

# SELECTING A PROCESS PARADIGM FOR AN EMERGENT DISRUPTIVE TECHNOLOGY: EVIDENCE FROM THE EMERGING MICROSYSTEMS TECHNOLOGY BASE

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## Introduction

Emergent technologies often suffer from a lack of an installed manufacturing base and an obvious dominant manufacturing technique. Firms which base their search for competitive advantage on emergent disruptive technologies must make hard production choices and endure major manufacturing discontinuities. We, as well as many other firms, are now facing these challenges with the embrace of microsystems technologies. We add to the literature by providing a set of criteria for firms investing in emergent disruptive technologies.

Microsystems technologies form the second micro manufacturing technology base and are the harbingers of the next silicon revolution. This silicon revolution creates devices that like their micro fabricated semiconductor ancestors "think" but unlike their forebearers they can sense, act and communicate. Efficient manufacturing techniques for these devices have the potential to change every aspect of our daily lives. The microsystems technology base can be grouped into three disparate categories: Bulk Micromachining, Sacrificial Surface Micromachining (SSM), and LIGA. Each of these categories employs a markedly different set of capital and intellectual resources.

Sandia has long been associated as a pioneer in the development of new manufacturing techniques. Microsystems is just the current in a long line of manufacturing technologies that have been considered for mission critical system applications. We, as well as others, have had to make the hard choice of investing in specific microsystems manufacturing techniques. Important considerations in our technique choice include: the existing internal manufacturing bases, commonality with existing commercial manufacturing infrastructure, current and projected critical performance characteristics, learning curves, the promise to add new but un-thought-of functionality to existing systems, and the anticipated ability to qualify devices built from the technique for mission critical applications.

## I. Background

The next decade will see a revolution in the electronics industry in which the functionality of Integrated Circuits (IC's) grows beyond the traditional role of processing and storing data and controlling electrical functions. The intelligent microsystem revolution is the next step in the evolution of the electronics industry and will begin to allow complex systems-on-a-chip to directly interact with their environment by sensing, actuating, and communicating without the need for external hardware. The electronics industry is already evolving towards increased functionality on a single chip. For instance, microprocessors and microcontrollers have grown from multi-chip sets in

the 1980's to single chips that contains logic devices as well as static memory, non-volatile memory, and, in some cases, dynamic memory. Similarly, mixed signal (analog/digital) functions did not appear in the marketplace until quite recently.

The intelligent, integrated microsystem revolution will be the next leap in functionality for the electronics industry. Figure 1 is an electron micrograph of a spider mite on an example of one of these devices which consists of a set of mechanical gears made in a conventional IC foundry with conventional microelectronic manufacturing techniques and equipment. The emerging trend is towards monolithic integration of the control electronics and the micromechanical elements whether they are sensor elements or actuator

elements. The obvious advantage of an integrated system is size, but the real driver will be cost. The electronics world provides numerous examples such as the personal computer and the cell phone where the cost advantage of integrating a greater portion of a system onto a single chip has been demonstrated. The question is whether monolithic integration of mechanical structures for sensing or actuating can be accomplished in a similar cost-effective manner.

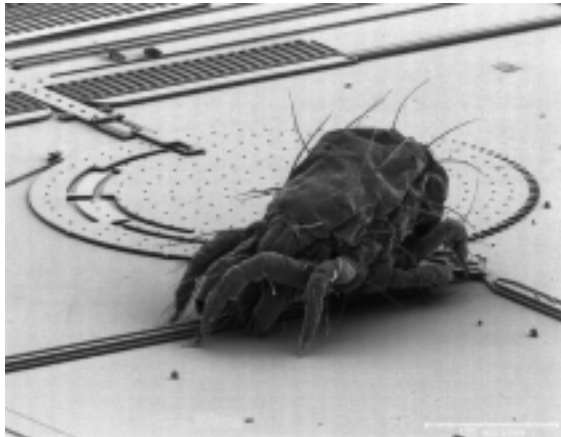


Figure 1. An electron micrograph of a spider mite sitting on a set of polysilicon gears built in Sandia's polysilicon surface micromachining process.

The market for microsystems based on semiconductor processing began to emerge in the 1970's with the introduction of the bulk micromachined pressure sensor. Today, these pressure sensors see applications as diverse as in-vivo

blood pressure monitoring and automotive manifold air pressure sensing. Figure 2 summarizes the projection of six different market studies (Marshall, 1997) for microsystems between 1995 and the year 2000. Although these studies differ somewhat because of varying definitions of the microsystem market itself, different cost growth models, and different groups surveyed (suppliers vs. end users), the clear trend among the projections is that the market has tremendous growth potential and will range from US \$3 billion to \$30 billion by the year 2000.

Microsystems technology heavily leverages developments made in semiconductor processing over the past decade. Although there are a variety of technologies that fall under the umbrella of microsystems, the vast majority of these technologies depend on the precision lithography and etching developed as part of the semiconductor industry. Some technologies such as polysilicon surface micromachining or the integration of these devices with microelectronic devices in a monolithic manufacturing process such as those commercially demonstrated by Analog Devices, Inc. (ADI) with their ADXL series of accelerometers and Texas Instruments (TI) with their Digital Micromirror Device (DMD) draw their manufacturing techniques almost entirely from the semiconductor area. Other techniques such as LIGA (a German acronym for lithography, electroforming, and injection molding) leverage only the lithography from the semiconductor world.

The attraction of the technology to the semiconductor industry is not primarily to

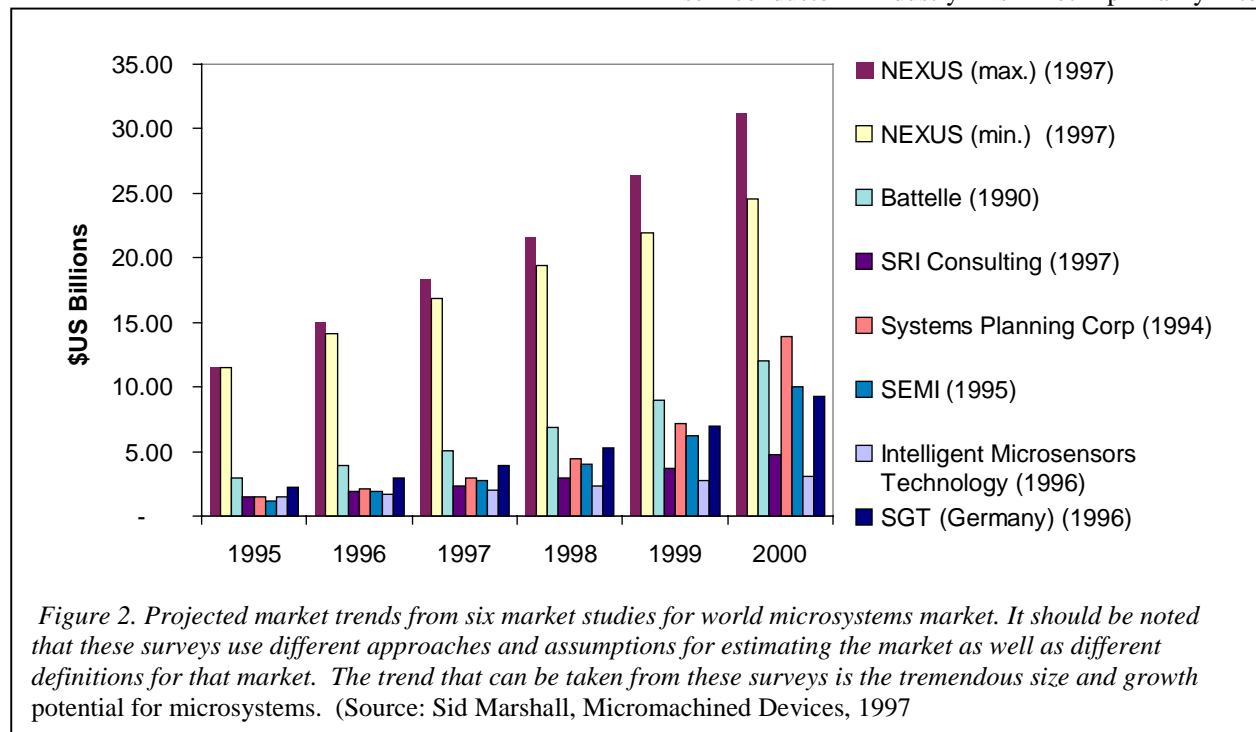


Figure 2. Projected market trends from six market studies for world microsystems market. It should be noted that these surveys use different approaches and assumptions for estimating the market as well as different definitions for that market. The trend that can be taken from these surveys is the tremendous size and growth potential for microsystems. (Source: Sid Marshall, Micromachined Devices, 1997)

manufacture small integrated devices, but to manufacture inexpensive, small integrated devices. The monolithic ADI accelerometer is a prime example of a manufacturing technology that produces a sophisticated sensing device that is competitive in the highly cost-conscious automotive industry. The scaling to the production level needed to service the automotive industry taxes even an IC production line such as that being used at ADI. However, the concept and production of monolithic devices has been so successful at ADI that they have decided to pursue next generation accelerometers and new devices through an agreement to license a more modular integration process developed at Sandia National Laboratories. The Sandia process allows greater optimization of both IC and MEMS processes by separating their fabrication into distinct modules.

Although cost may be a dominant driver, reliability is of prime concern and is closely related to the manufacturing process. The semiconductor industry has demonstrated that integration onto a single chip significantly improves reliability. A monolithically integrated MEMS/CMOS product, TI's DMD, exemplifies this second important trait of semiconductor manufacturing. For DMD display applications, a few or even one pixel of several million can easily be discerned by the human eye. Therefore, near-perfect performance of all the mirrors for the lifetime of the product is necessary. TI chooses to use a semiconductor manufacturing process to accomplish this.

## **II. Factors Influencing Process Paradigm Choice**

When we embraced MEMS as "disruptive" (Bower and Christensen, 1995) technology base for critical applications, we had to choose from among many competing MEMS manufacturing paradigms since no dominant "architectural" manufacturing technology had yet emerged (Abernathy and Clark, 1985). Sandia considered both well-known concepts and factors critical to the Sandia mission. We considered six criteria in our choice of a disruptive manufacturing (MEMS) technique. They included: the existing internal manufacturing bases (Pralhad and Hammel, 1990), commonality with existing commercial manufacturing infrastructure (Walsh et al., 1995), current and projected critical performance characteristics (Foster, 1982), learning curves (BCG, 1986), the promise to add new but un-thought-of functionality to existing systems, and the anticipated ability to qualify devices built from the technique for mission critical applications.

A firm's choice to embrace MEMS technologies, is heavily dependent on the firms underlying manufacturing capabilities (Morone,

1993; Prahalad and Hamel, 1991). Due to the difficulty a firm endures when embracing extreme forms of disruptive technologies, most applications focus on providing the firm a discontinuous (Morone, 1993) or radical (Marquis, 1969) innovation or a product platform with significant cost and or performance advantages over existing manufacturing technologies. Further discontinuous innovations form the platform upon which a new set of continuous (Florida and Kinney, 1990), or incremental innovations (Clark and Henderson, 1990), are based. Sandia embraced MEMS technologies for this reason. Of the several models of the process of innovation, Marquis (1969) is especially applicable for the MEMS-based product marketplace because it addresses the results of discontinuous innovation. In the first stage of the Marquis model, called idea recognition, the source of innovation is deemed to come either from the recognition of technological feasibility, that is a "technology push," or from the recognition of potential demand, also known as a "market pull."

Even though the embrace of a new technology demands the creation of new technological competencies and can represent the passing of traditional core competencies for the sake of new core competencies, many firms utilize existing competencies to leverage their efforts into emergent technologies. We, for example, have utilized the existing competency base in microelectronics manufacturing to leverage and guide our embrace of specific manufacturing paradigm from among the competing emergent MEMS technologies. This highly influenced our choice of a primary MEMS technology. Even though Sandia has extremely successful activities in both Bulk and LIGA micromachine technologies, the majority of the investment in MEMS is currently in SSM, the technology that most significantly leverages the existing microelectronics competency at Sandia National Laboratories.

We also investigated the existing commercial infrastructure (Walsh et al., 1996) as a critical factor influencing choice among competing disruptive technology paradigms. LIGA technologies required, for the most part, infrastructure that did not exist. A LIGA-based manufacturer had to bear the majority of the infrastructure burden. Bulk micromachining had some existing infrastructure but many of their processes were not entirely compatible with standard silicon IC microfabrication. The existing IC industry manufacturing infrastructure is directly transferable to SSM up until the SSM devices reach release and packaging.

We investigated the current and projected critical performance characteristics (Foster, 1982) of

the three major MEMS technology streams. Here the competing technologies are often complementary each providing superior value in differing application arenas (Walsh et al., 1996). The vast majority of Sandia's applications are compatible with SSM technologies but applications also exist for LIGA and bulk micromachining.

"The rate at which individuals and organizations learn may be the only sustainable competitive advantage, especially in knowledge intensive industries." (Stata, 1995). We, if for no other reason than this, would have included learning curve aspects into our critical decision path. Learning and the learning curve phenomena are directly related to the amount of goods produced. SSM, with the exception of pressure sensors, has the largest installed base of MEMS devices. Further, many firms are investigating SSM answers to products currently produced by bulk and LIGA techniques and few are investigating the transpose. Finally, SSM, much like IC microfabrication, lends itself to large batch production which allows the manufacturer to move quickly down the learning curve.

To these well-known factors, we have added two others: the promise to add new but un-thought-of functionality to existing systems and the anticipated ability to qualify devices built from the technique for mission-critical applications. The final device complexity available from SSM components sparks the imagination to add new functionality to devices and systems. The acceptance of SSM in volume manufacturing applications such as ADI's accelerometers and TI's digital micromirror device provides some confidence in our future ability to qualify devices built with SSM techniques for critical applications.

### III. Summary

Emergent technologies often suffer from the lack of an installed manufacturing base and an obvious dominant manufacturing technique. Firms that base their search for competitive advantage on emergent disruptive technologies must make hard production choices and endure major manufacturing discontinuities. Sandia, as well as many other firms, are now facing these challenges with their embrace of Microsystems technologies. Six important criteria have been identified to aid in their selection of technologies: the existing internal manufacturing bases, commonality with existing commercial manufacturing infrastructure, current and projected critical performance characteristics, learning curves, the promise to add new but un-thought-of functionality to existing systems, and the anticipated

ability to qualify devices built from the technique for mission critical applications.

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