Commercialization of Microelectromechanical Systems (MEMS)

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ABSRACT

Microelectromechanical systems (MEMS), at their core are a set of technologies that employ the processes developed in the integrated circuit (IC) and semiconductor industries to construct electro- mechanical devices. In the case of Microopticelectromechanical systems (MOEMS), optical elements are also integrated into these devices.

MEMS technology holds the promise of significantly miniaturizing, reducing the cost of, and enhancing the performance of many sensors and actuators, evidence its widespread use in the manufacture of accelerometers, ink jet printer heads and various chemical gas sensors.

Despite its stellar success in these "killer-applications," MEMS technology has failed to realize the widespread success many had predicted for it. Nonetheless, this technology has recently been explored extensively for new electro-optics applications, specifically in telecommunications for dense wavelength division multiplexing (DWDM) and optical switching.

This thesis examines various models of dynamic technology adoption and explores how they apply to MEMS technology. Furthermore, by way of historical comparison to the development of application specific integrated circuit (ASIC), it will identify various developmental similarities. Finally, a unique model outlining the critical driving forces behind the adoption of MEMS technology will be constructed.

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1 Introduction

1.1 Background

The rapid and effective commercialization of technical advances is critical to the success of high-technology industries. The process of commercialization of new technologies results from the complex interplay between the evolution of technical advancement and the ability of the firms, both within an industry and external to that industry, to recognize the value of those technologies. Furthermore, these firms must assemble the means and expertise to exploit the potential of these technologies to commercial ends. This ability to exploit the commercial potential of new technology is arguably the most important source of competitive advantage to all high technology companies. It is for this precise reason that the study of the diffusion of technology has been the subject of extensive research over the past several decades.

The study of the diffusion of innovation has attracted the interest of a wide variety of disciplines, including education and learning, organizational behavior, communications, marketing and sociology. In each field, there exists numerous theories that seek to explain how and what factors influence the adoption and diffusion of technology. Suffice to say here, many factors from all these fields influence technology diffusion and adoption. It is this complexity of interchange between many factors, coupled with the short- and long-term dynamics of these interactions, that make the field of system dynamics particularly well suited for the study of this topic.

Nonetheless, technology diffusion can be viewed as a special kind of communication in which the message is about a new idea. The very novelty of the idea gives the message a special characteristic, that of uncertainty. Uncertainty implies a lack of predictability. It is the goal of this thesis to examine this property of the process of adoption. Information is perhaps the most notable antidote to uncertainty. Thus, it is also the goal here to better define and understand the dissemination of information and knowledge, and to examine the role of knowledge transfer as a driving force in the adoption of MEMS technology, and indeed any technology. More specifically, it is the dissemination of information throughout an "infrastructural value-chain" that represents a form of social change, without which adoption will be slowed.

1.2 Purpose and Approach

This thesis will seek answers to the questions: What factors shape the demand for new technology, specifically MEMS technology, and how can an organization shape those factors so as to improve its success in the marketplace? The investigation will begin with the basic model for technology adoption proposed by Lyneis[1] and will explore in some detail its three key concepts: 1) the availability of potential conversions, 2) the willingness to switch and 3) user need. The concept of user toolkits forwarded by von Hippel[2] will be examined in light of the Lyneis model. In addition, a recent working paper on industry disruption by Clay Christensen[3] will be considered.

The manner in which several companies have attempted to influence these various factors in the ASIC and MEMS industry will also be identified, particularly the willingness to switch on the part of potential customers. Moreover, the history of LSI Logic will be considered, and the approach it employed will be compared with the business strategies of Cronos and IntelliSense in the MEMS industry. Finally, several business strategies will be proposed for successfully introducing new MEMS-based products.

2 Literature Review

2.1 Diffusion and Innovation

One of the earliest works on the study of technology diffusion and adoption is the Laws of Imitation by the French sociologist Gabriel Trade in 1903[4]. In this book the first expression of the concept of "opinion leaders" and

"S-shape adoption patterns" were forwarded. While work counted in the area, it was in 1943 that a seminal study examining the adoption of hybrid seed corn by Iowa farmers was published by Ryan and Gross[5] and the beginnings of a conceptual and mythological distinct area of research was forged. Rogers formalized this cross-disciplinary field of technology adoption in 1962 with the publishing of his book, Diffusion of Innovations.[6] In 1995, Rogers revised and expanded his book with over one hundred generalizations.

Rogers defined the diffusion of technology as "the process by which innovations spreads to members of a social system." He described an innovation as being "any practice or object perceived as new by an individual." Based on this view, it is tempting to begin to apply an approach articulated in the system dynamics literature to describe adoptions of new products to MEMS, with perhaps the product being "knowledge." Rogers goes on to present a simple classification system scheme consisting of five conceptually distinct characteristics: 1) relative advantage, 2) compatibility with values, needs and past experiences of potential adaptors, 3) complexity of understanding and using innovation, 4) "trialability," i.e., the ability to use the innovation on a limited basis and 5) "observability," or the communicability of results. Rogers supports his findings with empirical studies, suggesting that each of these attributes can affect the rate of adoption, although it is clear that the relative importance of each is dependent on the particular context in which adoption takes place. Nonetheless, this framework suggests a broad series of causal loops that can form the basis from which to begin to generate a dynamic model.

Traditional adoption has been examined in the context of an individual's adoption of new products. Research has tended to look at those factors that differentiate the various classes of adaptors, which generally have been defined as: 1) risk-taking innovators, followed in order by 2) highly respected early adopters, 3) deliberate early majority, 4) the skeptical late majority, and the entrenched laggards.[7]

Alternatively, a model has also been forwarded that examines adoption as a problem-solving behavioral pattern in which individuals progress through a series of steps: 1) becoming aware of a problem, 2) recalling and gathering information about possible solutions, 3) evaluating alternative solutions, perhaps with limited attempts, 4) deciding on the appropriate solution and 5) evaluating the decision.[8] This is similar to the work 1971 of Robertson[9], where he describes a conceptual model consisting of three fields: 1) the cognitive field consisting of problem perception, followed by awareness and understanding, 2) the attitude field consisting of attitude formation and legitimization and 3) the behavior field consisting of trial and adoption. Robertson points out that the process leading to adoption could be interrupted or cut short at any point. Other investigators eventually added a final stage to the Robertson model, that of confirmation, which determines the continued or discontinued use of a product.[10] Discontinuance occurred as a result of dissatisfaction with the innovation or by displacement by a newer technology. It is these models based on Robertson that are perhaps worth considering in the context of organizations as adaptors of new technology (not creators) and as the basis for a generic framework or series of causal loops for studying the adoption of new technology.

In more recent years, a number of investigators have developed frameworks that attempt to further characterize innovation along a number of dimensions, such as technological, economic and organizational. For example, Abernathy and Clark [11] list four types of innovation: 1) niche, 2) regular, 3) architectural and 4) revolutionary, which are distinguished along the dimension of "transilience". Transilience is defined as a measure of the impact of the innovation on the firm's competencies. This, in turn, measures the competitive advantage of the firm. Innovations that open up new markets, require new channels of distribution, or establish new relationships with customers (or forms of communication with customers) would all have greater transilience. Similarly, innovations that radically depart from established technologies that require new designs and manufacturing techniques are characterized by higher degrees of technological transilience. Architectural innovations are disruptive along both dimensions (market and technology). Niche innovations are disruptive along market dimensions. Regular innovations build on existing markets and technologies. Revolutionary innovations make obsolete a company's (perhaps an industry's) technical skills and knowledge while preserving market connections.

Henderson and Clark[12] present a model that considers the impact not only on the components of a product, but also on the relationship among the components as well. In their model, radical innovations overturn the core design concepts of the components and the way they interact. They characterize incremental innovations as reinforcing design concepts and preserving the existing lineages among the components. Architectural innovation retains existing core designs, but at the same time, alters the relationship between the components. Modular innovation utilizes new components, but generally preserves the relationships among them or the configuration within the product. Both these frameworks view successful commercialization as being related in large measure to the ability of organizations to acquire and distribute new architectural knowledge.

Foster forwards another view of technological progress.[13] His model forwards the notion that successful firms are those that recognize the limits of existing technology. The concept revolves around a framework that empirically recognizes the occurrence of S-curves in technological progress. Foster applies his model by plotting various performance parameters against effort to further improve those parameters. Thus, as the rate of improvement in performance begins to decline, the technology is said to be reaching its natural limit. While the Foster model is consistent with historical data, it only accounts for endogenous factors and does not account for such exogenous factors as market and competitive forces. Similarly, Utterback[14] views the flattening of the S-curve as arising from the establishment of a dominant design for the technology or product that results from competition in the market among rival firms.

Christensen[15] has examined growth in the disk drive industry, and in so doing has developed the hypothesis that incumbent firms, while quite successful at fending off new entrants by utilizing sustaining innovations around existing technology, are generally unable to recognize disruptive technological changes. He categorizes many of these disruptive changes as architectural in nature, i.e., they involve new configurations of existing components within a product. It is by virtue of these disruptive innovations that companies are forced to shift to entirely new value networks, where their previous business practices might be unsustainable. More importantly, firms cannot rely on existing customers to decide whether to commercialize a new technology. Christensen intimates by way of example that typically these innovations perform more poorly than existing technologies along a set of criteria favored by existing customers, but fill the unique requirement of newcomer firms along differing dimensions of performance.

There are essentially two assertions to the Christensen model. The first is that there is a trajectory of performance improvement that customers can actually absorb or utilize over time. The second assertion is that there is a distinctly different trajectory of performance improvement that the innovators in an industry provide to their market. Christensen's studies reveal that the trajectory of technology is generally steeper than the abilities of customer to utilize the improvement. It is this difference between the trajectory of performance and customer need, which eventually opens the way for people serving lower-tiered markets to begin to attack customers in higher-tiered markets.

Similarly, Cooper and Schendel[16] found that typically new technologies were more expensive and under performed relative to established technologies, at least along the traditional dimensions of performance. They observed that newcomer firms often were the first to commercially introduce a new technology. Furthermore, while these frequently created new markets, success depended in large measure on initially capturing a niche market segment within an established market. The response of established firms to these new technologies varied, but could be characterized as one of the following: 1) improving older technology, 2) avoiding directed competition by ceding market share or 3) participating in the new technology through some form of internal development.

Clearly, then, the degree to which an innovation or new technology is to be considered disruptive can be viewed along many dimensions (e.g. product performance and market needs primarily) and from various perspectives (e.g. existing users, new users, manufacturer and supply primarily). Is MEMS technology disruptive by the criterion established by these investigators? If so, how might its success be accessed in various markets? By all measures, the technology is disruptive in many industries; however, the success of MEMS technology will vary greatly, depending on the specific application, markets and incumbent technologies at play.

2.2 Dynamic Models

There have appeared in recent years an increasing number of numerical models studying time series data related to the diffusion of innovation or first purchases. Much of this work has evolved from models built to examine the growth of population and the spread of infectious diseases. One of these models is SIR model developed by Kermack and McKendrick in 1927.[17] The importance of this model was its second order nature and the ability of the disease to die-out, without always causing an epidemic. In addition, this allowed for the observation of the tipping-point. For any given system there is a critical combination of contact frequency, infectivity, and disease duration just great enough for the positive loop to dominate the negative loops. Below this point, the system is stable and on average people will recovery faster than new cases are generated. Beyond this point, the system becomes unstable and once the disease arrives it will spread uncontrollably, limited only by the remaining susceptible population. The SIR model also involved the concept of the herd immunity, i.e., once a sufficient population is infected the reproduction rate will fall below one and the disease will become dormant.

A second important model in the evolution of the study of diffusion is the logistic growth model. First published in 1838 by Francois Verhulst, it was reexamined by Richardson in1991.[18] The dynamic model from which the logistic or S-shape curve is derived is a very simple one, consisting of only a single differential equation. It is based on the assumption that adoption takes place solely as a result of the imitation and word-of-mouth interaction between adopters and non-adaptors.

Bass introduced an important extension to the logistics growth model that allowed for the inclusion of more real world complexities in 1969.[19] It took the form:

$dN/dt = (a + b\,N_a)\,(N_p - N_a)$ where:
N_a = the number of adaptors
N_p = the number of potential adaptors
a = the coefficient of innovation
b = the coefficient of imitation

The Bass model was based on the notion that non-adopters can be persuaded to become adopters as a result of interactions either internally or externally to the network of adopters. If $a = 0$ in this equation, the logistics model is operation and all persuasion comes from internal sources. If $b = 0$, then the exponential model is in effect and all persuasion comes from external sources with no limit. Empirical best-fit testing of the model usually generate very small values for "a", reconfirming the basic usefulness of the logistics model.

The Bass model includes several simplifying assumptions that others have sought to relax in order to gain further insight and allow the model to be applied more generally and realistically. One method for this is to allow the internal and external coefficients to vary over time in response to changes in the intensity of marketing[20,21]. A second extension allows for the multiplicative effect of price reductions arising from the manufacture's increasing experience with the product. The cumulative number of adopters (N) is used as a proxy for this increased in experience.[22] A third extension considers the effect of sales of other products on sales of the new product. The nature of this effect is a function of whether the two products are independent, complementary, contingent or substitutes[23]. The model has also been extended to allow the coefficients to depend on location, resulting in a time-space diffusion model.[24] Other extensions to the Bass model have also been proposed that, allow for a change in the number of potential adaptors (N_p) through exogenous means, i.e., these changes occur independent of the adoption process itself (endogenously)[25] Models which allow for exogenous changes to potential adaptors, are generally based on a two-step process of learning consisting of awareness and acceptance.[26]

Sharif and Ramanathan in1982 proposed an extension to the Bass model of particular relevancy to the adoption of new technology.[27] In their model, various outcomes of the decision process are allowed, including adoption, rejection, re-adoption by rejecters, and permanent disapproval. This model is appropriate for analyzing multi-level technology substitution, a situation in which old, intermediate, and new products are simultaneously vying for market share.

Finally in a model proposed by J. Lyneis,[28] he lays out a basis for generally determining: 1) how much to invest in an existing technology vis-à-vis next generation of technology, 2) when to introduce a new generation of technology, 3) how much to spend on marketing and 4) how to price the new product. In the process of generating his general model Lyneis attempts to ensure that the formulation and output of the model produces results consistent with several existing forecasting and assessment techniques, including: 1) ability to generate S-curves to demonstrate technological progress, 2) cost experience curves and there influence on pricing strategy, 3) price performance trade-off curves, 4) diffusion or product life cycle deploying the concept of lead user to laggards (discussed previously) and 5) substitution curves developed consist with Fisher-Fry techniques. Lyneis accomplishes this by defining a matrix of three overreaching factors: 1) the user need, i.e., technology push vs. market pull; 2) market growth rate, i.e., the higher the growth rate the more new users there are relative to replacement users, and therefore the higher the willingness to switch to the new technology and 3) product lifetime vs. technology lifetime, i.e., the shorter the technology lifetime relative to the product, the more critical will be the timing of technology adoption relative to the replacement cycle of the older technology.

2.3 Origins of Innovation in MEMS and Relevance

MEMS owe their roots to the integrated circuit industry, which played an indispensable and inseparable role in creating the basic knowledge out of which grew the MEMS industry. MEMS technology began at the Sandia National Laboratories, in California, when the US government required a highly robust, mechanical system to act as locking-triggers for its nuclear arsenal.[29] It had been known for some time that electronic triggering devices were subject to disablement from larger electro-magnetic pulses (EMP) associated with nuclear explosions. The fear was that such an event, perhaps the result of a nuclear first strike, would render the US arsenal crippled and thus remove its deterrent effect. Thus, among other technologies, MEMS was born. There existed a substantial barrier to deploying this technology because of a lack of reliable data to support its use in such a critical application. Thus, efforts where made to find commercial applications whereby a large number of MEMS-based devices might be sold and tested in real world application, which would, in turn generate the data required in deploying the technology for military application.

To this day, Sandia National Laboratories remains one of the most advanced and encompassing MEMS development laboratories. But some have claim the origins of MEMS technology can instead be found at Draper Laboratories in Massachusetts[30]. An independent non-profit laboratory loosely affiliated with MIT, Draper conducts research and development on missile guidance systems for its primary customer, the US military. Some of the earliest work on MEMS accelerometers was conducted at Draper, which was related to the laboratory's missile guidance research. Nonetheless, as with many technologies, the US government's role was important and its motives were primarily defense-related.

Two of the most successful early commercial applications of MEMS technology were pressure- and acceleration-based sensors. One of the earliest applications of bulk micro-machined devices (BMD) was pressure sensors used in aerospace. The signficant reduction in weight offered by these devices was a critical driving force in their adoption, given that typically one-third of the cost of operating a commercial jet is associated with fuel consumption.[31] Additionally, in the case of accelerometers, MEMS-based accelerometers have been adopted and have all but supplanted previously employed technologies for the sensing of crashes and the subsequent deployment of air bags.[32] This compelling need for lightweight, low cost, highly reliable devices was created almost entirely by the government mandating the adoption of air bag technology for use in passenger cars.

As in the cases of these two products, it is important to note that initial adoption and deployment resulted from a compelling need for a unique technical or commercial solution, or indeed, a government mandate for a product. This is consistent with the findings of Utterback,[33] who reviewed a large number of retrospective studies and noted that market factors appear to be the primary influence on innovation, and play a critical factor in 60 to 80% of important innovation. Clearly then, as in the framework forwarded by Lyneis, a compelling performance-to-price ratio can be viewed as the strongest determinate in the adoption of MEMS technology. Indeed, today it is generally accepted that most innovation is driven by market demand, i.e., market pull innovation.

A second important observation of MEMs history is that the successful development of this technology resulted not internally to the commercializing companies, but in large part externally through the effort of Sandia National Laboratory and Draper Laboratories, followed by many universities. This is consistent with the findings of Myers and Marquis,[34] who in their extensive study of 157 historical cases of the commercialization of technology, found that 98 of these ideas were the result of information obtained from outside the firm. Similarly, Langrish[35] found that 102 of 158 key ideas instrumental in the commercialization of 51 innovations came from outside the companies. Indeed, according to Utterback,[36] if the many innovation identified by firms as being commercially successful are studied, it can be concluded that a signficant number (23 to 33%) have been wholly adopted from other firms. If this premise is accepted as being valid, it is clear then that a central requirement for the commercialization of an innovation is some form of information sharing about both the technical dimension of the innovation and the system specific knowledge that could employ this innovation. This engenders the critical question, who are the originators of these ideas and how are they communicated into the firm that ultimately commercializes the innovation?

While there are many factors affecting the commercialization of innovations, seemly two consistently important factors remain paramount. One is the driving force described by Lyneis[37] as the price-to-performance ratio. The second is the capturing of information and the source of innovation.

Von Hippel[38] describes the sources of innovation in a number of industries and, in doing so, broadly categorizes these sources as lying distributed across the functional value chain of an industry. He identifies functional roles of organization as users, manufacturers, suppliers and others.

Von Hippel goes further and attempts to explain why these variations in the sources of innovations occur and how they can be predicted. His hypothesis is, "the analysis of temporary profits (economic rents) expected by potential innovators can by itself allow us to predict the functional source of innovation usefully often." Furthermore, von Hippel defines the innovator as "the individual or firm that first develops an innovation to a useful state, as proven by documented, useful output." Thus, the abilities of firms to protect and benefit from innovations will differ as a consequence of their functional role. For example, innovative users can protect process and process machinery innovations as trade secrets better than other types of innovators. In the case of an equipment manufacturer, the process of selling obviously requires persuasion based on the demonstration of technical competence and/or differentiating features. Thus, innovations are more difficult to protect. In the case of an industry that is process intensive, the ability to protect innovation as trade secrets is far greater. The data presented are sufficiently compelling to suggest that methods of capturing this shared innovative are predicable useful and could provide a source of competitive advantage. Thus, stemming from von Hippel's work, it might be expected that in process intensive industries including MEMS and ASIC, which afford some measure of protection to innovation, sharing of innovation might be feasible and desirable in speeding the adoption of the technologies.

2.4 Conclusions

The Lyneis[39] model will serve as the starting point for the examination of the MEMS industry. It incorporates many important dynamics forwarded by a number of authors discussed in this review. Additionally, it is possible to capture within its framework, the majority of important dynamics revealed in these studies examining both the ASIC and MEMS industries. In combination with this model, the concepts of "Toolkits for User Innovation" forwarded by von Hippel,[40] which are relevant to particular aspect of user design software in the MEMS and ASIC industries, will be applied.

3 Industry Review – Micro-Electro-Mechanical-Systems (MEMS)

Micro-electro-mechanical-systems (MEMS) describe, at once, a technology, a methodology and a set of physical products. While a universal definition is lacking, MEMS products can be generally characterized as subsystems involving a number of micron-sized components and structures. Frequently, the structures are assumed to be active or moving; however, it has come to be accepted that they simply require a significant vertical dimension from the plane of the material on which they are formed,[41] i.e., they require a significant three-dimensional nature to their form and/or function. As part of a high-level architecture, the structures enable a distinctive set of functionalities previously unobtainable with devices of this scale. They enable close integration of a variety of functions, typically sensing and actuation with computation and communication. This has led to the development of a large number of MEMS devices in both the commercial and military sectors. Table 3-1and Table 3-2 summarize the broad market segments and revenues that categorize the MEMS industry.[42] It is important to note that the reports on which these tables are based, exclude devices such as micro-fluidics, micro-optics and optical scanners because it is believed these devices lack "mechanical components," as discussed above. While this may not be entirely true and excludes some important categories of MEMS devices, the data provide a sense of how the market is believed to be evolving.

Table 3-1: Analysis and Forecast of the U.S. MEMS Market by Units in 1999 (in Millions of Dollars)

Year	Units	Unit Growth (%)	Average Units Price ($)	Price Growth (%)	Revenues ($ millions)	Revenue Growth Rates (%)
1995	35.51	-	9.54	-	338.91	-
1996	46.56	31.1	8.78	(8.0)	408.89	20.7
1997	58.77	26.2	8.05	(8.3)	473 29	15.7
1998	71.99	22.5	7.48	(7.1)	538.44	13 8
1999	87.18	21.1	7.05	(5.7)	614.95	14.2
2000	102.90	18.0	6.76	(4.1)	696.01	13.2
2001	118.83	15.5	6.56	(3.0)	779.68	12.0
2002	136.27	14.7	6.45	(1.7)	878.76	12.7
2003	155.63	14.2	6.31	(2.1)	982.33	11.8
2004	173.38	11.4	6.16	(2.4)	1068.20	8.7
2005	191.96	10.7	6.06	(1.7)	1162.55	8.8
CAGR (1998-2005)		15		(3)		12

Source: Frost and Sullivan Report #5999-32, 1999.

Table 3-2: Analysis and Forecast of the U.S. MEMS Market by Percent in 1999 (in Millions of Dollars)

Year	Automotive (%)	Defense and Aerospace (%)	Industrial (%)	Medical (%)
1995	53.6	16.2	21.4	8.9
1996	57.6	14.9	18.8	8.7
1997	59.8	14.3	17.1	8.8
1998	61.0	14.3	15.8	9.0
1999	62.7	13.9	14.5	8.9
2000	63.9	13.9	13.4	8.8
2001	64.3	14.3	12.7	8.8
2002	64.7	15.0	12.0	8.3
2003	65.1	15.6	11.6	7.7
2004	65.0	16.1	11.6	7.3
2005	64.2	17.0	11.8	7.0

Source: Frost and Sullivan Report #5999-32, 1999.

It is instructive to compare these 1999 figures to a similar 1997 report summarized in Table 3-3[43]. While the earlier report clearly overestimates the market growth and actual revenues, it was generally accepted at the time that the potential for this technology was enormous, some even suggesting that these numbers were understated. However, as the market has played out, this enthusiasm has been tempered by the constraints of the technology.

Table 3-3: Analysis and Forecast of U.S. MEMS Market by Dollar in 1997 (in Million of U.S. Dollars)

Year	Automotive	Medical	Information Technology & Industrial	Military and Aerospace	Total
1994	255.7	129.5	438.3	49.1	872.5
1995	298.0	146.1	459.0	54.8	957.9
1996	355.0	164.4	492.8	62.2	1,074.3
1997	419.0	187.0	527.0	71.6	1,204.6
1998	491.5	216.7	575.0	79.6	1,363.1
1999	562.0	245.7	645.9	95.8	1,549.4
2000	645.7	291.3	733.3	110.7	1781.0
2001	758.5	354.8	836.0	133.3	2,082.5
2002	879.6	444.7	995.1	156.9	2,476.3
2003	1,019	562.9	1,222	176.7	2,980.4
2004	1,172	716.0	1,514	202.7	3,604.5
CAGR	16%	21%	16%	16%	17%

Sources: Frost &Sullivan Report#5549-16, 1997.

NB: (1) Data prior to 1997 is actual.
(2) Airbag system and Manifold Absolute Pressure (MAP) sensors constitute 90% of the automotive MEMS sector.
(3) In 1998, the market division was: inkjets 75.6%, displays 5.4%, and industrial 19%.

Today, the industry landscape has more than 50 companies active in the U.S. MEMS market. A large number of these are start-up companies from research laboratories or institutes either marketing a product or technology, or entering partnerships with industry participants.[44] Nonetheless, the majority of revenue for MEMS, remains generated from crash sensors and pressure sensors for medical and automotive use, and is dominated by large semiconductor/sensor firms such as Analog Devices, Motorola and HP. As will be seen latter, it is perhaps no accident that these major players are in the ASIC industry.

Today's major MEMS market applications include accelerometers (or inertial sensors), pressure sensors and ink jet printer cartages. These products require diverse technical and process capabilities, and it is this diversity that characterizes the MEMS industry. Table 3-4, which is taken from a presentation by the US Defense Advanced Research Projects Agency (DARPA), is an excellent characterization of the degree of diversity in the MEMS industry.[45]

Table 3-4: Market Segment and Companies Supported by DARPA

Technology Area	Typical Devices/ Applications	Companies	Market Baseline ($Millions)	Market 2003 (Est.) ($Millions)
Inertial Measurement	Accelerometers, Rate Sensors, Vibration Sensors	TI, Sarcos, Boeing, ADI, EG&G IC Sensors, AMMI, Motorola, Delco, Breed, Systron Donner, Honeywell, Allied Signals	$350-$540	$700-$1400
Microfluidics and Chemical Testing/ Processing	Gene Chip, Lab on Chip, Chemical Sensors, Flow Controllers, Micronozzles, Microvalves	Battelle, Sarnoff, Microcosm, ISSYS, Berkeley MicroInstruments, Redwood, TiNi Alloy, Affymetrix, EG&G IC Sensors, Motorola, Hewlett Packard, TI, Xerox, Canon, Epson	$400-$550	$3000-$4450
Optical MEMS (MOEMS)	Displays, Optical Switches, Adaptive Optics	Tanner, SDL, GE, Sarnoff, Northrop-Grumman Westinghouse, Interscience, SRI, CoreTek, Lucent, Iridigm, Silicon Light Machines, TI, MEMS Optical, Honeywell	$25-$40	$450-$950
Pressure Measurement	Pressure Sensors for Automotive, Medical, and Industrial Applications	Goodyear, Delco, Motorola, Ford, EG&G IC Sensors, Lucas NovaSensor, Siemens, TI	$390-$760	$1100-$2150
RF Technology	RF switches, Filters, Capacitors, Inductors, Antennas, Phase Shifters, Scanned Apertures	Rockwell, Hughes, ADI, Raytheon TI, Aether	(Essentially $0 as of 1998)	$40-$120
Other	Actuators, Microrelays, Humidity Sensors, Data Storage, Strain Sensors, Microsatellite Components	Boeing, Exponent HP, Sarcos, Xerox, Aerospace SRI, Hughes, AMMI Lucas Novasensor, Sarnoff, ADI, EG&G IC Sensors, CP Clare, Siemens, ISSYS, Honeywell, Northrop Grumman IBM, Kionix, TRW	$510-$1050	$1230-$2470

Source: W. Tang, DARPA Micro System Technology Office, 2001.

Furthermore the consensus next killer-application, optical telecommunications components, will similarly have many unique technical and process requirements. Thus, unlike the ASICs market that will be discussed later, the MEMS market is far less homogenous and can be characterized as an assemblage of niche markets. Where unit volumes for some MEMS are substantial, running into the millions of units, production volumes are far more modest then in the ASICs industry. Competition in this market is based predominately on price and performance, together with company reputation for quality and on-time delivery.

3.1 Process Technologies

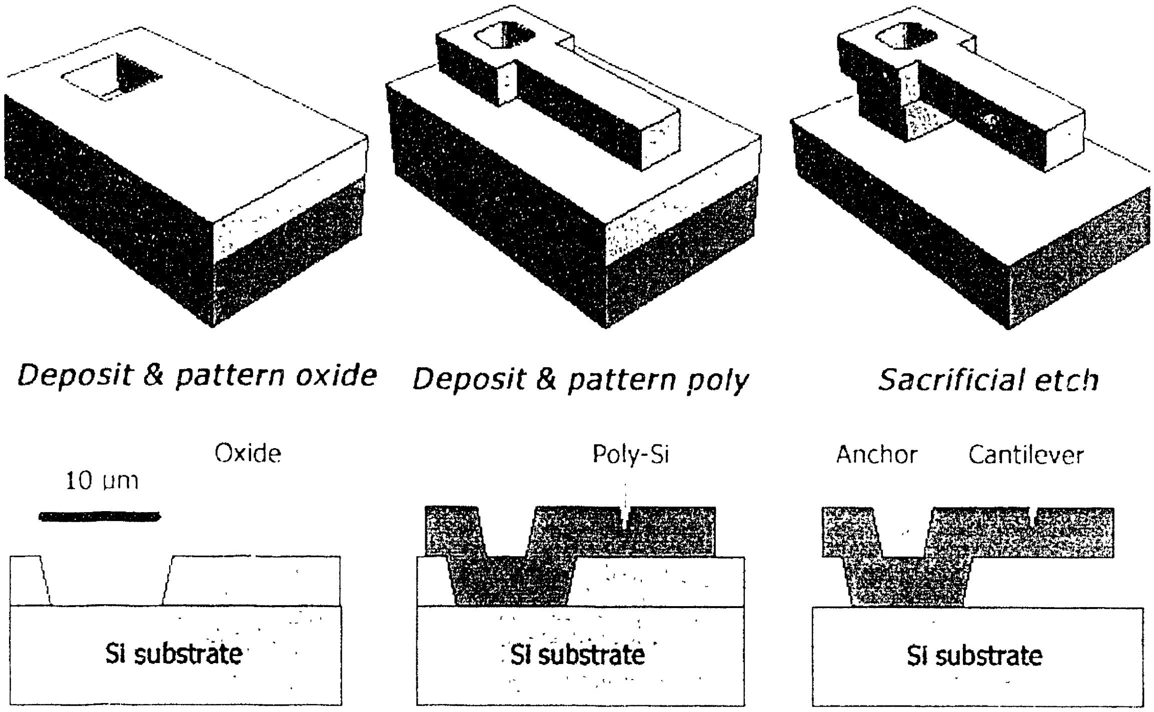
MEMS processing technologies have their roots in the integrated circuit (IC) industry, particularly in complimentary metal oxide semiconductor (CMOS) fabrication. Nonetheless, distinct mythologies have emerged over time with important technical distinctions. Within the context of MEMS, components and structures are generally formed via three process technologies:

1) surface micromachinning (SMM)
2) bulk micromachinning (BMM) and
3) high-aspect-ratio Micromachinning (HARM).

3.1.1 Surface Micromachinning

SMM most closely resembles that of CMOS processing. With SSM, thin film material layers are deposited on a wafer or substrate. Generally, the substrate is intended only as a supporting foundation. These deposited layers, which can be sacrificial or structural in nature, are generally composed of polysilicon (doped and un-doped) or silicon dioxide. These were well understood and characterized materials by the CMOS foundries that originally developed these techniques and thus their use was straightforward. Through a series of patterning via traditional optical photolithography, coupled with a number of processes of etching (wet and dry), structural elements can be formed and partially released from the substrate so as to allow mechanical actuation. Figure 3-1 depicts a simple illustration of a process to form a cantilever beam.

Figure 3-1: Basic Process Formation of Polysilicon Cantilever Structure Via SSM



Source W Tang, DARPA Micro System Technology Office, 2001

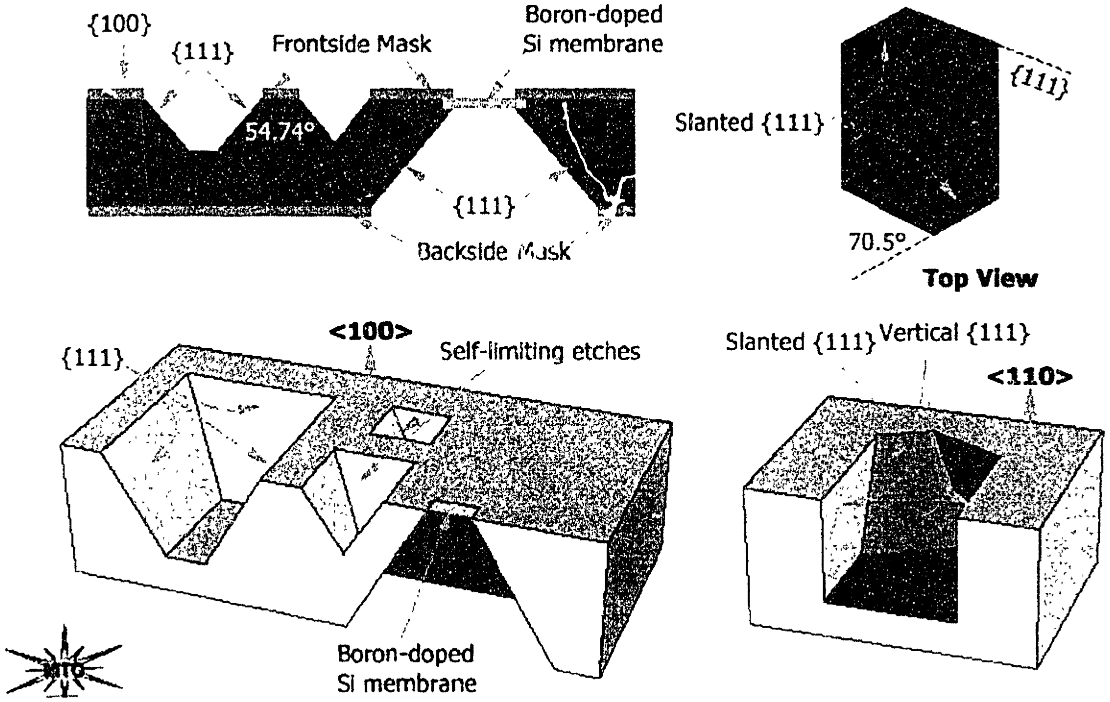
The primary advantage of SSM is its ability to readily integrate with electric circuitry Recognizing this, the US Defense Advanced Research Projects Agency (DARPA) supported the development of a standardized, cost-effective SSM fabrication process, known as MUMPs™ (multi-user-MEMS-process) This was supported primarily at the North Carolina Micromachining Center (NCMC), which evolved into Cronos, Inc (see Section 3.3)

The primary disadvantage of SSM is that thermal stress gradients and differences in thermal expansion among the deposited layers can generally cause instability and deformation in devices

3.1 2 Bulk Micromachinning

Bulk micromachinning (BMM) refers to the creation of features and structures directly in the wafer or substrate Originally developed in the 1950 for the creation of silicon pressure sensors, it is a mature technology when embodied in a silicon wafer. This methodology primarily revolves around the use of wet chemical agents that selectively etch silicon along specific crystallographic planes. Utilizing masking materials that are carefully aligned to various cryptographic planes and patterned as described above, these masks, which are resistant to the various chemical agents, allow for the selective formation of a number of distinct and useful features in the surface of the wafer (Figure 3-2).

Figure 3-2: Basic Surface Features Created Using BMM Via KOH Etching



Source: W. Tang, DARPA Micro System Technology Office, 2001.

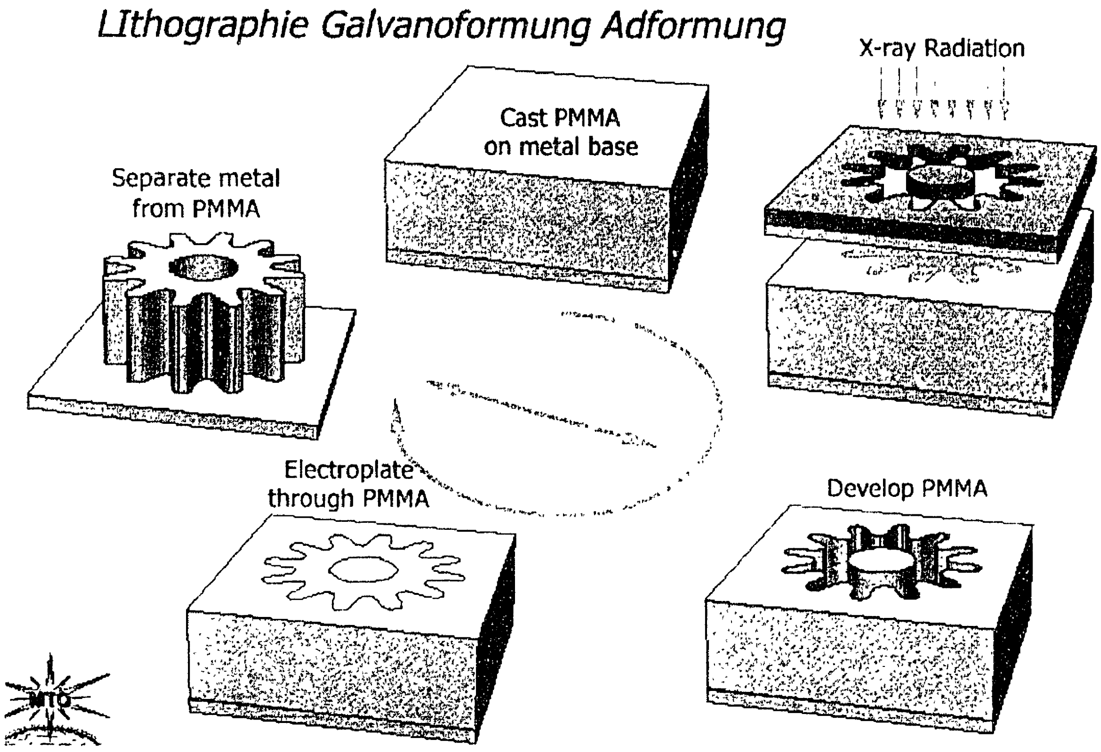
BMM is extremely simply and inexpensive compared to many other micromachining techniques. It produces very stable devices, but it does suffer from very high material usage.

3.1.3 High-Aspect Ratio Micromachining

Many non-traditional and new process methodologies have evolved to meet the demand for devices with great vertical dimension relative to the substrate surface. Primary among these are LIGA (a German acronym for: lithography-electroplating-molding) and deep reactive ion etching (RIE).

LIGA is a process whereby a mold of a desired structure is "grown" or formed on a substrate. This is done in three steps. First, a metal substrate is coated with a thick layer of photoresist on which a mask is patterned and developed. To penetrate the thick photoresist, and thus achieve the desired large vertical dimension relative to the feature size (aspect ratio), high-energy synchrotron X-rays are used to transfer the mask image into the resist. Second, the patterned metal substrate is then formed into a mold by growing or forming a metal structure in the developed regions within the photoresist where the metal is then exposed to an electroplating bath. Finally, the mold is used to form structures via injection molding or embossing, usually with a polymer.

Figure 3-3: Basic Methodology of LIGA



Source: W. Tang, DARPA Micro System Technology Office, 2001.

Despite its unique ability to form very high-aspect ratio parts, LIGA is severely limited because of the need to use x-rays. Thus, compromises such as SLIGA, which combine some feature of LIGA with other micromachining, have been developed.

Reactive ion etching (RIE) is a technique in which a low-pressure gas-plasma is directed to the surface of a material. These highly reactive ions and/or charged particles remove material through a combination of physical and chemical action. By masking a substrate with a material that is selectively resistant to the impinging beam of reactive particles, vertical structures can be created in substrates. While commonly used in IC production for years, recent advances in material and equipment have allowed this technique to be used to create even deeper, high aspect-ratio structures. Unfortunately, this equipment is expensive and the rates at which material can be removed severely limits its application.

3.2 MEMS Industry Architecture

Today, many smaller companies operate within emerging and niche markets and offer custom MEMS application-specific manufacturing for a variety of industries. The most notable of these markets is in the telecommunication sector, which has seen industry giants such as Nortel, JDS Uniphase and Corning acquire in quick succession Cortek and Xros, Cronos, and IntelliSense, respectively. The combined acquisition price for these three moderately small companies – whose combined work forces were approximately 150 persons and combined revenues were $15 million -- was in excess of $2.5 billion. These valuations were a reflection of the project growth of the optical switching and dense wavelength dispersion multiplexing (DWDM) markets. Table 3-5 summarizes the recent market projects for the optical switch market segment.

Table 3-5: Optical Switching Market Projections for North America and Europe

Region	1999 ($b)	2000 ($b)	2001 ($b)	2002 ($b)	2003 ($b)	2004 ($b)	Annual Growth Rate
North America	104.6	431	1631.4	3544.7	6475.1	10372	212%
Europe	47.2118	118	324.5	976.6	2685.5	4821.7	195%

Sources: Global Industry Analysts, Report #CF3-0319

With these acquisitions, much of the industry's open foundry capacity has become captive. Only Standard MEMS remains largely independent, with the remainder of capacity being in universities, laboratory environments and to a lesser extend excess capacity in captive houses. While these MEMS companies have each been purchased so as to ensure the role of their parents in the coming changes to the telecommunication components industry, an important business model is evidenced in two of these recently purchased MEMS foundries, Cronos and IntelliSense (see section 3.3). As will be seen in the review of the ASIC industry, there is recognition on the part of these acquiring companies that the development of full-custom application specific MEMS is complicated and fraught with risk for both the customer and foundry. Indeed, this complication in development frequently leads to extended development periods characterized by significant design iterations. It is often impossible to separate the performance of a device from the process used to fabricate it, or indeed, the equipment on which the process was developed. This fundamental incompatibility between the development cycles for new MEMS devices and industry needs is one of the most important factors impeding the more rapid adoption of MEMS technology. The degree of linkage between process and device performance also distinguishes MEMS from ASIC, which have a far more modular architectural design and process independence.

Nonetheless, as in the early history of ASIC, there has been the emergence of a new business model exemplified by MEMGens that of the "fabless" foundry, meaning that the company own no fixed manufacturing assets. Also present is the emergence of independent design software tools by such companies as Coventar and MEMScAP. Indeed, another sign of the developing industry is the marketing of specialized equipment for the MEMS industry by large companies. Furthermore, there will result general over capacity as each group bets on its position in the market, much as in the case of accelerometers (section 3.4). This is particularly true in this market since appropriability will be somewhat difficult. This results from the breadth of design space and multitude of designs that might address a specific market need. Thus, it seems that the complimentary asset, namely manufacturing assets, will be the initial source of competition. However, as each firm's assets compete and are built assuming optimist market share projections, pressure will mount to achieve better capital utilization. Whether this over capacity will lead to rapid commoditization in other

MEMS application markets remains to be seen, but it seems likely, given the historical precedent in the semiconductor industry.

This phenomenon of rapid commoditization and overbuilding of capacity has been reviewed extensively by Van Bree[46] in the semiconductor industry at large. His study reveals that this behavior continues in a predicable cyclical fashion and is generally exacerbated by normal economic cycles.

3.3 Case Review of Cronos and IntelliSense

Within the MEMS industry, it is instructive to briefly examine the business models of two notable companies that have achieved recent success. As noted, both Cronos and IntelliSense were recently acquired by JDS Uniphase and Corning, respectively. Unique to both of these companies is their use of design software as well as the degree to which they have employed process modularity to drive the adoption of MEMS.

Founded in1993 under the umbrella of The Micromachinning Center of North Carolina (MCNC),[47] the original mission of Cronos was to serve as an incubator and technology research center in semiconductor technology, particularly in the area of CMOS technology. Originally the company was to be supported by the state and federal government, but political fortunes favored a rival organization in Texas that grew to become SemiTech.

Recognizing the need for a new direction, the management team at NCMC quickly reoriented the organization into the MEMS arena. Based on the same premise as SemiTech, the initial funding was aimed at preserving and accelerating the US role in the emerging field of MEMS technology. To that end, the US Defense Advanced Research Projects Agency (DARPA) supported the development of a standardized, cost-effective SSM fabrication process MUMPs™ (multi-user-MEMS-process). MUMPs is a three-layer polysilicon surface micromachining process architecture. The design rules for the process are somewhat flexible within the defined terms of layer structure. These consist of a non-patternable silicon-nitride isolation layer, a polysilicon ground plane layer, two structural polysilicon layers, two silicon dioxide release layers, and one metal layer used for electrical connectivity and/or reflectively enhancement.[48] In many ways this can be though of as an analogous "master-slice" when describing the gate array architecture used in the ASICs industry.

Cronos attributes much of its success in promoting the adoptions of MEMS technology to the MUMPs™ process. The firm reports that MUMPs™ has never been a moneymaker, but instead was particularly useful at pushing the technology into universities. Overall, there has been limited commercial use for the process as it was constructed beyond market development of brand name and future potential customers. Ultimately, more complex and proprietary designs tend to emerge for addressing commercial markets. Nonetheless, in Cronos' sale literature, it promotes they forward the MUMPs™ process as "the most affordable and accessible MEMS prototyping offering in the world."[49] The process allows users to purchase a number of one-centimeter square die sites on a pre-scheduled production run. The user simply submits a design, and within 8 weeks, 15 unreleased chips (see section 3.1.1) for each die set purchased are delivered. Further distinguishing Cronos is its explicit reference and use of "MEMS components library based on proprietary actuation and process technology."[50] It is highly likely that the evolution of this business model owns its origins to the initial involvement of Cronos in the CMOS industry, a notion supported in the firm's product literature.

> "Leveraging MEMS' inherent qualities of miniscule size and robust reliability, Cronos has created a standardized manufacturing platform for MEMS processes and components consisting of simple building blocks that comprise an application-specific approach to MEMS. This approach streamlines MEMS devices into communications products, significantly reducing time-to-market for component and system manufacturers."

Sandia National Labs promotes its own development services and has it own "standard process."[51] The laboratory promotes a formalized program, SAMPLES (**S**andia **A**gile **M**EMS **P**rototyping, **L**ayout Tools, **E**ducation, and

Services), an introductory short course on Sandia's Ultra-planar Multi-level MEMS Technology (SUMMiT V) and how to design real micromechanical systems in this five-layer process. Similar to MUMPs™, users can purchase space on wafer masks to have their designs fabricated using the SUMMiT V process.

Cronos recently announced a promotional agreement with Coventar, formerly Microcosm Technologies. Established in 1996, Coventar provides MEMS development software, although it attempted to broaden its value proposition by providing in their words:

> ". a comprehensive approach to MEMS-enabled product development. The Coventar solution combines robust design automation software, professional engineering services, an extensive network of manufacturing partnerships, and a proven methodology that enables companies to efficiently move products from concept to volume manufacturing."[52]

Coventar's initiative with Cronos, JumpStart™, couples Conventar's Catapult™ design tool with integrated layout generators for the Cronos' MUMPs™ and a reserved slot on a the fabrication run. With this tool, developers can "create, verify, and optimize a design using Microcosm's Catapult™ layout software, then seamlessly transfer the design to Cronos for fabrication according to their design specifications."[53] As will be observed, not only does this strategy on the part of Conventar and Cronos borrow from IntelliSense, but it also echoes in many respects, the efforts of LSI Inc. and VLSI Inc. in the ASICs industry in earlier years (see section 4.3).

Fariborz Maseeh founded IntelliSense in 1991 "with the plan to become vertically integrated in design and manufacturing". He began as a consultant in the field of MEMS and over time "incorporated his experience and knowledge into a software tool" which, in turn, became the mainstay of the IntelliSense's business. [54] Today, the firm's software is widely used and recognized in the MEMS community. Nonetheless, IntelliSense expanded into the foundry business and, having becoming a subsidiary of Corning, plans to further expand its fabrication capacity.

3.4 Case Review of Accelerometers

The prototypical killer application that has characterized the emergence of MEMS technology into everyday life is the crash senor, or accelerometer. Robinson has reviewed the history of the development of the MEMS accelerometer for crash sensing and airbag deployment.[55] Presented here is a brief synopsis of Robinson's review to highlight some of the key driving forces behind MEMS.

Prior to 1995, Breed Automotive (now Breed Technologies) dominated the automotive crash sensor market, supplying nearly 59% of all the crash sensors used in US made cars. These eletromechanical sensors where limited in their appeal to automakers for a number of reasons, primary among these was their cost, which was between $15 to $18 each, with three to five devices being required for each car. Also important was the sensors inability to discriminate between the severity of collisions, and between collisions and other types of impacts.

It was into this environment that the MEMS-based accelerometers were introduced. Unlike previous electro-mechanical switches, MEMS accelerometers converted acceleration into a proportional output voltage. Early work on these devices was conducted at the University of California, Berkeley, and at numerous smaller companies (IC Sensors, SemSym and NovaSensor). Recognizing the commercial applicability of these devices, large integrated circuit companies (Motorola and Analog Devices) quickly followed suit. These new devices addressed the major shortcomings of the electromechanical switches being employed at the time. Since the sensors were processed using silicon semiconductor-based batched processing, costs were significantly reduced. Furthermore, the ability of the devices to produce variable signal output allowed the sensors to be coupled with signal processing ICs, which enabled a single point "smart " sensor capable of self-calibration, self-diagnoses and crash discrimination. These signficant economic and performance advantages led quickly to the universal adoption of MEMS accelerometers for crash sensing and air bag deployment. This unique combination of superior performance and price is perhaps the best definition of the so-called killer-applications.

The mere existence of a killer-application does not ensure that any specific company will be able to capture the value offered by the opportunity afforded. In this instance, the functional buying relationship and norms of the industry were such that automakers preferred to buy complete subsystems, rather than individual components. Thus, sensor manufactures were forced to partner with existing system integrators. In many ways, then, the development of the infrastructure and relationship to sell to automakers limited the ability of the sensor manufactures to capture much of the value chain, and necessitated carefully select partners who might bring these elements to the partnership. In essence, this industry-specific knowledge was in ways, equally important to the early adoption of MEMS based accelerometers in the design of automobiles.

The early manufacture of MEMS-based accelerometers can be categorized in one of two ways:

1) Semiconductor companies that specialize in the production of microelectronic devices (e.g., Motorola, Analog Devices and EG&G) and
2) Integrated automobile component and system suppliers (e.g., Delco Electronics, Bosch and Siemens).

These groups each tried to leverage their primary strength. Two basic design architectures emerged: monolithic and hybrid. Analog Devices (AD) led the development of monolithic devices, which incorporated both the signal processing and mechanical structures onto the same silicon chip. It was hoped that this integration would enhance the device performance and lead to manufacturing cost advantages. Packaging represents a significant portion of the device cost (about 25%) and, thus, the single chip approach represented a judgment that the added cost of integrating more processing into the chip (and thus yields) would be offset by gains on packaging costs.

Motorola leads the hybrid design, which separates the processing and mechanical elements onto two separate chips. Since device cost scale with silicon area, material cost tended to be higher for this approach. Furthermore, there are added costs in mating the two chips. However, this approach involves far less process complexity, and the device yields are expected to be higher. Moreover, companies with existing ASIC facilities (including AD and Motorola) could avoid duplicated capital costs that are inherent in building specialized integrated process facilities.

As the MEMS accelerometer industry evolved, it became clear that automobile makers would continue to foster strong rivalry among their suppliers and demand increasingly lower prices. Coupled with the need of the sensors manufacturers to maintain high utilization of their facilities in order to distribute fixed costs, margins plummeted and power shifted to system integrators. Indeed, Breed Technologies the manufacturer of the original electromechanical crash switch, responded quickly and moved to diversify and vertically integrate, purchasing AlliedSignal's safety restraint business and forming a joint venture with Siemens Automotive to sell complete safety restraints systems. Breed went so far as to backward integrate and purchased Vaisala Technologies in order to develop competencies in micromachined sensors.

4 Industry Review – Application Specific Integrated Circuits (ASICs)

The relatively short history of the application specific integrated circuit (ASIC) industry has been marked by volatility. There have been numerous mergers and exits, numerous new products and processes, and many new methodologies. Few agree entirely on the precise definition of ASIC, with the term being applied to virtually every type of chip that was designed to perform a specific set of tasks. One way to define ASIC is by their intended use and the source of the design. This definition has been adopted for this thesis. ASICs are integrated circuits designed predominately by end-users, specifically for their proprietary application. For example, a maker of an automobile might specify an ASIC to perform some or all of the product specific electronic functions for engine control required in the design. In contrast, application-specific standard products (ASSP) are integrated circuits that have a specific narrow range of applications, but are developed for multiple users. The term "chip-set" is often used to refer to these devices. An example is ICs that incorporate a number of major functions for personal computers. In contrast to ASSP are standard integrated circuits with a function useful in a wide myriad of applications, e.g., memory chips.

Like many industries, customers remain the driving force behind the development of the ASICs industry. Although a few large, broad-based semiconductor companies dominate the market, the wide range of customer requirements has created market opportunities for hundreds of smaller suppliers. Nonetheless, customer adoption of this technology has been slower then predicted. Forecasts for industry growth during the mid-1980s predicted that ASICs would capture fully 50% of the total semiconductor market. However, by 1990, the number was only about 15%. The overall industry is substantial, with sales in 1994 of $13.5 billion.[56]

From media reports, it might be concluded that the ASIC market is dominated by high-performance, 100,000+ gate devices. But this remains a small portion of the overall market. Nonetheless, it is these relative few applications that push the market in conjunction with the EDA (electronic design automation) tools that are used to design these high-end devices. It has been reported that the vast majority of electronic design engineers have never designed an ASIC and thus the expectation that system designers would naturally migrate to this technology has not come to pass. A great deal of time is necessary to research, acquire and install trained people to successfully use these tools.[57]

Another signficant factor having an impact on the acceptance of ASIC is their perceived risk. Today, there is a 50% chance that an ASIC will be fully operational when first introduced. With the high development costs and long lead-time of many ASIC production methodologies, there is an understandable reluctance on the part of many to utilize ASIC designs.

These long lead times have had an interesting side effect, which reveals itself in the way computer aided engineering (CAE) tools are developing. Most software vendors tend to cater to the needs of their existing customers, the most experienced and knowledgeable ASIC designers. Thus, CAE designers are lead to ever increasing levels of sophistication and mature products, at least from the perspective of their existing users. Even so, adoption is inevitable, given the increasingly complex nature of electronics and the need for tailored electronics in such devices as cellular phones. However, this failure to recognize the needs of the potential new or more mainstream electrical engineers makes adoption far more difficult. As will be seen, this has created an opportunity for a different model.

4.1 Process Technologies

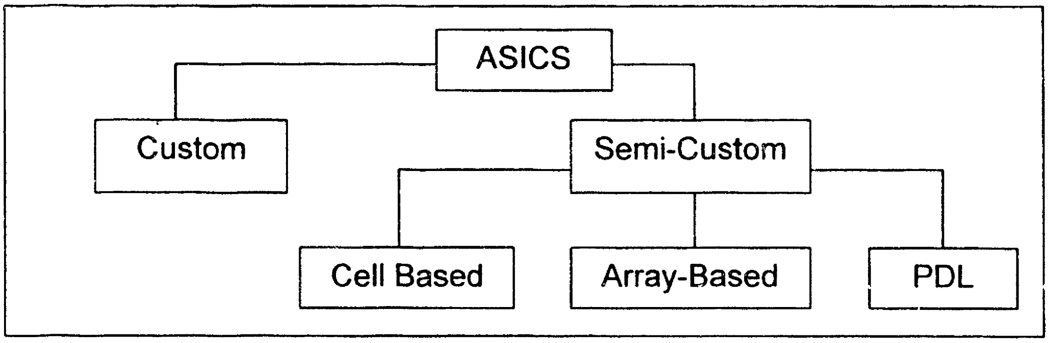
Integrated circuits are generally constructed on the surface of thin silicon wafers and processed through a series of steps that involve the deposition of various thin layers of semiconducting, insulating and metal layers. These layers are patterned with photo-resistance materials that are exposed to light and devolved much like a photograph. These patterns are then transferred into the deposited layer through various forms of chemical etching that preferentially attacks the deposited layer relative to the undeveloped photo resist, which acts to mask certain areas. The semiconductor and isolating materials serve to form such elements as resistors and capacitors, while the metal serves to interconnect these elements. The combination of these elements form transistors and are the basis of modern integrated circuits (ICs).

ICs can be produced with a variety of semiconductor technologies, including metal-oxide-semiconductor (CMOS) or bipolar. Components of like function are built differently in each of these technologies, and each technology is selected for various overall performance characteristics, such as power consumption or switching speed.

4.2 ASIC Industry Architecture

Once having decided to employ ASIC as a solution, there are a number of various solutions, or design architectures, that can be applied. This are summarized in the ASIC family tree shown in Figure 4-1:

Figure 4-1: ASIC Architectural Family Tree



Sources: Adopted from Schroeter, 1992, Figure 2.2, p.10)

These architectures have evolved over time as a means of providing customized solutions, with significantly reduced time and cost. A key component of these architectures that reduces development time and costs is their enabling of less knowledgeable engineers to design integrated circuits without having to have extensive knowledge of the physical make-up and properties of the semiconductor devices themselves. The four basic architectures are:

1) full-custom architecture,

and three semi-custom architectures namely;

2) cell-based,
3) array-based, and
4) programmable logic (PLD) architectures.

Full-custom designs are so called because their entire fabrication is unique to the particular ASIC chip under consideration. By comparison, semi-custom approaches use predefined cell structures that are layered on a prefabricated transistor grid. The degree to which the user can define interconnections and layout determines the specific semi-custom architecture.

In the full-custom architecture, each circuit element in the design (transistor, resistor, capacitor and interconnect) is drawn out and positioned in the circuit layout. This gives the maximum design flexibility because each circuit element can be optimized along a number of dimensions and the amount of silicon real estate that is consumed can be minimized. This approach is typically used when it is known that very high volume production will result. With this method, however, there are considerable development costs and time. Furthermore, because these designs are typically specific to the process constraints of a given fabricator (i.e. line widths and spacing), these designs are frequently not portable to other facilities. Thus, while full-custom encompasses the majority of ASIC production starts, it is the only ASIC architecture whose use is declining.[58]

Cell-based architecture offers a compromise between full-custom and array-based architectures. It uses predefined circuit elements called cells, but allows the user to vary the layout. Cells are pre-tested circuit modules that simplify design for the user, who no longer requires special knowledge of the internal transistor level design of the circuit element. The cells are generally stored in a library that is specific to the ASIC's vendor's process. The user simply selects and places the symbol of a desired circuit element in a circuit schematic, simulates the design, and then forwards the design to the vendors, who translates the circuit design into a physical layout design compatible with their process. Cell libraries continue to exhibit ever-greater complexity such that they permit integration of relatively high-level functions, e.g., core microprocessors, peripheral controllers, random-access memory (RAM), readonly memory (ROM) and mixed digital/analog processors. Unlike array-based architecture, cell-based architecture has a multi-layer nature and is tied in some measure to the individual vendors' process capabilities, and thus is more difficult to import to new vendors or into which to incorporate new processes. New process-independent methodologies are being developed for this architecture (complied custom), and cell-based architecture is the fastest growing architecture today (Table 4-1).

In large part, this growth is being driven by the higher complexity of many of today's applications (e.g., wireless devices). As the complexity of the design increases so too does the required number of gates. For example, the design cost for a 10,000 gate design may be twice as much for the cell-based approach as for its equivalent gate array design. But as 100,000 gate applications are approached, the cost of a prototype will be nearly equivalent for both approaches. In addition, irrespective of the design complexity, the cell-based architecture will generally result in a smaller device and thus lower production costs on a per unit basis. Thus, there is a shift in architecture preference driven mostly by new higher need applications. Even given this growth, adoption of this cell-based architecture has been inhibited by a number of factors, particularly its higher development cost and time (Table 4-2).

Table 4-1: Changes in Market Share for the Four ASIC Architectures

ASIC Type Market Share	Full Custom (%)	Standard Cell (%)	Gate Array (%)	FGPA (%)	Total Market Size (Billions)
1986	52	11	30	7	$ 4.7
1994	20	30	40	10	$ 13.5
1999	12	40	38	10	$23.6

Source McClean (1995, Figure 4-13)

Array-based architecture, which represents the largest ASIC market, is primarily driven by its lower design costs and shorter fabrication cycle times (Table 4-2). Indeed, many engineers begin with an array-based approach and only later convert to a cell-based option when it becomes clear that larger production volumes will be required. Array architecture is based on one of two semi-standard prefabricated chips -- channeled or channelless gate arrays.

Channel arrays contain empty channels of silicon separating rows of unwired transistor pairs. A masked pattern of metal interconnects is then used to interconnect the transistors using dedicated routing channels in the silicon space. In the channelless arrangement, also called sea-gate, the silicon channels are non-existent and the entire array is covered with potential active and usable transistors. In this arrangement, unused transistors act as routing channels, with the metal being deposited directly over them. Although this form is less area-efficient, it supports a larger number of transistors. Thus, each arrangement is used, with the primary distinction between the arrangements being based on the number of metal mask layers that are desirable or practical.

Another advantage of the array-based architecture is its ability to be quickly revised. When a design error is discovered or system specification changes that requires a new protyotype (e.g., mask generation, fabrication, assembly and test), the cost of this iteration when compared to the all-layer approaches such as cell- and full-custom, is far less (Table 4-2).

Table 4-2: Attributes Affecting Customer Choices Among ASIC Technologies

ASIC Type Market Share	Full Custom	Standard Cell	Gate Array	FGPA
Time to Design	51-104 WKS	12-52 WKS	4-26WKS	< 2WKS
Time to Build Prototype	8-12 wks	6-10 wks	1-3wks	<10 MIN
Typical Development Fees Charges by Suppliers	$50-500K	$20-200K	$10-100K	$ 0
Maximum Density of Gates on Chip (1/cm)	< 350K	<250K	<100K	<10K
Unit Manufacturing Cost	Lowest	Medium	High	Highest
Multi-Sourcing Difficulty	Highest	Medium	Low	Lowest
Cost of Iteration	Highest	Medium	Low	Lowest

Source McClean (1995, Figure 4-13)

Where high logic density is not required, a programmable logic device (PLD) may be an attractive alternative. In particular, field programmable gate arrays (FPGAs) are prepackaged, semi-complete ICs that can be customized to a finished state by the end-user. This architecture uses gate arrays that are totally interconnected via fusible or anti-fusible interconnects. The end-user can then custom program the nonfunctioning ASIC by field programming the device.

This is accomplished by using relatively inexpensive vendor-supplied software and hardware. The encoder device applies a series of electrical pulses to the prepackaged chip to melt and remove undesirable interconnections between the various logic elements or fuses and create interconnection in anti-fuse devices. As revealed in Table 4-2, this architecture is selected when the number of chips required is relatively low.

FPGA architecture has advanced significantly and continues to encroach on the other architectures. In discussions with Lance Mills,[59] Head of Research and Development at the Hewlett-Packard Semiconductor Division, he indicated that soon as many as 100,000 gates will be accommodated by such companies as Zylinks in FPGA. Referred to in the industry as product postponement, this architecture has begun to be incorporated as standard-cells within other architectural types, allowing for some degree of site-specific programming.

4.3 Case Review of LSI Logic

In 1966, the number of resistors, diodes and transistors that could be economically produced was about 20. At the time, Gordon Moore, then head of Fairchild Semiconductors Research and Development, postulated that the number of components, know as system complexity, would double every year to 18 months. This prediction meant that the nature of the emerging integrated circuit industry was going to change and that ever greater complexity would rapidly approach, and that "...existing product lines of a few simple, high-volume, standard ICs would be replaced by many specialized, low-volume medium and high-complexity ICs."[60] It was clear then that new architectures and development tools would be required and Fairchild setout to create computer-aided design (CAD) and computer aided engineering (CAE) tools to deal with the coming era.

What emerged around 1971 was the first documented IC-CAD. Called Micromosaic, it incorporated many new features, including both a logic simulator and automated pattern layout. Perhaps ahead of its time, Fairchild, for a variety of reasons, was unable to profitably maintain the Mircomosiac ASIC program.

There was a general industry consensus that semi-custom ICs could not be manufactured profitably and thus the operation was shutdown. It was now left to small niche players and captive house suppliers to develop ASIC. The small niche players in particular lacked the scale to sustain cutting-edge technologies and struggled mightily against the captive incumbents. Indeed, even the captive houses had begun to flinch at the increasing cost of modern wafer manufacturing plants. At the same time, it also became apparent that excess capacity had been built in the 1970s and competition to utilize existing facilities was intense and was pushing down prices. Around 1980, ASIC suppliers could be categorized into four groups.

1) Major electronic house captives, including Honeywell, Digital, IBM, Data General, Wang, TRW and Hughes;
2) Major US merchant-market semiconductor suppliers, including Texas Instruments, Motorola, National Semiconductor and Fairchild;
3) Major Japanese semiconductor firms, including NEC, Hitachi and Fujitsu and;
4) Small US niche suppliers, including AMI, Zymos, California Devices and Universal Semiconductors.

Into this difficult environment two future dominate ASIC suppliers would enter, LSI Logic and VLSI Technology. The following is excerpted from Silicon Destiny, The Story of Applications Specific Integrated Circuits and LSI Logic Corporation, by Rob Walker and Nancy Tersini[61]

In 1979, Schlumberger, the French industrial giant acquired Fairchild. In what can only be called a severe clash of cultures, then president and CEO, Wilf Corrigan departed Fairchild to start his own semiconductor company. Under Schlumberger, Fairchild Semiconductor, the inventor of the integrated circuit, continued to suffer market erosion and significant losses and was eventually sold to National Semiconductor at a substantial loss. The following quote is from a resurrected business plan of Rob Walker, a cofounder of LSI, who years before had been disappointed by Fairchild's decision to discontinue the Mircomosiac ASIC program and had considered his own start-up. It captures the intent of the new venture called LSI Logic and emphasizes the importance the plan placed on the development of design tools.

> "The purpose of this document is to propose a new business opportunity. The general area of the proposed business is custom design and manufacture of electronic devices, subsystems and systems. As a first endeavor, the development and tooling required for custom design, assembly, and test of non-memory large-scale integrated (LSI) semiconductor products will be provided."[62]

In further analyzing their business plan, the LSI founders determined that the design cycle time, the period of time between design and volume production, was between one to two years for an ASIC. In part, it was this finding that led the founders to select array-based architecture as the basis for their company, since it would reduce the system complexity and allow for easier development of design tools.

Having decided to proceed into the market with a gate-array architecture because of its ease of design and flexibility, it became necessary to obtain licensing for the underlining fabrication methodology, namely CMOS (Complimentary Metal Oxide Semiconductor). Initial licenses from US suppliers reflected the reality that suppliers lagged well behind their Japanese counterparts in terms of complexity. At the time, LSI US-based design had 1200 gates, while Fujistsu of Japan was producing much faster 4800 gate arrays. It was then Wilf Corrigan, a founder of LSI, traveled to Japan and visited the leading producers of CMOS, Hitachi, Fujitsu and NEC seeking a source of master slices from which to develop LSI's custom ASIC.

It was during one these trips that both the potential and risks of LSI's business model was succinctly articulated. Mr. Yasufuka, a senior manager at Fujitsu, commented on LSI's plan to put development software in the hands of its customers.

> "That is a brilliant strategy. If you do that and the software is good, you will win." When pressed as to why Fujitsu did not employ such a strategy, Yasufuka replied, "Our software is so valuable that if we exposed it to outsiders, they will steal it."[63]

In fact, Fujitsu was even unwilling to transfer the software to its US subsidiary out of fear of loss of their competitive advantage.

Ultimately, LSI would enter into a relationship with Toshiba in which it exchanged its CAD and engineering technology related to ASIC design, for Toshiba's CMOS manufacturing technology. At the time, Toshiba had no presence in the US ASIC merchant-market and the deal made a great deal of sense for both companies. Today, both companies are top-tier ASIC competitors and their decision to join forces was, in large part, responsible for their current enviable positions.

LSI quickly became dominant in CMOS gate-array. Many competitors challenged them using the higher speed; smaller and more customizable cell-based architecture believing that gate-array would become obsolete. However, as seen in Table 4-1, gate array remained a dominant architecture for many years to come. Thus, it appears clear that the market value lies in the speed of development and in the reduction in development uncertainty offered by the architecture-software combination.

It was not immediately obvious that CAD tools were sufficiently user-friendly for this strategy to be successful. As a consequence, LSI as well as others, established design centers where manufactures helped engineers and customers who lacked experience with ASIC design. LSI quickly realized that to maintain its position, not only would its software have to evolve, but also it would need to secure additional intellectual property in the form of design-cells for the software library. Equally important was the need to develop an understanding of the system requirements and use of their ASICs. As a consequences, LSI hired system engineers to develop the necessary expertise and worked to establish close customer ties.

LSI's initial goal was to develop a viable CAD environment for design of gate arrays within one year of forming the company. The few CAD tools available at the time were not particularly good or well integrated. A good tool would be required to address the key problem solving tasks in designing an ASIC.

ASIC design generally begins with a functional description of the circuit using symbolic representation of various logic elements with interconnects between the elements. Embedded in the software are the limits of the design space. Next, a software simulation of the circuit is run to detect any errors in the logic function of the design. Typically today, the output of this portion of the process is transferred to the selected chip vendor, where a separate software program is used to translate the logic design into a physical layout with specific information about the geometric location of various cells, arrays and interconnects. Again, design limits are imposed to properly reflect the capabilities of the vendors manufacturing processes. This physical design is then simulated to identify any errors that might have developed in translating the symbolic circuit into its physical layout. Typically these track the form of timing errors. When any translation errors are corrected, the design output is used to drive the computerized fabrication equipment.

LSI and many others recognized early on, that a successful tool would require significant computer power. Particularly important to LSI was simulation and layout, because these would be most important to delivering working chips without the all to familiar redundant design iterations characteristic of the ASIC industry at the time.

VLSI also worked toward this approach of using user design software and was the first to sell software tools to its customers. However, its initial software focused on full-custom and cell-based design. Several reasons slowed the adoption of the firm's product. First, the larger gate-array supplier base meant lower prices for these chips. Also, design cost for gate-arrays was lower as well, and the market seemed to feel that gate-arrays offered sufficient performance for most applications.

In the early 1980s, the academic world led by Carver Mead at Caltech, proposed a new approach to design tools. The concept was to automate as much of the design of ASICs as possible. Silicon foundries that would sell the silicon by the pound, similar to steel mills, would then manufacture the ASICs. While certainly these silicon compliers had their place and were successful in certain segments involving regular structures, many companies soon discovered the limits of this concept. Venture capitalists invested, hundreds of millions of dollars, but eventually these companies failed because they did not recognize the close coupling of process to product. The contribution of tacit knowledge embedded in the high quality semiconductor manufacturing companies was simply underestimated.

While there were many failed third party design automation companies, eventually third party design tools did emerge in earnest. Cadence, focusing on using experienced IC engineers in their design process and emphasizing a strong semiconductor or system partner for their development assumed leadership in ASIC design automation. In 1996, the top three ASIC design tool suppliers were Cadence, Design Systems and Mentor Graphics, with 49%, 20% and 20% of the market, respectively. Mentor Graphic and LSI had teamed earlier, but the market rejected this arrangement and LSI was forced to support multiple logic simulation design tools. The relationship between process-independent CAE (PICAE) system providers and ASIC manufacturers has remained complicated. A dispute has developed over the ownership and relative value of logic libraries and performance models, with PICAEs believing that the manufactures should provide free access to these libraries and manufactures moving to encrypt these elements to prevent them from being reverse engineered into other ASIC manufacturer's libraries.

Today, LSI Logic remains a top-tier ASIC producer. In reviewing the history of the ASIC industry and in particular the history of LSI, a number of factors contributing to its success emerge, including a business strategy that involves:

1) the selection of the array-based architecture,
2) the development of user-based design tools,
3) careful selection of Toshiba as a partner with complementary technology,
4) development of a deep understanding of the systems using their product, and
5) development of a broad and well protected cell library.

5 Business Model Description and Comparison

5.1 Industry Comparisons

In comparing the historical evolution of the MEMS and ASIC industries, there are a number of striking similarities in their maturity processes. Primarily among these is the emergence and use of sophisticated software tools that enabled the process and architectural elements of the technology to be codified. These tools in-turn formalized and facilitated a process of knowledge transfer and shifted, in some measure, the focus of product development and application of this technology to those with system-specific and industry-related knowledge. This development of an infrastructural architecture to facilitate organization knowledge transfer turned out to be key to the adoption and expanded use of these technologies.

A second common and key component of the maturity of these industries was the evolution of a series of architectural process regimes that were, in and of themselves, able to be codified and yet sufficiently expansive that they could allow sufficient design flexibility. Undeniably, MEMS and ASIC devices share many properties, including a number of advantages and unique strengths:

- In many cases, they represent the only possible solution to achieve the desired performance and functionality, making them enabling technology in various applications.

- As with any customization, they may offer the ability to include unique value-added, differentiating features.
- Similar to what MEMS may offer, ASIC frequently offer significant size, weight, and power savings.
- The overall integration of a number of electronic or mechanical components into a modular subsystem offer significant opportunities for a decrease in total parts, leading to a decrease in system costs and an increase in reliability.
- The design security that frequently makes reverse engineering difficult if not impossible is important to protecting appropriablility.

However, there are also several important shortcomings to these technologies:

- Substantial time and money are required for developing prototypes.
- System design risk is noteworthy. Nearly 50% of all ASICs fail to operate in target systems on the first pass[64] and similar experience can be expected for MEMS.
- The design, once established, is generally inflexible and later design changes can be difficult and expensive to incorporate.
- Designs are typically inexorably linked to a particular supplier, making multi-sourcing difficult and significantly shifting the power in the vendor/supplier relationship.
- Costs are highly dependent on ultimate production volume. This increases the importance of sales and market projections, which are notoriously difficult to make, and thus, exposure to cost uncertainty is higher.

Furthermore, many of these factors are exacerbated by generally shrinking product life cycles and the increased criticality of market entry timing, particularly in markets with large network externality effects such as telecommunication.

The above notwithstanding, there are differences between the MEMs and ASIC industries. As previously noted, one major difference is the degree of product and process co-dependence, a dimension of knowledge complexity. This coupling appears tighter in the case of MEMS, given the broader parameters in design space and perhaps the overall lack of maturity of the technology. Perhaps it is the complexity of design parameter space that is critical to the relatively slower adoption of MEMS technology when compared with ASIC technology. Electronics have a limited number of fundamental building blocks (e.g., resistors, capacitors and conductors) from which to evolve a design. This has allowed for a more clearly delineated set of design architectures that have yet to emerge in the MEMS industry. Indeed, it may be that no such architectural arch-types emerge and that the importance of software design tools takes on a different importance in the two industries. Nonetheless, it appears the SMM appears to be emerging as the dominant architectural process today. This is likely the result of its ease of integration and similarity to CMOS technology.

It is not entirely surprising that the similarities between the MEMS and ASIC industries exceed their differences. Importantly, MEMS technology was viewed more as evolutionary from the perspective of those skilled in the art of CMOS. This is important from two perspectives. First, it emphasizes that technology is an intangible construction of the collective mind of individuals, organizations or industries and is only manifested in products or services. As discussed in chapter one, this is why technology adoption must be thought of fundamentally as a process of communication.

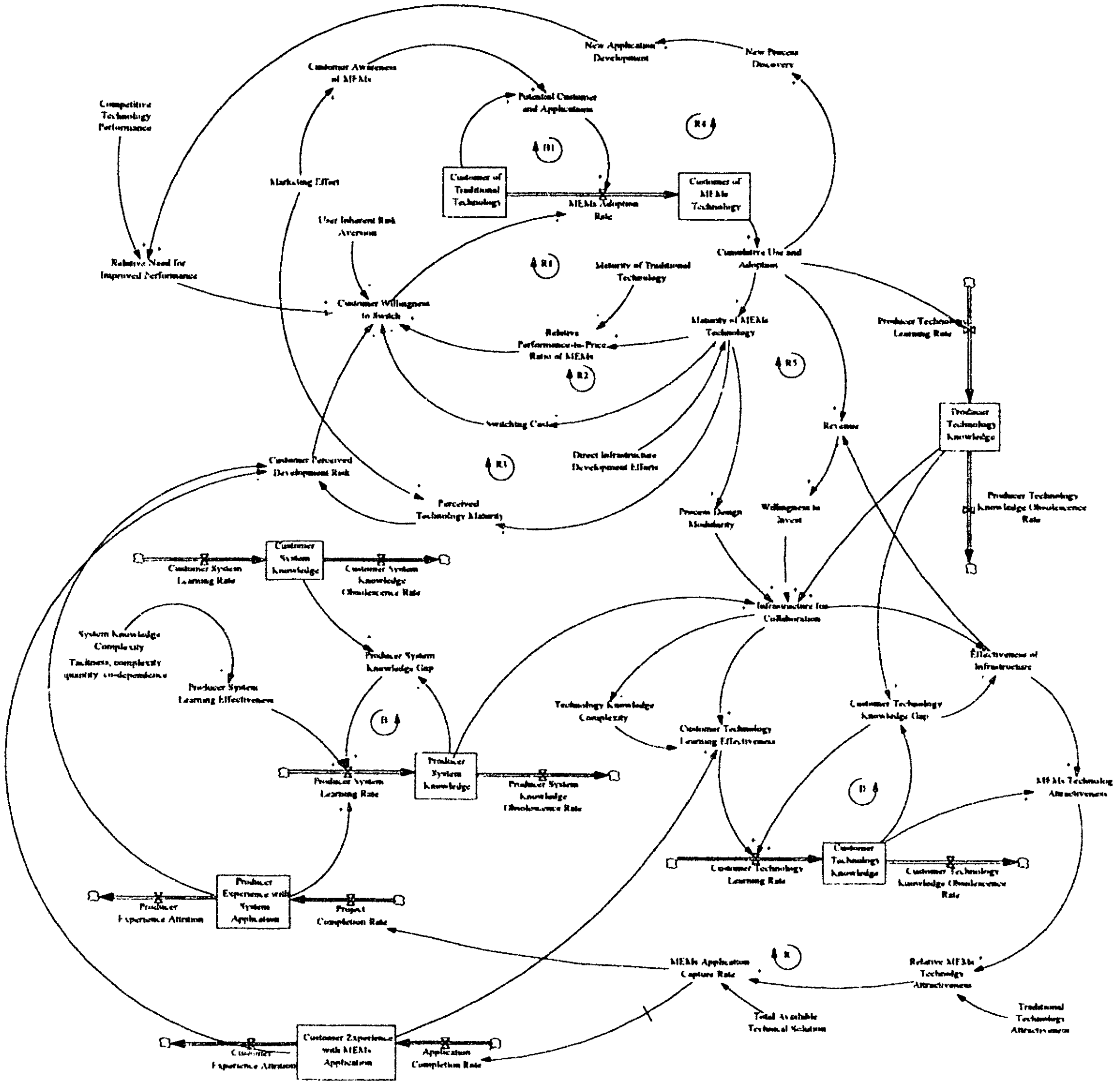
This leads to the second important perspective about the nature of disruptive technologies. The classification of a technology as disruptive is unique to an organization or individual's perspective and must be considered along multiple dimensions, i.e., product, process and market. From this perspective, MEMS exhibit a greater degree of disruptiveness than perhaps does ASIC technology.

Even so, the barriers to the adoption of MEMS and ASIC technologies are similar to those identified for many industries and can be generally categorized as price-to-performance ratio, the relative risk of the technology, cost and market timing risks, and the difficulty in capturing and "productizng" or capturing the value of innovation.

5.2 Market Pull

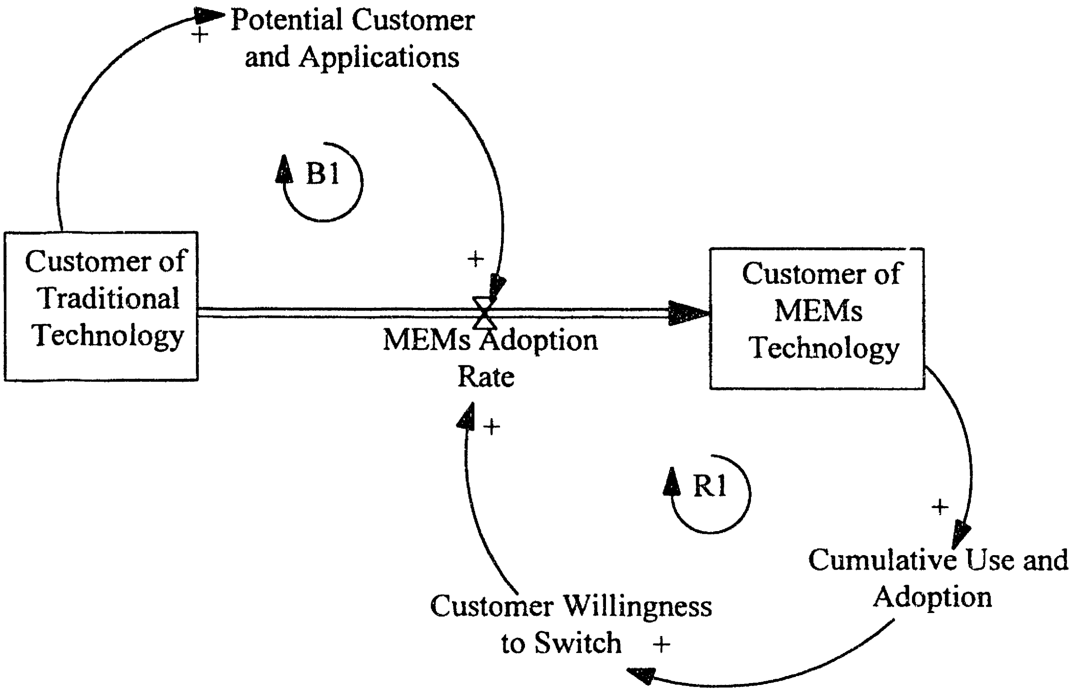
Figure 5-1 presents an overreaching systems thinking model that encompasses a number of the dominant behaviors in the adoption of technology in the MEMS industry.

Figure 5-1: System Thinking Model for Technology Adoption



At play in this model are a number of reinforcing and balancing loops that drive the adoption rate of MEMS technology. In its simplest form, the model can be thought of as an extension of the Bass diffusion model, where the Customers of MEMS Technology are derived from a pool of Customers of Traditional Technology (Figure 5-2). As various direct marketing efforts make more users aware of MEMS technology, the pool of Potential Customers and Applications drive the adoption rate. Once general awareness has been achieved the other factor predominately driving the Adoption Rate is the customers Willingness to Switch to MEMS technology. As constructed here, this is a simplified and self-limiting process where eventually the number of potential new customers inevitable diminishes. However, while not explicitly capture in this model segment, there is the potential of adding new users. As industries evolve and new applications emerge, what might be considered the pool of Customers of Traditional Technologies will grow. This results from the often times complex interdependence of industries and technologies will give way to new opportunities for complementary technologies to emerge.

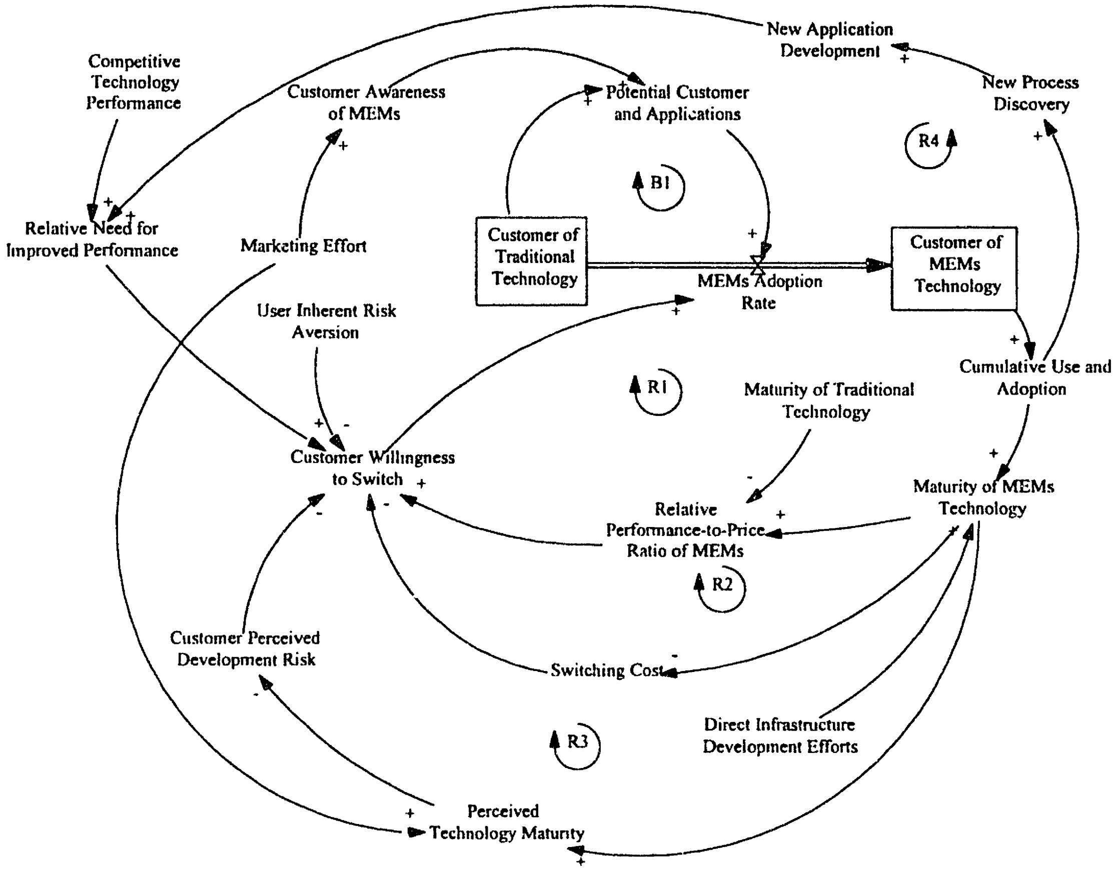
Figure 5-2: Basic Adoption Cycle



Driving the Customer Willingness to Switch are five predominating factors (Figure 5-3): the Relative Price-to-Performance Ratio, the Switching Costs, the Perceived Development Risk, the Inherent Risk Aversion and Relative Need for Improvement.

The first is the Relative Price-to-Performance Ratio of MEMS technology, compared to the available existing technology. In the case where there is no available technology or where MEMS technology is truly enabling this influence is very strong. This was clearly operating in the case of crash sensors and epitomizes the killer-application.

Figure 5-3: Factors Influencing Customer Willingness to Switch



The second factor, Switching Costs, constitutes a number of elements encountered by companies in adopting the new technology that require real resource allocation. In this instance, Switching Costs can be thought of as representing a real dollar cost. This might be as simple as the requirement to purchase new capital equipment, or as complex as hiring new engineers to utilize and support the new technology. Switching costs can also encompass more broadly viewed elements. As discussed previously, the very technology interdependence that gives rise to new opportunities, can generate added design costs for reintegration. Establishing new vendor relationships too can be a source of considerable cost. Likewise, establishing new relationships and understandings can add significant short-term transaction costs. As the new technology experiences broader adoption, specialized equipment and skilled workers will become more available, thus reducing the switching costs. Indeed, companies and governments can make an important contribution to the Maturity of Technology through direct investments infrastructure elements as was seen in the case of Cronos.

The third element affecting the customers' willingness to switch is the Perceived Development Risk. Particularly in the case of customized solutions represented by many ASICs- and MEMS-based devices, the risk of product failure is considerable. This perceived risk is strongly influenced by the Maturity of Technology. Companies in general are reluctant to adopt technologies that they view as being immature in order to avoid being stuck with products that are unsupportable and unserviceable. Selecting a losing standard as in the case of Beta vs. VHS, can have dire consequences. Each company has its own risk profile in this regard, which is represented by its Inherent Risk Aversion, which is the fourth factor influencing willingness to switch.

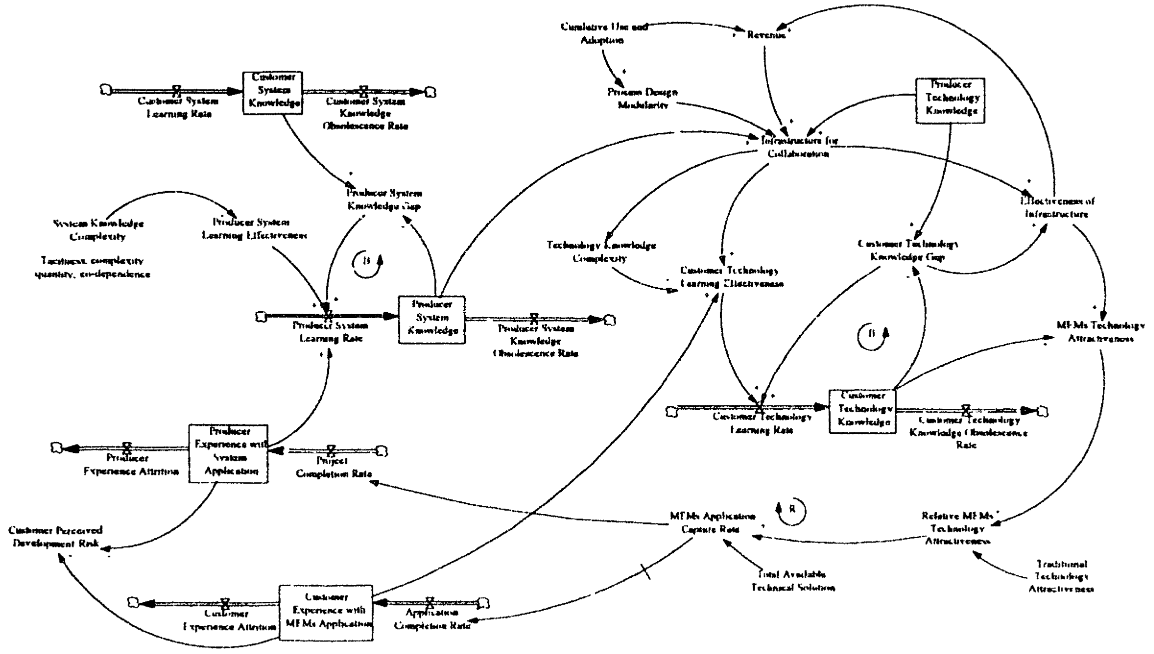
The fifth factor to consider is the customer's Relative Need for Improvement. User technical requirements are driven in large part by the performance of competitors' products and services and/or by the availability of competing technologies. An extremely important condition occurs when the needs of the customers exceed the existing performance of the technologies. In this instance, there will be a strong market-pull scenario that will dominate the dynamics. Again, this can lead to the emergence of a killer application as the maturity of the technology is advanced in response to market demand. Indeed, it could be asserted that the emergence of MEMS into the crash sensor market was the consequence of exogenous influences by the government on the need for improved performance. Also important in the model is recognition that the need for improvement is not static, i.e., user expectations are continuously increased as new applications and processes are developed. Again, it might be asserted that this is a primary source of disruptive technologies.

5.3 Technology Push

Thus far, the investigation has addressed the relatively straightforward scenarios in which there is strong market demand based primarily on better price-to-performance and limited switching costs. However, these strong market forces inevitably attract new entrances and the emphasis and nature of competition begins to shift from product innovation to process innovation and the need for cost reductions and speed to market. As was seen in the crash sensor, market this can quickly lead to commoditization, particularly in capital-intensive industries such as MEMS and ASICs, where capital utilization is a key driver to the revenue component of the model. Thus, it becomes imperative for companies to establish a robust process by which to develop new products.

In the case where the driving forces for adoption are weak and the perceived development risk is great, a different dynamic is established. Figure 5-4 displays the basic dynamics at play in affecting Customer Perceived Development Risk. First, this framework presupposes a simplifying assumption that the technology is fundamentally capable of achieving the desired performance objective and thus does not limit the customer's perception of risk *a priori*. That is not to say that there are not important dynamics at play in this regard, merely that it is assumed that customer expectation and perceptions are consistent with the fundamental reality of the technology. Rather, it is the ability of the customer and the owner of the technology to sufficiently share their knowledge that fundamentally alters the perceived development risk. If it is accepted that uncertainty about development results primarily from a lack of information, then it can be seen that the use of user-design software can alter the dynamics of technology adoption. Even so, many companies have established a very different dynamic by over-selling or over-promising the capabilities of a new product or technology. In so doing, they destroyed the Perceived Technology Maturity when it was inconsistent with the actual Technology Maturity. If Marketing Effect were disaggregated and a term for market effectiveness incorporated a dynamic that produces an unintended consequence and actually increases the perceived development risk of a new technology and ultimately slows adoption will result (Figure 5-4).

Figure 5-4: Effects of Learning of Customer Perceived Development Risk



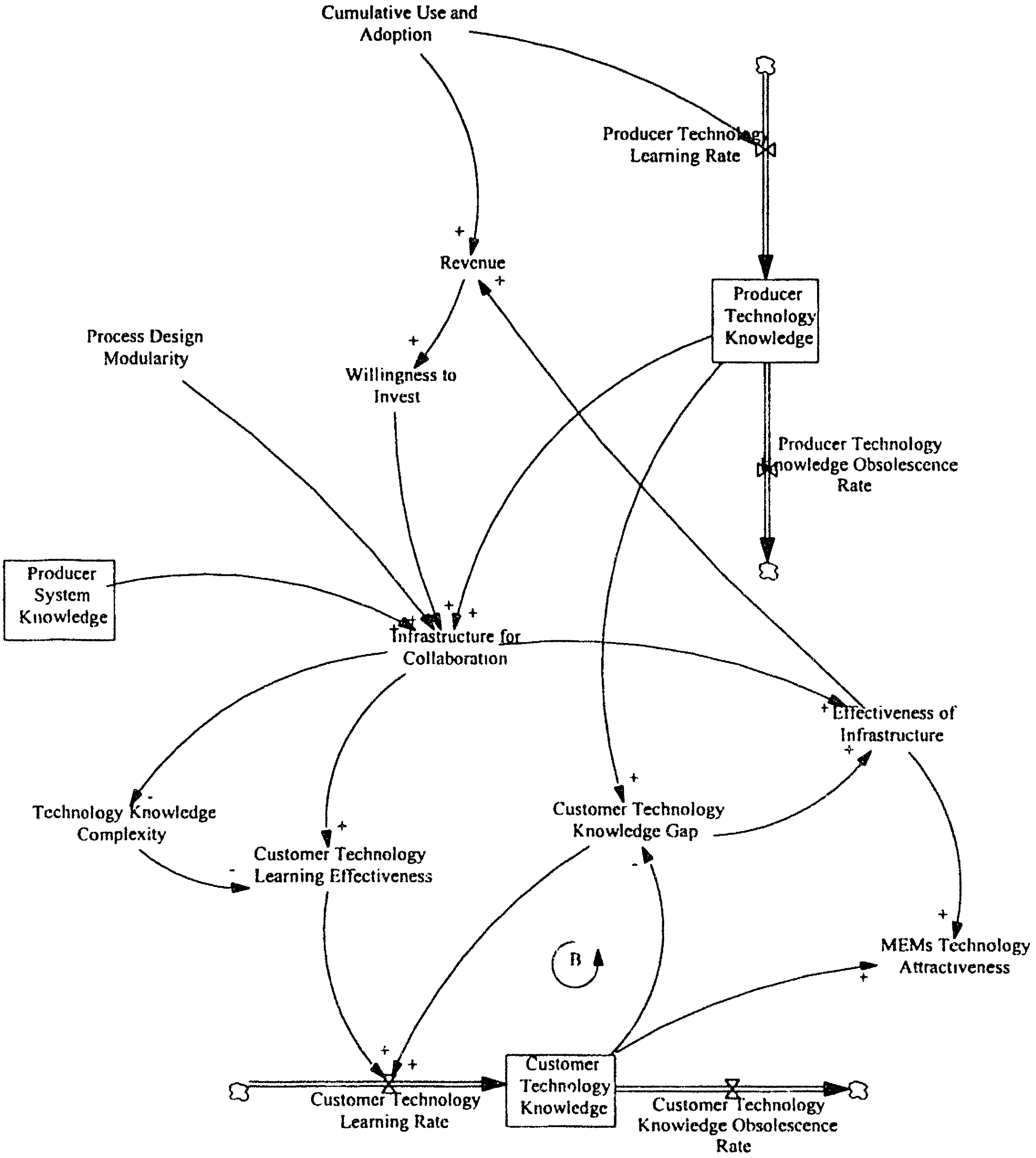
In examining how to affect the perceived development risk, two stocks of knowledge are examined, Customer Experience with MEMS Application, and MEMS Producer Experience with the System Application. Each of these stocks has an attrition rate related to such items as the departure of personnel, but which is increased by the overall MEMS Application Capture Rate, which predominately results from the Relative MEMS Technology Attractiveness when compared against alternative technologies.

An important ancillary to this experienced attrition through personal loss is how this can have significantly positive effects when the personal movement is between elements of the value chain or indeed between competitors within a portion of the value chain. This dynamic is perhaps best know in Silicon Valley, where personal movement has been attributed to mutual industry gains. This source of information exchange might also broadly be incorporated into infrastructure for collaboration, but is not explicitly acknowledged in this model:

Two items in particular increase the MEMS Technology Attractiveness, Customers MEMS Technology Knowledge, and Infrastructure for Collaboration. The concept of infrastructure for collaboration requires some explanation. Any processes or resources that are allocated to facilitating the transfer of technology knowledge from the producer to the potential customer might be considered infrastructure for collaboration. This would include the development of software that codified process and architectural information that enhanced the learning rate of the customer. It could be argued that such items do not, in fact, enhance the learning rate, but rather reduced the required learning. This is a subtle distinction and will remain unchallenged here. Direct exchanges of information through publications, conferences, meetings, and personnel encounters are also included in this category. Indeed, as will be discussed later, the very organizational structure and business processes adopted can broadly be considered as a form of infrastructure for collaboration. Figure 5-5 further segments the overall model and describes several major influences on the infrastructure for collaboration revealed in the analysis of the ASIC and MEMS industries.

A significant item affecting this infrastructure is the availability of resources to invest. This is the result of revenue generation and is important for driving the longer-term dynamics of MEMS technology adoption. Through this reinvestment in infrastructure a company is able to drive the Customer Experience with MEMS Technology Application and ultimately reduce its perceived development uncertainty and driving adoption.

Figure 5-5: Importance of Infrastructure for Collaboration



As discussed, the Process Design Modularity or availability of defined architectures greatly influences the ability to codify the technology in a way that is usable. This represents a dynamic tension in which design flexibility is lost, but at the same time adoption is accelerated through enhanced learning rate. However, many industries' process and design modularity increase over time.

The other factors affecting the infrastructure for collaboration are the MEMS producers own Technology Knowledge and System Knowledge. In the cases outlined here, one aspect of the infrastructure in the form of user design software is considered, however, this need not be the case. A company that chooses to specialize in the design and fabrication of a specific classification of MEMS might imbed its infrastructure within the organization by hiring and developing both technical and market expertise in a matrix organization. Indeed, it is likely that some of this will take place in most organizations. This raises the question as to whether it is possible to support the broad base of markets and systems with a generic set of processes, development platforms and architectures. As in many industries, some degree of specialization will take place and the effectiveness of the alternative strategies will depend on many factors, including the complexity and importance of the system and technology knowledge.

Lastly, the model recognizes the role of Knowledge Complexity for both the system and technology. If knowledge complexity is defined as the quantity, tacitness and co-dependence of the knowledge, this might be seen to alter the Effectiveness of Learning. One way to understand this involves a comparison of the knowledge required to build a commercial jet and a mechanical pencil. In the model presented here, accommodation has been made through the use of collaborative infrastructure to reduce the complexity of technology as the knowledge is codified.

Thus far there has been little discussion of the concerning dynamics that this model raises. It is important to note that risk dynamics are present. The simplest of these revolves around the Customer Technology Knowledge Gap. Should the Customers Technology Knowledge increase relative to the Producer Technology Knowledge, the Customer Technology Knowledge gap will decrease, which, in turn, will diminish the Effectiveness of the Infrastructure. This, in turn, will negatively affect revenue, and a balancing loop dynamic is established in which the infrastructure of collaboration subsequently deteriorates.

This is one dynamic that owners of the technology fear and that some believe might ultimately lead to the loss of competitive advantage and the ability to capture rents. The ultimate extension of this might be the disintegration of the value chain from the perspective of the MEMS producer, wherein the processing technology and supporting software are sufficiently advanced to the point that customers are generally over-served by the technology. In this scenario, the added advantage of the infrastructure for collaboration becomes driven predominately by the producer's system knowledge, since the advantage in knowledge of the technology is lost. This would tend to lead to encroachment of system manufactures (customers) through vertical integration, as it is likely their system knowledge will lead the MEMS producer system knowledge. It might be contended that that this is precisely what has accrued in the MEMS industry, as evidenced by the large-scale acquisitions by Corning, JDS Uniphase and Nortel. To be sure, the perceived market opportunity for optical components that MEMS technology might uniquely serve was an important consideration. But this only serves to underscore the importance of market and system knowledge.

This scenario underscores the importance of delay in any models. It would difficult to enumerate all the delays in the proposed model given. Indeed, such an endeavor would require significant effort and is beyond the scope of this work. However, it must be noted that there are a number of important delays that can have a signficant impact on companies and the dynamics at play. Recognition of these delays is one of the most critical and difficult considerations in a business. The remainder of this discuss will rely heavily on a working paper by C. Christensen, M. Verlinden and G. Westerman outlining a number of dynamics tat were examined while looking and at the dynamics of horizontal and vertical integration of firms.[65]

As reported by these authors, during the early deployment of any technology, product functionality is generally unsatisfactory. Competition in this early phase is thus focused on improving product functionality and is driven in large measure by a shared understanding between the customers' system-specific knowledge and the producers' technology-specific knowledge. This means that product design is highly interdependent during this early phase of the industry and a robust infrastructure for collaboration should offer a competitive advantage. It is for this reason that it can be speculated that vertical integration of firms would predominate in the early stages of an industry (or perhaps market application or niche), as this is arguably the most efficient organizational form to promote collaboration. As alluded to earlier, organizational form can be broadly captured in the present model by the term "infrastructure for collaboration."

As the functionality of products begins to meet or even surpass the needs of customers, customers capture diminished marginal utility from further product improvement. The basis of competition thus begins to shift to such items as time-to-market, and interesting dynamics appear to emerge. First, the ability to conveniently customize the features and functions of a product to address smaller and more profitable niche markets becomes the basis for competitive advantage. Here again, this would tend to favor a robust infrastructure, but one that is more market-oriented, and user design software would seem to be just such a vehicle. This also appears favor of more modular architectures that, in turn, enable more rapid and efficient customization. This modularity of design allows for increased outsourcing and displays as horizontal stratification of firms and industries. In effect these dynamics can be categorized as enhancing the infrastructure for collaboration that ultimately drives the attractiveness of MEMS. Within the context of the present model, this dynamics appear to be captured, although somewhat differently. Cumulative use and adoption is seen to directly increase process design modularity that, in turn, improves the infrastructure for collaboration and ultimately increases the attractiveness of MEMS technology to customers. Customer system knowledge, perhaps in the form of more modular system design, is transferred to producers and, in turn, is again modeled as enhancing the infrastructure for collaboration.

Christensen argues that over time, the lower overhead and scale economies that focused component suppliers enjoy, coupled with the speed to market and flexibility advantages enjoyed by non-integrated assemblers, enable a population of horizontally stratified firms to displace vertically integrated firms, as seen in the personal computer industry.[66]

Christensen illustrates an important and relevant case in point. In the micro-processor industry, although complex instruction set (CISC) processors have continued to improve their speed such that they are becoming disruptive to traditionally higher performing reduced instruction set (RISC)-based processors, they have begun to overshoot the needs of mainstream business applications. Thus, in less demanding tiers of the market, lower function less costly chips, such as the Intel Celeron®, are becoming more available and modular. Design cycles for these chips have begun to compress and are increasingly being fabricated in independent silicon foundries.[67]

This is not to say that re-integration does not occur. Christensen and his co-authors have found that the factor that drives the re-ascendance of integration is the occurrence of a performance gap, as manifested in an increase in the functionality that customers need. Again this is captured in the present model as the need for improvement on the part of the customer, which is driven both endogenously through the discovery of new processes and applications with MEMS technology, and exogenously through the performance of alternative technologies. Indeed, Christensen addresses the very case in point when he looks at the re-integration of the photonics industry in which MEMS is playing a significant role. He points out that in the pre-Internet era, the bandwidth availability to transmit simply voice long distance was sufficient. He argues that predictably the industry was not integrated, but instead, was supplied by specialized firms in the areas of glass fiber, cable, laser pumps, modulators, amplifiers, connectors and multiplexers, with the interactions between these items defined by industry standards. As the Internet has emerged, view in the model presented here as competitive technology performance, a virtually insatiable demand for bandwidth has been created that has been marked by a rush to reintegration at the sub-system level. This results from the need to build higher speed, higher capacity networks that, in turn, require a better infrastructure to combine both system and technology knowledge. This being the case, Christensen's model would seem to accurately predict the vertical integration taking place in the optical MEMS segment. [68]

These observations and theories would be consistent with the model proposed in the present work. As design and process modularity increase, customer learning is enhanced in the short-term and adoption of MEMS technology adoption is likewise enhanced. As design speed is enhanced thorough this modularity and infrastructure build out, competitive advantage is initially enhanced. However, ultimately the effectiveness of the infrastructure appears to diminish as the ability to differentiate products is diminished. The basis of competitive advantage thus appears to become dominated by system- and industry-specific knowledge as customers becomes functionally over served by the underlying technology.

6 Conclusions

To this point, a systems thinking model has been presented that describes the elements driving the adoption of MEMS technology. In doing so, the historical maturation of the ASIC industry, and in particular the histories of LSI Logic and Cronos and IntelliSense have compared to one another. It seems apparent the adoption of products in these industries is driven predominately along niche markets, where the price-to-performance ratio afforded by the technology is clearly superior to the existing technology. However, what is also apparent is that software design tools have played an integral part in overall industry development. These software tools are pertinent to any technology with board applicability and a vast heterogeneity in user demand, which makes product customization valuable to the customer and where significant development risk exists. These tools also play a critical role in codifying the vast amount of tacit knowledge in these process-intensive industries. Furthermore, these software tools serve as an important link into the differing sources of innovation. In essence, they serve as a common point of reference and a de-facto infrastructure that facilitates the transfer of system-specific and technology-specific knowledge among the participating parties. Indeed it could be expected that generally the users of these tools will be lead-users who will strongly foretell of future market trends. Thus, enhanced access to these users could form the basis of a competitive advantage.

An important element to offering such system is to be first to market. First-mover advantage should allow for some degree of standard emergence for a user design language and format that will have a good chance of being generally adopted by the market. Furthermore, if originators can insure easy translation of design into their own production faculties they should have an additional competitive advantage, even if the standard were to become open.[69]

That is not to say there are not limits to the usefulness of software tools. While these toolkits allow for a greater scope for user and suppliers to apply their knowledge, they will not, as a rule, result in products of the highest achievable performance. For example, typical ASIC gate arrays generated via software tools takes up significantly more physical space and generally has lower performs characteristics then do full-custom designs. Similarly, where superior performance in MEMS devices is required, the tight coupling of process and design generally requires a custom solution. Software design tools, by necessity, incorporate automated design rules that cannot translate designs into products for new markets where system knowledge is likely lacking. It may be that some day, artificial intelligences will be applied to such systems and these systems may compete with human designers. But, it is the applicability of MEMS technology to a wide variety of systems and industries that is difficult to *a priori* codify and will limit these tools applicability.

Furthermore, these toolkits might have negative effects for existing business models and may not offer a competitive advantage over the long run to all organizations. Businesses that have invested heavily in sales and marketing organizations and other resources to produce custom designs and production facilities may destroy their value proposition by the adoption of such tools.

The longer-term role of these tool kits is also unclear. Initial introduction of these tools kits seems to provide a strategic advantage to the purveyors of these tools, particularly when linked closely to production capabilities. However, overtime, as the industry matures and increasing niche specialization occurs, the ties between the design tool and software appear to weaken. Eventually, independent design toolmakers emerge whom, can target the specialized process of multiple production companies. This is what has happened in the ASIC industry with the emergence of Cadance and others, and which now is happening in the MEMS industry with the emergence of such companies as Coventar and MEMScAP. Thus, where once the introduction of a software design tool allowed companies to benefit from the design and production of products, they can find themselves reduced to reliance on production capability only. In a capital-intensive business, this can lead to strong capital utilization pressure and ultimately commoditization. It may be possible to forestall such an outcome by accepting and integrating other processes into the tools. However, this would likely be problematic because competitors may be resistant to sharing their specialized process knowledge.

On the other hand, if producers fail to introduce their own tool kits they also run the risk of being marginalized. Supporting a design tool of a competitor would necessitate the disclosure of competitive information about process and capabilities. Thus, participation is such an open arrangement with competitors in the value chain makes this agreement to cooperate difficult. This would again support the emergence of agnostic software toolmakers that share the value chain.

Nonetheless, there has been and will continue to be a significant role to be played in the development of the MEMS industry by these design tools. It is likely that producers who participate broadly in the industry will, overtime, adopt such software design tools. Specialized niche plays will likely adopt external tools and customize or develop their own design tools, much as was done in the ASIC industry.

As to industry structure, one type is reflected in the case of Analog Devices. Where market demand is sufficient for the economies of scale necessary to justify the high fixed costs of building a substantial fabrication facility, vertical integration and market specialization will be strongly encouraged and will likely dominate. Traditional relational ties will probably control the coupling between system and technology providers in these market segments. Should general overcapacity target this niche market, low margins will likely result and the competitive pressures in these market niches will be substantial. Within this same context, there will be system (or sub-system) manufactures, who continue to embed key proprietary components within the overall operation. Here, the sales of higher value systems and the advantages of imbedded infrastructure might hold sway. Some companies will certainly seek to outsource. Here again, however, the tight coupling of design and process place the system integrators at a disadvantage and subject to hold up by component makers.

At the other extreme, there will be the emergence of an alternative strategy, the "fables" foundry. This approach minimizes the firm's capital requirements and enables it to remain flexible and address smaller niche and potentially high margin segments. Key to success here will be careful control of intellectual property, which will be difficult given the tight coupling between device design and fabrication process. Until such time as processing technology is more modularized and manufacturing expertise not the source of significant advantage this model will likely be marginalized.

What lies between these two extremes is best described as moderate-size custom design firms. A centerpiece of this business model will likely remain user-design software with tight coupling to process. These software tools are critical to rapid recognition of market demands and trends, and will enable these companies to enter at a relatively high margin point in the product lifecycle, and then transition away from large-scale production where low-margins will hold sway. It will remain difficult to decide the amount of capital investment that these companies should undertake. Within this framework, there will likely be room for agnostic software design tool manufacturers, who can capture the specialized processes of multiply fabricators, but there ability to capture rents remains to be seen.

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