

# 12

## MEMS/MST COST MODEL

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1.0	Introduction.....	459
2.0	Benchmark Profitability Measures .....	459
3.0	Cost Structure Considerations.....	461
4.0	Degree of Vertical Integration .....	465
5.0	Cost Components of Production Steps ....	469
6.0	Cost-Structure Evolution .....	477
7.0	Pricing of MEMS Devices .....	478
8.0	Conclusion .....	481
9.0	Appendices.....	482

### **Executive Summary**

The International roadmap committee identified cost modeling to be a key enabler for microsystems commercialization. Contributors to this chapter directly address facilities, capital equipment as well as operational costs for microsystems companies that embrace IC and Non-IC like front end microsystems manufacturing schemes. Further our contributors address different facility typologies such as; those designed only to manufacture microsystems, those that were design to manufacture semiconductor and microsystems devices and finally those facilities that were converted to manufacture primarily microsystems devices. The focus of the cost-modeling chapter is not to provide a firm with a canned cost model but rather to identify key components that drive profitable cost structures and capitalization choices for firms. The chapter was developed from information derived from over forty front-end microsystems manufacturing firms.

The information presented assists firms addressing; make/buy decisions, production flexibility, commodity vs. value pricing, the impact of volume on pricing, risk-adjusted rates

of return and other parameters. Cost elements are driving the commercial industry away from application specific process development toward more general, flexible approaches.

A number of trends are appearing from the effort provided by the contributors to the chapter. We provide seven here:

- 1) The number of facilities providing front-end manufacturing services has increased dramatically over the past five years.
- 2) The numbers of fabrication facilities being converted from IC only manufacturing to microsystems manufacturing has increased dramatically but the contributors do not see this trend continuing.
- 3) The number of manufacturing facilities primarily designed to manufacture microsystems devices has steadily increased and will continue to do so.
- 4) The cost for choosing the non-dominant processing technology for in-house manufacturing has risen dramatically and is likely to continue to do so
- 5) Choosing an outsourcing manufacturing strategy is increasing and this trend is likely to continue.
- 6) Cost structures for front-end manufacture vary greatly between differing manufacturing technologies due to capital costs, output desired and number of microsystems devices forecasted to be sold.
- 7) Sophisticated option theory will drive firm based production selection in the future as the total number of front end manufacturing process choices declines (see Foundry chapter).

Differing merchant manufacturing strategies provide examples of options for the firm or individual seeking to commercialize or design microsystems. The Sony's San Antonio facility, for example, demonstrates an outsourcing-manufacturing model based on the co-manufacture of semiconductor products and MEMS devices. This limits the types of microsystems technologies they can produce, however, it does allow them to take advantage of volume semiconductor device process for a large portion of their microsystems manufacturing. Other merchant and captive microsystems producers such as Axsun demonstrate the efficacy of the designed for microsystems manufacturing approach.

The long-term development and viability of the microsystems industry is highly dependent on the ability of companies to earn an adequate return for investors. Many studies project the growth rate in top-line revenues for the overall MEMS/MST industry. However, growth in revenues does not necessarily translate into increasing net income. The “Bottom-line” income of a firm is a function of both the revenue from selling the product and the costs necessary to produce and deliver the product. Lack of profitability is one of the largest barriers to the expansion of the field. Increasingly capital expenditures and operational expenditures are driving technological choice. The authors demonstrate in Table 1 alternative IC like manufacturing technologies. We lump them into Sacrificial Surface Micromachining (SSM), Bulk Micromachining (BULK) and processes utilizing High Aspect Ratio Etching or (HARSE). We illustrate how “Up Front” capital expenditures along with operational expenditures drive profit minded Microsystems companies to manufacturing choice based on target production, here the expenditures and produced units are illustrative. The chapter leaders hope that this chapter will help facilitate further discussion in this area and lead to further refinements as industry cost structures evolve.

## **1.0 Introduction**

The long-term development and viability of the microsystems industry is highly dependent on the ability of companies to earn an adequate return for investors. Many studies project the growth rate in top-line revenues for the overall MEMS/MST industry. However, growth in revenues does not necessarily translate into increasing net income. The “Bottom-line” income of a firm is a function of both the revenue from selling the product and the costs necessary to produce and deliver the product. A lack of profitability is one of the largest barriers to the emergence of any disruptive technology. The microsystems field is no exception. One “Report Card” (see Commercialization chapter) on the state of the industry, gave MEMS/MST profitability the lowest mark of any of its measurement categories, a C-. This chapter focuses on factors that influence the costs to a firm.

The chapter takes the following approach in discussing cost structures for applications within the MEMS/MST field. First, it raises the issue of reasonable returns on investment. Second, it addresses the nature of cost structures and integration issues that impact the efficient use of resources. Next, the chapter provides general cost ranges and the fixed or variable nature of design, manufacture and packaging costs. Finally, the discussion uses this framework to derive likely cost structure and organizational trends for the industry.

## **2.0 Benchmark Profitability Measures**

Over time, a firm must earn a profit to attract and retain private capital. A question that arises in examining the cost structure of firms is “What is a reasonable return on investment?” Private sources of capital are taking on a larger role in the MEMS/MST industry relative to government funding. Bastianen, et al., report that from 1999 to 2000 private funding of foundries increased from approximately 60 to 80% of total funding.

Profitability ratios provide a meaningful analytical tool for the comparison of wealth generation across firms and industries by scaling net income (revenue less expenses) by measures of resources dedicated to the business. One of the primary profitability ratios is “Return on Assets.” In accounting terms, the asset section of the balance sheet includes a measure of the entire investment in the business. The total value of assets is equal to the sum

of both debt and equity financing. The return-on-assets ratio offers the benefit of measuring utilization of resources regardless of funding source.<sup>1</sup>

Table 1 provides the upper quartile, median, and lower quartile return on assets for 1995 through 1999 and the average of these amounts for firms in the U.S. semiconductor industry. These amounts provide a benchmark range for the MEMS/MST industry from a related field.

**Table 1. Return on Assets for the Semiconductor Industry for 1995-1999.**

Year	Upper quartile	Median	Lower quartile
1995	14.9	8.5	1.9
1996	19.0	10.6	2.4
1997	14.3	5.0	0.3
1998	14.3	6.4	(2.8)
1999	14.6	5.3	1.4
Average	15.4	7.2	0.6

Over this five-year period, the average of the upper quartile was approximately 15.4%, the median was 7.2%, and the lower quartile was 0.6%. One would expect that the firms in the upper quartile, the ones that make the most efficient use of the asset base, would have greater access to capital than those in the lower quartile.

The semiconductor industry is a relatively mature field. The expected return on assets for the MEMS/MST industry will likely have to be higher than that of the semiconductor industry due to the higher risk of a new technology and the current investment environment (i.e., investors will demand a higher rate of return to compensate for higher risk).<sup>2</sup> Given this high risk, median expected return on assets in the 15 to 20% range would not seem unreasonable. However, even within the MEMS/MST field, this expectation may vary based on the maturity and market acceptance of the particular application area. In practical terms, a start-up firm in a relatively new application area will have a difficult time attracting capital due to an extremely high-required return on total invested capital.

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<sup>1</sup> The source of capital brings trade-offs in control, flexibility, and cash flow. For instance, the use of debt financing offers the advantage of maintaining control of the firm. It also allows equity investors to obtain financial leverage if the firm is profitable (i.e., equity holders keep the excess profits). However, if cash flow takes a turn for the worse, the firm is not afforded the same flexibility as with equity financing. Of course, the degree of risk involved with the firm will dictate the terms offered by either providers of debt or equity financing.

<sup>2</sup> Venture capitalists often use discount rates up to 70 percent on very early stage investments.

All else being equal, there are two ways to increase the return on assets: 1) increase revenues relative to the asset base, and/or 2) decrease expenses relative to the asset base. The general focus of this chapter is on the second method. The following sections discuss elements of cost structures that work to drive efficient use of assets.

### **3.0 Cost Structure Considerations**

All industries face common factors that determine how firms are organized to profitably supply market demand. For instance, the mixture of variable costs and fixed costs in producing a given product has implications for the number and characteristics of firms surviving in the market. The maturity of the market segment also drives the supplier's cost structure. This portion of the chapter addresses aspects of these issues.

#### **3.1. Variable and Fixed Costs**

The field of economics has long provided analytical tools that can be used for predictions regarding the organization of an industry. The basic building block is an analysis of fixed and variable costs. A fixed cost is a use of resources that does not vary with the level of output. A variable cost is a use of resources that does vary with the level of output. The sum of variable and fixed costs is equal to total costs. These costs can be related to the total costs of the firm in terms of the following equation:

$$AC = (TVC + TFC)/q = TVC/q + TFC/q = AVC + AFC$$

Where,

AC = Average cost per unit

TVC = Total variable cost

TFC = Total fixed cost

q = Quantity produced (total yield)

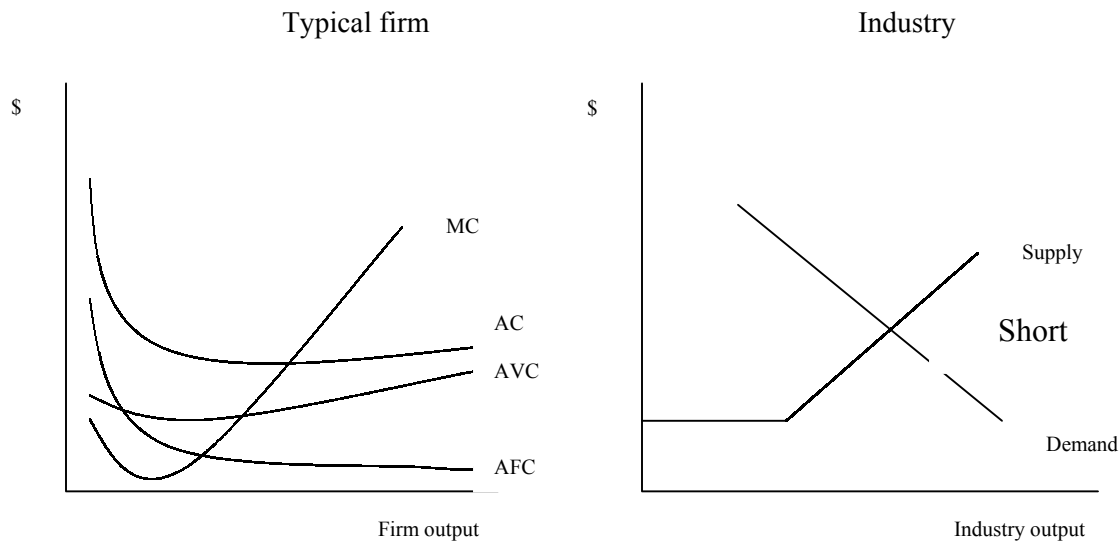
AVC = Average variable cost per unit

AFC = Average fixed cost per unit

The marginal cost (mc) is the increment to total cost resulting from producing one more unit of output. Appendix 7 demonstrates how this equation can be combined with the firm's required return on assets to derive a per-unit contribution margin analysis. This equation can

be used to examine the per-unit contribution necessary to support a given level of fixed costs and required return on investment.

Economic theory holds that each firm will produce up to the level where marginal cost is equal to marginal revenue. The aggregate production of the firms in the industry gives the overall supply curve. These concepts can be related in Figure 1.



**Figure 1. Short-run Market Equilibrium**

The “Typical Firm” portion of the figure illustrates various elements of the cost structure of firms. The average fixed cost per unit decreases as output increases. The average cost per unit decreases as the quantity produced increases as long as marginal cost is less than average cost. By definition, marginal cost, beyond the first unit, is driven by variable costs. Thus, the ratio of variable costs to fixed costs controls the point where marginal cost exceeds the average cost per unit. As long as marginal cost is below average cost, economies of scale exist. In other words, the production of an additional unit reduces average cost per unit if the incremental cost is below the average cost. If marginal cost exceeds average cost, there are diseconomies of scale.

In the “Industry” portion of the figure, the supply curve is the sum of the individual firms’ marginal cost curves and the demand curve is the total market demand at various prices. The market clearing price is where the demand and supply curves intersect. In the

long run, firms must operate at or above the average cost per unit. In the short run, firms will continue to produce as long as marginal revenue equals or exceeds marginal cost. Firms will not shut down if marginal revenue is covering variable costs. A problem for the MEMS/MST industry is that prior to building a facility or incurring research and development costs, the existing and foreseeable market demand may not cover this cost.<sup>3</sup>

In the example illustrated in Figure 1, the supplying firm or firms are earning large profits in the short run. The market-clearing price is well above the typical firm's average cost per unit. However, theory suggests that, barring barriers to entry, firms will enter the market to capture the high profits, ultimately, driving costs down to the level of the suppliers' long-run average cost. In this case, the product becomes a commodity.

This point may be of critical importance to long-run cost structures in various segments of the MEMS/MST industry. Segments that have low barriers to entry will ultimately have to price products on the basis of average cost of production. Firms that enjoy barriers to entry will still have to be conscious of costs in order to maximize profits; however, they will have a greater ability to charge customers on the basis of the "Value" of the product.

These straightforward economic concepts have multiple implications to the cost structures discussed in this chapter. One of the primary factors to consider is the relative importance of fixed costs to the firm. If a firm faces large fixed costs and a relatively small market, the technology may not be economically viable for production. For instance, in terms of Figure 1, if the demand curve is shifted to the left (i.e., demand falls) and the average fixed cost curve is raised, a firm's average production cost per unit may exceed what the market is willing to pay for any level of output.<sup>4</sup> The only available option for such a firm may be to use an outsource provider of manufacturing capacity that effectively aggregates volume across a number of firms.

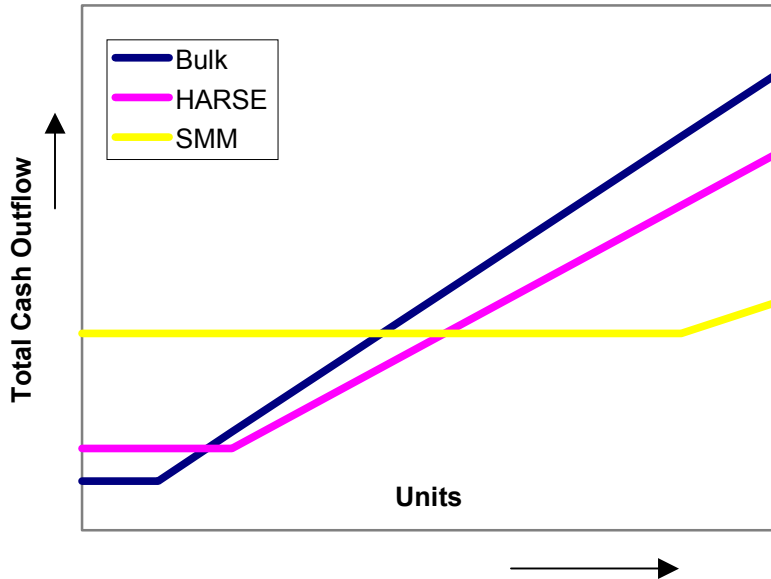
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<sup>3</sup> The practical implications of this statement can be seen in recent announcements to delay expansion and/or cut back on the labor force in response to reduced market demand.

<sup>4</sup> The MEMS/MST industry faces high relative fixed costs. Two predominate categories are facilities cost and research and development expenditures. As discussed in this analysis, the ability to use market structures (i.e., "fabless" manufacturing techniques) to decrease average fixed cost may differ for these two uses of resources.

Figure 1 also demonstrates the advantage to outsource providers for bringing in extra work to cover unused capacity. This strategy is sound if the price charged to the customer at least covers the variable cost of production. Over longer periods of time, the outsource provider must earn a return on the fixed investment. This factor may favor “hybrid” production. A manufacturer that produces both internal products and allows outside utilization of its production capacity during slower periods may have a better chance of providing a longer-term return on investment. The hybrid producer can use this to its advantage vis-à-vis the pricing of “Pure” MEMS/MST foundries (i.e., the hybrid producer can charge based on variable costs). These factors are discussed more fully below in terms of vertical integration.

The application of these concepts is complicated in the MEMS/MST field by the existence of multiple production technologies. Figure 2 uses a hypothetical relative cash outflow to illustrate this factor for bulk micromachining, high-aspect-ratio silicon etching (HARSE), and surface micromachining methods.<sup>5</sup>



**Figure 2. Hypothetical Total Cash Outflow at Different Production Levels using Different Manufacturing Methods.**

<sup>5</sup> The interested reader can construct a more detailed analysis of the ratio of fixed to variable costs for different production methods from information provided in the accompanying appendices.

The choice (when there is a choice) of production method entails different ratios of variable to fixed costs. These ratios may change the appropriate choice at different production volumes. This uncertainty also increases the value of outsourcing to smaller start-up firms.

If a firm faces large fixed costs and a relatively large market, an early entrant may enjoy a natural protection from competition from other firms. The early entrant may have the opportunity to increase production to take advantage of economies of scale and associated learning effects. A later entrant may not have the resources to quickly ramp up to the same level of production and match the early firm's average cost.<sup>6</sup> Another important consideration is the intellectual property rights held by a firm. This may give the firm protection from competition from later entrants. In this case, the firm may face a relatively inelastic demand curve.

As discussed in more detail later in this chapter, these considerations suggest the opportunity for various contracting mechanisms between firms, to share the burden of fixed and/or variable costs of production. However, these opportunities will be related to the intellectual property rights held by individual firms and the similarity of the manufacturing process for the component. This factor is considered below in terms of vertical integration in an industry.

#### **4.0 Degree of Vertical Integration**

One of the major issues facing a new industry or component of an industry is the degree of vertical integration. The issues are particularly acute if the market for a product is small, as is the case for many MEMS/MST applications. If the demand for a product is small and there are limited economies of scope between the product and related products (i.e., it is difficult to reach high volume when aggregating across products), the total output of the product in the industry will be small. In this case, economic theory holds that firms producing the product will tend to be vertically integrated.<sup>7</sup> The reason for this result is that outside firms are

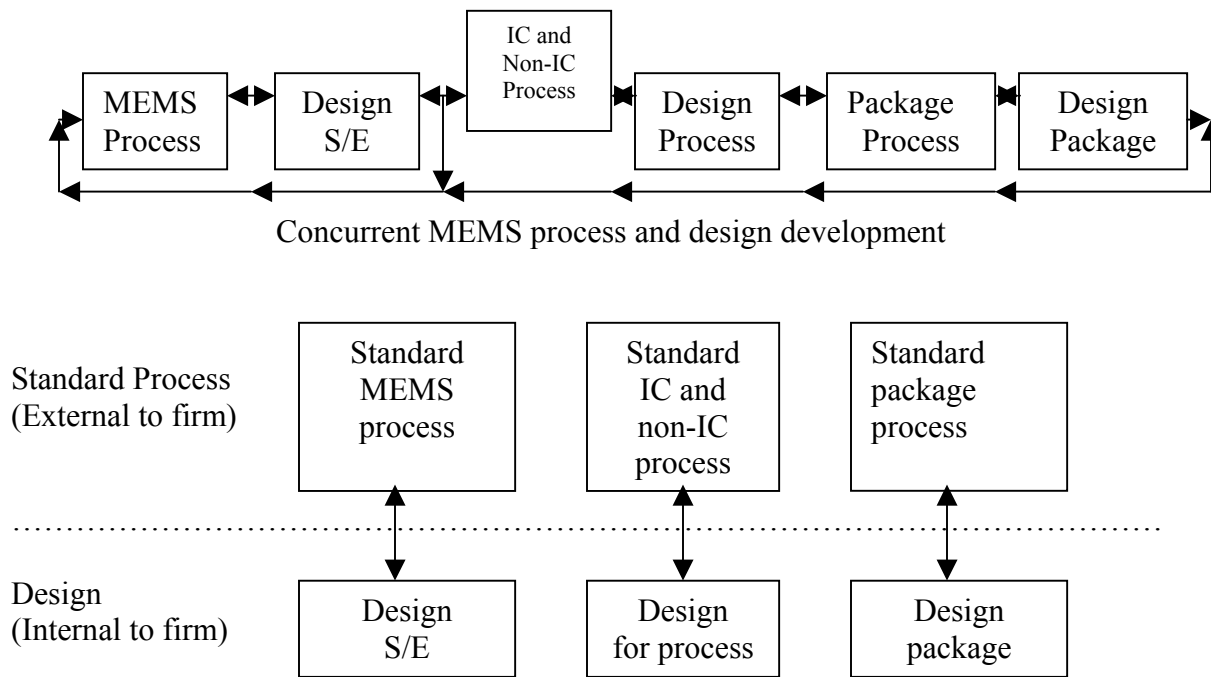
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<sup>6</sup> If other barriers to entry such as intellectual property rights do not protect the firm, then other firms will eventually enter the market to compete for the high profit amounts.

<sup>7</sup> This statement assumes the firm comes into existence. The difficulty in manufacturing products at a reasonable cost may act as a barrier to entry.

unwilling to develop specialized facilities to provide manufacturing services for a portion of the process. The specialized firm's setup costs per unit may be too high or it may face uncertainty in the continued demand from the purchasing company(ies). If a firm wants to produce the product, it must internally perform all of the functions without the benefit of specialization.

As the industry expands, it becomes profitable for third-party providers to specialize in elements of the production process. The aggregate market volume levels increase to the point where third-party providers can profitably achieve economies of scale. In terms of Figure 1, an individual firm may not require the production volume necessary to reach the minimum point on the AC curve. With production standardization, a third-party contractor may be able to aggregate demand across firms moving to more efficient production.<sup>8</sup> Of course, the profitable aggregation of production volume may entail a trade-off in the customization of the product.



**Figure 3. Concurrent versus Fabless MEMS Product Development. (Source: Hsu 2000).**

<sup>8</sup> The market share and size commanded by the individual firm will impact the organizational structure. For instance, General Motors produces enough cars that it can internally achieve economies of scale in terms of fixed cost. Its decision to outsource certain components is likely driven by other factors (e.g., cash flow management, labor contracting issues).

This concept has large implications to the MEMS/MST industry. Diagramed in Figure 3 are two production models for the manufacture of a MEMS-based product.

The first portion of Figure 3 illustrates production in a vertically integrated MEMS/MST firm. The firm performs all of the functions internally from design through packaging. This configuration may not be economically viable under the economic considerations discussed above. As one commentator states regarding the MEMS/MST field:

*"The economies of scale achievable by larger service foundries will make them extremely competitive. However, this will not happen until the MEMS industry has a diverse product base accompanied by large production volumes. Until then, the high cost of capital equipment, high labor costs, development delays, and fast price erosion will create challenges for MEMS companies. This has prompted some investors and analysts to question the viability of the MEMS business. (Hsu 2000)."*

The second approach is the "Fables" method. The firm contracts out production processes to third-party providers. The key word on the figure is "Standard" processes. The processes must be general enough to avoid large switching costs for the third-party provider.<sup>9</sup>

In addition to the opportunity to reap cost savings through economies of scale, firms also receive option value from utilizing a "Fables" approach. The firm does not have to sink large dollar amounts into equipment that may soon become outdated. It can also switch between manufacturing techniques that best suit each project. In other words, there is a "Real Option" value in maintaining flexibility.

The third-party's risk of ownership is less than an individual firm's risk. Similar to an insurance company, the third-party provider may be able to diversify the risk over a "Portfolio" of clients. The client firm will pay for the third-party's risk of ownership; however, this price may be much lower than if it bore the entire risk itself.

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<sup>9</sup> A variation of the "fables" model is a general contractor model. A third-party company acts as a contractor for the customer firm. The contractor provides design services, etc., and also contracts with subcontractor firms to manufacture, test and package the product. This model holds the potential for a trade-off in the reduction of transaction fees (i.e., the contractor has information on subcontractor firms) with the equivalent of a brokerage fee paid to the contractor.

Various portions of the production process may hold different opportunities for outsourcing. For instance, a firm may be able to design a product to conform to standard design rules; however, the product may require specialized packaging techniques not available from third-party contractors. These differences in economies of scale for portions of the process will continue to place a premium on firm specific cost models.<sup>10</sup>

Even with the opportunity for “Fables” production, other issues may lead firms to favor vertical integration. These factors include the following:

- 1) Integration to lower agency and other transaction costs.

One of the potential problems with a fables method is so called “Agency Costs.” Agency costs arise when the contractor has conflicting incentives with the client. In a MEMS setting, the client may be worried about loss of intellectual property rights through an inadvertent transfer due to the agent’s incentive to learn and apply knowledge to other clients. Agency issues induce costs of contracting and monitoring of the relationship between the client and the contractor.

- 2) The need for extensive coordination in manufacturing.

A producer may face a situation where the steps in the production process are very interrelated. In this case, it may not be feasible to delegate certain production processes to third parties. The process may be more efficient when conducted similarly to part 1 of Figure 3.

- 3) Integration to assure supply.

Third-party providers may not provide a timely source of supply. Processes not dedicated to specific clients may result in delays due to switching processes, shortage of materials, labor problems among a host of other potential problems. The firm may feel more comfortable performing the process “in-house” to obtain a greater degree of control.

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<sup>10</sup> A firm specific cost model must take into account interactions between production steps. For instance, designing a product to take advantage of economies of scale in the manufacturing step may increase costs at the later testing, assembly, and packaging stages.

#### 4) Integration to assure consistent quality.

A firm may have an incentive to bring production processes “In-house” to assure uniform quality. The firm may run into quality differences between the products produced by third-party providers.

Bastianen, et al., addresses the issue of the current level of integration in “Foundries for MST, A Status Overview II.” They find that there is not much indication that foundries are specializing in certain technologies or market areas. It appears that foundries are offering broad services based on the direction of market demand. However, the study does note one indication of specialization. They found that in 1999, 50% of surveyed foundries had eight or more clients responsible for 80% of the revenue. In 2000, the percentage of surveyed foundries with 80% of revenue from eight or more clients had decreased to 30%. Bastianen, et al., came to the following conclusion:

*"It has yet to be seen if the forces supporting the foundry market, namely economy of scale and cross-fertilization forces that move individual firms away from vertical integration, will be stronger than the forces minimizing the role of the foundries in the MST market, namely the control of technologies by the MST system supplier and success of their own products, forces that move firms toward vertical integration."*

The nature of the cost structure and market demand will likely supply the ultimate answer. In terms of roadmapping the evolution of likely cost structures, the above analysis suggests that start-up firms must use outsource manufacturing providers. This outsourcing will come with an initial trade-off in the ability to customize features. As MEMS/MST applications gain market acceptance, there may be an increase in the number of firms that utilize vertical integration.

## **5.0 Cost Components of Production Steps**

The following sections examine the cost of resources used in producing MEMS/MST products in each of the steps detailed in Figure 3. Ownership of the assets necessary to perform each step may be internal or external to the firm (the difference between Part one and Part two of Figure 3); however, the owner of the assets must expect to receive adequate compensation for the investment (i.e., return on assets). The key factor is the efficient use of

the resources given the constraints of design, functionality requirements, etc. As discussed in the product section that follows, the relative maturity of each product category will, to some extent, determine whether the production of the product is more of an “Art” or a “Science.”

An examination of cost components of the production steps immediately raises accounting questions. A primary issue is proper matching of revenues and expenses. In other words, how should expenses be allocated across periods to give an accurate picture of profitability? Two of the most difficult areas in which to answer this question are research and development costs (front-end non-recoverable engineering costs) and allocation of building and equipment costs. Each of these categories acts as fixed costs where the average cost per unit produced decreases as production levels increase.

Accounting convention holds that up-front R&D costs are immediately expensed because their benefit to future periods cannot be accurately determined. However, these expenditures can create intellectual property, unrecorded on the balance sheet, which can benefit future periods. Table 2 provides an example of the reporting impact of this rule for four publicly traded companies operating in the bioMEMS field.

**Table 2. R&D Percentage of Expenses for bioMEMS Companies**

	Revenue 2000	Expenses 2000	R&D as a percentage of expense	Revenue 1999	Expenses 1999	R&D as a percentage of expense
Firm one	3,468,000	71,575,000	29.28%	2,936,000	11,253,000	62.22%
Firm two	200,830,000	262,196,000	21.89%	109,074,000	139,333,000	31.24%
Firm three	7,062,000	23,851,000	63.12%	3,595,000	11,656,000	88.03%
Firm four	18,381,000	69,739,000	41.41%	1,793,000	24,058,000	48.62%

Each of the four firms shown reported a loss. However, a significant proportion of the loss was due to the treatment of R&D in the cost structure. Initial return on assets is negative; however, the hope is that the R&D investment will produce high positive returns in future periods. In fact, future return on assets will be biased upward due to the immediate expensing of these costs (i.e., no asset recorded on the balance sheet). The data in Table 2 also gives an insight into what may be a trend in the evolution of a firm’s cost structure. In each case, although the total dollar value of R&D is increasing, its year-over-year percentage of total costs is decreasing.

Building and equipment costs clearly benefit multiple periods. Again, the question is the proper allocation across periods. In gathering data for this Cost Model chapter, various rules of thumb are apparent in the calculation of depreciation. One example of rule of thumb is shown in Table 3.

**Table 3. Common Depreciation Periods**

Asset type	Depreciable life
Building	30 years
Facilities equipment (e.g., water system, storage tanks, etc.)	10 years
Tool sets	5 years

These periods will vary with the specific situation of the firm.<sup>11</sup> For instance, a building or tool set may become obsolete in a very short period of time due to advancing technology. On the other hand, a used tool set may be purchased with the expectation of a short life span. The individual firm must take these factors into account in the specific cost structure. The following sections address some of the cost issues involved in the design, manufacture, packaging and testing stages of production. As a component of this discussion, approximate prices are provided for various building, equipment and labor elements necessary across manufacturing methods. The actual total costs for a firm will depend on developing a balanced tool set for the chosen manufacturing method and level of production. If a firm out-sources production, these costs will be incurred indirectly through the price paid to the manufacturer to cover its costs.

### 5.1. Design

Design is the first critical step in the production of a MEMS/MST-based product. This term encompasses a large amount of work from initial R&D to preparation for volume production. The steps in the design process include the following:

- Development of masks.
- Manufacture of pre-production validation samples.
- Development of package design and testing.
- Planning of manufacturing process implementation.

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<sup>11</sup> The depreciation period will also vary for tax-accounting purposes.

A very custom design will likely result in an expensive design process as well as limitations on manufacturing methods.

In terms of Figure 1, design costs act as a fixed cost. As production volumes increase, the per unit cost of the design and process set-up decreases. To achieve initial profitability, the design process must result in a manufacturable product with a high volume of market demand (thereby allowing the spreading of the development fixed cost), or a large value proposition to a smaller group of customers (thereby allowing a price that covers a high average cost per unit). The design issue may also be one of scope. If the design can be used to produce a family of similar products, the effect is amortizing the fixed cost over a larger number of products.

The labor and equipment necessary in the design process are expensive. To provide a range for the level of costs, Appendix 1 lists approximate costs of various design tools. Appendix 5 gives ranges of salaries for various labor positions. One can easily see that scaling these amounts to required levels quickly results in a large fixed investment.

Utilization of out-sourced providers may significantly reduce the required investment in equipment. However, the firm will still have to compensate the outsource firm for its share of the equipment depreciation, labor costs allocated to the project, and return on its investment. These charges will likely vary with the complexity of the design. In addition, the firm will have to take into account possible agency costs with the third-party provider. The firm may want to explore alternatives to cash payment for services. For instance, the firm may offer the service provider an equity stake in the company (a means of conserving cash flow).<sup>12</sup>

A more intangible benefit of using an outsource provider is the opportunity for learning in the firm. The client firm may be able to more efficiently gain expertise in the design process, with the assistance of the outsource provider, rather than through simple trial and error. As with many aspects of cost structures, this effect is likely to be the strongest in the early portions of the application's life cycle.

Decision criteria for the investment in specialized design assets, both equipment and people, include the following:

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<sup>12</sup> Although, in today's environment, the outsource may be unwilling to accept the risk of an equity investment in lieu of cash.

- Stage of the market for the product.
- Frequency of design work.
- Importance of protecting IP.
- Firm cash flow.

As the market for an application matures, it seems likely that design will become a smaller portion of the overall cost structure. In addition, natural efficiencies in the process should arise as learning occurs. The focus of the cost structure may move towards manufacturing costs and incremental innovations.

## **5.2. Manufacturing Processes**

Three primary approaches are currently being utilized in manufacturing MEMS/MST products: surface micromachining, bulk micromachining, and high-aspect-ratio micromachining (HARM or HARSE from above).<sup>13</sup> Each of these methods involves advantages and disadvantages in terms of cost, complexity, functionality, material and its IC compatibility. Many of these trade-offs and descriptions of the processes are considered in other roadmap chapters. The focus here is on general cost drivers. The trade-off in function and production method again emphasizes the importance of firm specific cost models. The following sections discuss general building, facility equipment, tool set, and process costs.

## **5.3. Building Costs**

For purposes of illustration, this section provides cost data for three levels of clean-room environments. Part 1 of Appendix 2 provides per-sq.-ft. new-construction costs for components of the facility under Class 1, Class 100 and Class 10,000 standards. The illustration in Part 2 of the appendix is based on a 10,000 sq.-ft. clean-room facility and a ratio of non-production to production facility area of 4:1. The resulting total size of the facility is approximately 40,000 to 50,000 sq. ft. The approximate total cost of the facility is \$38,000,000; \$25,000,000; and \$17,000,000; for Class 1; Class 100; and Class 10,000 environments, respectively.

This illustration indicates the level of the increase in cost as the environment conditions become more stringent. This basic analysis shows why the less expensive clean-room facility has been the general route of entry into MEMS/MST production (bulk micromachining). The

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<sup>13</sup> The most common of HARM techniques is LIGA.

building facility is a fixed cost to the owner. It is easier to cover these costs with lower production volumes in a less-expensive facility.

#### **5.4. Facility Equipment Costs**

The building provides the basic infrastructure for manufacture. However, production requires a host of other equipment. Appendix 3 provides costs for some infrastructure equipment that is common across facility types. This list again gives an idea of the large capital investment in a MEMS/MST production facility.

#### **5.5. Tool-Set Costs**

Tool-set costs can quickly rival the cost of the building infrastructure. However, they have a much shorter useful life. The cost of tools can place a heavy drag on the entire cost structure. Appendix 4 provides approximate new and used prices for various tool-sets required across manufacturing methods.<sup>14</sup> In addition to these costs, a typical rule of thumb is 15% of the cost for installation and 5 to 10% for annual maintenance costs.

#### **5.6. Process Costs per Unit**

Process costs are direct costs associated with the production of the dies. They include the following items:

- Wafer costs with implications to yield.
- Electricity costs.
- Labor.
- Chemicals and gases.

Two of the factors impacting production volume of dies are the size of the wafer and yields. The diameter determines the area available for dies on a given wafer. For instance, a six-inch wafer (150 mm) has approximately twice the area of a four-inch wafer (100 mm). Likewise, an eight-inch wafer (200 mm) has approximately four times the area of a four-inch wafer. The implications to production economics of this difference are clear. The ability to use a larger wafer may result in lower average cost per die. The trade-off is that the equipment for larger wafer sizes costs more than for smaller wafer sizes. The expected

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<sup>14</sup> The tool-set costs for LIGA do not include the equipment costs for a synchrotron. The charge on a per-use basis is approximately \$200-\$400 per exposure.

market volume may drive the decision as to the size of wafer. Appendix 6 provides costs for various types and wafer sizes.

A second variable impacting production volume is the yield of useful dies per wafer. The yield may be related both to the complexity of the design and the sophistication of the manufacturing tool-sets. A complex design is likely to result in decreased yields. In addition to design as a fixed cost, it likely has an interactive effect with the variable process costs. A lower yield increases per-unit materials costs, labor, etc. In addition, the complexity of design may impact the “Up-time” of the facility. MEMS/MST production suffers relative to standard IC production in that yield levels have not reached the six-sigma level. This concern can vary across different manufacturing methods, partly as a function of the number of process steps. Appendix 6 provides an approximate number of process steps, mask steps and primary materials used across the spectrum of IC to non-IC-compatible manufacturing methods.

Appendix 5 lists labor cost per person. The total labor cost per wafer will be a function of the amount of time necessary for each step. Thus, labor costs will be a function of complexity including the number of process and mask steps. In addition to these costs, the per-unit cost must bear the burden of allocated overhead costs in the nature of selling, general, and administrative costs.

### **5.7. Summary of Front-End Manufacturing**

For most firms, investment in the operation and maintenance of a manufacturing facility is huge. The return on this investment is a function of the volume of product moving through the process. Fixed costs play a large part across manufacturing methods. It appears that it will be uneconomical for a firm to own its own production facilities unless it is producing at a high level of output. In addition, independent foundries are likely uneconomical unless the MEMS/MST industry can design products with economies of scope that result in large production volumes.

### **5.8. Packaging Costs**

MEMS/MST packaging faces numerous challenges due to the varied environments in which the products will function. MEMS/MST devices interact with the environment in a variety of forms including electrical, optical, and mechanical. This interaction can lead to

extremes of temperature, moisture, and dust, all of which can have a detrimental impact on performance. Packaging costs can be viewed in two separate veins. One is the initial design and testing necessary to produce a viable package solution for the application. The second vein is the actual process costs of packaging the product.

The initial design of the package can be categorized as a portion of the design process. It acts as an initial fixed cost in the cost structure. The development of the package may be a pure function of trial and error. This process can be much more of an “Art” than a “Science.” In a MEMS/MST environment, packaging has a direct impact on the design of the functionality of the product. The engineering functionality is somewhat meaningless if the product cannot operate within a given environment.

Factors determining the design cost on an individual firm basis will be similar to those for general design: design tools and specialized labor. Once a satisfactory packaging solution is developed, the process may approach more standardization. Appendix 1 also includes some tool-sets used for packaging individual dies.

Packaging is viewed as one of the main obstacles to MEMS/MST commercialization. Inputs from multiple advisors to this chapter indicate that this portion of the cost structure can often account for up to 80% of the total cost of the finished product. The primary difficulty with holding down the per-unit cost of packaging is that this portion of the process does not offer the same economies of scale as does the front-end portion of the process. Packaging is very labor and materials intensive. In other words, the ratio of variable costs to fixed costs is higher than that for front-end manufacturing. Packaging does not lend itself as well to inexpensive out-sourcing. Packaging may require specialized processes that require additional switching costs for out-source providers.

The dilemma of packaging may be difficult to overcome. The overall answer to decreasing packaging’s drag on overall economies of scale is difficult to find. One area of focus is work at the wafer level. For instance, if the die can be somewhat encapsulated at the wafer level, this increases economies of scale and decreases the need to develop specialized packaging solutions. A second general cost driver may be increasing overall yield through learning effects.

In addition to the above costs, an additional cost that is tied to design, manufacturing, and packaging expenditures is qualification and reliability. For instance, the complexity of the design may have an impact on the longevity of the product. Similarly, the amount of interaction the product has with the outside environment impacts the product's durability. The qualification of a product may come down to a choice between product differentiation strategies as discussed next.

## 6.0 Cost-Structure Evolution

Production economics are different in various life stages of the product application. Cost structures evolve as markets grow and as capabilities increase. It makes sense to analyze cost structures in terms of broad applications in the MEMS/MST field. In accomplishing this task, Table 4 takes a portion of the "M3 Product Evolution Timetable" from the Commercialization chapter and lists the products based on the order of the end point of the "Cost Reduction/Application Expansion" stage. The table addresses components of the cost structure. The terms "High," "Medium," and "Low" refer to the current absolute dollar amount in the average cost of each of these MEMS product categories. The table does not refer to additional components of the system to which the MEMS device may be integrated. In many cases, the product can be manufactured under more than production method. The choice of method will be related to functionality needs and elements of the above described costs.

**Table 4. Components of the MEMS Cost Structure**

MEMS device type	Cost reduction/application expansion phase	Design costs as a component of the cost structure	Manufacturing costs as a component of the cost structure	Packaging costs as a component of the cost structure <sup>15</sup>
Pressure sensors	1975-1990	Low	Low	High
Accelerometers	1990-1998	Low	High	Low
Nozzles	1990-1998	Low	High	Low
Bio/chemical sensors	1999-2004	High	High	High
RF switches	2001-2005	High	High	High
Gas sensors	1998-2005	High	High	High
Micro relays	1998-200	High	High	High

An analysis of the table supports the view that small and medium-sized firms face high hurdles to commercializing MEMS. These firms are generally associated with the newer application areas and face three large cost hurdles: high fixed design costs, high fixed manufacturing costs, and high fixed packaging costs. In addition, the risk of unproven technology areas reduces available capital.

It appears that these hurdles will push newer MEMS/MST applications into a predictable track. Capital constraints will likely keep these start-up firms from internal vertical integration. This factor will limit the ability to produce custom applications. Due to capital constraints and risk, these applications will likely be developed under the fabless approach. Firms will be unable to directly purchase assets, so they'll rely on third-party providers' investment in equipment. However, as the product and markets mature, the cost structure will move firms away from the fabless model and towards vertical integration.

For instance, in the more mature application areas, such as pressure sensors and accelerometers, the process will move towards commodity pricing using existing technology. Production economics will likely move towards spreading fixed costs across as many dies as possible. One might expect movement in this market segment towards larger wafer diameters and larger physical plants. This action will decrease the average cost of each part in selling into a very large market.

The cost structure also implies that firms in the intermediate stages, those between initial development and full commercialization, will likely be potential targets for mergers and acquisitions. A merger may make sense to accelerate the process from outsourcing to internal integration. General strategies based on cost structures are discussed next.

## **7.0 Pricing of MEMS Devices**

As mentioned in the beginning of this chapter, return on assets is a function of both revenue and expense relative to the investment in assets. Basic economic forces are likely to move segments of the MEMS/MST industry towards two pricing structures, one based on cost and one based on value. Porter (1985) introduced a simple matrix useful for identifying the positioning of a product in terms of competitive advantage and competitive scope (Figure 4).

Porter's analysis results in three generic strategy firms seeking a competitive advantage. One is targeting a broad market group with a cost leadership strategy. This strategy is to try to be the low-cost producer in the industry and often results in a standard, no-frills, product designed to achieve economies of scale. To have an above-average return on assets, the firm will have to achieve cost leadership while pricing the product at or near the industry average. If the product is deemed below average quality or functionality, it will command a lower price and remove some of the benefit of cost leadership.

		Competitive Advantage	
		Lower cost	Differentiation
Competitive scope	Broad target	1. Cost leadership	2. Differentiation
	Narrow target	3A. Cost focus	3B. Differentiation focus

**Figure 4. Porter's Three Generic Strategies based on Cost Structure, Differentiation, and Market Focus.**

A second strategy is to focus on a broad target with a differentiation strategy. Under this plan of action, the firm attempts to command a premium price through offering additional functionality or quality to the product. At the same time, the firm must achieve differentiation at approximately the industry's average cost structure level to receive an above-average return on assets. As is evident in the discussion to this point, this goal may be difficult to accomplish due to the added cost in producing a product with added value.

Porter's third generic strategy is focus. In this strategy, the firm chooses the cost leadership or differentiation strategy and applies it on a narrow competitive scope within an industry. The cost focus takes advantage of cost behavior in certain segments, while the

differentiation focus exploits the special needs of buyers in certain segments. These differences imply that the producers serving the broader markets may not be able to meet the needs of the smaller segments.

Porter theorizes that it is very difficult to simultaneously achieve both cost leadership and product differentiation in either a broad or focused target market. For instance, if one firm can achieve very desirable product features with a given cost structure, it is likely another firm can follow suit. One of the instances when a firm may be able to achieve both goals is if it pioneers a major innovation. In this case, the firm may be able to differentiate its product within the existing cost structure. However, once other firms have access to the same technology, the firms will once again be forced to choose between a cost leadership and product differentiation approach.

MEMS/MST firms have had some success in achieving both cost leadership and differentiation in the broad market. For instance, the airbag accelerometer was an innovation that quickly excelled in both areas. However, in the broader MEMS/MST industry, given the fixed investment in design, manufacturing facilities, and packaging costs, it may be difficult for newer firms to compete with either a cost leadership or a differentiation strategy aimed at the broad market. For instance, the MEMS/MST firm may find it difficult to initially compete with the cost structure of non-MEMS/MST-based firms. Likewise, the MEMS/MST-based firm may find it difficult to charge a premium price for product differentiation while maintaining a cost structure on comparable terms with the broad industry.

It appears that, based on the cost structure, the MEMS/MST-based firm will tend to adopt a segment-focused strategy with an emphasis on product differentiation. This strategy will allow the firm to meet the needs of a group possibly on the fringes of the broader market. The firm will have to be able to charge a premium price to cover the fixed costs of production. However, if successful, this targeting strategy may give firms a foothold to later move down the average cost curve and possibly shift more into the broader market.

## **8.0 Conclusion**

The authors would like to thank the dozens of individuals that have directly and indirectly contributed to this chapter through their response to surveys, and discussions regarding the movement in cost structures of the industry. The upcoming years present significant challenges for the overall MEMS/MST field to make good on its initial promise. With the current environment squeezing the growth in “Top-line” revenues, the focus will, by necessity, shift to reducing costs. From a cost structure perspective, the existence of a large number of out-source providers may now provide the necessary infrastructure to accomplish this decrease in costs, leading to a profitable industry.

## 9.0 Appendices

### 9.1. Appendix 1: Design, Packaging, and Test Tools

Tool	Estimated cost (new) \$k	Estimated cost (used) \$k
Dicing saw	120	90
Die bonder	200	100
Wirebond	100	50
Electronics assembly bench	50	50
Wafer probe for MEMS	300	200
ATE for MEMS devices, packaged	100	75
Mask design CAD terminals	200	200
Pick-and-place tool	200	120
Packaging metrology tools	150	100
Widebed plotter	50	35
Seal for package	150	100

### 9.2. Appendix 2: Approximate Building Cost

#### Part 1

<b>New-facility cost</b>	<b>\$ per square foot</b>
Class 1	3,000
Class 100	1,700
Class 10,000	900
Non-production area	200

#### Part 2

<b>Facility type</b>	<b>Cost</b>
10,000 sq. ft. Class-1 clean room	\$30,000,000
40,000 sq. ft. non-production area	8,000,000
Total	\$38,000,000
10,000 sq. ft. Class-100 clean room	\$17,000,000
40,000 sq. ft. non-production area	8,000,000
Total	\$25,000,000
10,000 sq. ft. Class-10,000 clean room	\$9,000,000
40,000 sq. ft. non-production area	8,000,000
Total	\$17,000,000

### 9.3. Appendix 3: Facilities Equipment Costs

Equipment	Estimated cost (new) \$K
Pure-water system	300
Waste-water system	100
Storage of pure and toxic gases	500
Liquid nitrogen	200
Chemical and materials storage	100
Gas cabinets and bunker	2,500
Hydrogen tank	200
Oxygen tank	200

### 9.4. Appendix 4: Process Tool Costs

Process tool	Estimated cost (new) \$K	Estimated cost (used) \$K	Sacrificial surface	Bulk	LIGA
Workflow management tools	90	35	X	X	X
Wafer-cleaning line	350	125	X	X	
Photoresist-line track C/D/B	550	250	X	X	X
Reticle-inspection tool	100	50	X	X	X
Mask clean/store	60	25	X	X	
Registration measurement	100	50	X	X	
PR inspection station	500	250	X	X	
1- $\mu$ m stepper	1100	600	X		
PR stab	100	50	X	X	X
PR strip	100	50	X	X	X
Dryers	200	100	X	X	
Wet bench	120	30	X	X	
HF wet etch bench	60	25	X	X	
Safety and alarm systems	500	500	X	X	
LPCVD/P	1000	500	X		
Diff	1000	500	X	X	
PECVD	1100	500	X		
Evaporator	450	250	X	X	X
Sputter	900	600	X	X	X

Reactive-ion etch (RIE) Ox/N	1200	700	X	X	
Chemical-Mechanical Polish (CMP) Ox	700	350	X	X	
Deep RIE	1000	1000	X	X	X
Electroplating baths	600	600	X	X	X
Wet chemistry Hoods, benches	450	200	X	X	X
Hot embosser	350				X
Extruder	650				X
Injection molder	350				X
Lapper	60				X

### 9.5. Appendix 5

#### Labor Costs

Function	Salary in \$	Load	Total per employee
Operator	33,000	1.5	49,500
Engineer	90,000	1.5	135,000
Secretary	20,000	1.5	30,000
Marketing	50,000	1.5	75,000
Shipping/receiving	35,000	1.5	52,500
Quality control	65,000	1.5	97,500

### 9.6. Appendix 6

#### Process Steps, Mask Steps and Materials across Manufacturing Methods

Process type	Sacrificial surface micromachining (SSM)			Bulk micromachining	High-aspect-ratio micromachining (HARM)		
	3	4	5		Deep reactive-ion etching (DRIE)	LIGA	Deep UV
Number of levels	3	4	5		Deep reactive-ion etching (DRIE)	LIGA	Deep UV
Process steps	80-120	200-250	300-350	20-50	60-80	80-100	80-100
Mask steps	6-8	8-10	12-20	4-8	8-10	10-15	10-15
Materials	Silicon Silicon-nitride Germanium-aluminum			Silica Glass Silicon-dioxide Aluminum	Plastics Aluminates Ceramics Plated materials		

## 9.7. Appendix 7

### Derivation of Contribution Margin Analysis

Equation 1: Profit = (SP – AC) \* Q

Equation 2: Profit = RoA \* Asset Base

Equation 3: AC = (TVC + TFC)/Q

Equation 4 – Substituting Equations 2 and 3 into Equation 1:

$$\text{RoA} * \text{Asset Base} = (\text{SP} - (\text{TVC} + \text{TFC})/\text{Q}) * \text{Q}$$

Rearranging Terms:

$$\text{Contribution Margin Equation: } (\text{SP} - \text{AVC}) = \frac{(\text{RoA} * \text{Asset Base}) + \text{TFC}}{\text{Q}}$$

#### Definition of Variables:

- SP = Selling price per unit,
- AC = Average total cost per unit,
- RoA = Return on assets,
- Asset Base = Total invested capital,
- TVC = Total variable costs,
- TFC = Total fixed costs,
- Q = Quantity of finished products.