 was less than $1 billion. Projections of the market size for MEMS based products vary greatly (see Exhibit 2). Sales and the number of applications for MEMS based products are growing rapidly, although the underlying production technologies are numerous and their infrastructure is at different stages of development.

There are three major MEMS production technology groupings: traditional bulk micromachining, Sacrificial Surface Micromachining (SSM), and High Aspect Ratio Micromachining (HARM). The status of these technologies in relation to the infrastructure model will be considered following the provision of necessary background information about the three families of production technologies — Technology Push: stage 4 – *stable new technology* and Market Pull: stage 3 – *market augmentation* (see Exhibit 1). Traditional bulk micromachining is a mature production technology. It has been used for the production of pressure sensors, since the 1950's. Technological advances in bulk micromachining technology have widened its market applications. Traditional bulk micromachining has developed an infrastructure and is used to produce pressure sensors for aeronautical, automobile and medical use. Users include entrepreneurial efforts, like Lucas Novasensor, and large corporate enterprises, including General Motors and Ford and MEMS Foundries such as Sentir.

Sacrificial Surface Micromachining (SSM) has the next most robust infrastructure of any MEMS production technology — currently moving between stages two and three of the infrastructure model in Exhibit 1. Current commercial applications include the air-bag accelerometer used in the automotive industry. It is the key production technology for commercialization efforts at many firms, such as Texas Instruments and Analog Devices and the focus of technology development at national labs such as Sandia National Laboratories in Albuquerque.

High Aspect Ratio MEMS (HARM) includes micromachining technologies such as LIthogafie Galvanik Abeforming, (LIGA) and Deep Ultra Violet lithography techniques. These technologies are often referred to as technological substitutes for traditional bulk micromachining and SSM, but in the future are expected to be complementary, rather than competing, production technologies. HARMs technologies are currently becoming commercially viable — moving from stage one to stage two of the infrastructure model in Exhibit 2. These technologies allow for the fabrication of high aspect ratio plating molds. These molds provide new ways to produce micromachined parts at a fraction of the current cost.

The current status of the three different MEMS production technologies, in relation to the infrastructure model, can be developed (see exhibit 1). Managers and technologists investigating MEMS, in stage one of the model, typically utilize a force fit between manufacturing and market channels. Initially, at the *Basic Research* and *Non-existent Market Channels* steps technologists utilize existing lithrographic techniques optimized for microfabrication to produce expensive products of limited utility.

Stage two, *State of Industrial Manufacturing* and *Initial Market Acceptance* steps, in the infrastructure process (see Exhibit 1), depicts a technology initiating a successful Technology-Product-Market paradigm shift. The pilot or limited production of product results in modifications to existing manufacturing equipment. The advances of clever "home-made" solutions, that leverage existing technologies, commence. In the cases of MEMS lithography, "home-made" double-sided lithographic aligners constructed from obsolescent microfabrication aligners emerged to support the manufacture of products. Market channels also widened, as a result of high-technology entrepreneurs entering the industry. For example, entrepreneurial firms like Novasensors provided a highly specific product for a single market niche. Initial market channels involved an entrepreneur, with knowledge of MEMS and a specific problem in a specific industry, convincing firms in that industry to test a product based on MEMS technology to solve a specific problem. (Novasensor convinced firms in aerospace to use a lightweight MEMS based sensor for measuring pressure.)

Next, in Stage three (see Exhibit 1 – *Bottlenecks, Technological Development* and *Market Augmentation* steps), techniques are designed to optimize the characteristics of the technologies resulting from the discontinuous innovation. Market channels increase and widen as variations of the same product are applied to the same market and the same product is introduced into different markets. (In the case of Novasensor, they produced new pressure sensor designs to measure different pressure ranges for existing customers in the aerospace industry and sold existing pressure sensors to new customers in the automotive industry.) At this time, industry newsletters and dedicated representative organizations appeared. An industry manufacturing standard does not yet exist, however . Consequently, suppliers provide competing technologies. In the case of MEMS lithography, three different suppliers competed with the new sacrificial UV lithography and LIGA based X-ray lithography.

In stage four, the *Stable New Technology* and *New* Markets steps, a robust infrastructure emerges for some competing techniques. Sacrificial Surface Micromachining (SSM) is approaching a robust infrastructure. Three suppliers support this technique. Furthermore, Sandia National Laboratories has developed their second iteration of SSM tools. The typical MEMS firms are now large corporations, as opposed to high-tech entrepreneurial start-ups. The salesman-entrepreneur is replaced by the sales-engineer. The use of strategic market partners to obtain market leverage is also common. At this point, a mature infrastructure exists and the behavior of manufacturers, customers, and suppliers is similar to that in many mature markets.

Having initiated an example of MEMS production technology - through the infrastructure model, we will now explain the status of the different MEMS production technologies. Traditional bulk micromachining is in the second stage, *modifications to existing processes,* of the model. Novasensor, Motorola, Brede and other firms have modified traditional manufacturing techniques to produce limited volumes of product. Furthermore, Okmetic and Siltec, material vendors, and LAM and Karl Suss, equipment vendors have recently offered products specific to the MEMS market. These developments suggest that traditional bulk micromachining will soon have a *robust infrastructure*. Sacrificial micromachining lacks some of the technological capabilities of traditional micromachining, but can draw on millions of person-years of microtechnology development work. Consequently, it may still develop a *robust infrastructure* before traditional micromachining. HARM technologies are not yet commercially viable. Consequently, they are still in the first stage of the model *force fit prototypes.* It is anticipated that HARM technologies will soon enter the second stage of the model. The stage of infrastructure development for all three major technology groups has been clarified using the infrastructure model (Exhibits 1). MEMS's infrastructure building activities are placed in perspective by offering a brief history and stating current activities.

As stated earlier, bulk micromachining has been in use since the 1950's. A number of years passed prior to the incorporation of a component, which was manufactured with MEMS technologies, into a product. The first product was a sensor for the aerospace industry. The sensor offered a reduction in weight of over an order of magnitude. (In aerospace applications weight reductions are highly valued due to the substantial savings in fuel. For example, for a transatlantic flight about 1/3 of the weight is fuel. For space applications the fuel to vehicle weight percent of fuel is much higher.) The delay in commercialization is unsurprising, since many different researchers have suggested that the time lag from invention to business innovation for various types of radical innovations averages between eleven and thirteen years.

Since 1993 the rate of patent filing has increased dramatically (see Exhibit 3). This suggests that inventors are increasing activity in the MEMS field and perceive their advances to have commercial value. Consequently, it is worth considering infrastructure building activity around this timeframe. There has been government intervention to support the development of MEMS infrastructure. However, consideration of market based infrastructure is more valuable to understand the emergence of the market. Consequently, some examples of government intervention are briefly noted. The European Community (EC) is supporting four regional MEMS service centers to facilitate the development of MEMS based devices and markets in the EC. These service centers are a corporate/university partnership that may accelerate the infrastructure development process. In Japan, the Micromachine Center has over thirty-one corporate members as well as University research center involvement. In America, federal government activities include the "HiMEMS" alliance that has the mission to initiate the development of local commercial infrastructure for LIGA. The effect of infrastructure development of Phase I and II of model is to develop infrastructure specific to the disruptive technology base fueling this emergent industry. Having offered some of the highlights of governmental activity focussed on the generation of a MEMS infrastructure, we will return to our discussion of corporate activities and infrastructure development.

SEMI is attempting to establish the SEMI name as a participant and a resource for MEMS activities and information, educate SEMI members about the MEMS technology base and the market opportunities MEMS offers and provide networking opportunities for SEMI members in the MEMS marketplace. In pursuit of these goals efforts were made in 1994 to raise awareness and interest in potential opportunities for firms that could be suppliers, users, and customers. Examples of this include an international strategy symposium given on MEMS to SEMI suppliers. As a consequence SEMI members including: Karl Suss, Disco, Okmetic, JT Baker, Ultratech Steppers, Siltec, Shipley, Lam Research Corp., and Virginia Semiconductor Inc. have developed an interest in MEMS markets. Consequently, SEMI has developed a series of international informational meetings.

During the same period, advances were made in product development and commercialization. Analog Devices commercialized their SSM accelerometer for airbag use; and Texas Instruments and Sony formed an alliance to commercialize Texas Instrument's Digital Micromirror Device technology (DMD) for commercial electronic applications. Efforts to raise awareness and involvement in emerging markets, like MEMS, encourage infrastructure development by increasing customer awareness and acceptance and supplier interest and involvement. Surprisingly, pioneering firms in MEMS and other emerging industries gain by sharing some proprietary information, due to the positive effect that shared technical and market information has on the development of infrastructure. Having examined the infrastructure model in term of an example, MEMS, we will now consider the implication of the model to policy makers and corporate strategists.

IMPLICATIONS TO POLICY MAKERS AND CORPORATE STRATEGISTS

For a discontinuous innovation, an examination of the level of customer awareness, acceptance, and use of products and an examination of the supply base for consumable and capital goods allows the corporate strategist to understand the emerging industry's location on the infrastructure model. This is of importance to the strategist, since it will assist the strategist in understanding what activities and investments are required in other parts of the supply chain for their venture to succeed. If your firm identifies MEMS manufactured products as an emerging industry is in the first phase of the infrastructure model, participating firms require patient capital. You must be willing and able to develop their own supplies and supply base. Furthermore, resources are required to take potential customers from a lack of awareness of a product to being aware of the product to being knowledgeable users and advocates of the products that are based on the technology. Obviously, the early growth stage of an industry is appealing to entrepreneurs (sometime referred to as getting in on the ground floor), but the lack of infrastructure suggests that success is unlikely, unless substantial patient capital and/or cooperation with other firms (including potential competitors) exists. In the case of MEMS, SEMI is attempting to foster cooperation between firms, thereby increasing progress through stages II (State of Industrial Manufacturing) and III (Bottlenecks, Technological Development), so that infrastructure can develop with only small investments being required by many firms. As the progression towards a robust infrastructure occurs firms require less resources, since supplies can be acquired cheaply and easily.

The infrastructure model allows the policy maker to examine an emerging market and determine what actions are required to encourage the growth of the infrastructure. By monitoring the change in infrastructure, the policy maker can determine when current actions should be modified. For example, a major milestone for an emerging technology is the commercialization of the first product. Programs like the Small Business Industrial Research (SBIR) program assist in the development of infrastructure. The SBIR program assists in the creation of suppliers and the development of a more robust supply base. By doing so the SBIR assists in reducing the time required to move through the *state of industrial manufacturing* and *bottlenecks, technological development* stages of the technology push part of the infrastructure model (see exhibit 1). Afterwards, changes to government purchasing guidelines can be made to enable use of products developed by the emerging industry. By understanding the current status of the emerging infrastructure, policy makers can implement programs that are more suitable for supporting the infrastructure to the next stage and firm's can develop strategies that are in line with both their resource base and the existing emerging industry infrastructure.

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Exhibit 1: Infrastructure Model

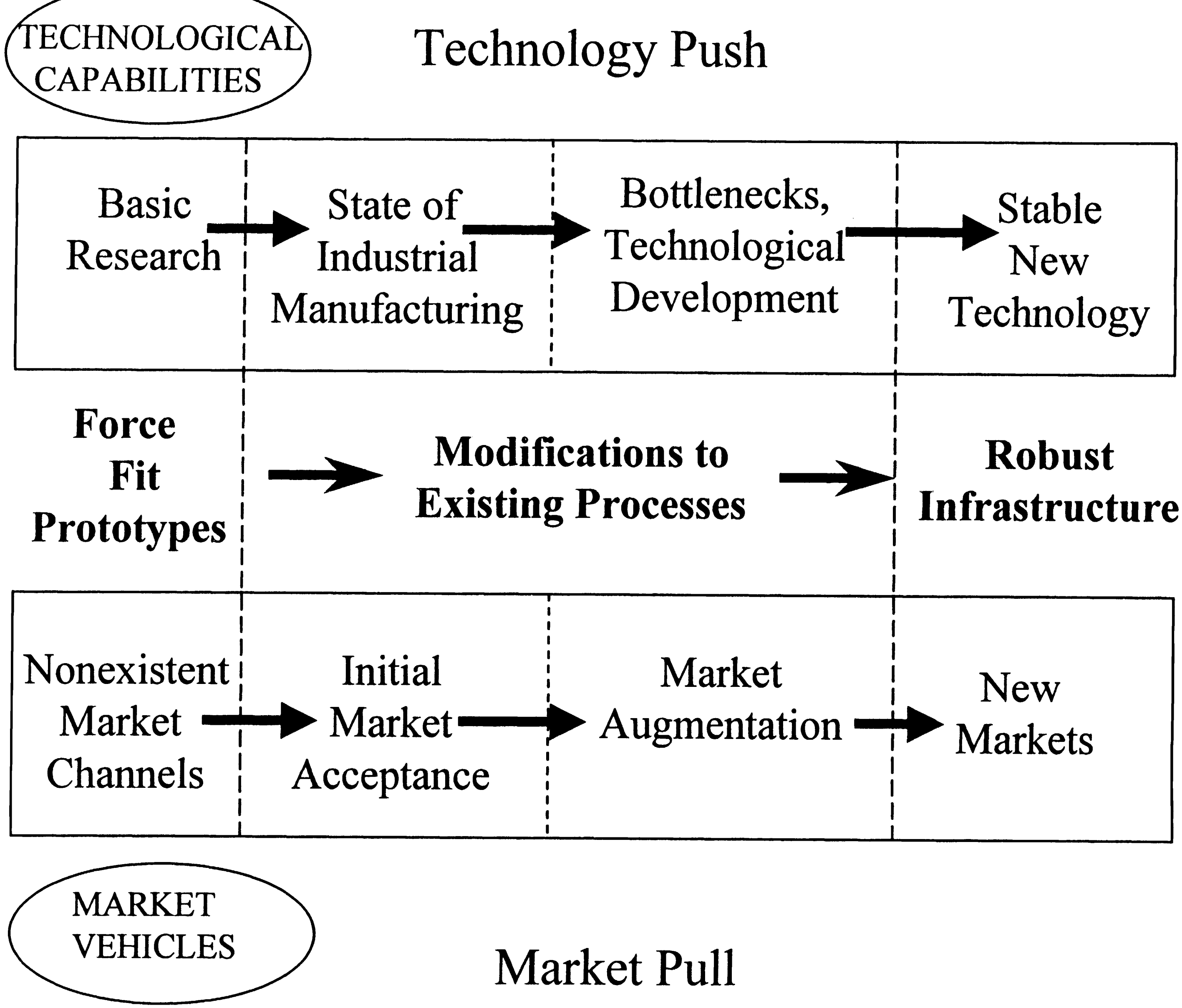

Exhibit 2: Forecasts of the Size of the Market for MEMS Products (Nagel et al., 1997)

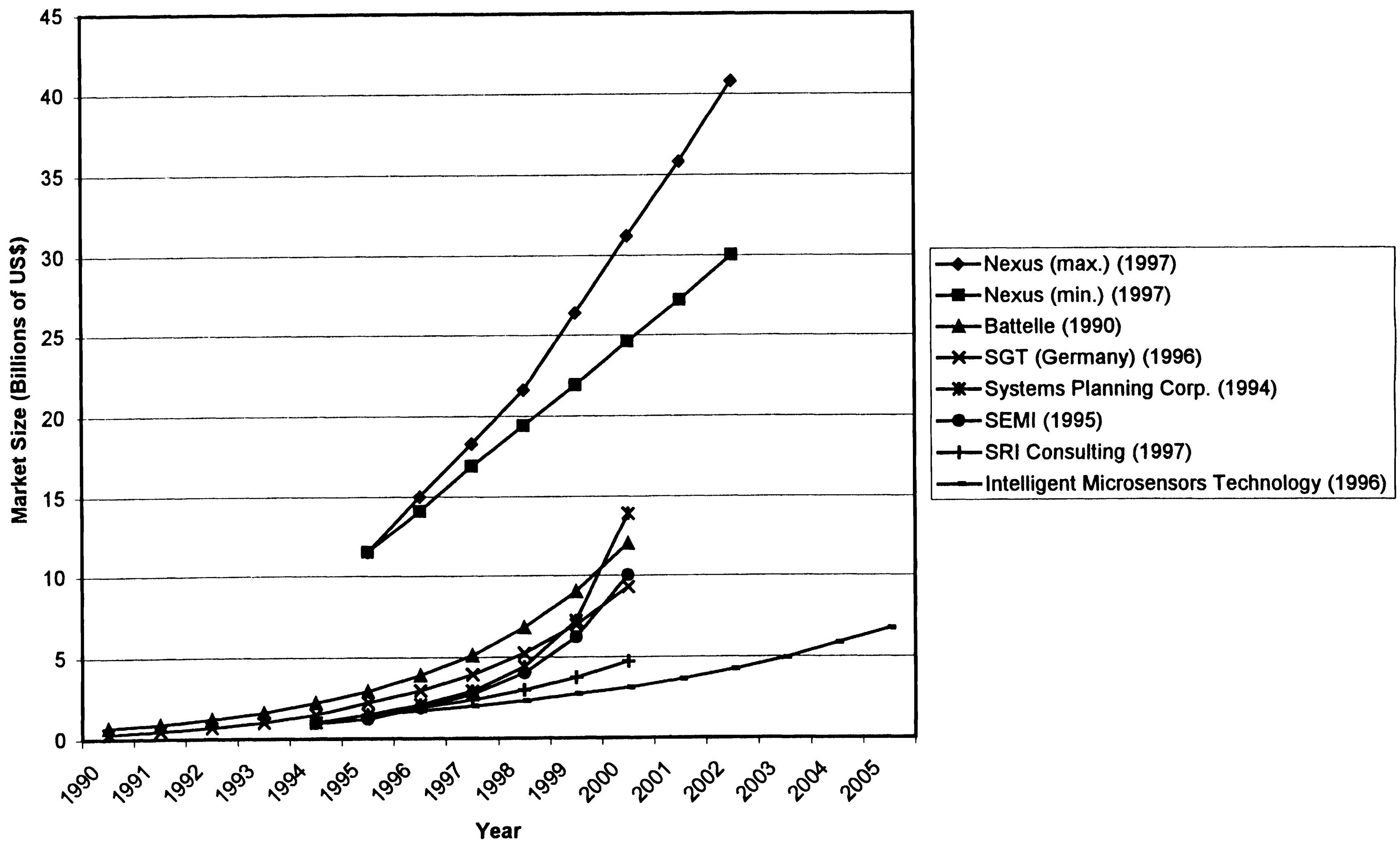

Exhibit 3: Rate of Filing of MEMS Related Patents in USA, Europe, and Asia (Nagel et al., 1998)